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Crystallizing Innovation: The Emergence of the LCD at RCA, 1951-1976

Gross, Benjamin H.

Princeton, NJ : Princeton University

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CRYSTALLIZING INNOVATION: THE EMERGENCE OF THE LCD AT RCA, 1951-1976

Benjamin H. Gross

A DISSERTATION

PRESENTED TO THE FACULTY

OF PRINCETON UNIVERSITY

IN CANDIDACY FOR THE DEGREE

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BY THE PROGRAM IN

HISTORY OF SCIENCE

Advisor: Michael Gordin

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ABSTRACT

This dissertation considers the development of the liquid crystal display (LCD) at the Radio Corporation of America (RCA) as a means of gauging the degree of autonomy possessed by Cold War industrial researchers. It argues that the assembly of the first LCD prototypes and RCA's subsequent inability to market that technology depended upon the capacity of scientists and engineers at the corporation's Princeton research facility to harness institutional, financial, and literary resources to advance their professional objectives. By focusing its analysis on the workbench instead of the boardroom, this study presents RCA's technical staff as participants in the formation and implementation of corporate R&D strategy rather than passive recipients of managerial policies.

Unlike the executives who unveiled LCDs to the public in 1968, this discussion situates RCA's interest in liquid crystals alongside earlier attempts to develop a flat-panel successor to the cathode ray tube. Company chairman David Sarnoff's 1951 request for a "light amplifier" inspired researchers in Princeton to explore the possibility of wall-mounted displays, and the devices they developed over the next five years transformed how personnel throughout the corporation conceived of television's future. Even after budget concerns at the end of the decade prompted management to discourage such work as overly speculative, RCA engineers seized upon military contracts and the firm's renewed interest in digital computing to pursue "mural television" research into the 1960s.

Despite the proliferation of flat-panel technologies during this period, only the LCD succeeded in moving from the laboratory to the factory due to the efforts of a research group organized by electrical engineer George Heilmeier. Through progress

reports and conversations with managers and marketing experts, Heilmeier and his colleagues persuaded leaders at RCA's laboratories and operating divisions to sponsor their liquid crystal investigations and establish a pilot manufacturing plant. Though this advocacy persisted after 1968, a lack of internal funding and a growing awareness of the LCD's technological limitations provoked concerns among the Princeton staff, whose increasingly pessimistic forecasts of the project's commercial viability contributed to the decision to sell the RCA liquid crystal operation to Timex in 1976.

TABLE OF CONTENTS

Abstract . . . . . *iii*

Table of Contents . . . . . *v*

Acknowledgments . . . . . *vi*

Epigraph . . . . . *xiv*

Chapter 1-Introduction 1
"A true technical breakthrough": Reconstructing the Origins of the LCD

Chapter 2 27
"Like a picture on the wall": Flat-Panel Display Research at RCA, 1951-1956

Chapter 3 67
"A fumbling prelude": Cold War Reorganization and Mural TV Research, 1956-66

Chapter 4 112
"Turbulence began here": From Williams Domains to the Guest-Host Effect, 1961-1965

Chapter 5 155
"We had to think of a sexy name.": Dynamic Scattering From Theory to Prototype, 1965-1968

Chapter 6 202
"What happened to all the empires": RCA and the Commercialization of the LCD, 1968-1976

Chapter 7-Conclusion 260
"The ingredients of a good novel": Past and Future Histories of the LCD

List of Abbreviations 276

Bibliography 278

ACKNOWLEDGMENTS

On the 10th of April 1968, a month before RCA announced the creation of the first liquid crystal displays, Alfred Hitchcock received his only Academy Award. Though his film *Rebecca* was named Best Picture in 1940, producer David O. Selznick had accepted the prize, leaving Hitchcock without an Oscar to call his own. Now, nearly three decades later, the Academy's Board of Governors decided to recognize the film-maker's contributions to modern cinema with the Irving G. Thalberg Memorial Award for lifetime achievement. Following a summary of his career by fellow director Robert Wise, Hitchcock strolled across the stage to the familiar strains of Gounod's "Funeral March of a Marionette" and delivered one of the shortest Oscar speeches on record: "Thank you."

Hitchcock's example flickered to mind as I sat down to compile the acknowledgments for this dissertation and realized that there was no way I could adequately express my thanks to everyone involved in its composition. The elegance of the director's solution was understandably appealing. Embracing this tactic, however, would run counter to my efforts to restore complexity to accounts of collaborative research. While some might revel in the irony of such a stylistic maneuver, I will instead attempt the difficult, yet often repeated, scholarly ritual of winnowing down a seemingly endless list of colleagues and friends into a handful of pages.

To begin, I would like to thank the members of my committee, whose critiques have sharpened my dissertation's arguments and will provide essential guidance in any future attempts to transform it into a book. Bill Leslie's explorations of Cold War science laid the intellectual foundation for my research on the subject and I am grateful for his

willingness to comment on Chapter 6 in connection with the 2011 Hagley Research Seminar Series and act as my external reader. Since my arrival at Princeton, I have benefitted from Angela Creager's intellectual insights as much as her sense of humor. As my first reader, Emily Thompson provided feedback on every chapter of this dissertation and pressed me to consider the broader historiographic implications of RCA's flat-panel display investigations. Finally, I am indebted to my advisor, Michael Gordin, who has consistently proven himself to be the very model of an academic mentor. Over the past five years, he has served as my editor, teacher, advocate, and sounding board. At the risk of verging into counterfactual history, I find it nearly impossible to imagine this dissertation's successful completion without his involvement.

I would also be remiss if I did not take a moment to honor Michael Mahoney, whose seminars on material epistemology and the Scientific Revolution were my earliest formal introductions to the history of technology. It was Mike who, during a discussion of the Royal Society, warned me not to let the social and political aspects of a scientific institution's history eclipse the research activities of its members, a piece of advice that has guided my scholarship ever since. Though his passing in the summer of 2008 limited his involvement with this project, I believe that he would appreciate its contents, as well as the fact that it was composed entirely in WordPerfect.

Like all dissertations, this one depended upon a sizable number of professional archivists and librarians. Foremost among these was Alexander Magoun, the director of the David Sarnoff Library in Princeton, who in the fall of 2007 first suggested that the development of the LCD might be a worthwhile research topic. In addition to his detailed

knowledge of RCA's history, Alex granted me unprecedented access to the firm's technical archive, ensuring that I accumulated sufficient materials to sustain my work after the facility's closure in 2009. I would also like to thank Lynn Catanese, Carol Lockman, Philip Scranton, Jon Williams, and the rest of the staff of the Hagley Museum and Library in Wilmington, DE for incorporating the Sarnoff Library's documents into their collections and allowing me to utilize their other RCA holdings. I am similarly grateful to the College of New Jersey for offering to house the Sarnoff Library's collection of artifacts, including several prototype LCDs, and wish Emily Croll the best of luck with her duties as curator of the planned museum in Ewing.

Most of this dissertation was written using books and journals obtained under the auspices of the Princeton University library system, and history librarian Elizabeth Bennett helped me navigate its intricacies on numerous occasions. I also consulted with Melissa Acosta and Stephen Ferguson of the library's department of Rare Books and Special Collections, Willow Dressel of the university's Engineering Library, and the staff of the Seeley G. Mudd Manuscript Library. Outside of Princeton, I received research assistance from George Curley from the University of California, Riverside, Lou Galie and the legal department of the Timex Corporation, Cara Gilgenbach of Kent State University's Special Collections and Archives, Sheldon Hochheiser of the IEEE History Center, Darrel Hopper and Frederick Meyer of the Air Force Research Laboratory at Wright-Patterson Air Force Base, and Jim Maxwell of the Liquid Crystal Institute.

A major advantage of studying recent history is the opportunity to interact with people who either witnessed or were directly involved in the events under investigation. I

am extremely grateful to the former members of RCA's technical staff who supplied oral histories in connection with this project, and to Joseph Castellano, Ennio Fatuzzo, George Heilmeier, Jean Kane, Karl Knop, James Moffa, Robert Ricci, and Richard Santilli for recounting their experiences via e-mail or in-person meetings. Though Margaret Graham's affiliation with RCA post-dated the period I study, her book on the VideoDisc, based on first-hand observations and discussions with company personnel, served as a model for my work, and her comments on my prospectus were greatly appreciated. Thanks as well to the participants in the monthly RCA alumni luncheon for sharing their stories of the company's glory days during meals at Conte's, Olive Garden, or Super Star East Buffet.

Princeton's history department supported the bulk of my dissertation research, and I relied heavily upon the administrative expertise of Minerva Fanfair, Brooke Fitzgerald, Judith Hanson, Lauren Kane, Lynn Kratzer, Pamela Long, Debora Macy, Audrey Mainzer, Reagan Maraghy, Kristy Novak, Etta Recke, and Amy Shortt. During the 2009-2010 academic year, I was honored to serve as the Charles C. Price Fellow at the Chemical Heritage Foundation (CHF). Beyond the tangible benefits of a private office and access, via Elsa Atson and Ashley Augustyniak, to the monographs in CHF's Othmer Library, the most rewarding aspect of my time in Philadelphia was being able to engage with other scholars sharing my interest in the history of the physical sciences. Often, such discussions took place as part of the organization's Brown Bag Lunch series or CALCIUM works-in-progress seminar, which provided venues to present preliminary versions of Chapters 2, 3, and 6 of this dissertation. But frequently, they occurred over a

mug of tea prepared by Hilary Domush, Sarah Hunter, or James Voelkel or during lunches organized by Ronald Brashear or Anke Timmermann.

Ultimately, the context of these conversations was less important than their participants, and I am pleased to have befriended all of the individuals mentioned above, as well as CHF research fellows Nicholas Best, John Ceccatti, Roger Horowitz, Matteo Martelli, Evan Ragland, Annalisa Salonius, Matthew Shindell, and our counterparts from the Philadelphia Area Center for the History of Science, Carin Berkowitz and Anna Geltzer. I also gained a great deal from my interactions with the staff of the Center for Contemporary History and Policy (CCHP), including David Caruso, Hyungsub Choi, and Erica Stefanovich. Though I could not know it at the time, my tenure at CHF foreshadowed an eventual return as a postdoctoral fellow, and I am grateful to CCHP director Jody Roberts for his patience as I put the finishing touches on this dissertation.

Besides the Hagley and CHF presentations described earlier, I have had the chance to share portions of my research in a variety of other settings. An early draft of Chapter 4 served as the basis for talks at the Society for the History of Technology (SHOT) meeting in 2008 and a 2009 doctoral summer school hosted at the Cité des Télécoms in Pleumeur-Bodou, France. The Princeton-Harvard Joint Workshop in the History of the Physical Sciences (a.k.a. "Phunday") provided a supportive environment to discuss my prospectus and portions of Chapters 2 and 6, and I thank my colleagues at Harvard, MIT, and Cornell for their comments. Chapter 2 was also the source of my contribution to the 2010 meeting of the Society for Social Studies of Science (4S), which due to the persistence of Bart Penders and David Schleifer will soon be published in an issue of the *Bulletin of Science,*

Technology & Society. Sections of Chapters 4, 5, and 6 were incorporated into a talk the same year at the Oral History in the Mid-Atlantic Region's conference on science, technology, and innovation. In the fall of 2011, I anticipate presenting Chapter 3 at SHOT and an abridged version of Chapter 5 at a CHF-Hagley joint workshop entitled "The Life of New Materials."

Closer to home, I was privileged to submit my prospectus and drafts of Chapters 2 and 5 to the Princeton history of science program seminar. One of the great strengths of Princeton's program is the diversity of faculty and graduate student perspectives represented in these weekly meetings. Among the former group, I found the comments of Graham Burnett, Dan Garber, Anthony Grafton, Katja Guenther, Susan Naquin, Eileen Reeves, Helen Tilley, and Keith Wailoo particularly helpful. I would also like to thank Catherine Abou-Nemeh, Lindy Baldwin, Michael Barany, Dan Bouk, Howard Chiang, Hannah-Louise Clark, Henry Cowles, Will Deringer, John DiMoia, Carrie Eisert, Yulia Frumer, Nathan Ha, Reut Harari, Evan Helpler-Smith, Cynthia Houng, Chin Jou, Bob MacGregor, Chris McDonald, Flori Pierri, Aviva Rothman, Margaret Schotte, Jeff Schwegman, Jeris Stueland, Ksenia Tarchenko, Iain Watts, Doogab Yi, and Adrian Young for their perceptive questions and unwillingness to settle for easy answers.

Of course, there is more to graduate school than the library and the seminar room. Striking a balance between academic and extracurricular activities is not always easy, but over the past five years my fellow history of science students and people like Tuna Artun, Erin Brightwell, Sara Brooks, Thomas Carlson, Zachary Chitwood, Natalie Holstein, Kyrill Kunakhovich, Jessica Lowe, James and Jessica Pickett, Zoe Ragland, Joseph Ricci,

Ben Schmidt, Jeannette Shindell, Alexis Siemon, Aaron Sizer, Herb and Laurie Squire, Annie Twitty, Jeremy Wallace, Afton Woodward, Bingyu Zheng, and Joshua Ziefle have helped me move toward that goal. Even if they did not realize it, playing board games, watching movies, or taking to the softball field as a member of the Fightin' Enlightenment were just as crucial as time spent in the archives to ensuring that this dissertation got written. I would also like to thank the staff of the Debasement Bar, who permitted me to serve, with Jordan Boyd-Graber, Clay Hambrick, and Alex Kloth, as host of "the best damn pub quiz in Princeton" for more than three years.

Alongside all the people I have met during my time in Princeton, I have continued to depend upon friendships formed as a student at Simsbury High School and Yale University and as a teacher at Overbrook High School in Philadelphia. Though we have long since scattered across the globe, Mike Anderson, Jeremy Banzhaf, Liz and Keith Bonawitz, Evan and Emily Burke, Miriam Clinton, Evan Davidson, Mike Gann, Colin and Julie Girgenti, Jenna Koch, J.D. Martin, Alex McBurney, Scott Meek, Matthew Mugmon, John Murphy, Freeden Oeur, Tom O'Reilly, Alex Rosati, James Sinclair, Sean and Sarah Tulin, James Turner, Charles Umiker, and the entire Woodruff clan–especially David, Matthew, and Kate–have all made the stress of graduate school far more manageable. Hopefully, entering the job market will not preclude my participation in any of our future ultimate frisbee games, trips to the Standard Tap, or summer vacations in Maine.

Finally, I owe the deepest debt of all to my family. Since I embarked on this journey five years ago, they have offered nothing but unconditional support for my decision. When I was in elementary school, my father Jeffrey introduced me to RCA and

David Sarnoff through a screening of Ken Burns' *Empire of the Air*, inspiring a fascination with the history of electronics that has persisted to this day. From my mother Janna, I inherited my love of libraries, a particularly useful trait for an aspiring academic. Even after moving to Cincinnati to start a pediatric residency, my sister Andrea has always been willing to find time in her schedule to compare notes on the merits of our respective graduate educations. I am grateful to everyone who contributed to this project, but it is to my family that this dissertation is ultimately dedicated. Thank you.

"In reviewing the past, one's thoughts inevitably turn to the future of electronics and RCA, for it is there that the most interesting history will be written."

-Elmer Engstrom, "A History of Radio Corporation of America" (1963)

CHAPTER ONE–INTRODUCTION

"A true technical breakthrough": Reconstructing the Origins of the LCD

One day in late May 1968, a group of reporters gathered in a small auditorium on the ground floor of 30 Rockefeller Plaza, awaiting an announcement from the Radio Corporation of America (RCA). Those arriving early perused a press release, whose contents seemed at times to have been drawn from a science-fiction novel. From any other source, the promise of "an all-electronic clock with no moving parts" and flat screens that could be utilized in everything from automobile dashboards to stock tickers might be deemed fantastic, but over the past fifty years RCA had cultivated an unsurpassed reputation for electronic innovation.[1] Due to its central role in the development of commercial radio broadcasting and both monochrome and color television, the press was willing to grant the company the benefit of the doubt, even if this latest invention relied upon an unfamiliar set of substances with a paradoxical name: liquid crystals.[2]

A fact sheet pre-circulated by RCA's public relations department clarified that liquid crystals were organic compounds possessing the mechanical properties of a pourable liquid and the regular molecular arrangements of a crystalline solid.[3] James Hillier, the vice president in charge of RCA Laboratories and acting master of ceremonies, explained that his company's interest in these substances began "several years ago when some of our scientists discovered that an electric field could change the molecular

[1] RCA News, "RCA ANNOUNCES BREAKTHROUGH IN LIQUID CRYSTAL FIELD; DEMONSTRATES THIN-SCREEN DISPLAYS OF PRINT, PICTURES, MOVING IMAGES," Press Release (28 May 1968), David Sarnoff Library (DSL), 1-2.

[2] For more on RCA's contributions to the radio and television industries, see: Margaret B.W. Graham, *The Business of Research: RCA and the VideoDisc* (New York: Cambridge Univ. Press, 1986 [1988]); Robert Sobel, *RCA* (New York: Stein and Day, 1986).

[3] RCA, Dept. of News & Information, "FACT SHEET: LIQUID CRYSTAL DISPLAYS," Zanoni Personal Archive (ZPA), 1.

orientation of certain liquid crystals and make them reflect light."[4] This behavior was slow and confined to a small range of high temperatures, but chemists and physicists at the David Sarnoff Research Center (DSRC) in Princeton soon found a means of electrically inducing turbulence in another class of liquid crystals, causing the previously transparent samples to take on the milky-white appearance of frosted glass.[5] Working in conjunction with electrical engineers, these researchers synthesized materials capable of exhibiting this "dynamic scattering" effect at room temperature and incorporated them into a new form of electronic display. These devices were thin, consisting of two pieces of specially treated glass separated by a liquid crystal layer, and offered lightweight, rugged construction compared to existing cathode ray tubes. In addition, since liquid crystals reflect light rather than emit their own, they had low power requirements and would not wash out in bright ambient conditions.

In conjunction with members of the Princeton research team, Hillier demonstrated several prototype liquid crystal displays (LCDs).[6] These included a light shutter, which could be placed in window or door glass panels "to provide privacy with the push of a button," as well as the promised "all-electronic clock."[7] Perhaps most compelling of all was a high-resolution image display, hinting that liquid crystals might eventually allow for the creation of flat-screen, portable televisions. "You could take such a set to the beach,"

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[4] James Hillier, "Draft of Remarks By Dr. Hillier At Liquid Crystal Press Conference, 28 May 1968," Bernard Lechner Collection, DSL, 2.

[5] Hillier, "Draft of Remarks...," 2.

[6] Joseph A. Castellano, *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry* (Hackensack, NJ: World Scientific, 2005), 48-51; Bernard Lechner, Interview with author, Princeton, NJ, 24 Apr. 2009. See also: George Heilmeier, "Press Conference Presentation [28 May 1968]," Bernard Lechner Collection, DSL; Bernard Lechner, "Press Conference Presentation [28 May 1968]," Bernard Lechner Collection, DSL.

[7] Hillier, "Draft of Remarks...," 4-6.

Hillier joked, "and, in between bikini watching, see the Mets on TV figure out a new way to lose a ball game."[8]

Hillier was quick to acknowledge that although RCA's engineers had constructed a small display capable of being addressed with standard TV signals, the engineering hurdles associated with scaling up to a fully-functional liquid crystal television remained quite high.[9] "We believe we have achieved a true technical breakthrough—a new electro-optic effect—that in the years to come will have a significant effect upon the information handling business," he explained. "But thus far, it is a research breakthrough. It may be years before even the simplest application we have discussed can be brought to fruition."[10] Hopefully when that occurred, Hillier noted before yielding the floor to questions, "you will learn about it at an RCA press conference similar to this one."[11]

Hillier's predictions proved correct, but as this dissertation will illustrate, only to a point. For while the LCD, found in everything from laptops and wristwatches to calculators and televisions, has emerged as one of the most pervasive devices of the twenty-first century, RCA abandoned efforts to market the technology less than a decade after its 1968 announcement. This study explains that decision by situating liquid crystals alongside previous RCA efforts to create a flat-panel replacement for the cathode ray tube. Specifically, it considers how personnel associated with those projects contributed to the formation of R&D policy between 1951 and 1976. Rather than treat scientists and

[8] Hillier, "Draft of Remarks...," 7.
[9] For more on the small-scale matrix-addressed display shown at this press conference, see: Bernard Lechner, "Press Conference Presentation [28 May 1968]," Bernard Lechner Collection, DSL; Bernard Lechner, "History Crystallized: A First-Person Account of the Development of Matrix-Addressed LCDs for television at RCA in the 1960s," *Information Display* (Jan. 2008): 28-30.
[10] Hillier, "Draft of Remarks...," 8.
[11] Hillier, "Draft of Remarks...," 8.

engineers as passive recipients of corporate strategy, I argue that the outcomes of RCA's various flat-panel initiatives depended upon the ability of technical staff members to persuade managers of a given project's commercial or strategic value, regardless of changing company priorities, funding sources, and organizational structures.

The case of the LCD offers numerous examples of scientists exerting control over the course of research in an industrial setting, as well as the limits of their agency. Drawing upon documents preserved in RCA's technical archive, it is possible to trace the liquid crystal project's changing status as researchers harnessed a range of institutional, financial, and literary resources to acquire allies, pursue new scientific objectives, and confront opponents throughout the corporation. In the absence of comparable holdings from RCA's headquarters and operating divisions, these laboratory notebooks and project reports, supplemented with oral history interviews, constitute the most comprehensive collection of materials associated with the first-ever attempt to commercialize the LCD.[12] The resulting discussion therefore emphasizes the DSRC, partly by necessity, but also by design, since Princeton researchers oversaw the majority of RCA's flat-panel investigations and worked closely with the company's management and manufacturing staffs to incorporate the results of these efforts into commercial products.

[12] The majority of RCA's business records were lost following the corporation's 1986 purchase by General Electric. Until its closure at the end of 2009, the David Sarnoff Library in Princeton served as the principal repository for RCA technical documentation. Those materials are now in the possession of the Hagley Museum and Library in Wilmington, DE, which already possessed a collection of documents from RCA's manufacturing division in Camden, NJ. The Hagley's combined archival holdings are now the world's largest documentary collection of material related to RCA and its divisions, excluding its broadcasting arm (NBC). For further information on the status of RCA-related archives, see: "David Sarnoff Library-Frequently Asked Questions," accessed 30 Jul. 2011, http://www.davidsarnoff.org/faq.html.

The placement of RCA's scientists and engineers at the center of this case study also facilitates engagement with three ongoing areas of discussion among historians of corporate science. First, my account of the LCD's origins contrasts the realities of Cold War innovation with the ideal embodied in the so-called "linear model." At the same time, this analysis confirms the applicability of laboratory notebook analysis as a means of reconstructing the cognitive and social dynamics of collaborative technological development. Finally, RCA's ultimate inability to capitalize upon its first-mover position and become a major liquid crystal producer provokes reflection upon the contingency of technological success and failure and how historians of industrial research and their subjects define these categories.

Moving Beyond the Linear Model

As eager as RCA was to present the liquid crystal display as a revolutionary electronics breakthrough, the origin story it presented in 1968 reflected longstanding attitudes towards the organization of corporate research. The belief that basic science, such as the experiments resulting in the first observation of dynamic scattering, drove technological innovation traced its genealogy to the end of World War II. Following their involvement in wartime research projects, American scientists sought to maintain a high level of federal support for their work once hostilities drew to a close.[13] Many were wary,

[13] For more on the transformation of American science during World War II, see: James Phinney Baxter, *Scientists Against Time* (Cambridge, MA: MIT Press, 1946 [1968]); Margaret B.W. Graham, "Industrial Research in the Age of Big Science," in *Research on Technological Innovation, Management and Policy*, vol. 2, ed. Richard S. Rosenbloom (Greenwich, CT: JAI Press Inc., 1985), 47-60; Peter Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago: Univ. of Chicago Press, 1997), 239-311 (Ch. 4); David Hounshell, "The Evolution of Industrial Research in the United States," in *Engines of Innovation: U.S. Industrial Research at the End of an Era*, ed. Richard S. Rosenbloom & William J. Spencer (Boston: Harvard Business School Press, 1996), 41-46; Daniel Kevles, *The Physicists: The*

however, of yielding control over the nation's newly expanded scientific infrastructure to politicians or military officials. Foremost among these was Vannevar Bush, the wartime head of the Office of Scientific Research and Development (OSRD), who presented his vision of postwar research policy in a 1945 report entitled *Science, the Endless Frontier*.[14]

Bush's report drew a sharp distinction between basic research, conducted "without thought of practical ends," and the applied research overseen by the government, military, and industry.[15] Though he deemed sponsorship of both categories of inquiry essential to America's national welfare, Bush argued that the government should act to ensure their institutional separation. Basic research would be conducted in universities, insulated from any organization with operating goals beyond the expansion of scientific understanding. The imposition of short-term deadlines typical of applied research risked undermining the accumulation of fundamental knowledge that Bush deemed "the pacemaker of technological progress."[16] After all, he asserted, "new products and new processes do not appear full grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science."[17]

Bush was hardly the first person to discuss the dichotomy between basic and applied research–or, more broadly, between science and technology.[18] Still, his ideas came

History of a Scientific Community in Modern America (Cambridge, MA: Harvard Univ. Press, 1971 [1995]), 287-323; Donald E. Stokes, *Pasteur's Quadrant: Basic Science and Technological Innovation* (Washington, D.C.: Brookings Institution Press, 1997), 45-57.

[14] Vannevar Bush, *Science, the Endless Frontier: A Report to the President on a Program for Postwar Scientific Research* (Washington, D.C.: National Science Foundation, 1945).

[15] Bush, 13.

[16] Bush, 14.

[17] Bush, 14.

[18] For a concise overview of the evolution of the science-technology dichotomy from ancient Greece until World War II, see Stokes, 26-45. For a discussion of the division between pure and applied science in the American context, see: Ronald Kline, "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880-1945," *Isis* 86, no. 2 (Jun. 1995): 194-221.

into increasing prominence during the five years of congressional hearings preceding the 1950 formation of the National Science Foundation.[19] His failure to dissuade military agencies established in the midst of these debates (e.g. the Office of Naval Research) from investing heavily in university research programs may have doomed his proposed division of scientific responsibilities, but by the mid-1950s, Bush's notion that new technologies resulted solely from undirected, fundamental research had acquired the status of conventional wisdom.[20] This "linear model"[21] gained additional traction when policymakers, concerned that America had lost its scientific edge in the wake of Sputnik, implemented a series of reforms that encouraged corporations seeking federal research funds to funnel them towards basic science.[22]

[19] For more on the NSF debates, see: Kevles, 349-366; Stokes, 50-54.

[20] For a thoroughly researched account exploring how Bush's ideas became the dominant framework for discussing innovation among American policymakers, see: Glen Ross Asner, "The Cold War and American Industrial Research" (Ph.D. diss., Carnegie Mellon University, 2006).

[21] In his contribution to a 2002 volume on the relationship between science and industry, David Edgerton, echoing a 1985 *Osiris* article by George Wise, argues that Bush's "linear model" was embraced solely by the policymaking elite. He also claims that the "linear model" concept was the creation of historians trying to avoid critical engagement with other models of innovation. In his dissertation, Asner addresses such concerns, noting that people seeking "evidence of a simple transmission of the linear model from the world of ideas through government and to industry will be disappointed," since it was rarely discussed as a coherent set of ideas and was not implemented in a unified manner. Nevertheless, he counters, "the history of postwar industrial research is incomprehensible without attention to the linear model and government policy." (Asner 42-44) This study agrees with Asner's advisor, David Hounshell, who responded to Edgerton's essay by observing that just because Cold War scientists did not use the term "does not mean that they did not subscribe to a system of belief or cognition that is consistent with what scholars from a variety of disciplines have, during the last twenty-five years called 'the linear model.'" (60) See: David Edgerton, "'The Linear Model' Did not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century," *The Science-Industry Nexus: History, Policy, Implications*, ed. Karl Grandin, et al. (Sagamore Beach, MA: Watson Publishing International, 2002), 31-57; David Hounshell, "Industrial Research," in Grandin, et al., 59-65; George Wise, "Science and Technology," *Osiris* 2nd series, 1 (1985): 229-246.

[22] These policies included changing the federal tax code (e.g. adding rapid amortization regulations that permitted companies to deduct investments in new facilities at an accelerated rate), industrial dispersal policies that encouraged the geographic fragmentation of corporate operations, and military funding policies, especially reforms to the Department of Defense's Independent Research and Development (IR&D) program, which allowed contractors to charge both basic and applied research with no specific objectives to all military contracts. See Asner, 173-206, 247-354. For more on the consequences of these policies on American physics research in both universities and corporate labs, see: Paul Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940-1960,"

RCA was not exempt from this trend. While it did not capitalize upon government incentives to construct new laboratory facilities like its rivals at AT&T and IBM, the company's Princeton research center set aside the balance of fundamental and applied research previously advocated by its chairman, David Sarnoff, in favor of a stronger basic science agenda.[23] Facing an increasingly competitive postwar marketplace, RCA's recruiters traveled to graduate schools in search of researchers familiar with recent advances in solid-state electronics. Government contracts played a vital role in this "building block" strategy, covering the costs of exploratory research attractive to scientists, who might otherwise have shunned a position in industry.[24]

The simultaneous influx of federal money and theoretically inclined personnel profoundly transformed the research environment at RCA and other firms, but whether these changes accelerated the development of new commercial products, as Bush had predicted, was less certain. In 1964, James Hillier acknowledged a gap between the DSRC's focus on fundamental research and the applied mindset of the operating divisions, which complicated the process of developing new technologies.[25] That same year, the Department of Defense initiated a study, codenamed Project Hindsight, to gauge the value of different components of the military's R&D program.[26] Its findings, published in a 1966 report, that 91% of innovations in twenty major weapons systems came from mission-

Historical Studies in the Physical and Biological Sciences 18, no. 1 (1987): 149-229.

[23] Graham (1986), 48-75. This holistic characterization of Sarnoff's research philosophy, whereby RCA's laboratories would be responsible for both basic and applied research, is discussed in greater detail in Chapter 2. For more on the linear model and its consequences on the architecture of Cold War research laboratories, including IBM's Thomas Watson Research Center and Bell Laboratories, Holmdel, see: Scott G. Knowles & Stuart W. Leslie, "'Industrial Versailles': Eero Saarinen's Corporate Campuses for GM, IBM, and AT&T," *Isis* 92, vol. 1 (Mar. 2001): 1-33.

[24] Graham (1986), 68-74.

[25] RCA Laboratories, *Research Report 1964*, DSL, 1-2; Graham (1986), 76-80, 85-87.

[26] Asner, 302-324.

oriented, rather than basic, research cast doubt upon what the study's authors called "the simple, direct sequence taught by the folklore of science [i.e. the linear model]."[27]

Such conclusions did not immediately persuade either RCA or the Defense Department to renounce the linear model, but foreshadowed the 1971 congressional decision, made in light of growing public discontent with the Vietnam War, to eliminate funding for projects without identifiable ties to military operations.[28] In the aftermath of this decision, corporations and academics struggled to develop alternative frameworks for understanding innovation, spurring a new wave of historical investigations of industrial laboratories. These studies, written during the 1970s and 1980s, adopted stances antithetical to the linear model, highlighting the apparently successful fusion of basic and applied science in laboratories run by General Electric (GE), AT&T, Du Pont, and Kodak.[29] Building upon this foundational research, more recent scholarship has continued to explore issues left unaddressed in Bush's original report, such as different companies' attitudes towards technology transfer, how collaboration between corporations and outside organizations fostered innovation, and the degree to which the state or consumers shape these processes.[30]

[27] Asner, 313-315; Kline, 220.

[28] The chief sponsors for this shift in government science policy were Sen. Mike Mansfield (D-MT), Sen. William Fulbright (D-AR), and Sen. William Proxmire (D-WI), who oversaw the 1971 addition of language to Section 203 of the Military Procurement Authorization Act, which insisted that all IR&D funded projects possess "a potential relationship to a military function or operation." (Asner, 347) For more on the legislative battles leading up to this regulation, see: Asner, 336-349; Kevles, 414-420.

[29] See, for example: David A. Hounshell and John Kenly Smith, Jr., *Science and Corporate Strategy: Du Pont R&D, 1902-1980* (New York: Cambridge Univ. Press, 1988); Reese V. Jenkins, *Images and Enterprise: Technology and the American Photographic Industry* (Baltimore: Johns Hopkins Univ. Press, 1976); Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (New York: Cambridge Univ. Press, 1985); George Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (New York: Columbia Univ. Press, 1985).

[30] These three themes are derived from the introduction and organization of articles in Sally H. Clarke, et al., ed., *The Challenge of Remaining Innovative: Insights from Twentieth-Century American Business* (Palo Alto, CA: Stanford Business Books, 2009). While Bush intended *Science, the Endless Frontier* to

All three of these themes are evident in the burgeoning historiography of consumer and semiconductor electronics of which this dissertation is a part. Technology transfer–the process through which scientific breakthroughs are reconfigured into marketable devices–plays a central role, for example, in Ross Bassett's study of the rise of metal oxide-semiconductor (MOS) transistors.[31] Bassett credits the success of entrepreneurial start-ups like Fairchild Semiconductor and Intel in commercializing this technology to the flexibility of their R&D organizations compared to more established competitors like IBM.[32] Bassett and fellow historian Christophe Lécuyer also take pains to emphasize the collaborative aspects of the electronics industry, attributing the rise of Silicon Valley to the circulation of scientific information and production techniques among a closely linked network of firms.[33] Such community building was not limited to the semiconductor industry. Throughout the history of telecommunications, corporations have formed partnerships to promote or oppose changes in broadcasting regulations, from fights over

show how the state could best cultivate technological innovation, his contention that "[t]he simplest and most effective way in which the Government can strengthen industrial research is to support basic research and to develop scientific talent" ignored a wide range of options utilized by the state to regulate corporations, ranging from tax policy to antitrust regulation (16). For more on the importance of incorporating consumer perspectives into historical studies of technology, see Ruth Schwartz Cowan, "The Consumption Junction: A Proposal for Research Strategies in the Sociology of Technology," in *The Social Construction of Technological Systems*, ed. Wiebe E. Bijker, et al., (Cambridge, MA: MIT Press, 1987), 261-280.

[31] While this dissertation concentrates upon technology transfer within a single firm, the term can also apply to a wide range of interactions among different businesses, universities, governments, and cultures. Case studies embodying a variety of these relationships can be found in Grandin, et al. and Clarke, et al. as well as Henry Etzkowitz, *The Triple Helix: University-Industry-Government Innovation in Action* (New York: Routledge, 2008).

[32] Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins Univ. Press, 2002). Hyungsub Choi extends this comparative approach across international boundaries in his dissertation, "Manufacturing Knowledge in Transit: Technical Practice, Organizational Change, and the Rise of the Semiconductor Industry in the United States and Japan, 1948-1960" (Ph.D. diss., Johns Hopkins University, 2007).

[33] Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970* (Cambridge, MA: MIT Press, 2006); Bassett, Ch. 5 (139-166).

FM radio bandwidth to more recent debates over high-definition digital television standards.[34] In each case, the preferences of consumers, whether the military agencies funding integrated circuit research or citizens wishing to purchase new TV sets, and the federal government's regulatory authority affected the form of the resulting technology.

This dissertation extends these questions of technology transfer, knowledge circulation, and government intervention to RCA's laboratories. It draws heavily upon the work of historians like Bassett and Hyungsub Choi, who examined the evolution of RCA's semiconductor research program, as well as Margaret Graham's thorough analysis of the corporation's ill-fated VideoDisc project.[35] All three of those accounts call attention to the tangled relationship between RCA's laboratories and operating divisions, inter-firm alliances and antagonisms, and the effects of antitrust and licensing policies on R&D organization.

What distinguishes my analysis of RCA's liquid crystal displays and their flat-panel precursors from the authors listed above is its sustained focus upon a single firm's technical staff. Previous investigations have analyzed the activities of industrial researchers primarily as a means of tracking changes in the institutional contexts in which they worked. These studies give little weight to the roles that laboratory personnel played in such transitions, concentrating instead on those charged with the direct implementation of

[34] For more on the early history of FM radio, see: Gary L. Frost, *Early FM Radio: Incremental Technology in Twentieth-Century America* (Baltimore: Johns Hopkins Univ. Press, 2010) and Christopher Sterling & Michael C. Keith, *Sounds of Change: A History of FM Broadcasting in America* (Chapel Hill, NC: Univ. of North Carolina Press, 2008). Detailed discussions of the debates surrounding American analog and digital television broadcasting standards can be found in: Alexander B. Magoun, *Television: The Life Story of a Technology* (Baltimore: Johns Hopkins Univ. Press, 2009) and Joel Brinkley, *Defining Vision: How Broadcasters Lured the Government into Inciting a Revolution in Television* (New York: Harcourt Brace, 1997).

[35] Bassett, 33-45, 139-145, 162-165; Choi, 13-52; Graham (1988).

corporate science policy. Consequently, while these authors aim to move beyond Bush's linear model, they risk perpetuating another one-dimensional framework, where managers alter the contours of the laboratory environment without input from the scientists they employ. This dissertation rejects such a unilateral conception of corporate science and utilizes the daily research records preserved in RCA's technical archive to argue that the company's plans for a new technology resulted from extended interactions between the laboratory scientists responsible for its creation and their superiors.

The Fine Structure of Corporate Science

Considering that the majority of today's scientists work in the private sector, surprisingly few discussions of corporate research exist that are written from the perspective of the industrial laboratory.[36] Research managers, rather than scientists or engineers, dominated the early historiography of corporate science. By lionizing figures like GE's Willis Whitney, Bell Labs' J.J. Carty and Frank Jewett, or General Motors' Charles Kettering, authors implicitly endorsed the thesis set forth in 1977 by historian Alfred D. Chandler, Jr.[37] In his magisterial study, *The Visible Hand*, Chandler argues that the managerial hierarchies characteristic of the "modern multiunit business enterprise" provided firms with the means to coordinate all aspects of their business more efficiently than market forces might otherwise allow, including the research activities conducted in

[36] Steven Shapin, "The Scientist in 2008," *Seed Magazine*, 19 (20 Nov. 2008): 58-62. Shapin observes that private industry is currently responsible for approximately 70% of U.S. R&D, including 20% of work traditionally classified as "basic research."
[37] See, for example: Stuart W. Leslie, *Boss Kettering: Wizard of General Motors* (New York: Columbia Univ. Press, 1983); Reich (1985); Wise, *Willis Whitney* (1985).

their laboratories.[38] Contrary to the jeremiads of economists like Joseph Schumpeter, who feared that the routinization of R&D activity would stifle innovation, Chandler suggests that managerial hierarchies effectively supplanted individual entrepreneurs as generators of new technology and economic growth.[39]

Over the years, Chandler's argument came under attack from critics,[40] who accused him of technological determinism,[41] ignoring the diversity of the American business environment,[42] and treating the expansion of corporate power as a uniformly positive phenomenon.[43] None of these attacks succeeded in completely loosening the grip of *The Visible Hand* from discussions of corporate laboratories. Research managers remained central to historical analyses of industrial laboratories, even in those cases where the contributions of corporate scientists are considered in some detail. David Hounshell and John Kenly Smith, Jr., for example, discuss the origins of neoprene and nylon, but these are diversions from their book's central concern with the efforts of Du Pont

[38] Alfred D. Chandler, Jr., *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, MA: Belknap Press, 1977), 1-6. See also: Steven W. Usselman, "Still Visible: Alfred D. Chandler's *The Visible Hand*," *Technology and Culture* 47, no. 3 (Jul. 2006): 584-596.

[39] Clarke, et al., 1-2; Hounshell (1996), 26. Chandler elaborated upon these ideas in 1990's *Scale and Scope: The Dynamics of Industrial Capitalism* (Cambridge, MA: Belknap Press, 1990).

[40] The critical reaction to Chandler's thesis is discussed in: Clarke, et al., 2-3; David Hounshell, "Hughesian History of Technology and Chandlerian Business History: Parallels, Departures, and Critics," *History and Technology* 12, no. 3 (1995): 205-224; Usselman, 589-596.

[41] Such attacks are based on the prominent role of railroads and telegraphs as coordinating technologies in Chandler's study. See: Hounshell (1995), 209-211.

[42] See, for example: Philip Scranton, *Endless Novelty: Specialty Production and American Industrialization, 1865-1925* (New York: Cambridge Univ. Press, 1997). Building upon his previous studies of the Philadelphia textile industry, Scranton shows how Chandler's multiunit enterprises were only one subset of a diverse range of American business models which have largely been ignored due to their non-reliance on mass production techniques.

[43] The most prominent critic along these lines was David Noble, whose *America by Design: Science, Technology, and the Rise of Corporate Capitalism* (New York: Knopf, 1977) was published the same year as *The Visible Hand*. Noble provocatively argued that the democratizing potential of technological innovation was overtaken by corporations who manipulated America's political and educational systems to ensure that the newly-emerging class of professional engineers were under their control. See also: Hounshell (1995), 209-211; Usselman, 589-591.

executives to tailor research strategies in response to changing economic and political conditions.[44] Similarly, Margaret Graham describes the achievements of researchers developing RCA's home video technology , but explicitly states that the purpose of her analysis is "to examine aspects of the VideoDisc innovation experience from a management standpoint."[45]

Though current scholarship acknowledges the pitfalls of uncritical acceptance of the Chandlerian prioritization of managers over scientists, inverting that dynamic has proven more challenging.[46] Even Steven Shapin's *The Scientific Life*, which includes a pair of chapters comparing Cold War understandings of the scientific profession among academic and industrial researchers, relies almost exclusively on the perspectives of industrial managers in discussing the latter.[47] Shapin justifies this decision by noting that most managers possessed workbench experience and often maintained some presence in the laboratory. Without "significant or systematic ethnographic studies of working industrial researchers," he argues, their perspectives, encapsulated in periodicals devoted to research management, provide the clearest glimpse into corporate scientists' attitudes towards their work.[48]

[44] Hounshell & Smith, 223-274. It is worth noting, for example, that both neoprene and nylon are discussed within the context of a fundamental research program implemented by Du Pont Chemical Department Director, Charles Stine. Though the authors acknowledge that the ultimate success of Stine's program was mostly the result of attracting a particularly talented researcher (Wallace Carothers), they credit Stine for cultivating an attractive research environment and encouraging Carothers to pursue his interest in polymerization. (248)

[45] Graham (1988), 7.

[46] For examples of recent management-focused studies of innovation, see: Margaret B.W. Graham, "Corning as Creative Responder: A Schumpeterian Interpretation of Disruptive Innovation" and Kenneth Lipartito, "Rethinking the Invention Factory: Bell Laboratories in Perspective," in *The Challenge of Remaining Innovative: Insights from Twentieth-Century Business*, ed. Sally H. Clarke, et al. (Palo Alto: Stanford Univ. Press, 2009), 85-113, 132-159.

[47] Steven Shapin, *The Scientific Life: A Moral History of a Late Modern Vocation* (Chicago: Univ. of Chicago Press, 2008), 127-164.

[48] Shapin, 130.

Shapin is correct that compared to their academic counterparts, corporate scientists receive a disproportionately low amount of scholarly attention. Yet much as scholars abandoned the linear model upon realizing its shortcomings, they have also started to set aside the notion that corporate research strategies are simply imposed on researchers, whose actions contribute little to the overall course of technological development. A sense of this transition can be obtained through a comparison of Pap Ndiaye's treatment of chemical engineering in his 2001 study of Du Pont and that of Hounshell and Smith over a decade earlier.[49] Where Hounshell and Smith are content to describe how Du Pont's management trained and recruited increasing numbers of chemical engineers, Ndiaye demonstrates how this new group of professionals leveraged their expertise to secure higher positions in the company's R&D establishment.[50] To Ndiaye, the boundaries between research scientist and research strategist are permeable, with chemical engineers participating with increasing frequency in top-level conversations regarding Du Pont's science policy.[51]

Ndiaye's engineers represent an extreme case of industrial scientists climbing the corporate ladder to dominate a company's scientific agenda, but he is not alone in framing researchers as actively involved in the implementation of corporate R&D strategy. Bassett,

[49] Pap A. Ndiaye, *Nylon and Bombs: Du Pont and the March of Modern America*, trans. Elborg Forster (Baltimore: Johns Hopkins Univ. Press, 2007). Originally published as *Du nylon et des bombes: du Pont de Nemours, le marché l'Etat Américain, 1900-1970* (Paris: Belin, 2001).

[50] Ndiaye, 62-105. Ndiaye observes that chemical engineers were trained to break down complicated chemical procedures in terms of basic (unit) operations such as crystallization and distillation and possessed a strong theoretical grounding in fluid dynamics and the mechanics of heat transfer. These skills left them well-positioned to solve problems in the field of high-pressure chemistry, which were essential for the production of both ammonia and nylon.

[51] For Ndiaye, the epitome of the chemical engineer/manager is Crawford Greenewalt, who parlayed his involvement in the nylon project into a position overseeing the construction of the Manhattan Project's plutonium production facilities in Hanford, WA, and, in 1948, became president of the company.

Choi, and Lécuyer all call attention to the locality of semiconductor manufacturing knowledge and the extent to which engineers served as agents for the transmission of production techniques within a firm, between corporations, and, in Choi's case, across international boundaries.[52] But for the most part, all of the authors listed above, including Ndiaye, are more interested in the mobilization of knowledge *once it has been acquired*, not the processes through which that expertise was obtained. Like the earlier management-centered discussions they purport to replace, their books consider the substance of industrial science as a means of evaluating the institutional structures within which it was conducted rather than an investigative end unto itself. Their characterization of industrial research as a collaborative and contingent endeavor belies their coverage of laboratory practice, which emphasizes individuals over groups and final products rather than the experimental and cognitive trajectories leading to them.

Restoring scientists and engineers to a central position in the historiography of industrial research necessitates consideration not merely of the means through which technical knowledge supplied them with new forms of social capital, but also the circumstances prompting its mobilization. Such an understanding would encompass both externally imposed changes in the organization of research and internally generated priorities derived from the day-to-day challenges of laboratory work. Accomplishing this task requires historians to supplement the project reports and memoranda retained in corporate archives with the notebooks and personal reflections of the scientists

[52] Margaret Graham's recent discussions of the Corning Glass Works also call attention to the central role that craft knowledge played in ensuring the company's ability to take on major projects like the Mt. Palomar telescope mirror. See: Graham (2009) and Margaret B.W. Graham and Alec T. Shuldiner, *Corning and the Craft of Innovation* (New York: Oxford University Press, 2001).

themselves. To borrow a phrase from Frederic Holmes, the juxtaposition of the "fine structure" of industrial science alongside discussions of broader corporate strategy provides an effective means of gauging the degree of autonomy possessed by researchers employed in for-profit settings.[53]

Laboratory notebook analysis has traditionally been the province of historians of science like Holmes, who utilized that approach to reconstruct the investigative pathways followed by Antoine Lavoisier, Claude Bernard, and Hans Krebs.[54] Holmes was among the first in his field to expound on the dangers of treating published accounts as accurate representations of scientific practice, and his work paved the way for future case studies of prominent individuals like Pasteur and Hertz.[55] Scholars of technological innovation, meanwhile, have been slower to adopt the practice, which while well-suited for examining entrepreneurial inventors of the 19th century, is harder to apply to the interdisciplinary teams that became typical during the 20th century.[56] Nevertheless, some historians of consumer electronics have begun to incorporate notebook analysis into their

[53] F.L. Holmes, "The Fine Structure of Scientific Creativity," *History of Science* 19, no. 1 (Mar. 1981): 60-70. See also: Frederic L. Holmes, "Laboratory Notebooks: Can the Daily Record Illuminate the Broader Picture?" *Proc. of the American Philosophical Society* 134, no. 4 (Dec. 1990): 349-366.

[54] Frederic L. Holmes, "Laboratory Notebooks and Investigative Pathways," in *Reworking the Bench: Research Notebooks in the History of Science*, ed. Frederic L. Holmes, et al. (Boston: Kluwer Academic Publishers, 2003), 295-307. In this article, Holmes describes his efforts to reconstruct the investigations of these three scientists as well as Matthew Meselson and Frank Stahl's experiments on DNA replication.

[55] Holmes' interest in literary notebooks can be dated to at least the 1974 publication of *Claude Bernard and Animal Chemistry: The Emergence of a Scientist* (Cambridge, MA: Harvard Univ. Press, 1974). For more of his writings on notebooks as a literary genre see: Frederic L. Holmes, "Scientific Writing and Scientific Discovery," *Isis*, 78, no. 2 (1987): 220-235. See also: Gerald L. Geison, *The Private Science of Louis Pasteur* (Princeton: Princeton Univ. Press, 1995); Jed Z. Buchwald, *The Creation of Scientific Effects: Heinrich Hertz and Electric Waves* (Chicago: University of Chicago Press, 1994).

[56] For examples of notebook analysis in the history of technology, see: W. Bernard Carlson and Michael E. Gorman, "Understanding Invention as a Cognitive Process: The Case of Thomas Edison and Early Motion Pictures, 1888-91," *Social Studies of Science* 20 (1990): 387-430; Robert D. Friedel, et al., *Edison's Electric Light: Biography of an Invention* (New Brunswick, NJ: Rutgers Univ. Press, 1986); Seth Shulman, *The Telephone Gambit: Chasing Alexander Graham Bell's Secret* (New York: W.W. Norton & Co., 2008).

methodological arsenal. Michael Riordan and Lillian Hoddeson's engagingly written history of the transistor, for example, uses laboratory notes to trace the interactions of personnel at Bell Labs.[57] A documentary history of Fairchild Semiconductor, compiled by Christophe Lécuyer and David Brock, goes even further, including excerpts from personal records, patent notebooks to capture the full range of R&D activities leading up to the 1961 creation of the planar integrated circuit.[58]

These fine-grained reconstructions of collaborative scientific experimentation and technological development reaffirm that the generation of new knowledge or marketable products is an emergent phenomenon, dependent upon the interactions of a multiplicity of actors. The sheer number of personnel involved in larger industrial programs has limited the possibility of enumerating their specific contributions and reinforced historians' tendency to focus their attention on a handful of key decision makers. While such figures play an important role in its pages, this dissertation positions them within a broader cast of characters by concentrating upon several projects with sizable, but not overwhelming, staff rosters.

At their peaks, none of the flat-panel display programs at RCA's Princeton lab, including the LCD, included more than twenty people, most of whom deposited detailed records of their activities in the company's technical archive. These documents, along with oral history interviews, permit at least a partial disaggregation of the research conducted by the corporation's chemists, physicists, and engineers, as well as the actions they took to

[57] Michael Riordan and Lillian Hoddeson, *Crystal Fire: The Birth of the Information Age* (New York: W.W. Norton, 1997).
[58] Christophe Lécuyer and David Brock. *Makers of the Microchip: A Documentary History of Fairchild Semiconductor* (Cambridge, MA: MIT Press, 2010).

overcome institutional obstacles encountered along the way. Furthermore, they verify that the emergence of the LCD depended as much upon researchers' technical acumen as their ability to tailor work to match the public rhetoric of company executives, secure military contracts or corporate partnerships to finance product development, and collaborate with manufacturing and advertising staffs to market their new devices.

A Successful Failure?

The liquid crystal displays unveiled to the public in 1968 launched a major global industry, but RCA sold off its LCD holdings in 1976 and never became a major player in the business it helped spark. Unsurprisingly, the dramatic rise and fall of RCA's liquid crystal initiative has inspired an array of explanations from project participants and outside observers. Their opinions can be roughly divided into two groups. The first, epitomized by David Dunmur and Tim Sluckin, emphasizes the technical shortcomings of the dynamic scattering display.[59] According to this argument, the company's reluctance to abandon this proprietary technology hindered its ability to compete with "twisted nematic" displays, which proceeded to dominate the industry from the early 1970s forward.[60] The second, echoing the retrospective testimony of research group leader George Heilmeier, blames managers at RCA's headquarters and manufacturing divisions, who saw liquid crystals as a

[59] David Dunmur & Tim Sluckin, *Soap, Science and Flat-Screen TVs: A History of Liquid Crystals* (New York: Oxford Univ. Press, 2011), 203-205.

[60] Lechner also points out in his 2008 article that the addressing circuitry used with these displays could not match the performance of existing televisions, leading management to believe it was not a worthwhile long-term investment (30). For further comparisons of dynamic scattering and twisted nematic displays, see: Dietrich W. Grabis, "The LCD Market: The Origin and Underlying Reasons for the Growth of Liquid Crystal Display Technology in the USA-Focus: Electronic Watch and Calculator Applications" (D.B.A. diss., Golden Gate Univ, 1980), 32-38; Hirohisa Kawamoto, "The History of Liquid-Crystal Displays," *Proc. IEEE* 90, no. 4 (Apr. 2002): 483-484.

threat to the company's existing television, semiconductor, and computer businesses.[61] Advocates of this position have claimed this behavior confirms a lack of technological vision among RCA's leaders following chairman David Sarnoff's resignation as well as the shortsightedness of American corporations compared to their Japanese rivals.[62]

Divided as they are over the rationale behind RCA's withdrawal, all of the authors who have written on the subject agree that the corporation's dalliance with liquid crystals was a failure. None of them, however, explains what constitutes a technological failure or the merits of studying unsuccessful devices. In approaching dynamic scattering mainly as a stumbling block on the road leading to today's wall-mounted televisions, these authors treat failure as well-defined and self-evident, when in fact the opposite is the case.

The dangers of haphazardly applying this category can be readily illustrated by comparing the LCD project with a pair of RCA "failures" alluded to earlier. On the one hand is the VideoDisc player, which was unable to carve out a serious niche in the home video market in spite of its competitive prices and simplicity of operation.[63] In contrast, RCA's investment in complex CMOS (complementary metal oxide-semiconductor) integrated circuitry hobbled the firm's entry into the semiconductor memory business, but laid the groundwork for similar low-power devices to become the industry standard during

[61] George H. Heilmeier, "Liquid Crystal Displays: An Experiment in Interdisciplinary Research that Worked," *IEEE Trans. on Electron Devices* ED-23, no. 7 (Jul. 1976): 780-785. Dunmur & Sluckin also acknowledge management's reluctance to develop LCDs, but also criticize Heilmeier for refusing to consider rivals to dynamic scattering on personal grounds. Heilmeier's colleague Joseph Castellano also criticizes RCA's managers, but suggests that their behavior might reflect deeper structural obstacles hindering entrepreneurial behavior in large corporate settings. (Castellano, 78)

[62] Bob Johnstone, *We Were Burning: Japanese Entrepreneurs and the Forging of the Electronic Age* (New York: Basic Books, 1999), 88-117; Thomas P. Murtha, et al., *Managing New Industry Creation* (Stanford: Stanford Univ. Press, 2001), 55-59; Stuart Peters, *National Systems of Innovation: Creating High-Technology Industries* (New York: Palgrave Macmillan, 2006), 129-182; Hedrick Smith, *Rethinking America* (New York: Random House, 1995).

[63] Graham (1988) remains the definitive study of the VideoDisc project.

the 1980s.[64] The liquid crystal display program encompasses aspects of both of these stories. Like the VideoDisc, dynamic scattering LCDs generated few profits and could not match the performance of rival technologies. At the same time, many of the scientific and technical breakthroughs resulting from RCA's research, such as active matrix addressing circuitry and room-temperature liquid crystal mixtures, are incorporated into all of today's LCD televisions.[65]

Accepting that not all failures are created equal is the first step in moving beyond the use of such examples to validate oversimplified narratives of technological progress. It would be a mistake to assume, for example, that the LCD was the only "successful" flat-panel display technology developed at RCA during the quarter-century covered in this study. As Jonathan Coopersmith observed in his studies of the fax machine, success and failure are highly situational, and the inability of a prototype to meet a given set of performance requirements does not automatically render it worthless.[66] Such devices, he notes, "indicate differences over which technological path to pursue" towards a given objective, as well as the support that advocates of different paths are able to muster to achieve those goals.[67] This dissertation embraces Coopersmith's reliance upon the tenets of social constructivism and actor-network theory to examine how different flat-panel technologies became identified as failures and how their supporters reacted to this categorization.[68] The resulting analysis reveals that the relative standing of any flat-panel

[64] Bassett, 161-165.
[65] Castellano, 28; Lechner, 28.
[66] Jonathan Coopersmith, "Failure & Technology," *Japan Journal for Science, Technology, and Society* 18 (2009): 93-118 and "Old Technologies Never Die, They Just Don't Get Updated," *International Journal for the History of Engineering & Technology* 80, no. 2 (Jul. 2010): 166-182.
[67] Coopersmith (2009), 102.
[68] For a more rigid application of actor-network theory to failed technological systems, see: Bruno Latour, *Aramis, or the love of technology* (Cambridge, MA: Harvard Univ. Press, 1996).

display project within the DSRC, including the LCD, correlated closely with RCA researchers' skill in establishing and maintaining its commercial relevance to managers, manufacturers, and consumers.

Coopersmith's attention to the proximal causes and consequences of a technology's failure contrasts with Kenneth Lipartito's interest in excavating the motivations behind its creation. In an article chronicling the collapse of AT&T's Picturephone system, Lipartito argues that the company's decision to invest in video telephony stemmed from a historically informed understanding of technological change, stressing the inevitability of adding sight to sound in telecommunications.[69] The rhetorical power of this narrative outlived the technology itself and, Lipartito claims, continues to inspire efforts to develop similar devices. "Even as a failure," he writes, "Picturephone was a real machine that suggested the underlying vision might find its way into reality."[70]

Coopersmith and Lipartito's respective attitudes towards the study of technological failure provide a pair of complementary methodologies that are equally applicable here. For while it is possible to reconstruct the trajectory of liquid crystal research at RCA using Coopersmith's actor-network inspired approach, Lipartito's emphasis on corporate rhetoric recasts the LCD as an embodiment of RCA's longstanding interest in a potential successor to the cathode ray tube. As we shall see, David Sarnoff's 1951 request that RCA scientists develop a "light amplifier" that could serve as the basis for a wall-mounted TV continued to inspire research projects long after Sarnoff

[69] Kenneth Lipartito, "Picturephone and the Information Age: The Social Meaning of Failure," *Technology and Culture* 44, no. 1 (Jan. 2003): 63-65.
[70] Lipartito, 78. For more on the role of rhetoric in the creation and acceptance of new technologies, see Marita Sturken, et al., ed., *Technological Visions: The Hopes and Fears that Shape New Technologies* (Philadelphia: Temple Univ. Press, 2004).

abandoned hope of its completion. Most of the resulting devices remained confined to the laboratories, but like the Picturephone, they hinted at the possibility of a forthcoming commercially viable option. For a brief period in the late 1960s, liquid crystals appeared to fulfill that promise. How this came to pass and why the LCD was set aside despite the persistence of Sarnoff's dream of a flat-panel television will be explored in the chapters that follow.

Chapter Overview

The story of flat-panel display research at RCA begins in 1951, when the company renamed its Princeton research facility in honor of company chairman David Sarnoff. At the dedication ceremony, Sarnoff challenged his technical staff to develop three new technologies in time for a dinner five years later commemorating the fiftieth anniversary of his career in electronics. Chapter 2 considers the fate of one of these gifts, the "Magnalux" light amplifier, to emphasize the cyclical relationship between the rhetoric associated with the device and the artifact shown at Sarnoff's golden anniversary party. Although Sarnoff's initial description of Magnalux resembled an improved theater television system, over the intervening five years he referred with increasing frequency to its serving as the basis for a television that could hang on the wall like a painting. When researchers constructed a pair of prototypes embodying each of these descriptions, RCA's managers had to decide which to present as the instantiation of Sarnoff's vision. This chapter examines the technological, institutional, and economic factors shaping this debate and scientists' efforts to sustain both projects after 1956.

Unfortunately, RCA's flat-panel television projects faced stiff resistance from the company's newly-appointed president, John Burns. In the wake of a federal consent decree depriving the DSRC of long-term funding, Burns implemented a series of reforms intended to limit fundamental research and encourage closer ties between the laboratories and operating divisions. As Chapter 3 illustrates, however, these policies, most notably an increased dependence on military contracts and the establishment of an independent Computer Research Laboratory (CRL), provided researchers with new opportunities to pursue "mural television" research. Indeed, even after the revenues from color TV restored the DSRC's research budget, it would be CRL personnel rather than established television experts who built the only flat-panel display to leave the labs prior to 1968: a 1200-element electroluminescent display delivered to the U.S. Air Force. The expertise these engineers acquired during this period led to their subsequent involvement in a project aimed at creating a similar device using liquid crystals.

Chapter 4 presents the origins of RCA's liquid crystal research and the factors prompting DSRC personnel to embrace a one-time laboratory curiosity as the basis for a new form of electronic display. This discussion contrasts the motivations of two researchers who confirmed that liquid crystals could electronically control the passage of light. Physical chemist Richard Williams' interest in liquid crystals stemmed from ongoing investigations into the effects of electric fields on materials' absorption spectra. In 1964, electrical engineer George Heilmeier revisited Williams experiments from two years earlier while searching for an improved laser light modulator. While both men recognized the display potential of these substances, only Heilmeier pursued the idea further, eventually

demonstrating a new means of electronically triggering a color change in dyes dissolved in liquid crystals. I show how, contrary to the recollections of project participants, this "guest-host" effect, which persuaded Heilmeier's superiors to organize a formal liquid crystal display project, was the result of a systematic, collaborative research effort that set the tone for later work on the subject.

Chapter 5 covers the events described in the 1968 press conference and how Heilmeier's team worked with RCA's management and public relations staffs to construct an accessible, but problematic, origin story for the LCD. With reference to laboratory notebooks and project reports, I demonstrate that the version of events Hillier presented to the public omits significant technical details, such as the experiments facilitating the transition from the guest-host effect to dynamic scattering, as well as personnel integral to the construction of the first practical LCDs. These documents also reveal that, despite instances of cooperation, the unity of the liquid crystal group was somewhat exaggerated, as chemists, physicists, and engineers pursued their objectives in relative isolation. Furthermore, I suggest that the timing of the press conference resulted less from any specific scientific achievement than negotiations between a research team eager to end an embargo on scientific publication and managers who saw the LCD as a tool to fundamentally alter the corporation's image.

Among this latter group, none was as influential as Robert Sarnoff, who succeeded his father as RCA's chief executive officer in 1968. The younger Sarnoff reinvented RCA as a conglomerate, supplementing its traditional focus upon consumer electronics through the purchase of firms in the publishing, car rental, and frozen food industries. Chapter 6

describes how this transformation affected efforts to commercialize the LCD. I show how Heilmeier's team reached out to other DSRC personnel, engineers at the corporation's semiconductor division, and RCA's marketing staff for assistance developing products based on dynamic scattering. While these attempts led to the opening of a pilot manufacturing plant, management considered the operation a diversion from Robert Sarnoff's ongoing campaign to make RCA a leader in electronic computing and opposed any further expansion. As a result, the company ceded whatever advantage it might have acquired as the LCD industry's first-mover to new rivals in the U.S., Europe, and Asia. By the time DSRC research managers once again turned their attention to liquid crystals, most of the technology's strongest advocates had left the company. RCA's 1976 decision to sell its LCD patents and factories to Timex met with almost no opposition.

The dissertation concludes in Chapter 7 with a reflection upon the difficulties associated with constructing narratives of collaborative innovation, an issue that remains as pertinent to today's scholars as it did to the scientists and managers considered in previous chapters. Through a close reading of the 2006 IEEE (Institute of Electrical and Electronic Engineers) milestone honoring RCA's liquid crystal investigations, I discuss the choices historians must make in order to distill the corporate research experience into a single coherent narrative. Much as RCA's leadership emphasized certain facets of the liquid crystal project at the 1968 press conference, I argue, this dissertation represents only one iteration of a much larger story spanning the creation, dissemination, and cultural ramifications of all forms of electronic display.

CHAPTER TWO
"Like a picture on the wall": Flat-Panel Display Research at RCA, 1951-1956

It was, by all accounts, a most unusual birthday party. The guest of honor had turned sixty in February 1951, but the celebration was planned for the following September. Furthermore, while he spent the majority of his time in Manhattan, the event was held in a far less urban, though no less civilized, setting: Princeton, New Jersey. In addition, though the festivities were large enough to receive press coverage, the invitees who garnered the most attention were not actually in attendance. Still, absence did not prevent both major candidates from the previous presidential election, Harry Truman and Thomas Dewey, from sending congratulatory telegrams to David Sarnoff, the chairman of the Radio Corporation of America (RCA), on an occasion that the executive deemed more significant than his birth in a Russian *shtetl*: the forty-fifth anniversary of his entry into the field of electronics.[1]

Much had changed since 1906, when Sarnoff taught himself Morse code as an office boy at the Marconi Wireless Telegraph Company. That firm had long since vanished, purchased by General Electric (GE) in 1919 as part of the government-sanctioned business maneuvering that led to the creation of RCA.[2] Sarnoff, in turn, had

[1] *Dedication of Plaque to David Sarnoff: Commemorating his 45 years of service in Radio and Naming the Princeton Laboratories of RCA as the DAVID SARNOFF RESEARCH CENTER* (Princeton: RCA Laboratories Division, 1951), 5, 11. For an example of press coverage, see: "Sarnoff Honored; 45 Years in Radio," *New York Times*, 28 Sep. 1951, 32.

[2] For more on RCA's origins, see: Margaret B.W. Graham, *The Business of Research: RCA and the VideoDisc* (New York: Cambridge Univ. Press, 1986 [1988]), Ch. 2-3; Robert Sobel, *RCA* (New York, Stein & Day, 1986), Ch. 1; J.C. Warner, "A History of Radio Corporation of America–The Years to 1938," *RCA Engineer* 3, no. 1 (Jun.-Jul. 1957): 3-9. For more on the early U.S. radio industry, see: Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900-1932* (Princeton: Princeton Univ. Press, 1985); Thomas S.W. Lewis, *Empire of the Air: The Men Who Made Radio* (New York: Burlingame Books, 1991); W. Rupert Maclaurin, *Invention and Innovation in the Radio Industry* (New York: Macmillan, 1949).

risen through the new company's ranks, and used his growing authority to establish RCA's independence from shareholders at GE and Westinghouse.[3] At the same time, he shifted the firm's focus from international wireless communication to commercial broadcasting, and expanded its manufacturing facilities through the acquisition of the Victor Talking Machine Company in Camden, a GE tube manufacturing plant in Harrison, New Jersey and a Westinghouse lamp factory in Indianapolis.[4] He also presided over the growth of the corporation's research infrastructure, culminating with the September 1942 opening of a central laboratory in Princeton.[5]

Exactly nine years later, Sarnoff returned to Princeton as chairman of RCA's board of directors, though he was more proud of the rank of Brigadier General, which he earned coordinating news reports during the D-Day invasion.[6] The corporation had turned its attention from radio to television, but Sarnoff's commitment to RCA's technical staff remained strong. Now they wished to repay the favor. After a celebratory luncheon, RCA executive vice-president Charles Jolliffe unveiled a plaque declaring that the Princeton facility would be renamed "The David Sarnoff Research Center."[7] (DSRC)

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[3] Sarnoff's career is detailed in several biographies, including Kenneth Bilby, *The General: David Sarnoff and the Rise of the Communications Industry* (New York: Harper & Row, 1985) and Carl Dreher, *Sarnoff: An American Success* (New York: Quadrangle/The New York Times Book Co., 1977). Eugene Lyons' *David Sarnoff* (New York: Harper & Row, 1966), composed in consultation with its subject, is also a potentially useful source, so long as one bears in mind that Sarnoff exerted strict editorial control over the manuscript to such a degree that many critics "found its adulatory tone distasteful" (Bilby, 271).

[4] Graham, 42-47.

[5] Kenyon Kilbon, "Pioneering in Electronics: A Short History of the Origins and Growth of RCA Laboratories, Radio Corporation of America, 1919 to 1964," unpublished typescript, revised August 1964, 121-127. Paginated copy available online at http://www.davidsarnoff.org/kil.html, accessed 28 Oct. 2009.

[6] Sarnoff replaced Owen Young as president of RCA in 1930 and received a promotion to chairman in 1947, following the death of the previous officeholder, Gen. James Harbord.

[7] As Alexander Magoun notes, this plaque continues to hang in the lobby of RCA's former Princeton laboratories. See: Alexander Magoun, *David Sarnoff Research Center–RCA Labs to Sarnoff Corporation* (Charleston, SC: Arcadia Publishing, 2003), 53.

In response to this announcement, Sarnoff, or "the General" as he preferred to be known, delivered a speech that would be the subject of short-term press speculation and long-term reflection among RCA's technical staff.[8] After thanking his colleagues, he noted that his family was in attendance and that among family "it is not regarded improper...to make a suggestion occasionally or to throw out a friendly hint about the kind of present you would like for your birthday or your anniversary."[9] With that in mind, Sarnoff laid out three gifts that he wanted RCA's scientists and engineers to develop in time for his fiftieth anniversary celebration in 1956.

This chapter explores the fate of one of these gifts, the "Magnalux" light amplifier, as a means of comparing how RCA's management, laboratory scientists, and manufacturing staff understood the relationship between fundamental research and innovation. After outlining the content and context of Sarnoff's 1951 speech, it will examine how DSRC researchers responded to his call for a "true amplifier of light," the technologies considered as the basis for such a device, and how economic and institutional factors contributed to the abandonment of the project.[10] Previous histories of RCA have cited the General's "birthday presents" as examples of a corporate leader "forcing the unforcible" by mandating the pursuit of goals beyond the reach of his technical staff.[11]

[8] For more on Sarnoff's preferred appellation, see: "The General," *Time*, 27 Jul. 1951, 74-80; Bilby, 151-152. For press coverage of Sarnoff's speech, see: "Sarnoff Honored; 45 Years in Radio"; "General David Sarnoff, Miracle Man of the Electronic Age...," *The Advertiser*, Oct. 1951, 13 [Article contained in "David Sarnoff Publicity," Box 18 of 28, Folder 34, David Sarnoff Library (DSL)]. For RCA's own account, see: "Sarnoff Challenges Scientists of RCA to Make Three Important Inventions," *Radio Age* 11, no. 1 (Oct. 1951): 5-7, 31. *Radio Age* was an RCA in-house magazine, published quarterly by the company's Department of Information. Its name changed to *Electronic Age* in 1957 to reflect the corporation's broadening research interests.

[9] *Dedication*, 18.

[10] *Dedication*, 18.

[11] Graham, 67. See also: George Brown, *And Part of Which I Was: Recollections of a Research Engineer* (Detroit: Harlo Press, 1982), 267-287.

Such characterizations exaggerate the unity of light amplification research at RCA by treating the quest for Magnalux as one with an single, obvious technological objective. Instead, I argue that the ambiguity of Sarnoff's initial request led RCA engineers to pursue a variety of solutions, all the while uncertain of the criteria defining a given prototype as a success. Such distinctions only emerged as a result of the cyclical interaction between RCA executives and researchers. For just as the DSRC staff tailored Magnalux prototypes to match the descriptions voiced by Sarnoff and his senior staff, these managers altered their predictions based on consultation with personnel in Princeton. Unlike subsequent flat-panel display projects, which RCA pursued under a veil of secrecy, the public nature of the Magnalux story offers a unique opportunity to witness industrial scientists shaping public discussions of R&D strategy.

Reacting to "Magnalux": Sarnoff's Proposal for a Light Amplifier

While some accounts of Sarnoff's 1951 speech accept the speaker's introductory comment that "I have not prepared a speech for this occasion," the fact that his remarks extend over thirteen single-spaced pages in a subsequently printed booklet suggest the opposite to be the case.[12] This assumption is in line with the importance he placed, as a Russian immigrant, upon mastery of the English language as a means of exerting authority.[13] "In his view, his speeches were the stuff of history," biographer Kenneth Bilby observed, "and he crafted them with infinite care, often devoting hours to chiseling a single phrase."[14]

[12] See, for example, Kilbon, 199; Lyons, 300. For the full text of Sarnoff's speech, see: *Dedication*, 15-27.
[13] Dreher, 183.
[14] Bilby, 5-6.

Considered alongside this customary attention to rhetorical detail, Sarnoff's birthday gift requests come across as vague, particularly in the case of the light amplifier. Unlike the other two presents–a video recording system using magnetic tape (the "Videograph") and an air conditioner without any moving parts ("Electronair")–the light amplifier had no obvious precedent. On the surface, the General's request seemed clear enough:

> One of the presents I would like to have you invent is a true amplifier of light. I have been talking about that for some years and I can get into very animated technical discussions with scientists and engineers as to whether there is such a thing or not...But I think we can all agree that, while we have learned how to amplify electricity, we have not yet learned how to amplify light...Now I should like to have you invent an electronic amplifier of light that will do for television what the amplifier of sound does for radio broadcasting.[15]

To Sarnoff, the antecedent for the light amplifier was the loudspeaker, which allowed audio signals to escape from operators' headsets and facilitated the emergence of radio broadcasting. In a similar fashion, the light amplifier "would provide brighter pictures for television which could be projected in the home or the theatre on a screen of any desired size."[16] Morever, this device, which he named "Magnalux," literally a "big light," would improve upon the projection setups RCA used to display television pictures in American cinemas as early as 1940.[17] Those systems, Sarnoff pointed out, "can, of course, enlarge pictures optically, but in the process light is lost and the pictures become dimmer instead of brighter. What is needed is a true amplifier of light itself."[18]

[15] *Dedication*, 18-19.
[16] *Dedication*, 19.
[17] *Dedication*, 19-20. Sarnoff credited Orrin Dunlap, a member of RCA's intellectual property department for coming up with the term, "Magnalux." These demonstrations will be discussed in more detail in the following section.
[18] *Dedication*, 19.

Beyond these generalities, Sarnoff left the technical basis for the Magnalux a mystery. To George Brown, who later became an RCA vice-president, it appeared the General had drawn a false distinction between audio and video signal amplification. "Since sound in a radio set comes out of the loudspeaker with sufficient volume because the electrical signals corresponding to the sound are amplified by means of vacuum tubes," he recalled, "I assumed that we already had the problem under control for picture signals were also amplified electrically."[19] In effect, Sarnoff was asking his engineers to reconsider a problem they had previously solved. But while the vacuum tube and its solid-state analog, the transistor, could bolster the strength of a video signal, neither could increase the brightness of the resultant image as the General had described.

Given his passion for predicting future developments in telecommunications, it is possible that Sarnoff had no specific technology in mind while composing his remarks.[20] Yet the General maintained close relations with his research staff and regularly contacted them to discuss the latest advances in electronics. As much as he enjoyed casting himself as a technological prophet, Sarnoff preferred to secure some assurance of his predictions' validity before presenting them to the public.[21] Assuming he did so prior to this speech, his omissions may have been meant to avoid the appearance of restricting the creativity of RCA scientists or accusations that his idea was infeasible. More importantly, like any good

[19] Brown, 268.

[20] Bilby, Dreher, and Lyons' biographies confirm Sarnoff's fondness for predicting new technologies. Further evidence of this behavior can be found in David Sarnoff, *Looking Ahead: The Papers of David Sarnoff* (New York: McGraw Hill, 1968). This volume contains Sarnoff's 1916 "Music Box Memorandum," which anticipated the rise of commercial broadcasting, a 1930 speech predicting the invention of color television, and an article submitted for publication in July 1945 warning of the dangerous potential of weapons based on splitting the atom.

[21] Both George Brown and Elmer Engstrom, the vice-president in charge of RCA Laboratories in 1951, asserted that Sarnoff contacted them for advice prior to the composition of his speeches. See: Brown, 277-278; Graham, 240, n. 16.

prophet, Sarnoff recognized the wisdom of embracing a degree of ambiguity to accommodate the unexpected, especially given the changes already underway within the DSRC and throughout the American electronics industry.

A Laboratory in Transition: The David Sarnoff Research Center in 1951

Sarnoff's birthday gift request came at a tumultuous moment in the history of his company. Retreating from the near total wartime conversion of its research facilities, by 1951 RCA found its plans to control the postwar consumer electronics market threatened by William Paley, chairman of the Columbia Broadcasting System (CBS).[22] For more than a decade, RCA and CBS had been engaged in a struggle to set technical standards for American television programming. RCA's subsidiary, the National Broadcasting Company (NBC), commenced commercial broadcasts in 1939, with the intent of using the profits from monochrome set sales to develop a color system.[23] In 1940, Paley undercut these efforts by announcing that CBS had developed a market-ready color TV apparatus, which

[22] Kilbon notes that in June 1941, 75% of RCA's research staff were engaged in defense projects supported by either internal or government funds. By December 1941, this had increased to 90%, and in 1942, the year the Princeton labs opened, "the percentage rose to virtually 100" (132). Among RCA's contributions to the war effort were improved radar and sonar equipment, fire control systems, and various electronic imaging devices. For more on RCA's involvement in wartime research, see Elmer W. Engstrom, "A History of Radio Corporation of America, Part II: The Years 1938 to 1958," *RCA Engineer* 4, no. 1 (Jun.-Jul. 1958): 29-31; Kilbon, Ch. 6 (128-175) and: Radio Corporation of America, *RCA's Contributions to the War Effort Through Communications, 1930-1946* (Camden, NJ: RCA Victor Division, [1946]); Radio Corporation of America, *RCA's Contributions to the War Effort Through Radar, 1932-1946* (Camden, NJ: RCA Victor Division, [1946]); Radio Corporation of America, *RCA's Contributions to the War Effort Through Sonar, 1934-1946* (Camden, NJ: RCA Victor Division, [1946]); Radio Corporation of America, *RCA's Contributions to the War Effort Through Television, 1930-1946* (Camden, NJ: RCA Victor Division, [1946]). I am indebted to James Moffa, formerly of RCA's public affairs office in Cherry Hill, NJ, for preserving this four volume set and to Elizabeth Bennett, Stephen Ferguson, and Angela Creager for their assistance finding it a home in the Princeton University Library's Department of Rare Books and Special Collections.

[23] For more on RCA's pre-war television programming, see: Jeff Kisseloff, *The Box: An Oral History of Television* (New York: Viking, 1995), 42-62.

projected images through a series of tinted filters attached to a motor-driven disk.[24] Unlike the proposed RCA system, whose electronically generated images would, in theory, still be viewable on existing black-and-white sets (albeit in monochrome), the CBS system would render millions of televisions obsolete.[25]

With the future of their industry at stake, Sarnoff and Paley began lobbying the Federal Communications Commission (FCC) to endorse broadcasting standards favoring each company's respective approach.[26] The FCC postponed discussion of the matter until after World War II, but in 1950, it authorized broadcasts using CBS' "field-sequential" system.[27] Sarnoff appealed the ruling, but the Supreme Court supported the FCC's decision. Only the military's requisitioning of electronics materiel following the outbreak of hostilities in Korea prevented CBS from commencing large-scale color set production.[28] The Korean conflict also provided RCA with an opportunity to refine its "compatible color" system and confirm its superiority to Paley's "whirling disc."[29]

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[24] As Bilby observes, the CBS system was by no means original. Scientists at RCA and Bell Labs had experimented with the use of rotating disks to transmit and display color television images, as had British research John Logie Baird (Bilby, 177-178). For further technical information on the CBS system, see: Albert Abramson, *The History of Television, 1880-1941* (Jefferson, NC: McFarland & Co., Inc., 1987), 262-272; Russell W. Burns, *The Struggle for Unity: Colour Television, the Formative Years* (London: The Institution of Engineering and Technology, 2008), 101-124.

[25] Sobel estimates that nearly 12 million monochrome TV sets had been sold in the U.S. between 1946 and 1950 (161-162).

[26] For more on this regulatory dispute, see: Burns, 126-146; Alexander Magoun, *Television: The Life Story of a Technology* (Westport: Greenwood Press, 2007 [2009]), 71-76; Sobel, 122-142.

[27] The term "field sequential" refers to the fact that the three primary color images (red, green, blue) making up a complete television picture were displayed on screen in succession, rather than simultaneously as in the proposed RCA system. For a contemporary explanation of this distinction, see: Donald G. Fink, *Television Engineering*, 2nd. ed. (New York: McGraw-Hill Co., 1952), 441-444.

[28] Bilby, 193-195.

[29] The term "whirling disc" is derived from "The General," 74. RCA referred to its color television system as "compatible" with existing monochrome sets, as opposed to the CBS system. For more on RCA's efforts to perfect this system, see: Albert Abramson, *The History of Television, 1942-2000* (Jefferson, NC: McFarland & Co., Inc., 2003), 37-59; Burns, 147-163; Magoun (2009), 98-108.

Consequently, color television retained its status as RCA's highest priority project in 1951, a constant goal for a company struggling to adapt to the realities of the postwar electronics market. Between 1942 and 1945, the complement of technical staff in Princeton had remained fixed, as RCA devoted itself to wartime radar and television projects.[30] Now an increasing number of competitors and the arrival of new semiconductor devices confirmed the need to broaden its research base.[31] Sarnoff delegated responsibility for this task to Elmer Engstrom, the vice-president in charge of RCA's laboratories. Engstrom oversaw the establishment a research training program, which exposed new staff members to work underway in different labs before their formal assignment to a project.[32] He also worked with Douglas Ewing, an engineering group leader from RCA's Camden branch, to expand the DSRC's recruiting program and forged partnerships with Rutgers and Princeton, so that students who had previously been unable to take graduate courses because of the war could attend classes either part-time or at night.[33]

Engstrom and Ewing's efforts were the vanguard of a major realignment in RCA's research strategy, institutionalizing the notion that basic research was the principal source of technological advancement. In taking these steps, the company joined firms like AT&T, Du Pont, and IBM, whose postwar R&D policies have been described as reinforcing a "linear model" of innovation.[34] As early as 1945, Engstrom worried that RCA's wartime research had reached the limits of electronic understanding. "Technological advances have

[30] Kilbon, 134.
[31] Kilbon, 176-179. For more on the postwar expansion of the electronics industry, see Alfred D. Chandler, Jr., *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries* (New York: The Free Press, 2001).
[32] Kilbon, 181-182.
[33] RCA Laboratories, *Research Report 1951*, DSL, 16.
[34] For more on the historiographic debates surrounding the linear model, see the introduction of this dissertation.

been rapid," he noted, "and have now reached the point where further progress is being materially held up because of lack of knowledge of basic phenomena."[35] Hiring more theoretically inclined researchers was the obvious solution to this deficiency, and by 1951, the DSRC's annual report boasted that its staff had more than doubled since 1945 and that their solid-state research program was "probably the broadest in any industrial laboratory in the country."[36]

The target audience of David Sarnoff's birthday gift speech was therefore one in transition, moving away from the familiar world of vacuum tube technologies toward the enigmatic realm of the solid state. As shall be seen, attempts to develop the General's light amplifier followed a similar trajectory. Engstrom and Ewing's emphasis upon fundamental research and the corresponding marginalization of product development in Princeton over the next five years would also have significant consequences for the DSRC's organizational standing and the eventual fates of the Magnalux prototypes developed during that period.

From Cathode Rays to the Solid State: Nicoll & Kazan's Light Amplifying Panels

Despite Sarnoff's attempts to distance Magnalux from existing projection television setups, RCA engineers' familiarity with that technology rendered it a logical

[35] Quoted in Kilbon, 178.

[36] RCA Laboratories, *Research Report 1951*, 15. This report indicates that the technical staff employed at the DSRC numbered 293, more than twice the 125 RCA scientists and engineers working at Princeton during the war. For confirmation of wartime staff numbers, see: Kilbon, 134; *1942-1967: Twenty-five Years at RCA Laboratories* (Philadelphia: Smith-Edwards Co., 1967), 2. For further discussion of RCA's semiconductor research program, see: Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins Univ. Press, 2002) and Hyungsub Choi, "Manufacturing Knowledge in Transit: Technical Practice, Organizational Change, and the Rise of the Semiconductor Industry in the United States and Japan, 1948-1960" (Ph.D. diss., Johns Hopkins Univ., 2007), 13-51.

starting point in their search for a practical light amplifier. These systems utilized cathode ray tubes (CRTs), the functional cores of RCA's conventional television sets. A CRT was a vacuum tube containing a piece of metal that emitted a stream of electrons when heated. In a standard television, magnetic coils or electrically charged plates guided this beam across a phosphor-coated faceplate to create an image.[37] The basic principle of image creation remained the same for RCA's projection system, with the light from the resulting picture passing through a series of lenses that projected it on to a movie screen.[38]

Early demonstrations of this system in the 1940s impressed reporters, who anticipated that the technology would lead to increased revenues for cinemas and the venues "involved in staging the affair which is to be telecast."[39] Projection television really came to the fore, however, as a propaganda tool during the postwar debates over color broadcasting standards. Through the use of multiple picture tubes, RCA engineers were able to superimpose the primary (i.e. red, green, and blue) components of an image on to a screen, creating an image that one journalist claimed "might easily have been mistaken by a tolerant eye for a fairly well photographed Kodachrome or Technicolor film."[40] Such

[37] For additional historical or technical information on the cathode ray tube, see: Abramson (1987); Norman H. Lehrer, "The Challenge of the Cathode Ray Tube," in *Flat-Panel Displays and CRTs*, ed. Lawrence E. Tannas, Jr. (New York: Van Nostrand Reinhold Company, 1985), 138-176; Magoun (2009); Sol Sherr, *Electronic Displays* (New York: John Wiley & Sons, 1979), 69-181 (Ch 2).

[38] As Larry Hornbeck, one of the developers of the Digital Micromirror Device (DMD) at Texas Instruments points out, RCA was not the only company attempting to develop a projection television display. Swiss physics professor Fritz Fischer, for example, demonstrated a prototype of his "Eidophor," which deposited electrons on a spinning oil coated mirror rather than a phosphorescent screen, in 1943. This technology would be commercialized in the early 1950s, with GE releasing a color version called the Talaria in 1958. For more details on the Eidophor or other early projection systems, see: Larry Hornbeck, "From cathode ray tubes to digital micromirrors: A history of electronic projection display technology," *TI Technical Journal* (Jul.-Sep. 1998): 7-46.

[39] "Purely Gossip–," *Wall Street Journal*, 12 May 1941, 11. For additional press coverage of RCA's early projection television demonstrations see: "Projection 'Gun' Shoots Televiews; The Aim is to Hit a Theatre Screen," *New York Times*, 12 May 1940, 142; "Television Show Given in Theatre," *New York Times*, 10 May 1941, 11.

[40] B.R. Crisler, "New York Sees Color Television on Theater-Size Screen," *Christian Science Monitor*, 17

successes encouraged some involved with these demonstrations to discuss the possibility of a home projection system.

The leader of these efforts was David Epstein, one of the original designers of the optical system used to expand CRT images to fill a movie screen.[41] Epstein understood that several technical hurdles had to be overcome before projection television could enter America's living rooms. As Sarnoff observed, the most significant challenge would be counteracting the diminution of brightness that accompanied image enlargement. In public demonstrations, Epstein and his colleagues had solved this problem through the use of large voltages, several times greater than the typical home television, to maximize CRT light output. Further complicating matters, in smaller spaces, any misalignment of the three CRTs required to generate color pictures resulted in severe optical distortion.[42]

Epstein devised a solution to the alignment problem using a compact optical system, which arranged the three CRTs in a "T" shape and used dichroic mirrors to selectively filter certain colors of light.[43] Though the use of these mirrors resulted in light loss, he was able to construct a self-contained projection display by 1954.[44] The result was a far cry from Sarnoff's Magnalux. Rather than projecting on a screen of any size, this

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Oct. 1951, 7. For further press coverage, see also: "RCA Produces Color Television Show for Theatre Reception," *Wall Street Journal*, 17 Oct. 1951, 22; Walter Ames, "Television Radio News And Programs," *Los Angeles Times,* 18 Oct. 1951, 28. For RCA's own account, see: "Color Television on Theatre Size Screen, *Radio Age* 11, no. 1 (Oct. 1951): 3-4, 31.

[41] Confirmation of Epstein's role in adapting the optics developed for the Schmidt astronomical camera for use in projection television can be found in: Kilbon, 77 and 224; I.G. Maloff & D.W. Epstein, "Reflective Optics in Projection Television," *Electronics* 17, no. 12 (Dec. 1944): 98-105. David W. Epstein, "Projection Apparatus," US Patent 2,295,779, filed 17 Aug. 1940 and issued 15 Sep. 1942; David W. Epstein, "Image Projection System," US Patent 2,454,144, filed 27 Sep. 1944 and issued 16 Nov. 1948.

[42] Fink, 142-143.

[43] David Epstein and Solomon Lasof, *PTR-509: Color Television Projectors for the Home*, 25 Oct. 1955, DSL.

[44] RCA Laboratories, *Research Report 1954*, DSL 29-30.

device resembled a traditional cabinet TV with a 25 inch display. Furthermore, while the resolution was comparable to direct-view televisions, the contrast was significantly inferior, leading to the project's termination in 1955.[45]

As Epstein devoted his attention to CRT-projection systems, other members of his research group were considering alternative approaches toward light amplification. Frederick Nicoll was a Canadian-born physicist who helped develop the reflection-free glass used in Epstein's projectors and wartime radar displays.[46] After arriving at the Princeton laboratories, he was assigned to the compatible color television initiative. It was in conjunction with these activities that he first encountered Benjamin Kazan, a CRT expert who had transferred to the DSRC from the Signal Corps Engineering Laboratories in Ft. Monmouth, NJ.[47] Kazan's research centered around storage tubes–CRTs capable of retaining still images for display over a long period of time, rather than the moving images on regular televisions–but the two men still found enough common ground to collaborate on new form of electron gun for color TV sets.[48]

After earning an award in 1952 for their color television research, Kazan and Nicoll's search for a new project led them to a potential solution to the light amplification problem.[49] Ironically, their idea was derived from work conducted at the Massachusetts laboratory of one of RCA's competitors, Sylvania Electric Products, into a phenomenon

[45] RCA Laboratories, *Research Report 1955,* DSL, 75. See also: *PTR-509*, 23-25.
[46] "Nicoll, Frederick H.," in DSRC Biographies Collection, Box 4, Folder 15, DSL.
[47] "Paid Notice: Deaths, Kazan Benjamin," *New York Times*, 11 Feb. 2009. Accessed online: 5 Nov. 2009.
[48] Benjamin Kazan and F.H. Nicoll, *PEM-284: A Common Cross-Over Triple Beam Gun*, 26 Feb. 1953. Accession #2069, Box 45, HML. To paraphrase Sherr (see n. 37), a storage tube is a CRT whose light output is determined by factors other than phosphor decay time (135). For more on Kazan's storage tube research, see Kilbon, 256-259. See also: Benjamin Kazan and Max Knoll, *Electronic Image Storage* (New York: Academic Press, 1968).
[49] Nicoll and Kazan are listed as having won an "incentive award" from the DSRC's management in: RCA Laboratories, *Research Report 1952*, DSL, 3. Exactly what such an award entailed is not explained.

that top DSRC scientists dismissed as a hoax as recently as 1950. Like RCA, Sylvania had made a significant postwar investment in solid-state research, including studies of an obscure effect described in the 1930s by a Parisian chemist named Georges Destriau. While experimenting on fluorescent compounds, Destriau had discovered a class of materials that emitted light when subjected to an electric field. Once he confirmed that his observations did not result from accidental exposure to ultraviolet or infrared radiation, Destriau published his findings, and the phenomenon became known as "electroluminescence."[50]

Destriau's experiments elicited mixed responses from chemists. Humboldt Leverenz, the head of RCA's phosphor group, summarily dismissed the effect's existence in a 1950 textbook on the luminescence of solids, claiming instead that it resulted from "electric discharges in gases."[51] His counterparts at Sylvania were more willing to grant the Frenchman the benefit of the doubt, and in 1952 the company demonstrated its "panelescent" light technology at an MIT solid-state conference.[52] The following year, Sylvania offered consumers a self-illuminating bedside alarm clock for a suggested price of $47.95.[53] News of these achievements forced Leverenz to abandon his skepticism, and he

[50] L.E. Tannas, Jr., "Electroluminescent Displays," in *Flat-Panel Displays and CRTs*, ed. Lawrence E. Tannas, Jr. (New York: Van Nostrand Reinhold Company, 1985), 240. Originally, Destriau named the phenomenon "electrophotoluminescence," but changed the name on the recommendation of his colleague Maurice Curie (the nephew of Pierre) since the presence of light was not prerequisite for the effect.
[51] Humboldt W. Leverenz, *An Introduction to the Luminescence of Solids* (New York: John Wiley & Sons, 1950), 152.
[52] Tannas, 241; Watson Davis, "Electric Light Without Bulbs," *Science News Letter* 59 (25) (23 Jun. 1951): 394-395
[53] "Lights from 'Panelescence,'" *Wall Street Journal,* 14 Jul. 1953, 13; "Bulletin Board," *Chicago Daily Tribune*, 14 Jul. 1953, B5. An amusing description of both electroluminescent furniture ("The dinner table or the boudoir dressing alcove could be built with principal surfaces that give light.") and the proposed alarm clock ("No clock will be complete unless it is self-lighting, in addition to ringing bells and turning on the radio and the coffee maker at the appointed time.") can be found in Davis' 1951 article.

authorized DSRC chemists to synthesize electroluminescent phosphors with an eye toward potential display applications.[54]

Nicoll and Kazan were among the first to take advantage of these materials. They started by reproducing the experiments conducted at Sylvania, and successfully created an electroluminescent panel whose luminance exceeded that of a typical home television.[55] "The life of a sample at this level is very short with present materials and techniques," they reported, "but the experiment indicates the future possibilities of electroluminescence as a light source."[56] Having confirmed these substances were bright enough for display applications, they now faced the challenge of moving from a simple light-emitting element to a grid-shaped device they imagined serving as a precursor to a TV-resolution display.[57]

It is important to emphasize that, up to this point, Nicoll and Kazan's experiments focused upon image production, not light amplification. Given their previous research interests, these early electroluminescence investigations were not contingent upon Sarnoff's birthday gift request. If the same was true of their next experiment is less clear. What is known is that the two men became aware of research into another solid-state effect called photoconductivity. Photoconductive substances carried an electric current

[54] Kilbon, 329. Leverenz stated in a 1975 interview that the long-term aim of this work was "to achieve an all-electronic television," but expressed skepticism that the shape of a television would affect sales more than the quality of the network programming. For more, see: Humboldt W. Leverenz, an oral history conducted in 1975 by Mark Heyer, IEEE History Center, New Brunswick, NJ, USA.

[55] RCA Laboratories, *Research Report 1952*, 99. Kazan and Nicoll report a luminance of 150 foot-Lamberts upon the application of 2000 Vac at a frequency of 6,000 cycles. A foot-Lambert is defined as 1 lumen of luminous flux per square foot. As Sherr notes, luminance is typically a more effective measurement for comparing the light output of two displays, since "brightness" is a psychological term referring to an observer's ability to perceive luminance. To provide some perspective on Kazan & Nicoll's measurement, the peak highlight brightness of Epstein's projection television was 30 foot-Lamberts (*PTR-509*, 13). A modern CRT television has a luminous output between 60-120 foot-Lamberts. (See Donald Say, et al. "Monochrome and Color Image-Display Devices," in *Television Engineering Handbook* (rev. ed.), ed. K. Blair Benson (New York: McGraw Hill, Inc., 1992) 12.22.

[56] RCA Laboratories, *Research Report 1952*, 99.

[57] RCA Laboratories, *Research Report 1952*, 99.

when exposed to light, and Nicoll and Kazan realized that this ability might replace the cumbersome manual switching used with their earlier samples.[58]

To test this hypothesis, they obtained a small photoconductive crystal of cadmium sulfide, connected it in series with one of their electroluminescent cells and applied a voltage across the circuit. The strength of the electric field across the electroluminescent panel and its resulting light output depended upon the amount of light shining on the photoconductor. When the cadmium sulfide was dark, the voltage across the panel was basically zero, but as the illumination increased so did the panel's brightness.[59] Further experiments revealed that the amount of light emitted by the electroluminescent material could be several times greater than the incident light focused on the photoconductor. As they explained in the DSRC's 1952 report, "under steady state conditions, it is possible to obtain some light amplification."[60]

Regardless of whether their work was inspired by Sarnoff's speech, Nicoll and Kazan knew they had uncovered a viable technological basis for a solid-state light amplifier–one of the General's presents–and they accelerated their research over the following year in hopes of generating television-quality images "with a panel of two or three feet diagonal."[61] The individual photoconductive crystals from their earlier experiments did not possess the uniformity required for such a device, so they enlisted Leverenz's chemists to create new photoconductive powders that permitted the assembly

[58] Photoconductivity had been studied since the 1870s, but had come to prominence with RCA during the 1950s due to its use in an improved television camera called the Vidicon. For more, see: Magoun (2009), 122 or Kilbon, 246-252.
[59] Benjamin Kazan and F.H. Nicoll, *PTR-458: An Electroluminescent Light-Amplifying Picture Panel*, 16 May 1955, DSL, 1.
[60] RCA Laboratories, *Research Report 1952*, 99.
[61] *PTR-458*, 2.

of panels measuring 6 x 6 inches. These devices accurately reproduced images projected upon them using slides or a CRT, although the resulting picture was not perceptibly brighter and "the slowness of response of the available (PC) [photoconductive] powders...caused some smearing of moving objects."[62]

Kazan and Nicoll spent the remainder of 1953 testing different panel structures in order to resolve these issues, ultimately settling on a design using V-shaped grooves to maximize the photoconductor's exposure to light.[63] By the end of 1954, Nicoll and Kazan's panels, now measuring 12 x 12 inches but only 1/4 inch thick, were able to duplicate an image with a 15-20x increase in light intensity over the original.[64] They could also convert X-rays into visible light, suggesting an application in fluoroscopy equipment.[65] The one shortcoming of their original panel that they had not been able to overcome was the smearing of moving images. But, they concluded, with all the recent advances in photoconductive materials, "development of light amplifiers having higher gain and light output than existing types and with response times sufficient for T-V purposes thus appears as a reasonable possibility."[66]

"The Television of Tomorrow": Rajchman's Transfluxor-Driven Display

Taken at face value, Sarnoff's birthday gift speech proposed the refinement of an existing technology, projection television, transforming it into a device meant for the home

[62] RCA Laboratories, *Research Report 1953*, DSL, 23.
[63] *PTR-458*, 12-13; RCA Laboratories, *Research Report 1954*, 82.
[64] The maximum light gain is reported as 20x in *RCA Laboratories Research Report 1954* (82) but only 15X in *PTR-458* (Sheet I).
[65] RCA Laboratories, *Research Report 1954*, 81-82.
[66] *PTR-458*, 39.

consumer. In contrast, internal reports reveal that RCA scientists interpreted his remarks not as a call for improved projectors, but for a successor to the CRT itself. The DSRC's annual research report for 1953, for example, prefaced a discussion of Nicoll and Kazan's findings with the following observation:

> How long it will be before the cathode ray tube is replaced by some more effective means for reproducing a television picture is not predictable at this time. However, there is little doubt that this will come about. A program has been underway for some time now to investigate means other than cathode-ray tubes for reproducing color television images. Methods using electroluminescence give indications that they may be particularly attractive especially for the formation of large pictures."[67]

One explanation for the disparity between the General's public statements and RCA's internal reports is the likelihood that the former emerged from conversations between Sarnoff and his research managers. Sarnoff had long embraced obsolescence as an inevitable aspect of the electronics industry. As he explained near the end of his 1951 speech, instead of seeing the need for constant innovation as "a wicked ghost that threatens extinction, we see a beneficent wraith whose proddings stimulate opportunity, advance prosperity, and raise the standards of living."[68] Unlike earlier system-builders, who saw institutionalized research primarily as a means of refining existing technologies, Sarnoff came to view the DSRC as a wellspring of radical inventions essential to keeping RCA on the forefront of the consumer electronics industry.[69]

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[67] RCA Laboratories, *Research Report 1953*, 4.

[68] *Dedication*, 27.

[69] Graham, 35, 74-75. This characterization of industrial science as "system-improving" (conservative) rather than "system-originating" (radical) is derived from the writings of Thomas Hughes, who claims that the research agendas pursued at industrial labs during the first quarter of the 20th century (e.g. GE, Bell, etc.) reflected a "rigid commitment to conservative inventions and relative disinterest in radical ones." See: Thomas P. Hughes, "The Evolution of Large Technological Systems," in *The Science Studies Reader*, ed. Mario Biagioli (New York: Routledge, 1999), 217. See also: Thomas P. Hughes, *American Genesis A Century of Invention and Technological Enthusiasm, 1870-1970* (Chicago: Univ. of Chicago Press, 1989 [2004]), 138-183 (Ch. 4).

Given this research philosophy, it is not surprising that Sarnoff had started pondering his company's post-color TV strategy. During these deliberations, he would certainly have contacted Engstrom, who would have informed him of the DSRC's interest in solid-state phenomena permitting the construction of flat-panel displays. The relative novelty of solid-state research and the risks of inviting additional competition provide plausible explanations for Sarnoff's decision to avoid mentioning electroluminescence by name in his speech. Instead, he contented himself with oblique allusions to research on "electronics in solids" and hints that "[t]he television you know now as pioneers will not be the television of tomorrow."[70]

Still, if the General's intent was to inspire researchers to create "the television of tomorrow," Nicoll and Kazan's light amplifying panels would not fit the bill due to their inability to reproduce moving images. There were, however, other people at the DSRC interested in the prospect of an electroluminescent television, most notably a computer researcher named Jan Rajchman.

Rajchman had joined RCA in 1935 upon emigrating to the United States from Switzerland. As a member of television expert Vladimir Zworykin's laboratory in Camden, he participated in a military project to improve the fire control systems of anti-aircraft guns, which inspired an interest in analog, and later digital, computing.[71] Following the opening of the Princeton labs, Rajchman became a consultant for the ENIAC project, specializing in the construction of memory storage devices.[72]

[70] *Dedication*, 23.
[71] Jan Rajchman, Interview with Richard Mertz, 26 Oct. 1970. Computer Oral History Collection, 1969-1973, 1977, Archives Center, National Museum of American History. Accessed online 7 Nov. 2009. http://invention.smithsonian.org/downloads/fa_cohc_tr_rajc701026.pdf
[72] Jan Rajchman, Interview with Richard Mertz, 26 Oct. 1970. For further discussion of Rajchman's

While digital computing was a low priority project within RCA, Rajchman's interest in computer memories persisted after World War II. A partnership with fellow ENIAC alumnus John von Neumann, who was working at the nearby Institute of Advanced Study, resulted in the creation of the Selectron, a 256-bit random access memory device.[73] The Selectron's use of an electrically charged metal grid to store information foreshadowed Rajchman's 1950 fabrication of the first magnetic memory arrays built in an industrial laboratory.[74] Each of these consisted of a wire matrix with doughnut-shaped cores made of ferrite, a magnetic ceramic, at each intersection. Through the application of current to a given set of horizontal and vertical wires, one could switch the direction of a particular core's magnetic field, corresponding to a 1 or 0 in binary code.

Rajchman's interest in flat-panel displays stemmed from the realization that the mechanism used to select a particular core in his magnetic arrays might also activate a pixel on a screen. Theoretically, one could mimic an electron beam sweeping across a screen by activating a row of cores sequentially, eliminating the need for a vacuum tube.

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involvement with the ENIAC project, see: Dr. Jan Rajchman, an oral history conducted in 1975 by Mark Heyer and Al Pinsky, IEEE History Center, New Brunswick, NJ, USA; William Hittinger, "Jan A. Rajchman: 1911-1989," in *Memorial Tributes, Vol. 5* (Washington, D.C.: National Academy Press, 1992), 228-231.

[73] Kilbon, 323. Rajchman's Smithsonian and IEEE oral histories discuss the IAS computer project. A comprehensive discussion of the Selectron, including a detailed bibliography and reprints of contemporary technical and popular literature on the subject, can be found at: Charles Osborne, "The RCA Selectron," http://home.att.net/~thercaselectron/index1.html. Accessed 9 Nov. 2009.

[74] Rajchman's research coincided with Project Whirlwind, an MIT-based program whose initial mission to develop an airplane training simulator had evolved into a broader interest in real-time computing. Rajchman and the MIT research group led by Jay Forrester and William Papian developed core memory systems at approximately the same time, leading to subsequent intellectual property disputes. For more on Whirlwind, see: Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine*, 2nd ed. (Cambridge, MA: Westview Books, 2004), 141-163 (Ch. 7). For more on Rajchman's core memory project, see: Kilbon, 324-325; Rajchman, Interview with Richard Mertz, 26 Oct. 1970; Rajchman, Interview with Mark Heyer and Al Pinsky, 1975.

"For a long time," he wrote in 1952, "there has been the desire to produce a 'Mural Television Display' which would be a large flat box-like device with a large rectangular face and relatively small thickness. This then could be used on the wall of the viewing room."[75] Magnetic cores arranged in series with electroluminescent phosphors offered one basis for such a display, but more sophisticated systems would be required to move from on-off switching to the production of grayscale images.

Rajchman sketched out possible solutions to this problem in his laboratory notebooks, but set them aside to start work on RCA's myriabit (10,000 core) and megabit (1,000,000 core) computer memories.[76] These projects, intended to force DSRC engineers to confront the challenges of assembling large-scale core memory systems, unexpectedly supplied the technical basis for Rajchman's mural television.[77] To avoid manufacturing an unwieldy number of ferrite cores, Rajchman switched to using magnetic plates with evenly spaced rows of holes. As with core memory, the magnetic field around each hole could store a bit of information, but these apertured plates were more compact and faster both to produce and test for defects.[78]

The shift from magnetic cores to apertured plates did not occur without incident. "The idea was that an integrated approach was better than an individual approach," Rajchman recalled in a 1975 interview. "So, for example, we made plates and asked, 'How

[75] Jan Rajchman, *File 334*, DSL, 1.
[76] Jan Rajchman, *File 334*, DSL, 1-20; Jan Rajchman, *Notebook P-2519*, DSL, 38-55. Among the alternatives Rajchman considered were: 1.) an illuminated matrix array of photocathodes positioned behind a conventional phosphor screen; 2.) an array of electroluminescent cells activated via core memory, whose luminance depended on a pair of capacitors, one of which had a ferroelectric material as a dielectric; 3.) various mechanical systems using small metal sheets in a wire grid to create a reflective display; and 4.) a matrix-addressed array of incandescent light bulbs.
[77] For more on the myriabit system, see: RCA Laboratories, *Research Report 1952*, 96-98; Jan Rajchman, *File 334*, 22-38; Jan Rajchman, *Notebook P-2519*, 7-13.
[78] RCA Laboratories, *Research Report 1953*, 93.

close can you put the holes?'...When we put the holes very close together, we found they started to interact."[79] This magnetic "cross-talk" could wreak havoc on computer function, so Rajchman and his physicist colleague Arthur Lo launched an investigation of the phenomenon. One result of these experiments was the creation of a new magnetic storage element called the transfluxor, which provided Rajchman with the means to construct his flat-panel display.

It is unclear from journal articles or internal documents who first realized what a later technical report referred to as "the principle of the transfluxor."[80] George Briggs, a physicist who joined Rajchman's research team in 1954, believes that Lo, a solid-state expert, was responsible for the breakthrough. "He [Lo] came up with the transfluxor concept," Briggs explained in a 2009 interview. "He got the idea originally of just being able to use the transfluxor as an interrogation element where you didn't have to destroy the information in the memory."[81]

In its most basic form, the transfluxor consisted of a ferrite core with two holes of unequal diameter that could mimic the binary switching of a regular ferrite core or produce the intermediate values required for grayscale operation. With its simple construction and a reliability greater than contemporary transistors, Rajchman and Lo predicted that the transfluxor would "become a basic element in electronic circuits of the future" and enjoy widespread use in digital computing, automation, and communication

[79] Rajchman, Interview with Mark Heyer and Al Pinsky, 1975.
[80] Jan A. Rajchman and A.W. Lo, *PTR-473: The Transfluxor*, 20 May 1955, DSL, 5. See also: J.A. Rajchman and A.W. Lo, "The Transfluxor," *Proc. IRE* 44, no. 3 (Mar. 1956): 321-332; J.A. Rajchman, G.R. Briggs, and A.W. Lo, "Transfluxor Controlled Electroluminescent Display Panels," *Proc. IRE* 46, no. 11 (Nov. 1958): 1808-1824. The transfluxor's origins and subsequent dissemination were the subject of the author's submission to the 2010 Princeton-Harvard Workshop on the History of the Physical Sciences, entitled "The Tale of the Transfluxor: A Case Study in Electronic Microhistory."
[81] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.

systems.[82] One application conspicuously missing from this list was a flat-panel display, but Rajchman filled his notebook with entries on the subject and recruited additional staff to turn his idea into a reality.[83] When George Briggs arrived at the DSRC for an interview, for example, Rajchman bluntly informed him that upon becoming a member of the technical staff, he would be working on mural television. "That interested me if you could do it successfully," Briggs remembered later. Needless to say, he took the job.[84]

Rajchman's plan was ambitious. He sought to create a 1200-element electroluminescent display with switching speeds comparable to existing TV sets.[85] Along with Lo, Briggs, and several chemists and technicians responsible for producing 1200 identical transfluxors, Rajchman spent the early months of 1955 assembling a mural TV prototype.[86] The screen measured 14 x 18 inches and was only 1.5 inches thick, but its associated drive circuitry contained dozens of vacuum tubes and filled up two carts, placed next to the display in order to maintain its thin appearance.[87]

In April 1955, Rajchman's team put the finishing touches on their mural television and invited half a dozen DSRC personnel, including Kazan and Nicoll, to witness a

[82] *PTR-473*, 2, 40.
[83] Jan Rajchman, *Notebook 41*, DSL, 1-10, 13-17, 20-25, 27-79, 91-97.
[84] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.
[85] Rajchman appears to have settled upon these parameters by November 1954. See: Rajchman, *Notebook 41*, 2.
[86] Rajchman, et al (1958), 1824; George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009. The main chemist involved in the project was Chandler "Pete" Wentworth, who had previously provided Rajchman with ferromagnetic materials for his apertured memory plates. Technicians Joseph Walentine and James Teza were assigned the task of stamping out transfluxors using precision metal dies and threading thin, Teflon-coated wires through each core multiple times.
[87] Rajchman, *Notebook 41*, 39-41; Jan A. Rajchman, *PEM-1013C: Mural Television*, 26 Oct. 1955, DSL, 9. George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009. It is unclear precisely how many vacuum tubes were used in the construction of this display. Briggs, who was responsible for assembling the drive circuitry, estimated that two standard RCA 6L6 tubes were used for each drive line and confirmed that drive lines went horizontally and vertically in the display. Assuming that there was one drive line for each row (30) and each column (40) as implied by Rajchman et al. in their 1958 paper, this suggests that there were at least 140 vacuum tubes involved.

demonstration. A specially configured camera supplied video signals, which traveled through the drive circuitry before appearing on the screen as pale green moving images. "The picture was uniform, showed good half-tone range and high contrast," Rajchman reported later.[88] The frame rate was lower than anticipated (15 frames/sec., as opposed to 30), but this was sufficient to provide an "adequate illusion of continuous action."[89] The device's transfluxors also permitted one to freeze and store a given screen image indefinitely without requiring additional standby power.[90]

These technical achievements came at a price. With only 1200 electroluminescent cells, the display's resolution was significantly lower than existing televisions. Moreover, due to the time spent wrapping wires through each transfluxor, Rajchman explained in his report, "[s]o much artifice is required at every picture element that the fabrication of a sufficient number of elements for standard television would be extremely costly and impractical. Also the power consumption and associated electronic circuits are very onerous."[91] Even if improved manufacturing techniques permitted the construction of larger displays, electroluminescent phosphors emitted less light than a CRT. "They needed a long exposure," Briggs noted, "You had to have a darkened room to see the meatball [i.e. RCA's circular logo] or Rajchman's face."[92] Theoretically, the application of higher voltages might surmount this issue, but as Briggs learned firsthand, such voltages caused the phosphors to burn out and emit foul smelling smoke.[93]

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[88] *PEM-1013C*, 9.
[89] Rajchman, et al. (1958), 1819.
[90] Rajchman, et al. (1958), 1819.
[91] *PEM-1013C*, 10.
[92] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.
[93] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.

In spite of these weaknesses, Rajchman's mural television proved that one could produce a moving electronic image without the use of a vacuum tube. Higher resolution or full color screens would have to wait, but Rajchman imagined similar devices could be used "in cases where a relatively small number of picture elements is tolerable...Radar displays, outputs of computing systems, displays of numerical and alphabetical information are examples of such applications."[94] Meanwhile, he felt RCA should devote its resources to designing new display circuitry and transfluxor production techniques. "It is believed that the solutions to these essential problems will not only yield a second mural television working model greatly improved with respect to the first," Rajchman concluded, "but will also pave the way for still better systems."[95]

TV Without Tubes?: Sarnoff's Changing Vision, 1953-1956

Nicoll and Kazan's presence at Rajchman's mural television demonstration confirmed that the three men did not work in isolation. Nor did their shared confidence in electroluminescent television remain confined to the DSRC. For example, at the end of May 1955, Rajchman submitted a patent for an "Electrical Display Device" based on his electroluminescent prototype.[96] He included a diagram "illustrating how a mural image reproducer might be utilized in the living room of a modern home."[97] Rajchman described the scene, showing a group of friends watching performers on a wall-mounted display, as follows:

[94] *PEM 1013C*, 10-11.
[95] *PEM 1013C,* 13.
[96] Jan Aleksander Rajchman, "Electrical Display Device," US Patent 2,928,894, filed 31 May 1955 and issued 15 Mar. 1960.
[97] Rajchman, US Patent 2,928,894, 22.

> It is noted that the mural image reproducer...is a flat large image display device which is hung at an appropriate position on a wall, in much the same manner as a favorite painting. The mural image reproducer is flat. Its control cable...is coupled in turn to a remotely located control box...which would be utilized to adjust the television channel received and the contrast and brightness of the reproduced image.[98]

In its key features, this device corresponded closely to Rajchman's prototype, with one exception: the wired control box, which could adjust the channel or other display parameters. Rajchman had anticipated the creation of a tabletop control system "small enough to fit in a cigar box," but as he reported in 1955, such a setup was far removed from the carts of electronic equipment used in his current display.[99] The description in this patent was, however, reminiscent of depictions of mural television circulating in the popular press thanks to statements from RCA's corporate leaders.

In August 1954, months before Rajchman's team completed their transfluxor-driven device, David Sarnoff delivered a speech in Chicago predicting that "at some point in the future–I will hazard a guess and say five years from now–no tubes will be needed in a television set—not even the picture tube."[100] Electroluminescence would allow for larger displays without bulky cabinets. Each screen would be "connected directly by a small cable with a little television box–about the size of an average cigar box that can be placed anywhere in the room."[101] Sarnoff's proposed control mechanism utilized transistors (not

[98] Rajchman, US Patent 2,928,894, 22.
[99] RCA Laboratories, *Research Report 1956*, DSL, 2.
[100] "Aspects of Broadcasting Present and Future," *Radio Age* 13, no. 4 (Oct. 1954): 7. Also excerpted in Sarnoff, *Looking Ahead*, 122-123. Sarnoff had publicly referred to the DSRC's efforts to fulfill his birthday requests as early as 1953, but did not specifically refer to electroluminescence as a display technology at that time. See: "Sarnoff Honored by Radio Engineers with First Founders Award," *Radio Age* 12, no. 3 (Apr. 1953): 5.
[101] "Aspects of Broadcasting," 7.

tubes!) and permitted the manipulation of image attributes such as size, brightness, and contrast, and switching between black-and-white and color.

Nor was the General alone in advancing such claims. In an August 1955 speech in San Francisco, DSRC head Elmer Engstrom asserted that improved materials and miniaturized electronic circuitry "will give us mural television. Its form will be that of a thin screen decorating a wall and controlled remotely from a small box beside the viewer elsewhere in the room."[102] It is likely that Engstrom, or another high-ranking DSRC official, was also involved in the creation of a drawing, produced in partnership with the U.S. Chamber of Commerce, which showed how RCA's televisions might look in 1975. This image, published in the July 1955 issue of the company's *Radio Age* magazine, was "[p]repared in consultation with scientists at the David Sarnoff Research Center of RCA" and bears a striking resemblance to Rajchman's patent application from two months before.[103]

With the benefit of hindsight, the parallels between these descriptions and Rajchman's mural television appear obvious, but before 1956, neither Sarnoff nor any other RCA executive commented on the computer researcher's prototype. The only concrete accomplishments along these lines brought to the public's attention were Kazan and Nicoll's light amplifying panels, which a December 1954 press release announced as an interim step towards the development of "a thin, flat picture screen on the wall."[104]

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[102] "Electronic Horizons: A Revolution in Materials," *Radio Age* 14, no. 4 (Oct. 1955): 23. For the full text of Engstrom's speech, see: Horizons in Electronics–A Revolution in Materials (WESCON, San Francisco, 26 Aug. 1955); Elmer W. Engstrom Papers, Box 1, Vol. 8, Department of Rare Books and Special Collections, Princeton University Library.

[103] "Products of the Future...," *Radio Age* 14, no. 3 (Jul. 1955): 16.

[104] "RCA Claims Big TV Advance in Light Device," *Chicago Tribune*, 20 Dec. 1954, C7.

Sarnoff posed for promotional photographs alongside a light amplifier, but admitted that it was not ready for the market."You may wonder what philosophy prompts me to reveal these new developments publicly while they are still in the experimental stage," he mused in a January 1955 speech. The answer, Sarnoff claimed, was simple: publicizing research was essential to maintaining RCA's technical leadership. "We welcome competition. It spurs our own activities and increases the possibilities for earlier achievement of desired results."[105]

The truth was more complex. Sarnoff's paeans to the benefits of communication concealed the fact that the commercial rivalries he praised had also provoked an action he might otherwise have avoided. For although Sarnoff had previously referred to DSRC light amplification research, he chose to reveal the full extent of that work only after learning that General Electric would demonstrate its own light amplifying panels before the end of 1954.[106] Nicoll and Kazan's amplifier was not market-ready, but RCA's publicity department would not let GE coopt one of the General's presents.[107] While GE forced Sarnoff's hand, his response demonstrated a keen grasp of strategic information

[105] David Sarnoff, *New Developments in Electronics* (New York: Dept. of Information, Radio Corporation of America), David E. Lilienthal Papers, Box 400: 1955 Correspondence: Name Files: (O-Sp); Public Policy Papers, Department of Rare Books and Special Collections, Princeton University Library, 12. For press coverage of this event, see: Robert K. Plumb, "Electronic Device Can Duplicate Every Sound," *New York Times*, 1 Feb. 1955, 35. For RCA's version of events, see: "Major Developments of RCA Research," *Radio Age* 14, no. 2 (Apr. 1955): 7-9.

[106] Sarnoff's referred to having "seen electronic light amplified experimentally in ratios of more than twenty to one" at an October 1954 event commemorating the 75th anniversary of Edison's lightbulb. He did not present any photographs of the devices involved, but expressed the belief, echoed in his Jan. 1955 speech, that increasing that ratio to 100 to 1 was essential to creating a practical light amplifier. See: "Sarnoff Predicts Electronic Light," *New York Times*, Jan. 1955, 25; W.K. "Bright Future for Electronics," *New York Times,* 24 Oct. 1954, E9.

[107] For more on GE's light amplifier project, see: D.A. Cusano, "Radiation-Controlled Electroluminescence and Light-Amplification in Phosphor Films," *Physical Review* 48 (1955): 547-548; Harry C. Kenney, "'Picture on Wall' Envisaged for Television," *Christian Science Monitor*, 23 Dec. 1954, 3; Robert K. Plumb, "Light Amplified by New Principle," *New York Times*, 22 Dec. 1954, 42.

disclosure. In one move, RCA simultaneously regained the initiative from GE, confirmed the extent to which the General's request inspired tangible results, and provoked speculation as to whether true "picture-on-the-wall television" would be revealed to the audience at his golden anniversary dinner.[108]

Magnalux Revealed: Light Amplification at the General's Golden Anniversary

The ceremonies commemorating Sarnoff's fiftieth anniversary in radio dwarfed those of 1951 in every respect. Rather than a luncheon in Princeton, over one thousand people crowded into New York's Waldorf-Astoria Hotel in late September 1956 for a dinner honoring the General's contributions to the electronics industry.[109] Once again, the president of the United States and governor of New York sent congratulatory letters, but now Dwight Eisenhower and Averell Harriman were joined by Richard Nixon, Winston Churchill and Adlai Stevenson in extending their well-wishes to the guest of honor.[110] The corporation itself had grown over the preceding half decade, with company profits breaking all previous records. "My completion of fifty years in harness happily coincides with the first 'billion dollar year' in the history of our company," Sarnoff announced. "What a magnificent anniversary present!"[111]

Of course, RCA's technical staff had spent five years preparing three gifts of their own. Speaking on behalf of the DSRC, Elmer Engstrom recounted Sarnoff's requests.

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[108] Plumb (1955), 35.
[109] *Dinner in Honor of David Sarnoff (Chairman of the Board, Radio Corporation of America): Commemorating His Fifty Years of Service to Radio, Television and Electronics* (New York: Radio Corporation of America, 1956). See also: "Fifty Years in Radio," *Radio Age* 15, no. 4 (Oct. 1956), 3-7.
[110] *Dinner*, 38-57. Sarnoff also received letters or telegrams from Herbert Hoover, Lyndon Johnson, Arturo Toscanini, Bernard Baruch, and Lee de Forest.
[111] *Dinner*, 23.

Now, he proclaimed, "five years have passed, the day has come, and this is truly a day of fulfillment because we have met your desires and I think in some instances exceeded them."[112] While in-person demonstrations would be held in Princeton the next day, Engstrom brought slides so that those unable to attend could still witness all three gifts in action. Following these explanatory remarks, he asked for the room to be darkened and proceeded to describe each device, beginning with the Magnalux.

Based on internal research reports and press coverage, an informed observer could have deduced that Sarnoff's light amplifier would be based upon electroluminescence. What was uncertain was which of the options under consideration–Nicoll and Kazan's panels or Rajchman's mural television–would serve as the embodiment of Magnalux. The former's ability to increase an incoming image's brightness seemed closer to the General's initial request, but the latter aligned with his recent predictions about television's future. Indeed, Sarnoff once again insisted that full-color "picture frame television sets" would replace existing CRTs in a *New York Times* article published the day of his anniversary dinner, which included yet another variation of the picture from Rajchman's 1955 patent.[113] His prepared remarks for the evening also declared that electroluminescence would "give us brighter and bigger TV pictures and ultimately replace the TV tube altogether with a thin, flat-surface screen that will be hung like a picture on the wall."[114]

Yet when Engstrom dimmed the house lights, it became clear that RCA's leaders did not consider Rajchman's mural television ready for public scrutiny. Instead, Engstrom

[112] *Dinner*, 9.
[113] David Sarnoff, "Electronic Revolution, Present and Future," *New York Times*, 30 Sep. 1956, 38, 42. The image is likely derived from the previously discussed artwork submitted to the U.S. Commerce Dept.
[114] *Dinner*, 10.

described an improved light amplifying panel while showing a slide of Benjamin Kazan projecting an image of Sarnoff onto a "picture frame type panel."[115] In the two years since their invention went public, Nicoll and Kazan had designed panels capable of amplifying incoming light by more than 1,000 times.[116] The displays retained the slow response times of their predecessors, but Engstrom emphasized their potential inclusion in radar or X-ray equipment.[117] The latter option was particularly encouraging, since RCA's panels might lower the radiation dose required to diagnose a patient while providing brighter images than existing fluoroscopes.[118]

Once Engstrom completed his presentation, Sarnoff thanked RCA's research staff "for their pioneering courage, their perseverance, [and] their competence unmatched in the field."[119] He noted that the challenges associated with creating a functional light amplifier, as well as working prototypes of the other two presents, were immense. "But the fact remains that in five short years they have succeeded in turning what were bold dreams and hopes into proud realities."[120] These devices validated Sarnoff's faith in fundamental research and, more broadly, his confidence in the intrinsic manageability of corporate innovation. If industrial leaders set ambitious goals and provided scientists with the resources necessary to achieve them, even seemingly impossible technological marvels might one day enter the marketplace. This philosophy perhaps explains why Sarnoff

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[115] *Dinner*, 10.
[116] For more on efforts to improve the light amplifier, see: B. Kazan and J. Berkeyheiser, *PEM-840: Improvements in the Panel Light Amplifier*, 13 Mar. 1957, DSL; B. Kazan, "An Improved High-Gain Panel Light Amplifier," *Proc. IRE* 45, no. 10 (Oct. 1957): 1358-1364.
[117] *Dinner*, 11.
[118] *Dinner*, 11. RCA Laboratories, *Research Report 1956*, 24-25.
[119] *Dinner*, 24.
[120] *Dinner*, 24.

retained references to the future promise of electroluminescent television in his speech despite the difficulties transforming Rajchman's mural display into a commercial reality.

Whither Magnalux?: Economic and Institutional Contexts of Technological Success

The next day, Sarnoff traveled to Princeton for the formal presentation of his three birthday gifts.[121] Once again, Elmer Engstrom acted as master of ceremonies, guiding the General past exhibits showing off the technologies requested five years before. First, they walked through a room whose temperature was regulated by wall-mounted thermoelectric panels. Then it was off to a faux living room, where they watched NBC programming recorded off the air using a new magnetic tape player. Finally, there was a demonstration of the now familiar light amplifying panels. Sarnoff explained that these presentations showed how new scientific concepts could be translated into commercial devices. "How long this will take nobody knows. As an uneducated guess I'd say that between now and the end of five years you could expect to see practical products embodying these principles on the market."[122]

After Sarnoff left, the scientists responsible for creating his birthday gifts took him at his word and continued to pursue their commercialization. Though Electronair panels proved inefficient for home use, a refrigerator based on the same concept would find a place on nuclear submarines, where silent operation was essential and power was readily

[121] For press coverage of this event, see: Robert K. Plumb, "RCA Unveils TV Tape Player, Light Amplifier, Silent Cooler," *New York Times*, 2 Oct. 1956, 37; "RCA Unveils Models of Electronic Devices to Honor Sarnoff," *Wall Street Journal*, 2 Oct. 1956, 3; "Sarnoff Sees New Devices," *Baltimore Sun* 2 Oct. 1956, 19. For RCA's official account, see: "Electronic 'Gifts' From RCA Research," *Radio Age* 15, no. 4 (Oct. 1956), 8-13.
[122] "RCA Unveils Models," 3.

available.[123] The Videograph group reached a cross-licensing agreement with Ampex, a California-based startup firm, to market a magnetic tape system capable of recording monochrome and color broadcasts.[124] Nicoll and Kazan, meanwhile, demonstrated their prototypes to the American Roentgen Ray Society and developed standardized panel manufacturing procedures.[125] Even Rajchman and his team, whose transfluxor-driven display had been ignored by Sarnoff and the popular press, worked to refine their designs.[126] The DSRC's 1956 annual report went so far as to declare Rajchman's mural television a major continuing project and promised that this research would continue "with an increased staff and on a broader front."[127]

Once again, Sarnoff's "uneducated guess" appeared poised to come true, but before the anticipated five year transition between laboratory and factory had elapsed, both electroluminescent display projects were terminated. In the absence of RCA management records, it is tempting to attribute this decision to purely technological factors. But while the DSRC's annual reports refer to engineering obstacles hindering the completion of a functional flat-panel TV, accepting such a position ignores the extent to which organizational and economic considerations altered RCA's research environment during the 1950s.[128]

In his 1951 speech, Sarnoff described RCA's Princeton laboratory as an institution "which does basic research and applied research and translates the images of the mind into

[123] Brown, 269-270.
[124] Brown, 270-287; Graham, 68.
[125] RCA Laboratories, *Research Report 1957*, DSL, 27.
[126] RCA Laboratories, *Research Report 1956*, 26-27.
[127] RCA Laboratories, *Research Report 1956*, 2.
[128] RCA Laboratories, *Research Report 1956*, 2-3, 26; RCA Laboratories, *Research Report 1957*, 2-3, 16-17.

useful products and services for the public."[129] This holistic conception of RCA's research environment may have been more accurate during the postwar years when close working relationships existed between the company's laboratories and manufacturing divisions, but as Engstrom and Ewing pushed to reorient the DSRC towards more theoretical investigations, these links began to weaken.[130] Where the DSRC staff had once consisted of engineers from the divisions, its ranks now swelled with university-trained researchers unfamiliar with the challenges of technology transfer.[131] This schism was exacerbated after Ewing's 1954 appointment as the DSRC's administrative director.[132] Citing a need for greater operational flexibility, Ewing implemented a new "building block" strategy, transferring product-related research to the divisions in order "to allow the research laboratories freedom to work on the more speculative and long-range projects."[133]

The "building block" strategy established the DSRC's reputation as a "country club" where funds were wasted on outlandish projects with limited commercial value, like the General's birthday gifts. To personnel at RCA's product divisions, the money flowing into Princeton was a diversion from what should have been the company's main priority: color television. RCA had finally secured FCC approval for their preferred broadcasting

[129] *Dedication*, 25-26.
[130] Choi, 13-51; Graham, 72-73.
[131] Graham, 70.
[132] Ewing's promotion coincided with Engstrom's promotion from Executive Vice-President, RCA Laboratories to Executive Vice-President, Research and Engineering, though the latter remained the titular head of RCA Laboratories. See: Kilbon, 190-191; "Five Executive Promotions Announced by RCA," *Radio Age* 13, no. 3 (Jul. 1954): 28.
[133] RCA Laboratories, *Research Report 1955*, 1. Ewing also abandoned the formation of project-based research groups in favor of "temporary task groups" drawn on an ad hoc basis from six newly created discipline-based laboratories (Physical and Chemical Research, Electronic Research, Systems Research, Acoustical and Electromechanical Research, Radio Research, and Special Projects Research). See also: Graham, 71-74.

standard at the end of 1953,[134] and the divisions were eager to recoup the company's $50 million investment in the compatible color system.[135]

As assembly lines whirred into motion, Sarnoff claimed that consumers would buy 75,000 color sets by the end of 1954.[136] In this instance, his penchant for prediction failed. Only 5,000 sets were sold, leading skeptics to accuse RCA of having exaggerated their system's capabilities. Other companies scrapped plans to manufacture color sets and RCA was left to pioneer the technology on its own. Low sales over the next two years prompted *Time* to label color television "the most resounding industrial flop of 1956," but by then RCA had too much at stake to abandon the technology.[137] "We had our arms around color," Elmer Engstrom recalled, "and we couldn't let got as the others could."[138]

More than their technological deficiencies, the convergence of the DSRC's shift toward basic research and the divisions' focus upon color television spelled doom for Nicoll, Kazan, and Rajchman's respective flat-panel projects. Both of the Magnalux prototypes required significant development prior to commercialization, but the divisions, who were responsible for such work under Ewing's building block strategy, saw no incentive to create a successor to the CRT. "Everything we did had opposition from managers in Camden and various places," George Briggs explained, "They just wanted to

[134] The resulting NTSC (National Television Standard Committee) standard remained the basis for American color television broadcasts between 1953 until 2009, when it was replaced by the ATSC (Advanced Television Systems Committee) digital transmission standard.
[135] Ascertaining the exact magnitude of RCA's investment in color TV can be something of a challenge. The $50 million figure is quoted from Kilbon (242) which cites the value as the total spent on color television by 1954. Graham estimates that $10 million was spent on this work by RCA Labs alone, but provides no information as to the source of this data. (Graham, 66) Bilby suggests that by 1955, Sarnoff had spent $65 million in color developmental and manufacturing costs. (Bilby, 209)
[136] Bilby, 208; Magoun (2009), 107.
[137] "Faded Rainbow," *Time*, 22 Oct. 1956, 96.
[138] Quoted in Bilby, 209.

have as much money as possible to develop the tubes that were needed, the cathode ray tubes for color television."[139]

Nicoll and Kazan might have avoided such disputes with their panels, which were no longer being presented as potential television replacements, but clinical tests at the University of Pennsylvania ruled them unsuitable for commercial fluoroscopy.[140] Despite a partial reversal of the building block strategy by the end of the decade, RCA no longer viewed electroluminescent displays as a significant project.[141] With none of the pomp surrounding its presentation four years earlier, the DSRC's management canceled work on Nicoll and Kazan's light amplifier in 1960, consigning it to obscurity alongside Rajchman's mural television.[142]

The Legacy of the Light Amplifier(s)

Neither Sarnoff, nor his subordinates within RCA publicly acknowledged the abandonment of light amplification research at the DSRC. The General continued to harbor an interest in mural television, going so far as to install a conventional CRT within the walls of his Manhattan office, its screen concealed by a painting that would slide away in response to dialing a specific combination of digits on his telephone.[143] But after his golden anniversary dinner and the follow-up demonstrations in Princeton, the color TV campaign dominated his private thoughts and public speeches.[144] The commercial realities

[139] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.
[140] Clinical testing of the light amplifiers' applicability to fluoroscopy began in 1957, according to RCA Laboratories, *Research Report 1957*, 7.
[141] Graham, 81-85. The DSRC's retreat from Ewing's building block strategy is discussed in Ch. 3.
[142] RCA Laboratories, *Research Report 1960*, DSL, 54.
[143] Bilby, 6.
[144] As shall be seen in Ch. 3, despite Sarnoff's persistent advocacy, RCA would not profit from its investment in color television until the early 1960s.

of the television market eclipsed the light amplifiers that Sarnoff once framed as that technology's future.

The use of the plural term, "light amplifiers" in the previous sentence was deliberate. As the above discussion has shown, neither Sarnoff nor RCA scientists ever approached the Magnalux as a unified project with a coherent goal. The General had used the DSRC's 1951 dedication ceremony as a means of stimulating investigations into areas his research managers thought might prove valuable to the corporation.[145] There were precedents for such behavior within the world of corporate science; AT&T's research head J.J. Carty attempted something similar when he declared in 1909 that his company would demonstrate a transcontinental phone line at the Panama-Pacific Exposition five years later.[146] But unlike Carty, who promised (and later delivered) an improvement on an existing technological system, Sarnoff explicitly framed his "big light" as a break with the past.[147] Despite his awareness that solid-state research would likely facilitate its creation, at the outset he never possessed a clear conception of the Magnalux's final form and therefore kept his request deliberately vague.

As a result, Sarnoff's birthday gift speech took on the character of a Rorschach test to members of RCA's technical staff, with DSRC personnel responding to the General's entreaties on the basis of their preexisting research interests.[148] Epstein's

[145] Graham, 67.

[146] Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (New York: Cambridge Univ. Press, 1985), 158-170. Despite their similarities (i.e. their public nature, five year deadlines, etc.), I am unaware of any studies linking Carty's call for a transcontinental telephone system with Sarnoff's 1951 birthday gifts speech.

[147] Hughes (see n. 69) would characterize Carty as requesting a conservative invention, one which improved or expanded an existing system, while Sarnoff's Magnalux implied a radical break from previous CRT-based television research.

[148] The conceit of a new technology, or the rhetoric surrounding it, as a Rorschach test is derived from Sherry Turkle, "'Spinning' Technology: What We are Thinking about When We Are Thinking About

experience working with theater television, for example, led him to construe Magnalux as a home projection system. Similarly, Nicoll and Kazan's research did not initially revolve around light amplification, but Sarnoff's speech pointed them in that direction following experiments combining electroluminescence and photoconductivity. Rajchman likewise imposed his own interests onto Magnalux, viewing it primarily as a means to test the applicability of computer memory addressing techniques to the construction of electronic displays. While one can trace a rough continuity between these approaches, there was no agreement within the DSRC over which adhered most closely to Sarnoff's original vision.

Without this consensus, Sarnoff could not be certain of his light amplifier's eventual capabilities. Just as his speech had altered the trajectory of display research at the DSRC, between 1951 and 1956 he and other RCA executives revised their predictions for Magnalux based on the latest updates from Princeton. Instead of the projection-type system Sarnoff first described to the DSRC's staff, these officials increasingly referred to Magnalux as an image-brightening electroluminescent display and later as a fully operational mural television. Despite the vacillation between these final two options in the months preceding the General's golden anniversary, Kazan, Nicoll, and Rajchman nevertheless induced a shift in their superiors' technological rhetoric, which further confounded attempts to ascertain which device Sarnoff would ultimately endorse.

The final determination of this question reaffirmed both the limits of scientists' agency within a corporate research organization and the contingency of criteria defining a technological success. Under Engstrom and Ewing's stewardship, DSRC personnel gained

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Computers," in *Technological Visions: The Hopes and Fears that Shape New Technologies*, ed. Marita Sturken, et al. (Philadelphia: Temple Univ. Press, 2004), 19-33.

an unprecedented amount of autonomy to pursue fundamental research. While such an environment encouraged the rapid development of the various Magnalux prototypes and the resulting shift in how researchers and executives conceived of mural television, it also alienated the Princeton labs from other parts of the corporation. For as much as much as Rajchman's display may have appealed to Sarnoff, he recognized that its inability to match the picture quality of existing CRTs, even with static images, would make it difficult for the divisions to support, particularly given the delayed payoff on color television. Nicoll and Kazan's panels, which were not limited solely to TV applications would provoke less hostility, while permitting the General to claim that his birthday wishes had been fulfilled.

The quest for Magnalux appears at first glance to be a straightforward story: An executive requested a technology within a certain timeframe and then received it. This was certainly the version of events that Sarnoff presented to his guests at the Waldorf-Astoria in 1956, but the uncritical acceptance of this narrative conceals the scientific, organizational, and economic factors that shaped its outcome. The boundaries between success and failure in this case were malleable, depending as much upon a light amplifier's performance and relevance to existing product lines as the capacity of RCA scientists and engineers to reconfigure managerial expectations. This lesson resonated with members of the firm's technical staff, who would build upon the foundations that Nicoll, Kazan, and Rajchman had laid, even as the company's leadership sought to curtail such long-term projects in order to better support applications under development at the divisions. Little did these managers realize that their policies would provide DSRC personnel with the institutional and financial resources with which to pursue the General's dream of a flat-

panel television, long after the word “Magnalux” had vanished from the firm’s collective memory.

CHAPTER THREE
"A fumbling prelude": Cold War Reorganization and Mural TV Research, 1956-66

The average American in 1980 lived ten to fifteen years longer than his counterpart in the 1950s thanks to improved diagnostic techniques and the elimination of polio, tuberculosis, and cancer. The atomic generators installed in his basement became commonplace well before the start of the new decade, allowing chemists and engineers to develop new uses for fossil fuels. His mail was delivered by guided missiles whose contrails stretched across an increasingly crowded sky, filled with both pilotless passenger aircraft and fleets of personal helicopters. Admittedly, this helped "make the principal airways almost as busy as the highways on the ground," but electronic traffic control ensured safe travel in all directions.[1] Similar advances in automation ensured more efficient manufacturing lines, granting industrial workers increased leisure time during which to pursue "the better, and perhaps the best, in art, music, and letters."[2]

All of these technological and cultural advances, "unprecedented in kind and in volume," were possible due to an incipient revolution in electronics, at least according to Radio Corporation of America (RCA) chairman David Sarnoff.[3] To illustrate the "fabulous dimensions of the teeming novelties now gestating in hundreds of laboratories, large and small," Sarnoff highlighted one initiative underway at his company's central research facility in Princeton.[4] For several years, he explained, scientists at the David Sarnoff Research Center (DSRC) had been studying "a new form of light," known as

[1] David Sarnoff, "The Fabulous Future," in Editors of *Fortune*, ed., *The Fabulous Future* (New York: E.P. Dutton & Co., 1956), 19. Sarnoff's article was originally published in the Jan. 1955 issue of *Fortune* (82-83, 114-116, 118). To simplify citation, all page references will refer to the reprinted essay.
[2] Sarnoff, 21.
[3] Sarnoff, 14.
[4] Sarnoff, 17.

electroluminescence, which certain materials emitted when subjected to an electric field. These substances offered the possibility of electric light "freed from the prison of the vacuum bulb," which Sarnoff anticipated would transform American homes and cities.[5] From street lights and astronomical cameras to night vision equipment and shop window displays, the potential applications of electroluminescence were endless. And of course, it would fundamentally alter the technology with which RCA was most closely associated, making "obsolete the television tube of today, while bringing bigger and sharper pictures in color as well as in black and white."[6]

While Sarnoff did not mention it, DSRC scientists were already working to incorporate electroluminescence into flat-panel displays. Soon after his *Fortune* article hit newsstands in January 1955, he posed for photographs alongside an electroluminescent panel capable of displaying static, TV-quality images. Later that spring, a group of researchers led by computer researcher Jan Rajchman completed construction of a functional, albeit low-resolution, electroluminescent television display.[7] Though the DSRC's annual report for 1955 conceded the shortcomings of these devices, it expressed confidence that such obstacles could be surmounted.[8] It appeared that Sarnoff's dream of a "mural television" that could hang on the wall like a painting might bear fruit sooner than 1980.

Yet as this chapter will show, the bright promise of Sarnoff's fabulous future dimmed somewhat during the late 1950s, as the corporation struggled to recoup its

[5] Sarnoff, 17.
[6] Sarnoff, 17.
[7] Both of these electroluminescent displays are discussed at length in Ch. 2.
[8] RCA Laboratories, *Research Report 1955*, 77.

multimillion dollar investment in color television. Already facing pressure from RCA's operating divisions to curtail fundamental investigations of questionable value to the company's existing businesses, DSRC researchers found their autonomy attacked on two additional fronts. First, they faced an external threat from the Eisenhower administration, whose vigorous pursuit of antitrust litigation endangered the corporation's research budget. In the midst of these legal battles, Sarnoff appointed a new second-in-command, John Burns, whose five years as RCA's president were characterized by greater oversight of the DSRC's activities and efforts to link them to more immediate commercial objectives.

From the perspective of personnel engaged in mural television projects, Burns' time at RCA proved a mixed blessing. Believing that the corporation's faltering profits resulted from overspecialization, he reduced the amount of funding devoted to consumer electronics research in favor of a new strategy intended to make the firm a competitor in the field of digital computing. Although one DSRC engineer claimed at the time that "many people believe that picture-on-the-wall displays represent a kind of ultimate toward which engineers should work," the policies Burns implemented between 1957 and 1961 ended the corporation's first wave of flat-panel prototypes.[9]

Rather than approaching mural TV as just another casualty of Burns' computer campaign, I instead argue that the organizational changes he initiated would actually provide the DSRC's technical staff with valuable resources to pursue flat-panel display research following his departure from the company. By curtailing the amount of money the DSRC received from the corporation, for example, Burns encouraged heavier reliance

[9] H.B. Law, "A Review of Some Flat Display Devices," *RCA Engineer* 7, no. 3 (Oct.-Nov. 1961): 20.

on government contracts, which permitted the renewal of projects that might previously have been deemed overly speculative. In addition, his choice of laboratory director, James Hillier, proved more willing to sponsor long-term research and encouraged the revival of mural television studies. Finally, Burns' interest in electronic data processing led to formation of an independent Computer Research Laboratory, which offered a site for display development separate from the company's established TV experts. When DSRC researchers observed the unique electro-optic properties of liquid crystals in the early 1960s, it would be from within this schizoid research environment, divided between television and computer researchers, that they would recruit a team to incorporate them into functional displays.

Conservative Attacks and Radical Approaches: Mural TV Research, 1955-1957

The electroluminescence research Sarnoff described to *Fortune*'s readers traced its origins to a speech he had given in 1951, asking RCA's technical staff to deliver a "light amplifier" in time for the 1956 celebration of his half-century long career in electronics. Such a device might, he noted later, facilitate the creation of a functional mural television display.[10] Though RCA's research staff was unable to achieve this long-term goal by the appointed deadline, their fascination with the concept did not abruptly cease after Sarnoff's golden anniversary dinner. Indeed, by 1957, half a dozen projects had emerged with the explicit aim of constructing a "television reproducer thin enough to be hung on

[10] See Ch. 2 of this dissertation.

the wall like a picture," enough for the subject to receive an extended discussion in the DSRC's annual report.[11]

DSRC managers classified these efforts as "conservative" or "radical," depending upon how each approached the questions of switching and illumination. Devices embodying the so-called "conservative attack" accomplished both functions using a guided electron beam, just like a traditional television set. Switching occurred wherever electrons struck a particular point on the screen, while modulating the beam to correspond with a video signal ensured that the tube surface emitted the proper amount of light. In contrast, the "radical approach" abandoned the use of cathode rays, treating an image reproducer like a "miniature telephone exchange in which 200,000 numbers are called in sequence to inform each one what the illumination should be for the next 1/30 second."[12]

From a corporate perspective, RCA possessed no strong attachment to either method, so long as a display could match or exceed existing cathode ray tubes (CRTs) in "economy, compactness, image size, brightness, and quality."[13] Consequently, between 1955 and 1957, research continued along both lines at the DSRC. Unsurprisingly, those with previous television systems expertise preferred to concentrate on conservative

[11] RCA Laboratories, *Research Report 1957*, 2-3 and 16-18. Among the general approaches to mural television projects (and associated personnel) listed in this report were: 1.) Use of Electroluminescence and Magnetics (Rajchman, Briggs, and Ballard); 2.) Use of Electroluminescence and Ferroelectrics (Briggs & Goldsmith); 3.) Use of Electroluminescence and Photoconduction (Nicoll); 4.) Use of Gas Discharges (Briggs & Schwartz); 5.) Use of Edge-Illuminated Transparent Panels (Hansell & Cooke); and 6) Use of Thin Cathode-Ray Tubes (Chang & Weimer). This list does not include the electroluminescent panels that served as the official "light amplifier" presented to Sarnoff in 1956. By 1957, those devices were considered more likely candidates for inclusion in X-ray equipment such as fluoroscopes. This conclusion did not prevent panel developer Frederic Nicoll from pondering new means of utilizing the combination of photoconductivity and electroluminescence in television applications. See, for example: RCA Laboratories, *Research Report 1956*, 26-27; RCA Laboratories, *Research Report 1957*, 17, 27-28.
[12] RCA Laboratories, *Research Report 1957*, 3.
[13] RCA Laboratories, *Research Report 1957*, 16.

strategies, such as expanding the deflection angle in existing CRTs[14] or devices like the Aiken tube, a modified CRT with the electron gun positioned near the corner of the screen instead of behind it.[15] Radical approaches to the problem tended to be the province of computer researchers like Jan Rajchman, whose 1200-element electroluminescent display built upon his previous studies of matrix-addressed core memories. Members of Rajchman's group extended these techniques to other projects, such as an array of small gas discharge "glow elements"—essentially an early attempt to build a plasma display.[16]

Prototypes constructed along both conservative and radical lines proved capable of generating TV images, but at the end of 1957, only modified CRTs had left Princeton for evaluation by engineers at RCA's electron tube and television divisions.[17] The DSRC's management admitted its preference for the conservative approach, ostensibly for technical

[14] By 1957, Sylvania had developed a wide-angle black-and-white set called the "slim line" which advertised a 21 inch picture that was only 13 1/4" deep, "up to 12" slimmer than old fashioned TV" See, for example: "Sylvania...cuts the cabinet in Half!"*Life* Magazine, 9 Sep. 1957, 92-93 and "The Bottom for TV?" *Time*, 30 Jun. 1957, 80. For a general overview of the incremental improvement of the color picture tube and efforts to obtain increased deflection angles and larger screen sizes, see Edward Herold, "A History of Color Television Displays," *Proc. IEEE* 64, no. 9 (Sep. 1976): 1331-1338. For specific work on this topic conducted at RCA during the late 1950s, see: *RCA* Laboratories, *Research Report 1955*, 17; RCA Laboratories, *Research Report 1956,* 10-11; RCA Laboratories, *Research Report 1957*, 13-14; RCA Laboratories, *Research Report, 1958*, 16-17; RCA Laboratories, *Research Report 1959*, 47.

[15] H.S. Allwine, et al., *PEM-1012C: An Experimental and Theoretical Investigation of a Flat Picture Tube*, 4 Oct. 1955, DSL. Among the personnel involved in the investigations outlined in this report was David Epstein, who had previously overseen the creation of RCA's theater television projectors and supported the efforts of Frederic Nicoll and Benjamin Kazan to construct their electroluminescent light amplifying panels. For more on the Aiken tube, see: W.R. Aiken, "A Thin Cathode-Ray Tube," *Proc. IRE* 45, no. 12 (Dec. 1957): 1599-1604; W. Ross Aiken, "History of the Kaiser-Aiken Thin Cathode Ray Tube," *IEEE Trans. on Electron Devices* ED-31, no. 11 (Nov. 1984): 1604-1608; Walter Goede, "Flat Cathode-Ray Tube Displays," in *Flat-Panel Displays and CRTs*, ed. Lawrence E. Tannas, Jr. (New York: Van Nostrand Reinhold, 1985), 177-236.

[16] RCA Laboratories, *Research Report 1957*, 17-18; J.W. Schwartz, *PEM-719: Line Storage Gas Discharge Picture Reproducer: Practical Approach to Panel Television?*, 28 Jun. 1956, DSL. Among the personnel who worked with Schwartz on his "gas discharge" display was George Briggs, who had previously constructed the addressing circuitry for Rajchman's electroluminescent mural television. For more on Briggs' involvement in both of these projects, see: George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.

[17] RCA Laboratories, *Research Report 1957*, 3.

reasons. Rajchman, they acknowledged, had come the closest to confirming the feasibility of radical addressing, but his "system with present materials was not competitive with existing cabinet-type TV."[18] They also made clear that their actions were not intended to signal an end to other mural television research, which might succeed in overcoming these problems.[19] For his part, Rajchman accepted this assessment without complaint, though his subsequent actions hinted at the deeper economic and legal factors underlying this shift in the course of flat-panel work at the DSRC. Never one to focus exclusively on any one project for too long, he would soon have an additional incentive to abandon his electroluminescent display after RCA's leadership turned to him to reinvigorate the DSRC's computer research program.

Chasing Rainbows: Changing Corporate Priorities, 1956-1958

RCA's interest in electronic computing dated to the late 1930s, but prior to 1950 the firm's involvement was limited to government projects. Unlike IBM or Remington Rand, RCA preferred to position itself as a supplier of electrical components instead of complete computer systems.[20] Sarnoff authorized the creation of a small commercial computing group in 1951, but military contracts continued to sponsor the bulk of the corporation's postwar data processing efforts.[21] RCA competed against IBM for the

[18] RCA Laboratories, *Research Report 1957*, 17. Rajchman estimated that electroluminescent materials would have to be ten times more efficient and have operating voltages one hundred times lower before they could match the performance of existing TV sets.
[19] RCA Laboratories, *Research Report*, 16.
[20] Franklin Fisher, et al., *IBM and the U.S. Data Processing Industry: An Economic History* (New York: Praeger Publishers, 1983), 72-73; Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: Brookings Institution, 1988), 123-124; Robert Sobel, *RCA* (New York: Stein & Day, 1986), 170-171.
[21] Carl Dreher, *Sarnoff: An American Success* (New York: Quadrangle/New York Times Book Co., 1977), 248-249; Sobel, 171-172. Both Dreher and Sobel credit the efforts of RCA engineer Loren Jones

chance to design the SAGE (Semi-Automatic Ground Environment) system for the Air Force and refined the Typhoon guided-missile simulator it delivered to the Navy in 1947.[22] Even the company's first digital computer was commissioned by the Army's Ordnance Tank-Automotive Command for "stock control of replacement parts for combat and transport vehicles."[23] Upon delivery in March 1957, the resulting $4 million vacuum tube-based system proved bulky and slow, offering, in the words of one observer, "the size of a house but with dog-kennel performance."[24] However, its name—Bizmac—implied that RCA did not intend to confine its future computer activities to the military sphere. Only six Bizmacs were ever sold, but A.L. Malcarney, vice-president of the company's commercial electronics division, informed the *New York Times* that RCA had "just scratched the surface" of the computer market.[25]

III with convincing Sarnoff that, in the General's words, "computers will be the next 'estate' in electronics." (Sobel, 171-172) Jones had previously worked on the Teleran air traffic control system. (Kilbon, 245).

[22] For confirmation of RCA's involvement in the SAGE project, see: Sobel, 172-173; Fisher, 72. A detailed discussion of the SAGE project can be found in Martin Campbell-Kelly and William Aspray, *Computer: A History of the Information Machine* (Boulder: Westview Press, 2004), esp. Ch. 7. The Typhoon project is described in: Kenyon Kilbon, "Pioneering in Electronics: A Short History of the Origins and Growth of RCA Laboratories, Radio Corporation of America, 1919 to 1964," unpublished typescript revised August 1964, 254-256. Paginated copy available online at http://www.davidsarnoff.org/kil.html, accessed 28 Oct. 2009 and Jan Rajchman, "Early Research on Computers at RCA," in *A History of Computing in the Twentieth Century: A Collection of Essays*, ed. N. Metropolis, et al. (New York: Academic Press, 1980), 465-469. For confirmation of the Typhoon system's continued refinement in the Laboratories during the early 1950s, see: RCA Laboratories, *Research Report 1951*, 28; RCA Laboratories, *Research Report 1952*, 19-20.

[23] "Army Buys a Big Brain to Keep Track of its Tank Parts," *New York Times*, 9 Dec. 1955, 41.

[24] H.R.J. Grosch, "The Way it Was 1957: A Vintage Year," *Datamation* 18 (Sep. 1977): 77. Quoted in Flamm, 123. Flamm rightly points out that Bizmac included several advanced design concepts, including the ability to connect up to 200 tape drives and handle programs without human intervention, but it took so long time to develop that upon release its component technologies were outdated. Newspaper accounts were more willing to take RCA at face value. See, for example: Damon Stetson, "'Brain' Accounts for Army's Gear," *New York Times*, 8 Mar. 1957, 27; "Army 'Drafts' RCA's Bizmac for Service...," *Wall Street Journal*, 8 Mar. 1957, 5.

[25] Alfred R. Zipser, "RCA Stepping Up Computer Making," *New York Times*, 14 Apr. 1957, F1+. For further RCA perspectives on the Bizmac, see also: "RCA's BIZMAC Goes to Work," *Radio Age* 15, no. 1 (Jan. 1956): 8-10; "Bizmac–World's Largest Electronic 'Brain,'" *Radio Age* 16, no. 2 (Apr. 1957), 16; J. Wesley Leas, "Engineering the RCA Bizmac System," *RCA Engineer* 1, no. 4 (Dec. 1955-Jan. 1956): 10-

RCA's renewed interest in computing coincided with the apparent commercial failure of color television. Despite Sarnoff's optimistic predictions that 1.5 million color sets would be in operation by the end of 1956, the actual figure was closer to 75,000, leading critics to accuse RCA of "premature tub thumping."[26] A combination of high prices, unreliable performance, and insufficient color programming left the public cold and RCA hard-pressed to recover its $100 million investment in the technology.[27] In a 1957 statement to shareholders, Sarnoff acknowledged that the company had lost nearly $7 million the previous year due to its color ventures, but argued that "[s]uch 'starting up' expenditures are inescapable for anyone who would pioneer and lead the way in a new field."[28] Yet efforts to draw parallels with RCA's previous successes with black-and-white television failed to prevent other electronics firms from abandoning color. Some cited the technical deficiencies of RCA TV consoles, like GE President Ralph Cordiner, who joked that "[i]f you have a color set, you've almost got to have an engineer living in the house,"[29] Others, like CBS vice-president Richard Salant, justified their actions on financial grounds. "There's no public demand and no advertiser interest," Salant asserted in 1958. "Nobody gives a damn now. Suddenly, some day, color TV will blossom. We guessed wrong when we thought it would come much sooner."[30]

11; W.K. Halstead, "The RCA Bizmac Electronic Accounting System," *RCA Engineer* 1 No. 4 (Dec. 1955-Jan. 1956): 12-21.

[26] "Faded Rainbow," *Time*, 22 Oct. 1956, 96.

[27] Kenneth Bilby, *The General: David Sarnoff and the Rise of the Communications Industry* (New York: Harper & Row Publishers, 1985), 213. According to Bilby, the $100 million mark was reached in 1957.

[28] "RCA Sales Again Top Billion-Dollar Mark," *Radio Age* 16, no. 1 (Jan. 1957): 4. See also: "Loss on Color TV to R.C.A. $6,900,000," *New York Times*, 26 Dec. 1956, 38.

[29] "Faded Rainbow," 96.

[30] "Chasing the Rainbow," *Time*, 30 Jun. 1958, 36+.

The difficulties RCA faced during this period were partially self-induced, the result of intellectual property policies that alienated firms that might otherwise have been eager to enter the color TV business. Perhaps as a result of its origins as a holding company consolidating the radio patents of GE, Westinghouse, and AT&T, RCA was perennially concerned with maintaining control over technologies it developed.[31] After a brief attempt to restrict the allocation of electronic components to dealers who agreed to handle its entire product line, in 1928 the company settled into a long-term policy of "package licensing." Under this arrangement, firms wishing to produce and sell a piece of radio or television equipment covered by an RCA patent could buy a license granting permission in exchange for royalties on all future sales.[32] The term "package licensing" derived from the company's practice of requiring firms to purchase licenses for *all* of its patents, even if only one were being used in a given product.

It is difficult to overstate the consequences that adopting this all-or-nothing licensing policy had on RCA and the American electronics industry. By erecting a significant barrier to entry for any company interested in manufacturing radio or television equipment, RCA eliminated competition from smaller firms while simultaneously profiting from larger organizations that could somehow afford its royalty costs.[33] In addition, beginning in 1934, Sarnoff channeled the bulk of RCA's patent revenues back into

[31] In addition to the three firms mentioned here, RCA also incorporated patents from the United Fruit Company. For more on the origins of RCA, see: Margaret B.W. Graham, *The Business of Research: RCA and the VideoDisc* (New York: Cambridge Univ. Press, 1986 [1988]), Ch. 2-3; Sobel, Ch. 1.
[32] Alfred D. Chandler, Jr., *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries* (New York: The Free Press, 2001), 18-21; Graham, 41. Initially, royalties were fixed at 7.5% the wholesale value of a completed radio set, with a required minimum of $100,000/yr.
[33] Graham, 41.

research and development, providing his technical staff with a source of funds unlinked to short-term profits and allowing the company to sustain work on television through the Depression and beyond.[34] Contact between members of RCA's research and patent departments grew even closer after the opening of the company's Princeton laboratories, and between 1952 and 1956, DSRC patents had generated more than $96 million in royalties.[35]

Of course, as RCA's patent pool expanded to include more than 10,000 radio and television components, so too did resentment among its competitors, who found their corporate strategies increasingly subjugated to Sarnoff's. Both Philco and Zenith sued RCA for its use of package licensing, but the death blow to RCA's patent policies came not from a rival electronics company but the federal government.[36] In February 1958, the Department of Justice filed what the *New York Times* referred to as "by far the most important criminal antitrust action in the five years of the Eisenhower Administration."[37]

[34] Graham, 56-58. For more on RCA's television research during the Depression, see Kilbon, Ch. 3.

[35] For royalty totals, see "RCA to Open Up 10,000 Radio, TV Patents as it Settles Antitrust Suit," *Wall Street Journal*, 29 Oct. 1958, 3.

[36] An extended discussion of the Zenith antitrust suit can be found in Philip J. Curtis, *The Fall of the U.S. Consumer Electronics Industry* (Westport, CT: Quorum Books, 1994), Ch. 2-Ch. 4. For press coverage of the Philco and Zenith cases, see: "Philco Suit Cites Electronics Plot," *New York Times*, 15 Jan. 1957, 40; "Zenith Beats RCA," *Time*, 23 Sep. 1957, 88+; "Zenith and RCA Settle $61 Million Suit Out of Court," *Wall Street Journal*, 10 Sep. 1957, 12; "Zenith to Get $10 Million from RCA, 2 Others in Antitrust Suit Settlement," *Wall Street Journal*, 16 Sep. 1957, 6; "Suit Against RCA Settled by Zenith," *Washington Post,* 10 Sep. 1957, A17.

[37] Anthony Lewis, "RCA Is Indicted In Criminal Case Under Trust Law," *New York Times*, 22 Feb. 1958, 1+. Lewis' article also includes a concise summary of the government's past investigations into RCA's trade policies. Highlights include the 1940 Senate hearings where an RCA lawyer was accused of bribery and the 1952 firing of Antitrust Division head H. Graham Morrison following his refusal to dismiss a grand jury investigation into RCA's activities. (The case was later dismissed by Attorney General James McGranery on his last day in office.) For more on the 1958 criminal complaint against RCA, see also: "U.S. Jury Indicts RCA on Antitrust Violation," *Los Angeles Times*, 22 Feb. 1958, 4; "RCA Insists All Its Patents Are Open, And Asserts Policies Spur Competition," *New York Times*, 22 Feb. 1958, 33. The 1958 criminal action was actually preceded by a civil complaint filed against RCA in November 1954. For more details on that case, see: "U.S. Suit Hits RCA's Patent License System," *Wall Street Journal*, 22 Nov. 1954, 5; "Antitrust Suit Alleges Conspiracy to Control Developments in Radio, TV," *Christian Science Monitor*, 20 Nov. 1954, 18; Frank Kent, Jr., "U.S. Anti-Trust Suit Filed Against RCA," *Washington Post*,

Eager to avoid bad publicity and further litigation, RCA accepted a government offer to negotiate an out-of-court settlement. The resulting consent decree, announced in October 1958, marked the end of package licensing on "radio-purpose" [i.e. radio and television] electronics.[38] RCA agreed to pay a $100,000 fine and offer any domestic firm the chance to "[l]icense on a royalty free basis all its existing patents without taking the entire package."[39] In addition, 100 of the company's color TV patents, along with related patents developed by half a dozen other companies, would be placed in a common royalty-free pool to encourage industry-wide experimentation without placing RCA at a competitive disadvantage.[40]

Sarnoff considered the 1958 consent decree among the most humiliating incidents in his career.[41] Even though he was not personally named as a defendant, RCA's exclusive control over color television was lost forever, as were the patent royalties that had ensured the independence of its research facilities. The DSRC's 1954 shift towards fundamental or "building block" research had depended upon this revenue stream to forestall concerns

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20 Nov. 1954, 3; "RCA Under Fire," *Time*, 29 Nov. 1954, 86+.

[38] Consent decrees—legally binding settlements negotiated between the government and defendant—came into increasing use during the Eisenhower administration as a way of quickly resolving antitrust litigation. Such arrangements allowed both sides the chance to avoid the expense of a prolonged trial. In addition, consent decrees, unlike findings in a criminal antitrust suit, did not constitute prima facie evidence in subsequent antitrust cases. For more on consent decrees, see Theodore Kovaleff, *Business and Government During the Eisenhower Administration* (Athens: Ohio Univ. Press, 1980), 49-53; Hyungsub Choi, "The Boundaries of Industrial Research: Making Transistors at RCA, 1948-1960," *Technology & Culture* 48 (Oct. 2007): 776-777; Vartanig G. Vartan, "Consent Decrees Aid Trust-Busting," *Christian Science Monitor*, 23 Jul. 1958, 5.

[39] "RCA to Open Up 10,000 Radio, TV Patents As It Settles Antitrust Suit," *Wall Street Journal*, 29 Oct. 1958, 3. See also: Edward Ranzal, "R.C.A. Yields in Trust Suit; Will Ease Patent Licensing," *New York Times*, 29 Oct. 1958, 1+; "Boost for Color TV," *Time*, 10 Nov. 1958, 76.

[40] "Boost for Color TV," 76; Bilby, 215-216.

[41] Bilby, 215-216. Sarnoff, according to Bilby, tried his best to ignore this litigation. He seldom spoke of the consent decree within the company, refused to discuss its details with the business press, and ensured that Eugene Lyons glossed over the period in his company-sanctioned biography. See: Eugene Lyons *David Sarnoff* (New York: Harper & Row, 1966).

about consumer applications or marketing deadlines. Now these funds, the most clearly identifiable financial returns of the corporation's steadfast commitment to research, had been eliminated, and the DSRC faced difficult decisions about which projects to prioritize given its new budget constraints. It was within this context that the corporation turned to computers, which were not considered "radio-purpose electronics" under the terms of the consent decree, as a major research focus.[42] Overseeing this transition was RCA's newly-appointed president, John Burns.

"Management's Renaissance Man": The DSRC Under Burns, 1957-61

Sarnoff's decision to replace RCA president Frank Folsom took few within the corporation by surprise. Folsom's experience as a merchandiser for Montgomery Ward and RCA Victor had been crucial to the rapid proliferation of black-and-white television, but the commercial and legal battles surrounding color–as well as the recent death of his wife—had taken an emotional toll on the aging executive.[43] Despite his respect for Folsom, Sarnoff felt that RCA needed more dynamic leadership to counter challenges to its leadership in consumer electronics.[44] The obvious candidate, particularly to those at the DSRC, was Elmer Engstrom, the company's former research head, who had recently been named an executive vice-president.[45] Rather than draw upon the company's existing pool of talent, however, Sarnoff decided to recruit John Burns, a senior partner at the consulting firm of Booz, Allen, and Hamilton.

[42] Graham, 80-81; Chandler, 34-35.
[43] Bilby, 213; Graham, 60.
[44] Bilby, 213; Sobel, 173.
[45] Brown, 291; Graham, 81.

In a January 1957 public statement, Sarnoff reassured shareholders and staff that his choice for president was "no newcomer to RCA for he has been intimately associated with our activities for the past ten years."[46] Indeed, Burns, a nationally recognized management expert, had guided Sarnoff and Folsom's postwar efforts to reconstitute RCA as a large-scale manufacturing firm.[47] Though Burns was an outsider, the General admired his technical background, including a Harvard doctorate in metallurgy and production line experience at Republic Steel, and his strict enforcement of cost-cutting measures.[48] He expressed hope that this "unique combination of scientific and engineering knowledge, experience in industrial production and operation and exceptionally broad understanding of business generally" would allow RCA "to keep pace with the changing demands and great opportunities of the rapidly expanding electronics industry."[49] In the short term, "keeping pace" with the industry meant reinvigorating the company's color television campaign so that its flagship product would no longer be a drain on resources. Beyond that, Sarnoff and the rest of RCA's board of directors believed that Burns' consulting experience would expedite the diversification of RCA's core businesses outside the domain of home entertainment.[50]

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[46] "RCA Elects J.L. Burns as President," *Baltimore Sun*, 16 Jan. 1957, 23. For additional press coverage of Burns' election, see: "One-Time Laborer in Steel Mill is Elected President of RCA," *New York Times*, 16 Jan. 1957, 41; "Burns Elected RCA President," *Los Angeles Times*, 16 Jan. 1957, 20; "RCA Names Burns President," *Washington Post*, 16 Jan. 1957, D5. For RCA's own account, see: "RCA's New President," *Radio Age* 16, no. 2 (Apr. 1957): 8

[47] Sobel, 144-145.

[48] Bilby, 213-214; Sobel, 144-145. For more on Burns' professional background, see also, "RCA Elects J.L. Burns as President," 23; "RCA's New President," 8; Alfred R. Zipser, "Personality: Pilot for RCA in Space Field," *New York Times*, 17 May 1959, F3; "Management's Renaissance Man," *Time*, 7 Sep. 1959, 72.

[49] "RCA Elects John Burns, Business Consultant, President and Director," *Wall Street Journal*, 16 Jan. 1957, 8.

[50] Bilby, 213-214; Graham, 81.

For his part, Burns framed his presidency as an opportunity to redefine RCA's strategic priorities. "RCA cannot be all things to all people," he cautioned, "but it must be in a leadership position in important things in our chosen fields. This means increased growth and effort, but it also points up the great need for selectivity and the timing of our efforts."[51] Officially, color television remained the company's primary focus, and Justice Department officials hailed Burns' involvement in the negotiations culminating in the 1958 consent decree as "a stroke of industrial statesmanship."[52] Nevertheless, the terms of the antitrust settlement rendered any television research that did not directly increase RCA's market share an unprofitable proposition. Given his interest in the company's bottom line, Burns viewed the consent decree as a justification to reexamine the firm's commercial objectives and research organization.

Burns initiated his reforms by authorizing an "over-all simultaneous review" of "all projects under way in the research activity" by a panel consisting of the vice-president of research, the various laboratory directors, and representatives from the divisions.[53] Where previous evaluations had occurred on a case-by-case basis with minimal divisional oversight, this new arrangement, emphasizing commercial applications over fundamental research, was a major infringement upon the independence of RCA's researchers.[54] These panels, in effect, forced members of the Princeton technical staff to justify their previously unrestricted "building block" investigations annually, a move applauded by the divisions

[51] "RCA's New President," 8.
[52] "Boost for Color TV," 76. Burns is specifically credited in this article with devising the idea of the color TV patent pool.
[53] RCA Laboratories, *Research Report 1957*, 1.
[54] RCA Laboratories, *Research Report 1957*, 1; Chandler, 36; Graham, 81-82.

and veteran engineers but opposed by the DSRC's theoretically inclined majority.[55] To implement this new policy and smooth over any tensions between Princeton and the divisions, in early 1958 Burns appointed James Hillier–a research physicist and the co-inventor of the electron microscope–as vice-president in charge of RCA Laboratories, replacing "building block" advocate Douglas Ewing.[56]

Working through Hillier, Burns promoted a strategy of "broadening the base," moving the DSRC's focus away from consumer electronics and towards large-scale industrial systems.[57] Fundamental research did not disappear from the Princeton labs, but Burns and Hillier encouraged members of the technical staff to coordinate their work with products already under development at the divisions, such as energy conversion devices, high fidelity audio recorders, and electronic traffic control systems.[58] More significantly, Burns, acting "[i]n accordance with the decision made by RCA management to participate

[55] Graham, 70-71, 81-82. According to the 1958 research report, the DSRC technical staff consisted of over 50% chemists, metallurgists, mathematicians, and physicists as opposed to 35% in 1945, reflecting the increased focus upon solid-state phenomena within the labs. Similarly, the percentage of staff members with doctorates had increased from 25% in 1945 to approximately 50%. Graham divides the staff of RCA Laboratories into two groups: "scientists" and "research center veterans." The "scientists" were young and highly trained, having joined the lab in the hopes of doing discipline-oriented work comparable to that conducted in a laboratory. The veterans, in contrast, had less formal training, but more practical experience and an interest in solving technical problems. In addition, veterans had often worked at RCA when research facilities were attached to manufacturing divisions and were therefore familiar with the complexity of the manufacturing process. It is important to note that Burns' popularity among "veterans" was not universal. George Brown, one of the more practically-minded problem-solvers at RCA Labs (prior to his transfer to Camden in 1957), refers to Burns in his memoir as "a very affable person...[who] would perhaps have been a success if he had listened more and talked less." *And Part of Which I Was* (Princeton: Angus Cupar, 1982), 291.

[56] Graham, 81-82. For more on Hillier's professional background, see James Hillier, "The Engineer and the Corporation: RCA Laboratories," *RCA Engineer* 8, no. 1 (Jun.-Jul. 1962): 3.

[57] Zipser, "Personality: Pilot for R.C.A. in Space Field," 82.

[58] Graham, 82. For confirmation of these projects and several others including the Electrofax copying process and the "phonetic typewriter" (an early attempt to automatically convert speech into text), see: RCA Laboratories, *Research Report 1957*, 9-12; RCA Laboratories, *Research Report 1958*, 8-15; RCA Laboratories, *Research Report 1959*, 2-3. RCA's publicity department also felt that these types of projects were worthy of press attention, as seen in a pair of articles in *Popular Mechanics*: Lothar Stern, "Go Behind the Scenes to Look Ahead in Electronics," *Popular Mechanics*, Mar. 1959, 213+; Lothar Stern, "Behind the Scenes in Electronics," *Popular Mechanics*, Apr. 1959, 160+.

vigorously in sales of data processing equipment," ordered a substantial increase in resources allocated to the DSRC's computer research group, expanding its membership from five people in 1957 to twenty-five by 1959.[59]

During his time at RCA, no figure became as closely associated with the resurgence of commercial computing as Burns, whose consulting experience left him well-suited to lead such a venture. Shortly before being tapped as president, Burns had overseen a major reorganization at IBM and recognized the difficulty of whittling down that company's estimated 87% market share while simultaneously investing in color television.[60] His strategy was to develop technically sophisticated computers compatible with IBM software but with lower costs and increased reliability.[61] In September 1957, six months after the delivery of the Bizmac, Burns negotiated a cross-licensing arrangement with IBM president Thomas Watson, Jr., and the following year he announced the creation of the RCA 501, the company's first completely transistorized computer.[62]

RCA boasted that the 501 was "the world's most advanced electronic data processing system," but in spite of such innovative features as an early COBOL compiler, sales were sporadic. Burns eventually acknowledged that the company had taken a loss on

[59] RCA Laboratories, *Research Report 1957*, 1; RCA Laboratories, *Research Report 1959*, 12.

[60] Sobel, 173-175. As Sobel notes, Burns actually inspired a feud between Sarnoff and IBM president Thomas Watson, Jr. In 1956, Watson wanted to hire Burns as a consultant but was worried about conflicts of interest since Burns had worked as a consultant for RCA. Following Sarnoff's assurances that RCA had no interest in entering the commercial computing field, IBM hired Burns to oversee a management reorganization effort. A few months later, much to Watson's annoyance, Burns had joined RCA and begun to expand its electronic data processing program. The 87% figure is derived from Zipser, "RCA Stepping Up Computer Making," F1.

[61] Sobel, 176. Both Sobel and Dreher make reference to RCA's initial efforts to arrange an alliance with Burroughs, the nation's third largest computer manufacturer after IBM and Sperry Rand. The resulting partnership, in Sobel's words, "might have turned out to be the best possible challenger to IBM," but Burroughs' president John Coleman died before the deal could go through and RCA decided to proceed on its own.

[62] "R.C.A. and I.B.M. Sign Computer Patents Pact," *New York Times*, 11 Sep. 1957, 45; "IBM, RCA Sign Patent Agreement," *Washington Post*, 11 Sep. 1957, B6; Fisher, 72; Flamm 123-124; Sobel 176-177.

its investment.[63] Still, neither he nor other RCA executives considered the decision to enter data processing unsound. As Elmer Engstrom explained, "RCA not only staked out its share in one of the major electronics growth markets but, equally important, it acquired the basis for continuing preeminence in other electronics fields where computers and computer systems were indispensable to progress."[64] Specifically, following the launch of Sputnik, RCA was positioned to benefit from the resultant outpouring of federal communications and computing contracts. Eager to make up for the recent loss of patent revenues, the company's research managers became particularly enthusiastic in their efforts to secure federal funding, justifying such work as "sufficiently fundamental in character that it cannot fail to have important significance in our long-range commercial programs."[65] By 1960, more than half of the research conducted in RCA's laboratories was government funded.[66]

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[63] RCA Electronic Data Processing Division, "All New Transistor RCA 501 Electronic Data Processing System," PDF available online at http://www.computerhistory.org/brochures/, accessed 26 Jan. 2010; RCA Electronic Data Processing Division, "RCA 501 Electronic Data Processing System," PDF available online at http://www.computerhistory.org/brochures/, accessed 26 Jan. 2010. For a more detailed technical discussion of the RCA 501 and its features, see: H.M. Elliott, "The RCA 501 System," *RCA Engineer* 4, no. 5 (Feb.-Mar. 1959): 39-41; Chandler, 38; Fisher, 72; Flamm, 124; Sobel, 176-177. For Burns' discussion of RCA's loss on electronic data processing, see Alfred R. Zipser, "R.C.A. Sales of Data Systems Running 200% Above '59 Level," *New York Times*, 25 Sep. 1960, F1+.

[64] Elmer W. Engstrom, "A History of Radio Corporation of America, Part III: The Years 1958-1962," *RCA Engineer* 9, no. 1 (Jun.-Jul. 1963): 3.

[65] RCA Laboratories, *Research Report 1958,* 1. See also: Ross Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins, 2002), 35-37; Choi, 777.

[66] RCA Laboratories, *Research Report 1960*, 3. This figure is accurate if one considers the entirety of RCA's R&D organization, including funds dedicated to Project Pangloss (the command communication system for the Navy's Polaris weapons system) and C Stellarator Associates, a fusion research facility overseen by RCA, Allis Chalmers Co., Princeton University, and the AEC. Absent these two projects, approximately 33% of RCA research depended upon government sponsorship. For a summary of both the Pangloss and C Stellarator projects, see: RCA Laboratories, *Research Report 1961*, 7-8. More details on Pangloss can be found in Kilbon, 343, while the C Stellarator project is discussed in both Kilbon, 343-345 and Edward Herold, "Focus on a Career Engineer–Excerpts from Bygone Days: An Autobiography," unpublished typescript revised Jun. 1983, 49-50. Paginated copy available online at http://www.davidsarnoff.org/ewh.html, accessed online 7 Dec. 2009.

The popular press hailed Burns as "management's Renaissance man" for embracing "profitable diversification" and "corporate versatility," but the growing focus on defense electronics at the David Sarnoff Research Center did not bode well for RCA's mural television projects.[67] Granted, the DSRC's annual research report from 1958 correctly commented that an economical "picture-type reproducer thin enough to hang on a wall" remained elusive.[68] According to physicist George Briggs, who assembled the drive circuitry for Rajchman's electroluminescent display, such technical challenges might have been overcome given sufficient time, but "the thing that made that impossible was the Cold War."[69] Between Burns' distaste toward fundamental research and increased government funding opportunities, incentives to continue flat-panel TV work dwindled as researchers turned to projects with short-term military or industrial applications.

Given the technological similarities between matrix-addressed magnetic memories and the addressing systems utilized in "radical" mural televisions, personnel associated with these projects were among the first reassigned to the DSRC's computer research group. Leading the team was none other than Jan Rajchman, who dispensed with his electroluminescent displays to oversee a $25 million Navy-sponsored initiative codenamed "Project Lightning," which sought to develop a processor capable of making computations in a billionth of a second–approximately one thousand times faster than existing commercial models.[70] Although RCA's electronic data processing division in Camden was

[67] Zipser, "Personality: Pilot for R.C.A. in Space Field," F3; "Management's Renaissance Man," *Time*, 7 Sep. 1957, 72.
[68] RCA Laboratories, *Research Report 1958*, 3.
[69] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009.
[70] RCA Laboratories, *Research Report 1957*, 7-8; R.K. Lockhart, "Development of a 1000-MC Computer," *RCA Engineer* 6, no. 4 (Dec. 1960-Jan. 1961): 11-13; Jan Rajchman, "RCA Computer Research...Some History and a Review of Current Work," *RCA Engineer* 8, no. 6 (Apr.-May. 1963): 8-9; Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009; Bassett, 36-37; Samuel S. Snyder,

responsible for delivering the complete system, the DSRC assumed primary responsibility during the project's early stages, since the terms of the contract mandated the invention of entirely new logic and memory devices.[71] Instead of utilizing transistors, which were the established focus of several other Defense Department contracts, between 1957 and 1962 RCA researchers considered a variety of other candidate technologies for "ultra fast" computing, including tunnel diodes, phase-locked microwave oscillators, and low-temperature superconductors.[72] During this time, Project Lightning, along with other defense-related computing work dominated the research agendas of Rajchman and his colleagues, leaving radical approaches toward mural television to fall by the wayside .[73]

Conservative attacks on the mural television problem possessed a slightly longer life span following Burns' strategic realignment, but by the end of the decade each of the CRT-based projects under consideration between 1955 and 1957 had folded. No matter how one positioned the electron gun or altered the beam deflection angle, none of these modified CRTs could consistently match the technical performance of the conventional

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"Computer Advances Pioneered by Cryptologic Organizations," *Annals of the History of Computing* 2, no. 1 (Jan. 1980): 60-70. Both the 1957 Research Report and Rajchman confirm that the Navy was at least the nominal sponsor of Project Lightning, but Bassett and Snyder confirm Lechner's assertion that "all of our dealings were with a group down in Maryland called the National Security Agency." Curiously, all aspects of the project except its ultimate use (i.e. cryptography) remained unclassified, leading to some trouble when Rajchman, who did not have a security clearance, tried to report on his team's progress.

[71] RCA Laboratories, *Research Report 1957*, 8.

[72] Lockhart, 11-13; Rajchman, "RCA Computer Research...," 8-9; Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009; Karl Zaininger, Interview with the author, Princeton, NJ, 7 Aug. 2009. Detailed technical explanations of all three of these approaches can be found in the Laboratories' research reports between 1957 and 1962. Snyder's article provides a more concise summation alongside descriptions of Lightning-related work conducted at other corporations (e.g. IBM, Sperry-Rand) and universities (e.g. MIT, Kansas, Ohio State).

[73] George Briggs, Interview with author, Princeton, NJ, 12 Oct. 2009. Briggs specifically cites his collaboration with Rabah Shahbender to develop radiation-resistant logic, though it appears this research began in 1963. See: RCA Laboratories, *Research Report 1963,* 39-41. Research reports from this period confirm that Briggs was involved in efforts to develop large-capacity and magnetic sheet random access memories.

color picture tube. The growth of electronic data processing activities and RCA's ongoing crusade for color placed constraints on the company's research budget that made the development of a wall-mounted television increasingly difficult for scientists and engineers in Princeton to justify. In the DSRC's annual reports, the previously distinct sections on "mural television," "thin cathode ray tubes," and "electroluminescent displays" disappeared after 1959, subsumed within broader discussions of picture tubes.[74]

At no point did Burns or any RCA personnel outside of Princeton publicly acknowledge the abandonment of Sarnoff's dream of a flat-panel television. To the contrary, as engineers were conceding that "[s]uch a device still stands as a challenge today—a very difficult problem," RCA's marketing staff was asking consumers "How'd you like to hang your TV picture on the wall?"[75] As a 1959 home improvement supplement in *Popular Science* pointed out, "it may be several years before you can literally do that," but "with RCA's new line of 'Mural-TV' sets you can easily get the same effect."[76] The company offered to install custom-cabinets for a standard black-and-white or color set creating the illusion of a flat-panel display.[77] RCA advertisements promised "the smart custom beauty of built-in TV that gives you extra floor space, extra enjoyment."[78]

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[74] Compare: RCA Laboratories, *Research Report 1957*, 16-18, 27-29; RCA Laboratories, *Research Report 1958*, 21-24; RCA Laboratories, *Research Report 1959*, 46-55; RCA Laboratories, *Research Report 1960*, 49-55; RCA Laboratories, *Research Report 1961*, 48.

[75] Law, 23; "How to Install Mural TV," *Popular Science-Special Home Improvement Supplement*, Vol. 175, No. 3 (Sep. 1959): 174.

[76] "How to Install Mural TV," 174.

[77] As discussed in Ch. 2, David Sarnoff had a similar device installed in RCA's New York headquarters. See: Bilby, 6.

[78] "Extra Value Feature...," *New York Times*, 27 Dec. 1960, 7; "Extra Value Feature...," *New York Times*, 29 Dec. 1960, 6; "RCA Victor has a gift for making people happy...," *Life* 47, no. 21 (23 Nov. 1959): 103. For more on the benefits of a mural television setup in the home, see: "Built-In Entertainment," *Electronic Age* 19, no. 2 (Spring 1960): 10; "What to Do If Entertainment Sets a Baffling

Nor were such promises restricted to the printed page. At a May 1961 press conference, RCA executives showed reporters life-size mockups of television displays they predicted would be available for purchase within the next decade, including "[a] large-screen color television console, less than five-inches in depth."[79] Among the speakers present at this event was John Burns, who posed next to a model mural television despite having essentially terminated laboratory research into such a product.

"Not a revolutionist": Burns' Departure and the Future of Mural TV at RCA

As Burns chatted with the press about the changes in store for television in the 1970s, his future at RCA appeared secure. In a *Wall Street Journal* interview published the following month, he expressed confidence that the company's earnings, which had dropped sharply in 1960, would recover by the end of the year.[80] With one exception, all of RCA's divisions were operating in the black.[81] Even color television, which had hung like a $130 million millstone around the company's neck, had started generating seven-figure profits, large enough to convince long-time holdouts like Zenith to abandon their opposition to the technology.[82] Admittedly, electronic computing continued to sap the

Stage in Home," *Chicago Tribune*, 3 Mar. 1962, N9.

[79] "R.C.A. Shows TVs and Radios of '70s," *New York Times*, 10 May 1961, 65; "Tiny TV Sets Forecast," *Wall Street Journal*, 10 May 1961, 7. For RCA's account of this event, see "Sets of the 70's," *Electronic Age* 20, no. 3 (Summer 1961): 16-17.

[80] "RCA Says There is 'Good Chance' '61 Sales And Net Will Top '60's," *Wall Street Journal*, 2 Jun. 1961, 6.

[81] "RCA Says...," 6. Color receivers first turned a profit in 1959. By the end of 1960 Sarnoff informed stockholders that profits from color TV "will be measured in seven figures." See: "R.C.A. Color TV Picture Clearer," *New York Times*, 27 Dec. 1960, 38. For more on the significance of Zenith's decision to enter the industry, see: Bilby, 218; Alfred R. Zipser, "Move By Zenith Hailed by R.C.A," *New York Times*, 24 Feb. 1961, 37+; Frederick H. Guidry, "Tinted Horizons," *Christian Science Monitor*, 21 Mar. 1961, 4; Donald Kirkley, "Hue-Happy Video is Nearing Gold," *Baltimore Sun*, 2 Apr. 1961, F11. "Zenith's Bright Picture," *Time*, 30 Jun. 1961, 65-66.

[82] "RCA Says...," 6.

company's finances, but Burns asserted that this was a natural result of relying on long-term rental income and not the sale of computer equipment. "We are a major factor now in the computer business," he declared. "Our program to cross over from investment to firm and mounting profits is on target."[83]

Sarnoff defended Burns' performance at the company's 1961 shareholders meeting. "Burns is not a revolutionist," the General explained. "He's an efficiency expert of the first order...I'm satisfied with him."[84] In spite of Sarnoff's public expressions of confidence, privately he harbored similar concerns about his lieutenant's performance.[85] Burns could claim several successes during his presidency, including the consolidation of RCA's consumer products operation in Indianapolis and the expansion of the firm's involvement in defense projects like the Ballistic Missile Early Warning System (BMEWS) and TIROS weather satellite.[86] At the same time, his management style provoked resistance throughout the corporation. Opposition might have been expected at the Princeton labs, where Hillier warned that overemphasizing applications threatened RCA's long-term research prospects.[87] But frustration was also evident at the divisions assigned to electronic data processing projects, which were the supposed beneficiaries of Burns'

[83] "RCA Says...," 6.
[84] "RCA First Period Sales Set Record; Net Trailed '60," *Wall Street Journal*, 3 May 1961, 11.
[85] Bilby, 258-259; Sobel, 178.
[86] For more on the Indianapolis consolidation, during which the headquarters of RCA's Home Instruments operation and sales subsidiary moved from Cherry Hill, NJ to a site nearer to production facilities in the Midwest, see: "RCA to Move Headquarters of 2 Units to Indianapolis," *Wall Street Journal*, 9 Aug. 1960, 4; "EDP Expands to Florida and Cherry Hill; Home Instruments to Relocate at Indianapolis," *RCA Engineer* 6, no. 3(Oct.-Nov. 1960): 38. "RCA's 4th Period Indicated Profit Fell; Volume Rose," *Wall Street Journal*, 28 Feb. 1961, 5. Both the BMEWS and TIROS projects are summarized in Engstrom, "A History of Radio Corporation of America Part III," 3-4.
[87] Graham, 83.

strategy. Personnel in Camden, for example, complained of sudden, counterproductive policy changes and long-distance micromanagement.[88]

Sarnoff might have overlooked such concerns if Burns' ideas generated higher earnings, but the company's computing efforts increasingly seemed an expensive diversion from RCA's core interests in radio and television. In 1960, after the RCA 501 failed to live up to company expectations, Burns announced the creation of two new transistorized models.[89] The smaller RCA 301, intended for businesses with basic data processing needs, enjoyed modest commercial success, but as one executive recalled, the larger 601 model suffered from "severe technical problems, both in a functional and in a manufacturing sense...so much so that the company began to look for a way out of the program."[90] The failure of the 601 left RCA with a serious blotch on its reputation and without a high power system to anchor its computer line.[91] Burns dismissed these setbacks, arguing as he had for years that the corporation's future rested with "three C's": computers, controls, and communications."[92] As Sarnoff observed, this credo neglected the most important C of all: color television. After the chairman took Burns to task for this omission at a board

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[88] Brown, 291-293. Brown, who worked in Camden as head of the Industrial Electronic Products (IEP) division between 1957 and 1959, was particularly frustrated with Burns and his "remarkably incompetent staff...issuing instructions and orders soon countermanded by other members of the same staff."

[89] Kenneth Hufford, "RCA Unveils Data Systems," *Christian Science Monitor*, 14 Apr. 1960, 14.

[90] Fisher, 74. The executive quoted here is Edwin McCollister, a vice-president at EDP during this period. For more on the RCA 301 and 601, see: Sobel, 177-178 and Flamm, 124. For technical specifications of each system, see: H. Kleinberg, "The RCA 301...Flexibility at Low Cost-An Engineering Challenge," *RCA Engineer* 6, no. 4 (Dec. 1960-Jan. 1961): 8-10; A.T. Ling and K. Kozarsky, "The RCA 601...Speed and Flexibility in a Large Scale System," *RCA Engineer* 7, no. 2 (Aug.-Sep. 1961): 42-45.

[91] Fisher, 74; Sobel, 178.

[92] Brown, 297; Sobel 174. The pervasiveness of Burns' "three C's" mantra is visible in several RCA publications from the period, including: John L. Burns, "Forty Years of Electronic Progress," *Electronic Age* 18, no. 3 (Summer 1959): 2-3; "Those Three Fabulous C's in the Electronics Alphabet," *Electronic Age* 18, no. 3 (Summer 1959): 11-13; "The Three C's...Electronics' Newest Surge," *Electronic Age* 19, no. 2 (Spring 1960): 13; and "IEP Effects Major Reorganization," *RCA Engineer* 6, no. 3 (Oct.-Nov. 1960): 38.

meeting, RCA's vice-president for engineering George Brown predicted that the latter "would not be with us much longer for to forget color television was a venial sin."[93]

Regardless of whether Sarnoff was genuinely offended by Burns' "3 C's" remark, disappointed in his lieutenant's failure to establish RCA's profitable entry into the commercial computing market, or responding to complaints from the divisions, Brown's prediction soon came to pass.[94] In November 1961, the corporation's board of directors stripped Burns of his major operating responsibilities. While he continued to manage NBC, supervision of the electronic data processing, home instrument, and semiconductor divisions passed to Elmer Engstrom.[95] A month later, Burns announced his resignation "for personal reasons" and Engstrom, whom Sarnoff had passed over to select Burns nearly five years earlier, was named president of RCA.[96]

As they had with Burns, the press cited Engstrom's combination of technical expertise and administrative ability as qualifications for the position.[97] To RCA researchers, however, Burns was an outsider whose top-down efforts to transform the

[93] Brown, 297. Brown had been promoted to this new position in March 1959. It seems he intended to say that forgetting color television was not a venial sin, i.e. it would not be easily forgiven.

[94] Bilby suggests that Sarnoff grew disenchanted with Burns' management techniques, particularly his alienation of outside directors and attempts to usurp authority beyond his official responsibilities, while Sobel links Burns' departure directly to the failure of the RCA 601. (Bilby, 258-259; Sobel, 178) Within the press, it was assumed that Sarnoff's actions were a rejection of Burns' handling of the company's computer business. See, for example: "Engstrom's Selection as RCA's President Termed Move to Boost Lagging Earnings," *Wall Street Journal*, 4 Dec. 1961, 8; "New Head at RCA," *Time*, 8 Dec. 1961, 89-90; "RCA Has Made Major Executive Changes in Electronic Group," *Wall Street Journal*, 27 Dec. 1961, 7.

[95] Brown, 297; "Engstrom's Selection," 8; "New Head at RCA," 89-90.

[96] For press coverage of Burns' departure, see the articles listed in n. 94 as well as: "Burns Quits R.C.A. Presidency; Elmer W. Engstrom is Elected," *New York Times*, 2 Dec. 1961, 28; "Engstrom Gets Burns' RCA Post," *Chicago Daily Tribune*, 2 Dec. 1961, C5. Bilby and Dreher suggest that a deeper combination of personal and professional conflicts between Sarnoff and Burns contributed to the latter's departure (Bilby 258-259; Dreher 172-173). Bilby clarifies that Sarnoff may have broken an earlier agreement not to groom his son Robert to become chairman, limiting Burns' opportunities for future advancement.

[97] See for example, "Engstrom's Selection," where one RCA director notes that "It's not every day, you know, that you combine in one man administrative ability with technical know-how." (8)

corporation's core business model reflected a deep misunderstanding of its R&D procedures. Engstrom, by contrast, started his career as an electrical engineer and maintained close ties to laboratory personnel as he climbed the corporate ladder.[98]

The replacement of the aggressive, ambitious Burns with the precise, professorial Engstrom signaled a return to the company's earlier growth strategies. Electronic data processing remained an important aspect of RCA's business, but Engstrom phased out work on the 501 and 601 models to focus on the smaller, but more popular, RCA 301.[99] The DSRC, meanwhile, continued to consult with the company's operating divisions, but its 1962 annual report rejected Burns' preference for short-term development over long-term research. Instead, it reiterated the DSRC's "most important role...that of providing technical innovations" and that "the disciplines involved have required that the search for innovation be directed to the building blocks of our products, the materials and active components, rather than to the products themselves."[100]

With Engstrom's ascension to RCA's presidency, the stage appeared set for at least a partial reversion to DSRC's previous emphasis on fundamental investigations. The belated payoff from color television and foreign patent royalties (permissible under the terms of the 1958 consent decree) supplanted its previous reliance on domestic licensing revenues. And although Hillier insisted on maintaining close ties with the rest of RCA's

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[98] Graham, 81. "Dr. Elmer W. Engstrom Elected President of RCA," *RCA Engineer* 7, no. 4 (Dec. 1961-Jan. 1962): Center Spread [between pages 30 and 31]; "RCA's New President," *Electronic Age* 21, no. 1 (Winter 1961-1962): 28.

[99] Fisher, 202; Sobel, 179-180. Sobel correctly notes that this focus was confined to the early years of Engstrom's presidency (1961-1963), as RCA's began designing a full line of Spectra computers in 1964 as a direct response to IBM's System 360 computers.

[100] RCA Laboratories, *Research Report 1962*, 1.

divisions, he also endorsed the return of speculative research, including flat-panel display projects, to Princeton.[101]

"Practical Guys" and Ph.D.'s: Flat-Panel Display Research in the SRL, 1961-1966

The obvious venue for mural television research at the DSRC was the Systems Research Laboratory (SRL), which had previously overseen the development of the compatible color picture tube. By 1961, the SRL had grown bloated and unwieldy, with a staff of more than one hundred researchers assigned not only to radio and television projects, but also "the development of new systems involving electronic techniques," such as radar antennae and computer memories.[102] This diverse portfolio might have appealed to a polymath like Rajchman, who transferred to the SRL in 1955, but Hillier viewed the lab's cumbersome size and lack of focus as problematic.[103] Unlike Sarnoff, who considered color television a mature technology, Hillier believed that continued improvement of displays was not only possible, but essential to guaranteeing RCA's ability to compete in the home electronics market.[104]

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[101] Graham, 83-84. As Graham points out, the package licensing system was ideally suited for nations like Germany and Japan who saw technology as a means of rebuilding their economies after World War II. Both Bilby and Chandler convincingly argue that Sarnoff's decision not to compete by brand name in foreign markets would eventually backfire, particularly in the Japanese context.

[102] Radio Corporation of America, *Working in Research at RCA* (Princeton: [RCA Labs?], 1956), 9. The number of staff associated with the SRL is derived from RCA Laboratories, *Research Report 1960*, 6.

[103] Kilbon, 340. For confirmation of Rajchman's transfer, see: "Organization List, RCA Laboratories Division," 1 Jan. 1955, DSL, 4.

[104] For confirmation of Sarnoff's belief that the color television campaign was over by the early 1960s, see: David Sarnoff, "Electronic Prospects for the 1960s," *Electronic Age* 19, no. 1 (Winter 1959-1960): 2-7; David Sarnoff, "Communications: A Look Ahead," *Electronic Age* 20, no. 3 (Summer 1961): 2-7; "RCA's Comeback," *Time,* 4 Jan. 1963, 61. See also: Bilby, 218-219, Sobel, 179. For Hillier's perspective on RCA's research priorities during this period, see: Graham 84-85.

Hillier therefore took it upon himself to streamline the SRL and steer it back to its traditional emphasis on television. With Burns' blessing, in September 1961, he siphoned off a sizable portion of its staff to establish a new Computer Research Laboratory (CRL), allowing the remaining scientists and engineers to concentrate on a single mission "to improve the performance and reduce the cost and size of RCA color television receivers."[105] Early on, these efforts included only the synthesis of improved phosphors and electron beam deflection studies reminiscent of "conservative" CRT work pursued a few years earlier.[106] Concerns over increased color TV competition at the end of 1962, however, spurred SRL director Allen Barco to organize a new research program with an explicit mandate "to investigate and evolve successors to the present type of cathode ray displays," particularly "low cost, thin, flat, lightweight displays with high brightness, contrast, resolution, and speed."[107]

Although Barco was the nominal leader of the flat-panel display project, he delegated the majority of his administrative responsibilities to two SRL group leaders, Jay Brandinger and David Kleitman. Both were relative newcomers to Princeton—Brandinger arrived in 1959 and Kleitman in 1958—but their technical backgrounds and managerial styles were otherwise quite different. Brandinger had spent seven years solving radio reception problems at an RCA research facility on Long Island before transferring to the DSRC.[108] His display group reflected his strong practical bent and involved several of the

[105] RCA Laboratories, *Research Report 1961*, 7. The establishment of the Computer Research Laboratory will be discussed in the next section.
[106] RCA Laboratories, *Research Report 1961*, 7.
[107] RCA Laboratories, *Research Report 1962*, 9. For more on evolution of the color television market during the years covered in this chapter, see: Michael Porter, *Cases in Competitive Strategy* (New York: The Free Press, 1983), 453-471.
[108] "Jay Brandinger-Who's Who in RCA Videodisc," http://www.cedmagic.com/mem/whos-who/brandinger-jay.html, accessed online 9 Feb 2010. RCA's Long Island laboratories were remnants of

company's most experienced television system engineers. Ray Kell, for example, had spearheaded the corporation's earliest color television projects in the 1940s, while Dalton Pritchard helped determine how to transmit a color signal within the bandwidth allotted by the Federal Communication Commission for black-and-white television.[109]

Where Brandinger, an engineer, treated the development of a flat display as a task best solved by a group of established CRT experts, Kleitman, who parlayed his success as a phosphor chemist into an SRL leadership position, focused instead on Barco's directive to investigate "basic phenomena and techniques that can be developed and used in the new displays."[110] He received permission to hire a group of five recent Ph.D. graduates to consider the problem from a wide range of disciplinary perspectives.[111] One of those recruits, John van Raalte, arrived in Princeton in 1964, after earning an electrical engineering degree from MIT. He immediately noticed a difference between Kleitman's

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the company's earliest radio research facilities, which were founded in the 1920s. For more information, see: Graham, 49, 56; Kilbon, Ch. 1; J.C. Warner, "A History of Radio Corporation of America–The Years to 1938," *RCA Engineer* 3, no. 1 (Jun.-Jul. 1957): 3-9.

[109] John van Raalte, interview with author, Princeton, NJ, 3 Jun. 2009. Van Raalte also mentions Harold Law and Gordon Freedenall as members of Brandinger's group, although neither is listed as involved in flat display research in DSRC research reports. For more on Kell's involvement in early television, see: Brown, 120, 134-136; Kilbon, 219-224. Pritchard is a fascinating figure in the history of color television. In addition to his publicly acknowledged work on color signal transmission, during the mid-1950s he was responsible for a secret project intended to preempt efforts by RCA's competitors to develop a simplified color picture tube. (See "Chasing the Rainbow" for confirmation of work of this kind being done at Philco, DuMont and GE) Pritchard's solution was to replace the standard array of red, green, and blue phosphors with a single "penetration phosphor" that emitted different colors depending on the voltage used to excite it. Such an arrangement would require only a single electron gun and obviated the need for a faceplate to ensure that a beam struck only a particular color of phosphor. For more on this project, see, RCA Laboratories, *Research Report 1958*, 20; Dalton H. Pritchard, "Penetration Color Screen, Color Tube, and Color Television Receiver," US Patent 3,204,143, filed 8 May 1961 and issued 31 Aug. 1965; Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009.

[110] RCA Laboratories, *Research Report 1962*, 9. For more on Kleitman's background as a phosphor chemist, see: "RCA Laboratories Announces 1959 Achievement Awards," *RCA Engineer* 5, no. 6 (Apr.-May 1960): 56; Martin L. Kaiser, III with Robert S. Stokes, *Odyssey of an Eavesdropper: My Life in Electronic Countermeasures and My Battle Against the FBI* (New York: Carroll & Graf, 2005), 13-15.

[111] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009. The five Ph.D.'s alluded to above were: John van Raalte, Istvan Gorog, Fred Spong, Mike Kaplan, and Mike DeMeis.

team of intelligent but inexperienced Ph.D.'s and Brandinger's "very savvy systems engineers":

> I think the people that I call the "practical guys," you know the Dalton Pritchards and Ray Kells, knew intuitively what to work on and had good ideas and drove toward success or whatever, and nobody really knew how to manage a bunch of young Ph.D.'s...[Istvan] Gorog had done something on plasma physics. Mike Kaplan was an organic chemist. You know, at the time [it was] not at all clear how he [i.e. Kaplan] would fit into a display group.[112]

While Brandinger and Kleitman's research groups did not work in total isolation from one another, their flat-panel projects provided an apparent test case to determine which of the DSRC's major demographic constituencies–research center veterans ("practical guys") or scientific specialists with advanced academic degrees but no training in how to incorporate their findings into products ("Ph.D.'s")–was better qualified to tackle the consumer electronics challenges of the 1960s.[113] The inability of either team to develop a market-ready flat-panel display rendered that question moot, but the array of technological options each mobilized in pursuit of that goal reveals an underlying affinity toward "conservative"displays throughout the SRL. Regardless of disciplinary background, researchers in both groups clung to the same addressing mechanism: a beam sweeping across a screen.

Among Brandinger's group, the consensus emerged that the key to RCA's future flat-panel ventures could be found in its past research into projection television.[114] Kell and

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[112] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.

[113] Again, this characterization owes a debt to Graham, 70-71. Despite drawing distinctions between Brandinger and Kleitman's group, Van Raalte's experiences prove that these lines were not necessarily rigid. While working on laser displays (as described below), he also contributed to Dalton Pritchard's work on electro-optic projection and later took over Ray Kell's schlieren light valve research. See, for example, John van Raalte, *Notebook 26374*, DSL; John van Raalte, *PTR-2698: SLV-A New TV Projection System*, 27 Mar. 1969, DSL.

[114] RCA Laboratories, *Research Report 1963*, 26.

Pritchard each proposed new projector systems based upon familiar CRT technology. Kell drew upon the example of the recently commercialized Eidophor system, replacing that device's oil-coated mirror with an aluminum film separated from the face of a CRT by a metal mesh.[115] An electron beam striking the film caused it to distort. When an external light source was directed at the film, these distortions could then be translated into a projected image through the use of a specially designed optical system.[116] Pritchard's setup also relied upon cathode ray addressing and external illumination to produce a black-and-white television picture. In this case, the electron beam's target was an electro-optic crystal, whose ability to rotate polarized light depended upon the amount of charge applied to its surface.[117] Because these systems did not generate their own light, they were able to match or exceed the brightness of earlier projection systems while operating at much lower voltages. At the same time, neither was capable of producing color images and each relied upon image-forming targets that were not amenable to mass fabrication.[118]

While Brandinger's team confined its projection research to CRT systems, Kleitman's group was, in Van Raalte's words, "more focused on brand new technologies

[115] Both Kell's system and the Eidophor utilized schlieren optics to project a television image on to a screen. For a concise discussion of both the Eidophor and schlieren optics, see: Larry Hornbeck, "From cathode rays to digital micromirrors: A history of electronic projection display technology," *TI Technical Journal* (July-Sep. 1998): 7-46.

[116] RCA Laboratories, *Research Report 1963*, 26; RCA Laboratories, *Research Report 1964*, 30-31; RCA Laboratories, *Research Report 1965*, 30; RCA Laboratories, *Research Report 1966*, 24; John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009; John van Raalte, *PTR-2698*.

[117] RCA Laboratories, *Research Report 1963*, 26; RCA Laboratories, *Research Report 1964*, 30; RCA Laboratories, *Research Report 1965*, 30-31; RCA Laboratories, *Research Report 1966*, 24. Full technical details on Pritchard's system can be found in D.H. Pritchard, *PTR-2205: Electro-Optic Light Valve TV Display*, 4 Jan. 1967, DSL.

[118] RCA Laboratories, *Research Report 1966*, 9. On a unity gain screen, Kell's projection system produced a luminance of 25 ft-L using a 100 W light source, slightly lower than the peak highlight brightness of Epstein's projection system. Pritchard's system measured between 50 and 100 ft-L, roughly comparable to a modern CRT television, with 50-250 W of external light. See: RCA Laboratories, *Research Report 1966*, 23-24.

and finding out what they might have to offer for displays."[119] Research reports confirm that one technology in particular captivated Van Raalte and his colleagues: the laser. A DSRC quantum electronics group had been studying the use of lasers in radar and communication systems since 1960, but it was Kleitman who realized their display potential.[120] The combination of solid-state physics, electrical engineering, and optics involved in laser construction also made them an ideal project for a team of newly-minted Ph.D.'s. By 1965, Kleitman's group had devised two new ways to modulate the wavelength of laser light. These color-switching techniques suggested the possibility of high-resolution "laser beam projection displays," but the team had not assembled a prototype and soon several members abandoned TV research to branch into holography.[121]

The decision to abandon laser projection represented an admission of its technical infeasibility and the fundamental limits that adherence to particle beam scanning, whether the particles involved were electrons or photons, imposed upon display design. Given the structural constraints associated with designing a large, thin CRT, projection was the closest that either SRL group came to developing a flat display while adhering to a

[119] John van Raalte, interview with author, Princeton, NJ, 3 Jun. 2009.

[120] RCA Laboratories, *Research Report 1963*, 27. For more on the early history of maser and laser research at RCA, see: Joan Lisa Bromberg, *The Laser in America, 1950-1970* (Cambridge, MA: MIT Press, 1991), 27-31; Bruce Shore, "Lasers: New Power from Light," *Electronic Age* 21, no . 3 (Summer 1962): 8-11; J.M. Brumbaugh, et. al., "The Maser...Microwave Amplification by Stimulated Emission of Radiation," *RCA Engineer* 6, no. 5 (Feb.-Mar. 1961): 21-25; H.R. Lewis, "The Laser–An Introduction," *RCA Engineer* 8, no. 5 (Feb.-Mar. 1963): 6-7. The commercial bent of RCA's laser program diverges from Paul Forman's argument that government funding necessarily twisted quantum electronics research towards military ends. See: Forman, "Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940-60, *HSPS* 18 (1987): 149-229.

[121] RCA Laboratories, *Research Report 1965*, 32. Color switching was achieved through the use of either an interferometer or a birefringent crystal to alter the Q-factor of the laser's resonant cavity to produce a high intensity pulsed output beam. The team described both Q-switching techniques in C.P. Wen, et. al., "Intra-Cavity Color Selection in Ion Lasers," *IEEE Journal of Quantum Electronics* QE-2, No. 11 (Nov. 1966): 711-713. For more on Q-switching, see Bromberg, 131-132. For confirmation of this new interest in holography, see: John van Raalte, Interview with author, 3 Jun. 2009. RCA Laboratories, *Research Report 1966*, 25; RCA Laboratories, *Research Report 1967*, 37-38.

conservative addressing scheme. Kleitman authorized a few tentative forays to move his lab beyond the beam in pursuit of a true panel television, casting experiments with a new form of x-y addressed electroluminescent panels as an attempt to "bridge the gap between vacuum and solid-state displays."[122] In spite of his continued claims that such "hybrid" technologies remained an ongoing priority, the SRL's flat-panel display research ended in 1966, as did the laboratory itself.

Before the end of the year, the SRL was consolidated into a new Consumer Electronics Research Laboratory (CERL), one of Hillier's moves to ensure the DSRC did not lapse completely back into the building block mindset of the 1950s. The CERL's "responsibility for research that will generate new and/or improved electronic services for the consumer" emphasized improving existing television systems over the creation of new displays. Work continued on the CRT-based devices that Brandinger had nurtured to the prototype stage, but solid-state displays disappeared from the CERL's research docket, leaving such projects to be pursued not by the DSRC's television experts but the engineers associated with RCA's Computer Research Laboratory.[123]

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[122] RCA Laboratories, *Research Report 1966*, 9. For more on the SRL's electroluminescent panel work, involving the use of CdSe control and storage elements, see: RCA Laboratories, *Research Report 1963*, 24; RCA Laboratories, *Research Report 1964*, 29; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009. The Kleitman group's contributions, particularly the work of Lucian Barton and Warren Moles, are specifically cited in G.K. Zin and L.J. Krolak, "A Solid-State Matrix-Addressed Display," *IEEE Trans. on Electron Devices* ED-12, no. 12 (Dec. 1965): 632-637.

[123] For more on Kell's deformable-film display, see RCA Laboratories, *Research Report 1967,* 37; John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009. Pritchard's display was transferred to RCA's Defense Electronics Products division in Camden for further development at the end of 1967. For a summary, see: *PTR-2205*.

Where "Lightning" Struck: Flat-Panel Display Research in the CRL, 1961-1966

The establishment of the DSRC's Computer Research Laboratory (CRL) in 1961 corresponded with the imminent conclusion of RCA's commitment to Project Lightning. Since 1957, Jan Rajchman had supervised dozens of scientists and engineers as they constructed the logic and memory circuits required to achieve a thousand-fold increase in computing speed. Their newly acquired institutional independence arrived just as their processors departed Princeton for final development at RCA's operating divisions, leaving Rajchman and his CRL colleagues in search of new avenues to explore.[124]

One area ripe for potential CRL involvement was the improvement of RCA computer peripherals. As a cost saving measure, the corporation had previously relied on external suppliers to provide printers, card readers, and punches.[125] The unreliability of these devices, however, contributed to customer dissatisfaction with RCA's 301 and 601 computer systems, and in 1962, the firm decided to finance a peripherals development program.[126] Most of this work would be conducted at the operating divisions, but as the DSRC's annual report noted, "there are many aspects of the field [i.e. peripheral equipment] which present a fertile ground for research, and the Laboratories has had a number of continuing projects for several years."[127] The post-Lightning CRL would expand its earlier focus on memory systems and processors to include such diverse projects as optical character recognition, magnetic tape drives, and display devices.

[124] RCA Laboratories, *Research Report 1961*, 33. Project Lightning began in July 1957 and was divided into three phases. Although RCA's Electronic Data Processing division administered the project, work conducted during the first two of these periods (Jul. 1957-Dec. 1958 and Jan. 1959-Jun. 1960, "was of a purely research nature and was performed by the Laboratories." The final phase of the project (Jul. 1960-May 1962) transferred the memory and logic systems to the divisions prior to assembly and delivery.
[125] Fisher, 74-75.
[126] Fisher, 75.
[127] RCA Laboratories, *Research Report 1962*, 39.

This last area was particularly appealing to Rajchman, who saw the manpower and money that Burns funneled into computer research as the means to resurrect his earlier electroluminescent television prototype. Rajchman recognized that his display had suffered from unreasonably high power requirements due to its reliance on magnetic switching elements called transfluxors. He therefore assigned the task of devising a more efficient form of addressing circuitry to an electrical engineer named Bernard Lechner. Lechner had joined RCA in June 1957, expecting to work on television, but found himself assigned to Project Lightning a year later.[128] Initially, he recalled, "I didn't really know anything about digital circuitry or digital applications of magnetic devices," but after several years toiling over logic devices for Project Lightning, he attained considerable circuit-building experience.[129] This skill, along with his continued interest in displays, left him prepared to inherit Rajchman's mural television project.

As a frequent user of RCA's technical library, Lechner was aware of Rajchman's prototype as well as other efforts to create a matrix-addressed electroluminescent display. During the DSRC's flat-panel hiatus, several people had published articles suggesting that the power requirements of such a device could be reduced by replacing the magnetic

[128] Bernard Lechner, Interview with the author, Princeton, NJ, 9 Apr. 2009; Bernard Lechner, Interview with Alexander Magoun, Princeton, NJ, 25 May, 2004. Like all recruits at RCA Labs, Lechner participated in the Research Training Program (RTP) intended to expose him to a variety of research fields prior to receiving his permanent assignment. His first assignment was to study magnetic devices as a part of Rajchman's group. He then moved on to work with Harry Olson on the Hear/See videotape project (see Graham, 91-94 for more), and became so involved that he waived the typical third rotation. When the time came to decide his ultimate laboratory assignment, he deferred to the judgment of associate research director Humboldt Leverenz that computing, not television, was RCA's future and went back to work for Rajchman. Lechner admits that he violated company policy by not keeping organized lab notebooks during his time at RCA. I encountered only three in the Sarnoff Library's collections, containing the details of his first two years of research at the Labs (Bernard Lechner, *Notebook 3775*, DSL; Bernard Lechner, *Notebook 4084*, DSL; Bernard Lechner, *Notebook 8593*, DSL).

[129] Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009.

transfluxors with ferroelectric switching circuitry.[130] Ferroelectric materials' behavior under an electric field was analogous to that of ferromagnetic materials under a magnetic field; in both cases, the substance formed field-aligned regions called domains whose polarity could be switched to correspond to a 1 or a 0 in binary code.[131] The advantage of ferroelectricity in this case was its compatibility with electroluminescent phosphors, theoretically offering a significant reduction in the power utilized to drive a display.[132]

On Rajchman's recommendation, Lechner familiarized himself with "some work that was being done in Zurich on ferroelectric materials."[133] Specifically, a researcher at RCA's European laboratory named Ennio Fatuzzo was investigating high-speed ferroelectric switching with an eye toward creating an "FE-EL [ferroelectric-electroluminescent] Mural TV."[134] Rajchman believed that Fatuzzo's findings might enable construction of a display based on the "transcharger," an electrostatic analog to the

[130] Jess Josephs, "A Review of Panel-Type Display Devices," *Proc. IRE* 48, No. 8 (Aug. 1960): 1380-1395; H.B. Law, "A Review of Some Flat Display Devices," 20-23; E.A. Sack, "ELF-A New Electroluminescent Display," *Proc. IRE* 46, No. 10 (Oct. 1958): 1694-1699.

[131] For further information on ferroelectricity, see: E.T. Jaynes, *Ferroelectricity* (Princeton: Princeton Univ. Press, 1953); Werner Känzig, *Ferroelectrics and Antiferroelectrics* (New York: Academic Press, 1957); M.E. Lines & A.M. Glass, *Principles and Applications of Ferroelectrics and Related Materials* (New York : Oxford University Press, 2001); Yuhuan Xu, *Ferroelectric Materials and Their Applications* (New York: Elsevier, 1991). Special thanks to George Taylor for providing a concise explanation of this complex phenomenon in his interview with the author on 14 Oct. 2009.

[132] Briefly, this difference in operating power is due to the closer impedance match between a ferroelectric capacitor and an electroluminescent cell. Matching the impedance of two components in an AC circuit maximizes its overall efficiency and lowers the amount of power required to operate a device.

[133] Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009. RCA's Zurich facility was intended to encourage closer contact with the European scientific community and oversee increasingly important foreign licensing operations on the Continent. For more information on the Zurich lab, see Karl Knop, E-mail correspondence with author, 3-4 Sep. 2009; C.G. Mayer, "Laboratories, RCA, Ltd.," *Radio Age* 15, no. 1 (Jan. 1956): 20-21.

[134] Bernard Lechner, interview with author, Princeton, NJ, 9 Apr. 2009; George Taylor, Interview with author, Pennington, NJ, 14 Oct. 2009. Fatuzzo's interest in electroluminescence can be traced at least to Oct. 1961, when he arrived Princeton for a six-month stint at the DSRC. His laboratory notebook from that period, labeled "FE-EL Display/Mural TV" contains diagrams of circuits similar to those utilized in Lechner's display. The DSRC's annual report for 1962 also notes that by the end of that year, Fatuzzo had submitted an engineering memorandum of the subject. (*PEM-2144: Study of the Feasibility of an FE-EL Mural TV,"*). Sadly, this document is missing from both the DSL and HML collections.

ferromagnetic transfluxor, capable of performing the same selection and storage functions at a much lower power.[135]

The transcharger concept was neither new, nor confined to RCA. Rajchman and Briggs had used the term in a 1955 patent, and Catholic University professor Charles Pulvari had concluded in 1959 that such a device could find a home in "large screen display devices with storage properties."[136] Yet the construction of a functional display required more than theoretical explanations and isolated prototypes. "This all makes sense, a large flat panel, only if you could integrate the structure so it would be mass produced at reasonable cost," Lechner clarified in a 2009 interview. "So the question was how do you make a flat panel that would do that?"[137] Transchargers offered one solution, but they came in a variety of configurations and it was unclear which would work best in displays, much less how one might produce the 1200 necessary to match the performance of Rajchman's previous device. Nor was it possible, on the basis of Fatuzzo's research, to determine which ferroelectric compound possessed the right combination of electrical properties for matrix addressing.[138]

To answer these questions, Lechner secured a contract with Wright-Patterson Air Force Base to "develop simple and inexpensive solid-state control circuitry capable of

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[135] A technical explanation of the transcharger, based on B.J. Lechner, "A Ferroelectric Transcharger-Controlled Electroluminescent Matrix Display,"*Solid-State Circuits Conference–Digest of Technical Papers* VIII (Feb. 1965): 86-87, is included with the associated figure.

[136] C.F. Pulvari, "The Transpolarizer: An Electrostatically Controlled Circuit Impedance with Stored Setting," *Proc. IRE* 47, no. 6 (Jun. 1959): 1123. See also: Jan A. Rajchman and George R. Briggs, "Electroluminescent Apparatus," US Patent 3,041,490, filed 31 May 1955 and issued 26 Jun. 1962.

[137] Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009.

[138] RCA Laboratories, *Research Report 1962*, 116. These properties included low coercive voltages (i.e. the amount of voltage needed to make bring the polarization of the ferroelectric back to zero), fast switching times (<20μs), square hysteresis loops, and minimal switching when subjected to half of a coincident addressing signal.

meeting future Air Force solid-state display needs."[139] Once funding was in place, he assembled "the beginnings of the nucleus of what became a group."[140] There was no shortage of skilled electrical engineers in the CRL, but most of RCA's ferroelectricity research was being carried out in Zurich. Fortunately, Rajchman recognized this deficiency and recruited George Taylor, an Australian who had just completed a dissertation on ferroelectric computer memories at the University of London. Taylor traveled to New York in the summer of 1962, intending to "continue some of the ideas that I had been working on [in] my thesis," but almost immediately turned his eye towards displays.[141]

Indeed, Taylor would play a central role in the early phases of the CRL project. As the team's ferroelectricity expert, he was responsible for determining both the chemical composition of the transchargers and a system for efficient batch production. By December 1962, he had decided to utilize ferroelectric ceramics, rather than the crystalline materials that were the focus of his dissertation, writing that the former "have the advantage that they can be made in relatively large sheets which are suited for the mass fabrication of transchargers required for the display system."[142] Over the next year, Taylor

[139] B.J. Lechner, et. al., *AFFDL-TR-67-71: Development of a Solid-State Matrix Display*, July 1967, WPAFB Technical Library, ii. See also: B.J. Lechner, et. al., *AFFDL-TR-66-5: Preliminary Development of a Solid-Sate Matrix Display*, Jan. 1967, WPAFB Technical Library. Special thanks to Darrel Hopper and Frederick Meyer of the Air Force Research Laboratory for forwarding electronic copies of these documents and allowing me to examine several of the ferroelectric displays described in this section during a visit to Dayton in July 2009. Lechner described Rajchman's suggestion to pursue a contract in his interview with the author, Princeton, NJ, 9 Apr. 2009.

[140] Bernard Lechner, Interview with Alexander Magoun, Princeton, NJ, 25 May 2004.

[141] George Taylor, Interview with author, Pennington, NJ, 14 Oct. 2009. Taylor's earliest laboratory notebook confirms that his initial research centered around partial switching in triglycine sulfate for matrix memories. It is also clear that he was aware from the outset that this work "would also allow the transcharger design for the proposed FE-EL mural TV system to be simplified from a 5 to a 3 cell arrangement." (Taylor, *Notebook 18717*, 1).

[142] George Taylor, *Notebook 18717*, DSL, 44.

"studied zillions of different variations of composition" before settling on a niobium-doped, lead-based ceramic for use in the display.[143] He then turned to Chandler Wentworth, the materials expert who had helped Rajchman with transfluxor production, for assistance producing uniform ferroelectric strips to serve as the base of the transcharger.[144]

During the intervening period, Lechner worked with engineers Anatole Samusenko and Juri Tults, designing a series of intermediary models to illustrate the operating principles of a transcharger-driven electroluminescent display. By September 1965, these included a seven-segment numeric indicator, two 36-element displays ("regular" and "high resolution"), as well as a larger 120-element (10 x 12) device.[145] The smaller displays were meant as "exercisers," utilizing simple transistorized electronics to demonstrate compatibility with standard video signals, but thanks to Tults' creative circuit design, the 120-element model could display moving images captured by a TV camera.[146]

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[143] George Taylor, Interview with author, Pennington, NJ, 14 Oct. 2009; RCA Laboratories, *Research Report 1964*, 121-122. According to *AFFDL-TR-66-5*, Taylor actually studied 27 different ceramics in the family $Pb_{0.99}[(Zr_xSn_y)_{1-x}\ Ti_z]_{0.98}Nb_{0.02}O_3$ in addition to 19 others doped with materials other than niobium. The material he finally chose was referred to as 50/50-14-2Nb, with the first three numbers corresponding to the percentage subscripts x, y, and z in the general formula provided.

[144] George Taylor, Interview with author, Pennington, NJ, 14 Oct. 2009; RCA Laboratories, *Research Report 1964*, 121-122.

[145] RCA Laboratories, *Research Report 1963*, 25-26; RCA Laboratories, *Research Report 1964*, 29-30; RCA Laboratories, *Research Report 1965*, 57-58. The September 1965 date is based on the submission of Lechner, et. al., *AFFDL-TR-66-5*. The existence of two different versions of the 2 x 18 array is confirmed by a June 1965 entry in George Taylor, *Notebook 27204*, 44-45, which lists three display models "required under the terms of the Government Contract 13314 and 13327." The first 2 x 18 array contained 0.04 sq. in. cells while the high-resolution display contained 0.01 sq. in cells. (The third model listed is the 120 element model.) In addition to the devices listed, *AFFDL-TR-66-5* notes the existence of a "high-brightness model" containing only two electroluminescent cells (0.5-in. square) with a brightness in excess of 40 ft-L, but neither Taylor's notebook nor the DSRC's annual reports mention this device. (70-74) It was also not available for inspection at WPAFB during the author's 2009 visit.

[146] Lechner, et. al., *AFFDL-TR-66-5*, 60-74. Tults is credited in the introduction of this report as the designer of the electronics for the 120-element model, and full details of their construction can be found in Appendix I (91-126). The term "exerciser" is Lechner's and is used in the context of electroluminescent displays in his 9 Apr. 2009 interview.

These devices persuaded the Air Force to sponsor the completion of a 1200-element (30 x 40) display. The CRL team's earlier displays had demonstrated the possibility of adapting evaporation techniques used in semiconductor manufacturing to deposit up to six transcharger circuits on a ferroelectric substrate. Now they scaled up the process, placing twenty transchargers on a two square-inch piece of ceramic.[147] Two of these strips made up each of the thirty rows of the final display, whose construction began at the end of 1965. To further simplify assembly, the CRL display dispensed with the individual electroluminescent cells used in Rajchman's prototype, in favor of a single pane of glass sprayed with an electroluminescent coating. "So we had two clear steps toward integration that he [i.e. Rajchman] didn't have," Lechner explained. "First of all, the EL panel was fully integrated. One piece. And secondly, the transchargers were integrated to the extent of having a half row at least on one piece of ceramic rather than the individual cores with wire wound by hand."[148] Though the use of these integrated components sped up the manufacturing process, Lechner still took personal responsibility for the last phase of the model's construction. "Not that I didn't trust the capability of the technicians," he noted. "But you know, anybody can make a mistake, and I didn't want to be in the position to blame somebody."[149]

"The complete system was first operated on June 28, 1966," Juri Tults recorded in his lab notebook. "Static as well as moving images picked up by the tv camera were

[147] RCA Laboratories, *Research Report 1965*, 58. The ferroelectric strips in the 1200 element display measured 4 in. x 0.5 in. x 3 mil.

[148] Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009.

[149] Bernard Lechner, Interview with Alexander Magoun, Princeton, NJ, 25 May 2004. In addition to the personnel already mentioned, Jerry Horvath, Jack Bowers, and R.L. Noack are listed in the various Air Force reports as having provided technical assistance during the construction of the panel.

displayed on the display panel."[150] The ten-inch diagonal FE-EL prototype was smaller than Rajchman's 23-inch model, but the larger number of picture elements per inch resulted in higher resolution images.[151] As a report excerpted in George Taylor's notebooks commented, "the results have been surprisingly good considering the resolving power of the display is severely limited by only having 1200 elements. It was found, for example, that as many as 15 words could be read on the screen. Also, features were sufficiently detailed to enable human faces to be identified."[152]

After demonstrations for RCA's top managers (including Sarnoff), Lechner and Tults took an overnight train to Dayton to deliver the display to the Air Force.[153] Lechner boasted in his final report that his team's FE-EL device was "the most advanced display of its kind that has been built to date."[154] Although the transchargers were only an intermediate step toward fully integrated circuitry and the display's picture elements exhibited occasional variations in brightness, the CRL team told their patrons that improved manufacturing techniques would alleviate both of these shortcomings. Despite these assurances, the Air Force chose not to renew its contract, and by the end of 1966, the CRL's transcharger-driven display project drew to a close. Absent this support, there

[150] Juri Tults, *Notebook 29309*, DSL, 46.

[151] For full technical details of the construction and performance of the completed 1200-element FE-EL display, see: B.J. Lechner, et. al., *AFFDL-TR-67-71: Development of a Solid-State Matrix Display*, July 1967, WPAFB Technical Library, 64-97; George W. Taylor, "The Design and Operating Characteristics of a 1200-Element Ferroelectric-Electroluminescent Display," *IEEE Trans. on Electron Devices* ED-16, no. 6 (Jun. 1969): 565-575.

[152] George Taylor, *Notebook 29288*, 88.

[153] Juri Tults, *Notebook 29309*, 47; Bernard Lechner, Interview with Alexander Magoun, Princeton, NJ, 25 May 2004. Tults' notes reveal that the reality of the situation was somewhat more complex than presented here. The device was first operated on 28 Jun. 1966. On 7 Jul. 1966, it was demonstrated at WPAFB prior to an additional set of demonstrations at RCA Laboratories prior to final delivery to Dayton on 3 Aug. 1966. Though Tults does not list the guests at these demonstrations, Taylor confirmed in his 14 Oct. 2009 interview with the author that Sarnoff was present.

[154] Lechner, et. al., *AFFDL-TR-67-71*, 98.

proved to be little incentive for RCA to devote attention to a monochrome display incapable of matching the brightness of existing televisions. "Board displays several feet in size are practical for special applications through the FE-EL approach," the DSRC's report for 1966 concluded, "but for smaller screens the system does not appear economical."[155]

"A fumbling prelude": Questions of Agency in Cold War Corporate Science

In 1955, David Sarnoff had prophesied that "[t]here is no element of material progress we know today–in the biological and chemical fields, in atomics and electronics, in engineering and physics–that will not seem, from the vantage point of 1980, a fumbling prelude."[156] A decade later, it appeared that this unflattering description could also apply to RCA's flat-panel displays, the very devices that Sarnoff singled out as epitomizing the technological promise of his "fabulous future." The brief surge in mural television projects following the publication of his *Fortune* article receded swiftly as the legal and economic consequences of RCA's color television campaign prompted a reevaluation of the company's research strategy. Under the leadership of John Burns, display studies took a back seat to computing so that over time even the most conservative CRT-based projects failed to garner internal support. The revival of such work following Burns' resignation offered some hope of moving beyond the vacuum tube, but none of the flat-panel prototypes developed in either the SRL or CRL over the next five years was the basis for

[155] RCA Laboratories, *Research Report 1966*, 7.
[156] Sarnoff, "The Fabulous Future," 20.

a marketable product, with only one (Lechner's FE-EL display) leaving the DSRC for delivery to a customer.

Given the speed with which the firm distanced itself from Burns' strategies after 1961, most histories of RCA devote almost no attention to his presidency or its effects on the corporation's laboratories.[157] With the exception of electronic data processing, such accounts reinforce Sarnoff's assertion that Burns was "not a revolutionist" and imply his actions had few lasting consequences for personnel working in other areas. At first glance, the DSRC's flat-panel display investigations conform to this pattern. Engineers ceased their efforts to develop a replacement for the CRT between 1957 and 1961, but soon after Burns left the company, they returned to the problem as though nothing had changed.

Nevertheless, I contend that during these five years, Burns transformed the research environment in which this new wave of mural television projects would be carried out. The emphasis Burns placed upon the pursuit of government contracts following the 1958 consent decree, for example, persisted at the DSRC, even after the influx of color TV revenues compensated for RCA's lost patent royalties.[158] In addition, the appointment of James Hillier as leader of the Princeton labs provided scientists interested in long-term research with a powerful ally, particularly if, as was the case with mural television, such

[157] This trend is particularly evident in officially sanctioned histories such as Eugene Lyons' *David Sarnoff* or Kilbon's "Pioneering in Electronics," but with the exception of Graham, outside scholarship on RCA during the Burns era is surprisingly bleak. Sobel devotes extensive attention to Burns' computing projects but little else, while Dreher mentions Burns twice: once to describe the personality clashes which led to his departure (172-173) and once in reference to RCA's computers. Bilby, in contrast, barely mentions electronic data processing (or other research conducted between 1958 and 1961), but provides a detailed analysis of Burns' arrival and departure from the firm.

[158] The continued importance of government research is reiterated throughout the DSRC's annual reports from the early 1960s. The 1963 report, for example, asserts that one of Laboratories' main priorities is ensuring that RCA maintains "sufficiently advanced technical competence to ensure its continuing to secure its fair share of Government electronics business." (1)

work could be construed as relevant to the corporation's established business interests. Finally, Burns' diversification strategy provided an alternative venue for mural television research through the establishment of the Computer Research Laboratory, whose mission grew to encompass the development of displays.

Of course, Burns did not intend to lay the groundwork for a flat-panel revival, as evidenced by the summary cancellation of such projects during his time in office. Yet through his decisions, he inadvertently supplied the DSRC with the financial and organizational resources necessary for two distinct groups of scientists and engineers to return to the problem of developing a wall-mounted television. Indeed, one may attribute the relative success of the CRL team to its ability to capitalize upon these resources more effectively than their SRL counterparts. Once Hillier authorized the restoration of mural television research, Brandinger and Kleitman's groups divided their energies among a large number of projects based on "conservative" addressing schemes without obtaining external funding. CRL researchers, in contrast, made use of their newfound autonomy to concentrate upon a single display utilizing the "radical" matrix-addressing techniques that SRL television experts largely dismissed as impractical. They also secured an Air Force contract to sustain studies of the physical properties of ferroelectric ceramics.

Considering this dissertation's stated interest in recapturing the industrial research experience from the perspective of the workbench as opposed to the boardroom, John Burns seems an unlikely figure to place at the center of a discussion of RCA's flat-panel display initiatives. Yet the persistence of the mural television ideal among the firm's technical staff can only be appreciated in light of Burns' attempts to redefine the

corporation's strategic objectives and the DSRC's role in fulfilling them. For despite his short-term success diverting Princeton researchers away from seeking a successor to the color picture tube, Burns' policies sowed the seeds for the continuation of these investigations. Whether refracted through an established technology, like the CRT, or more recent alternatives like the laser or electroluminescence, the image of a television thin enough to hang on the wall lingered in the minds of RCA scientists and engineers, who seized upon the same regulatory structures that had hindered flat-panel research under Burns to pursue that objective throughout the 1960s. Indeed, soon after dropping off his FE-EL prototype in Dayton, Lechner became involved with a new push to develop a reflective display using liquid crystals, a project that, in his words, "turned out to be much more promising."[159]

[159] Bernard Lechner, Interview with author, Princeton, NJ, 9 Apr. 2009.

CHAPTER FOUR
"Turbulence began here": From Williams Domains to the Guest-Host Effect, 1961-1965

In December 1964, David Kleitman, a group leader in the Radio Corporation of America's System Research Laboratory (SRL) invited two members of the company's technical staff to witness an experiment.[1] Over the past year, chemist Lucian Barton and engineer Warren Moles had worked with colleagues at the David Sarnoff Research Center (DSRC) and RCA's operating divisions to develop a new form of electroluminescent display.[2] Now they joined Kleitman and SRL leader Allen Barco to watch George Heilmeier, a relative newcomer to the DSRC, demonstrate the results of his investigations into an obscure class of substances known as liquid crystals.[3] Heilmeier filled a small glass cell (~1 cm^2) with an orange mixture, placed it on a heated microscope stage, and shone polarized light through it. After connecting the slide to a power supply, he gradually increased the voltage across the mixture and, as Barton recorded in his notebook, the cell "changed color from orange to red in a quite uniform manner what really surprised me."[4] Kleitman and Barco, always on the lookout for new display technologies, were equally impressed, and, Barton wrote, "[t]hey want to consider liquid crystals as first priority problem to work out."[5]

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[1] Lucian Barton, *Notebook 24188*, DSL, 84-85. Barton's notebook entry is dated 11 Dec. 1964.
[2] For more on Barton and Moles' efforts to develop an electroluminescent matrix display utilizing cadmium selenide and other hysteretic conductors as control and storage elements, see: Barton, *Notebook 24188*, 1-83; Lucian Barton, *Notebook 22987*, DSL, 12-100; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009; Warren Moles, *Notebook 26365*, DSL, 1-6; RCA Laboratories, *Research Report 1963*, 24-25; RCA Laboratories, *Research Report 1964*, 29. The Kleitman group's contributions are also cited in G.K. Zin and L.J. Krolak, "A Solid-State Matrix-Addressed Display," *IEEE Trans. on Electron Devices* ED-12, no. 12 (Dec. 1965): 632-637.
[3] Lucian Barton, *Notebook 24188*, 84.
[4] Lucian Barton, *Notebook 24188*, 85
[5] Lucian Barton, *Notebook 24188*, 85.

Shortly after Barton and Moles' meeting with Kleitman, Heilmeier found himself on the receiving end of a summons. News of his color-switching liquid crystals had spread throughout the DSRC, eventually reaching the desk of Vladimir Zworykin, the inventor whose kinescope picture tube and iconoscope camera laid the groundwork for RCA's entry into the field of electronic television.[6] Zworykin had retired from active laboratory duty a decade earlier but remained on-site in Princeton as a technical consultant and honorary vice-president.[7] Though he had set aside television research to focus on medical electronics, Heilmeier's liquid crystal experiments piqued his interest.[8] Once again, the younger scientist presented his findings, noting that the mixture consisted of a "guest" dye dissolved in a liquid crystal "host" and that the solution's color changed under an electric field.[9] When Zworykin asked about the research that led to this discovery, Heilmeier recalled in a 1976 article:

> I explained to him how I had *stumbled* on the guest-host color switching effect. I'll never forget his reflective reply: "Stumbled perhaps, but to stumble, one must be moving." We were moving. It was only the beginning.[10]

Indeed, Heilmeier's successful demonstration of guest-host color switching persuaded Barco, Kleitman, and other members of RCA's management that liquid crystals

[6] For more on Zworykin's life and career, see: Albert Abramson, *Zworykin, Pioneer of Television* (Urbana: Univ. of Illinois, 1995).
[7] Abramson, 198-199. See also: "Dr. Zworykin Elected Honorary Vice-President of RCA," *Radio Age* 13, no. 4 (Oct. 1954): 27.
[8] Kenyon Kilbon, "Pioneering in Electronics: A Short History of the Origins and Growth of RCA Laboratories, Radio Corporation of America, 1919 to 1964," unpublished typescript, revised August 1964, 270-273. Paginated copy available online at http://www.davidsarnoff.org/kil.html, accessed 28 Oct. 2009. In addition to his duties at RCA, Zworykin also served as director of medical electronics at the Rockefeller Institute between 1954 and 1962. For more on work he oversaw during this period, see: J.D. Ratcliff, "Medicine's New Electronic Wizardry," *Popular Mechanics*, Dec. 1958, 76-81.
[9] Heilmeier adopted the term "guest" to refer to dyes dissolved in a liquid crystal as early as 27 Jul. 1964. See: George Heilmeier, *Notebook 24160*, DSL, 101.
[10] George H. Heilmeier, "Liquid Crystal Displays: An Experiment in Interdisciplinary Research that Worked," *IEEE Trans. on Electron Devices* ED-23, no. 7 (Jul. 1976): 782. (original emphasis)

might serve as the basis for an electronic display and led in short order to the formation of a research team dedicated to studying their technological potential.[11] Yet although the organizational consequences of Heilmeier's research are well-documented, Zworykin's question concerning its origins has since received only partial answers.[12] The most detailed account Heilmeier provided on the subject, a 1976 article submitted to the IEEE's *Transactions on Electron Devices*, alluded to a generic interest in "ways in which I could control the local fields of materials by means of an applied electric field," but withheld explanation of the specific rationale underlying his experiments with liquid crystals.[13] Other than a single reference to studies on liquid crystals' electro-optic properties conducted two years earlier by fellow DSRC employee Richard Williams, it contained no discussion of collaboration with other members of RCA's technical staff.[14] Furthermore, this account framed the discovery of the guest-host effect as resulting from a single experiment, with no mention of previous trials or technical difficulties.[15]

Heilmeier acknowledged from the outset that his 1976 article contained omissions. "It is not my intention to write a detailed technical review," he explained in its

[11] RCA Laboratories, *Progress Report: Liquid Crystals, Mar.-May 1965*, DSL. The organization of the liquid crystal research group will be discussed at length in Ch. 5.
[12] See, for example, Joseph Castellano, *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry* (Hackensack, NJ: World Scientific, 2005), 18-33, 40-47.
[13] Heilmeier (1976), 781. Heilmeier also utilized the 1976 article as the basis for a workshop discussion after being awarded the 2005 Kyoto Prize. See: George H. Heilmeier, "Liquid Crystal Displays: Reminiscence of the Early Days," Workshop: The 2005 Kyoto Prize in Advanced Technology, available online at http://ww.inamori-f.or.jp/laureates/k21_a_george/img/wks_e.pdf, accessed 17 Jan. 2008.
[14] Heilmeier (1976), 781. To clarify, Heilmeier did refer to close research partnerships with other DSRC personnel, most notably Sol Harrison and Joel Goldmacher, prior to switching to liquid crystals. He also listed several members in the research group that formed following the demonstration of the guest-host effect. Other than Williams, however, none of these individuals are acknowledged as having been involved in either the decision to study liquid crystals or the demonstration of the guest-host effect.
[15] Heilmeier (1976), 781. The experiment in question involved an unnamed "strong dye," which was used to dope butoxy benzoic acid (BBA). As shall be seen, although this description corresponds with the recommended experimental setup in Heilmeier's first article on the subject, it dramatically oversimplifies the process through which he settled upon those materials

introduction. "Your editor requested a personal account and that is what I've tried to generate."[16] Other than its casual tone, his retrospective retained many of the stylistic norms of a scientific article, emphasizing pertinent results and avoiding any hint of their contingency.[17] It also reinforced the popular conception of science as a solitary activity where advances derive from isolated flashes of brilliance, rather than one filled with prolonged deliberation and collaboration aimed at overcoming experimental setbacks.[18]

Previous historians, eager to acquire a more comprehensive account of scientific activity, have supplemented analyses of published articles or reminiscences like Heilmeier's with additional sources, such as research notes or oral histories.[19] While the majority of these studies have concentrated upon academic laboratories, this chapter demonstrates the applicability of this approach to industrial settings by reconstructing the investigative pathways culminating in the observation of the guest-host effect. RCA's insistence that members of its technical staff document their research to protect against

[16] Heilmeier (1976), 781. Heilmeier's article was one of twenty compiled into a special edition of the *IEEE Transactions on Electron Devices* timed to correspond with the U.S. bicentennial, highlighting what the editors deemed "the most important inventions in the field of tubes and semiconductors." The editors stated they "were aware that this approach might lead to a subjective view, but we believed that a high degree of professional fairness and the perspective of elapsed time would avoid any major controversies." See: Gerald L. Pearson & Roland H. Haitz, "Foreword," *IEEE Trans. on Electron Devices* ED-23 (Jul. 1976): 595.

[17] For more on the codification of the scientific paper as a literary genre, see: Peter Dear, ed. *The Literary Structure of Scientific Argument* (Philadelphia: Univ. of Pennsylvania Press, 1991); F.L. Holmes, "The Fine Structure of Scientific Creativity," *History of Science* 19, no. 1 (Mar. 1981): 60-70.

[18] For attempts, inspired by cognitive psychology, to demystify the idea of "Eureka" moments in the history of science, see: Howard E. Gruber, "On the Relation Between 'Aha Experiences' and the Construction of Ideas ," *History of Science* 19, no 1 (Mar. 1983): 41-59; Alan Rocke, *Image & Reality: Kekulé, Kopp, and the Scientific Imagination* (Chicago: Univ. of Chicago, 2010).

[19] A detailed discussion of notebook analysis in the histories of science and technology is contained in the introduction of this dissertation. See also: Frederic Holmes, et al., ed., *Reworking the Bench: Research Notebook in the History of Science* (Boston: Kluwer Academic Publishers, 2003). For more on the use of oral histories to explore recent scientific practice, see: Soraya de Chadarevian, "Using Interviews to Write the History of Science," in *The Historiography of Contemporary Science and Technology*, ed. Thomas Söderqvist (Amsterdam: Harwood Academic Publishers, 1997), 51-70.

future intellectual property litigation ensured the accumulation of extensive notebook holdings, patent records, and internal correspondence related to liquid crystal display (LCD) research.[20] These materials and interviews with surviving researchers confirm that, modesty aside, Heilmeier did not "stumble" upon the guest-host color switching effect. His findings resulted from a series of methodical decisions made over several months in consultation with chemists and technicians, whose contributions are absent from the published record. Moreover, I argue, juxtaposing these disparate treatments of the LCD's origins reveals the extent to which corporate researchers tailor descriptions of their work to match the conventions of different genres of scientific communication.

A Taste for Exciting Research: Heilmeier's Early Electro-optics Investigations

Three years before his conversation with Zworykin, George Heilmeier had been a Ph.D. candidate in search of a dissertation, and liquid crystals, which would eventually secure his reputation within RCA, were not among his research interests. The only child of a working-class family living in the Mayfair section of Philadelphia, he received a scholarship from the University of Pennsylvania and earned a bachelor's degree in electrical engineering in 1958.[21] Following graduation, he joined RCA and took advantage

[20] As mentioned in Ch. 3, due to RCA's origins as a holding company consolidating the radio patents of GE, Westinghouse, and AT&T, its managers were particularly vigilant about obtaining patents for its inventions. *RCA Engineer*, the firm's in-house technical magazine regularly ran articles describing the importance of patents and instructing members of the technical staff how to maintain an organized laboratory notebook. See, for example: Joel B. Johnson, "Protecting Dates of Invention," *RCA Engineer* 3, no. 1 (Jun.-Jul. 1957): 38-41; Morris Rabkin, "Inventive Progress," *RCA Engineer* 2, no. 1 (Jun.-Jul. 1956): 47-50; O.V. Mitchell, Patents, RCA, and You," *RCA Engineer* 9, no. 2 (Aug.-Sep. 1963): 2-6.

[21] Amy Calhoun, "George Heilmeier," *Penn Engineering*, Fall 2009: 10-11; George H. Heilmeier, "A Moveable Feast," Commemorative Lecture: The 2005 Kyoto Prize in Advanced Technology, available online at http://www.inamori-f.or.jp/laureates/k21_a_george/img/lct_e.pdf/, accessed 17 Jan. 2008.

of the DSRC's advanced study program to pursue a doctorate at Princeton.[22] By the spring of 1961, Heilmeier had completed a master's thesis on solid-state microwave amplifiers, but he found the idea of expanding this work into a dissertation unappealing.[23] "The competition for new ideas was getting tougher," he reflected later, "and, having a taste for exciting research, I wasn't particularly interested in slugging it out on a mundane problem just to get my degree."[24]

As a result, microwave devices were completely absent from a list of potential dissertation topics that Heilmeier compiled in his laboratory notebook during this period.[25] The majority of his ideas revolved around the characterization of semiconductors, and after consulting with mentors at the DSRC and his academic advisor, he "left the relatively safe world of inorganic materials behind" to commence a year-long investigation of phthalocyanine—an organic compound better known for its use as a blue pigment than its electrical properties.[26] Heilmeier's friend and colleague, Sol Harrison, had studied this compound as a possible low-cost replacement for traditional, inorganic semiconductors and persuaded the younger electrical engineer to join his group in the DSRC's Electronics Research Laboratory (ERL).[27] Working alongside Harrison, Heilmeier explained the

[22] For further information on educational programs available to RCA engineers, see: H.G. Matz, "RCA Graduate Study Program," *RCA Engineer* 5, no. 5 (Feb.-Mar. 1960): 2-3.
[23] George H. Heilmeier, "An Analysis of Parametric Amplification in Periodically Loaded Transmission Lines" (Master's thesis, Princeton Univ., 1959). Heilmeier earned both M.S.E. and M.A. degrees in solid-state materials and electronics from Princeton in 1960 and 1961, respectively, as confirmed in: G.H. Heilmeier, "Liquid crystals–the first electronic method for controlling the reflection of light," *RCA Engineer* 15, no. 1 (Jun.-Jul. 1969): 14.
[24] Heilmeier (1976), 780.
[25] George Heilmeier, *Notebook 14445*, DSL, Front Index.
[26] Heilmeier (1976), 780. Heilmeier refers to conversations with Leon Nergaard (the head of RCA's Microwave Research Laboratory) and Princeton professor George Warfield.
[27] Heilmeier (1976), 780. Although Heilmeier commented upon the intellectual benefits of "living on the Princeton campus in the residential Graduate College environment" in his Kyoto Prize Commemorative Lecture (Heilmeier, "A Moveable Feast," 5), by 1961, he had married and moved back to Philadelphia. He and Harrison carpooled to work from the city, as described in Heilmeier's 1976 essay and confirmed by

movement of charges within phthalocyanine crystals using band theory. Within a year, he submitted a Ph.D. thesis based on these findings, which claimed that organic semiconductors would one day offer electronics manufacturers "more flexible and cheaper materials, lower requirements for purity and simpler fabrication."[28]

Heilmeier and Harrison's organic semiconductor experiments were part of a company-wide effort to resolve challenges associated with the construction of integrated circuitry. RCA's first step in this direction was the micromodule, a self-contained array of uniformly shaped components layered on a ceramic wafer and encased in a cube of epoxy resin.[29] DSRC researchers also considered other approaches, including thin-film devices and integrated semiconductor circuits.[30] Compared to these alternatives, a 1962 *RCA Engineer* article deemed Harrison's plan to manipulate materials' chemical composition or molecular structure for use in specific circuit components "too early in the state-of-the-art to expect meaningful advances."[31] Nonetheless these "molecular electronics" efforts

Louis Zanoni, Interview with author, Ewing, NJ, 1 Jul 2009. For more on Harrison's previous phthalocyanine research, see RCA Laboratories, *Research Report 1960*, 122-123; RCA Laboratories, *Research Report 1961*, 112-113.

[28] George H. Heilmeier, "Semiconduction in Phthalocyanine: A Study in Organic Semiconduction" (Ph.D. diss., Princeton Univ., 1962), VII.

[29] As with many projects during the late 1950s and early 1960s, the micromodule traced its origins to a military contract, in this case with the U.S. Army Signal Corps. For more on the micromodule, see: O.B. Cunningham and B.V. Dale, "The Micromodule: A Revolutionary Electronic Equipment Design Concept," *RCA Engineer* 4, no. 3 (Oct.-Nov. 1958): 29-33; C. Eddison, "Materials and Processes for the Micromodule," *RCA Engineer* 5, no. 4 (Dec. 1959-Jan. 1960): 52-55; Harry Kihn, "Integrated Electronics...A Survey," *RCA Engineer* 7, no. 6 (Apr.-May 1962): 14-19; Renato DiStefano, Jr., "Designing Micromodules for System Applications," *RCA Engineer* 7, no. 6 (Apr.-May 1962): 47-49; "Little Giants of Electronics," *Electronic Age* 18, no. 2 (Spring 1959): 2-5; "Micromodules on the March," *Electronic Age* 21, no. 4 (Autumn 1962): 5-7.

[30] Kihn, 15-17; Bruce Shore, "Ceramic Circuits," *Electronic Age* 21, no. 2 (Spring 1962): 2-5. See also: Ross Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: The Johns Hopkins Univ. Press, 2002), 33-45.

[31] Kihn, 17. A similarly low opinion of "molecular circuitry"–the hypothetical culmination of Harrison's approach where multiple electronic components would be incorporated into the structure of a specially-grown crystal–is present in Shore's *Electronic Age* article from the same period. (Shore, 4) For more on the origins of molecular electronics, see: Hyungsub Choi and Cyrus C.M. Mody, "The Long History of Molecular Electronics: Microelectronics Origins of Nanotechnology," *Social Studies of Science* 39, no. 1

attracted support from the Air Force, which awarded Harrison's group a contract the following year to "explore the possible uses of organic materials in solid state devices."[32]

Heilmeier found two of the solid-state applications specified in the Air Force contract particularly interesting: thin-film devices and electro-optic light modulators.[33] Even before securing military funding, he had demonstrated a functional field effect transistor using copper phthalocyanine and explored the effect of high electric fields on the optical properties of organic crystals.[34] He divided his attention between these two topics until the second half of 1963, when he set aside his transistor work to concentrate on the development of an organic material capable of modifying the phase, power, or polarization of a laser beam.[35] As he explained, "[t]he laser had emerged on the scene at about this time

(Feb. 2009): 11-50. Choi and Mody do not discuss molecular electronics at RCA, preferring to focus instead on the much larger program initiated at Westinghouse in 1957. There is little doubt, however, that the substitution of various metal ions for hydrogen in the core of phthalocyanine molecules in order to modify that substance's charge transport properties (as described in RCA Laboratories, *Research Report 1962*, 69-70; RCA Laboratories, *Research Report 1963*, 137, 154-155; RCA Laboratories, *Research Report 1964*, 143-144) constituted a molecular electronics project.

[32] S.E. Harrison, et al., *Utilization of Organic Materials for Molecular Electronics*, Technical Documentary Report No. AL TDR 64-178 (Jul. 1964), DSL, iii. See also: S.E. Harrison, et al., *Utilization of Organic Materials for Molecular Electronics*. Technical Report AFAL-TR-65-32 (Feb. 1965), DSL; Interim Engineering Reports No. 1-4 filed respectively on 15 Sep. 1963, 15 Dec. 1963, 15 Mar. 1964, and 15 Sep. 1964 in connection with Contract No. AF 33(657)-11662, DSL. As Choi and Mody point out, the Air Force was also the primary funding source for molecular electronics research at Westinghouse.

[33] Harrison, et al. (Jul. 1964), iii. The introduction to S.E. Harrison, et al. (Feb. 1965), DSL notes two additional types of devices under consideration: photoconductors and high mobility semiconductors, although the latter of these is not included in the first three interim engineering reports or the documentary report from July 1964.

[34] Both Harrison, et al. (Jul. 1964) and Interim Engineering Report No. 1 (Sep. 1963) confirm that the Air Force contract began in June 1963. Heilmeier recorded that "[a] successful CuPc [copper phthalocyanine] TFT has been demonstrated" in Jan. 1963. (George Heilmeier, *Notebook 19929*, DSL, 27-28) Heilmeier's interest in electro-optics reached at least as far back as July 1962, when he noted that unlike conventional semiconductors, "phthalocyanine might be of interest for modulation purposes" since it could be subjected to strong fields without damage, possessed low photoconductive gain, and was easily fabricated into thin layers. He discontinued this research after failing to observe an electro-optic effect in a phthalocyanine film (George Heilmeier, *Notebook 15988*, DSL, 82-85).

[35] This shift is particularly evident in Heilmeier, *Notebook 20858*, DSL. Between 28 Apr. and 19 Jun. 1963, Heilmeier alternated between transistor and electro-optic research. The remainder of the notebook (through 21 Sep. 1963) is entirely dedicated to the latter. Entries concerning field effect devices return in November and return to their former prominence by the beginning of 1964. See: George Heilmeier, *Notebook 22280*, DSL, 44-47 and 60-80. For explanations of the scientific principles behind electro-optic

and was commanding most of the attention at the Laboratory. I wanted a piece of the action."[36]

Heilmeier soon staked out an area of study that built upon his molecular electronics background. The establishment of the DSRC's quantum electronics group in 1960 reflected the growing recognition among RCA researchers of the laser's value to future communication systems, assuming high-speed modulators could be developed permitting the use of optical and infrared wavelengths of light.[37] A typical modulator consisted of a crystal whose refractive index changed upon being subjected to an electric field, but most of the substances utilized were either difficult to synthesize or suffered from prohibitive power requirements.[38] Heilmeier had considered this problem during his research on phthalocyanine, and although that material proved ineffective, he believed that organic crystals, which were comparatively easy to grow and modify, offered a solution.[39] The Air Force contract provided an impetus to return to this work, and he decided to

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light modulation (e.g. the Pockels effect), see: Robert G. Hunsperger, *Integrated Optics: Theory and Technology* (New York: Springer, 2009), 170-200; Rüdiger Paschotta, *Encyclopedia of Laser Physics and Technology* (Weinheim: Wiley-VCH, 2008), 145-147.

[36] Heilmeier (1976), 780. By 1963, both RCA Laboratories and the various operating divisions had expanded their laser research to such an extent that the Feb.-Mar. 1963 issue of *RCA Engineer* (Vol. 8, no. 5) was dedicated to the subject. (See Ch. 3 for more on RCA's laser research program.)

[37] RCA Laboratories, *Research Report 1960*, 67; RCA Laboratories, *Research Report 1961*, 61-62; 82; RCA Laboratories, *Research Report 1962*, 68; RCA Laboratories, *Research Report 1963*, 82-83. Further information on RCA's laser modulation systems can be found in D.J. Blattner and F. Sterzer, "Modulators and Demodulators for Laser Systems," *RCA Engineer* 8, no. 5 (Feb.-Mar. 1963): 16-19.

[38] Blattner and Sterzer summarize the strengths and weaknesses of the three main modulators under consideration at RCA in their 1963 *RCA Engineer* article. Both ammonium dihydrogen phosphate (ADP) and potassium dihydrogen phosphate (KDP) required high power for operation at desired bandwidths. Also, both substances operated only when the electric field was applied longitudinally (i.e. in the same direction as the light beam), and it could be difficult to obtain transparent conducting electrodes of high quality for use in such a setup. [cf. Harrison, et al. (Jul. 1964), 11] Copper chloride (CuCl) could be utilized with a transverse electric field and at lower power levels, but crystals larger than a few cubic millimeters were nearly impossible to grow.

[39] George Heilmeier, *Notebook 15988*, DSL, 82-85.

concentrate on hexamine (hexamethylene tetramine), which possessed a crystalline structure analogous to existing modulators.[40]

Between June and November 1963, Heilmeier confirmed the existence of an electro-optic effect in hexamine and devised a mathematical explanation linking the change in a crystal's refractive index to the behavior of electrons in its component molecules when an electric field was applied (i.e. the molecular Stark effect).[41] He also built upon this model to propose a new form of electro-optic modulator. If hexamine's bulk optical properties mirrored those of its component molecules, he reasoned, one could obviate the need to grow large single crystals by embedding a large number of "guest" molecules in a clear polymer "host," which could then be incorporated into a laser system.[42] In theory, this "non-crystalline" modulator could operate at extremely high frequencies, but hexamine's softness and water solubility made it difficult to encapsulate and the desired electro-optic behavior failed to manifest in any test samples.[43]

These setbacks did not dissuade Heilmeier from pursuing other laser modulation techniques. In June 1964, he sketched out a particularly compelling alternative in his

[40] George H. Heilmeier and Wolfgang Liebmann, *PEM-2297: A Note on the Crystal Growth and Evaluation of Hexamine as Optical Modulator*, 9 May 1963, DSL. Heilmeier's interest in hexamine can be dated to 8 Feb. 1963 (Heilmeier, *Notebook 19929*, 38). By May he had concluded that hexamine would be well-suited for laser applications (Heilmeier, *Notebook 20858*, 14). Liebmann, a semiconductor researcher, grew the crystals for Heilmeier's initial experiments, but left the DSRC by the end of 1963 to lead the MOS joint development program at IBM (Bassett, 212-213).

[41] George Heilmeier, *Notebook 20858*, 47-66; George Heilmeier, *Notebook 22280*, 1-42. The full details of Heilmeier's theoretical model relating hexamine's electro-optic properties to the molecular Stark effect are included in Harrison, et al., *Utilization of Organic Materials* (AL TDR 64-178), 28-35. For further information, see also: G.H. Heilmeier, "The Dielectric and Electrooptical Properties of a Molecular Crystal–Hexamine," *Applied Optics*, Vol. 3, No. 11 (Nov. 1964): 1281-1287.

[42] Heilmeier, *Notebook 22280*, 1-7. The terms "guest" and "host" are first used to refer to solutes and solvents on p. 66 of the same notebook.

[43] Heilmeier (1976), 780-781; Heilmeier, *Notebook 22280*, 12-13, 41-42, 57-59, 66-68, 82-84; George Heilmeier, *Notebook 24160*, 1, 12. Heilmeier also considered the use of hexamine isomorphs and structurally similar compounds like stannic chloride ($SnCl_4$). For further details on this project, see Harrison, et al., *Utilization of Organic Materials* (AL TDR 64-178), 15-17.

laboratory notebook.[44] The crux of this new idea was the realization that optical activity—the capacity of a substance to rotate the plane of a polarized beam of light—could be observed in both solid crystals and liquid solutions. Heilmeier therefore suggested the creation of a liquid laser modulator using a highly polar solvent such as nitrobenzene. In such a scenario, he argued, "an electric field dependence of the [optical] rotation through the action of nitrobenzene on the solute molecules suggests itself."[45] Before the field was applied, the molecules of the unnamed solute were randomly distributed among the elongated polar molecules of the solvent. The lack of internal organization meant that the solution would not affect light passing through it. When subjected to an external voltage, the polar solvent molecules would align themselves in rows parallel to the resulting field. "Now the solute molecules find themselves in the high field created by the solvent," he wrote, "and a stark [sic] effect is possible."[46]

Over the next month, Heilmeier determined that his original plan required modification. Further calculations based on his previous hexamine research indicated that "the fractional change in molecular rotation is expected to be quite small," certainly insufficient for nitrobenzene to alter the polarization plane of a laser beam.[47] Rather than abandon the liquid laser modulator concept, Heilmeier shifted his approach, proposing the use of electric fields to change the absorption spectra of dye solutions. As he explained in a typed research summary dated 27 July 1964:

> The absorption spectrum (or color) of a dye in solution varies widely depending on the solvent. This effect can in some cases be attributed to the influence of the local

[44] Heilmeier, *Notebook 24160*, 72.
[45] Heilmeier, *Notebook 24160*, 72.
[46] Heilmeier, *Notebook 24160*, 72.
[47] Heilmeier, *Notebook 24160*, 78-79.

> high fields of the solvent molecules on the solute dye. We are investigating the possibility of producing such effects by use of an external electric field. This would enable one to produce color changes that would be a function of an electrical signal.[48]

As before, Heilmeier originally planned to utilize nitrobenzene in this experiment, but he again dismissed the idea as impractical since in "the smaller external fields which are practical to apply" only one in a thousand nitrobenzene molecules would orient themselves properly to induce a spectral shift.[49] Fortunately, while seeking an alternative solvent better suited to the task, he uncovered a pair of articles published the previous year by another scientist working at the DSRC. His name was Richard Williams, and his research contributed to Heilmeier's conclusion that a "guest" dye–a term derived from the latter's hexamine research–dissolved in a liquid crystal "would be useful for light modulation and displays."[50]

From Light Valves to Liquid Crystals: Richard Williams' Electro-optics Research

The path that led Richard Williams to Princeton was hardly straightforward. After completing a Ph.D. in physical chemistry at Harvard in 1954, he obtained a job offer from Eastman Kodak, but before he could formally accept the position, fate–in the form of the American military establishment—intervened.[51] Despite having served in the Navy during World War II, the Army drafted Williams and sent him to basic training at Fort Knox. A few months later, he received a reassignment to the Army Chemical Center in Edgewood,

[48] Heilmeier, *Notebook 24160*, 100. The shift in format from the usual handwritten notebook entries to a typed research summary suggests that the latter may have been intended for Henry Lewis, the head of laser research at RCA and Heilmeier's superior within the Electronics Research Laboratory.
[49] Heilmeier, *Notebook 24160*, 100.
[50] Heilmeier (1976), 781.
[51] Richard Williams, Interview with author, Princeton, NJ, 8 Apr. 2009.

Maryland. Presumably, he explained, this move resulted from his superiors' realization that "I had a Ph.D., which gave me a bit more résumé than the usual hillbilly from Kentucky with whom I had been spending a couple of months."[52]

Just as Williams' degree facilitated his transition from boot camp to the laboratory, his academic connections helped him secure employment at the conclusion of his military service in 1955. His dissertation advisor, George Kistiakowsky, needed a new instructor to supervise Harvard's physical chemistry laboratory, a position that provided opportunities for independent research and might serve as a springboard to a faculty appointment.[53] Williams accepted the job, but after three years concluded that a professorship would not be forthcoming. Instead his gaze returned to industry, and in the summer of 1958, he became a member of the DSRC's technical staff.[54]

Upon arrival at RCA, Williams joined a materials research group led by Simon Larach, which was responsible for the analysis of phosphors and photoconductors.[55] In spite of the DSRC's retreat from fundamental research following the 1958 consent decree, these "photo-electronic" materials were vital components in image detection, reproduction, and storage devices, as well as RCA's new line of computing and control systems.[56] Williams, whose research interests had shifted from chemical kinetics to

[52] Richard Williams, Interview with author, Princeton, NJ, 8 Apr. 2009.
[53] Kistiakowsky is perhaps better known to historians of Cold War science for his involvement in the Manhattan Project and his 1959 appointment as Eisenhower's presidential science advisor. For more on his wartime research, specifically the development of the implosion lens system required to detonate a plutonium bomb, see: Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon and Schuster, 1986). For more on his postwar role, see: G.B. Kistiakowsky, *A Scientist at the White House: The Private Diary of President Eisenhower's Special Assistant for Science and Technology* (Cambridge: Harvard Univ. Press, 1976).
[54] Richard Williams, Interview with author, Princeton, NJ, 8 Apr. 2009.
[55] For an overview of Larach's career, see P.N. Yocom, "Simon Larach," *Physics Today*, Nov. 2000: 73.
[56] Larach's superior, Physical and Chemical Research Laboratory director R.W. Peter, emphasized exactly this point in a 1959-60 *RCA Engineer* article. See: R.W. Peter, "Materials Research," *RCA*

photochemistry during his recent stint in Cambridge, found himself able to pursue such work with "a good bit of autonomy."[57]

Along with photoconductivity specialist Richard Bube, Williams embarked on a long-term project to characterize the electrochemical properties of cadmium sulfide (CdS).[58] By the end of 1960, he published an article explaining the generation of electric currents when a CdS crystal immersed in an electrolyte was exposed to light.[59] He also collaborated with Bube to verify the photoemission of electrons from a metal to a semiconductor before investigating the effects of strong electric fields on the absorption spectra of crystals.[60] "I did some experiments on...some with cadmium sulfide and with some other materials. Lead iodide [PbI_2] was one of them," he explained. "Colored materials where if you had the right wavelength of light and you applied a voltage to it,

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Engineer 5, no. 4 (Dec. 1959-Jan. 1960): 4-9. (My use of the term "photo-electronic" to refer to phosphors and photoconductors is also derived from this article). For more on photoconductors' use in computers and control systems, see: R.H. Bube, "Photoconductivity," *RCA Engineer* 5, no. 4 (Dec. 1959-Jan. 1960): 28-32. For more on the 1958 consent decree, which prevented RCA from collecting royalties from its television patents, see Ch. 3.

[57] Richard Williams, Interview with author, Princeton, NJ, 8 Apr. 2009. For Williams' early interest in chemical kinetics see: Richard Williams, "Kinetic Studies of Boron-Trifluoride-Amine Addition Reactions" (Ph.D. diss., Harvard Univ., 1954); G.B. Kistiakowsky and R. Williams, "Kinetics of Coordinate Bond Formation," *Journal of Chemical Physics*, Vol. 23, No. 2 (Feb. 1955): 334-338. For the shift to photochemical processes including phosphorescence, fluorescence, and the polarization of electronic transitions, see: R. Williams, "Observation of the Relative Polarizations of Electronic Transitions," *Journal of Chemical Physics*, Vol. 26, No. 5 (May 1957): 1186-1188; R. Williams, "Delayed Fluorescence of Complex Molecules in the Vapor Phase," *Journal of Chemical Physics*, Vol. 28, No. 4 (Apr. 1958): 577-581; R. Williams, "Polarization of the Phosphorescence of Naphthalene and Phenanthrene," *Journal of Chemical Physics*, Vol. 30, No. 1 (Jan. 1959): 233-237. [N.B. All of these articles were submitted for publication prior to Williams' arrival at RCA.]

[58] Richard Williams, Interview with author, Princeton, NJ, 8 Apr. 2009. For more on the state of photoconductivity research after Williams' arrival at RCA, see R.H. Bube, "Photoconductivity." Though he does not name Kazan or Nicoll specifically, Bube alluded to their use of cadmium sulfide as "part of experimental picture display and light-amplifier systems, where the properties of the photoconductor are beneficially combined with those of electroluminescent materials." (29) See Ch. 2 for further details.

[59] Richard Williams, "Becquerel Photovoltaic Effect in Binary Compounds," *Journal of Chemical Physics* 32, no. 5 (May 1960): 1505-1514.

[60] Richard Williams and Richard H. Bube, "Photoemission in Photovoltaic Effect in Cadmium Sulfide Crystals," *Journal of Applied Physics* 31, no. 6 (Jun. 1960): 968-978.

you could shut off the light absorption near the absorption edge. It would shift the absorption edge so, in effect, it went black."[61] Williams briefly considered how this behavior could be integrated into a high-frequency light valve, which might, for example, protect a pilot from being blinded by the flash of an atomic bomb.[62]

Williams did not frame these early light modulation experiments as stepping stones towards a new type of display and was unaware of RCA's earlier attempts to develop a flat-panel television. Though conceptually, the creation of a thinner replacement for the cathode ray tube (CRT) was "so obvious I would think it wasn't even discussed," for Williams the construction of a flat-screen TV "was not really the motivating factor" behind his research. At best, the pursuit of new electro-optic effects might enable the construction of a "slow" light valve (in contrast to the high-frequency switching induced in lead iodide), capable of operating at television rates. Without integrated circuits or advanced addressing techniques, he noted in a 2009 interview, "you could conceive of making a pattern of those [light valves], and that was easy...Beyond that, it was hard to think very hard [or] think very much about it."[63]

Nevertheless, Williams pondered the production of an improved slow light valve throughout the second half of 1961. Although his laboratory notes from this period

[61] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. Richard Williams, "Electric Field Induced Light Absorption in CdS," *Physical Review* 117, no. 6 (15 Mar. 1960): 1487-1490; Richard Williams, "Effect of High Electric Field on the Absorption of Light by PbI_2 and HgI_2," *Physical Review*, 126, no. 2 (15 Apr. 1962): 442-446. Williams notes in his 1962 *Physical Review* article that he worked with both lead and mercuric iodide, but "[m]ore extensive experiments were done with PbI_2 than with HgI_2 because the PbI_2 crystals were thinner and more uniform than those of HgI_2." (444) See also: RCA Laboratories, *Research Report 1959*, 94.

[62] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. The relevance of Williams' research to high-frequency light modulation for "optical masers" (i.e. lasers) was also mentioned in RCA Laboratories, *Research Report 1961*, though it is unclear based on his notebooks how involved Williams was with RCA's emerging laser research projects.

[63] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009.

emphasize his ongoing investigations of cadmium sulfide and metal-semiconductor interfaces, at some point prior to April 1962, he decided that the electro-optic properties of liquid crystals merited further consideration.[64] Liquid crystals had been an object of scientific study since the late 19th century, when Austrian botanist Friedrich Reinitzer discovered a substance (cholesteryl benzoate) that did not undergo a simple transition from solid to liquid upon heating.[65] Instead, the material possessed two distinct "melting points."[66] At the first, it changed from a solid into a cloudy liquid, and at a second, higher temperature, it became transparent.[67] Reinitzer forwarded his findings to Otto Lehmann, a physical chemist who determined that, in its cloudy intermediate state (later referred to as the "mesomorphic state" or "mesophase"), cholesteryl benzoate retained its fluidity, but affected polarized light like a solid crystal, indicating a degree of molecular organization greater than an isotropic liquid.[68] Lehmann described substances with these properties as

[64] Richard Williams, *Notebook 15811*, DSL, 1-74. See also: Richard Williams, "High Electric Fields in Cadmium Sulfide: Field-Effect Constriction of Current Flow and Dielectric Breakdown," *Physical Review* 123 no. 5 (1 Sep. 1961): 1645-1651; R. Williams, "High Electric Fields in CdS," *Journal of Physics and Chemistry of Solids* 22 (Dec. 1961): 129-133; Richard Williams, "Dielectric Breakdown in Cadmium Sulfide," *Physical Review* 125, no. 3 (1 Feb. 1962): 850-854; Richard Williams, "Photoemission of Holes from Tin into Gallium Arsenide," *Physical Review Letters* 8, no. 10 (15 May 1962): 402-404.

[65] Castellano, 1; David Dunmur & Tim Sluckin, *Soap, Science, & Flat-Screen TVs: A History of Liquid Crystals* (New York: Oxford Univ. Press, 2011), 17-20. Peter Palffy-Muhoray suggests that the French naturalist Buffon was the first to observe liquid crystals during microscopy studies of myelin, but admits that neither Buffon nor Rudolf Virchow, who formally identified the substance in 1850, understood the structures they were examining. See: "The diverse world of liquid crystals," *Physics Today* (Sep. 2007): 54-60. For more on the history of liquid crystal research prior to 1888, see: Peter J. Collings, *Liquid Crystals: Nature's Delicate Phase of Matter* (Princeton: Princeton Univ. Press, 1990 [2002]): 24-27.

[66] Dunmur & Sluckin, 18-19. For cholesteryl benzoate, these two temperatures were 145.5°C and 178.5°C, respectively.

[67] Dunmur & Sluckin, 17-20. For Reinitzer's description of this phenomenon, see: Friedrich Reinitzer, "Contributions to the understanding of cholesterol," ["Beiträge zur Kenntiss des Cholesterins"] *Monatshefte für Chemie (Wien)*, Vol. 9 (1888): 421-441 in *Crystals That Flow: Classic Papers From the History of Liquid Crystals*, ed. & trans. Timothy J. Sluckin, et al. (New York: Taylor & Francis, 2004), 26-40.

[68] A substance is referred to as isotropic if its properties remain consistent regardless of physical orientation. For more on Lehmann, see: Dunmur & Sluckin, 20-27; Otto Lehmann, "On Flowing Crystals," ["Über fliessende Krystalle"] *Zeitschrift für Physikalische Chemie*, Vol. 4 (1889): 462-472 in Sluckin, et al., 42-52.

"Fliessende Krystalle" ("flowing crystals") and within twenty years of Reinitzer's observation, European scientists had reported over 200 compounds exhibiting similar behavior.[69]

By 1962, the novelty of discovery had dwindled, and liquid crystals, once the research province of such luminaries as Max Born, Louis de Broglie, and J.D. Bernal had become a laboratory curiosity worthy of only a cursory mention in physical chemistry textbooks.[70] Industrial applications were largely nonexistent and, according to Williams, "they were not well known to engineers or the kinds of guys who did most of the Labs' work on vacuum tubes and picture tubes and photoemission."[71] For his part, Williams had little practical experience with liquid crystals since learning about them in graduate school. Still, after surveying the latest literature on the subject in the DSRC technical library, "I was quite aware of the general nature of them, and some of them were commercially available in compounds, catalogs of organic compounds, and so that seemed like a possibility. So that's where I started."[72]

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[69] G.W. Gray, *Molecular Structure and the Properties of Liquid Crystals* (New York: Academic Press, 1962), 4; Georges Friedel, "The Mesomorphic States of Matter," ["Les états mésomorphes de la matière"] *Annales des Physique*, Vol. 18 (1922): 273-474 in Sluckin, et al., 167. Both Gray and Friedel credit Lehmann and Daniel Vorländer, a chemistry professor at the University of Halle, for the large number of liquid crystals discovered between 1889 and 1908.

[70] James L. Fergason, "Liquid Crystals," *Scientific American*, 211, no. 2 (Aug. 1964): 79. Fergason, a researcher at Westinghouse, and his colleague Glenn Brown, a chemistry professor at Kent State University, were among the few American researchers working with liquid crystals during the late 1950s. Brown's papers, including correspondence with Fergason and various RCA liquid crystal researchers, can be found in the special collections of Kent State University's library. (Accession 2001.70). For post-WWII textbook discussions of liquid crystals, see: Samuel Glasstone, *Textbook of Physical Chemistry*, 2nd ed. (New York: D. Van Nostrand Co., 1946), 514-517; E.B. Millard, *Physical Chemistry for Colleges, 7th ed.* (New York: McGraw-Hill Book Co., 1953), 189-190.

[71] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. Fergason's team at Westinghouse investigated the use of cholesteric liquid crystals as temperature sensors beginning in the late-1950s. Neither his 1964 *Scientific American* article surveying the state of the field nor any subsequent secondary literature (e.g. Castellano, Dunmur & Sluckin) indicates any other liquid crystal research underway in industrial laboratories during the early 1960s.

[72] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. Williams recorded few specific

Entering a New Domain: Williams' Liquid Crystal Research

The setup Williams assembled for his April 1962 exploration of "low frequency light modulation using liquid crystals" bore a partial resemblance to that used in his earlier lead iodide experiments.[73] In both instances, he placed a crystal sample between two glass plates whose inner faces were lined with a transparent tin oxide coating (referred to as "Tic"), allowing for the selective application of an electric field across the sample.[74] He then positioned the assembled cell on a microscope stage lit from below in order to observe any changes in its optical properties. The main difference between the two experimental setups was the inclusion of a "Tic plate heater" to ensure the liquid crystal samples were kept within the proper temperature range to exhibit mesomorphic behavior.[75] In the case of para-azoxyanisole (PAA), a readily available liquid crystal and the subject of his first experiments, Williams had to warm samples "to the approximate temperature range of 110-140°C" before any observations could be made.[76]

literature references in his laboratory notebooks, but interviews and articles suggest that he examined both American and European journals, including the extensive German literature on the subject. One item that he probably did not peruse prior to his April 1962 experiments was George Gray's *Molecular Structure and the Properties of Liquid Crystals* (London: Academic Press, 1962). Gray's book was the first English-language volume on the subject. Williams referenced it in his 1963 articles, but the RCA technical library only received a copy in August 1962, months after his first liquid crystal observations. (David Sarnoff Library, *Accession Records*, DSL, 24 Aug. 1962)

[73] Williams, *Notebook 15811*, 75. Williams acknowledged in an interview with the author on 16 Apr. 2009 that the same basic skill set was necessary to assemble each setup.

[74] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. Williams noted in this interview that one factor that facilitated his liquid crystal research was the availability of conductively coated glass, which was not a commercial product at the time. The etymology of the abbreviation "Tic" to refer to tin oxide remains unclear despite its wide use. According to a 1959 patent written by Benjamin Kazan, Tic stands for "transparent, iridescent conductive," but the author is aware of no other sources to corroborate this abbreviation. See: Benjamin Kazan, "Half-Tone Image Production," US Patent 2,896,087, filed 3 May 1954 and issued 21 Jul. 1959.

[75] Williams, "Effect of a High Electric Field," 442. There was one other noteworthy distinction between the two setups. While examining the light absorption of lead and mercuric iodide, Williams placed the two samples between mica sheets in order to prevent injection of electrons from the electrodes into the crystal samples. Presumably, Williams did not deem such precautions necessary in his liquid crystal experiments.

[76] Williams, *Notebook 15811*, 75. In subsequent articles, Williams reported the mesomorphic range for

On April 10, after Williams determined the correct amount of yellow PAA crystals needed to produce a thin fluid layer (~0.1 mm) within the cell, he slowly increased the DC voltage across the sample. At first, the electric field had only a negligible effect, but Williams noticed that "[o]n applying a DC voltage as shown there is a crinkling effect at ~1000 V/cm and vigorous turbulence at ~10 000 V/cm."[77] Once the field was turned off, the PAA reverted to its settled, transparent state. "You could just see that without any instrumentation...," Williams remembered. "You apply the voltage and the liquid begins to look cloudier than it did, and that's because the light scattering properties are changed. Quite significantly, so it's obvious. It doesn't take hours of staring in a dark room or anything to see it. It was easy."[78] Viewing the sample through crossed polarizers, a common crystallographic technique used to reveal otherwise invisible structural aspects of anisotropic materials, increased the contrast further, prompting Williams to include them in his experimental sketches.[79]

Williams immediately recognized the possibility that this effect "may be useful for low frequency light modulation" and referred to the possibility of a "liquid crystal light valve" on the next page of his notebook. He repeated the experiment, using a photomultiplier to record the intensity of light transmitted through the PAA sample as a function of applied voltage. A graph of his findings indicated a sharp change in light intensity when 8-10 volts, corresponding to a field of 800-1,000 V/cm, were applied to the cell. "Turbulence began here," he wrote, "and can be observed through the microscope."

PAA as 116-134°C.

[77] Williams, *Notebook 15811*, 75.

[78] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009.

[79] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009; Williams, *Notebook 15811*, 75. For more on the behavior of polarized light transmitted through liquid crystals, see: Collings, 69-72.

Further investigations showed little distinction between PAA subjected to either a DC or AC field up to a frequency of 15 kilocycles. In both cases, at a fixed threshold voltage, "[a] stable pattern is formed which becomes turbulent as the voltage increases."[80] On April 13, three days after these first observations, Williams photographed this pattern, a series of long parallel regions that he referred to as a "domain structure," between crossed polarizers at 90x magnification.[81]

Williams wasted little time in showing his findings to other members of his research team, including his lab-mate Richard Bube, group leader Simon Larach, and physicist Ross Shrader.[82] In an uncharacteristic move for one who largely ignored company policy regarding the witnessing of research notebooks, Williams recruited Bube and Shrader to validate the pages describing his liquid crystal experiments.[83] Yet Williams did not secure their signatures until the end of the month, nor did he abandon his other research interests in favor of liquid crystals. In fact, the Monday after he photographed the domain structure of PAA, he returned to his previous work on metal-semiconductor interfaces.[84] On the basis of his research notes for the remainder of April, as Williams

[80] Williams, *Notebook 15811*, 77.
[81] Williams, *Notebook 15811*, 78; Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. The term "domain" was a reference to ferroelectric substances, which formed similarly shaped regions of alternating electric polarity when subjected to an electric field. Williams thought the two phenomena might be linked.
[82] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009; Simon Larach, *Notebook 982*, DSL, 59. Williams also recalled showing his findings to veteran photoconductivity researcher Al Rose and Richard Bube's technical assistant, Harold McDonald. Williams did not work closely with a technician until the end of the 1960s.
[83] Williams, *Notebook 15811*, 75-78. In fact, the only other instances in this entire notebook, covering the period from Oct. 1961-May 1962, where Williams went out of his way to obtain a witness' signature were on 15 Mar. 1962 in connection with a photovoltaic cell composed of tin evaporated on p-type silicon. (p. 67) and 1 May 1962 (p. 84) following a proposal for a cold-emission cathode. In each case, he only obtained one signature, from Bube and Alvin Goodman, respectively.
[84] Williams, *Notebook 15811*, 79.

revisited the photoemissive properties of lead iodide and proposed a new form of "cold" cathode, it was almost as though his liquid crystal experiments had never taken place.[85]

Multitasking was Williams' *modus operandi* throughout his career, and the choice to cycle back to research he had been pursuing prior to liquid crystals was not in and of itself surprising.[86] More noteworthy was the suddenness with which he decided, at the beginning of May 1962, to dedicate the next three months solely to the study of liquid crystals and their domain structure. This shift in priorities appears to have been triggered by discussions with Simon Larach and the joint recognition that in spite of their high temperature requirements, liquid crystals could be utilized in displays.[87] Larach, "who was very interested in forwarding the concept," encouraged Williams to continue studying liquid crystals and compose a patent disclosure outlining possible applications.[88] As a result, on May 2, Williams initiated an extensive series of measurements of the switching properties of PAA at different temperatures.[89] This project, along with comparative

[85] Williams, *Notebook 15811*, 80-85; Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. Theoretically, a cold cathode would emit electrons in a high electric field without being heated, in contrast to the "hot" cathodes used in traditional CRTs.

[86] Richard Williams, Interview with the author, Princeton, NJ, 30 Apr. 2009.

[87] Larach, *Notebook 982*, 59; Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009.

[88] Richard Williams, Interview with author, Princeton, NJ, 30 Apr. 2009.

[89] Williams, *Notebook 15811*, 87, 89, 90-93. Coincidentally, May 2 was also the date which Larach recorded in his notebook that "R. Williams has found a field effect in nematic types of liquid xtals" and proposed "utilizing this in a display device," though it is possible that this was an addendum following a May 10 discussion with Ross Shrader. (Larach, *Notebook 982*, 59) The term "nematic" refers to one of the three general categories of liquid crystal determined by Georges Friedel in 1922 on the basis of their molecular organization. Briefly, nematic crystals consist of elongated, rod-like molecules whose long axes are parallel to one another and are capable of moving past one another like matches sliding around inside a box. The term derives from the Greek term "nematos," meaning thread, due to the unique texture such materials exhibit when viewed between crossed polarizers. The other two categories, smectic and cholesteric, also consist of rod like molecules. In the former these are packed into tight layers leading to compounds with high viscosity comparable to the soaps from which they get their name (from the Greek "smectos"= "soap-like"). Cholesteric compounds, named for the esters of cholesterol in which they were first observed, also have molecules arranged in layers, but the parallel alignment within each layer is reminiscent of the nematic phase. They are sometimes referred to as chiral nematic substances since each layer twists in either a left-or right-handed direction compared to the one next to it, leading to a helical configuration that scatters light from its surface. See Castellano, 2-3; Fergason, 79-80; Gray, 1-13.

investigations of domains in other liquid crystal materials and the relationship between domain size and specimen thickness, filled his research agenda through the end of July.[90]

Over the course of the next year, Williams circulated two technical reports describing his liquid crystal experiments, received permission from management to submit them for journal publication, and filed a patent for "an improved electro-optical element" utilizing mesomorphic materials.[91] Unfortunately, with the exception of a single diagram showing a switching circuit used in his domain experiments, between August 1962 and August 1963, he did not describe any aspect of this research in his laboratory notebooks.[92] This lacuna complicates efforts to evaluate changes in his theoretical understanding of liquid crystals' electro-optic behavior and their integration into display devices. Some of these omissions–such as the origins of Williams' preliminary theory of domain formation[93]

[90] Williams, *Notebook 15811*, 88, 94-95; Richard Williams, *Notebook 17672*, DSL, 1-14. The only additional liquid crystals mentioned in Williams' notebooks from 1962 are dibenzalbenzidene and 2-4 nonadieonic acid, though he also conducted tests on structurally similar compounds such as azoxybenzene. In Williams' 1963 *Journal of Chemical Physics* article, he claimed to have seen domains in anisaldazine and p-methoxycinnamic acid, but no record of these observations appears in his notebooks.

[91] Richard Williams, *PTR-1370: Domains in Liquid Crystals*, 28 Jan. 1963, DSL; Richard Williams, *PTR-1371: Liquid Crystals in an Electric Field*, 28 Jan. 1963, DSL; Richard Williams, "Electro-optical Elements Utilizing an Organic Nematic Compound," US Patent 3,322,485, filed 9 Nov. 1962 and issued 30 May 1967. *PTR-1370* was later published as Richard Williams, "Domains in Liquid Crystals," *Journal of Chemical Physics* 39, no. 2 (15 Jul. 1963): 384-388 after being received on 21 Mar. 1963. *PTR-1371* was published the following week as "Liquid Crystals in an Electric Field," *Nature* 199 (20 Jul. 1963): 273-274. In addition to these mainstream publications, Williams also submitted a brief summary of his work to *RCA Engineer*, the corporation's in-house technical magazine: Dr. R. Williams, "Domain Structure in Liquid Crystals," *RCA Engineer* 9, no. 3 (Oct.-Nov. 1963): 74. However, by the time it was published, he had already left Princeton for a European sabbatical (see below).

[92] The majority of Williams' research notes during this period concern the electro-optic properties of CdS, CdSe, and NaCl crystals as well as preliminary work on his cold cathode proposal. The switching circuit diagram, dated 26 Mar. 1963, can be found in: Richard Williams, *Notebook 20170*, DSL, 18.

[93] In *PTR-1370* and *PTR-1371*, as well as their corresponding journal articles, Williams described the domains that formed in liquid crystals as analogous to the regions of alternating polarity present in ferroelectric materials subjected to an electric field. The very use of the term "domain" to describe the crinkling effect in his liquid crystal samples was a reference to similar patterns seen in ferroelectric and ferromagnetic materials. (Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009) George Taylor recalled holding conversations with Williams about possible parallels between ferroelectric and mesomorphic materials, suggesting that Williams was actively considering such ideas after Taylor's

and experiments intended to disprove alternative explanations[94]—can be deduced through a careful consideration of the published record supplemented with oral history interviews. These findings confirm Williams' later comment that following the observation of domains, his research revolved around gaining a quantitative understanding of their behavior, "trying to learn all about these and to define what could be done and what can't be done."[95]

It would be a mistake, however, to assume that Williams entirely ignored displays due to the absence of references in his laboratory notebooks or journal articles. Both sets of documents provide at best a partial cross-section of Williams' cognitive processes during this period, with the former reflecting a personal preference for fundamental investigations into liquid crystals' physical properties and the latter responding to the editorial restrictions imposed by RCA's patent department. For although the corporation encouraged members of its technical staff to publish their research, the DSRC's management insisted that they avoid revealing the practical ramifications of new scientific concepts.[96] The triangulation between Williams' research notes, articles, and interviews,

arrival at the DSRC in August 1962 (George Taylor, Interview with author, Pennington, NJ, 14 Oct. 2009).

[94] As Williams observed in his 16 Apr. 2009 interview with the author, his first article on domain formation (*PTR-1370*, republished in *Journal of Chemical Physics* as "Domains in Liquid Crystals") "consists to a considerable extent of showing that it was not certain things people would bring up." In some cases, such as the high resistivity values used to show domains were not the result of electrolytic deposition, the evidence cited can be linked to specific observations in his notebooks. Other experiments hinted at in this article, including the replacement of tin-oxide electrodes with other metals (to confirm domains did not result from chemical interaction between the electrode and liquid crystal) and viewing domains with different wavelengths of light (to eliminate the possibility of interference phenomena) possess no corresponding notebook entry.

[95] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009.

[96] Research connected to a military project was, of course, subject to stricter security requirements. For more on publication policies and attempts to resolve the tensions, both real and perceived between academic and industrial research norms, see: Leonard Reich, *The Making of Industrial Research: Science and Business at GE and Bell, 1876-1926* (New York: Cambridge Univ. Press, 1985); Steven Shapin, *The Scientific Life: A Moral History of a Late Modern Vocation* (Chicago: Univ. of Chicago Press, 2008);

while permitting a partial reconstruction of his liquid crystal experiments, is therefore not readily extended to his work on display devices due to the conventions and constraints associated with each genre.

Fortunately, Williams worked in a research environment that encouraged frequent interaction with other personnel, who expanded upon his ideas in their own laboratory notebooks. As Williams devoted himself to deciphering the mechanism of domain formation, his colleagues Simon Larach and Ross Shrader decided to construct a small display device based upon his "optical field effect."[97] This demonstration model consisted of a heated liquid crystal sample sandwiched between a pair of glass plates whose inner faces were coated with transparent conductive strips.[98] After positioning the plates so that the strips formed an x-y grid, one could trigger the formation of domains at a given intersection by applying voltage to the corresponding set of electrodes. "The field effect modifies the reflectivity or transmissivity of collimated illumination impinging on the array," Larach recorded, noting that possible designs "include, but are not limited to, X-Y, and ρ-θ [i.e. polar] displays."[99] By the end of July, Larach and Shrader had demonstrated a 4 x 4 version of this device to their superior Humboldt Leverenz, as well as Leverenz's boss—and the overall head of the DSRC—James Hillier. They also invited other researchers with a specific interest in flat-panel displays, including SRL personnel, like

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George Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (New York: Columbia Univ. Press, 1985). Ann Johnson's study of anti-lock brake systems, *Hitting the Brakes: Engineering Design and the Production of Knowledge* (Durham, NC: Duke Univ. Press, 2009) also contains an interesting aversion of the traditional private knowledge-public knowledge dichotomy in corporate research labs.

[97] Simon Larach, *Notebook 982*, 65.

[98] Larach, *Notebook 982*, 65. Larach does not specifically mention a heating stage, but no substances exhibiting mesomorphic behavior at room temperature were available in 1962.

[99] Larach, *Notebook 982*, 65-66.

Allen Barco and David Kleitman, and computer engineers, like Jan Rajchman and Bernard Lechner, to observe their work.[100]

Though Williams was aware of these visits, he apparently stayed in the background during demonstrations, to the point that Lechner recalled in an interview that "I had no idea at the time that Dick Williams was involved at all."[101] Larach's notebook, in contrast, urged readers to "see patent disclosure of R. Williams," linking his device to the first published document to outline how liquid crystals might be integrated into a flat-panel display.[102] After summarizing the general properties of mesomorphic materials, Williams presented two variations of his initial experimental setup, which utilized a previously unobserved "light scattering effect" to modulate either reflected or transmitted light.[103] Both configurations could be expanded to include "a plurality of conductive paths or electrodes on each substrate," which might then be arranged in an x-y grid, as in Larach and Shrader's demonstration model.[104] "Such a device may be used to display patterns or pictures, and is particularly suitable for display of information in rectilinear coordinates," he noted, though he also described a polar display "easily adapted to indicate the range and angle information of a body."[105]

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[100] Larach, *Notebook 982*, 65. Leverenz, Hillier, Rajchman, Kleitman, and Barco are among the "various individuals" specifically referenced as witnesses in Larach's notebook. Lechner's presence is based upon an oral history interview conducted with the author in Princeton, NJ on 17 Apr. 2009, as well as Bernard Lechner, "History Crystallized: A First-Person Account of the Development of Matrix-Addressed LCDs for Television at RCA in the 1960s," *Information Display* (Jan. 2008): 26-27.

[101] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009.

[102] Larach, *Notebook 982*, 65.

[103] Williams, US Patent 3,322,485, 6.

[104] Williams, US Patent 3,322,485, 7.

[105] Williams, US Patent 3,322,485, 7-9.

Williams' patent, filed in November 1962, was not the first to propose a display device based upon liquid crystals. That honor belonged to a pair of British employees of the Marconi Wireless Telegraph Company, who in 1934 asserted that mesomorphic materials could regulate light output in electromechanical televisions—essentially serving as the shutter in a projection system.[106] Though this device was similar to his preliminary conception of a low-frequency light valve, Williams now imagined a more ambitious system, utilizing an array of liquid crystal elements to form an image. He also alluded to the possibility of upgrading this setup to a full-fledged mural television, commenting that the switching times of existing liquid crystal samples were "compatible with present television standards."[107]

These optimistic predictions belied Williams' conclusion by the end of the patent writing process that applications based upon liquid crystals would not be forthcoming. Demonstrations of their electro-optic properties elicited universally positive reactions throughout the DSRC, but "it was hard to get people interested...in the device end

[106] Barnett Levin and Nyman Levin (Marconi's Wireless Telegraph Company), "Improvements in or relating to Light Valves," UK Patent 441,274, filed 13 Jul. 1934 and issued 13 Jan. 1936, in Sluckin, et al., 487-495. Sluckin, et al. also evaluate this patent's claims in an introductory essay on the development of liquid crystal display technology (467-468). In brief, the Marconi patent suggested using liquid crystals as the basis of a Kerr cell, a device which could be rendered birefringent following the application of an electric field. Several early television systems utilized Kerr cells, typically filled with nitrobenzene, in conjunction with a pair of crossed polarizers to modulate a spot of light that was swept across a screen using a rotating mirror drum. For more on this patent, see Dunmur & Sluckin, 194-198. For general information about these electromechanical television systems, see: Albert Abramson, *The History of Television, 1880-1941* (Jefferson, NC: McFarland & Co., 1987) and Alexander Magoun, *Television: The Life Story of a Technology* (Westport, CT: Greenwood Press, 2007). For a contemporary explanation of the Kerr cell, see G. Parr, "The Kerr Cell in Television," *Television Today,* Part 2 (1935): 90-94. Available online at: http://www.tvhistory.tv/ , accessed 15 Mar. 2010.

[107] Williams, US Patent 3,322,485, 8. In addition to pointing out the compatibility of existing optical devices with existing broadcast standards, Williams references Rajchman's mural television patent (US patent 2,928,894, filed 31 May 1955 and issued 15 Mar. 1960), noting that with proper row and column selector circuitry and electrode strips of the proper dimension "a photograph or picture can be displayed on a device of this type."

because the typical electrical engineer who was working here had never heard of liquid crystals."[108] A few personnel, notably Jan Rajchman, wished to move the project forward, but the lack of room-temperature mesomorphic materials severely limited its prospects.[109] Instead, Williams spent the first half of 1963 working on a military-sponsored study of the effects of high electric fields on ionic solids.[110] The first published reports of the discovery of domains appeared in July, but within a month, Williams departed for a nine month assignment at RCA's laboratory in Zurich, leaving any discussion of liquid crystal display devices to fade on the other side of the Atlantic until George Heilmeier came along.[111]

Pleochroic Possibilities: Heilmeier's Preliminary Liquid Crystal Experiments

Heilmeier had met Williams shortly after arriving at the DSRC and despite being assigned to different research groups, their shared interest in electro-optic light modulation provoked frequent conversations. "We talked all the time..." Williams remembered. "We often had lunch together, saw each other, walked into his lab, and so on."[112] Heilmeier, in

[108] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009.

[109] Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009; Lechner, "History Crystallized," 27. Lechner states in both his interview and article that Rajchman tried to persuade management to search for room-temperature materials, but that no further work was done until after George Heilmeier revisited the subject in 1964.

[110] Richard Williams, *Notebook 20170*, DSL, 1-56; Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009; Richard Williams, "High Electric Fields in Sodium Chloride," *J. Phys Chem. Solids* 25, no. 8 (Aug. 1964): 853-858. In his article, Williams indicates that his research "was sponsored by the U.S. Army Research Office (Durham) under Contract Number DA 31-124-ARO(D)-84" (858).

[111] Williams, "Domains in Liquid Crystals"; Williams, "Liquid Crystals in an Electric Field"; Richard Williams, Interview with author, Princeton, NJ, 8 Apr. 2009; Richard Williams, Interview with author, Princeton, NJ, 16 Apr. 2009. On the basis of his notebooks, Williams appears to have arrived in Zurich in late August 1963 and returned to Princeton in early June 1964 (Williams, *Notebook 17943*, DSL).

[112] Interview with author, Princeton, NJ, 30 Apr. 2009. It is worth noting here that Louis Zanoni, Heilmeier's technician, asserted in two separate interviews that he never saw Williams in their laboratory. Zanoni nonetheless acknowledged that "George had a lot of respect for Williams and they were very friendly" and that occasionally "George would go over to his [i.e. Williams'] office." Louis Zanoni, Interviews with author, Ewing, NJ, 1 Jul. and 21 Aug. 2009.

turn, referred to Williams as "one of the finest physical chemists in the country" and acknowledged their many "helpful discussions" in subsequent journal articles.[113] Based on this evidence, it is tempting to conclude that upon returning from his Swiss sabbatical, Williams advised Heilmeier to utilize liquid crystals in his dissolved dye experiments. One can imagine Heilmeier's frustration over his inability to induce an electronic color shift in nitrobenzene solutions and Williams' suggestion that the domains observed in mesomorphic samples might facilitate that process. Yet while the two men later co-authored a study on ferroelectric behavior in liquid crystals, their laboratory notebooks do not refer to any conversations on the subject prior to Heilmeier's July 1964 proposal "to investigate the spectra of dyes in a liquid crystal medium."[114] Williams' familiarity with the behavior of liquid crystals under applied fields made him a logical sounding board for Heilmeier's ideas, but no documentary evidence exists suggesting his involvement moved beyond an advisory capacity.[115]

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[113] Heilmeier (1976), 781; George H. Heilmeier, "Transient Behavior of Domains in Liquid Crystals," *Journal of Chemical Physics* 44, no. 2 (15 Jan. 1966): 647; G.H. Heilmeier, L.A. Zanoni, and L.A. Barton, "Dynamic Scattering in Nematic Liquid Crystals," *Applied Physics Letters* 13, No. 1 (1 Jul. 1968): 47.

[114] Heilmeier, *Notebook 24160*, 101; Richard Williams and George Heilmeier, "Possible Ferroelectric Effects in Liquid Crystals and Related Liquids," *Journal of Chemical Physics* 44, no. 2 (15 Jan. 1966): 638-643. Williams is not mentioned by name in Heilmeier's notebooks during the first half of 1964, while Heilmeier's sole appearance in Williams' notes is a reference to a "TGS [triglycine sulfate] Crystal provided and electroded by Heilmeier" likely related to work on a ferroelectric field effect device (FEFED). (Williams, *Notebook 17943*, 70)

[115] Richard Williams, Interview with author, Princeton, NJ, 30 Apr. 2009. In this interview, Williams claimed that it was conceivable that he suggested Heilmeier explore the use of liquid crystals, but that he had no specific recollection of having done so. For his part, Heilmeier cited Williams' 1963 paper in the first published article on the guest-host effect, but later stated that "the first LCD prototypes were built based on our discoveries [i.e. Heilmeier's research group, of which Williams was never a formal member.], not those of others." His technician, Louis Zanoni agreed with this assessment. "Williams did not contribute, period." he noted in a 2009 interview, "You ask George, and he'll tell you he [i.e. Williams] did not contribute to the discovery of the liquid crystal display that George has created." See: George Heilmeier, "LCDs-Some Reminiscences of the Early Days," Remarks delivered at IEEE Milestone Ceremony, 30 Sep. 2006, DSL; Louis Zanoni, Interview with author, Ewing, NJ, 21 Aug. 2009.

Although Heilmeier's decision to shift his focus from polar solvents to liquid crystals was in all likelihood made independently, he did not pursue this research program on his own. Like his previous work on organic semiconductors and his ongoing investigations into ferroelectric field effect transistors, Heilmeier's liquid crystal experiments depended, even at this early stage, upon the contributions of numerous individuals. One of the earliest was Louis Zanoni, a naval veteran from Trenton who graduated with honors from RCA's in-house technical school before coming to the DSRC in 1957.[116] Zanoni established himself as a skilled technical staff associate (TSA), with an aptitude for requisitioning materials and equipment.[117] "I was not a cleanup guy. I was a technician, and I had lots of contact with all the services of the laboratory...," he explained. "I could go to any shop, any place, ask them for something. They would help me, provide anything I needed."[118] Zanoni later transferred into Sol Harrison's organic semiconductor group, where he began working with George Heilmeier.[119]

Zanoni impressed Heilmeier with his "extremely capable technical assistance" during their work on hexamine, and the two formed a partnership that would extend well

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[116] Louis Zanoni, Interview with author, Ewing, NJ, 1 Jul. 2009. The author is also indebted to Mr. Zanoni for granting access to his personal papers concerning his career at RCA (and beyond), which will be referred to as ZPA (=Zanoni Personal Archive) in subsequent notes. For additional information about the RCA Institutes, where Zanoni received his training, see "Needed: Talented Technicians," *Electronic Age* 18, no. 3 (Summer 1959): 27.

[117] Louis Zanoni, Interview with author, Ewing, NJ, 1 Jul. 2009. The magnetics group in question consisted of three members of RCA's technical staff (MTSs): Philip Baltzer, Arthur Miller, and Peter Wojtowicz. Zanoni was designated a TSA after the position was established in 1958 in an effort to attract "much needed supporting personnel" to the Labs. TSAs had a higher level of education than technicians and could eventually become a full MTS. (See RCA Laboratories, *Research Report 1958*, 2)

[118] Louis Zanoni, Interview with author, Ewing, NJ, 1 Jul. 2009.

[119] Louis Zanoni, Interview with author, Ewing, NJ, 1 Jul. 2009. The exact date of this transition is unclear, but Zanoni signed as a witness in Heilmeier's notebook as early as Dec. 1961. (Heilmeier, *Notebook 15988*, 7)

beyond that project's conclusion.[120] Two months after Heilmeier's proposal to explore the display potential of dyes dissolved in liquid crystals, he and Zanoni commenced their investigation by recreating Williams' experimental setup. They sandwiched a heated sample of PAA, chosen "since it has been extensively studied and its properties are well known," between a pair of Tic-coated Pyrex plates and applied an electric field.[121] Once they confirmed the existence of domains, they dissolved various dyes into the PAA and repeated the procedure.[122] If Heilmeier's predictions were correct, the rearranged liquid crystal molecules would induce a change in the dye's absorption spectrum, indicated by a color change in the sample. Alternatively, as he noted in July, the domain pattern could be used to realign a pleochroic dye, one whose molecules absorbed different wavelengths depending upon their orientation with respect to polarized light.[123]

Results during the first two weeks of experiments proved frustratingly inconclusive. Heilmeier worried that the interior surfaces of the glass plates affected the orientation of the liquid crystal molecules.[124] Further complicating matters was the tendency of the PAA crystals to distort any potential color change the dyes exhibited, a trend that was particularly noticeable upon viewing with polarized light.[125] To resolve the

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[120] G.H. Heilmeier, "The Dielectric and Electrooptical Properties..." 1287. As an MTS, Heilmeier outranked Zanoni, but the two formed a strong personal and professional relationship during their time at the DSRC. In a 21 Aug. 2009 interview with the author, Zanoni asserted that this difference in rank had no effect on their interactions in the laboratory. If anything, he claimed, Heilmeier went out of his way to ensure that Zanoni was treated the same as other MTSs. As evidence, he cited Heilmeier's insistence that Zanoni receive the 1968 David Sarnoff Award along with other members of the liquid crystal group, even though TSAs were not normally eligible for such recognition.

[121] George Heilmeier, *Notebook 25463*, DSL, 40. This notebook page is dated 1-5 Oct. 1964.

[122] Heilmeier, *Notebook 25463*, 43. Heilmeier initially selected merocyanine dyes which were likely to be soluble in PAA, including methyl red and indophenol blue.

[123] Heilmeier, *Notebook 25463*, 39. See also: Heilmeier, *Notebook 24160*, 101.

[124] Heilmeier, *Notebook 25463*, 44.

[125] Heilmeier, *Notebook 25463*, 56.

first issue, Heilmeier and Zanoni developed a new cleaning technique for glass substrates prior to cell assembly: washing slides in strong acids, rinsing them in distilled water, and rubbing them dry in one direction to ensure uniform molecular alignment in their samples.[126] Overcoming the intrinsic difficulties associated with PAA, however, necessitated improved materials. To that end, Heilmeier approached Joel Goldmacher, an organic chemist with whom he had consulted in connection with the Air Force molecular electronics contract.[127] Goldmacher had previously supplied Heilmeier with a list of PAA-soluble dyes and now worked with Zanoni to provide purified PAA samples against which to compare previous results.[128] Additional assistance came from Daniel Ross, a laser researcher who shared Heilmeier's interest in optical modulators and offered him a new series of dyes to test for pleochroism.[129]

The eventual demonstration of Heilmeier's predicted electro-optic effect in mid-October 1964 was above all a collaborative effort, reliant upon his and Zanoni's growing

[126] Louis Zanoni, Interview with author, Ewing, NJ, 1 Jul. 2009. The precise implementation of this procedure is something of a mystery since Zanoni did not recall the precise type of acid used and there are no references to liquid crystal research in his notebooks prior to Jan. 1965. In a notebook entry dated 1-5 Oct. 1964, Heilmeier described cleaning a glass plate in chromic acid, rinsing it in distilled water, and rubbing it dry, but this substrate was used to orient dye molecules prior to testing their absorption spectra. (Heilmeier, *Notebook 26463*, 45). Although Zanoni noted in interviews that cleaning the glass was his "#1 project," there are no other specific references in Heilmeier's notebook to the steps involved until 9-10 Dec. 1964 when he described "recent samples" being "treated with HCl and rinsed in distilled water prior to melting the liquid crystal+dye." (Heilmeier, *Notebook 25463*, 82) Given Heilmeier's acknowledgment in connection with the 12 Oct. dye testing that "molecules in thin films tend to orient there [sic] axis in the direction in which the glass substrate was rubbed," it is probable that he had at least begun thinking about such issues in relation to his liquid crystal samples.

[127] Heilmeier, *Notebook 25463*, 59. Goldmacher was the first organic chemist to join the staff of RCA Laboratories, arriving in Princeton in 1963. According to semiconductor researcher Karl Zaininger, who was working at the DSRC at the time, Heilmeier was at least partially responsible for convincing RCA's management to recruit an organic chemist (Karl Zaininger, Interview with author, Princeton, NJ, 11 Sep. 2009). For more on Goldmacher's professional background, see Castellano, 24.

[128] Heilmeier, *Notebook 25463*, 59; Joel Goldmacher, *Notebook 25011*, DSL, 14.

[129] Heilmeier, *Notebook 25463*, 58. For more on Ross' career at RCA, see "Daniel L. Ross," [RCA 1978 Company Biography] available online at http://www.cedmagic.com/mem/whos-who/ross-daniel.html, accessed 18 Jun. 2010.

technical expertise and Goldmacher and Ross' improved materials. As before, the experiment revolved around a dye, in this case Ross' Azo-Dye #17, dissolved in a liquid crystal and secured between two transparent electrodes.[130] In place of PAA, whose yellowish tint thwarted earlier observations, Heilmeier substituted trans-p-methoxycinnamic acid (MOCA), a colorless liquid crystal, which existed in a mesomorphic state between 172° and 187°C.[131] Using the resulting pinkish-red mixture, "[a] cell was fabricated in the usual manner," and placed on a heated microscope stage with a polarizer positioned between the light source and the sample.[132] The general procedure was reminiscent of Williams' earlier experiments, but the results differed significantly. As Heilmeier recorded in his notebook, when fifty volts were applied to the sample, "the region in the field became almost colorless and returned to red when the field was removed."[133] When the dye concentration was increased until the MOCA appeared deep red, "a red to orange dichroism characteristic of dye #17 was observed."[134]

With this experiment, Heilmeier and his colleagues confirmed that it was possible to alter the absorption spectrum of "guest" dyes dissolved in a liquid crystal "host." They

[130] Heilmeier, *Notebook 25463*, 60.

[131] Heilmeier, *Notebook 25463*, 57. Heilmeier does not specify the source of the MOCA used here. According to Joseph Castellano, Goldmacher "prepared the first materials that Heilmeier and Zanoni used in their experiments," but Goldmacher's notebook from the period does not mention the compound. (Castellano, 24). In his 1 Jul. and 21 Aug. 2009 interviews with the author, Zanoni does not recall the specific origins of the liquid crystals used in these early experiments, attributing them to either Goldmacher or future collaborator Lucian Barton. The latter option appears unlikely given that Barton seems to have only learned about Heilmeier's liquid crystal work in December 1964 (Lucian Barton, *Notebook 24188*, DSL, 84). Heilmeier acknowledged Goldmacher and Ross "for materials assistance" in the first article on this new color-changing effect, but it is also possible that he learned about MOCA from the published record (e.g. Williams' 1963 *Journal of Chemical Physics* article) and obtained it in some other fashion. See: G.H. Heilmeier and L.A. Zanoni, "Guest-Host Interactions in Nematic Liquid Crystals. A New Electro Optic Effect." *Applied Physics Letters* 13, no. 3 (1 Aug. 1968): 92.

[132] Heilmeier, *Notebook 25463*, 60.

[133] Heilmeier, *Notebook 25463*, 60.

[134] Heilmeier, *Notebook 25463*, 60. If a pleochroic compound has only two distinct absorption states associated with its orientation to polarized light, it is referred to as dichroic. See: Castellano, 19.

also recognized the potential commercial significance of electronic color switching and Heilmeier promptly filed a patent disclosure form describing their experimental setup and brainstorming practical uses for the new effect.[135] Some of these, like an "electronically controlled light shutter for photographic applications or laser Q switching" or a device to control the wavelength, intensity, and polarization of fluorescent radiation, could be traced to his interest in electro-optic modulators.[136] Others, such as a spectrophotometer to analyze pleochroic dyes, had limited relevance outside of an industrial laboratory. But for Heilmeier, the highest priority applications of this new discovery, ranking first on his list of possible products, were display panels. "Since large area flat panels can be fabricated & driven by low voltages," he wrote, "this device should find application in displays where such properties are desirable."[137] Unlike Williams, who chose to confine discussion of display devices to his 1962 patent, Heilmeier expounded in his notebook upon the possibility of liquid crystal displays with full color capability. "With suitable dyes," he wrote, "one could cover the visible portion of the spectrum by passing light through a series of such panels."[138]

Moving Away From MOCA: Stabilizing the Guest-Host Effect

Despite his enthusiasm, Heilmeier recognized that electronic color switching would require additional refinement before it could be incorporated into a functional flat-panel display. In the short term, it was essential to find a replacement for MOCA, which, though

[135] Heilmeier, *Notebook 25463*, 61. The current status of this disclosure form (RCA Docket No. 55417) is unknown. Fortunately, Heilmeier summarized the pertinent details in his laboratory notebook.
[136] Heilmeier, *Notebook 25463*, 62.
[137] Heilmeier, *Notebook 25463*, 61.
[138] Heilmeier, *Notebook 25463*, 61.

vital to the initial demonstration of the new electro-optic effect, decomposed after an hour's exposure to the temperatures required to maintain a liquid crystal state.[139] Heilmeier and Zanoni continued to work with both pure MOCA and MOCA-dye solutions for a month in hopes of developing a theoretical explanation for their electro-optic behavior, but a means of inhibiting the chemical's breakdown remained elusive.[140] "It is felt that the high temperatures used with this material facilitate its decomposition in the presence of the conducting SnO [Tic] film on the pyrex," Heilmeier wrote on November 17th. "Such decomposition might result in the formation of a styrene+CO_2 (followed by polymerization) and possible [sic] some oxygen from the reduced SnO."[141]

Gas bubbles had complicated some of Heilmeier's earliest PAA investigations, and this thermal instability, accelerated via reactions with the transparent conductive coating used in his liquid crystal cells, rendered MOCA unfit for inclusion in future experiments.[142] His notebooks do not indicate whether he consulted with Goldmacher or Ross while considering substitutes, but Heilmeier ultimately selected p-n butoxy benzoic acid (BBA) as his new solvent of choice for studying guest-host interactions.[143] While sharing MOCA's transparency and capacity to form domains, BBA was a more stable compound

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[139] Heilmeier, *Notebook 25463*, 60. A month later, Heilmeier reduced the estimated life-span of MOCA to "half an hour or so."

[140] Heilmeier, *Notebook 25463*, 63-67, 70-75. These studies resulted in the first color photographs of electronic color switching, comparisons of response times in PAA and MOCA, and the realization that pure MOCA solutions could be electronically tuned to generate different colors. The last of these phenomena will be described in greater detail below.

[141] Heilmeier, *Notebook 25463*, 76.

[142] Heilmeier, *Notebook 25463*, 44.

[143] BBA is cited as an ideal solvent for demonstrating guest-host color switching in the first published article on the subject (Heilmeier & Zanoni, "Guest-Host Interactions in Nematic Liquid Crystals"). It is also one of two liquid crystals mentioned in Heilmeier's patent, filed in 1965, outlining possible applications of the effect. See: George H. Heilmeier, "Control of Optical Properties of Materials With Liquid Crystals," US Patent 3,551,026, filed 26 Apr. 1965 and issued 29 Dec. 1970.

that exhibited mesomorphic behavior at lower temperatures.[144] In addition, tests confirmed that "[i]n the benzoic acid, dye #17 behaved like it did in most of the MOCA samples," with the mixture's color shifting from orange-red to "almost white" when the field was applied.[145]

Possession of a stable, transparent solvent permitted Heilmeier to move away from the observation and characterization of field-induced color shifts and toward an explanation of their underlying mechanism. As previously discussed, Heilmeier had outlined two possible explanations for his predicted optical effect before beginning his liquid crystal research. In the first case, the application of an electric field triggered the formation of domains, with the liquid crystal's molecules aligning in a uniform direction.[146] The dissolved dye molecules, surrounded by a swarm of well-ordered solvent molecules would be subjected to intense, localized electric fields, thereby altering their absorption spectra. Alternatively, the liquid crystal host served not as a means of applying a field to the dissolved dye, but rather to change the spatial orientation of the pleochroic molecules with respect to polarized light, triggering a color change.

At the outset, Heilmeier abstained from expressing a preference for either of these theories in his notebooks. Even though the notion of localized electric fields altering the

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[144] Heilmeier, *Notebook 25463*, 76.

[145] Heilmeier, *Notebook 25463*, 76.

[146] Initially, it was assumed that the molecules of BBA would align parallel to the applied field, but in fact, the electric dipole moment of this substance was perpendicular to its molecular axis (i.e. It exhibited negative dielectric anisotropy), leading the molecules themselves to align perpendicular to the direction of the applied field. Later on, Goldmacher synthesized substances such as p-ethoxybenzilidene aminobenzonitrile (PEBAB) and butyl anisylidene amino cinnamate whose dipole moment was parallel to its molecular axis (i.e. positive dielectric anisotropy) and consequently aligned parallel to the applied field. For further information, see: Castellano, 53-54; Joel Goldmacher, *Notebook 25011*, 57-58, 91, 99; Heilmeier, *Notebook 25463*, 96; George Heilmeier, *Notebook 26848*, DSL, 38-39; Heilmeier, "Control of Optical Properties...," 2-3.

optical properties of a solution had prompted his decision to explore liquid crystals in the first place, he was open to the physical realignment option and selected Azo-Dye #17 for his MOCA experiments on the basis of its pleochroic properties. After switching to BBA, he started to shed this ambiguity and embrace the latter option. "I feel the field 'on' configuration probably orients the dye molecules so that their plane is parallel to the direction of [polarized light] propagation," he wrote, indicating that this corresponded to Dye #17's observed transition from red to white.[147]

Attributing field-induced color changes to the reorientation of dye molecules, however, was not the same as obtaining experimental confirmation. As Heilmeier wrote in December 1964, "[t]he mechanism by which guest dye molecules are oriented by a field acting on a liquid crystal host is still in question. It could be either steric or electric."[148] In order to settle the matter, Heilmeier and Zanoni replaced the dye in one of their liquid crystal cells with micron-sized aluminum flakes, confirming that solute particles physically rearranged themselves in response to an electrically aligned solvent but not whether this behavior was the result of domain formation or localized electric fields.[149] Spectrographic analysis of a typical BBA-Azo-Dye #17 sample proved similarly vague. "The observation of a shift in the absorption in an applied field still does not answer the question of whether the orientation is primarily steric or electrostatic," Heilmeier warned in the year's final

[147] Heilmeier, *Notebook 25463*, 77.
[148] Heilmeier, *Notebook 25463*, 88.
[149] Heilmeier, *Notebook 25463*, 88. This test resembles experiments conducted by Heilmeier's colleague (and frequent notebook witness), Philip Heyman, who explored the possibility of a reflective display using aluminum flakes suspended in oil during the final quarter of 1963. (See Philip Heyman, *Notebook 23006*, DSL, 1-56) Zanoni's involvement is based partly on Heilmeier's use of the first person plural in describing the experiment (i.e. "We have obtained...") and partly from their joint authorship of a patent disclosure form based upon this work. See: George Heilmeier and Louis Zanoni, "Nematic Liquid Crystal Reflective Display Panel," RCA Docket No. 55,869, 4 Jan. 1965, ZPA.

notebook entry, "or both."[150] After all, "even if the molecules were sterically ordered by the cooperative effect of the liquid crystal in an applied field the local field would be different giving rise to a modified dye spectrum."[151]

By January 1965, Heilmeier concluded that the resolution and performance of the equipment used in his previous analysis were insufficient to disaggregate the spectral shifts caused by the physical rotation of dye molecules from those generated by localized electric fields.[152] He therefore repeated his observations of the BBA-Azo-Dye #17 solution with a new spectrophotometer and performed a series of calculations based on the changing widths of the sample's absorption peaks as he increased the voltage across the cell.[153] The resulting data revealed some variation in wavelength due to localized electric fields, but this effect was relatively small and, as Heilmeier wrote later, "masked by the orientation of the 'guest dye' molecule along with the nematic liquid crystal host."[154] He also observed a similar combination of electrostatic and steric effects, with the latter predominating, when he replaced Azo-Dye #17 with methyl red.[155] The observation of electronic color switching in another pleochroic dye was not surprising, but in contrast to Ross' specially

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[150] Heilmeier, *Notebook 25463*, 97. The spectral curves associated with this analysis were included on the following two pages.

[151] Heilmeier, *Notebook 25463*, 97.

[152] Heilmeier, *Notebook 26848*, 2.

[153] Heilmeier, *Notebook 26848*, 2-6.

[154] Heilmeier (1976), 781-782. Heilmeier provided a less straightforward explanation in his notebook, labeling one term in a mathematical description of the observed spectral shift as confirming "a mixing of the solvent & external field perturbations." In contrast, Warren Moles, recorded on 12 Jan. 1965 that Heilmeier believed that "[t]he liquid crystal may possess a dipole moment which allows it to be rotated by the applied field. This in turn carries the dye along also. This is the theory proposed by Heilmeier." (Heilmeier, *Notebook 26848*, 6; Warren Moles, *Notebook 26535*, 10) Heilmeier is more specific about the effect of an electric field on pleochroic dye spectra in his 1970 patent. (Heilmeier, "Control of Optical Properties...," 3) For an explanation of the term "nematic," see n. 89.

[155] Heilmeier, *Notebook 26848*, 15-16. Recall that Heilmeier and Zanoni had examined methyl red in their early PAA experiments, but set it aside following the success of the MOCA-Azo-Dye experiments. See n. 122 for further details.

synthesized compounds, methyl red was widely known and commercially available, which perhaps explained why the orange-yellow color shift observed in the BBA-methyl red solution appeared in the first article and patent describing what became known as "the guest-host effect."[156]

Dueling Discovery Narratives: Constructing Histories of Corporate Science

Heilmeier's success convincing RCA of electronic color switching's commercial potential and the secrecy associated with his newly organized LCD project delayed the publication of his results until 1968.[157] Such restrictions, intended to guarantee the corporation's intellectual property claims over any future liquid crystal products, did not extend to patents. Consequently, in April 1965, Heilmeier filed a patent application describing an array of devices, including light modulators and flat-panel displays, based upon "controlling the properties of materials mixed with liquid crystals."[158] These two documents, along with Heilmeier's subsequent historical reminiscences, served a common rhetorical function, securing credit for a discovery or invention. As with Williams' patent, article, and research notebooks, however, the varying norms and expectations associated with each genre of scientific communication resulted in two divergent accounts of the process through which Heilmeier "stabilized" the guest-host effect.[159]

[156] Heilmeier, *Notebook 26848*, 16.

[157] Heilmeier and Zanoni, "Guest-Host Interactions..." The secrecy of the project is confirmed in oral history interviews with Bernard Lechner, John van Raalte, and Wolfgang Helfrich, and will be discussed in Ch. 5.

[158] George H. Heilmeier, "Control of Optical Properties of Materials With Liquid Crystals," US Patent 3,551,026, filed 26 Apr. 1965 and issued 29 Dec. 1970, 1.

[159] For more on the distinctions between patents and journal articles as genres of scientific writing, see: Peter Galison, *Einstein's Clocks and Poincaré's Maps: Empires of Time* (New York: W.W. Norton, 2003), 291-292; Greg Myers, "From Discovery to Invention: The Writing and Rewriting of Two Patents," *Social Studies of Science* 25, No. 1 (Feb. 1995): 57-105.

In his article, for example, Heilmeier omitted all evidence of his original rationale for working with liquid crystals: his belief that the local electric fields generated by their realignment could trigger a shift in a dissolved dye's absorption spectrum. Instead, he presented the rotation of the dichroic dye molecules as the logical consequence of previous observations of mesomorphic substances under applied fields, including Williams' domain experiments.[160] On the whole, the article took pains to emphasize the collaborative aspects of discovery, not just by gesturing toward a broader research pedigree, but by listing Zanoni as a co-author and explicitly thanking "Drs. J. Goldmacher and D. Ross for materials assistance."[161] Heilmeier left the nature of that assistance unclear, since the article described only one experiment, using a BBA-methyl red solution, and ignored any trials using other dyes or crystals. Heilmeier and Zanoni were only slightly less circumspect with regard to possible technological applications, noting that the guest-host effect "may be a useful tool for the spectroscopist" and might "find application as a light valve."[162]

One may partially attribute Heilmeier's reticence regarding electronic color switching's practical utility to the fact that he had not received a patent based on his 1965 disclosure.[163] That document presented a parallel, yet complementary, portrait of the guest-host effect's origins. Unlike an article, whose claims are strengthened based on ties to the scientific community, a well-written patent avoids drawing similarities with work

[160] Heilmeier and Zanoni, "Guest-Host Interactions...," 91. The citation in question refers to Williams' 1963 *Journal of Chemical Physics* article, although it is incorrectly listed as being published in 1965. (The journal volume and page numbers, however, confirm that this, in fact, from 1963.) This article also lists Heilmeier and Williams' previous work on the ferroelectric properties of liquid crystals.
[161] Heilmeier and Zanoni, "Guest-Host Interactions...," 92.
[162] Heilmeier and Zanoni, "Guest-Host Interactions...," 92.
[163] Heilmeier's patent was issued on 29 Dec. 1970, more than five years after initial filing.

described in other publications so as not to compromise the inventor's claim to originality.[164] Heilmeier's was no exception to this rule, including references to other scientists only to distance the guest-host effect from their findings.[165] Though RCA permitted the submission of patents with multiple authors, DSRC personnel, including both direct contributors (e.g. Zanoni, Goldmacher, and Ross) and immediate precursors (e.g. Williams) were omitted.[166] But if the patent implied that the guest-host effect resulted from the work of just one person, it also provided a more detailed, albeit indirect, view of what those investigations entailed. Though the thermal instability of the MOCA-Azo-Dye #17 system precluded its inclusion in the patent's text, references to alternative liquid crystals (e.g. butyl anysilidene amino cinnamate) and dyes (e.g. indophenol blue) suggested that Heilmeier considered a broader range of materials than the final combination listed in his article.[167] Furthermore, the patent mentioned both proposed

[164] Myers, 84-91.

[165] Heilmeier, "Control of Optical Properties...," 9-10. The patent includes references to five U.S. patents describing various light controlling devices and techniques for manufacturing them, though only three (Dreyer, #2,400,877, Dreyer, #2,544,659, and Fergason, #3,114,836) actually involve the use of liquid crystals. There is also a reference to the 1936 British patent on a liquid crystal light valve. (See n. 106, above.) Gray's *Molecular Structure and the Properties of Liquid Crystals* and Brown, et al.'s "The Mesomorphic State" are listed in the main text of the patent, while the "Other References" section contains an article on the magnetic properties of liquid crystals [G. Föex, "Magnetic Properties of Mesomorphic Substances, Analogies with Ferromagnetics," *Transactions of the Faraday Society* 29, no. 9 (Sep. 1933): 958-967] and a June 1954 interim report on light transmission through liquid crystals written by Brown connection with Air Force project AF 33 (616)33 (Quarterly Report of the University of Cincinnati to U.S. Air Force under Contract No. AF 33(616)33, 1 Jun. 1954). The latter document, along with other interim reports associated with the project, is present in the Glenn Brown Papers (Accession 2001.70), KSU Special Collections, Box 11.

[166] RCA's subsequent liquid crystal patents provide numerous examples of dual-authored patents, including collaborations between members of the technical staff and technicians. See, for example: Joel E. Goldmacher and George H. Heilmeier, "Nematic Liquid Crystal Mixtures For Use in a Light Valve," US Patent 3,499,702, filed 5 Dec. 1967 and issued 10 Mar. 1970; George H. Heilmeier and Louis A. Zanoni, "Electro-Optical Device," US Patent 3,499,112, filed 31 Mar. 1967 and issued 3 Mar. 1970.

[167] Heilmeier, "Control of Optical Properties...," 2-3. While Heilmeier and his colleagues only began to consider the use of anisylidene butyl cinnamate (ABC) in December 1964, by that point he had dissolved indophenol blue in both PAA (prior to the MOCA experiments) and BBA, confirming color switching in the latter case. Full details can be found in Heilmeier, *Notebook 25463*, 96. and Heilmeier, Notebook *26848*, 13-14, 43, 84, 96. Heilmeier, Zanoni, and Goldmacher's notebooks from Jan.-Apr. 1965

mechanisms of the guest-host effect, noting that the absorption spectra of pleochroic dyes could also vary as a function of local electric fields.[168]

Additional evidence dispelling the illusion of a single "Eureka" moment underlying the guest-host effect could be found in the patent's presentation of three specific embodiments of Heilmeier's invention. The first of these, a light valve consisting of the familiar BBA-methyl red sandwich cell, is described in the journal article, but the other two reveal aspects of the investigative process otherwise rendered invisible in the public record. Considered alongside his laboratory notebooks, they confirm how closely Heilmeier's theoretical investigations of guest-host interactions intertwined with efforts to incorporate the effect into practical devices. His experiments on aluminum flakes in BBA, for example, were reconfigured from their original purpose—ascertaining the cause of guest dye orientation in a liquid crystal solvent—into an optical modulator that reflected more or less light in response to an applied field.[169] Similarly, Heilmeier's attempts to confirm that the mechanism behind electronic color switching led him to propose a display consisting of a liquid crystal cell scanned by light whose polarization was synchronized with a video signal.[170] While each dye generated only a limited range of colors, Heilmeier commented, as he had during the MOCA experiments, that several panels could be

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disclosure confirm further research on other materials not mentioned in the patent. The most prominent of these were p-ethoxybenzylidene-4-aminobenzonitrile (PEBAB) and anisylidene p-amino phenyl acetate (APAPA), though the latter was first referenced on 26 Apr. 1965, the exact date that Heilmeier filed his patent for guest-host color switching.

[168] Heilmeier, "Control of Optical Properties...," 3.

[169] Heilmeier, "Control of Optical Properties...," 5-6. Heilmeier and Zanoni filed a joint disclosure form for a "Nematic Liquid Crystal Reflective Panel," which appears to have been assimilated into Heilmeier's broader 1965 patent. The latter document covered devices utilizing both dyes and flakes in a mesomorphic solvent. See: George Heilmeier and Louis Zanoni, "Nematic Liquid Crystal Reflective Display Panel," RCA Docket No. 55,869.

[170] Heilmeier, "Control of Optical Properties...," 6-7.

"stacked so the light beam passes through each plate. A suitable choice of dyes will result in the desired range of color variation."[171]

Heilmeier may have been reflecting upon the ambitiousness of his patent's claims when he wrote in 1976 that following the discovery of the guest-host effect it seemed "[t]he wall-sized flat panel color TV was just around the corner—all that you had to do was ask!"[172] His decision to distance himself from that comment in 2005, noting that "excitement can certainly cloud one's objectivity" serves as a reminder of the danger of treating any one account of corporate innovation as truly comprehensive.[173] Personal reflections, whether written or oral, showcase the limitations of memory and the all too human tendency to condense extended periods of time into narratives emphasizing moments assigned significance in retrospect.[174] As seen in the preceding discussion, the different tactics utilized in patents and articles to advance an individual's claim to originality can likewise affect representations of the people and procedures involved in the generation of scientific results. Even laboratory notebooks, arguably the most thorough contemporary record of researchers' daily practice, preserve details their authors saw as relevant to either their professional interests or their employers' commercial ones.

The differences between these narratives do not automatically invalidate their utility to scholars seeking to reconstruct the origins of the LCD or, more broadly, the evolution of Cold War electronics. To the contrary, such accounts demonstrate the degree of control corporate scientists exerted over the presentation of their research. In addition,

[171] Heilmeier, "Control of Optical Properties...," 7. For a more detailed technical explanation of this device, see the associated figure.
[172] Heilmeier (1976), 781.
[173] Heilmeier, "Liquid Crystal Displays: Reminiscence of the Early Days," 3.
[174] de Chadarevian, 56-59.

the complementary strengths and weaknesses of each literary genre permit a more thorough appreciation of the innovation process. The juxtaposition of laboratory notebooks, articles, patents, and retrospective discussions, for example, reveal how unpredictable outcomes can result from the logical procession along a given research pathway.[175] Heilmeier could not imagine upon arrival at RCA that his organic semiconductor investigations would give way to liquid crystals and, ultimately, the LCD. These documents permit us to treat this transition as the result of methodical decisions rather than random "stumbling," showing how the collaborative atmosphere of the DSRC and a personal fascination with electro-optic light modulation led him to consider liquid crystals a worthwhile topic of investigation, even after Williams had set them aside.

Indeed, at the start of 1965, Heilmeier was convinced that a similar dynamic would expedite the incorporation of liquid crystal mixtures into a full line of electronic display devices. This prediction proved correct, but only to a point, for although Heilmeier and Zanoni could already produce simple images, like RCA's "meatball" logo by etching patterns in their cells' conductive coatings,[176] neither anticipated the emergence of another electro-optic effect, referred to as "dynamic scattering," which would supplant electronic color switching as the basis of the first commercially available LCDs. Heilmeier's ability to adjust to unexpected circumstances had facilitated the successful demonstration of the guest-host effect, but would soon lead to its ultimate marginalization.

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[175] For more on the unpredictability of research pathways, see: Frederic L. Holmes, "Laboratory Notebooks and Investigative Pathways," in Holmes, et al., ed., 295-307.
[176] Louis Zanoni, *Notebook 16971*, DSL, 93.

CHAPTER FIVE
"We had to think of a sexy name.": Dynamic Scattering From Theory to Prototype, 1965-1968

When Joseph Castellano volunteered to attend the first international conference on liquid crystals in August 1965, he could not have anticipated spending an evening with several of his fellow scientists at a burlesque house in Cleveland. An organic chemist by training, Castellano had recently joined the liquid crystal research group at the Radio Corporation of America (RCA) and wished to learn more about the state of the field and perhaps preview an article draft with leading experts.[1] To that end, he traveled from RCA's main research laboratory in Princeton to the newly-established Liquid Crystal Institute at Kent State University, where the conference organizers had scheduled five days of technical sessions as well as assorted recreational activities.[2] Castellano's expedition to a vaudeville-style striptease was not an officially sanctioned conference event, but he and his associates deemed it worthwhile all the same. "The show was quite entertaining," he recalled, "and one of our European colleagues commented that this show was better than anything he had seen in Paris."[3]

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[1] Joseph Castellano, *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry* (Hackensack, NJ: World Scientific, 2005), 34. Castellano was particularly eager to meet George Gray, author of the first English-language textbook on liquid crystals. See: G.W. Gray, *Molecular Structure and the Properties of Liquid Crystals* (New York: Academic Press, 1962).

[2] Among the recreational opportunities listed in the program were handball, tennis, swimming, golf, a theatrical production, and two trips to watch the Cleveland Indians compete against Kansas City in evening baseball games. For further details, see: *International Liquid Crystal Conference* [Program] (Kent, OH: Kent State University, 1965) in Liquid Crystal Institute Records, 1965-1998, Kent State University Special Collections, Box 1, Folder 6, 5-6.

[3] Castellano, 38. Castellano neither indicates who made this comment nor provides a list of the people who went with him to Cleveland. He does note that on several occasions, he spent time with a group consisting of George Gray, Joel Goldmacher, George Heilmeier, Horst Sackmann, Wolfgang Elser, and Juergen Pohlmann, but there is no way to confirm who was present on the night in question.

On the one hand, Castellano's trip to Cleveland reflected the predominantly masculine character of Cold War physical science.[4] At the same time, it confirmed that the conference was fulfilling one of its intended functions, the cultivation of a stronger sense of community among researchers whose shared object of study, liquid crystals, belied a diversity of institutional and disciplinary backgrounds. Over one hundred scientists from half a dozen countries, representing universities, military research groups, and corporate laboratories, gathered in Kent that summer to listen to papers on everything from the synthesis of liquid crystals to their use as solvents for nuclear magnetic resonance.[5] Curiously, given the large number of industrial researchers in the audience, discussion of potential applications for these substances, which possessed the optical properties of a crystalline solid but could flow like a liquid, was almost nonexistent.[6] James Fergason, a researcher at Westinghouse, described the development of liquid crystal temperature sensors that changed color when exposed to heat, and a Buffalo-based research team

[4] The community of liquid crystal scientists was not exclusively male; indeed, a female chemist (Jean Kane) was among the first recruited to RCA's research group and at least one woman (Helena Selawry) presented a paper at the Kent State conference. Nevertheless, it is telling that the event's organizers felt the need to arrange for a separate "ladies program" for the wives of registrants, "including teas and visits to local points of interest." (*International Liquid Crystal Conference* [Program], 6) The literature on gender and science during the Cold War is quite extensive, but for material specifically related to the physical sciences, see: Chemical Heritage Foundation, "Women in Science" [Oral History Project], available online at http://www.chemheritage.org/research/policy-center/oral-history-program/projects/women-in-science.aspx, accessed 20 Aug. 2011; Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (Cambridge, MA: Harvard Univ. Press, 1971 [1995]); Margaret Rossiter, *Women Scientists in America: Before Affirmative Action, 1940-1972* (Baltimore: Johns Hopkins Univ. Press, 1995).

[5] *International Liquid Crystal Conference* [program]. The full program is also reprinted in Castellano, 271-273. Several of the papers presented at this conference were gathered in Glenn H. Brown, et al., ed., *Liquid Crystals: Proceedings of the International Conference on Liquid Crystals held at Kent State University, August 16-20, 1965* (New York: Gordon and Breach, 1967).

[6] *International Liquid Crystal Conference* [program]. The conference's emphasis upon basic research is explicitly referenced in a press release issued prior to the event: "Kent State University Information Service," [Press Release dated 10 Aug. 1965] (Kent, OH: Kent State University, 1965) in Liquid Crystal Institute Records, 1965-1998, Kent State University Special Collections, Box 1, Folder 34.

demonstrated how one could measure the size of tumors using similar materials, but otherwise the talks tended toward the theoretical.[7]

Even the contingent from RCA's David Sarnoff Research Center (DSRC), one of the nation's leading consumer electronics labs, avoided speculation regarding the practical value of their liquid crystal investigations. The head of the DSRC's research group, George Heilmeier, presented the results of studies into the formation and decay of domains, the series of long, parallel stripes that formed in certain types of liquid crystals when subjected to an electric field.[8] Later, he joined with the discoverer and future namesake of these domains, Richard Williams, to discuss possible mechanisms for their behavior.[9] Joel Goldmacher, the organic chemist who had provided Heilmeier with his earliest liquid crystal samples, did not present a paper himself, but acted as a session chair.[10] Nothing in their contributions to the Kent State conference would lead anyone to

[7] Castellano, 35-37. Both of these applications utilized cholesteric liquid crystals, one of the three main categories of liquid crystal (along with nematic and smectic) defined by Georges Friedel in 1922. Named for the cholesterol esters in which they were first observed, these materials possess a helical molecular organization which exhibits unique optical properties, most notably a temperature dependence in the wavelength of light scattered off their surfaces. For more on Fergason's research see: James L. Fergason, "Liquid Crystals," *Scientific American* 211, no. 2 (Aug. 1964): 77-85; James L. Fergason, "Cholesteric Structure–I, Optical Properties," in Brown, et al., ed., 89-103; J.L. Fergason, et al., "Cholesteric Structure–II, Chemical Significance," in Brown, et al., ed., 105-119. For more on the use of cholesteric materials in cancer diagnosis, see: O.S. Selawry, et al., "The Use of Liquid Cholesteric Crystals for Thermographic Measurement of Skin Temperature in Man," in Brown, et al., ed., 175-181.

[8] Castellano, 272. See also: George H. Heilmeier, "Transient Behavior of Domains in Liquid Crystals," *Journal of Chemical Physics* 44, no. 2 (15 Jan. 1966): 644-647. Heilmeier specifically focused his discussion on nematic liquid crystals, which possess rod-like molecules whose long axes are parallel to one another. The molecules in a nematic substance can slide past one another like matches shifting inside a box. The term "nematic" derives from the Greek word "nematos," meaning thread, due to the unique texture crystals of this type exhibit when viewed between crossed polarizers.

[9] Castellano, 272. See also: Richard Williams and George Heilmeier, "Possible Ferroelectric Effects in Liquid Crystals and Related Liquids," *Journal of Chemical Physics* 44, no. 2 (15 Jan. 1966): 638-643. For further details on Williams' observations of domains and Heilmeier's interest in the subject, see Ch. 4.

[10] Castellano, 272.

suspect that RCA's research staff considered liquid crystals as anything more than a scientific novelty.

Yet the truth was that RCA staff members were engaged in a burlesque act of their own, certainly less risqué than what Castellano had witnessed in Cleveland, but no less real. For all the openness and sociability they demonstrated at Kent State concealed a rather significant secret. At the end of 1964, Heilmeier's demonstration that a "guest" dye dissolved in a transparent liquid crystal "host" could change colors under an electric field persuaded the DSRC's management to expand efforts to utilize these materials in display devices.[11] By the summer of 1965, a formal project was underway, concentrating on another electro-optic effect which appeared more promising than guest-host color switching. Internal reports referred to it as the "reflective mode," but by the time RCA engineers incorporated it into the first liquid crystal display (LCD) prototypes, it had received a new name: "dynamic scattering."[12]

This chapter describes the transformation of dynamic scattering from a laboratory phenomenon known only to a handful of DSRC scientists into the basis of the "revolutionary new type of display" that RCA unveiled to the public in 1968.[13] Beginning with the initial observation of the effect in the spring of 1965, it traces how members of the company's technical staff disclosed their findings to research managers and the degree to which their accounts affected the timing and content of the corporation's

[11] For further information on the guest-host effect, see Ch. 4.
[12] See, for example, RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, David Sarnoff Library (DSL), 5.
[13] RCA News, "RCA ANNOUNCES BREAKTHROUGH IN LIQUID CRYSTAL FIELD; DEMONSTRATES THIN-SCREEN DISPLAYS OF PRINT, PICTURES, MOVING IMAGES," Press Release (28 May 1968), DSL, 1-2.

announcement. As the liquid crystal project grew to encompass dozens of researchers, managers relied upon internal progress reports to track advances in materials synthesis, theoretical models for electro-optic behavior, and device fabrication. The version of events preserved in these documents, with chemists, physicists, and engineers pursuing their respective objectives at different paces, diverges from public descriptions of a unified interdisciplinary team. Where the previous chapter attributed variations between accounts of technological innovation to corporate researchers' adherence to the literary conventions associated with different types of scientific publications, here I claim that officially sanctioned depictions of the LCD project emerged from extended interactions between DSRC personnel eager to publicize their accomplishments and managers wishing to reaffirm the value of a central research laboratory to a corporation in transition.

Scattered Origins: From the Guest-Host Effect to the Reflective Mode

George Heilmeier was not the first person in the world, or even at RCA, to investigate the effects of electric fields upon the optical properties of liquid crystals.[14] But unlike Richard Williams, who abandoned such work shortly after witnessing the formation of domains, he remained fixated on harnessing such substances to create large flat-panel displays. Initially, Heilmeier expected such devices would be based upon guest-host color switching, but he later admitted that this objective may have been overly ambitious:

[14] For examples of research conducted outside RCA into the behavior of liquid crystals under electric fields, see the list of citations from Richard Williams, "Liquid Crystals in an Electric Field," *Nature* 199 (20 Jul. 1963): 274 and Richard Williams, "Interfaces in Nematic Liquids," in *Ordered Fluids and Liquid Crystals*, ed. Roger S. Porter and Julian F. Johnson (Washington, D.C.: American Chemical Society, 1967), 61-67. Among the scientists referenced are German physicist W. Kast, and Russians Vsevolod Freedericksz and A.P. Kapustin, the latter of whom is sometimes credited with observing the existence of liquid crystal domains before Williams. See, for example, David Dunmur & Tim Sluckin, *Soap, Science and Flat-Screen TVs: A History of Liquid Crystals* (New York: Oxford Univ. Press, 2011), 204.

> The dyes and their liquid crystal hosts were not stable over long periods of time in applied fields, the effect was sensitive to surface orientation effects, it required polarized light, it was viewed in transmission, it required heating to maintain the host in its nematic phase, uniformity was a problem, and so on.[15]

Nonetheless, during the final months of 1964, he remained confident that improved materials and savvy engineering could overcome these obstacles. As he had throughout his earlier investigations, he turned to Joel Goldmacher for the former and technician Louis Zanoni for the latter.[16] In the first quarter of 1965, Goldmacher synthesized more than half a dozen new liquid crystals for Heilmeier and Zanoni to test.[17] They soon found that compounds exhibiting the guest-host effect could be roughly classified into two groups depending upon their domain structures. The materials in which Heilmeier had previously observed electronic color switching, such as butoxy benzoic acid (BBA), produced elongated rectangular patterns when exposed to an electric field, while newer compounds like anisylidene butyl cinnamate (ABC) appeared not to generate domains at all.[18]

To explain this difference, in mid-January 1965, Heilmeier conducted what he called "a very revealling [sic] experiment" on ABC, exposing the compound to low frequency AC voltage and observing its behavior over time.[19] By gradually changing the

[15] George H. Heilmeier, "Liquid Crystal Displays: An Experiment in Interdisciplinary Research that Worked," *IEEE Trans. on Electron Devices* ED-23, no. 7 (Jul. 1976): 781.

[16] As the next section will discuss, there were, in fact, other RCA staff members studying liquid crystals during this period, but their research was peripheral to the transition from the guest-host effect to dynamic scattering.

[17] Heilmeier's laboratory notebook (26848) describes experiments on the following compounds between January and March 1965 (p. 1-60): 1.) butoxy benzoic acid (BBA); 2.) anisylidene butyl cinnamate (ABC); 3.) p-n heptyroxybenzylidene-4-amino-2-bromobiphenyl; 4.) p-ethoxybenzylidene-4-aminobenzonitrile (PEBAB); 5.) p-n-nonyloxybenzylidene-amino-3-bromobiphenyl (NOBABB); 6.) 3-3'-dichloro-4,4'-di (p-n-heptyloxybenzylidene-amino) biphenyl (DHOBABB); 7.) p-n-heptyloxybenzylidene-1-amino-4-phenylazonapthalene; 8.) ethylanisylidene amino cinnamate. In addition, Zanoni's notebook from this period (*16971*, p. 87) references receiving a compound known as HBAC from Goldmacher, but no definitive expansion of this abbreviation is provided in either his, Heilmeier's, or Goldmacher's notes.

[18] Heilmeier, *Notebook 25463*, 96.

[19] George Heilmeier, *Notebook 26848*, DSL, 13.

field applied to the sample, Heilmeier showed that domains were actually forming and that their apparent absence could be attributed to differences in the distribution of electric charge within ABC and BBA molecules. Both were nematic compounds, consisting of long, cigar-shaped molecules whose orientation changed when subjected to an electric field. ABC molecules tended to reorient themselves with their long axes parallel to the field, while BBA molecules rotated until their long axes were perpendicular.[20] Since Heilmeier and Zanoni were viewing their samples in the direction of the field (i.e. perpendicular to the slides), the molecular ordering found in ABC-type compounds was rendered invisible.[21]

As was his custom, Heilmeier considered the implications of these findings upon the development of display applications. In late February, he noted that beyond its inclusion in a guest-host device, triggering the alignment of a dye-free ABC sample held between crossed polarizers rendered the crystal completely opaque.[22] Conceivably, such a setup could permit the construction of a black-and-white transmissive display, which would regulate the passage of light projected from behind. Another ABC-type compound, abbreviated PEBAB, offered similar performance with lower viscosity and higher switching speeds.[23] Yet Heilmeier was reluctant to commit to this approach due to its

[20] In the more formal parlance of physical chemistry, ABC exhibited positive dielectric anisotropy and BBA possessed negative dielectric anisotropy. For further information, see: Castellano, 52-54; Hirohisa Kawamoto, "The History of Liquid-Crystal Displays," *Proc. IEEE* 90, no. 4 (4 Apr. 2002): 463-464.
[21] Heilmeier, *Notebook 26848*, 13.
[22] Heilmeier, *Notebook 26848*, 38.
[23] Heilmeier, *Notebook 26848*, 39. PEBAB stood for p-ethoxybenzylidene-4-aminobenzonitrile (See n. 17)

reliance on brightness-reducing polarizers.[24] In addition, he argued that a transmissive system "which goes from black to light gives a better contrast ratio than vice versa."[25]

The same week that Goldmacher delivered his first batch of PEBAB, he also provided Heilmeier with a second compound, referred to as DHOBABB, which would point towards a solution to these problems.[26] DHOBABB was a pale yellow BBA-type material which, when subjected to a strong electric field (2 x 10^4 V/cm) underwent what Heilmeier variously described as a "bubbling" or "stirring."[27] Such behavior was not unprecedented. Heilmeier had witnessed it in previous samples, and before that Williams described how a "gentle stirring" in his liquid crystal experiments evolved into a "vigorous agitation" once the applied field reached a given threshold value.[28] What captured Heilmeier's attention in this case was a noticeable increase in DHOBABB's contrast. "The contrast ratio for field on & off in reflected light (no polarizers) was 6.3:1," he wrote, indicating on the next page of his notebook that "a standard TV monitor in our TV studio yielded a contrast ratio which was only 4:1" when measured with the same instrument.[29]

A few days later, Heilmeier repeated the experiment with a slightly different setup. "Previously we had noted the high contrast ratio obtained in reflection for the DHOBABB

[24] Heilmeier, *Notebook 26848*, 53; Lucian Barton, *Notebook 26876*, DSL, 23; Warren Moles, *Notebook 26365*, DSL, 47. As Moles wrote concerning Heilmeier's work in April 1965: "Systems which require polarizers for the ambient light automatically reduce the ambient to only 30% of the initial value on one pass through the material. This makes such schemes relatively unattractive in terms of highlight brightness compared to the ambient. To date no one has thought of any way to improve this situation and this is the first reason that such a scheme is impractical."
[25] Heilmeier, *Notebook 26848*, 24.
[26] Heilmeier, *Notebook 26848*, 39, 44; As mentioned in n. 17, DHOBABB's full name was 3-3'-dichloro-4,4'-di (p-n-heptyloxybenzylidene-amino) biphenyl.
[27] Heilmeier, *Notebook 26848*, 44, 47.
[28] Heilmeier, *Notebook 25463*, 96; Heilmeier, *Notebook 26848*, 10-11, 18, 40; Williams, "Domains in Liquid Crystals," *The Journal of Chemical Physics* 39, no. 2 (15 Jul. 1963): 385.
[29] Heilmeier, *Notebook 26848*, 44-45.

system when fields high enough to cause stirring were used," he explained. "It was of interest to check what resolution could be obtained for such a system in view of the field induced cavitation."[30] To that end, he asked Zanoni to etch the transparent conductive coating on one piece of glass so that it formed RCA's "meatball" logo and activated the field.[31] The results were disappointing. "The pattern is barely visible," Heilmeier lamented before setting aside the notion of a display based on stirring in liquid crystals, seemingly for good.[32]

For the rest of March and most of April 1965, Heilmeier concentrated on developing a dye-free PEBAB light valve, despite concerns that a crossed polarizer scheme where the material became dark under an applied field was "undesireable [sic] from the display standpoint" due to its low contrast.[33] He was therefore particularly grateful when Goldmacher provided him with a promising new compound: anisylidene p-aminophenyl acetate (APAPA). APAPA, he hoped, could facilitate the development of an improved light valve since it "was dark between crossed polarizers & became light when field was applied."[34]

Heilmeier's research would likely have continued on this path had he and Zanoni not run into difficulties preparing their APAPA samples. "It has been noted that not all APAPA samples orient such that they are dark between crossed polarizers & light when

[30] Heilmeier, *Notebook 26848*, 47.
[31] Heilmeier, *Notebook 26848*, 47. Though Zanoni is not specifically referenced in this notebook entry and does not mention this experiment in his own notes from the period, in his 21 Aug. 2009 interview with the author, he explained that etching patterns on the glass used in liquid crystal experiments was typically his responsibility.
[32] Heilmeier, *Notebook 26848*, 47.
[33] Heilmeier, *Notebook 26848*, 63.
[34] Heilmeier, *Notebook 26848*, 85.

field is applied," he wrote in May 1965.[35] In some cases, the material was sticking to the glass slides' conductive coatings, preventing molecular realignment and proper switching. Initially, he thought a series of acid washes would resolve the problem, but when those proved ineffective, he decided to adapt the stirring effect observed in DHOBABB as a cleaning technique.[36] He doped his APAPA sample with a small amount of BBA and "subjected the sample to violent stirring (by field) to produce mixing."[37] Not only did the resulting mixture retain the desired alignment, but, as Heilmeier reported:

> Some time ago we noted the high reflectivity of the stirred state of some nematic systems relative to the quiescent state without field. At that time the observations were made on yellow materials which responded quite slowly. We have now reviewed this effect in APAPA + ½% BBA and found it to be quite striking.[38]

Immediately, Heilmeier abandoned PEBAB in favor of APAPA, which offered the possibility of a high contrast display free from either polarizers or backlighting. As he had with electronic color switching, he invited DSRC personnel to watch transparent APAPA samples turn milky-white thanks to what he termed "the reflective or scattering mode."[39] Some of these visitors, like Bernard Lechner, recalled this light scattering behavior from demonstrations based on Williams' work three years earlier.[40] To others, it was a breakthrough and the key to devising the long sought after replacement for the cathode ray tube (CRT). Among the latter group was a key ally, who helped ensure Heilmeier

[35] Heilmeier, *Notebook 26848,* 97.
[36] Heilmeier, *Notebook 26848,* 97; Zanoni, *Notebook 16971*, DSL, 97-100; Louis Zanoni, *Notebook 27707*, DSL, 1-3.
[37] Heilmeier, *Notebook 26848,* 97.
[38] Heilmeier, *Notebook 28088*, 3.
[39] Heilmeier, *Notebook 28088*, 12. Preliminary measurements yielded contrast ratios between 8 and 10:1 and high switching speeds amenable to a variety of addressing schemes
[40] Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009. See also: Bernard Lechner, "History Crystallized: A First-Person Account of the Development of Matrix-Addressed LCDs for television at RCA in the 1960s," *Information Display* (Jan. 2008): 26-27.

received the manpower and financial resources required to assemble the first LCD prototypes. His name was David Kleitman.

Between Red Covers: "Mad Man" Kleitman and the Origins of RCA's LCD Project

Since the early 1960s, Kleitman had been in charge of a group in RCA's Systems Research Laboratory (SRL) responsible for exploring potential successors to the color CRT.[41] Though his personal eccentricities, such as collecting old cars on his front lawn, led some at the DSRC to refer to him as "Mad Man" Kleitman, the researchers on his team, like electrical engineer John van Raalte, respected his management style.[42] "We didn't have a whole lot of philosophical discussions," Van Raalte remembered, "but he had a broad interest in technology, and I think at the time he was willing to let people, you know, search for themselves and, you know, pursue thoughts, ideas, [and] interesting avenues."[43]

It was perhaps this openness that prompted Heilmeier, a member of Henry Lewis' laser group in the Electronics Research Laboratory (ERL) to cross organizational lines and approach Kleitman following the 1964 demonstration of the guest-host effect. Kleitman responded by arranging for two staff members, chemist Lucian Barton and electrical engineer Warren Moles, to assist Heilmeier in his attempts to characterize the physical properties of liquid crystals.[44] Heilmeier asked Barton to evaluate different strategies for lowering his samples' operating temperatures and Moles to study their

[41] Kleitman's rise within the SRL and the origins of his research group are discussed in Ch. 3.
[42] Castellano, 42; Bernard Lechner, Interview with author, 17 Apr. 2009, Princeton, NJ.
[43] John van Raalte, Interview with author, 3 Jun. 2009, Princeton, NJ.
[44] Barton's account of joining the liquid crystal group is described in Ch. 4.

switching behavior.[45] Heilmeier consulted with both men while studying ABC and PEBAB, but formal coordination remained limited to occasional meetings in Kleitman's office.[46] At times, this lack of organization could be disheartening. "Needed at this time–discussion of various aspects of the problem," Warren Moles wrote in March 1965. "It may be that we should get together the various people concerned with the project and attempt to define more clearly what we are after and how we will get there."[47]

The move from a loose agglomeration of individual liquid crystal researchers to an officially sanctioned project with established strategic objectives coincided with Heilmeier's observation of the reflective mode in APAPA. As Van Raalte, who would join Moles to work on LCD addressing systems explained, "Kleitman was the one who, as I recall, recognized the importance of a cell going from clear to white or white to black and said, 'That's fantastic! We've got to start a secret project on this.'"[48] And indeed, by the end of May 1965, Kleitman had secured the necessary authority to initiate an internally funded SRL/ERL study of the electro-optic properties of liquid crystals for display applications.[49]

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[45] Lucian Barton, *Notebook 24188*, 84-100; Warren Moles, *Notebook 26365*, 7-64. On Heilmeier's recommendation, Barton considered two major approaches to decreasing the crystal-nematic transition temperature: doping liquid crystals with structurally similar molecules and examining "lyotropic" systems in which substances became nematic which mixed with the proper amount of solvent (in contrast with "thermotropic" substances whose phase transition is temperature dependent). Moles, meanwhile, measured the capacitance and switching speeds of BBA, ABC, and other materials at various AC voltages and frequencies.

[46] Heilmeier, *Notebook 26848*, 36, 58, 64, 78; Barton, *Notebook 26876*, 6, 23, 61; Lucian Barton, *Notebook 24188*, DSL, 84-85. The staff directory from 1965 confirms that Kleitman's office was located next to Moles' and approximately equidistant from Heilmeier, Zanoni and Barton's laboratories, offering one possible reason for meetings to be held there. (RCA Laboratories, *Staff Directory-Jun. 1965*, DSL)

[47] Warren Moles, *Notebook 26365*, 41.

[48] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.

[49] RCA Laboratories, *Progress Report: Liquid Crystals, Mar.-May 1965*, DSL.

At the outset, the liquid crystal team consisted of only seven people, as well as Kleitman, who served as project supervisor.[50] It is a testament to Kleitman's persuasive abilities that despite this small size, the DSRC's leadership declared its work "company private," a status guaranteeing management support that was granted to only a handful of projects seen to possess particularly strong commercial prospects.[51] In daily practice, this secrecy was largely nominal. Information flowed freely within the group and interested RCA personnel who were not affiliated with the project, such as Williams, could visit the labs of group members.[52] The major consequence of receiving "company private" status was a blanket restriction against the publication of articles related to liquid crystal displays until the company secured its legal claim over any inventions the group might generate.[53]

This publication blackout explained the need for concealment when a portion of the group traveled to Kent in 1965. It also extended to the engineering memoranda and technical reports that RCA's technical staff were normally expected to submit to the DSRC's library.[54] Kleitman instead solicited research digests from his team members,

[50] RCA Laboratories, *Progress Report: Liquid Crystals, Mar.-May 1965*, 6.

[51] The term "Company Private" is derived from the LCD progress reports and elaborated upon in a letter from R.E. Quinn, a member of RCA's technical administration staff, dated 1 Jun. 1967 that accompanied RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, DSL. See: R.E. Quinn, "Interdepartmental Correspondence: LIQUID CRYSTAL DISPLAY REPORT-January-March 1967," DSL, 1. For confirmation of Quinn's position at the time of this letter, see: "Organization List, RCA Laboratories Division." 1 Apr. 1967, DSL, 10. For further discussion of other company private projects (e.g. Dalton Pritchard's penetration phosphor CRT, the line-screen beam index tube), see: Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009; John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.

[52] Frank Marlowe, Interview with author, Princeton, NJ, 24 Aug. 2009; John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009; Richard Williams, Interview with author, Princeton, NJ, 30 Apr. 2009.

[53] Castellano, 22; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009.

[54] Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009. RCA distinguished between a "technical report" and an "engineering memorandum." The former described the results of important engineering or research, and sometimes served as the basis for a future article. The latter recorded "results of engineering or research investigations limited in scope, but which may be of interest to other RCA units [i.e. divisions]." For further information on the composition and distribution of both types of technical

which he compiled and edited into confidential progress reports distinguished by their bright red covers.[55] Circulation of these documents was restricted to liquid crystal researchers and DSRC administrators, ranging from SRL director Allen Barco to James Hillier, RCA's vice-president of research and overall head of the DSRC.[56] Each copy was numbered and registered in the name of a specific recipient, who was expected to return it to the company's technical administration department after reading.[57]

Kleitman oversaw the compilation of these reports through June 1966. At that point he abdicated responsibility to Heilmeier, who, having already served as de facto group leader, now earned a formal promotion to that rank.[58] By the end of the following year, Kleitman's involvement in a DSRC push to develop a television-based facsimile system (known as Homefax), led to a clash with management and his permanent departure from Princeton.[59] While his scientific legacy at RCA was not especially remarkable, he left behind a more substantive institutional one by organizing the research team responsible for the creation of the first practical LCDs. Moreover, Kleitman established the basic format of the red-covered reports that provide an unbroken record of that group's activities prior to 1968. Their publication rate and number of subsections would vary, but the template Kleitman established in 1965–beginning each report with a materials update from the

documents, see: W.O. Hadlock, "Technical Reports and Engineering Memoranda: Questions and Answers," *RCA Engineer* 8, no. 6 (Apr.-May 1963): 2-5.

[55] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.

[56] Quinn, 1.

[57] Quinn, 1.

[58] For confirmation of Heilmeier's group leader status, see: "Organization List, RCA Laboratories Division." 1 Jul. 1966, DSL.

[59] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009. The date of Kleitman's departure is based on internal organizational charts as well, as his obituary: "Dr. David Kleitman," *San Francisco Chronicle*, 25 Feb. 2004, Z-99. More details concerning the Homefax project can be found in Margaret B.W. Graham, *The Business of Research: RCA and the VideoDisc* (New York: Cambridge Univ. Press, 1986 [1988]), 89-90 and in Ch. 6 of this dissertation.

chemists, moving on to theoretical analysis of the physical mechanisms underlying the reflective mode, and concluding with discussions of device fabrication and addressing–remained constant.

That structure also offers a ready-made framework to disaggregate the contributions of a roster of chemists, physicists, and engineers that more than doubled in size over the course of three years. In fact, due to gaps in the laboratory notebook record, these reports provide arguably the most effective means of approaching this task.[60] Still, as with other genres of scientific communication, the events they describe should not be embraced uncritically. The liquid crystal group's reports were, to borrow a term from Shapin, dual-purpose literary technologies, serving as research summaries for project participants and updates to DSRC managers concerned about the status of their investment in LCD technology.[61] Both of these objectives encouraged contributors to compress extended periods of research into a handful of sentences, and, as in a scientific paper, highlight experimental successes over the process through which they were achieved.[62] Where a journal article provides a single snapshot of a completed research project, however, these reports are analogous to a time lapse series of photographs,

[60] The absence of laboratory notebooks from RCA's technical archive can be attributed to a variety of causes. In some cases (e.g. Warren Moles) it is unclear whether personnel submitted all of their research materials or if those documents were simply lost in the intervening decades. A few staff members, like Wolfgang Helfrich, claimed in oral history interviews to have been unaware of the company's note taking policy while others, like Bernard Lechner, admit to ignoring it. Also, in at least one instance (Louis Zanoni), patent litigation led to the permanent confiscation of several laboratory notebooks.

[61] Steven Shapin, "Pump and Circumstance: Robert Boyle's Literary Technology," *Social Studies of Science* 14 (1984): 481-520.

[62] For more on the codification of the scientific paper as a literary genre, see: Peter Dear, ed. *The Literary Structure of Scientific Argument* (Philadelphia: Univ. of Pennsylvania Press, 1991); F.L. Holmes, "The Fine Structure of Scientific Creativity," *History of Science* 19, no. 1 (Mar. 1981): 60-70.

enabling one to trace changes in the group's research strategies and the areas they felt merited recognition in the years preceding the 1968 press conference.

The Search for an Ideal Mixture: Liquid Crystal Materials Research, 1965-1968

Throughout his guest-host and reflective mode experiments, Heilmeier had realized that the commercial viability of the LCD hinged upon his ability to procure improved materials.[63] Heating a television-sized panel to the 82-110°C required to maintain APAPA in a mesomorphic state (i.e. its "nematic range") was inefficient and unsafe for home use, and PEBAB and BBA required even higher temperatures.[64] If liquid crystal TVs were ever to become permanent fixtures in American living rooms, then low-temperature nematic compounds would have to be found. Heilmeier had broached the issue with Joel Goldmacher and Lucian Barton, but their preliminary efforts had proven ineffective.[65] With the establishment of a more organized research effort in late spring, they would gain new allies in their search.

The chemistry contingent of the liquid crystal research program was small, but embodied a broad range of professional experience. Goldmacher, the Brooklyn native hired as the DSRC's first organic chemist, worked with Lucian Barton, a veteran of the Polish and British armies who trained as a chemical engineer in Turin before emigrating to

[63] Heilmeier, *Notebook 25463* 76, 81; Heilmeier, *Notebook 26848*, 21, 30, 56-58, 64.
[64] RCA Laboratories, *Progress Report: Liquid Crystals, Mar.-May 1965*, 1. This report lists the nematic range of BBA as 147-161°C and the nematic range of PEBAB as 105-125°C.
[65] In addition to the approaches outlined in n. 45, Barton and Goldmacher also explored the mesomorphic behavior of fluorinated anils, i.e. compounds structurally similar to APAPA whose hydrogen atoms had been replaced with fluorine. Unfortunately, the resulting materials did not exhibit nematic behavior. For further information, see: RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, 1; Joel Goldmacher and Lucian Barton, "Liquid Crystals I. Fluorinated Anils," *Journal of Organic Chemistry* 32 (1967): 476-477.

the United States.[66] Joining them was Jean Kane, who took a position as a research chemist in David Kleitman's display group shortly after earning her master's degree from Mt. Holyoke College.[67] Kane assisted Goldmacher with the synthesis of new organic compounds until June 1965, when she withdrew on maternity leave.[68] Stepping in to take her place was Joseph Castellano, who had grown disillusioned with a job testing rocket propellants and contacted Goldmacher, a classmate from the City College of New York, to learn if there were any positions open at RCA. "As luck would have it, there was indeed an opening for an organic chemist in the newly emerging field of liquid crystals," Castellano wrote later, "I was certainly interested, but I still had no idea what liquid crystals were all about."[69]

Castellano was a quick study, and by the beginning of July, he, Barton, and Goldmacher had agreed upon a tripartite strategy to develop a room-temperature liquid crystal. "Encouraging results with APAPA" convinced all three to focus on compounds possessing a similar two-ring structure.[70] Goldmacher, who had the most experience synthesizing mesomorphic substances, would seek out new materials and purification

[66] Castellano (2005), 24-25. Barton arrived in the United States at the end of 1951. He worked for the Thiokol Chemical Corporation between 1952 and 1955, at which point he joined RCA. See also: "Lucian A. Barton," [RCA 1959 Company Biography] available online at http://www.cedmagic.commem/whos-who/barton-lucian.html, accessed 18 Jun. 2010.

[67] Jean Kane, e-mail message to author, 16 Jul. 2009. John van Raalte, who served as a witness for some of Kane's notebooks (e.g. Jean Kane, *Notebook 26883*, DSL; Jean Kane, *Notebook 31729*, DSL) suggested in his 3 Jun. 2009 interview with the author that Kleitman hired Kane due to an interest in cultivating a more diverse research team.

[68] RCA Laboratories, *Progress Report: Liquid Crystals, Mar.-May 1965*, 6; Jean Kane, e-mail message to author, 16 Jul. 2009. The timing of Kane's departure, two months before the Kent State liquid crystal conference, precluded her participation in that event.

[69] Castellano, 11. Coincidentally, Castellano had been working for the Reaction Motors Division of Thiokol Chemical Company, the same firm that Lucian Barton had left for RCA a decade earlier.

[70] RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, 1. Castellano clarifies that the compounds involved here were Schiff base derivatives referred to as either benzylidene anilines or "anils." They were prepared via the condensation of benzene ring-substituted aldehydes with similarly substituted amines. (p. 26)

techniques.[71] Barton and Castellano, meanwhile, would modify APAPA samples in two distinct ways. While Barton doped liquid crystals with small amounts of structurally similar non-mesomorphic compounds in order to extend their nematic range, Castellano would alter APAPA's molecular structure directly, substituting a variety of different end groups to weaken the prevailing intermolecular forces.[72]

Neither Barton nor Castellano's strategy was immediately successful. Barton's mixtures underwent the transition from solid to liquid crystal at a lower temperature, but the doping process also lowered the temperature at which the liquid crystal transformed into an isotropic fluid so that the nematic range was not extended.[73] For his part, by the end of August 1965, Castellano had tested seventeen different two-ring compounds and concluded that only those with APAPA's original alkoxy and acyloxy groups exhibited liquid crystalline behavior.[74] This finding, however, offered an obvious avenue for further research since both terminal groups could be expanded to include larger numbers of carbon atoms. He and Barton decided to collaborate in an investigation of the effect of such additions on the resulting compounds' mesomorphic properties.[75]

By March 1966, Castellano's strategy of terminal group modification had generated a compound, later referred to as APAPA-12, with a melting point of 50°C, "the lowest crystal-nematic point to date of any two ring system."[76] Though this was an

[71] Joel Goldmacher, *Notebook 27361*, DSL; RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1965*, DSL, 1.
[72] Castellano, 25; RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, 1-2.
[73] Castellano, 25; RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, 2.
[74] RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1965*, 2. For more on this research, see Joseph A. Castellano, et al., "Liquid Crystals. II. Effects of Terminal Group Substitution on the Mesomorphic Behavior of Some Benzylideneanilines," *Journal of Organic Chemistry* 33, no. 9 (Sep. 1968): 3501-3504.
[75] RCA Laboratories, *Progress Report: Liquid Crystals, Sep. 1965*, DSL, 1-3.
[76] RCA Laboratories, *Progress Report: Liquid Crystals, Mar. 1966*, DSL, 19. The nomenclature

improvement over unmodified APAPA, hope of obtaining a single compound capable of room-temperature operation seemed remote. Fortunately, in the intervening period, Castellano uncovered a somewhat counterintuitive physical property of his liquid crystal samples. In October 1965, he showed that two liquid crystals, combined in equal proportions, could form a mixture whose melting point was actually lower than either of its components.[77] In one instance, he mixed two APAPA compounds (APAPA-10 and APAPA-40), both of which had approximate nematic ranges of 82-110°C, and the resulting combination's melting point plummeted to 47°C.[78] Since the temperature required to convert the liquid crystal into an isotropic liquid remained fixed, Castellano had, in one fell swoop, doubled the sample's nematic range.

Nor was this effect limited to binary mixtures. Adding a third APAPA compound (APAPA-80) to the mixture described above lowered its melting point to an impressive 40°C. Heilmeier and Zanoni praised the new ternary mixture in the October 1965 progress report, noting that its wider nematic range "enables us to study such important device parameters as speed of response, contrast ratio and resistivity as a function of temperature."[79] Still, the chemists did not rest on their laurels. Goldmacher and Barton

associated with the various APAPA compounds changed throughout the course of the RCA project. Before 1967, an APAPA compound whose normal alkoxy end group was substituted for one with four carbons might be referred to as: p-butoxybenzylidene-p-aminophenyl acetate, B^2A^2, C4-APAPA, or APAPA-4. In the first quarter of 1967, as the chemists began altering both the alkoxy and acyloxy groups in APAPA molecules, they implemented a new two digit system; the first digit referred to the *total number* of carbons in the alkoxy group and the second to the number of carbons *added* to the acyloxy group. Thus, APAPA-4 became APAPA-40. The full names of pertinent liquid crystal derivatives are provided in Joseph Castellano, *Notebook 28304*, DSL, 23-31. A comparison of old and new systems can be found in RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, 2.

[77] Castellano (2005), 27; Castellano, *Notebook 28304*, 32; RCA Laboratories, *Progress Report: Liquid Crystals, Oct. 1965*, DSL, 3.

[78] RCA Laboratories, *Progress Report: Liquid Crystals, Oct. 1965*, 3. For the sake of consistency, all APAPA derivatives will be referred to using post-1967 nomenclature described in n. 77. APAPA-40's nematic range was listed as 82-113°C in the Oct. 1965 progress report.

[79] RCA Laboratories, *Progress Report: Liquid Crystals, Oct. 1965*, 6.

halted the development of new room-temperature crystals, choosing instead to increase stocks of APAPA derivatives for Castellano's mixtures.[80] Castellano, in turn, adjusted the proportions of each component in his ternary systems in hopes of further reducing their melting points below 40°, but to no avail. Taking a page from Barton's old playbook, Castellano doped his samples with a non-mesomorphic compound (dibutoxybenzene), which yielded a liquid crystal phase between 28 and 53°C. Unfortunately, the new material "tended to segregate itself from the other components of the mixture" when subjected to electric fields, rendering it useless for a reflective mode display.[81]

Despite these setbacks, the expanding nematic ranges of the individual APAPA compounds Goldmacher, Barton, and Castellano synthesized in early 1966, such as the aforementioned APAPA-12, offered reason to believe that a low-temperature liquid crystal mixture was forthcoming. Finally, in April 1966, Castellano reported the creation of a ternary mixture that broke the unofficial "room temperature" barrier by having a melting point below 25°C.[82] The event received relatively little fanfare in that month's progress report, presumably since Kleitman had, on the basis of preliminary work with APAPA-12, preemptively proclaimed the existence of a "lowered temperature LC material" in the

[80] The most prominent casualty of this trend was undecadienoic acid. Goldmacher and Barton synthesized a mixture of this material's cis-trans isomers between September and November 1965 which was found to be nematic between 24 and 49°C. Unfortunately, it polymerized at room temperature and despite claims that "[e]xperiments aimed at improving the speed and contrast ratio of this material are planned," it disappeared from official progress reports by December 1965. For more on this compound, see Castellano, 40-41; RCA Laboratories, *Progress Report: Liquid Crystals, Oct. 1965*, 2-4.

[81] RCA Laboratories, *Progress Report: Liquid Crystals, Jan. 1966*, DSL, 4.

[82] Castellano, 28; RCA Laboratories, *Progress Report: Liquid Crystals, Apr. 1966*, DSL, 2. Using the post-1967 nomenclature scheme, the mixture in question consisted of a 1:1:1 ratio of APAPA-10, APAPA-12, and APAPA-13 and had a nematic range of 23-105°C. Its original synthesis is recorded in Castellano, *Notebook 28304*, 76. In the same progress report, Heilmeier described another mixture consisting of APAPA-10, APAPA-40, and APAPA-12, which had a nematic range of 25-104°C (p. 7), though based on his laboratory notebooks it is unclear if he made it himself or received assistance from the chemists. See: George Heilmeier, *Notebook 30812*, DSL, 16.

previous research update.[83] Regardless, the spring of 1966 marked a turning point for the liquid crystal chemists. While Castellano continued to study various ternary systems and developed three-dimensional phase diagrams permitting one to determine the precise combination of materials required to produce a desired nematic range, other priorities, both old and new, soon rose to the top of their agenda.[84]

Having obtained materials for reflective mode devices, some of the chemists could now direct their attention to other liquid crystal phenomena, most notably the guest-host effect. After more than two years, electronic color switching now moved to center stage as Goldmacher, Castellano, and newly recruited technician Leonard Korsakoff applied their recent experience with APAPA to create room-temperature solvents for pleochroic dyes.[85] Like Heilmeier before them, they believed these new PEBAB derivatives would facilitate the construction of a flat-panel color display.[86] Experiments with a "tricolor 'stack'" of liquid crystal cells in the second half of 1967 yielded poor results, but attempts to demonstrate the feasibility of such a system persisted.[87]

In spite of this renewed interest in electronic color switching, the bulk of the chemistry research associated with liquid crystals between 1966 and 1968 focused on the

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[83] See: RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1966,* DSL, 1 [Quarterly Summary]; RCA Laboratories, *Progress Report: Liquid Crystals, Mar. 1966,* 19.

[84] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, 3-6; RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, DSL, 2-3, 7-11; RCA Laboratories, *Progress Report: Liquid Crystals, Jul.-Sep. 1967,* DSL, 2-13. (The last of these includes phase diagrams for PEBAB-type compounds in addition to APAPA.)

[85] RCA Laboratories, *Progress Report: Liquid Crystals, Jan-Mar. 1967*, 6-8; RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, 4-6. A room-temperature mixture based on PEBAB was first reported RCA Laboratories, *Progress Report: Liquid Crystals, Jul.-Sep. 1967,* 12.

[86] RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, 4-6.

[87] RCA Laboratories, *Progress Report: Liquid Crystals, Jul.-Sep. 1967*, 14; RCA Laboratories, *Progress Report, Liquid Crystals, Oct.-Dec. 1967*, DSL, 18; RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1968,* DSL, 6.

reflective mode, and specifically improving the life span and performance of APAPA mixtures subjected to electric fields. Beginning in the spring of 1966, Jean Kane, having returned to the DSRC on a part-time basis, dedicated months to running life tests, inserting liquid crystals into cells with electrodes made from different metals and observing their decomposition.[88] She also confirmed that oxygen accelerated the decay process, though the cause remained unclear until early 1968 when Castellano and physical chemist Alan Sussman determined that hydroxyl radicals in the APAPA triggered the reaction.[89] Based on this information, the chemists were poised to attack the decay problem, but it was evident that a greater theoretical understanding of what was now being called "dynamic scattering" would be required to resolve the issue.[90]

Defining "Dynamic Scattering": Models of Liquid Crystal Switching, 1965-1968

For nearly a year after advancing APAPA as the liquid crystal group's primary object of study, Heilmeier devoted little time to explaining its electro-optic behavior. Upon viewing the reflective mode for the first time in May 1965, he had concluded that "the scattering of light by the domains when the material is stirring is responsible for the effect," but conceded in the first red-covered progress report that "[t]he mechanism and

[88] RCA Laboratories, *Progress Report: Liquid Crystals*, *Mar. 1966*, 23. See also: Jean Kane, *Notebook 28090*, DSL, 59-100; Jean Kane, *Notebook 31729*, 1-100.
[89] RCA Laboratories, *Progress Report: Liquid Crystals, May 1966,* DSL, 2-4; RCA Laboratories, *Progress Report: Liquid Crystals, Oct.-Dec. 1967,* 17; RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968,* DSL, 4-11.
[90] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968*, 10-11. In what might be termed a case of history repeating itself, the two main strategies Sussman and Castellano proposed to hinder the decay reaction in APAPA–adding inhibitors and increasing the chain length on the ester portion of the molecule, echoed Castellano and Barton's respective approaches towards the synthesis of room-temperature liquid crystals in the spring of 1965.

cause of the stirring are unclear at this time."[91] Over the following months, he set such matters aside to characterize the electrical properties of various liquid crystals and consult with the chemists to determine which compound(s) would be used in the first LCD prototypes.[92] Occasionally, he gestured toward the mechanism of the reflective mode, only to postpone a sustained investigation of the subject. In one instance, he utilized viscosity and spectral data to deduce that light passing through an activated liquid crystal cell was being scattered multiple times, but refrained from further analysis due to the complexity of the mathematics involved. "With all due modesty," he explained, "we feel that the most we can hope for is a qualitative understanding of the field induced scattering from liquid crystals such as APAPA."[93]

Even such a qualitative understanding of this phenomenon, however, would require some quantitative calculations, and for Heilmeier, this process started in earnest in the spring of 1966. "For some time, I have been thinking about the mechanism for stirring in APAPA compounds," he wrote in a March notebook entry. "I feel that the stirring which produces the reflection properties should be viewed as a true turbulence and more attention should be paid to the hydrodynamics of the phenomenon."[94] He expressed similar notions in that month's progress report, entitling his submission "Some Comments on the Nature of the Dynamic Scattering Mode." Though Heilmeier may have used the

[91] Heilmeier, *Notebook 28088*, 3; RCA Laboratories, *Progress Report: Liquid Crystals, Mar.-May 1965*, 4.
[92] See, for example, RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, 2-5; RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1965*, 2-4; RCA Laboratories, *Progress Report: Liquid Crystals, Sep. 1965*, 4-5.
[93] RCA Laboratories, *Progress Report: Liquid Crystals, Dec. 1965*, DSL, 5. [Original emphasis]
[94] Heilmeier, *Notebook 30812*, 1.

expression in earlier conversations, this marked its first confirmed use in company documents.[95]

Heilmeier commenced his hydrodynamics investigations by asking if dynamic scattering was a case of "true turbulence," capable of scattering incident light. The answer to that question depended upon whether liquid crystals possessed a constant viscosity, which would mitigate against the formation of whorls and eddies.[96] But although he calculated that liquid crystals behaved like non-Newtonian fluids (i.e. with non-constant viscosities), his results also persuaded him "that turbulence in the normal sense (i.e. inertial forces>>viscous forces) cannot be responsible for the observed optical effects."[97] "The question arises as to what the fundamental mechanism of the dynamic scattering mode is if turbulence is not a factor," Heilmeier wrote in June 1966. Perhaps, he continued, "[s]ome insight might be gained by considering the bodies moving through the medium"—specifically, ions.[98]

Notebook entries show that numerous observations underlay Heilmeier's belief that ions were somehow linked to dynamic scattering. As early as May 1965, he had speculated upon "the importance of ions in the behavior of nematic melts" and the

[95] RCA Laboratories, *Progress Report: Liquid Crystals, Mar. 1966*, 22. It is possible that the term appeared in the August 1965 disclosure form Heilmeier and Zanoni filed for an "Electro-Optical Device" based on dynamic scattering, but the contents of the resulting patent, issued in 1970, contained references to later work, making it difficult to determine whether the term "dynamic scattering" was included initially or added later. It is also worth observing that Heilmeier continued to refer to "reflective" or "scattering" mode operation in his laboratory notebook until mid-May 1966 (*Notebook 30812*, 41) and that neither of Zanoni's two surviving notebooks includes the expression "dynamic scattering." See: George H. Heilmeier and Louis A. Zanoni, "Electro-Optical Device," US Patent 3,499,112, filed 31 Mar. 1967 and issued 3 Mar. 1970. The Aug. 1965 disclosure date for this patent is derived from: Louis Zanoni, "United States Patents Issued To: Louis A. Zanoni," ZPA, 1.

[96] RCA Laboratories, *Progress Report: Liquid Crystals, May 1966*, DSL, 7-8. The material used in these calculations was p-azoxyanisole (PAA) rather than APAPA, presumably because the rheological properties of the former had been more widely studied.

[97] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, DSL, 4. [Original emphasis]

[98] Heilmeier, *Notebook 30812*, 58.

possibility of their involvement in the formation of domains.[99] More recent comparisons of purified liquid crystal samples implied that ion concentration "played an important role in determining the electrical properties of the material."[100] Now, in the summer of 1966, he returned to the concept once again, arguing that light scattering took place in the wakes formed by ions passing through a liquid crystal medium.[101] To better observe such disturbances, Heilmeier and Zanoni devised a new experimental setup. Instead of the conventional sandwich cell geometry, where a liquid crystal sample was placed between two pieces of conductive glass, they now positioned the electrodes on a single substrate, applying a field perpendicular to the direction of viewing.[102] As Heilmeier increased the voltage across the sample in this "surface cell," he noticed something unusual.[103] "At about the same field strength necessary to initiate scattering in the sandwich cell," he reported later, "spike-like regions which appeared bright between crossed polarizers...were observed to initiate from the negative electrode and travel to the positive electrode."[104]

The speed with which these spikes bridged the gap between electrodes and the functional relationship between their transit time and the magnitude of the applied field were both consistent with Heilmeier's hypothesis that dynamic scattering resulted from ions passing through the liquid crystal.[105] But it was also possible, he realized, that the spikes resulted from "an alignment process involving only the applied electric field," with

[99] Heilmeier, *Notebook 28088*, 9.
[100] RCA Laboratories, *Progress Report: Liquid Crystals, Sep. 1965*, 4-5.
[101] Heilmeier, *Notebook 30812*, 58, 62.
[102] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 5. Further details are included in Heilmeier, *Notebook 30812*, 58-67.
[103] The term "surface cell" is utilized in both the June 1966 progress report and Heilmeier's subsequent articles on dynamic scattering.
[104] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966,* 5. [Original emphasis]
[105] RCA Laboratories, *Progress Report: Liquid Crystals, Jul. 1966*, DSL, 5-6; Heilmeier, *Notebook 30812*, 73, 86.

no ionic involvement whatsoever.[106] To eliminate this alternative, he and Zanoni modified the surface cell's electrodes, replacing the parallel stripes with a "cylindrical" arrangement producing a gradient (i.e. non-constant) electric field. Upon activation, the spikes once again emerged, traveling from cathode to anode "despite the fact that the field was above threshold for the effect (in the planar electrode case) for only part of the distance between cathode and anode."[107] It seemed that while a minimum field strength was required to initiate the light scattering effect, that field did not need to be applied uniformly across the cell in order for it to be sustained.

These findings, along with empirical data gathered by Zanoni and Barton, strengthened Heilmeier's confidence in a "momentum exchange" mechanism for dynamic scattering.[108] According to this model, at a certain threshold field, negative ions were emitted from the cathode. These ions collided with neutral liquid crystal molecules, causing them to move in the direction of ion transport, resulting in "a turbulence (or actual

[106] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 5.
[107] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 5; Heilmeier, *Notebook 30812*, 65-66.
[108] RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1966*, DSL, 5. Barton's contributions to the dynamic scattering investigations initially revolved around his work on doped liquid crystal solutions, specifically the effect of ionic dopants such as dodecyl isoquinolonium bromide on reflective mode operation. See: RCA Laboratories, *Progress Report: Liquid Crystals, Mar. 1966*, 22; RCA Laboratories, *Progress Report: Liquid Crystals, Apr. 1966*, 4. Later, he conducted extensive measurements of liquid crystal cell resistivity and helped Heilmeier and Zanoni measure cell switching speed. Zanoni's individual contributions are difficult to ascertain from progress reports, but his notebooks reveal an interest in determining how cell thickness, resistivity, and various chemical treatments of substrates and electrodes affected dynamic scattering (Zanoni, *Notebook 27707*, 68-100). Heilmeier's colleague Philip Heyman, who served as witness to the first guest-host experiments, also assisted the liquid crystal research team by measuring the current flowing through the liquid crystal cells in response to applied voltage pulses. For additional information see: George H. Heilmeier and Philip M. Heyman, "Note on Transient Current Measurements in Liquid Crystals and Related Systems, *Physical Review Letters*, 18 (1967): 583-585.

flow) in the liquid crystal and its associated optical effect."[109] Since the ions, once launched, continued moving forward after the field was removed, this model accounted for the spike formation seen in the surface cells.

To ascertain further whether momentum transfer was responsible for dynamic scattering, Heilmeier and Zanoni constructed a pair of additional experimental setups. In the first, they submerged two solid metal electrodes in a liquid crystal sample and placed a metal screen halfway between them.[110] If ions were actually transferring their momentum to nearby liquid crystal molecules then when an electric field was applied to the region between one of the solid strips and the screen, some optical distortion would be evident in the field-free region on the opposite side of the beaker. After resolving some issues with current arcing across the sample, Heilmeier and Zanoni witnessed the presence of dynamic scattering beyond the screen.[111] In a follow-up experiment, they positioned two mesh electrodes in the middle of a glass cylinder with capillary tubes for pressure measurement located on each end. As the voltage on the liquid crystal sample between the electrodes rose, they measured a decrease in pressure near the cathode and an increase at the anode which, in light of previous results, confirmed Heilmeier's theory.[112] "After several months

[109] RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1966*, 5-6.

[110] RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1966*, 6; RCA Laboratories, *Progress Report: Liquid Crystals, Sep. 1966*, DSL, 4. According to Heilmeier's notebook, in the final configuration, the solid electrodes were 10 mm apart with the screen positioned halfway between them. They were submerged in a sample 1.5 cm deep. (Heilmeier, *Notebook 32284*, DSL, 17) The figure's label (6e, rather than 6d) reflects the order Heilmeier et al. chose to present their experiments in the first published article on the subject rather than the order in which the experiments actually occurred. This setup is referred to as a "conductivity" cell since it was used in experiments relating current flow to ionic motion (e.g. comparing the current with the solid metal electrodes as the cathode and the mesh screen as the anode, and vice versa). See: George H. Heilmeier, et al. "Dynamic Scattering: A New Electrooptic Effect in Certain Classes of Nematic Liquid Crystals," *Proceedings of the IEEE* 15, no. 7 (Jul. 1968): 1162-1171.

[111] RCA Laboratories, *Progress Report: Liquid Crystals, Sep. 1966*, 4.

[112] RCA Laboratories, *Progress Report: Liquid Crystals, Sep. 1966*, 4-5; *Progress Report: Liquid Crystals, Oct. 1966*, DSL, 5-6. To clarify, Heilmeier identified five potential mechanisms by which an

of experimentation," he and Zanoni announced in the November 1966 progress report, "we find no evidence which contradicts a model for the DSM [dynamic scattering mode] based on the interaction of an ion in transit with the anisotropic nematic medium."[113]

Satisfied as Heilmeier may have been with this explanation for dynamic scattering, he understood that the model he had spent months verifying remained frustratingly incomplete. It was one thing to claim that ions were responsible for the field-induced turbulence in liquid crystals, but neither Heilmeier nor anyone else could explain the source of the ions themselves or why some materials, like APAPA, were more conducive to dynamic scattering than others, like PEBAB. As a result, beginning in 1967, Heilmeier and Barton started a second wave of investigations intended to address these deficiencies.[114] Through a systematic study of electrode geometry and the effects of changing sample thickness, resistivity, and temperature on the relaxation (turn-off) time of dynamic scattering, they devised partial responses to both questions by the end of the year.[115]

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electric field could exert a force on a fluid: 1.) electrostriction (resulting from the change in dielectric constant produced by field induced density changes); 2.) spatially varying dielectric currents; 3.) dielectrophoresis (the motion of matter caused by polarization effects in a nonuniform field); 4.) electrophoresis (motion of a charged particle and its associated counterion in an electric field); and 5.) electrohydrodynamic effects (mechanical forces produced by essentially unipolar electrical conduction). Of these, 1 and 2 could not account for the pressure rise observed at the anode. The consistent propagation of the effect from cathode to anode in the surface cell and metal mesh experiments argued strongly against 3 and 4, leaving only 5, an electrohydrodynamic effect based upon momentum transfer of ions in transit as the mechanism responsible for dynamic scattering. Heilmeier, Barton, and Zanoni elaborated upon their reasoning in the first published article on the subject (Heilmeier, et al., "Dynamic Scattering.") and in an internal company report dated December 1966: G.H. Heilmeier, et al., "A Flat Liquid Crystal Reflective Display Based on Dynamic Scattering," dated Dec. 1966, DSL. The latter document's provenance is a mystery, but its similarity with sections of the subsequently published article supports the theory proposed by Sarnoff Library executive director Alexander Magoun that it was a preliminary draft written with an eye toward a 1967 release of the work (Alexander Magoun, e-mail message to author, 7 Jan. 2008).

[113] RCA Laboratories, *Progress Report: Liquid Crystals, Nov. 1966*, DSL, 5.

[114] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, 9.

[115] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar.* 1967, 9-10; RCA Laboratories, *Progress Report Apr.-Jun. 1967*, 13-15.

In each case, the solution involved visualizing how electric fields affected liquid crystal samples on a molecular level. Although Heilmeier had initially assumed the ions responsible for dynamic scattering were ejected directly from the metal electrodes, further calculations suggested that the voltages involved caused some of the liquid crystal molecules (or impurities contained in the sample) to dissociate near the cathode.[116] Accelerated by the field, each of the resulting ions acted as what Heilmeier later termed a "molecular bullet" fired through the liquid crystal sample.[117] In the case of materials like PEBAB, whose molecules aligned with their long axes parallel to the electric field, these ions faced little resistance, but in APAPA-type substances, which organized themselves perpendicularly to the field, the ions had to push their way across the cell, like boats through a log jam.[118] The disruption of this once organized structure led to turbulence and the resultant light scattering effect.[119]

As had been the case the previous year, this revised model for dynamic scattering left Heilmeier and his colleagues with several mysteries, such as the chemical reactions involved in ion formation.[120] It also failed to account for several new electro-optic effects encountered during the course of their investigations, including a means of electrically

[116] RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, 13-15. Heilmeier's initial conclusions, as outlined in the previous quarter's report, were based on the observation that the current in liquid crystal samples bore a mathematical similarity to Schottky (i.e. field-induced thermionic) emission.
[117] George Heilmeier, Interview with Stewart Finley, *Men and Molecules*. Episode 515 ("Liquid Crystals: A Bright Promise"), c. 1970.
[118] George Heilmeier, Interview with Stewart Finley, *Men and Molecules*. Episode 515 ("Liquid Crystals: A Bright Promise"), c. 1970.
[119] RCA Laboratories, *Progress Report: Liquid Crystals, Jul.-Sep. 1967*, 15-16.
[120] Heilmeier, et al. allude to their uncertainty concerning the origin and nature of the ions involved in dynamic scattering in their 1968 article, noting that their conductivity research "leads us to suspect that the dissociating species is an impurity molecule." (1167) In a subsequent article published in 1970, they address this question more directly, arguing that "water molecules enable APAPA to accept an electron from the cathode and transport it as a negative ion." See: G.H. Heilmeier, et al., "Further Studies of the Dynamic Scattering Mode in Nematic Liquid Crystals," *IEEE Transactions on Electron Devices* ED-17, no. 1 (1 Jan. 1970): 23.

quenching field-induced turbulence and a new "storage mode" observed in mixtures of nematic and cholesteric liquid crystals.[121] To accommodate broader research into these phenomena, in the fall of 1967, Heilmeier enlisted additional personnel into the liquid crystal research group. Alan Sussman, the physical chemist who collaborated with Castellano in an effort to clarify the mechanism of liquid crystal decomposition, also participated in studies of charge carriers in APAPA.[122] Another recruit was German physicist Wolfgang Helfrich, whose initial lack of familiarity with the subject did not prevent him from creating new mathematical models describing the formation of domains and their behavior under applied fields.[123] These new researchers allowed Heilmeier to divert his energies away from such theoretical matters and concentrate instead on the engineering challenges surrounding the liquid crystal team's ultimate objective: the construction of dynamic scattering displays.

[121] RCA Laboratories, *Progress Report: Liquid Crystals, Dec. 1966,* 6-8; RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, 6-7. (See n. 7 for further information on cholesteric liquid crystals.) Heilmeier and Zanoni reported in December 1966 that short current pulses could be used to terminate dynamic scattering in a cell much faster than simply switching off the field. Goldmacher and Korsakoff first observed the storage effect the following June after combining the room-temperature ternary APAPA mixture with cholesteryl oleate and cholesteryl chloride. The resulting mixture was clear with no field applied. When a DC voltage was applied, the sample turned white, just like a normal dynamic scattering cell. Unlike previous cells, however, the scattering remained when the field was removed. It would remain in that state, with only minor degradation, over the course of several days. (Goldmacher reported 10% decay in 66 hours) Applying an AC voltage caused the cell to revert to its transparent state. Heilmeier, in typical fashion, recorded the chemists' finding in his notebook along with a list of possible applications including "a numeric indicator for TV or electronic watch." See Heilmeier, *Notebook 34299*, DSL, 92.

[122] RCA Laboratories, *Progress Report, Liquid Crystals: Oct.-Dec. 1967*, 18.

[123] Wolfgang Helfrich, Interview with author, Berlin, Germany, 28 Sep. 2009; RCA Laboratories, *Progress Report: Liquid Crystals, Oct.-Dec. 1967*, 10; RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968*, 14-16; RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1968*, 10-12.

From Static Display to Active Matrix: LCD Fabrication, 1965-1968

Much as Heilmeier enjoyed playing the theorist, he identified himself first and foremost as an electrical engineer. Before he ever witnessed field-induced opalescence in APAPA, he had pondered the problem of addressing: the means by which an incoming television signal would be converted into visual information on a liquid crystal display. Since flat-panel or "mural" TV research began at the DSRC, engineers had formulated two general approaches to this task.[124] One strategy, favored by the television experts in the Systems Research Laboratory, relied on a guided electron beam sweeping across a target, typically a phosphor-coated screen, to control switching and illumination. The other, pioneered by computer memory expert Jan Rajchman, abandoned cathode rays and the bulky vacuum tubes required to produce them in favor of an x-y matrix of individual switches positioned behind each display element. Heilmeier was aware of both of these systems and in February 1965 composed a five page notebook entry evaluating their compatibility with liquid crystals.[125]

Four months later, having confirmed APAPA's unique electro-optic properties, Heilmeier used a cell with a thin (0.006 inch) cover plate to demonstrate the possibility of addressing a reflective LCD with an electron beam. As he wrote, "[t]he sample was addressed through the glass with a Tesla coil & and where the sparks hit the glass, the sample became reflective."[126] Continuing along these lines, he and Zanoni constructed a cell with a perforated backplate whose holes were filled conductive material to permit

[124] These categories are derived from RCA Laboratories, *Research Report 1957*, 2-3, where they are respectively referred to as the "conservative" and "radical" approaches to mural television. For further discussion of displays based on each concept, see Ch. 3.
[125] Heilmeier, *Notebook 26848*, 24-28.
[126] Heilmeier, *Notebook 28088*, 15. These findings are also recorded in Zanoni, *Notebook 27707*, 8.

beam addressing.[127] To maximize contrast, Zanoni lined the inner surface of the cell with a black coating so that the only light reflected towards the viewers' eyes would come from the liquid crystals, not the backplate. Yet when they applied a voltage to the cell, something strange happened, or more accurately *did not* happen. "The contrast Ratio was Zero, even though stirring was Taking place," Zanoni recorded in his notebook.[128]

This result was entirely unexpected. After all, earlier sandwich cell experiments showed that APAPA reflected light when subjected to an applied field. Why would replacing the transparent glass electrode from those trials with an absorptive backplate prevent the liquid crystal from becoming turbulent? Heilmeier could only conceive of two explanations: either the non-reflective coating somehow inhibited the stirring in his samples or scattering was occurring, but light entering the cell was not reflected back to its source. He decided to test the second option first, coating each of the perforated plugs with a reflective gold dot. When the field was applied, the white color associated with dynamic scattering became visible over each hole, demonstrating that "light in the reflective mode seems to be first forward scattered then reflected from the back surface through the sample once again."[129]

While this discovery would impact the design of future dynamic scattering displays by requiring the inclusion of a reflective backing, it did not resolve whether the research team would need to confine its efforts to cathode ray addressed systems or if it could proceed to more radical, x-y switching configurations. Heilmeier posed this question to John van Raalte and Warren Moles, who concluded in August 1965 that while "TV speed

[127] Heilmeier, *Notebook 28088*, 23; Zanoni, *Notebook 27707*, 17.
[128] Zanoni, *Notebook 27707*, 18. The capitalizations are derived from the original notebook entry.
[129] Heilmeier, *Notebook 28088*, 37.

matrix addressing can be accomplished at present," additional components would be required to isolate and store the signal at each of the 250,000 display elements required to achieve full television resolution.[130] Existing diodes could fulfill these functions, but they were not amenable to batch fabrication or integrated circuit techniques, making the immediate prospects of a commercial display less auspicious.[131]

Van Raalte and Moles held out hope that new materials or cell structures might alter their findings. Until then, they decided to verify that liquid crystals could generate a high resolution, television quality image using what they called an "insulator addressed" system.[132] They coated a glass slide with a transparent conductor and a light-sensitive polymer called a photoresist. Then, they projected a photographic negative onto the photoresist, changing the chemical structure of those areas exposed to light so they could not be removed with an acid rinse. When a liquid crystal was placed in a sandwich cell with the newly etched plate, the areas where the photoresist was dissolved (the dark areas of the negative) underwent dynamic scattering and appeared bright. Regions where the photoresist remained (the light areas of the negative) were insulated and appeared dark.[133]

[130] RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1965*, 5. As Van Raalte and Moles explained in the previous progress report (RCA Laboratories, *Progress Report: Liquid Crystals, Jun.-Jul. 1965*, 5-6), the additional electronics were intended to compensate for the fact that the time required to induce stirring exceeded the 60 μs required to address a line in a standard television display (which can be calculated from the NTSC standard frame rate of 30 Hz and picture resolution of 525 lines per frame) as well as the discharge time of existing liquid crystal cells. The 250,000 display element figure is derived from RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 1.

[131] RCA Laboratories, *Progress Report: Liquid Crystals, Aug. 1965*, 5.

[132] RCA Laboratories, *Progress Report: Liquid Crystals, Nov. 1965*, DSL, 6. In addition to the "insulator addressed" display described here, Van Raalte and Moles also experimented with a system that placed a liquid crystal cell in series with a large area photoconductor. In theory, projecting an image on the photoconductor would cause its resistance to decrease, allowing current to reach the corresponding area of the liquid crystal and reproduce the pattern. Unfortunately, this setup, explicitly based upon the light amplifying panels developed by Benjamin Kazan and Frederic Nicoll (see Ch. 2), failed due to chemical incompatibilities between the photoconductor and the mesomorphic material. For further details, see: John van Raalte, *Notebook 27689*, DSL, 31-32, 48; Moles, *Notebook 26365*, 85-87.

[133] RCA Laboratories, *Progress Report: Liquid Crystals, Nov. 1965*, 6.

The result was an electronically activated static image suitable for projection or, if a mirror backplate was used, direct viewing.[134]

Van Raalte and Moles considered their new fabrication technique as a proof of concept rather than a basis for subsequent research, and returned to studying matrix addressing by early 1966.[135] This did not prevent Heilmeier and Zanoni from appropriating their methods to construct sample displays featuring images of everything from test patterns to RCA chairman David Sarnoff.[136] They also constructed a handheld "personalized flat display," to determine whether the need for a reflective back electrode imposed undue viewing restrictions. "We found that one could observe a satisfying image with the device held in the normal reading position," Heilmeier remarked in his notebook. "This was the case both indoors and out," though some adjustment of the lid, which ensured maximum contrast by permitting the mirrored backplate to appear dark, "was necessary to optimize viewing conditions."[137]

Impressive as Heilmeier and Zanoni's displays were, they did not significantly advance their long-term goal of developing a commercially viable liquid crystal television. In a midyear statement preceding the June 1966 progress report, Kleitman urged a renewed campaign, incorporating both cathode ray and matrix addressing, in pursuit of that objective.[138] "Even if the present x-y emphasis is increased..." he explained, "some

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[134] RCA Laboratories, *Progress Report: Liquid Crystals, Dec. 1965*, 8-9; Moles, *Notebook 26365*, 97-100; Van Raalte, *Notebook 27689*, 98-100; John van Raalte, *Notebook 30300*, DSL, 1-3.
[135] RCA Laboratories, *Progress Report: Liquid Crystals, Jan. 1966*, 8; RCA Laboratories, *Progress Report: Liquid Crystals, Feb. 1966*, DSL, 15-17.
[136] Heilmeier, *Notebook 30812*, 33; Zanoni, *Notebook 27707*, 63.
[137] Heilmeier, *Notebook 30812*, 28-31; Zanoni, *Notebook 27707*, 61-62.
[138] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 1-2.

attention within the corporation should be given to the determination of the role and problems of a beam addressed product."[139]

Heilmeier took Kleitman's recommendations under advisement, and before the end of the year, his group could report progress along both fronts. Although Van Raalte's formal affiliation with the liquid crystal team diminished after the summer of 1966, that November, he successfully modified a CRT-based projection system to address a liquid crystal target.[140] The display was only 2 inches square and mounted on the face of a bulky vacuum tube, but the resulting images, taken from live television signals, could also be projected on to a larger screen. It was the first time an over-the-air broadcast appeared as a moving image on an LCD, prompting Van Raalte to declare in his notebook that the "World's first electron-beam-addressed reflective television display was born."[141]

Van Raalte's display marked the apex of the electron beam approach to liquid crystal addressing. While he continued to tinker with his prototype over the coming months, this setup, he explained later, "was clearly only practical for making large, projected images."[142] The smaller, direct-view devices that Heilmeier had in mind would require matrix addressing circuitry, and in November 1966 he decided to accelerate the development of such a system. Up to this point, the liquid crystal initiative had remained relatively self-contained. Members sometimes sought out assistance for specific experiments or consulted with experts on matters beyond their disciplinary expertise, but

[139] RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 1-2.
[140] RCA Laboratories, *Progress Report: Liquid Crystals, Nov. 1966*, 4; John van Raalte, *Notebook 32280*, DSL, 18-29; John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009. As discussed in Ch. 3, the projection system in question was designed by fellow SRL researcher Ray Kell. Full technical details of Van Raalte's apparatus can be found in: John van Raalte, "Reflective Liquid Crystal Television Display," *Proc. of the IEEE* 56, no. 12 (Dec. 1968): 2146-2149.
[141] John van Raalte, *Notebook 32465*, DSL, 29.
[142] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.

otherwise group membership hovered around seven or eight people.[143] That changed at the end of 1966, when a separate team of engineers led by Bernard Lechner officially joined the LCD research effort.[144]

Lechner was a member of the DSRC's Computer Research Laboratory (CRL) and a protégé of its director, mural television pioneer Jan Rajchman. In early 1966, as he was putting the finishing touches on a 1200-element electroluminescent display for the Air Force, Heilmeier approached him to discuss liquid crystal addressing.[145] "I had conversations in those days with George [Heilmeier] and Lou [Zanoni] and Dave Kleitman and others...John van Raalte, I'm sure," Lechner remembered, "about, you know, how we'd make a matrix display out of this when we get some materials...that will work at room temperature."[146] Following completion of the Air Force project in August, Lechner and his team started lending additional support to the liquid crystal team, and in November they began submitting entries to the group's red-covered research reports.[147]

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[143] The first progress report of 1966, for example, lists D. Perkins providing assistance on diodes, R.E. Quinn consulting about TFT's (thin-film transistors), and B[ernard]. Lechner, whose work on addressing will be described in more detail momentarily. The June and July 1966 reports also mention assistance from Philip Heyman and Ed Pasierb. Of the people listed here, only Pasierb, a technician who conducted research on cadmium sulfide diodes, and Lechner would become ongoing members of the liquid crystal research team. RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1966*, 2 [Quarterly Summary]; RCA Laboratories, *Progress Report: Liquid Crystals, Jun. 1966*, 2; RCA Laboratories, *Progress Report: Liquid Crystals, Jul. 1966*, 4, 8.

[144] RCA Laboratories, *Progress Report: Liquid Crystals, Nov. 1966*, 9.

[145] RCA Laboratories, *Progress Report: Liquid Crystals, Jan. 1966*, 2. For more on Lechner's electroluminescent display, see Ch. 3.

[146] Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009.

[147] The completion date of the project is derived from Juri Tults, *Notebook 29309*, DSL, 47. The December 1966 progress reports claim that Lechner's group became involved in the last quarter of 1966. Pinning down an exact date is difficult due to gaps in the notebook record. Tults' first discussion of liquid crystals is in 23 Nov. 1966. Barton, however, recorded a meeting with Frank Marlowe, who will be discussed below, on 17 Oct. 1966.

The two sets of researchers pursued the shared goal of a matrix-addressed liquid crystal display in relative isolation and without regularly scheduled meetings.[148] This working arrangement was partially justified by the architectural realities of the DSRC, since as Lechner recalled, their laboratories were "almost as far away as we could get from each other physically in the building."[149] It also reflected the division of responsibilities within the project. Heilmeier's group concentrated upon the materials and mechanisms of dynamic scattering and the fabrication of individual display elements, while Lechner's engineers sought to use those cells "in practical display systems employing integrated solid-state addressing and driving circuitry."[150] There were occasional intersections between the two groups' activities, as when Heilmeier agreed, on Lechner's suggestion, to design and build an "exerciser," a small display consisting of two rows of eighteen elements that could be used to simulate addressing at standard television rates.[151] Once Zanoni returned the finished device to Lechner, however, the two teams once more withdrew to their separate labs.

The problem confronting Lechner was the same one that Van Raalte and Moles identified a year earlier: liquid crystal cells could switch at television speeds, but without a means of isolating each picture element and providing improved signal storage, they could not serve as the basis for a functional matrix display.[152] Heilmeier had initially assumed

[148] Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009.
[149] Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009. An examination of DSRC staff directories (1960-1976) confirms that Lechner's engineers had offices in the building's west wing while Heilmeier's group was clustered in the east and northeast wings.
[150] RCA Laboratories, *Progress Report: Liquid Crystals, Dec. 1966 (Section II* [Addressing]*)*, DSL, 2.
[151] Heilmeier, *Notebook 32284*, 51; RCA Laboratories, *Progress Report: Liquid Crystals, Nov. 1966*, 9; Bernard Lechner, Interview with author, Princeton, NJ, 17 Apr. 2009. Lechner drew upon the precedent of his recently completed electroluminescent display in submitting the specifications for this exerciser.
[152] Lechner, 28. To clarify, applying a voltage to a given horizontal and vertical electrode of a matrix-addressed liquid crystal display activates a pixel at the corresponding intersection. Unfortunately, unless

that a single diode placed in series with each liquid crystal cell would be sufficient to deal with these issues, but two of Lechner's engineers, Frank Marlowe and Juri Tults, confirmed that this so-called "classical" approach would result in turn-on delays and low brightness.[153] Ultimately, the team designed two distinct sets of panel circuitry to overcome the limitations of classical addressing, respectively referred to in progress reports as "double-diode capacitor" (D^2C) and "field-effect transistor capacitor" (FETC).[154]

After testing these designs on the LCD "exerciser" using discrete components, Lechner decided that the group should collaborate with RCA's semiconductor division in Somerville, NJ to fabricate two 1200-element displays, one for each system.[155] These prototypes were tiny, measuring slightly over 3/4 in. (~2 cm) diagonally, but each would be fully integrated, capitalizing upon RCA's latest advances in solid-state and semiconductor research.[156] Marlowe worked with Paul Weimer, the inventor of the thin-film transistor, to test the compatibility of thin-film components with liquid crystal

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pixels are electrically isolated from each other, this arrangement can lead to the partial activation of other display elements along the same row and column, reducing the overall contrast of the LCD. For further information on matrix-addressing circuitry, see: Dunmur & Sluckin, 237-238; Peter Collings, *Liquid Crystals: Nature's Delicate Phase of Matter* (Princeton: Princeton Univ. Press, 1990 [2002]), 82-88.

[153] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, 21. Marlowe and Tults refer to single-diode addressing as the "classical method" in RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, 30. Lechner also used the term in "Liquid Crystal Displays," in *Pertinent Concepts in Computer Graphics: Proceedings of the Second University of Illinois Conference on Computer Graphics*, ed. M. Faiman and J. Nievergelt (Urbana: Univ. of Illinois Press, 1969), 1-18. See also: Bernard J. Lechner, et al., "Liquid Crystal Matrix Displays," *Proc. IEEE* 59, no. 11 (Nov. 1971): 1566-1579.

[154] RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1967*, 31-32; Lechner, 28.

[155] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, 25. Again, Lechner seems to have been drawing on the example of his earlier electroluminescent display project, moving from a 2 x 18 preliminary exerciser to a 1200-element final product.

[156] RCA Laboratories, *Progress Report: Liquid Crystals, Oct.-Dec. 1967*, 26. The displays measured 639 mils by 479 mils (0.639 in. by 0.479 in.). These dimensions make slightly more sense if one considers: 1.) There were 30 rows of 40 liquid crystal cells; 2.) Each square liquid crystal cell measured 15 mils on a side; 3.) Each cell was separated by a 1 mil space from its neighbors.

devices.[157] Similarly, Tults collaborated with members of Charles Mueller's research group to construct a D^2C display using another RCA invention: silicon-on-sapphire integrated circuits.[158] Another member of Lechner's group, Edward Nester, reached out to Doris Flatley of the DSRC's integrated circuit center to obtain suitably large monolithic silicon substrates for the FETC display.[159]

In committing his group to these advanced integrated circuit technologies, Lechner hoped to streamline the manufacture of future displays, and in fact, today's liquid crystal industry relies upon variants of his FETC addressing scheme in all "active matrix" liquid crystal televisions and computer screens.[160] At the time, however, as technical difficulties, ranging from poor diode yields to broken silicon wafers, piled up, his group's reports took on a more pessimistic tone.[161] "Both of these approaches [D2C & FETC] represent rather ambitious undertakings in semiconductor technology and the progress has been slow," Lechner wrote in the spring of 1968. "Although the circuits are simple, 1200 of them are required and the wafer area is large (600 x 800 mils); also multilevel metallizations are

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[157] Lechner (2008), 29. For further information on the history of the thin-film transistor (TFT), see Ross Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins Press, 2002), 146-149.

[158] Lechner (2008), 29. As Bassett points out, silicon-on-sapphire (or SOS) represented a marriage of MOS technology and Weimer's thin-film transistor, which the company hoped would have the best features of both to achieve higher switching speeds and greater reliability. Ultimately, the high cost of SOS circuitry left it unable to compete with silicon components. (Bassett, 161-165)

[159] Lechner (2008), 29. As Frank Marlowe pointed out in his 24 Aug. 2009 interview with the author, "[s]ilicon processing had reached the point where wafers that were two inches in diameter were available. They were considered large."

[160] Lechner (2008), 28. Though the terms were not in use in the 1960s, an "active matrix" display is one in which an "active" device, typically a thin-film transistor, is used to switch on each display element, as opposed to a "passive matrix" setup which uses simpler x-y coincident addressing. Active matrix addressing circuitry is more complex, but permits one to create display panels with higher brightness and contrast. For more on the development of active matrix displays, see: Castellano, 175-189.

[161] RCA Laboratories, *Progress Report: Liquid Crystals, Jul.-Sep. 1967*, 25; RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968*, 27-28.

required."[162] Further complicating matters was the group's increasing reliance on solid-state researchers, both in Princeton and Somerville, who did not answer directly to either Lechner or Heilmeier and considered the liquid crystal project a diversion.[163] As Heilmeier and Zanoni constructed simpler devices, such as electronic windows and numeric counters, Lechner continued to postpone the expected completion date of his group's 1200-element displays until one April day in 1968, he received a memo from Al Pinsky, a member of RCA's public relations staff.[164] Apparently, the corporation had an announcement to make.

More Than Just "A Sexy Name": Dynamic Scattering Goes Public

The walls of silence surrounding the RCA liquid crystal project had started to crumble in November 1967, when Heilmeier, Barton, and Zanoni jointly authored a technical report on dynamic scattering. Unlike the red-covered progress reports, this document was accessible to the entirety of RCA's technical staff through the DSRC's library, and served as the basis for an article submitted to the *Proceedings of the IEEE* in January 1968.[165] The research center's annual report for 1967, published shortly thereafter, also included a section on LCDs and the first company-wide references to dynamic scattering.[166]

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[162] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968*, 27.
[163] Bernard Lechner, Interview with author, Princeton, NJ, 24 Apr. 2009; Lechner, 5-6.
[164] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, 11-13; RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968*, 19-20.
[165] G.H. Heilmeier, et al., *PTR-2366: Dynamic Scattering...A New Electro-Optic Effect in Certain Classes of Nematic Liquid Crystals*, DSL, 1 Nov. 1967. The submission date is derived from Heilmeier, et al. "Dynamic Scattering" (1968), 1162.
[166] RCA Laboratories, *Research Report 1967*, DSL, 7, 93.

What prompted these revelations after more than two years of secrecy is not immediately evident from the group's internal reports. The timing does not correspond with any of the breakthroughs that the various branches of the project deemed most significant. Unlike the chemists' March 1966 synthesis of room-temperature liquid crystal mixtures or the formulation of Heilmeier's "momentum transfer" model for dynamic scattering the following November, the research conducted in the last quarter of 1967 could be categorized as transitional. The development of new nematic mixtures, refined theoretical models, and improved, though still incomplete, addressing circuitry all furthered the group's strategic goals, but none of them would, in and of themselves, suggest that the time had come to reveal dynamic scattering to the world.[167]

Nevertheless, the documentary record indicates that Heilmeier and his colleagues were eager to disseminate their research and that by early 1968, the company's management found it increasingly difficult to defend a publication ban. The previous May, RCA received its first liquid crystal patent, based on Richard Williams' domain research, and by the middle of the year, more than a dozen additional applications would be filed covering all aspects of LCD manufacturing.[168] A DSRC patent counsel expressed confidence that these would be sufficient to establish "[b]road world-wide claim coverage" on dynamic scattering devices by the early 1970s.[169] Intellectual property concerns may have justified the initial decision to keep the liquid crystal project confidential, but those arguments were becoming less relevant with each passing month.

[167] RCA Laboratories, *Progress Report: Liquid Crystals, Oct.-Dec. 1967*.
[168] Richard Williams, "Electro-Optical Elements Utilizing an Organic Nematic Compound," US Patent 3,322485, filed 9 Nov. 1962 and issued 30 May 1967.
[169] J.F. Spivak to J.V. Regan, "Patent Coverage Related to Liquid Crystals," 27 Jun. 1968, DSL, 4.

Yet neither the liquid crystal researchers' desire for broader recognition nor the rising strength of RCA's patent portfolio can fully explain Al Pinsky's decision to schedule a press conference in the spring of 1968.[170] After all, Heilmeier had submitted his *IEEE* article in January and no RCA staff member had received a liquid crystal patent since Williams; the announcement could just as easily have been made earlier in the year. The decision to wait until the end of May likely resulted from conversations between Pinsky and DSRC head James Hillier, who viewed the liquid crystal project as possessing both symbolic and scientific value to a company in the midst of an identity crisis.[171]

In January 1968, RCA's longtime chief executive, David Sarnoff, stepped down from his post, leaving the corporation in the hands of his son, Robert. Unlike his father, Robert Sarnoff did not possess strong ties with the Princeton research staff, and upon taking power expressed an interest in changing RCA's corporate image through diversification into areas outside of electronics.[172] Hillier was aware that the younger Sarnoff's strategy threatened the DSRC's institutional standing and, more concretely, its budget. During the early months of 1968, he latched on to liquid crystals as a means of asserting the importance of a well-funded central laboratory. Dynamic scattering, he realized, could find applications not merely in consumer products, such as wristwatches or calculators, but in any field involving a machine with a visual interface. Here was a technology that, as Hillier would claim at the LCD press conference, showed that the

[170] A. Pinsky, "Preliminary Plans for Press Conference to Announce RCA Development of Liquid Crystal Electron Optic [sic] Effect," Interdepartmental Correspondence (dated 10 Apr. 1968), Bernard Lechner Collection, DSL.
[171] Bernard Lechner, Interview with author, Princeton, NJ, 24 Apr. 2009.
[172] Graham, 104-106; Alfred D. Chandler, Jr., *Inventing the Electronic Century* (New York: The Free Press, 2001), 40-42. Robert Sarnoff's background and strategic priorities upon becoming CEO are discussed further in Ch. 6.

DSRC's interests extended beyond television to include "basic and applied research in the whole spectrum of information handling."[173]

Both the DSRC's managers and the scientists and engineers involved in liquid crystal research had something to gain from presenting dynamic scattering to the public, and each would play a role in shaping the company's discussion of the subject. As master of ceremonies, Hillier sought to emphasize the "interdisciplinary" and "cooperative" research underlying the creation of the LCD, without overwhelming the audience with names or technical minutiae.[174] He therefore avoided detailed descriptions of the shift from electronic color switching to dynamic scattering and worked with Heilmeier and Lechner to select representatives to showcase the technology's capabilities.[175] The resulting roster contained some surprising omissions and additions. Among the liquid crystal research team, only Heilmeier, Zanoni, and the three main chemists (Goldmacher, Barton, and Castellano) were present, with Lechner and Tults representing the addressing effort.[176] No other personnel listed as active participants in the red-covered reports attended, though the group was joined on stage by Robert Lohman and Steven Hofstein. Heilmeier had contacted the two engineers for assistance designing transistorized circuitry for an all-electronic clock, but though publicity photographs implied otherwise, neither formally joined his team.[177]

[173] James Hillier, "Draft of Remarks At Liquid Crystal Press Conference, 28 May 1968," Bernard Lechner Collection, DSL, 1. Both here and in the DSRC's 1967 report, Hillier referred to RCA as being "in the information handling business," echoing the rationale used to justify the corporation's 1966 acquisition of Random House Publishing. See: RCA Laboratories, *Research Report 1967*, 1-4; Chandler, 42; Robert Sobel, *RCA* (New York: Stein and Day, 1986), 187-190.
[174] Hillier, 1.
[175] Pinsky, 1-2.
[176] Hillier, 3.
[177] Hillier, 3. Lohman's work on a "four digit numeric indicator ...for the electronic clock" is mentioned only once in the Jan.-Mar. 1968 progress report (20). Hofstein was a member of Lohman's group and is

Throughout the press conference, Hillier made certain to treat this disparate group of researchers, including Lohman and Hofstein, as a cohesive unit, despite the different goals and schedules established by the chemists and physicists on Heilmeier's team and the relative independence of Lechner's engineers. In a sense, the press conference represented another iteration of a process through which RCA's liquid crystal investigations were consolidated into a narrative–in laboratory notebooks, articles, patents, or oral histories—emphasizing certain details and minimizing others in order to further a particular argument.[178] Much as LCD researchers had regularly distilled months of work into a paragraph to persuade management their work deserved continued support, Hillier downplayed the scope and complexity of the group's internal dynamics in order to present the DSRC to both the public and his superiors as a site of productive, interdisciplinary collaboration. Unlike the scientists in the above example, however, Hillier was far enough removed from the liquid crystal project to require outside assistance to determine what aspects of the work merited inclusion in his account.

For those details, Hillier and Pinsky asked Heilmeier to prepare a "writeup... describing liquid crystals in semitechnical language–a fact sheet," which would also include a brief history of the LCD project and its participants.[179] This document would have a profound effect on future depictions of RCA's liquid crystal research. Specifically, it attributed the development of dynamic scattering displays to five researchers: Heilmeier,

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better known for his collaboration with Frederic Heiman which resulted in the creation of the MOS field effect transistor (MOSFET) utilized in modern microprocessors. For more on Hofstein and his involvement with the liquid crystal group, see: Karl Zaininger, Interview with the author, Princeton, NJ, 11 Sep. 2009.

[178] See Ch. 4 for a more extensive discussion of the different norms and conventions associated with these genres of scientific communication.

[179] Pinsky, 2.

Zanoni, Goldmacher, Castellano, and Barton. Though Hillier expanded this core group to include Lechner, Tults, Lohman, and Hofstein, their specific contributions vanished from subsequent press accounts, which adhered closely to Heilmeier's fact sheet.[180] Over the next year, RCA's public relations staff offered hints that the liquid crystal initiative involved additional staff, as in an autumn 1968 *Electronic Age* article referring to the contributions of Williams and Van Raalte.[181] But when the corporation decided to recognize the creators of the LCD with the David Sarnoff Outstanding Team Award in Science, only Williams, who had served as an informal consultant, joined the core group as a recipient.[182]

Of course, those omitted from RCA's public discussions of liquid crystals found alternative outlets to publicize their involvement, such as patents or journal articles. Still, even in the supposedly sacrosanct realm of academic publication, one can witness the perpetuation of Heilmeier and Hillier's jointly agreed upon talking points. Recall, for example, the article Heilmeier, Zanoni, and Barton submitted to the *Proceedings of the IEEE* in January 1968. That document possessed an extensive acknowledgments section, referring not only to Goldmacher, Castellano, and Williams, but also several others "who provided support and insight into many problems relating to practical display

[180] Presumably Hillier recruited these additional personnel due to their familiarity with the prototype devices on display during the press conference. While Lohman's picture appeared in several newspapers, most notably the *New York Times*, the other three additions to the core liquid crystal group received almost no mention in the press. The major exception was Lechner's appearance in a *Wall Street Journal* article, describing "the major stumbling block in developing a liquid-crystal TV set." See: "RCA Develops a New Visual Display Means Using Liquid Crystals," *Wall Street Journal*, 29 May 1968, 12.
[181] Bruce Shore, "Op Electronics," *Electronic Age* 27, no. 4 (Autumn 1968): 12-15. *Electronic Age* was RCA's in-house public relations magazine, published quarterly until 1971.
[182] "The David Sarnoff Outstanding Achievement Awards," *RCA Engineer* 14, no. 6 (Apr.-May 1969): 48; Richard Williams, Interview with author, Princeton, NJ, 30 Apr. 2009.

applications," including Van Raalte, Lechner, Moles, and Kleitman.[183] Six months later, the three scientists submitted an abbreviated discussion of the same subject to *Applied Physics Letters*. In the aftermath of the press conference, the new publication acknowledged only three people: Goldmacher, Castellano, and Williams.[184]

Admittedly, the difference in personnel included in these articles might reflect variations in their scope, with the former including applications and the latter limited to electro-optic effects. Indeed, a 1969 article Heilmeier wrote for *RCA Engineer* with sections devoted to various dynamic scattering prototypes, restored Lohman, Moles, and Hofstein as contributors to the "development of the liquid-crystal display concept."[185] Yet in subsequent retrospectives, such as a frequently-cited 1976 essay for the *IEEE*'s *Transactions on Electron Devices*, Heilmeier reverted back to the origin story that he and Hillier settled upon in 1968. With the exception of his fellow Sarnoff Award winners and Steven Hofstein, he did not mention any other personnel affiliated with the LCD project between 1965 and 1968.[186] Nor did he provide additional details concerning the discovery of dynamic scattering, treating it, like Hillier did, as the result of a single, self-evident experiment. "We had discovered how to electronically control the reflection of light in a

[183] Heilmeier, et al. (1968): 1171.

[184] G.H. Heilmeier, et al., "Dynamic Scattering in Nematic Liquid Crystals," *Applied Physics Letters* (1 Jul. 1968): 46-47. The article is listed as having been "Received 4 April 1968; in final form 10 June 1968."

[185] G.H. Heilmeier, "Liquid Crystals—the first electronic means for controlling the reflection of light," *RCA Engineer* 15, no. 1 (Jun.-Jul. 1969): 18. For an earlier version of this article, see: George H. Heilmeier, "Dynamic Scattering in Liquid Crystals," *Appliance Engineer* 2, no. 4 (1968): 21-25. In addition to the individuals mentioned here, Heilmeier also refers to the contributions of Zanoni, Barton, Goldmacher, Castellano, and "K. Mann." No further references this last individual are present in either the DSRC's annual reports or the liquid crystal group's red-covered updates.

[186] Heilmeier (1976), 782-784. Here I am referring to personnel listed as participants in the LCD progress reports, not managers like William Webster, Henry Lewis, and James Hillier, whom Heilmeier mentions on p. 784. The most glaring omission among the engineers is Van Raalte, whose name is absent from the main text despite photographs of his beam-addressed liquid crystal being prominently featured on p. 783.

most striking and dramatic way," he wrote. "We had to think of a sexy name for this effect and the term 'dynamic scattering' was coined."[187]

Historians should sympathize with the dilemma Hillier faced prior to the 1968 press conference. Condensing the dynamics of an industrial research enterprise spanning several years and numerous scientific disciplines into a coherent narrative remains a daunting task, even with access to the extensive documentary record preserved in RCA's technical archive. Given the scope of the liquid crystal project, some omissions were inevitable. The purpose of this chapter has not been to criticize either Hillier or Heilmeier for providing an inaccurate account of the LCD's origins, but rather to question how DSRC personnel decided when to announce the existence of dynamic scattering and what aspects of liquid crystal research merited inclusion in their discussions of the subject. As I have shown, corporate scientists contributed substantially to the construction of private and public narratives surrounding dynamic scattering's origins and practical implications. Only by examining this process can one evaluate the significance of personnel (e.g. Kleitman) or technologies (e.g. Lechner's non-functioning 1200-element display) omitted from the officially sanctioned version of events and, more importantly, the reasoning behind their exclusion. For the institutional and technological obstacles confronting the DSRC liquid crystal group did not disappear once the LCD went public. To the contrary, they would return in new forms during the years to come, as RCA struggled to move dynamic scattering out of the laboratory and into the marketplace.

[187] Heilmeier (1976), 782.

CHAPTER SIX
"What happened to all the empires": RCA and the Commercialization of the LCD, 1968-1976

An explosion of colors, reminiscent of fireworks, graced the cover of RCA's 1968 annual report to its shareholders.[1] Published in the spring of 1969, this document marked the first instance in four decades that David Sarnoff refrained from writing the introductory letter recounting the past year's achievements. Illness had struck the company's seventy-seven year old chairman the previous summer, and the weakened businessman ceded this responsibility to his son, and designated successor as chief executive, Robert Sarnoff.[2]

Despite having only served as RCA's president since 1966 and CEO for little over a year, the younger Sarnoff had already made his mark on his father's electronics empire. In a literal sense, he replaced the company's familiar logo, a circle containing the letters "RCA" underlined with a lightning bolt, with the squarish monogram that has persisted, under various owners, to this day.[3] This seemingly superficial change, along with the decision to refer exclusively to RCA, rather than the Radio Corporation of America, in

[1] RCA Corporation, *Annual Report 1968* (New York: RCA, 1969).
[2] Kenneth Bilby, *The General: David Sarnoff and the Rise of the Communications Industry* (New York: Harper & Row Publishers, 1986), 278-279.
[3] Bilby, 274-276; Robert Sobel, *RCA* (New York: Stein and Day, 1986), 193-194. For press discussions of RCA's new trademark, see: Lynn Taylor, "R.C.A. Extinguishes Trademark Flash," *Chicago Tribune*, 19 Jan. 1968, C8; "RCA launches new image," *Boston Globe*, 19 Jan. 1968, 25; Gordon Weil, "Updating Images," *Wall Street Journal,* 1 Aug. 1968, 22. RCA retained its new trademark until General Electric (GE) purchased the company in 1986. GE later sold RCA's television business to Thomson Consumer Electronics, a French firm which proceeded to license the RCA mark to a variety of businesses. For more on the sale to Thomson, see: Joel Brinkley, *Defining Vision: How Broadcasters Lured the Government into Inciting a Revolution in Television* (New York: Harcourt Brace & Co., 1997), 56-61; Alfred D. Chandler, Jr., *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries* (New York: The Free Press, 2001), 44-47; Alexander Magoun, *Television: The Life Story of a Technology* (Baltimore: Johns Hopkins Univ. Press, 2007 [2009]), 154.

official documents, reflected a deeper belief that the firm should not limit its future activities to the field of telecommunications.[4]

Embracing the strategy of expansion through acquisition that his father had pioneered, Robert Sarnoff reinvented RCA as a conglomerate, whose traditional focus on consumer electronics would be supported by newly-purchased companies like Random House Publishing and the Hertz Corporation.[5] "The word that best characterizes the modern RCA is diversity," he explained in the 1968 report.[6] To illustrate this point, Sarnoff referred to an accompanying twelve page fold-out which portrayed over 600 products and services, "a cross section of the 12,000 products and services created or marketed by RCA at home or abroad."[7] One had to marvel at the sheer variety of items represented. A single page showcased the cover of a John Updike novel, a Henry Mancini album, and both Captain Kirk and Mr. Spock, posed within phaser range of a superconductive magnet, a VHF transceiver, and RCA's Spectra 70 computer system.[8]

Lest his audience worry that RCA had become overly reliant upon established product lines, Sarnoff also included a section in his letter describing "a significant scientific effort in 1968" aimed at creating "the foundation for some promising new enterprises in the decade ahead."[9] Foremost among these, granted pride of place on the report's cover,

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[4] Bilby, 275; Sobel, 193.

[5] Chandler, 41-42; Sobel, 187-191. Both Chandler and Sobel emphasize that although Robert Sarnoff would later be heavily criticized for his diversification of RCA's holdings, David Sarnoff had engaged in similar tactics for years, from the 1929 purchase of the Victor Talking Machine, Co. to that of Random House in 1966.

[6] RCA Corporation, *Annual Report 1968*, 4.

[7] RCA Corporation, *Annual Report 1968*, 3.

[8] RCA Corporation, *Annual Report 1968*. The Spectra series of computers will be discussed later in this chapter.

[9] RCA Corporation, *Annual Report 1968*, 5.

was "a revolutionary new type of electronic display, based on research in liquid crystals."[10] This fantastic array of colors demonstrated the capacity of these substances, which flowed like liquids but possessed the optical properties of a crystalline solid, to modulate the reflection of light. As if borrowing the mantle of technological prophet from his father, Sarnoff proclaimed that liquid crystals "could lead to an entire new range of electronic display products–from wrist watches to pocket-size television receivers that could be viewed in broad sunlight."[11] These claims were conservative compared to those RCA scientists presented in a later section, suggesting that "[l]iquid crystal products of the future may encompass instrument displays for automobile dashboards and airplane cockpits, scoreboards, stock tickers, and, perhaps someday, flat screen television receivers."[12]

Confronted with such glowing predictions, RCA shareholders could be forgiven for anticipating future updates concerning this new technology. Yet the following year, liquid crystal displays (LCDs) were absent from the summary of company research activities, supplanted by news of a "new, low-cost color TV tape player" with programs recorded on hologram-embossed plastic.[13] At the precise moment when the LCD left the

[10] RCA Corporation, *Annual Report 1968*, 5.
[11] RCA Corporation, *Annual Report 1968*, 5. According to Bernard Lechner, the engineer who oversaw the creation of the first matrix-addressed LCD, both Robert Sarnoff and his father had witnessed the technological potential of liquid crystals firsthand, having attended a dress rehearsal of the May 1968 press conference introducing the new displays to the public. See: Bernard Lechner, Interview with author, Princeton, NJ, 24 Apr. 2009.
[12] RCA Corporation, *Annual Report 1968*, 23.
[13] RCA Corporation, *Annual Report 1969* (New York: RCA, 1970), 19. The definitive history of RCA's home video technologies, including the Selectavision Holotape device unveiled in 1969 is Margaret B.W. Graham, *The Business of Research: RCA and the VideoDisc* (New York: Cambridge Univ. Press, 1986 [1988]). For a firsthand account of RCA's early video player research, including the Holotape project, see: George H. Brown, *And Part of Which I Was: Recollections of a Research Engineer* (Princeton: Angus Cupar Publishers, 1982), 270-287.

laboratory for commercialization at RCA's operating divisions, it vanished from the corporation's annual bulletins.[14] LCDs appeared in a handful of photographs, but from 1970 to 1975, no mention was made in these reports of the liquid crystal factories that opened near RCA's semiconductor division in Somerville, NJ or the $9 million reportedly invested to secure a share of the emergent LCD industry.[15] Even the company's 1976 decision to terminate this work and sell off its liquid crystal facilities to Timex failed to merit a comment.[16]

The silence from RCA's leadership accompanying these changes in its liquid crystal program has permeated all subsequent discussions of the subject. Still, scholars have seized upon the case of LCDs to call attention to institutional obstacles to technology transfer at RCA, differences in leadership style between David and Robert Sarnoff, and the contrasting attitudes of American and Japanese firms towards long-term technological investment.[17] To compensate for the absence of company documents concerning the

[14] To be clear, this comment refers exclusively to work aimed at developing liquid crystal displays. The 1974 annual report did, for example, devote a paragraph to Donald Channin's use of liquid crystals to study electron flow in integrated circuits (discussed later in this chapter), but this was distinct from any display applications. See: RCA Corporation, *Annual Report 1974* (New York: RCA, 1975), 19.

[15] For examples of LCD photographs, see: RCA Corporation, *Annual Report 1971* (New York: RCA, 1972), 20; RCA Corporation, *Annual Report 1973* (New York: RCA, 1974), 10-11. The $9 million dollar total can be found in Martin Gold, "LCDs, Semicons in Timex Deal with RCA," *Electronic News*, 16 Feb. 1976, 63. As shall be discussed, this figure paled in comparison to other RCA losses during this period, such as its $250 million (post-tax) writeoff on electronic computing, which may explain its absence from the company's annual reports.

[16] Gold, 1.

[17] See, for example: Bob Johnstone, *We Were Burning: Japanese Entrepreneurs and the Forging of the Electronic Age* (New York: Basic Books, 1999), Ch. 3; Hirohisa Kawamoto, "The History of Liquid-Crystal Displays," *Proc. IEEE* 90, no. 4 (Apr. 2002): 460-500; Thomas P. Murtha, et al., *Managing New Industry Creation* (Stanford: Stanford Univ. Press, 2001), 55-59; Stuart Peters, *National Systems of Innovation: Creating High-Technology Industries* (New York: Palgrave Macmillan, 2006), esp. Ch. 6. Hedrick Smith, *Rethinking America* (New York: Random House, 1995), Ch.1. In contrast to the authors above, David Dunmur & Timothy Sluckin's *Soap, Science & Flat-Screen TVs: A History of Liquid Crystals* (New York: Oxford University Press, 2011) focuses less on RCA's management than on company scientists' preference for dynamic scattering displays over the twisted nematic devices that became the basis for the modern LCD industry. (p. 202-211) The distinction between these two technologies and the validity of Dunmur & Sluckin's claims will be discussed later in this chapter.

collapse of the liquid crystal initiative, these accounts instead rely upon the published reflections of the scientists responsible for the creation of the first LCD prototypes, most notably project leader George Heilmeier.[18] Like Heilmeier, they argue that RCA's inability to capitalize on liquid crystals resulted from poor management decisions at the company's headquarters in New York and its various operating divisions.[19]

Although his central role in RCA's liquid crystal program is beyond question, two factors mitigate against these authors' uncritical acceptance of Heilmeier's testimony concerning its cancellation. First, Heilmeier left RCA after receiving a White House fellowship in 1970, making him ill-suited to examine changes in the corporation's LCD strategy past that point. Secondly, as a member of RCA's technical staff, his perspectives on the liquid crystal project differ sharply from those of the engineers charged with organizing the first LCD assembly lines or the firm's managers or marketing experts. In privileging any one of these viewpoints, we obtain a distorted picture of each group's participation in the abandonment of what had once been the conglomerate's crown jewel.

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[18] With two exceptions, all of the authors referenced in the previous footnote refer, either directly or indirectly, to the version of events presented in George H. Heilmeier, "Liquid Crystal Displays: An Experiment in Interdisciplinary Research that Worked," *IEEE Trans. on Electron Devices* ED-23, no. 7 (Jul. 1976): 780-785. Hedrick Smith avoids citing this article, relying instead on interviews he conducted with Heilmeier and technician Ronald Friel (who, for some reason, is referred to as "Joe" Friel). Dunmur & Sluckin turn instead to Joseph Castellano's *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry* (Hackensack, NJ: World Scientific, 2005).

[19] This summary of Heilmeier's position is based upon his 1976 article; the updated version of that article he presented as a workshop upon receiving the 2005 Kyoto Prize in Advanced Technology; the interviews cited in Johnstone and Smith; Cade Metz, "Liquid crystals-Display genius no match for petty politics," *The Register*, 27 Apr. 2009, http://www.theregister.co.uk/2009/04/27/george_heilmeier/; and Joshua Shapiro, "George H. Heilmeier," *IEEE Spectrum* (Jun. 1994): 56-59. Castellano, an organic chemist and member of Heilmeier's team of liquid crystal researchers, offers a slightly more nuanced version of this argument in his book. He asserts that it is at least partially true that the collapse of RCA's LCD program "was due to lack of vision and commitment on the part of its management during the 1960s and 1970s," but also acknowledges the difficulties that corporations face in developing products from all of the technologies coming out of their laboratories (78).

Previous chapters of this dissertation have examined how corporate scientists and engineers mobilized institutional, financial, and literary resources to pursue their desired research objectives and enhance their professional standing. This chapter, in contrast, is dedicated to considering the limits of their agency in light of RCA's decision to withdraw from the liquid crystal industry. Between 1968 and 1976, I argue, the Princeton-based research group responsible for the creation of the first LCDs scaled back their ambitions in response to changing company priorities and an increased awareness of the new technology's shortcomings. Their actions complicated the efforts of personnel at the firm's manufacturing divisions to persuade company executives of liquid crystals' commercial potential, accelerating the project's ultimate collapse.

Finding a Niche: Liquid Crystal Research at the DSRC (1968-1970)

Just as RCA's 330,000 shareholders opened their mailboxes to find copies of the company's 1968 annual report, managers at each of the firm's operating divisions received a package of their own: a 186-page tome describing the spectrum of activities underway at the corporation's research laboratories.[20] This dense, encyclopedic volume bore little resemblance to the glossy, full-color booklet sent out to the public, but both documents featured LCDs prominently. Where the latter emphasized future products, the report from RCA Labs placed greater significance on the interdisciplinary liquid crystal research team at the David Sarnoff Research Center (DSRC) in Princeton.[21] "The liquid-crystal work

[20] The number of RCA shareholders is derived from RCA Corporation, Annual *Report 1968*, 5.
[21] For more on the origins and composition of this research team, see Ch. 4. RCA's LCD-related research was not confined to the DSRC. Starting in the spring of 1967, DSRC engineers worked with the semiconductor division in Somerville to develop a 1200-element, matrix-addressed LCD. Evidence of this collaboration can be found in DSRC's liquid crystal progress reports from 1967-69.

started several years before in some quite basic research," the introduction observed. "But its successful public demonstration was brought about by interdisciplinary applied research involving physicists, chemists, and electronic engineers working and communicating together."[22]

Later sections of the report would devote attention to ongoing liquid crystal investigations, but in foregrounding the multidisciplinary nature of the project in the introduction, the DSRC's leadership showcased the benefits of supporting a well-staffed central research facility.[23] This statement would not have been necessary were the laboratory's namesake still serving as CEO. David Sarnoff maintained an office in Princeton until the end of his life and spent many of his final days there supervising the construction of a new wing to house his personal papers.[24] Robert Sarnoff, on the other hand, did not share his father's technical inclination; he had acquired his position on the basis of his tenure as president of the National Broadcasting Company (NBC) and, of course, his last name.[25] The DSRC staff was therefore uncertain how things might change following the younger Sarnoff's ascension to power. Out of deference to his father, who preferred the old "meatball" logo, the DSRC was given an exemption from replacing "The

[22] RCA Laboratories, *Research Report 1968*, DSL, 1.
[23] RCA Laboratories, *Research Report 1968*, 91.
[24] Bilby, 280-281; Graham, 73-74. See also: Carl Dreher, *Sarnoff: An American Success* (New York: Quadrangle, 1977), Ch. 1. This new wing, dedicated as the David Sarnoff Library (DSL) in 1967, would later expand its holdings to include RCA's technical archive, from which much of the material cited in this dissertation was drawn. It closed in 2009, and its archival holdings were transferred to the Hagley Museum and Library in Wilmington, DE.
[25] Robert Sarnoff assumed the presidency of NBC in 1955 and oversaw the network's profitable transition to color broadcasting despite its higher costs and initial public resistance to the technology. Nonetheless, many believed that his 1957 appointment to RCA's board of directors and subsequent rise through the corporation's ranks was based on nepotism rather than his achievements as a TV executive. As mentioned in Ch. 3, one reason cited for RCA president John Burns' resignation in 1961 was his belief that Robert Sarnoff was being groomed to serve as head of the corporation, leaving Burns with no room for future advancement. For more on Robert Sarnoff's career, see: Bilby, 253-260; Dreher, 246-247; Sobel 184-187.

Radio Corporation of America" on its sign with the new RCA trademark.[26] Such gestures did little to insulate technical personnel from changes on the corporate level, most notably the new CEO's efforts to transform RCA from an electronics company into a conglomerate.[27] As the 1968 RCA Labs report summarized, the company was now more concerned with "satisfying consumer wants profitably rather than just selling products."[28] Implicit in this growing emphasis upon non-technical enterprises was a greater need for the DSRC to justify continued investment in long-term research.

This was not the first time that the DSRC's contributions to its parent company's profits had been called into question. After a 1958 consent decree prohibited the collection of patent royalties used to fund RCA's long-term research, then-president John Burns insisted that all DSRC projects should be linked to applications under development at the operating divisions.[29] Though his departure from the company and the arrival of revenues from color television prompted a return to the "building block" mindset of the early 1950s, Burns' choice to head the Princeton labs, James Hillier, believed the DSRC's status remained tenuous.[30] Once color television sales dried up, researchers would once again find themselves in trouble unless they could demonstrate their capacity to work with the

[26] Bilby, 275-276; Graham, 105.
[27] It is probable that Sarnoff's actions were inspired by the successful expansion of firms like International Telephone & Telegraph and Gulf+Western, which spearheaded the conglomerate merger movement during the late 1950s and early 1960s. For more on the origins and implications of this trend, see: Robert Sobel, *The Rise and Fall of the Conglomerate Kings* (New York: Stein & Day, 1984).
[28] RCA Laboratories, *Research Report 1968*, 1.
[29] Graham, 80-83. For comprehensive discussions of the 1958 consent decree, John Burns' policies at RCA, and the effect of both upon the DSRC, see Ch. 3 of this dissertation.
[30] Graham, 76-80.

divisions to create marketable products.[31] "The rest of the corporation would have to see the laboratory as a life raft not an albatross," Hillier recalled in a 1976 interview.[32]

Hillier attempted to shore up the DSRC's position through the 1964 formation of the Interim Research Planning Committee (IRPCO). Guided by the DSRC's laboratory directors, IRPCO would classify all ongoing research at Princeton according to its applicability to potential products, with the aim of slowly reducing the quantity of "sustaining research," i.e. projects with no obvious commercial significance.[33] Hailed by veteran engineers, who lamented the DSRC's turn towards the theoretical over the past decade, the IRPCO reforms met with resistance from scientists who had grown used to a large amount of autonomy in their work.[34] The result, in the words of one electrical engineer, was "a damn near technical revolt."[35]

It was within this tumultuous research environment that George Heilmeier organized his liquid crystal research team. Heilmeier opposed IRPCO's agenda, which threatened to cut off support for his LCD work before it achieved tangible results. He likely greeted the news that its reforms would lapse once Hillier left the DSRC to become a corporate vice-president at the end of 1968.[36] If so, he soon learned that rumors of

[31] David Hounshell observes that debates over the value of maintaining a central research facility were not confined to RCA during the late 1960s. Other firms, including GE, Du Pont, Kodak, and IBM, had also invested heavily in fundamental research after World War II, but found that "few, if any, blockbuster products" were emerging from their laboratories. Executives, disillusioned with Vannevar Bush's linear model, were increasingly diverting funds away from long-term research to more immediate commercial objectives. See: David A. Hounshell, "The Evolution of Industrial Research in the United States," in *Engines of Innovation: U.S. Industrial Research at the End of an Era* , ed. Richard S. Rosenbloom & William J. Spencer (Boston: Harvard Business School Press, 1996), 50-51.
[32] Quoted in Graham, 86.
[33] Graham, 87-88.
[34] Graham, 88-89; John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.
[35] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009.
[36] Graham, 89. Heilmeier's opposition to IRPCO is based on John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009. The timing of Hillier's promotion is confirmed in "Dr. Brown and Dr. Hillier Named to New Executive Positions," *RCA Engineer* 14, no. 3 (Oct.-Nov. 1968): 94.

IRPCO's demise had been exaggerated. For Hillier's replacement as head of the Princeton labs, William Webster, continued to support the committee's product-oriented mission, if not its name.[37] The distinguishing trend of research under his watch, Webster wrote in the DSRC's 1969 research report, would be "one of increased relevance to RCA's needs," accomplished through "some sacrifice of fundamental research in favor of advanced development."[38]

By that point, Heilmeier's team had demonstrated high-resolution image displays, window shutters, and digital counters utilizing liquid crystals, garnering praise from DSRC managers, including Hillier and Webster.[39] While this might have bestowed a measure of protection from further strategic realignments, it was in the interest of both Heilmeier and his colleagues to ensure that their projects, which until then had straddled the line between fundamental and applied research, could be construed as relevant to the company's commercial goals.[40] To that end, between 1968 and 1970, the DSRC's liquid crystal group resorted to three strategies that connected all of their investigations, even work that was heavily theoretical, to the generation of new products.

The first strategy, pursued by technicians like Louis Zanoni and Ronald Friel, consisted of fabricating a variety of new devices utilizing the well-established "dynamic scattering" mode of operation. As discussed in the previous chapter, a dynamic scattering LCD consisted of two sheets of conductively coated glass sandwiching a thin layer of

[37] Graham, 89.
[38] RCA Laboratories, *Research Report 1969*, DSL, 1.
[39] Heilmeier, 784.
[40] Considerable ink has been spilled in recent years concerning the problematic distinction between "basic" and "applied" research, perhaps most notably in Steven Shapin's *The Scientific Life: A Moral History of a Late Modern Vocation* (Chicago: Chicago Univ. Press, 2008). In this instance, my choice of terms is derived directly from previously cited RCA Laboratories reports (1968, 1969) and is intended to reflect the conceptions of my historical actors.

liquid crystal, whose appearance shifted from transparent to milky-white when subjected to an electric field.[41] Through the selective application of voltage to specially patterned glass, this effect could generate static grayscale images of photographic quality or simple moving patterns, such as a numeric indicator.[42] Zanoni had prepared examples of both of these items for the May 1968 press conference announcing the LCD's creation, but now, working with Friel, he expanded his repertoire to include voltmeters and both digital and analog clocks.[43] Typically, they delivered their handiwork to personnel at the operating divisions in Somerville or Camden, though occasionally they attended marketing meetings as demonstrators and, in one case, assisted an artist whose work with liquid crystals might generate beneficial publicity for RCA.[44]

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[41] This is a simplified description of dynamic scattering. For a more technical discussion of the phenomenon, see: George H. Heilmeier, et al., "Dynamic Scattering: A New Electrooptic Effect in Certain Classes of Nematic Liquid Crystals," *Proceedings of the IEEE* 15, no. 7 (Jul. 1968): 1162-1171. For more recent treatments aimed at non-specialists, see, Kawamoto, 465-468; Peter Collings, *Liquid Crystals: Nature's Delicate Phase of Matter*, (Princeton: Princeton Univ. Press, 1990 [2002]), 44-45.

[42] On p. 484, Kawamoto estimates the typical driving voltage of a dynamic scattering display as ~10-15V.

[43] For Zanoni's earlier LCD work, see: Louis Zanoni, *Notebook 27707*, DSL. Zanoni is specifically listed as working with chemists Lucian Barton and Leonard Korsakoff on devices for the press conference in RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1968*, DSL, 15. For more on the digital voltmeter, see Castellano, 57-58; RCA Laboratories, *Progress Report: Liquid Crystals, Oct.-Dec. 1968*, DSL, 26; RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1969*, DSL, 26. For the digital clock, see Castellano, 48-50 and RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1968*, DSL, 20. For the analog clock, see RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1969*, DSL, 26; RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1969*, DSL, 27.

[44] Interactions between DSRC personnel and the operating divisions will be discussed in the next section of this chapter. Zanoni described serving as a demonstrator on a marketing trip to California in an interview with the author, Ewing, NJ, 21 Aug. 2009. A reference to Zanoni's participation in "an extended marketing trip to the West Coast" is also present in *Progress Report: Liquid Crystals, Oct.-Dec. 1968*, DSL, 26. The artist referred to here was Earl Reiback, who wished to utilize a liquid crystal checkerboard mirror as part of "Reflections," a June 1969 exhibit of technological art hosted at New York's Howard Wise Gallery. Further information on RCA's contribution to the exhibit can be found in the Aug.-Sep. 1969 edition of *RCA Radiations* (an internal DSRC newsletter) preserved in Louis Zanoni's personal archive (ZPA), as well as *Progress Report: Liquid Crystals, Jan.-Mar. 1969*, 27-28; *Progress Report: Liquid Crystals, Apr.-Jun. 1969*, DSL, 27; *Progress Report: Liquid Crystals, Jul.-Sep. 1969*, DSL, 27.

Along with these new dynamic scattering prototypes, the LCD group also considered the incorporation of liquid crystals into existing RCA product lines. This second strategy initially focused upon the possibility of utilizing liquid crystals "to replace CRTs [i.e. cathode ray tubes] for commercial TV and other display applications."[45] Since 1966, Bernard Lechner and a group of engineers from the DSRC's Computer Research Laboratory had worked with Heilmeier to create what they hoped would be the long awaited basis for a flat-panel television display.[46] Lechner demonstrated that a matrix-addressed liquid crystal array could be switched at standard television rates, but scaling up the design of his laboratory "exercisers" for use in a planned 1200-element display, much less one capable of matching the resolution of commercial sets, would be more challenging.[47] At the end of 1968, citing "painfully slow" progress and "formidable problems with integrated circuitry," Lechner's team officially concluded work on the display panel project.[48] Instead they turned their attention to adapting liquid crystal light valves for use in other systems under development at the DSRC, such as the Electrofax photocopier and Homefax, a television-based facsimile system.[49]

[45] This phrase appeared in the "Objective" section of every liquid crystal progress report between 1967 and 1969.

[46] A summary of this work can be found in Bernard J. Lechner, "History Crystallized: A First-Person Account of the Development of Matrix-Addressed LCDs for television at RCA in the 1960s," *Information Display* (Jan. 2008): 26-30 and Bernard J. Lechner, "Liquid Crystal Displays" in *Pertinent Concepts in Computer Graphics: Proceedings of the Second University of Illinois Conference on Computer Graphics,* ed. M. Faiman and J. Nievergelt (Urbana: Univ. of Illinois Press, 1969), 1-18. For more on flat-panel display research at RCA prior to the organization of the LCD group, see: Benjamin Gross, "The Quest for 'Magnalux': Redefining Technological Success and Failure at RCA, 1951-1956," *Bulletin of Science, Technology, and Society* (forthcoming 2012) or Chapters 2-3 of this dissertation.

[47] Lechner (2008), 27-30; Bernard Lechner, Interview with author, Princeton, NJ, 24 Apr. 2009. Lechner and his team built multiple "exercisers," 2 x 18 mosaics of liquid crystal cells, to test different addressing circuitry. Preliminary designs for these devices can be found in George Heilmeier, *Notebook 32284*, DSL, 51-53.

[48] *Progress Report: Liquid Crystals, Oct.-Dec. 1968*, DSL, 33.

[49] To clarify the relationship between these two technologies: Electrofax was a proprietary document reproduction technique developed in the 1950s, which printed images on photosensitive paper coated with

Before setting aside the 1200-element display, Lechner availed himself of the final strategy adopted by members of the LCD team, one of particular value when the immediate commercial relevance of their research was no longer clear: he composed a proposal for government funding.[50] Prior to 1968, the company's self-imposed shroud of secrecy eliminated the possibility of securing external research support. Now Heilmeier and his team could approach agencies less closely wedded to the need for a short-term payoff than the DSRC's leadership in order to support their liquid crystal studies.

Lechner's attempt to sustain his group's LCD work was unsuccessful, but between 1968 and 1970, DSRC liquid crystal researchers received thousands of dollars from various military and civilian groups.[51] RCA scientists persuaded organizations with an interest in thin, lightweight displays, like the U.S. Air Force and the National Aeronautics and Space Administration (NASA) to advance efforts to characterize the chemical and physical properties of mesomorphic materials. In each instance, an ostensibly device-related project–such as gauging the applicability of dynamic scattering to Air Force cockpit instrumentation–justified extensive fundamental work, from the synthesis of new compounds to theoretical explanations of their behavior under applied fields.[52]

zinc oxide. The Homefax system utilized the Electrofax process to generate printed materials coordinated with a specific television broadcast (e.g. news reports or recipes). The contributions of Lechner's group to these applications are described in the 1968-1969 liquid crystal progress reports. For more on Electrofax, see "Electrofax," *Radio Age* 14, no. 1 (Jan. 1955): 20-21; J. Tults & D.L. Matthies, "Facsimile Printer using a liquid crystal array," *RCA Engineer* 17, no. 6 (Apr/May 1972): 40-43. For more on Homefax see: Graham, 89; W.D. Houghton, "Homefax–a consumer information system," *RCA Engineer* 16, no. 5 (Feb./Mar. 1971): 59-63.

[50] Bernard Lechner, "'Suggested Research Program' on Preliminary Development of a Liquid Crystal Display," c. 1969, Lechner Collection, DSL. Lechner notes in his 2008 *Information Display* article that this document was not aimed at any specific agency.

[51] Lechner (2008), 30. The amount of money associated with any given contract is not provided in the reports submitted by RCA personnel. The estimate here is based on Castellano's contention that "RCA obtained over $500,000 in LCD research contracts during the period from 1968 through 1972" (67).

[52] The example cited here refers to a 1970 report from DSRC staff to the Air Development Center in Rome, NY, whose 43 pages included 13 phase transition plots (indicating how the number of carbon

External funding also supplied an opportunity to reconsider electro-optic phenomena that had not garnered the same level of public notoriety as dynamic scattering. The Air Force Materials Laboratory in Dayton, Ohio, for example, expressed interest in liquid crystal mixtures that exhibited a storage effect, remaining opalescent even after the triggering field was removed, for use in navigation equipment.[53] Similarly, NASA's Electronics Research Center renewed investigations of guest-host color switching, the effect that inspired the initial organization of RCA's liquid crystal program, in hopes of developing a flat-panel TV for space capsules, where weight and cargo space were at a premium.[54] Once again, both the Air Force and NASA projects possessed clearly-defined technical objectives whose fulfillment validated a broader liquid crystal research agenda.

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atoms in a liquid crystal molecule affected its temperature of operation) and 6 pages discussing the mechanism of dynamic scattering, as compared to 3 pages (not including photographs) related to device fabrication and encapsulation. See: J.A. Castellano, et al., *Field Effect Liquid Crystal-Final Report* (Jan. 1970), DSL. An expanded version of this report, dated June 1970 (RADC-TR-70-96) and containing an evaluation from RADC Project Engineer Charles Blanc, is available through the Defense Technical Information Center (DTIC), http://www.dtic.mil/.

[53] J.A. Castellano, et al., *AFML-TR-73-51: Liquid Crystal Systems for Electro-Optical Storage Effects* (Dec. 1971), accessed via DTIC. As described in Ch. 5, chemists Joel Goldmacher and Leonard Korsakoff first observed what came to be called the "reflective storage mode" in the spring of 1967 using cells containing a combination of nematic and cholesteric liquid crystals. This report covers research conducted between 15 Jun. 1970 and 30 Sep. 1971, which culminated in the construction of a simulated "airborne ground position locator" that used this effect to provide pilots with their location based on "two radial beams transmitted from omnidirectional navigation stations" (45-47).

[54] J.A. Castellano, et al. *NASA CR-112032: Electronically Tuned Optical Filters* (Jan. 1972), DSL; J.A. Castellano, et al., [Project Reports] *Contract No. NAS-12-638: Electronically Tuned Optical Filters* (Apr. 1969, Apr. 1970), DSL; Castellano, 60. Confirmation of NASA's long-term interest in flat-panel replacements to the CRT can be found in: R.H. Hinckley to Dr. W.C. Dunlap, "Long Range Plan Revision," dated 20 Aug. 1965, Washington National Records Center (WNRC), "Chronological File-August 1965," Box 10, acc. 255-71A-2309, 11. NASA's specific interest in liquid crystals is confirmed in James Elms [director of Electronics Research Center] to NASA Headquarters, "Electronics Research Center Weekly Highlights Report," dated 6 Jun. 1968, WNRC, "Chronological File 1968," Box 3, acc. 255-71A-2309, 1-3. The latter document refers to NASA's long-term interest in dynamic scattering work at the DSRC (i.e. prior to May 1968), but I have found no additional documents in RCA's technical archives to confirm these claims. In addition to the guest-host effect discussed in Ch. 3 of this dissertation, Section III of the 1972 report (p. 10-32) describes research into another electro-optic effect, the so-called "field-induced phase change" from a reflective cholesteric to a transparent nematic mesophase.

From the outset, RCA's leadership had touted liquid crystal research as embodying the diverse range of scientific expertise present among the DSRC's technical staff. In fact, the adoption of the tripartite strategy outlined above suggests that its representativeness extended beyond disciplinary demographics. For much as Hillier and Webster, acting on their own, attempted to reconfigure the DSRC's contributions to an increasingly diverse RCA, so Heilmeier and his colleagues sought a niche for wide-ranging liquid crystal investigations within an increasingly profit-minded DSRC. Both groups wished to strike a balance between the freewheeling experimentation of Princeton's "building block" era and the focused product orientation of the post-IRPCO period, and to do so on their own terms rather than those of executives unfamiliar with laboratory research. Whether or not the DSRC as a whole would succeed in this task was unclear during the final years of the 1960s, but in the short term, its liquid crystal team felt confident enough to share its creations with the company's operating divisions and marketing staff.

Searching for Allies: LCD Manufacturing at Somerville and Raritan (1967-70)

In September 1967, Lawrence Murray, the head of the device physics group at RCA's Electronic Components Division (ECD) in Somerville invited associate engineer Richard Klein to accompany him to a meeting in Princeton.[55] A year earlier, after earning a master's degree in electrical engineering from Caltech, Klein had joined an ongoing advanced development effort, overseen by Murray, to build displays using light-emitting diodes (LEDs).[56] While the group kept in regular contact with the DSRC, Murray assured

[55] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Thanks to David Caruso, head of the Chemical Heritage Foundation's Oral History Program, for assistance in transcribing this interview.
[56] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Klein's colleague Sandor Caplan

Klein that on this trip they were going "to see something new."[57] Sure enough, upon arrival, Klein was escorted to a room where George Heilmeier and Louis Zanoni showed him a "piece of glass that I could vaguely see an image in."[58] Then Klein recalled, Heilmeier "put the electricity, the electrical, on and it was a TV test pattern. And you know the thing pops up, and I almost fell over!"[59]

Once Klein had recovered from his initial amazement, Heilmeier described the concept of dynamic scattering and explained that the Princeton group wanted Somerville's assistance converting these liquid crystal devices into products. The DSRC had already formed a partnership with ECD to design addressing circuitry for Lechner's matrix display, but Heilmeier wished to lay the groundwork for a more extensive partnership between the two organizations, culminating in the establishment of a pilot LCD manufacturing operation.[60] Murray's group, which had experience conducting fundamental research into electro-optic phenomena, provided an ideal venue for introducing liquid crystals to a division more comfortable working with silicon, and Klein enthusiastically embraced the new technology. "To me liquid crystal was a gimme!..." he noted later. "It had to go because it was the only technology that really matched up well with integrated

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provided additional first-hand perspective on RCA's LED display project in his interview with the author, Princeton, NJ, 10 Jun. 2009. See also: *Light Emitting Diode Displays*, Technical Proposal SP-68-47 (Somerville: RCA Electronic Components, 21. Jun. 1968), DSL; Lawrence A. Murray, et al., "Lighting up in a group," *Electronics* 41, no. 5 (4 Mar. 1968): 104-110.

[57] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Sandor Caplan confirmed in his 10 Jun. 2009 interview with the author that the ECD group obtained new diode materials from the DSRC. In addition, several members of the Somerville group, including both Klein and Caplan, had spent some time working at the DSRC.

[58] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[59] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[60] RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1967*, DSL, 24-25.

circuits. It was very low power. It could be scaled up in size. It didn't fight the light in the environment. It used the environment!"[61]

At first, Klein conducted experiments in relative isolation, with nothing but a handful of liquid crystal samples from the DSRC and assurances from his superiors that additional personnel and funding were forthcoming. The former promise turned out to be accurate. In 1968, Sandor Caplan, another member of Murray's LED group, joined Klein and assumed responsibility for material evaluation, testing "things like operating voltage, operating frequency, [and] temperature range of operation."[62] Though initially reliant upon the DSRC for chemicals and technical assistance, Klein and Caplan's team eventually expanded to include chemist Howard Sorkin, engineers Herman Stern and Henry Schindler, and manufacturing expert George Hiatt.[63] Together, this group would develop standardized procedures for the large-scale fabrication of LCDs.

As much as the ECD team may have respected their Princeton colleagues, the prototype devices Heilmeier presented to the public in 1968 were a far cry from commercial products. With the exception of the basic "sandwich cell" configuration, placing a thin liquid crystal layer between two pieces of conductive glass, nearly every

[61] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[62] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009. Caplan dates his involvement with the project to a January 1968 conversation with George Heilmeier at a Society for Information Display meeting in Philadelphia. The timing of this event would fit with Klein's contention that he worked alone on liquid crystals for several months before Caplan joined the project. It is more difficult to reconcile Caplan's claim that he was the first person at Somerville to learn about liquid crystals and that he "got Dick Klein involved," but in the absence of documentation (e.g. laboratory notebooks) from Somerville it is unlikely that this discrepancy will ever be resolved.

[63] Castellano, 64; Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009; Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Without organizational charts from Somerville, the dates when these individuals were assigned to the LCD project remain unclear. Klein suggested that all of them joined in 1969, but a 1972 *RCA Engineer* article by Schindler indicates that he did not become involved until 1970. See: H.C. Schindler, "Liquid-crystal dynamic scattering for display devices," *RCA Engineer* 17, no. 6 (Apr./May 1972): 35-39.

aspect of LCD construction underwent a transformation in the hands of the staff at Somerville. Heilmeier's team, for example, preferred to construct their displays using synthetic quartz, which retained a smoother surface than ordinary glass after the application of chemical coatings, but was also substantially more expensive.[64] The techniques they developed to fill and seal cells were similarly impractical. Klein summarized how these processes were performed prior to ECD involvement:

> First of all, they'd saw two little grooves parallel along the sides, okay? Then you'd take a piece of one mil Mylar, lay it on four sides. Okay. Put the sandwich together. Then you'd take a hypodermic needle, slide it along the groove and inject the liquid crystal, which would osmose across the space...and the excess would wind up in the two little grooves. It wasn't sealed. It was clamped.[65]

Over time, the Somerville group resolved each of these issues. Caplan procured a material, developed for airplane canopies by Pittsburgh Plate Glass, which was similar in texture and electrical behavior to quartz substrates but lower in cost.[66] Klein, Schindler, and Stern, realizing that chemical reactions between liquid crystals and most epoxies would render displays non-operational, settled on a mixture of ground glass, binders, and sealants known as "frit" to hold their devices together.[67] They also developed a replacement for the injection filling method, which had complicated the uniform distribution of dopants within the cell and relied on grooves that tended to clog.[68] In its

[64] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009; Louis Zanoni, Interview with author, Ewing, NJ, 21 Aug. 2009. Klein estimated that the per unit cost of quartz was approximately 30x that of glass. For DSRC discussions of the need for smooth electrode surfaces in LCDs and the superiority of synthetic quartz in this regard, see, for example, *Progress Report: Liquid Crystals, Oct.-Dec. 1967*, DSL, 13; *Progress Report: Liquid Crystals, Apr.-Jun. 1968*, 15.

[65] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[66] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009.

[67] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Stern and Schindler's involvement in the creation of hermetic sealing techniques is referenced in Castellano, 64. For more on frit sealing, which remains a common technique in LCD manufacturing, see Joseph A. Castellano, *Handbook of Display Technology* (New York: Academic Press, 1992), 303-305.

[68] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Chemical additives were sometimes

place, they drilled two small holes in opposite corners of the cell and used a vacuum to draw liquid crystal mixtures across the cell in a uniform layer.[69]

As Caplan and Klein refined their display construction techniques, other personnel considered the problem of scaling up from bench manufacture to an assembly line. Where previously there had been no need for large batches of liquid crystal material, Howard Sorkin now supervised the expansion of chemical production facilities.[70] At the same time, George Hiatt, as manufacturing manager, consulted with the staff to divide the production process into the discrete steps required on a factory floor.[71] By 1969, the staff and equipment associated with the liquid crystal project had grown so extensive that the group moved off-site to a company-owned warehouse in Raritan, a few miles away from RCA's main solid-state facility.[72] "There was no space available for, you know, such a gigundic [sic] undertaking at Somerville," Caplan remembered.[73]

Auspicious as the move into a new building might have been, uncertainty loomed over the Raritan liquid crystal operation. ECD had made good on its promise to increase the number of technical personnel assigned to the project, but managers at Somerville, Princeton, and corporate headquarters in New York were reluctant to expand its budget. Instead, the group relied heavily on the efforts of Jack Riddel, a marketing executive from RCA's tube manufacturing division who, in Caplan's words, "took a shine to this liquid crystal thing unbelievably."[74] Riddel mobilized his sales contacts and secured development

necessary to optimize ionic concentration for dynamic scattering. (See Ch. 5 for more details.)
[69] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.
[70] Castellano (2005), 64.
[71] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.
[72] The date of the move is based upon the author's interview with Klein as well as RCA Laboratories, *Research Report 1969*, 68. Caplan noted that the facility also housed a small in-house publishing group.
[73] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009.
[74] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009.

contracts for three very different products. The first came from an advertising firm called Ashley-Butler, which offered RCA $100,000 to construct an animated point-of-purchase display.[75] Veeder-Root, a leading producer of gauges and mechanical tabulation devices, matched that sum in exchange for a gas pump readout utilizing liquid crystals. Finally, the Jervis Corporation supplied $50,000 to incorporate liquid crystals into an automobile rear-view mirror that used dynamic scattering to reduce nighttime headlight glare.[76]

With a quarter million dollars at stake, ECD engineers sprang into action. These projects all drew upon preliminary research conducted at the DSRC, but each needed additional refinements to match customer specifications. In some cases, these modifications were straightforward, such as adding colored films to the gas pump displays to provide higher contrast.[77] Others required more ingenuity. Caplan's design for a day-night mirror worked well indoors, for example, but the slow response of liquid crystals at low temperatures led to a collaboration with Klein to devise a self-regulating heating mechanism.[78] Likewise, though Heilmeier and his team had considered the possibility of animated LCDs, determining the electrode layout for such a device and a mechanism to activate images in the proper sequence was left to the staff at Raritan.[79]

[75] Lawrence Gitman and Carl McDaniel define a point-of-purchase display as any strategically placed visual display or product display that informs potential customers about a product or service. See: Gitman & McDaniel, *The Future of Business: The Essentials* (Mason, OH: Thomson South-Western, 2008), 334.
[76] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009. Caplan and Klein's recollections differed with regard to the identity of the third firm. Caplan claimed it was the Jervis Corporation, while Klein initially thought it was Donnelly Mirrors. When this discrepancy was mentioned, Klein deferred to Caplan's view.
[77] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009.
[78] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009; Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Additional details about the day-night mirror's operation can be found in: Sandor Caplan, "Liquid Crystal Day/Night Mirror," US Patent 3,614,210, filed 6 Nov. 1969 and issued 19 Oct. 1971.
[79] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Heilmeier explicitly refers to conversations on using "LC-DSM [liquid crystal(s)-dynamic scattering mode] for point of sale displays" with Jack Riddel in a notebook entry dated 9 Jan. 1969. (Heilmeier, *Notebook 39358,* DSL, 34) In

These technical accomplishments may have impressed their customers, but for some within the operating divisions the absence of internal funding raised questions regarding RCA's commitment to LCDs. To Klein and his fellow engineers, it seemed "nobody in senior management who had any insight ever looked at this or ever talked to people and said, as I think you should..., 'What kind of products can you make?'"[80]

Actually, in September 1969, RCA's marketing staff initiated a six-month study to answer precisely that question. Working alongside a California-based consulting firm, the company invited delegates from its headquarters and operating divisions, including George Hiatt and Jack Riddel from ECD, to a pair of idea-generating sessions at New York's Hilton Hotel.[81] These discussions generated a list of more than 150 potential applications for dynamic scattering, including everything from automobile speedometers to zoo enclosures for nocturnal animals.[82] The marketing team sorted these ideas into generic product categories (e.g. alphanumeric displays, decorative and artistic displays) with assistance from Heilmeier, Riddel, and sources outside the corporation.[83] Then, drawing upon Heilmeier's "forecast of how the liquid crystal technology may be expected to

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addition, the following May, Louis Zanoni submitted a patent for a "Color Advertising Display Employing Liquid Crystal," (later US Patent 3,576,364, filed 20 May 1969 and issued 27 Apr. 1971) that simulated motion through the selective application of an electric field to different areas of a liquid crystal panel. This patent shares similarities with one subsequently filed by Klein, et al. in June 1970 (later US Patent 3,689,131, filed 29 Jun. 1970 and issued 5 Sep. 1972), though the latter replaces Zanoni's generic cam-based driving mechanism with a rotating cylinder lined with conductive strips, which regulated the sequential application of voltage to the display.

[80] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[81] Edward J. Homer, *Market Potential of Products Based on Liquid Crystal Dynamic Scattering* (New York: RCA Product and Marketing Planning, 30 Mar. 1970), DSL, 3-9, 111-122. The consulting firm in question was Product Planning Associates of Santa Barbara, CA, which, according to the report, possessed "substantial experience in new product development" (3).

[82] Homer, 111-122.

[83] Homer, 8. In addition to Heilmeier and Riddel, RCA's marketing staff also contacted Dr. Glenn Brown, the head of the Liquid Crystal Institute at Kent State University and attended trade shows sponsored by IEEE, the Society for Information Display, and *Electro-Optical Systems Design* magazine.

evolve," they evaluated each application's technical feasibility and economic competitiveness.[84]

In the end, the study "failed to identify any immediate opportunities for new end products based on liquid crystals," but noted that several existing types of products ("such as desktop calculators") could be enhanced through the inclusion of LCDs.[85] Nonetheless, the report concluded that most products available in the near-future seemed to have "relatively small market potential except alphanumeric displays, point-of-purchase advertising signs, and flat glass glazing products."[86] Not coincidentally, these three products corresponded precisely with the projects under development at Raritan.

Considered in retrospect, one item conspicuously absent from this list of recommendations was the electronic wristwatch. In the 1965 paper articulating his eponymous law, Gordon Moore had noted that only the lack of a display that could be driven by integrated circuits prevented the construction of such a device.[87] RCA's marketing study acknowledged that liquid crystals might one day overcome this hurdle, but noted that "an apparent incompatibility in the operating voltages of the watch circuit and the display" made the LCD watch a long-term prospect, one incapable of being subjected to a quantitative market forecast.[88]

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[84] Homer, 125. Heilmeier submitted two different technical forecasts for this report, dated 23 Jul. 1969 and 26 Mar. 1970.

[85] Homer, 85. [Original emphasis] Although electronic calculators had been sold since the mid-1960s, they relied upon Nixie tubes or vacuum fluorescent displays to present numerical information. Portable calculators with LED displays became available in 1971, with LCD devices reaching the market two years later. For further information, see: "Japanese Calculators of Single-Chip Circuit Are Demonstrated," *Wall Street Journal*, 28 Jan. 1971, 12; Johnstone, 37-42, 92-105.

[86] Homer, 85.

[87] Gordon E. Moore, "The Future of Integrated Electronics," Reprinted as Ch. 4 of David C. Brock, ed., *Understanding Moore's Law: Four Decades of Innovation* (Philadelphia: Chemical Heritage Foundation Press, 2006), 41. Thanks to my advisor, Michael Gordin, for reminding me of this reference.

[88] Homer, 45.

These conclusions did not dissuade the liquid crystal team in Princeton from arguing that the LCD watch merited more immediate attention. They had already filed a patent application for the concept based on their electronic clock prototype and believed that RCA's research into low-power CMOS integrated circuits promised a rapid resolution of the voltage incompatibility problem.[89] Their engineering colleagues in Raritan supported the idea, going so far as to construct mockup digital watch displays.[90] Together these two groups may well have convinced New York to reconsider their analysis had they not faced resistance from an unexpected source.

Klein and Caplan, the first two ECD personnel assigned to study LCDs, originally worked with a minimum amount of supervision from Lawrence Murray or others in the division's advanced development group. This state of affairs abruptly changed at the end of 1968. As the group prepared to move to Raritan, the corporation decided that the establishment of a factory operation required a more formal management structure. In place of Murray and his laissez-faire style, leadership of the ECD liquid crystal project passed to Norman Freedman, a chemical engineer who distinguished himself in the 1950s by devising a process to ensure the precise application of phosphor dots to the faceplates of color television tubes.[91] More recently, he had supervised the organization of a

[89] Castellano (2005), 63; Steven R. Hofstein, "Solid State Clock," US Patent 3,505,804, filed 23 Apr. 1968 and issued 14 Apr. 1970. This patent refers to both clock and watch applications. For more on RCA's CMOS (complementary metal-oxide-semiconductor) research, see Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins Univ. Press, 2002), 162-164.

[90] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[91] For more on Freedman, see: Kenyon Kilbon, "Pioneering in Electronics: A Short History of the Origins and Growth of RCA Laboratories, Radio Corporation of America, 1919 to 1964," unpublished typescript, revised Aug. 1964, 238. Paginated copy available online at http://www.davidsarnoff.org/kil.html, accessed 29 Oct. 2009.

superconductor devices laboratory at the DSRC.[92] Now it was hoped that Freedman's experience resolving manufacturing problems would facilitate the establishment of a successful liquid crystal assembly line.

As his subordinates soon realized, Freedman's methods were unsuited for this task. In the case of color television, Klein explained, "Norm's success was he beat, cajoled, robbed, stole, did whatever it took, but he got the problem solved."[93] This forceful approach, while effective with a product of unquestioned significance to the corporation, risked alienating personnel whose support would be vital to the future of a new technology like the LCD. Freedman refused, for example, to cede any control to personnel working at ECD's main semiconductor facility, even though it was obvious that liquid crystal applications would benefit from closer coordination with integrated circuit designers.[94] The ban on collaboration with Somerville was only one means by which Freedman consolidated his authority over the Raritan project. Along with his lieutenant, Walter "Lucky" Lawrence, he also imposed new regulations, such as requiring staff to write more frequent research bulletins, and regularly promoted personnel recruited from outside the operation over veterans like Klein and Caplan.[95]

Freedman's resistance to external intervention and the marginalization of his most experienced engineers effectively paralyzed the ECD liquid crystal program. Raritan's leadership confined its manufacturing efforts to alphanumeric devices, point-of-purchase displays, and dynamic scattering mirrors, none of which required substantial cooperation

[92] Kilbon, 342.
[93] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.
[94] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.
[95] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009; Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

with Somerville or Princeton. The DSRC team, which dedicated "roughly half" of its research effort in 1969 "to direct support of the liquid-crystal products activity at EC [Electronic Components] in Raritan," found its ideas rebuffed with increasing frequency.[96] From their perspective, the ECD operation was controlled by shortsighted individuals whom Heilmeier later accused of rejecting the electronic wristwatch due to a mistaken belief that "there was 'no market' and the problems of filling and sealing a liquid crystal cell...were alleged to be 'insurmountable.'"[97]

Freedman and his management team made convenient scapegoats for the holding pattern into which RCA's liquid crystal program had entered, but the tensions between Princeton and Raritan during this period were neither unprecedented nor unidirectional. Freedman's restrictive policies frustrated his staff and exacerbated disagreements with Somerville and the DSRC, but his strategy aligned with the corporation's longstanding aversion to capital investment and the findings of the 1969-70 marketing report, in which Heilmeier and Riddel were listed as principal contributors.[98] Nor could the rest of the Princeton team be cast as wholly blameless. For tremors of discontent had begun to

[96] RCA Laboratories, *Research Report 1969*, 68.

[97] Heilmeier, 785. DSRC organic chemist Joseph Castellano (2005) echoed these allegations, recalling that one divisional manager opposed the idea because "if someone put the watch in his shoe at the beach, the display would turn clear at the high temperature" (64).

[98] Homer, Acknowledgments and p. 7; Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009; Norman Goldsmith, Interview with author, Princeton, NJ, 14 Aug. 2009; Richard Klein, Interview with author, 15 Jun. 2009. Goldsmith and Caplan both made explicit references to RCA's disdain for capital investment. Caplan cited the example of the Numitron, a numeric indicator invented at RCA, which resembled a lightbulb with seven filaments and could be constructed with existing vacuum tube equipment. Announced to the public in 1969, the Numitron provided an obvious alternative to liquid crystal instrument readouts, much to the chagrin of Heilmeier and his team (Heilmeier, 784). Goldsmith, a chemist who worked at both Somerville and Princeton, referred to the later example of the VideoDisc program, which relied upon the same equipment used to press phonograph records. For more on the Numitron, see: F.J. Feyder, "Operation and application of NUMITRON digital display devices," *RCA Engineer* 17, no. 6 (Apr./May 1972): 27-31; R.D. Reichert, "Design and construction of Numitron digital display devices," *RCA Engineer* 17, no. 6 (Apr./May 1972): 32-34. For more on the VideoDisc, see: Graham, *The Business of Research*.

emanate from the DSRC, foreshadowing a larger earthquake that would shatter both the LCD research group and the corporation as a whole.

"Nixie tubes are better.": RCA's Computer Crisis and the LCD Collapse (1969-71)

Freedman's arrival disrupted institutional links with the DSRC, but the personal relationships between members of Heilmeier's group and engineers like Caplan and Klein initially defied the stereotypical characterization of RCA's central lab as an elitist "country club," unwilling to engage with manufacturing issues.[99] Not only did Princeton scientists contribute materials and circuit designs to the LCD assembly facility, but they worked with their division colleagues to build prototypes showcasing the technological potential of liquid crystals.[100] Nevertheless, as the pilot plant inched closer to operation and the burden of responsibility for product development shifted toward the divisions, some at ECD worried that the DSRC was no longer dedicated to the cause.

One could downplay occasions where Princeton personnel refused to provide Raritan's staff with access to equipment to troubleshoot malfunctioning displays "because it wasn't an interesting technical problem" as isolated incidents.[101] It was more difficult to

[99] Graham, 71. This characterization aligns with discussions of perceived differences between Princeton and Somerville in the author's interviews with Sandor Caplan (10 Jun. 2009), Norman Goldsmith (14 Aug. 2009), Richard Klein (15 Jun. 2009), Alan Sussman (19 Jan. 2011), John van Raalte (10 Jun. 2009), Richard Williams (30 Apr. 2009), and Karl Zaininger (11 Sep. 2009).

[100] Castellano (2005), 57-67; Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009; Louis Zanoni, Interview with author, Ewing, NJ, 21 Aug. 2009. Klein and Castellano both comment upon the contribution of chemists to the Raritan operation. Castellano also calls attention to devices he designed with technician Ronald Friel that utilized two "interdigitated" electrodes, lying side-by-side on a single substrate rather than requiring electrode placement on both sides of a sandwich cell. (This arrangement was, in effect, a precursor to modern in-plane switching LCDs.) In a 1970 report, Castellano and Friel alluded to their work's relevance to Raritan, noting that "[i]t may be possible to fabricate point-of-purchase displays easily and cheaply using the interdigitated pattern." See: RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Sep. 1970,* DSL, 15, 34.

[101] Klein described such an incident in his interview with the author, Clifton, NJ, 15 Jun. 2009.

ignore the departure of personnel associated with the Princeton liquid crystal initiative. Internal progress reports listed sixteen people associated with the LCD project when it went public in 1968. By the first quarter of 1970, that number had been cut in half.[102] Much of this reduction could be attributed to the decreasing involvement of Bernard Lechner and his team following the termination of their matrix display project, but key liquid crystal researchers— personnel who had been with the group from its initial organization in 1965—had also begun to fall away. Some, like chemist Lucian Barton, transferred to higher priority projects such as home video recording.[103] Others, frustrated at the pace and direction of LCD production, left to establish start-up firms based around the new technology. By the end of 1969, two of Heilmeier's earliest collaborators, Louis Zanoni and Joel Goldmacher, had left RCA to join Optel, a company founded by former DSRC laser researcher Zoltan Kiss, which planned to develop wristwatches using dynamic scattering.[104]

More disconcerting than scientists leaving the DSRC because they felt RCA did not recognize liquid crystals' commercial potential were those in Princeton who believed that the LCD had reached its short-term technological limits and did not merit continued investment. Though some RCA researchers have suggested in recent interviews that the

[102] RCA Laboratories, *Progress Report: Liquid Crystals, Apr.-Jun. 1968,* 1; RCA Laboratories, *Progress Report: Liquid Crystals, Jan.-Mar. 1970*, DSL, 1.
[103] Lucian Barton, *Notebook 39677*, DSL, 56-100. Barton became heavily involved with the VideoDisc recording project beginning in January 1969.
[104] Castellano (2005), 66-67, 91-95; Louis Zanoni, Interview with author, 21 Aug. 2009. Based on laboratory notebooks and progress reports, Goldmacher appears to have left RCA during the second half of 1969 to work at the St. Regis Paper Company before joining Optel. In his 19 Jan. 2011 interview with the author, physical chemist Alan Sussman suggested that the St. Regis detour was intended to circumvent RCA's non-disclosure policies prior to arrival at Optel, but evidence to support this claim remains purely hearsay. For more on Optel and its founder Zoltan Kiss, see: Charles G. Burck, "Optel's (Mis)adventures in Liquid Crystals," *Fortune*, Oct. 1973, 193-202, 206.

DSRC's management held this position,[105] nothing captures this sense of skepticism more effectively than a September 1971 domestic licensing report preserved in the company's technical archive.[106] In its original form, this document was meant to persuade other firms to purchase the rights to manufacture their own dynamic scattering displays. At some point, however, an anonymous staff member with a pair of scissors, some glue, and a perverse sense of humor decided to modify its contents, inserting new text and images over the original.[107] The title page, reading "RCA Liquid Crystals," was amended with a warning: "Be Suspicious." [108] A later page describing the preparation of liquid crystal materials included an image of a grinning scientist warming a teakettle in front of an equation-filled blackboard with a caption reading "Simple and idiot-proof."[109] And most damning of all, on the first page, next to a list entitled "Advantages of Liquid Crystal Displays" was a sentence proclaiming that "NIXIE TUBES ARE BETTER."[110]

The Nixie tube was the first commercially successful electronic numeric indicator, a gas-discharge device that Princeton scientists hoped to replace with relatively low power, rugged LCDs.[111] Whether or not the allegation that they were better than liquid

[105] Among the personnel who have voiced opinions to this effect in interviews are Frank Marlowe (24 Aug. 2009), Dennis Matthies (19 Aug. 2009), and John van Raalte (3 Jun. 2009, 10 Jun. 2009).
[106] *RCA Liquid Crystals: Domestic Licensing* (New York: Sep. 1971), DSL.
[107] A more thorough analysis of this modified document was the focus of the author's submission to the 2011 Princeton-Harvard Workshop in the History of the Physical Sciences, entitled "'NIXIE TUBES ARE BETTER': A Story of Sex, Booze, and the Early Years of the LCD."
[108] *RCA Liquid Crystals: Domestic Licensing*, Title page.
[109] *RCA Liquid Crystals: Domestic Licensing*, 17.
[110] *RCA Liquid Crystals: Domestic Licensing*, 1. Capitalization reflects that in the original text.
[111] Nixie tubes consisted of a glass enclosure, similar in shape to a light bulb, which was filled with neon gas. The tube contained a common anode and ten cathodes shaped like the digits 0-9. Applying a voltage to the appropriate cathode and the common anode caused that digit to glow orange. As the domestic licensing report noted, the operating voltage of Nixie tubes (~100 V) was much higher than that of dynamic scattering LCDs (~10-15V, according to Kawamoto, 484). For more on the development of the Nixie tube, see Larry F. Weber, "Plasma Displays," in *Flat-Panel Displays and CRTs,* ed. Lawrence E. Tannas, Jr. (New York: Van Nostrand Reinhold Co., 1985), 354-355; Castellano (1992), 113.

crystals was intended seriously, it reflected an awareness of the latter's susceptibility to criticism on both financial and technological grounds at an especially inopportune time. For September 1971 marked the moment when Robert Sarnoff's attempts to reinvent RCA collapsed, prompting the corporation to embark on a major reevaluation of its research priorities.

Over the preceding three years, Sarnoff had continued to endorse a strategy of diversification through acquisition. While some of the company's new ventures, such as Alaska Communications Systems, were related to its traditional focus on electronics, others, including Banquet Foods, real estate firm Cushman & Wakefield, and carpet manufacturer Coronet Industries, sparked concern among shareholders.[112] "We have already from soup to nuts," one woman protested to RCA's chairman at a meeting in February 1971. "Tell me, mister, where is it going to end? You are going to build an empire, and look what happened to all the empires!"[113] Sarnoff responded that, confronted with a sluggish national economy, the corporation needed to expand into areas with greater opportunities for growth. Elaborating on this position the next month, he observed that expansion into service industries would grant RCA freedom to achieve its technical goals, most notably "the establishment of a profitable computer business."[114]

RCA's commercial interest in electronic data processing dated to the mid-1950s, but one manager recalled that early on there was a "greater total effort in television from

[112] Sobel (1986), 197. RCA purchased Alaska Communications Systems from the U.S. Air Force.
[113] Scott R. Schmedel, "RCA's Plan to Buy Coronet Industries Clears Holders; Minority Objects Loudly," *Wall Street Journal*, 22 Feb. 1971, 6. Robert Sarnoff had been named chairman of RCA following his father's resignation in December 1970.
[114] RCA Corporation, *Annual Report 1970* (New York: RCA, 1971), 2. Sarnoff's letter in this report is dated 9 Mar. 1971.

the engineering point of view than there was in the computer."[115] The pendulum started swinging in the opposite direction following the color television boom,[116] and by the time Robert Sarnoff assumed the presidency of RCA in 1966, the company had achieved a modest commercial success with the Spectra 70 computer series.[117] Designed to be compatible with IBM's recently announced System 360, the Spectra line heralded the start of a renewed RCA campaign to compete against the nation's computing leader.[118] Robert Sarnoff harbored no illusions of ousting IBM from its dominant position within the industry, but believed it might be possible to leapfrog competitors like Sperry Rand and Honeywell to secure the second-place spot. "In order to accomplish this goal," he vowed in a September 1970 speech, "RCA is prepared to commit whatever resources are necessary."[119]

Unfortunately, Sarnoff's rhetoric exceeded the capacity of RCA's Computer Systems Division (CSD) to keep pace with IBM. CSD reported losses in 1969 and 1970,

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[115] Sobel (1986), 175. The manager quoted here is Arthur Beard, who worked as chief engineer for RCA's Computer Systems Division, as confirmed in Franklin M. Fisher, et al., *IBM and the U.S. Data Processing Industry: An Economic History* (New York: Praeger Publishers, 1983), 121. Ch. 3 of this dissertation outlines RCA's early involvement in the computer industry.

[116] As Christopher McDonald recently argued in his dissertation, RCA's renewed interest in computing paralleled a similar shift underway at Western Union during the same period. Both firms sought to reinvent themselves as "information companies" in order to maintain a leadership position in the field of telecommunications. See: Christopher McDonald, "Building the Information Society: A History of Computing as a Mass Medium" (Ph.D. diss., Princeton Univ., 2011).

[117] Sobel (1986), 181-183. For the sake of completeness, it should be noted that between the flawed RCA 601 mainframe (described in Ch. 3) and the Spectra 70, RCA also released an interim product known as the 3301.

[118] For technical information on the Spectra 70, see: A.D. Beard, "RCA Spectra-70–An Introduction to Basic Design and Philosophy of Operation," *RCA Engineer* 11, no. 3 (Oct.-Nov. 1965): 6-10; Chandler, 38-39; Fisher, 204 -213; Kenneth Flamm, *Creating the Computer: Government, Industry, and High Technology* (Washington, D.C.: The Brookings Institution, 1988), 122-125.

[119] William D. Smith, "RCA Introduces Four New Computers," *New York Times*, 16 Sep. 1970, 69. The four new computers referenced in this article's title were from the "RCA series," which was presented as RCA's answer to the IBM's System 370. For further information, see: Chandler, 39; Fisher, 215-217; Sobel (1986), 199-200.

and in spite of promises in both years' company reports of a long overdue crossover to profitability, the division's successor to the Spectra series proved a financial disappointment.[120] A series of internal audits throughout the first half of 1971 revealed that these predictions had been based upon faulty bookkeeping.[121] A revised estimate suggested that turning its computer business around would require RCA to invest one billion dollars in new capital by 1976, half of which would go directly to CSD. "I can think of two dozen things I would rather spend $500 million on," one member of the company's board of directors remarked upon hearing this news.[122]

Sarnoff, who had staked his reputation upon the success of RCA's computers much as his father had upon color television, resisted growing pressure from fellow executives to abandon the field.[123] Only after America entered into a recession and new evidence of CSD's financial instability accumulated during the summer of 1971 did he concede "that in view of everything we could not afford the price of staying in."[124] On September 16, almost exactly a year after publicly promising to make RCA number two in data processing, Sarnoff received the board's authorization to withdraw from the general purpose computer market.[125] Soon after, the company sold CSD to the Univac Division of

[120] RCA Corporation, *Annual Report 1969*, 8-9, 24; RCA Corporation, *Annual Report 1970*, 24. For more on the shortcomings of the "RCA Series," see: Fisher, 215-219.
[121] Fisher, 220; Sobel (1986), 202-203.
[122] Sobel (1986), 202. The board member quoted here is Martin Seretean, chairman and president of the recently acquired Coronet Industries. Seretean remained one of Sarnoff's harshest critics before resigning in early 1973. For more on Seretean and his frustration with Sarnoff's leadership, see: Brown, 320-323.
[123] Sobel (1986) notes that after RCA withdrew from the computer business, Sarnoff reconfigured the parallel between himself and his father to justify the decision to divest. Just as staying with color television "took a certain amount of courage and guts...," Sarnoff is quoted as saying, "It took courage to get out of computers" (206).
[124] Quoted in W. David Gardner, "Curtain Act at RCA," *Datamation*, 18 (19 Mar. 1972): 41.
[125] Gardner's article presents a compelling blow-by-blow reconstruction of the deliberations leading to RCA's withdrawal from the point of view of company executives and CSD personnel. Sarnoff's speech, as referenced in n. 119, was delivered on 15 Sep. 1970.

Sperry Rand for $127 million. It also set up a pre-tax reserve of $490 million to cover prospective losses in connection with the sale, the largest such write-off ever suffered to that point by an American business.[126]

Despite rumors of a power struggle with his company's board of directors, Sarnoff remained chairman of RCA following the computer divestiture.[127] He promptly imposed a freeze on acquisitions and implemented "the most stringent cost-reduction program in RCA history," one aimed "at all corporate and divisional levels, affecting administrative and operating units alike."[128] Factories closed across the country and the DSRC, where nearly half the staff had been drafted into computer-related work, faced an immediate 10% budget cut.[129] Within this environment, all projects were subject to additional scrutiny and those whose commercial potential and technological worth had already been called into question, such as the liquid crystal display, were particularly vulnerable. The already shrinking Princeton LCD group was thus reduced to a paltry half-dozen as personnel were let go or transferred into other projects.[130]

[126] Fisher, 226-227; Gardner, 41; Sobel (1986), 206-207. Fisher clarifies that the $490 million ($250 million after taxes) was to be used in anticipation of losses related to the disposition of assets "such as inventory, receivables, plant," "discharge of claims and obligations for commitments to employees for severance and release," and other purposes. Both Gardner and Sobel note that prior to 1971, the largest comparable write-off was the Ford Motor Company's $250 million (pre-tax) loss on the Edsel in 1959.
[127] Brown, 320; Philip Greer, "Struggle for Power at RCA?," *Washington Post*, 9 Apr. 1972, H; Sobel (1986), 207-208. Brown observes that although initially "there was no criticism by the board of any persons who might have been held responsible" for "the data-processing disaster," by early 1972 several of RCA's directors—most notably, Martin Seretean—started to openly criticize Sarnoff's leadership. A majority of the board's members, however, stayed loyal to Sarnoff, and he was able to retain his position.
[128] Chandler, 42; RCA Corporation, *Annual Report 1971*, 14.
[129] Graham, 144-145. Graham notes that the literal decimation of the Laboratories' budget corresponded to roughly a 6-7% cut in staff. The company's 1971 annual report referred to plant closures "in Indiana, New Jersey, Maine, and Wales" directly linked to the computer withdrawal (14). Gardner's article closes with a description of the nearly empty CSD building in Marlboro, Massachusetts.
[130] Castellano (2005), 70. The half-dozen estimate is based upon the handful of liquid crystal reports from Dec. 1971-Jan. 1973 preserved in the DSL's collections and does not include personnel working in other groups who provided occasional assistance. The lack of documentation from 1971 and the apparent termination of the distinct red-covered reports devoted to LCD research complicates efforts to ascertain

The cuts at the LCD pilot plant in Raritan were more extreme. "In 1971, when they canned the computer division, our group was, I think, 31 people," Klein recalled. "And they cut the group back to 8."[131] The survivors, who transferred back to the main semiconductor facility in Somerville, included Freedman and Lawrence, the two men whose policies had most isolated the liquid crystal operation from the rest of the corporation.[132] Neither Klein nor Caplan retained their positions, but they soon obtained jobs with Ashley-Butler, the advertising company responsible for financing their early point-of-purchase displays.[133]

Liquid crystal researchers constituted only a tiny fraction of the estimated 13,000 people who lost their jobs as a result of the RCA's withdrawal from the computer industry, but this purge represented the culmination of policies that had, over the preceding two years, undermined their efforts to commercialize the LCD.[134] Robert Sarnoff's acquisition-fueled venture into electronic data processing diverted resources away from consumer electronics products, like LCDs, that required sustained long-term

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changes in staff assigned to the project following the computer withdrawal. Based on the LCD group's less detailed contributions to quarterly progress reports on glass and organic materials research (1971-73) and laboratory notebooks, one may conclude that organic chemist Chan Soo Oh and physical chemist Alan Sussman (despite his claims in a 19 Jan. 2011 interview to have left RCA Labs in 1969) were among those released from the labs in late 1971 or early 1972. This will hopefully be confirmed once company organization charts are once again accessible.

[131] Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009.

[132] Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009. Schindler's 1972 *RCA Engineer* article also confirms that the liquid crystal operation returned to Somerville. (See n. 63.)

[133] Sandor Caplan, Interview with author, Princeton, NJ, 10 Jun. 2009; Richard Klein, Interview with author, Clifton, NJ, 15 Jun. 2009. Klein listed Herman Stern, Howard Sorkin, and Henry Schindler as being among those retained at Raritan, but was unable to name the remaining three staff members. Given the apparent lack of documentation from the Raritan facility, it is uncertain whether these figures can be identified.

[134] *RCA Annual Report 1971*, 15. This report notes that RCA employed 131,000 people at the end of 1970 and only 118,000 people by the end of 1971. Sobel suggests 7,500 of the fired personnel worked directly for CSD.

investment.[135] This lack of support in conjunction with deteriorating ties between the DSRC and the operating divisions, spurred the steady exodus of LCD personnel, leaving the project more likely to be affected by the 1971 layoffs.

RCA did little to staunch this outflow, with one noteworthy exception. Since 1964, George Heilmeier had been the strongest defender of liquid crystal research at the DSRC, but the infighting and politicking associated with transferring the LCD to the operating divisions sapped his passion for the work.[136] He considered leaving the company like his friends, Goldmacher and Zanoni. The corporation, fearful of losing one of its most celebrated engineers,[137] had already named Heilmeier head of "Solid State Devices Research" at the DSRC[138] and now offered him a new title, "Head, Device Concepts Research," to entice him into staying put.[139] When these failed to stop him from broaching

[135] For examples of Sarnoff's paeans to diversification, see *RCA Annual Report 1971*, 5-6; *RCA Annual Report 1972* (New York: RCA, 1973), 3; *RCA Annual Report 1973* (New York: RCA, 1974), 3.

[136] Heilmeier, 784-785; Metz, 2. According to Metz, Heilmeier's final decision to leave the corporation stemmed from a conversation in a limousine with two unnamed RCA managers, who discussed how the DSRC's LCD work could be used to win points with an associate. This account roughly corresponds with one described in the author's 11 Sep. 2009 interview with Heilmeier's colleague, Karl Zaininger. Zaininger also described a conversation in a limousine between Heilmeier and two managers (identified as William Webster and James Hillier), but claimed that their dispute concerned a lack of adequate internal recognition for his (i.e. Heilmeier's) accomplishments. Additional interviews with Wolfgang Helfrich (28 Sep. 2009) and Richard Klein (15 Jun. 2009) suggest that Heilmeier's departure may have been linked to a desire for a higher status position.

[137] In addition to the mainstream press coverage of his liquid crystal work, Heilmeier also earned two IR-100 awards from *Industrial Research* magazine (1968, 1969) and was named Outstanding Young Electrical Engineer (1968) and Outstanding Young Electrical Engineer in the USA (1969) by Eta Kappa Nu, the IEEE honor society. For confirmation of these achievements, see "Contributors," *IEEE Trans. on Electron Devices* ED-23 (Jul. 1976): 787; "Dr. G.H. Heilmeier honored by Eta Kappa Nu as outstanding young electrical engineer of 1968," *RCA Engineer* 14, no. 6 (Apr.-May 1969): 90; "RCA Leads in IR-100 Awards for 1969," *RCA Engineer* 15, no. 3 (Oct.-Nov. 1969): 95; "Heilmeier appointed White House Fellow," *RCA Engineer*, 16, 1 (Jun.-Jul. 1970): 77.

[138] The timing of this first promotion is somewhat ambiguous. The biography Heilmeier submitted to the *IEEE Trans. on Electron Devices* in 1976 indicates that he became head of Solid State Device Research in 1968. A more recent account posted in connection with the 2005 Kyoto Prize suggests Heilmeier received the position in 1966. See: "Contributors," 787; "George H. Heilmeier–The 2005 Kyoto Prize-Advanced Technology," available online at http://www.inamori-f.or.jp/laureates/k21_a_george/prf_e.html, accessed 17 Jan. 2008.

[139] An *RCA Engineer* announcement indicates that Heilmeier's second promotion occurred in the summer

the possibility of forming his own start-up, management replaced its carrots with sticks. Heilmeier remembered being warned that such a move "would be the biggest mistake of my life because they would sue the hell out of me."[140]

A White House fellowship ultimately supplied Heilmeier with the means to escape from Princeton and begin a new career in government service.[141] The corporation officially treated his 1970 departure as temporary, declaring that he was "on leave from RCA Laboratories" well after the conclusion of his one-year assignment as special assistant to Secretary of Defense Melvin Laird.[142] But while Heilmeier would remain identified with LCDs for the rest of his life, his absence from the DSRC was permanent and left his former group without its fiercest advocate both before and during the computer crisis.[143] Still, liquid crystal work persisted at RCA's laboratories and operating divisions without

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of 1969. See: "Engineering News and Highlights," *RCA Engineer* 15, no. 1 (Jun.-Jul. 1969): 95.

[140] Heilmeier quoted in Metz, 2. The fact that these titles did not convince Heilmeier to stay at the DSRC calls into question the explanation for his departure provided by Zaininger, Helfrich, and Klein. (See n. 136.) It is unclear, however, whether either of these "promotions" implied a significant increase in status, since both left Heilmeier subordinate to the director of the DSRC's Consumer Electronics Research Laboratory.

[141] Castellano (2005), 66. Castellano suggests that he may have been the one who persuaded Heilmeier to apply for a White House fellowship. Heilmeier discussed his decision in an interview with Stewart Finley. See: George Heilmeier, Interview with Stewart Finley, *Men and Molecules*. Episode 515 ("Liquid Crystals: A Bright Promise"), c. 1970.

[142] Finley's interview confirms Heilmeier's assignment. For an example of RCA continuing to treat Heilmeier's absence as temporary, see: "Engineering News and Highlights," *RCA Engineer* 20, no. 2 (Aug.-Sep. 1974): 95. On this occasion, Heilmeier was cited for receiving the Arthur Flemming Award as one of "Ten Outstanding Young Men in Government," for his work as Assistant Director of Defense Research and Engineering (Electronics and Computer Sciences).

[143] This association with liquid crystals was not always beneficial. Other LCD researchers would attack Heilmeier's decision to decline funding further LCD research upon becoming head of the Defense Advanced Research Projects Agency (DARPA) in 1975. For his part, Heilmeier remained committed to the position he presented at the 1972 IEEE Conference on Display Devices, when he asked "[h]ow many realistic scenarios are there in which we win because we have a flat-panel, matrix-addressed display in the cockpit, while the other guy has a CRT? And how many would we buy if they did exist?" (Quoted in Dunmur & Sluckin, 223) Compared to other technologies under consideration, such as stealth aircraft, Heilmeier later explained, LCD technology simply did not offer a significant increase in American defense capabilities (Johnstone, 104).

Heilmeier, though the dynamic scattering devices he perfected would soon face competition from an entirely new form of display.

Twisted Tales from Somerset County: Dynamic Scattering's Decline (1972-76)

In March 1972, Joseph Castellano published a review article surveying the present state of scientific research into liquid crystals.[144] An organic chemist who had replaced Heilmeier as leader of the Princeton LCD group, Castellano discussed recent advances in materials synthesis and future applications of dynamic scattering and guest-host color switching.[145] Though he referred to investigations underway at other U.S. firms as well as laboratories in Britain, France, Germany, and Japan, his article focused on electro-optic effects under active investigation at RCA.[146] Consequently, he chose to omit discussion of a paper published the previous year by a former member of the DSRC's technical staff named Wolfgang Helfrich.[147]

This omission was somewhat curious since Helfrich had been a part of RCA's liquid crystal research team and, in fact, shared an office with Castellano for several years.[148] The two worked on different aspects of the LCD project, with Castellano

[144] Joseph A. Castellano, "Liquid Crystals for Electro-Optical Application," *RCA Review* 33, no. 1 (Mar. 1972): 296-310.
[145] Castellano (1972). This article also contained sections related to storage mode LCDs and the field-induced phase change effect referred to in n. 54.
[146] Castellano (1972), 310-311. The list of 39 references contains 18 papers by researchers affiliated with the DSRC liquid crystal group. Other institutions (and personnel) represented included Bell Labs (F. Kahn), Farbwerke Hoescht AG (H. Kelker, et al.), Hitachi (K. Toriyama, et al.), the University of Hull (G. Gray & K. Harrison), the Laboratoire de Physique des Solides Faculté des Sciences, Orsay (P. De Gennes), Merck (Steinsträsser & Pohl), and Texas Instruments (D. Jones, et al.).
[147] M. Schadt & W. Helfrich, "Voltage-Dependent Optical Activity of a Twisted Nematic Liquid Crystal," *Applied Physics Letters* 18, no. 4 (15 Feb. 1971): 127-128.
[148] Castellano (2005), 72. RCA telephone directories from 1968-1969 confirm Castellano's recollection.

creating new liquid crystal mixtures as Helfrich, a physicist trained at the Technical University of Munich, devised mathematical models to explain their behavior under applied fields.[149] At first, these studies concentrated upon the *nematic* liquid crystals that demonstrated dynamic scattering.[150] Helfrich immersed himself in the DSRC's technical library and soon familiarized himself with the properties of these substances, whose molecules could be roughly envisioned as rods capable of sliding past one another with their long axes in parallel, much like matches in a box.

It was in the midst of these investigations that Helfrich encountered the writings of French crystallographer Charles Mauguin.[151] In a 1911 paper, Mauguin demonstrated that one could align the molecules in a nematic liquid by placing them upon a glass plate that had been rubbed in a uniform direction with a piece of paper.[152] Furthermore, if one placed a liquid crystal sample between two such plates and twisted one 90°, the molecules near each surface retained their original orientation, while those in the middle formed a helical structure.[153] When polarized light shone through such a sample, this helix behaved like a spiral staircase, rotating the light's plane of polarization as it moved from the top toward the bottom surface.[154]

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[149] Wolfgang Helfrich, Interview with author, Berlin, Germany, 28 Sep. 2009. For additional details on Helfrich's career prior to arriving at RCA in 1966, see: Castellano (2005), 72; Dunmur & Sluckin, 204-5.
[150] See, for example: W. Helfrich, *PTR-2473: A Molecular Theory of Flow Alignment of Nematic Liquid Crystals,*24 May 1968, DSL; W. Helfrich, *PTR-2567: Alignment Inversion Walls in Nematic Liquid Crystals in the Presence of a Magnetic Field,* 12 Sep. 1968, DSL; W. Helfrich, *PTR-2686: Conduction-Induced Alignment in Nematic Liquid Crystals: Basic Model and Stability Consideration* , 26 Feb. 1969, DSL.
[151] Wolfgang Helfrich, Interview with author, Berlin Germany, 28 Sep. 2009.
[152] Ch. Mauguin, "On the Liquid Crystals of Lehmann," [Sur les cristaux liquides de Lehmann] *Bulletin de la Société française de Minéralogie* 34 (1911), 71-117 in Timothy Sluckin, et al,, ed., *Crystals That Flow: Classic Papers From the History of Liquid Crystals* (New York: Taylor & Francis, 2004), 100-122.
[153] Mauguin, 112.
[154] Mauguin, 112-120; Dunmur & Sluckin, 74. The spiral staircase simile is derived from Burck, 195.

Although Mauguin's findings had been published for nearly sixty years, Helfrich was among the first to relate the optical properties of these "twisted nematic" systems to more recent studies of liquid crystals' electrical behavior. Eventually he approached George Heilmeier with an idea for a new type of LCD, which effectively combined the apparatus utilized in each set of experiments.[155] Helfrich proposed creating a twisted nematic structure inside a standard RCA sandwich cell, which would then be surrounded by a pair of crossed polarizing filters. Normally, any light passing through the first polarizer would be blocked by the second, but the presence of the helical liquid crystal "staircase" between them would rotate the light so it could proceed through the cell. Yet as Heilmeier and his colleagues had shown, applying a voltage to certain types of liquid crystals caused their molecules to realign with their long axes parallel to the field (i.e. perpendicular to the glass), demolishing the staircase and preventing all light transmission. This ability to electronically control the passage of light, Helfrich argued, could serve as the basis for a display device.[156]

[155] Helfrich acknowledged in his 28 Sep. 2009 interview that he did not keep careful records during his time at RCA, and it appears that he did not deposit any notebooks in the company's technical library. It is therefore difficult to reconstruct the investigative pathways leading to his new display device.

[156] To clarify, Helfrich's device relied upon the use of nematic materials like PEBAB (p-ethoxybenzylidene-4-aminobenzonitrile), which exhibited positive dielectric anisotropy. Castellano (2005) confirms that Helfrich would have known about such compounds from internal reports and discussions (72). It is worth noting that the operation of the twisted nematic device bears a resemblance to the field-induced phase change between a helical cholesteric mesophase and a non-helical, nematic mesophase, which the RCA group had investigated since the final quarter of 1967. (See n. 54.) Helfrich composed several technical reports on the effect of electric fields on cholesteric helices. See, for example: W. Helfrich, *PRRL-70-TR-164: Deformation of Cholesteric Liquid Crystals with Low Threshold Voltage*, 12 Aug. 1970, DSL; W. Helfrich, *PRRL-70-TR-236: Electrohydrodynamic and Dielectric Instabilities of Cholesteric Liquid Crystals*, 4 Nov. 1970, DSL. While these reports postdate the 1969 discussion in which Helfrich claims to have first described the twisted nematic display, they still suggest one possible source of inspiration for the device's operating principles.

Heilmeier listened to Helfrich's proposal twice, once in 1969 and once in 1970, but concluded in each case that the notion was not worth pursuing.[157] "And he gave me a reason for that," Helfrich recalled. "Because the two polarizers, they absorb too much light and therefore this is not an interesting effect...I told him the whole concept and he rejected it."[158] Disheartened by Heilmeier's response and the progressive dissolution of the Princeton liquid crystal group, Helfrich set aside his display concept until 1970, when he accepted a position at the Swiss pharmaceutical firm Hoffman-La Roche.[159] A month after arriving at his new laboratory in Basel, he and fellow physicist Martin Schadt successfully assembled a functional twisted nematic LCD.[160] After submitting a patent application, the two related their findings in a February 1971 article in *Applied Physics Letters*.[161]

Dunmur and Sluckin have suggested that Heilmeier's rejection of the twisted nematic display was rooted in a desire to squelch a rival that might divert attention away from "his" dynamic scattering devices.[162] By casting this decision as mostly personal, these authors ignore the extent to which institutional factors at RCA mitigated against the

[157] Oral history interviews with Goodman (21 Aug. 2009), Sussman (19 Jan. 2011), and Zanoni (21 Aug. 2009) suggest that Helfrich also discussed his ideas with other DSRC personnel before leaving RCA in 1970.

[158] Wolfgang Helfrich, interview with author, Berlin, Germany, 28 Sep. 2009. As discussed in Ch. 5, Heilmeier had initially considered using crossed polarizers to construct liquid crystal light valves, before abandoning them in favor of dynamic scattering.

[159] Dunmur & Sluckin suggest two reasons for Hoffman-La Roche's interest in sponsoring liquid crystal research: 1.) The firm had just signed an agreement with electrical manufacturer Brown Boveri et Cie (BBC) to develop new forms of medical equipment which might utilize LCDs; 2.) The liquid crystalline nature of cell membranes and lipids was attracting greater attention from biologists (211).

[160] Castellano (2005), 73-74; Kawamoto, 473.

[161] Schadt & Helfrich, "Voltage-Dependent Optical Activity." Helfrich and Schadt secured a Swiss patent for the twisted nematic display in the summer of 1971. By that point, James Fergason, who had left Kent State's Liquid Crystal Institute to establish the International Liquid Xtal Company (ILIXCO), had independently developed a similar device, leading to an extended legal battle for patent priority in the United States. Since these disputes and the resulting out of court settlement in 1976 did little to slow the spread of the new technology, they will not be discussed in depth here. Those interested in the details are encouraged to consult Castellano (2005), 75-79 or Dunmur & Sluckin, 217-220.

[162] Dunmur & Sluckin, 204-205.

adoption of Helfrich's new technology. Remember that in 1969, when Helfrich first presented his idea, the Princeton and Somerville liquid crystal groups had essentially committed the entirety of their limited development budgets to the commercialization of dynamic scattering. These efforts did not end following Heilmeier's exit from the corporation or the dramatic staff reductions of 1971.

At the DSRC, Castellano renewed attempts to secure contract funding and partnerships with RCA's operating divisions in Camden, Indianapolis, Van Nuys, and West Palm Beach.[163] Meanwhile, the remaining LCD personnel at ECD, renamed the Solid State Division (SSD) in April 1970, continued to move slowly towards the establishment of an assembly line, focusing on numeric indicators.[164] In February 1972, an SSD spokesman described plans to commence full-scale production of six types of dynamic scattering readouts for watches and "minicalculators" by the end of the year.[165] Only the following summer did DSRC scientists initiate a study comparing the performance of

[163] Castellano (2005), 67-70; Joseph Castellano, e-mail message to author, 31 Jan. 2011. Camden was the site of RCA's Government and Commercial Systems Division, an amalgamation of the company's former Defense and Commercial Electronics Products groups which coordinated with Princeton to develop new military applications of LCD technology. Indianapolis served as home to the corporation's Consumer Electronics Division, where Castellano tried to persuade colleagues to replace mechanical television tuners with a digital liquid crystal readout. West Palm Beach, FL housed an electronic component assembly facility which constructed an early mockup of a calculator with a dynamic scattering display. The Electromagnetic and Aviation Systems Division at Van Nuys, CA was originally dedicated to missile and surface radar projects, but in January 1970 became home to a satellite branch of the corporation's Advanced Technology Laboratories (ATL). The DSL possesses a small collection of documents and photographs from the Van Nuys facility confirming ATL's interest in flat-panel display technologies, including liquid crystals.

[164] Schindler, 35-39. The new division, an announcement in *RCA Engineer* explained, "was formed through the consolidation of RCA's Integrated Circuit Technology Center of Research and Engineering [i.e. Princeton] and the solid-state operations of Electronic Components [i.e. Somerville]." See: "New Solid-State Division Formed," *RCA Engineer* 15, no. 6 (Apr.-May 1970): 91.

[165] Barry Kramer, "Chemical Chameleons: Liquid Crystals, Once Merely Curiosities, May Become Boon to Industry, Consumers," *Wall Street Journal*, 29 Feb. 1972, 36. A February 1973 article in *Electronics Australia* suggests that RCA was able to meet this objective by July 1972. See: Linden Harrison, "Liquid Crystal Displays," *Electronics Australia*, Feb. 1973, 22-24.

dynamic scattering and so-called "field-effect" (i.e. twisted nematic) displays under different viewing conditions.[166] Along with technician Ronald Friel and electrical engineer Lawrence Goodman, Castellano surveyed more than 200 DSRC employees, reporting that "a significant large majority...preferred the cell with a specular reflecting back electrode using the dynamic scattering effect."[167]

While these results validated Heilmeier's opposition to displays reliant upon crossed polarizers, the survey also indicated that subjects' display preferences were heavily dependent upon ambient illumination. The white numbers in a dynamic scattering display were bright and legible under normal room lighting, but glare from the reflective backplate made them hard to read outdoors. Conversely, the black digits of the twisted nematic cell were not as bright indoors as a dynamic scattering display, but benefitted from increased contrast while in direct sunlight.[168]

These findings possessed obvious significance given RCA's interest in creating watch displays, and for the rest of 1972, the DSRC group placed a "major emphasis on materials" for twisted nematic devices.[169] But Castellano and his colleagues continued to explore dynamic scattering even as competitors, ranging from start-ups like Optel to established rivals like Texas Instruments (TI), abandoned the older displays.[170] Like RCA, these companies had an interest in watches and saw the benefits of a high contrast display

[166] Joseph A. Castellano, et al., *PRRL-72-TR-137: Human Factor Analysis of Reflective Liquid Crystal Displays*, 30 Aug. 1972, DSL. This study's June 1972 start date is confirmed in Joseph Castellano, *Notebook 45534*, DSL, 37.
[167] Castellano, et al., *PRRL-72-TR-137*, 14.
[168] Castellano, et al., *PRRL-72-TR-137*, 13-14.
[169] Joseph A. Castellano, *Liquid Crystal Research Program: 1972 Annual Report*, Jan. 1973, Joseph Castellano Collection, DSL, 1.
[170] Castellano (1973), 1. In addition to continued efforts to develop new dynamic scattering mixtures, this report also outlines work on improved addressing of matrix arrays and glare reduction techniques.

that was visible inside and out.[171] Moreover, twisted nematics required a fraction of the operating power of dynamic scattering displays, which promised to extend battery life and simplify integrated circuit design.[172] TI engineers constructed a prototype wristwatch with a twisted nematic display in 1972 and Optel, having already beaten RCA to the punch by being the first to supply dynamic scattering watches to consumers, began phasing in twisted nematic models by the end of 1973.[173]

By 1974, RCA's management recognized that dynamic scattering was falling by the wayside and that the small liquid crystal operation that SSD had nurtured since 1971 was at risk of losing its customer base. Despite increased competition and the precarious economic climate after the Arab oil embargo, that February the firm announced the construction of a new LCD factory in Somerset County, NJ. The 60,000 square-foot Franklin Township plant, dedicated to the design and manufacture of twisted nematic clock and calculator displays, would employ 100 people once it opened that October.[174] It was a move reminiscent of the establishment of the Raritan operation five years earlier, but to some it seemed as though the neither SSD nor New York had learned from the mistakes that had resulted in that facility's closure.

[171] For a more comprehensive list of U.S. companies involved in the early LCD industry, see Castellano (2005), Ch. 8.

[172] Castellano (2005), 89. According to Kawamoto, the power dissipated by a dynamic scattering display, ranged between 10-100μW/cm^2, while a twisted nematic display dissipated less than 1μW/cm^2. This difference is attributable to the fact that a dynamic scattering display requires a current flow through the cell while unraveling a nematic helix is a purely field dependent effect.

[173] Burck, 202; Castellano (2005), 91-95, 101-104; Louis Zanoni, Interview with author, Ewing, NJ, 21 Aug. 2009. Castellano does not claim that TI engineers Sun Lu and Derek Jones constructed the first twisted-nematic LCD wristwatch, only that they believe this to be the case.

[174] "RCA Building New Jersey Plant," *Wall Street Journal*, 21 Feb. 1974, 8; Bill D. Ross, "A Bank Loan to 2d-Graders," *New York Times*, 12 May 1974, 79. Although both of these articles refer to the facility as being located in Franklin Township, the existence of multiple townships with that name in New Jersey has led me to follow the lead of personnel like Lawrence Goodman and Alan Sussman, who referred to it as the "Somerset plant" during oral history interviews. The October 1974 start date is listed in RCA Laboratories, *Research Report 1974*, 180.

To be sure, personnel at the Somerset facility resolved many technical issues associated with the fabrication of twisted nematic displays. Physical chemist Alan Sussman, who was hired by SSD after being fired from the DSRC in 1971, designed a machine that assured proper molecular alignment by depositing thin inorganic films on glass substrates rather than physically rubbing them. That way, he explained, "there was less handling. You didn't want to leave fingerprints. You didn't leave, you know, grit and stuff."[175] Unlike rubbing, this technique also leant itself well to the high temperatures involved in frit-sealing, but Sussman observed that the resulting displays often possessed a non-uniform, pox-like appearance. He deduced that this was due to the simultaneous formation of nematic helices with left-handed and right-handed twists. His solution, adding a small amount of optically active material to induce a uniform directional orientation, soon became standard practice throughout the LCD industry.[176]

As had been the case at Raritan, these hurdles in manufacturing proved easier to overcome than those imposed by management. The newly appointed head of liquid crystal development, Pat Farina, chose to rely upon veterans from the company's previous assembly line to oversee daily operations, including "Lucky" Lawrence, who once again

[175] Alan Sussman, Interview with author, Princeton, NJ, 19 Jan. 2011. This "slant evaporation" technique, so named because the angle at which the films were applied affected the direction of molecular orientation, was not an RCA invention, nor was Sussman the first to utilize it for LCD construction. He does seem to have been responsible for its application within RCA to larger scale manufacturing. For further information see: Castellano (1973), 20-22; Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009; Lawrence A. Goodman, et al., "Topography of Obliquely Evaporated Silicon Oxide Films and Its Effect on Liquid-Crystal Orientation," *IEEE Trans. on Electron Devices* ED-24, no. 7 (Jul. 1977): 795-804; John L. Janning, "Thin film surface orientation for liquid crystals," *Applied Physics Letters* 21, no. 4 (15 Aug. 1972): 173-174.

[176] Kawamoto, 479; Alan Sussman, Interview with author, Princeton, 19 Jan. 2009. Sussman first published this idea in 1972 during a brief stint at Optel, but Kawamoto suggests that the idea pre-dated his firing from RCA in 1971. See: Alan Sussman, "Electrooptic Liquid Crystal Devices: Principles and Applications," *IEEE Trans. on Parts, Hybrids, and Packaging* PHP-8, no. 4 (Dec. 1972): 24-37.

proceeded to alienate his subordinates among the technical staff.[177] This tactical blunder might have been tolerable had RCA's executives not persisted in adhering to a contract-based funding strategy. The computer write-off had restored the company's traditional focus on consumer electronics and left it more wary than ever of expensive side projects. "If the Solid State Division could make a business out of watch displays and calculator displays, fine," DSRC engineer Lawrence Goodman, a frequent visitor to the Somerset facility, noted, "But the main interest, corporate-wide was television."[178] As before, the liquid crystal operation could not rely on New York to sponsor its activities.

If there was a silver lining to this gloomy fiscal situation, it was that the LCD had become a somewhat more established technology, meaning that firms that had hesitated to approach RCA in 1969 were now more likely to invest. Sure enough, in 1975, the company secured a $4 million dollar purchase order from Timex, the nation's leading watchmaker, which saw the arrangement as a means of dipping its toe into the realm of digital displays as it worked to establish its own liquid crystal and integrated circuit manufacturing facilities.[179] The Somerset plant, like Raritan before it, threw itself into this task, precluding discussion of any other LCD applications. So it was that RCA, the first-ever manufacturer of liquid crystal displays, found itself reduced to the role of contractor, assembling clock digits derived from a technology it had previously shunned and selling them under someone else's name.

[177] Alan Sussman, Interview with author, Princeton, 19 Jan. 2009. Patrick Farina is something an enigma. He is implied to be in charge of SSD's Liquid Crystal Engineering program in a 1973 issue of *RCA Engineer* (Apr-May 1973, 84), but his formal appointment as Director of Liquid Crystal Operations is not mentioned until 1975 (*RCA Engineer*, Apr.-May 1975, 92). Neither of these articles provide any information about his qualifications for the position or any previous experience with electronic displays.
[178] Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009.
[179] Castellano (2005), 132-133; Gold, 63; Kathleen McDermott, *Timex: A Company and its Community, 1854-1998* (New York: Timex Corporation, 1998), 182-183, 192-193.

The General's Dream Revisited: Liquid Crystal Research at the DSRC (1972-1976)

It was perhaps for the best that David Sarnoff did not have the chance to witness RCA's marginalization of liquid crystals. After spending three years bedridden with infections that gradually robbed him of his sight, speech, and hearing, the eighty year old executive, still popularly referred to as "the General," passed away in December 1971.[180] In obituaries, the press echoed the eulogy offered by New York governor Nelson Rockefeller, who praised Sarnoff's "capacity to look at the same things others were looking at but to see far more."[181] While newspapers emphasized his successes with radio and color TV, to the RCA researchers who gathered in Princeton to watch a broadcast of the funeral those words could apply to any number of technologies, including the LCD. Indeed, Sarnoff's public predictions of "mural televisions" that would hang on the wall like paintings inspired two decades worth of flat-panel display research at the DSRC.[182]

Now it seemed the General's death heralded an end to RCA's attempts to create a thin, wall-mounted replacement for the cathode ray tube (CRT), at least so far as liquid crystals were concerned. Critics have since placed the blame for this state of affairs squarely on the shoulders of Robert Sarnoff, grouping liquid crystals alongside computers as evidence that he lacked his father's ability to oversee complex technological projects.[183]

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[180] Bilby, 279-282. Sarnoff had earned the rank of Brigadier General for his role coordinating communications during the Allied invasion of Europe in 1944 and retained the nickname for the rest of his career.

[181] *Eulogies, David Sarnoff 1891-1971*, David Lilienthal Papers, Box 498: 1971 Correspondence: Name Files (S-Z); Public Policy Papers, Department of Rare Books and Special Collections, Princeton University Library, 2-3. See also: "David Sarnoff of RCA Is Dead; Visionary Broadcast Pioneer," *New York Times*, 13 Dec. 1971, 1; Lawrence Laurent, "Sarnoff : 'Electronics Prophet,'" *Washington Post*, 13 Dec. 1971, C4.

[182] See Ch. 2 for more on David Sarnoff's personal interest in flat-panel displays.

[183] See, for example, Heilmeier quoted in Smith (1995), 14-18. See also: Graham, 86, 231; Johnstone, 102-103; Sobel (1986), 207-210.

Such comparisons overstate the extent to which RCA's chairman exerted personal control over his corporation's laboratories. For although Robert Sarnoff's actions set the stage for the termination of liquid crystal television research at RCA, the killing blow came not from New York but from within the walls of the DSRC.

The decision stemmed from a series of meetings inaugurated in 1972 by William Webster. The company's *annus horribilis* had profoundly affected the DSRC head, who reportedly aged visibly during the final months of 1971, and he resolved to protect the Princeton labs from further layoffs.[184] In 1972, Webster organized several research planning sessions with representatives from RCA's operating divisions and corporate staff, examining the entirety of the company's research portfolio "with respect to such factors as risk, potential payoff, and timing."[185] Based on these discussions, the DSRC initiated several new programs supporting the company's renewed interest in consumer electronics, including one "with the goal of a flat panel display for TV receivers."[186]

Webster's choice to lead this project was John van Raalte, an early member of Heilmeier's research team and the first person to display a live television image on a liquid crystal screen.[187] Van Raalte was, by his own admission, "not as full time associated with the liquid crystals" as the rest of the group and had set aside LCDs since the 1968 press conference to concentrate on projection television experiments.[188] His familiarity with both

[184] Graham, 145.
[185] RCA Laboratories, *Research Report 1972,* DSL, 1.
[186] RCA Laboratories, *Research Report 1972,* DSL, 1.
[187] For more on Van Raalte's contributions to RCA's LCD research, see Ch. 5.
[188] John van Raalte, Interview with author, Princeton, NJ, 3 Jun. 2009. Van Raalte refined a projection television concept devised by Ray Kell in 1963, which produced an image by reflecting light off a deformable metal mirror scanned with an electron beam. (See Ch. 3.) See also: John van Raalte, *PTR-2698: SLV-A New TV Projection System*, 27 Mar. 1969, DSL; J.A. van Raalte, "New Schlieren light valve for television projection," *RCA Engineer* 16, no. 4 (Dec. 1970-Jan. 1971): 70-73.

CRT and flat-panel technologies prompted his appointment as head of display and device concepts research after Heilmeier abdicated the position in 1970 and, two years later, qualified him to serve as leader of the newly formed Flat TV Display Task Force.[189]

Webster placed Van Raalte in charge of "10-15 RCA Laboratories scientists with diverse technical backgrounds" who were asked to determine "the most promising approach towards the development of a large-area flat, consumer, color TV receiver."[190] The resulting device had to match the image quality and power requirements of existing televisions while expanding the screen size to an impressive 50" diagonal (30" x 40").[191] A conventional vacuum-filled CRT with those dimensions would be too bulky for most living rooms and at risk of implosion due to atmospheric pressure on its faceplate, so an alternative design would be required. Also, the requirement of a thin form factor likely meant abandoning the use of scanning electron beams in favor of some form of coincident addressing.[192]

Throughout the second half of 1972, Van Raalte's team evaluated candidate technologies for use in a flat-panel television. They quickly eliminated LEDs due to their

[189] Van Raalte's appointment to the former position is confirmed in *RCA Engineer*, 16, no. 3 (Oct.-Nov. 1970): 95.

[190] John van Raalte, *RCA Laboratories' Research Program on Large-Area, Flat TV Displays* (Nov. 1973), DSL, 1. This memorandum was intended to "review briefly the alternatives considered and the rationale used by the Flat TV Display Task Force" in compiling its recommendations the previous year. It does not contain a comprehensive list of the group's members, though it does contain a reference to a set of recommendations submitted by Van Raalte, Jan Rajchman, Istvan Gorog, and Neil Yocom (21). In a 10 Jun. 2009 interview with the author, Van Raalte confirmed the additional involvement of Charles Anderson, Carmen Catanese, Tom Credelle, John Endriz, Jules Levine, Tom Stanley, and James Tietjen.

[191] Van Raalte (1973), 1-2. This document never specifies a thickness limit, but Van Raalte estimated that it was "not bigger than 5 to 10 centimeters" (~2-4 inches) in his 10 Jun. 2009 interview with the author.

[192] Van Raalte (1973), 3-5. Van Raalte further specified that this would not be what would today be termed an active matrix display since "it is impractical to individually address some 5×10^5 picture elements." Instead, the DSRC team would focus on using "the coincidence of two or more signals on several conductors...to address only the element at their intersection" (3).

high cost, low brightness, and limited range of available color options.[193] Plasma displays at least provided the possibility of a full spectrum through the use of phosphors excited by ultraviolet light, but this process raised the device's power requirements and relied on unstable compounds.[194] Electroluminescence, which had served as a focus for DSRC flat-panel research since the 1950s, was likewise dismissed for failing to match the efficiency and reliability of existing TV phosphors.[195]

In addition to these emissive display technologies, the group also considered those that modulated the passage of external light rather than producing their own.[196] Liquid crystals fell into the latter category, and Van Raalte assigned Lawrence Goodman to give a presentation to the group enumerating the strengths and weaknesses of matrix-addressed LCDs.[197] Goodman likely echoed the report that Lechner and his team filed in 1970 at the conclusion of their display project, highlighting liquid crystals' low power requirements and ability to operate at television speeds.[198] Like Lechner, he also recognized that each of the ~500,000 pixels in the proposed display would require its own diode or transistor to ensure proper switching.[199] Goodman's research into improved thin-film devices suggested

[193] Van Raalte (1973), 12-13.
[194] Van Raalte (1973), 10-11. Today's plasma TVs utilize precisely the type of UV-excited phosphors Van Raalte describes here, though their efficiency and operating life have been considerably improved.
[195] Van Raalte (1973), 11-12. For more on early electroluminescence research at the DSRC, see Ch. 2-3.
[196] Van Raalte (1973), 13-15. In addition to LCDs, this report also contains brief discussions of electrophoretic and electrochromic displays. Electrophoresis refers to the movement of charged particles in an electric field. Today, electrophoretic displays are found in various digital reading devices such as the Kindle and Nook. Electrochromic substances change color when subjected to a voltage or current and are now used in "smart windows" whose transparency can be controlled electronically. For more on all three types of displays, see: L.A. Goodman, "Passive Liquid Displays: Liquid Crystals, Electrophoretics, and Electrochromics," *IEEE Trans. on Consumer Electronics* CE-21, no. 3 (Aug. 1975): 247-259.
[197] Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009. Goodman acknowledged his familiarity with Lechner's work.
[198] B.J. Lechner, et al., *PRRL-70-TR-079: Liquid Crystal Displays*, 24 Apr. 1970, DSL.
[199] Van Raalte (1973), 13. As described in Ch. 5, Lechner's team developed addressing schemes using both types of components during the course of their work.

one solution to this problem, but in the short term such manufacturing hurdles, along with restrictions on illumination, viewing angle, and color did not bode well for the LCD.[200]

The Flat TV Display Task Force's deliberations continued until December 1972, when they submitted a report to the DSRC's management summarizing their findings.[201] They concluded that each of the alternatives under consideration, including liquid crystals, possessed significant shortcomings that would require extensive research before they could match the luminous efficiency, peak brightness, and color gamut of commercial television.[202] "It is basically for these reasons," Van Raalte wrote in a clarifying memorandum the following year, "that the Task Force recommended that RCA Laboratories initiate a major research effort to develop a flat 30" x 40" cathodoluminescent TV display."[203] Rather than replace the CRT with an unproven technology, the Princeton engineers would redesign one that had withstood the test of time, incorporating a new internal support structure and replacing the electron gun with an area cathode capable of showering electrons across the entirety of the display.[204]

As Van Raalte pointed out in 1973, the Flat TV Task Force report was not a call to eliminate research into alternative display technologies. "For the small, monochrome display application," he observed, "both plasmas and DC-EL [**d**irect **c**urrent driven **e**lectro**l**uminescence] have already demonstrated near acceptable performance."[205] To the

[200] Van Raalte (1973), 13.
[201] J.A. Rajchman, et al., "Recommendations of the Flat Panel TV Task Force," 15 Dec. 1972. I have been unable to find a copy of this document, which is listed as the sole reference on p. 21 of Van Raalte (1973). It is hoped that a copy will emerge during the reorganization of the DSL collections.
[202] This list of criteria is drawn from RCA Laboratories, *Research Report 1972*, DSL, 101.
[203] Van Raalte (1973), 16.
[204] Van Raalte (1973), 16.
[205] Van Raalte (1973), 19. The Task Force distinguished between DC and AC driven electroluminescent displays due to differences in the life spans, brightness, and color availability of materials involved in each case.

membership of the Princeton LCD group, however, their fellow scientists' endorsement of the modified CRT strategy marked the end of organized attempts to incorporate liquid crystals into TV-type systems. The growing manpower assigned to the flat-panel CRT project and the active participation of two staff vice-presidents reaffirmed this conclusion.[206]

Between 1973 and 1975, liquid crystal research continued at the DSRC, but with priorities different from those propagated by Heilmeier and his colleagues in the 1960s. Fittingly, this change coincided with the decision of Joseph Castellano, Heilmeier's successor as head of the LCD project, to leave RCA and join a start-up display company.[207] Control over liquid crystal research passed to chemist Dan Ross, who, unlike his predecessors, made few efforts to seek outside support for display development. Under Ross's leadership, work continued into surface alignment treatments, addressing circuitry, and other processes seen as relevant to SSD, but otherwise Princeton's liquid crystal investigations pivoted towards fundamental electro-optic studies.[208] These explorations proliferated to such a degree that the group arranged a weekly seminar series to discuss the physics and chemistry of liquid crystals.[209]

[206] Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009; John van Raalte, Interview with author, Princeton, NJ, 10 Jun. 2009. The flat-panel TV (FPTV) project was listed as one of the DSRC's main priorities in all annual reports between 1972 and 1975. Shortly thereafter, the project staff was reassigned to support the rollout of the VideoDisc. The two vice-presidents referenced here are Tom Stanley (Staff Vice President, Research Programs) and Jan Rajchman (Staff Vice President, Information Sciences). Rajchman's involvement in this project shows that after two decades, he had not lost his enthusiasm for flat-panel display research. For more on Rajchman, see Ch. 2.

[207] George Taylor, a former RCA staff member whose work on electroluminescent displays is discussed in Ch. 3, recruited Castellano to work at his new company, Princeton Materials Science. Despite initial success making liquid crystal watch displays, the firm went out of business in 1975. See: Castellano (2005), 96-100; George Taylor, Interview with author, Pennington, NJ, 14 Oct. 2009.

[208] Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009; RCA Laboratories, *Research Report 1973*, DSL, 49, 130; RCA Laboratories, *Research Report 1974*, 41, 135-136; RCA Laboratories, *Research Report 1975*, 44-45.

[209] E.B. Priestley and Peter J. Wojtowicz, "An Introduction to the Science and Technology of Liquid

The mid-1970s decline of LCD research at RCA is perhaps most evident in the DSRC's handling of two projects pursued by physicist Donald Channin. Channin, a participant in the liquid crystal group's seminars, had parlayed his interest in optical waveguides into a pair of devices utilizing mesomorphic compounds.[210] One, a three-terminal light valve that he believed might be better equipped for TV applications than earlier sandwich cells, received little attention beyond a conversation with Webster.[211] The other, a nondestructive technique to observe the internal functions of an integrated circuit using a layer of nematic materials, provoked sufficient interest to merit a photograph in the *New York Times* and inclusion in the company's 1974 shareholders report.[212]

The publicity gap between these two projects is not, in itself, revealing since Channin's redesigned cell would not be incorporated into any products, but the fact that the only textual reference to liquid crystals in RCA's annual bulletins between 1970 and 1975 did not relate to display devices shows how much the technology's status had changed since 1968. The DSRC's leadership had once presented liquid crystal research as the best chance of bringing the General's dream of a wall-mounted TV to life, but now it

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Crystals," *RCA Review*, 35, no. 1 (Mar. 1974): 79-80. Many of the lectures presented during the course of this seminar were published in *RCA Review* as well as a book: E.B. Priestley, et al., ed., *Introduction to Liquid Crystals* (New York: Plenum Press, 1975).

[210] Donald Channin, Interview with author, Princeton, NJ, 17 Aug. 2009. See also: D.J. Channin, "Liquid-Crystal Optical Waveguides," *RCA Review*, 35, no. 4 (Dec. 1974): 652-666.

[211] Donald Channin, Interview with author, Princeton, NJ, 17 Aug. 2009; RCA Laboratories, *Research Report 1974,* 48. See also: D.J. Channin, "Triode optical gate: A new liquid crystal electro-optic device," *Applied Physics Letters*, 26, no. 11 (1 Jun. 1975): 603-605; D.J. Channin & D.E. Carlson, "Rapid turn-off in triode optical gate liquid crystal devices,"*Applied Physics Letters* 28, no. 6 (15 Mar. 1976): 300-302.

[212] *RCA Annual Report 1974*, 19; RCA Laboratories, *Research Report 1973*, 51; Stacy V. Jones, "Testing System is Found for Integrated Circuits," *New York Times*, 24 Jan. 1976, 39. For more information on this technique, see: D.J. Channin, "Observing integrated-circuit operation with liquid crystals," *RCA Engineer* 20, no. 2 (Aug-Sep. 1974): 70-73.

was content to confine such work to supporting the fabrication of watch displays at Somerset. As it turned out, even this limited goal would prove overly ambitious.

Victory in Defeat?: The RCA Liquid Crystal Project in Perspective (1968-88)

Rumors that RCA was negotiating the sale of its liquid crystal facility to Timex reached the press in February 1976, three months after Robert Sarnoff stepped down as the corporation's chief executive.[213] Simmering frustration with Sarnoff's management style and the steady erosion of profits since 1973 prompted RCA's board of directors to demand his resignation in what the *New York Times* referred to as a "palace revolt."[214] Upon taking office, Anthony Conrad–the first non-Sarnoff to run RCA in forty-four years–commenced another round of cost-cutting measures, beginning with the company's solid-state and picture tube divisions, which had posted a combined $48.3 million dollar loss in 1975.[215] The Somerset LCD factory was among the items that SSD placed on the chopping block. In April 1976, the division's vice president, Bernard Vonderschmitt, finalized a deal with Timex offering them the Somerset facility and the rights to RCA's sizable portfolio of liquid crystal patents in exchange for $2.45 million.[216]

[213] Gold, 1.
[214] Bilby, 295; Sobel (1986), 217-219; Gene Smith, "Sarnoff's Departure is Called Result of RCA 'Palace Revolt,'" *New York Times*, 7 Nov. 1975, 49.
[215] RCA Corporation*, Annual Report 1975* (New York: RCA, 1976), 6.
[216] "Agreement Between Timex Corporation and RCA Corporation for Purchase and Sale of RCA Corporation's Liquid Crystal Display Operations," 31 Mar. 1976, 3-5, 13-15. The author is indebted to Lou Galie, the Timex Group's senior vice-president in charge of technology, for his assistance procuring a copy of this agreement. The closing date (12 Apr. 1976) is confirmed in section 3.01 (5), the purchase price can be found in section 2.03 (3-4), and intellectual property is discussed in section 4.14 (13-15). According to Appendix K of this document, RCA's LCD program generated 68 patents, 25 pending patent applications, and 24 unfiled disclosures between 1962 and 1976.

Reaction to this announcement varied throughout the corporation. Personnel at Somerset, given the chance to join Timex's staff, welcomed the arrival of an employer who treated LCD manufacturing as more than a side project.[217] To researchers at the DSRC, whatever disappointment the news might have provoked was tempered by an awareness of SSD's financial weakness.[218] No one seemed particularly surprised, nor should they have been. For while it was not always obvious, RCA's LCD project had been undergoing a death by a thousand cuts since 1968. Managers in New York and Raritan, unwilling to divert resources towards an untested technology, had inflicted grievous wounds, but they did not act alone. As I have argued, RCA personnel, including some who had previously advocated for the expansion of liquid crystal research, also contributed to the project's termination. From Heilmeier's involvement in the composition of the 1970 LCD marketing report to the recommendations of the Flat TV Task Force, members of the corporation's technical staff demonstrated time and again their capacity to shape research policy.

Admittedly, a small group of scientists and engineers could only exert so much authority over top-level strategic planning, and the final decision to sell off the firm's LCD operation rested squarely with RCA's leadership. Acknowledging the limits of corporate researchers' agency, however, is not the same as denying its existence. Through direct interaction with executives and internal deliberations, DSRC scientists altered company-

[217] Alan Sussman, Interview with author, Princeton, NJ, 19 Jan. 2011; Robert Ricci, e-mail message to author, 7 Jan. 2011. Timex assigned Mr. Ricci as the Industrial Relations Manager at the Somerset plant and confirms that most of the other employees were previously employed by RCA.
[218] Donald Channin, Interview with author, Princeton, NJ, 17 Aug. 2009; Lawrence Goodman, Interview with author, Princeton, NJ, 21 Aug. 2009; John van Raalte, Interview with author, Princeton, NJ, 10 Jun. 2009.

wide perceptions of liquid crystals' marketability. Between 1968 and 1976, their distrust of management and growing familiarity with the deficiencies of existing LCDs resulted in increasingly pessimistic assessments of the technology's future, which in turn guided decision makers towards the Timex sale.

Recognizing that DSRC staff members were involved in the collapse of RCA's liquid crystal program subverts Chandlerian discussions of industrial science, which frame commercially successful research as resulting primarily, if not exclusively, from the guidance of corporate managers.[219] These accounts might praise the scientists responsible for a particularly profitable breakthrough, but avoid describing their subsequent involvement in its commercialization. Failed innovations are likewise attributed to managerial errors, reinforcing Cold War notions of high-minded investigators whose hands are left unsullied by the grime of the marketplace.[220]

This chapter, along with other recent histories of consumer electronics, has shown that such representations do a disservice to industrial scientists by casting them as victims

[219] The introduction of this dissertation discusses Chandler's contributions to the historiography of corporate science. For examples of management-centered studies of innovation, see: Sally H. Clarke, et al., ed., *The Challenge of Remaining Innovative: Insights from Twentieth-Century American Business* (Palo Alto, CA: Stanford Business Books, 2009), Parts I & II; David A. Hounshell and John Kenly Smith, Jr., *Science and Corporate Strategy: Du Pont R&D, 1902-1980* (New York: Cambridge Univ. Press, 1988); Leonard S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (New York: Cambridge Univ. Press, 1985); George Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (New York: Columbia Univ. Press, 1985).

[220] Despite the proliferation of excellent studies of technological failure, very few examine the question from the perspective of workbench scientists. Margaret Graham's *Business of Research* explicitly concentrates upon management, while Jonathan Coopersmith's discussions of the fax machine span the entirety of an industry. Kenneth Lipartito's work on the Picturephone perhaps comes the closest to meeting this criterion by considering how technological rhetoric shaped research objectives at Bell Labs during the 1960s and 1970s. See: Jonathan Coopersmith, "Failure & Technology," *Japan Journal for Science, Technology, and Society* 18 (2009): 93-118 and "Old Technologies Never Die, They Just Don't Get Updated," *International Journal for the History of Engineering & Technology* 80, no. 2 (Jul. 2010): 166-182; Kenneth Lipartito, "Picturephone and the Information Age: The Social Meaning of Failure," *Technology and Culture* 44, no. 1 (Jan. 2003): 50-81.

of circumstance rather than professionals capable of furthering their own agendas within a for-profit setting.[221] Though the LCD project's advocates in 1968 could not have anticipated its cancellation eight years later, the individual decisions leading to that outcome were made deliberately, by managers and scientists alike. This contrast between the apparent rationality of short-term decisions and their unforeseen long-term outcomes, previously touched upon the context of laboratory practice, also extends to the overall fate of RCA's liquid crystal program.[222] For even in defeat, RCA continued to affect the course of electronic display development at home and abroad.

Domestically, the sale of RCA's Somerset facility marked a tipping point in an ongoing debate among American watchmakers over the preferred display for a digital timepiece. Before 1976, the market was roughly divided between LED watches, introduced to the market in 1970, and the LCD devices pioneered by Optel. Despite their shorter battery life, LEDs retained a slight lead throughout the 1970s due to their reliability compared to early liquid crystal models.[223] Timex's acquisition of RCA's LCD operation signaled the reversal of that trend, leading competitors like TI and National Semiconductors to believe a shift toward liquid crystals was imminent.[224] Over the course of the next year "nearly all LED inventories were either written off or sold below cost

[221] Bassett, *To the Digital Age*; Hyungsub Choi, "Manufacturing Knowledge in Transit: Technical Practice, Organizational Change, and the Rise of the Semiconductor Industry in the United States and Japan, 1948-1960" (Ph.D. diss., Johns Hopkins University, 2007); Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970* (Cambridge, MA: MIT Press, 2006).
[222] See Ch. 4.
[223] Dietrich W. Grabis, "The LCD Market: The origins and Underlying Reasons for the Growth of Liquid Crystal Display in the USA–Focus: Electronic Watch and Calculator Applications" (DBA diss., Golden Gate University, 1980), 1-2, 38, 50-51. See also: Castellano, Ch. 8; Johnstone, 105-107; McDermott, 182-193; Robert Ricci, e-mail message to author, 7 Jan. 2011.
[224] Grabis, 109, 204-205; Peters, 164.

through dumping and give-away programs," and the LCD solidified its place as the dominant watch technology.[225]

The RCA liquid crystal program also played a role in the establishment of the Japanese LCD industry. Within months of the press conference unveiling the first liquid crystal displays, DSRC personnel started receiving inquiries from Japanese scientists interested in dynamic scattering.[226] One of these was Tadashi Sasaki, a research supervisor at the Hayakawa Electric Company, who invited RCA to collaborate on a low-power handheld calculator.[227] The DSRC had actually retrofit an existing desktop calculator with an LCD screen to demonstrate the concept's viability, but the leadership at Somerville deferred, claiming the technology was not mature.[228] As a consolation prize, they offered Sasaki's firm, renamed the Sharp Corporation in 1970, the licensing rights to RCA's liquid crystal patents for $3 million.[229]

RCA could justify this decision as consistent with the company's longstanding policy of overseas patent licensing. But while royalties from such arrangements saved the LCD project from cancellation on at least one occasion, they also facilitated Japanese encroachment on RCA's traditional radio and television businesses.[230] The resulting drop in revenues underlay Conrad's decision to authorize the sale of SSD's liquid crystal operation. Meanwhile, Sharp commenced an intensive liquid crystal research program of its own, leading to the 1973 release of the Elsi Mate EL-805, the world's first portable

[225] Grabis, 51.
[226] Castellano, 82-84, Louis Zanoni, Interview with author, Ewing, NJ, 21 Aug. 2009.
[227] Castellano (2005), 84-85; Johnstone, 88-92. One of Sasaki's researchers, Tomio Wada, had learned about LCDs from an NHK documentary entitled "Firms of the world: Modern Alchemy" (Kawamoto 468).
[228] Castellano (2005), 57-58. As mentioned in n. 163, Castellano worked with RCA's division in West Palm Beach on additional calculator applications.
[229] Johnstone, 105; Smith (1995), 22.
[230] Castellano (2005), 70; Johnstone, 12-14;

LCD calculator. Popularly referred to as the "Obake" or "ghost" calculator due to the slow response time of its dynamic scattering display, profits from the EL-805 allowed Sharp to expand its liquid crystal facilities.[231] By the end of the decade, the firm had exorcized the "ghost" by switching to twisted nematic displays and invested a total of $200 million on its LCD factories.[232] Only in hindsight did it become clear that in rejecting Sasaki's proposal, RCA had waived one of the last opportunities for an American company to shape the future of Japan's liquid crystal industry.[233]

The widening technological gap between East and West served as background to the 1988 announcement that Japanese engineers had succeeded in creating a wall-mounted color television, just as David Sarnoff had predicted more than three decades earlier.[234] In the end, it was Sharp, the company that had once turned to RCA as an ally in liquid crystal development, that now presented the world with an LCD comparable in size (14") and performance to existing CRTs. Sarnoff would have been disappointed that his company not only failed in this task but had ceased to exist after being bought out by General Electric two years earlier.[235] Still, the former members of his company's LCD initiative could take solace in the knowledge that both the general concept of a liquid crystal

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[231] Kawamoto, 468-471. Castellano (2005) observes that the EL-805 was not the first commercially sold LCD calculator. The Rockwell Model C1 went on the market a year earlier. Since this device needed to be plugged into the wall, the EL-805 is generally considered the first pocket calculator (142-143).

[232] Johnstone, 105; Kawamoto, 481; Murtha, et al., 58-62.

[233] For an extensive discussion of the Japanese LCD industry, see: Castellano (2005), Ch. 7.

[234] Castellano (2005), 200-202; Johnstone, 137-144; Kawamoto, 494-496. This was not the first time that LCDs had been used as the basis of a color television display. Five years earlier, researchers from Suwa Seiko had demonstrated a two inch matrix display based on guest-host color switching at a Society for Information Display meeting in Philadelphia, but this device was never considered a replacement for the home CRT. The full story of the rivalry between Seiko and Sharp to develop the first large-scale LCD television is recapped in Johnstone, Kawamoto, and Murtha, et al.

[235] In the final chapters of their books, Bilby and Sobel (1986) both provide detailed accounts of the business maneuvering preceding RCA's sale to GE.

television and the specific technologies underlying Sharp's device—room- temperature liquid crystals, matrix addressing, and twisted nematic displays—traced their origins to RCA's laboratories and factories. The Radio Corporation of America might be gone, but the General's dream survived and for liquid crystals, the future looked bright.

CHAPTER SEVEN–CONCLUSION
"The ingredients of a good novel": Past and Future Histories of the LCD

To drivers careening through Princeton on U.S. Route 1, the former David Sarnoff Research Center (DSRC) appears much the same as it did when its namesake walked its halls. The RCA insignia has vanished from the front lawn, replaced by a sign confirming the laboratory's new identity as a subsidiary of SRI International ("SRI-Sarnoff"), but the building's profile has remained constant since the late 1960s. There have been changes, of course, but observing them requires one to slow down, turn off the highway, and drive toward the marble and glass portico that replaced the facility's original entrance in 1966. This entryway, still inscribed with the "meatball" logo of its former owner, contains some of the newest additions to the research center's facade: a series of bronze plaques showcasing three of RCA's contributions to the history of electronics, including the development of a compatible color television system, the construction of the world's first meteorological satellite, and the invention of the liquid crystal display (LCD).[1]

The History Committee of the Institute of Electrical and Electronic Engineers (IEEE) commissioned all three of these plaques as part of its "milestone" program, which honors significant technical achievements in electrical engineering and computing.[2] The LCD milestone, dated September 2006, is embedded into the right side of the archway. Except for the diamond-shaped IEEE logo in the bottom-left corner, its contents are entirely textual. In addition to two lines indicating its institutional provenance, the plaque

[1] The full text of all three plaques can be found at "Milestones: List of IEEE Milestones," IEEE Global History Network, http://www.ieeeghn.org/wiki/index.php/Milestones:List_of_IEEE_Milestones, Accessed 19 Jul. 2011.
[2] The milestones for color television and the TIROS-1 Weather Satellite were dedicated in November 2001 and September 2010, respectively.

includes a title ("Liquid Crystal Display, 1968") and a summary of the research being commemorated:

> Between 1964 and 1968, at the RCA David Sarnoff Research Center in Princeton, New Jersey, a team of engineers and scientists led by George H. Heilmeier with Louis A. Zanoni and Lucian A. Barton devised a method for electronic control of light reflected from liquid crystals and demonstrated the first liquid crystal display. Their work launched a global industry that now produces millions of LCDs annually for watches, calculators, flat-panel displays in televisions, computers, and instruments.[3]

In two sentences, this citation presents a narrative with distinct chronological and geographical boundaries, a small cast of characters, and obvious scientific and commercial significance. Missing from the plaque, however, are any indications of authorship or methodology. There is no means of ascertaining which member(s) of the IEEE History Committee compiled the text, nor the amount of information derived from published sources, archival records, or consultation with project participants.[4] Space restrictions limiting the number of words on the milestone provide one explanation for these omissions, but there is an additional incentive to avoid raising such issues. The IEEE milestones derive their authority from the perceived accuracy of their treatment of technological innovation. Any suggestion that the wording on these plaques was subject to debate and not simply a recapitulation of "what really happened" throws their credibility into question. In this instance, the omission of details reinforces the validity of the history presented rather than undermining it.

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[3] "Liquid Crystal Display, 1968" IEEE Milestone, Princeton, NJ, Dedicated 30 Sep. 2006.

[4] The guidelines posted on the IEEE website indicate that although anyone may submit a draft citation as part of their milestone proposal, the History Committee "has the final decision on the wording of the citation to be recommended for approval to the IEEE Board of Directors." See: IEEE Global History Network, "Milestones: Milestone Guidelines and How to Propose a Milestone," accessed 19 Jul. 2011, http://www.ieeeghn.org/wiki/index.php/Milestones: Proposing_a_Milestone.

This dissertation has operated under another set of assumptions, dismissing the notion that there is a single, coherent version of "what really happened" with regard to the LCD's origins and embracing that ambiguity to reconstruct the complex internal dynamics of the innovation process. Viewed in this light, the IEEE milestone moves from being the definitive story of RCA's liquid crystal program to one account among many, each emphasizing different aspects of the corporate research experience. Ascertaining what merited inclusion on the plaque necessitates a close reading of its text, informed by the preceding chapters. Conversely, this analysis also sheds light on areas that both the milestone and my study have left unexplored, hinting at future histories of electronic display technologies waiting to be written.

Reading a Milestone

After perusing the IEEE milestone, a visitor passing through the lobby of SRI-Sarnoff will notice another bronze plaque near the receptionist's desk. This plaque, larger than its IEEE counterparts, bears the portrait of David Sarnoff and was given to RCA's longtime chairman in 1951 to celebrate the forty-fifth anniversary of his career in electronics. Despite their proximity, our hypothetical visitor would not presume any connection existed between these two memorials on the basis of their texts. Given that the IEEE plaque establishes in its first four words that the liquid crystal display was developed "[b]etween 1964 and 1968," one can hardly fault this assessment.[5]

Yet while internal reports and laboratory notebooks confirm that researchers assembled the first LCDs during this four year interval, the milestone citation approaches

[5] "Liquid Crystal Display, 1968" IEEE Milestone, Princeton, NJ, Dedicated 30 Sep. 2006.

their work in isolation, with no reference to the DSRC staff's longstanding interest in flat-panel displays. Those eager to comprehend the source of that fascination would be better served exploring the circumstances surrounding David Sarnoff's commemorative plaque, for it was after its 1951 presentation that Sarnoff first challenged RCA's technical community to invent a "true amplifier of light."[6] Over the next two decades, this request evolved into an explicit call from RCA executives and research managers for a television that could hang on the wall. Liquid crystals were merely one technology considered for use in such a device, and the technical expertise acquired in earlier projects, notably the electroluminescent displays constructed by DSRC computer researchers between 1951 and 1966, proved vital to the construction of the earliest matrix-addressed LCDs.

By confining discussion to the period between 1964 and 1968, the IEEE milestone extracts the LCD from the broader trajectory of flat-panel television research at RCA. More concretely, it does not discuss the factors that prompted George Heilmeier, the leader of the DSRC liquid crystal initiative, to begin working with these substances. Heilmeier's actions are sensible only if considered alongside his previous attempts to modify organic compounds for use as laser modulators and the investigations conducted by his colleague, Richard Williams, into the electro-optic behavior of liquid crystals. It was Williams who, in 1962, confirmed that liquid crystals subjected to an electric field could selectively modulate the passage of light and submitted the first RCA patent describing their incorporation into a display.[7] Though Heilmeier has referred on several occasions to

[6] See Ch. 2 of this dissertation or Benjamin Gross, "The Quest for 'Magnalux': Redefining Technological Success and Failure at RCA, 1951-1956," *Bulletin of Science, Technology & Society* 32, no. 1 (forthcoming 2012).

[7] Richard Williams, "Electro-Optical Elements Utilizing an Organic Nematic Compound," US Patent 3,322,485, filed 9 Nov. 1962 and issued 30 May 1967.

the significance of Williams' work, the absence of the latter from the official IEEE account accentuates Heilmeier's achievement.[8]

The milestone never claims that Heilmeier pursued the development of the LCD singlehandedly, noting instead that it was the product of "a team of engineers and scientists" more typical of Cold War research.[9] Given that nearly twenty DSRC staff members participated in the project at its peak, the omission of some from its text was unavoidable. The parameters for determining whose names were worthy of preservation in bronze are less clear and highlight the challenge of assigning credit in cases of collaborative innovation. One solution, embodied in the DSRC's other milestone plaques, would be to refer to the liquid crystal display as an achievement of the company's technical staff with no references to specific individuals. Another option would be to follow the lead of company management by citing the six men awarded RCA's highest technical honor "for basic studies of liquid crystals with imaginative ideas for their application to practical displays."[10] The IEEE chose a middle path between these two options by honoring Heilmeier, technician Louis Zanoni, and chemist Lucian Barton: the authors of the 1968 papers describing the "dynamic scattering" effect utilized in the earliest commercial LCDs.[11]

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[8] See, for example: George H. Heilmeier, "Liquid Crystal Displays: An Experiment in Interdisciplinary Research that Worked," *IEEE Transaction on Electron Devices* ED-23, no. 7 (Jul. 1976): 781.
[9] "Liquid Crystal Display, 1968" IEEE Milestone, Princeton, NJ, Dedicated 30 Sep. 2006.
[10] The six staff members awarded the David Sarnoff Outstanding Team Award in Science (RCA's highest technical honor for collaborative research) for 1968 were Heilmeier, Williams, Louis Zanoni, and chemists Lucian Barton, Joseph Castellano, and Joel Goldmacher. See: "The David Sarnoff Outstanding Achievement Awards," *RCA Engineer* 14, no. 6 (Apr.-May 1969): 48.
[11] George H. Heilmeier, Louis A. Zanoni, and Lucian A. Barton, "Dynamic Scattering: A New Electrooptic Effect in Certain Classes of Nematic Liquid Crystals," *Proc. IEEE* 56, No. 7 (Jul. 1968): 1162-1171; G.H. Heilmeier, L.A. Zanoni, and L.A. Barton, "Dynamic Scattering in Nematic Liquid Crystals," *Applied Physics Letters* 13, no. 1 (1 Jul. 1968): 46-47.

While Heilmeier's status as project leader explains his presence on the plaque, the implication that Zanoni and Barton acted as co-managers ("a team of engineers and scientists led by George H. Heilmeier with Louis A. Zanoni and Lucian Barton...") misrepresents the loose hierarchy that existed within the liquid crystal group.[12] Zanoni and Barton were among the earliest to join the core team praised by RCA's leadership, but their organizational standing was no greater than any other person involved (except Heilmeier).[13] Moreover, the IEEE, through its reliance on the published record to filter the staff roster, privileged their contributions above others of comparable significance, such as the synthesis of materials capable of exhibiting liquid crystalline behavior at room temperature or the aforementioned matrix-addressing circuitry.

In emphasizing Heilmeier, Zanoni, and Barton over the research staff as a whole, the milestone pins the completion of the LCD project to a specific point in time, corresponding with their 1968 articles on dynamic scattering. It likewise ensures that the events it describes remain bound, like the plaque itself, within the walls of the Princeton labs. For although 1968 marked the end of one phase of the DSRC liquid crystal project, the resulting devices were not ready for mass production. RCA's campaign to commercialize the LCD lasted for eight years, during which time the technology left the laboratory and found a new home under the auspices of the corporation's Solid State

[12] "Liquid Crystal Display, 1968" IEEE Milestone, Princeton, NJ, Dedicated 30 Sep. 2006.

[13] Arguably, the only figure associated with the liquid crystal project of comparable rank to Heilmeier was Bernard Lechner, who oversaw the engineering group responsible for the LCD's addressing circuitry. Lechner's absence from the IEEE milestone can be partially explained by the relative lateness of his group's involvement in the LCD initiative, several months after Heilmeier's core team assembled their first functional display prototypes.

Division (SSD). Until 1976, SSD engineers, chemists, and manufacturing experts at facilities in nearby New Jersey towns like Somerville and Raritan took up the task of incorporating liquid crystals into advertising displays, numeric counters, and other consumer products. Though RCA never became a major player in the fledgling LCD market, their work, as much as that of the Princeton LCD researchers, launched the "global industry" mentioned on the milestone, but one would never know from the narrative presented, which focuses attention squarely on the "research" half of R&D.

Reflecting on his time at RCA shortly after the company divested its liquid crystal operations, George Heilmeier remarked that "[i]n many respects the story of liquid crystal display technology has all the ingredients of a good novel. There was excitement, frustration, success, failure, and personal tragedy."[14] Although Heilmeier's reminiscences share the IEEE's focus on the DSRC and limited discussion of the investigative pathways leading to the LCD, he also acknowledges that liquid crystals' eventual dominance within the world of electronic displays was contingent upon overcoming an array of scientific, institutional, and economic hurdles.[15] To our hypothetical visitor, wandering the halls of SRI-Sarnoff and pondering the LCD milestone, the frustration and failure to which Heilmeier alluded are nonexistent. Through the act of praising the people responsible for one of the most pervasive technologies of the digital age, the IEEE citation not only limits its discussion to a small subset of those involved but strips away the substance of their endeavors: the imaginative leaps, adjustments to changing organizational and scientific constraints, and creative collaborations that underlie the corporate research experience.

[14] Heilmeier, 780.

[15] A comparison of Heilmeier's accounts of the origins of his LCD work and the version of events recorded in his laboratory notebooks and patents can be found in Ch. 4 of this dissertation.

Where the milestone plaque casts the invention of the LCD as an inevitability, this dissertation has shown that such a position downplays the agency of DSRC scientists and engineers, who seized upon a variety of institutional, financial, and literary resources to advance their professional objectives. In the case of David Sarnoff's light amplifier, the various electroluminescent display prototypes assembled between 1951 and 1956 prompted a shift in RCA executives' predictions regarding the future of television. Though the tenuous commercial prospects of color TV at the end of the decade prompted management to discourage such work as overly speculative, RCA engineers took advantage of military contracts and the firm's renewed interest in computing to pursue mural television research into the 1960s.

George Heilmeier's ability to organize a liquid crystal research group reaffirms the high level of autonomy possessed by members of RCA's technical staff during this period. Through progress reports and conversations with RCA managers and marketing experts, Heilmeier and his colleagues persuaded leaders at the company's laboratories and factories to sponsor their LCD research and establish a pilot manufacturing facility. Their efforts facilitated the production of the first commercial liquid crystal displays, even as Robert Sarnoff's acquisition-fueled computing campaign limited access to the manpower and materiel required to ensure its continued expansion and reduced researchers' confidence in the project's long-term viability.

The success of the LCD compared to earlier flat-panel prototypes was therefore not due simply to its technical merits, but also the ability of DSRC personnel to secure allies throughout the corporation, capitalize upon new funding sources, and define the

range of technological possibilities presented to company leaders, external contractors, and consumers. Far from being passive recipients of managerial policies, members of RCA's technical staff were instrumental to the formation and implementation of corporate R&D strategy, as well as the rhetoric surrounding it. Though the collapse of the LCD project confirmed the limits of their agency, in restoring these personnel to a central position in the history of electronic displays, this case study has taken a significant step towards recapturing the full range of cognitive, experimental, and social activities associated with Cold War innovation.

The World Beyond Our Screens

For a text characterized by its attention to the end products of corporate research, the IEEE milestone's discussion of LCD technology itself is also surprisingly ambiguous. The text claims that Heilmeier, Zanoni, and Barton led a team that "devised a method for electronic control of light reflected from liquid crystals and demonstrated the first liquid crystal display."[16] Based on the date range and the inclusion of these specific researchers, the "method" referred to here is dynamic scattering, but whether or not that was the basis of RCA's *first* liquid crystal display is less clear. Certainly, it was the technology incorporated into the displays the firm unveiled to the public in 1968. But prior to observing dynamic scattering, Heilmeier and Zanoni triggered an electronic color change in a liquid crystal-dye mixture and used this "guest-host" effect to display simple patterns. And two years before that, Richard Williams created a light shutter based upon the formation of domains in liquid crystals under an electric field.

[16] "Liquid Crystal Display," IEEE Milestone, Princeton, NJ, Dedicated 30 Sep. 2006.

The milestone skirts a potential priority dispute by conflating all three of these approaches into a single entity (the first liquid crystal display), a maneuver that raises the question of what separates the dynamic scattering display, which is ultimately being honored, from either of its RCA predecessors. From an economic position, the difference is self-evident, for although "twisted nematic" displays ended its tenure as an industry standard, dynamic scattering was the technology found in the earliest LCD watches and calculators. The functional distinction between RCA's liquid crystal technologies is not as obvious. Each consisted of a similar setup, a liquid crystal sample placed between two pieces of conductive glass and operated through the selective application of voltage across the sample. Granted, dynamic scattering displays possessed superior brightness and resolution, but those qualities do not diminish the significance of Williams' domain experiments or guest-host color switching to the development of the LCD.

In singling out dynamic scattering as RCA's earliest liquid crystal display, the milestone plaque equates technological accomplishment with commercial viability. Such a position, concentrating on display applications instead of the devices themselves, perpetuates a fallacy identified by theorist Marshall McLuhan in 1964, the same year Heilmeier commenced his LCD experiments. The opening chapter of *Understanding Media* contains McLuhan's now famous statement that "the medium is the message," as well as a warning against what he saw as an all too common tendency to confuse "the message" associated with a given technology with its "content."[17] To McLuhan, "the 'message' of any medium or technology [was] the change of scale or pace or pattern that

[17] Marshall McLuhan, *Understanding Media: The Extensions of Man* (Cambridge, MA: MIT Press, 1999 [1964]), 8-9.

it introduces into human affairs," while "content" referred to the ideas people consciously imposed upon media.[18] To illustrate this distinction, he presented the example of the electric lightbulb:

> The electric light escapes attention as a communication medium just because it has no "content." And this makes it an invaluable instance of how people fail to study media at all. For it is not till the electric light is used to spell out some brand name that it is noticed as a medium. Then it is not the light but the "content" (or what is really another medium) that is noticed.[19]

McLuhan feared that serious analyses of media and their social, cultural, and political resonances would be subsumed within discussions of their content, and this appears to have been the case with the LCD. On a small scale, this trend is evident in the IEEE milestone, which elevates dynamic scattering due to its capacity to portray brightly visible numbers and patterns, and omits earlier electro-optic effects less amenable to the task.[20] One can readily draw a comparison between McLuhan's lightbulb and Williams' domain experiments, ignored for their lack of content despite inspiring the first serious consideration of harnessing liquid crystals to replace the cathode ray tube. More broadly, this emphasis on the contents of screens, not the consequences of their use, permeates the historiography associated with liquid crystal displays. Authors have lavished attention on the LCD wristwatch, calculator, and television, but spent little time reflecting on how these devices have reconfigured patterns of work and leisure.[21]

[18] McLuhan, 8.
[19] McLuhan, 9.
[20] As discussed in Chapters 4 and 5, although guest-host displays proved amenable to the production of simple images (such as the RCA logo), they did not become the focus of concerted applications research within the DSRC until after the dynamic scattering initiative was well underway.
[21] See, for example: Joseph Castellano, *Liquid Gold: The Story of Liquid Crystal Displays and the Creation of an Industry* (Hackensack, NJ: World Scientific, 2005); David Dunmur & Tim Sluckin, *Soap, Science, & Flat-Screen TVs: A History of Liquid Crystals* (New York: Oxford Univ. Press, 2011); Thomas P. Murtha, et al., *Managing New Industry Creation: Global Knowledge Formation and Entrepreneurship in High Technology* (Stanford: Stanford Univ. Press, 2001); Stuart Peters, *National Systems of*

In fact, RCA researchers and managers started considering such questions from the moment David Sarnoff first hinted at the possibility of a wall-mounted television. During the 1950s and 1960s, company executives expanded upon Sarnoff's 1955 prediction that electronic flat-panel displays would "change the very appearance of our homes, stores, factories, streets, and cities."[22] Meanwhile, the research teams tasked with developing this technology also changed, as cathode ray-based systems were set aside in favor of solid-state devices. Groups previously dominated by electrical engineers expanded to include experts in molecular physics and organic chemistry, and reliance on internal funding gave way to dependence on government contracts and external alliances. The LCD's transition to the operating divisions also forced SSD personnel more familiar with silicon to devise new manufacturing protocols, though disagreements loomed over what types of applications to pursue. In short, even as RCA struggled to anticipate how liquid crystal displays would alter consumers' offices and living rooms, the research environment from which they emerged was undergoing a metamorphosis of its own.

RCA's example illustrates how, to paraphrase McLuhan, the innovative process responsible for the emergence of a new medium (i.e. the LCD) is itself subject to that medium's message. Case studies based upon this principle could shed new light upon the cyclical relationship that exists between the conceptions of a technology held by industrial scientists and research managers. Such analyses could span multiple firms, considering how each approached the task of commercialization when confronted with a growing pool of competitors. Returning to the example of the LCD, RCA's handling of liquid crystals

Innovation: Creating High-Technology Industries (New York: Palgrave Macmillan, 2006).

[22] David Sarnoff, "The Fabulous Future," in *The Fabulous Future: America in 1980*, ed. *Fortune* (New York: E.P. Dutton & Co., Inc., 1956), 17.

likely shaped the choice of projects pursued at Optel, Princeton Material Science, and Ashley-Butler, all of which recruited disaffected personnel from the DSRC and SSD.[23] A comparison of display research at these startups alongside established electronics companies like General Electric and Texas Instruments would grant insight into the amount of independence possessed by industrial scientists in different settings and how contact between research organizations shapes innovation policies.

These discussions need not be confined to the United States. The history of electronic displays transcends national boundaries and a greater emphasis on the intersection of corporate strategy, technological rhetoric, and laboratory practice would facilitate more detailed explanations of the dissemination of LCD technology to European and Asian markets. As expected, the decline of Western involvement in the display industry and the concomitant rise of Japanese, South Korean, and Taiwanese companies has already sparked numerous discussions of this topic.[24] The Japanese case study has drawn the most attention, with several works citing differences in economic policy and a cultural proclivity towards long-term investment as explanations for that nation's preeminence in the LCD and consumer electronics industries.[25] Most authors have

[23] For more on these three firms, see Castellano, 91-100 or Ch. 6 of this dissertation.

[24] Although Japan possessed a near monopoly on LCD manufacturing in the 1990s, accounting for an estimated 95% of global production, Korean and Taiwanese firms came into their own during the first decade of the 21st century. One 2009 report estimated that the proportion of Japanese displays had dropped to 11% in 2005, with South Korea and Taiwan each securing 40% market share. See: Samantha Sharpe, "Liquid Crystal Displays case report," Funding Breakthrough Technology Project, Centre for Business Research, Cambridge University (2009). Accessed online, 20 Mar. 2011: http://www.cbr.cam.ac.uk/pdf/LCD/%20case/%20report.pdf. These figures roughly correspond to those outlined in Murtha, et al., 161 and Peters, 183-206.

[25] In addition to Murtha, et al. and Peters, 152-182, see also: Alfred D. Chandler, Jr., *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries* (New York: The Free Press, 2001), 50-81; Hedrick Smith, *Rethinking America* (New York: Random House, 1995), 6-33.

adopted the firm as their primary unit of analysis and avoid delving too deeply into the activities of corporate laboratories. There are exceptions, but often these veer towards the opposite extreme, focusing on individuals responsible for technical advances vital to modern display makers and not how interactions with management affected the research leading to these discoveries.[26]

Bridging the gap between these two frameworks entails an appreciation of the evolving attitudes that Japanese (or Korean, Taiwanese, etc.) executives and scientists held toward the technological potential of the LCD. Moving beyond studies tracking the transmission of scientific or technical knowledge, we must consider the diffusion of ideas about potential applications of these new concepts and how those notions changed when confronted with the realities of corporate research.[27] The recovery of these perspectives mandates extensive perusal of the "private science" preserved in laboratory notebooks and project reports, along with oral histories, patents, and articles in the scientific and popular press.[28] The methodological challenges associated with this task are sizable, but as this

[26] Castellano, 82-90; Dunmur & Sluckin, 235-250; Hirohisa Kawamoto, "The History of Liquid-Crystal Displays," *Proc. IEEE* 90, no.4 (Apr. 2002): 460-500. Bob Johnstone's discussion of the role played by Japanese entrepreneurs in the evolution of that country's electronics industry comes closest to striking a balance between the firm-centered and scientist-centered approaches described here. Nevertheless, Johnstone is ultimately more interested in individuals and their research achievements than the organizations where such work was carried out. For his discussion of the LCD, see: Bob Johnstone, *We Were Burning: Japanese Entrepreneurs and the Forging of the Electronic Age* (New York: Basic Books, 1999), 88-144.

[27] For discussions of the transfer of technical knowledge within the electronics industry, see: Ross Knox Bassett, *To the Digital Age: Research Labs, Start-Up Companies, and the Rise of MOS Technology* (Baltimore: Johns Hopkins Univ. Press, 2002); Christophe Lécuyer, *Making Silicon Valley: Innovation and the Growth of High Tech, 1930-1970* (Cambridge, MA: MIT Press, 2006); Hyungsub Choi, "Manufacturing Knowledge in Transit: Technical Practice, Organizational Change, and the Rise of the Semiconductor Industry in the United States and Japan, 1948-1960" (Ph.D. diss., Johns Hopkins University, 2007). Choi's analysis of how the organization of semiconductor manufacturing changed in the U.S. and Japan in response to newly acquired technical knowledge should prove particularly valuable to future comparative studies of international technological diffusion.

[28] The category of "private science" is derived from Gerald L. Geison, *The Private Science of Louis Pasteur*. Princeton: Princeton Univ. Press, 1995.

dissertation has demonstrated, essential to the construction of balanced innovation narratives, reflecting the contributions of company leaders, laboratory scientists, and manufacturing personnel to the generation of new technologies. Such detailed reconstructions will also reaffirm the relevance of corporate archives at a time when the rise of digital recordkeeping has cast their future into question.[29]

By examining the LCD as both a product and producer of the research environment from which it emerged, this study also paves the way for future discussions of the extent to which electronic displays have altered human interaction over the past half-century. Today, screens surround us in our homes, workplaces, and public spaces, bombarding us with imagery at an unprecedented rate. Yet we remain transfixed, as McLuhan warned, upon their visible content rather than the invisible transformations they have wrought on the ways we socialize and consume information. Exposing these hidden patterns forces us to consider the origins, proliferation, and use of displays. The discipline of "television studies" provides a theoretical launching point for these investigations, but the category of "electronic display" encompasses a broader range of devices, including cellular telephones, laptop computers, portable media players, vehicle instrumentation, and electronic signage. While historians and sociologists have previously considered these devices in isolation, their shared reliance upon a common set of display technologies, including cathode ray tubes, liquid crystals, plasma discharge panels, and light-emitting diodes provides the basis for comparative analyses of human-machine interaction at the

[29] For more the tenuous status of corporate archives in the U.S., see: R. Joseph Anderson & Orville R. Butler, *History of Physics in Industry* (College Park, MD: American Institute of Physics, 2008).

dawn of the digital age. Only by engaging with these questions can we hope to peer beyond the surface of our screens and catch a glimpse of the world that they have made.

LIST OF ABBREVIATIONS

ABC:	anisylidene butyl cinnamate
APAPA:	anisylidene p-amino phenyl acetate
ATSC:	Advanced Television Systems Committee
BBA:	p-n butoxy benzoic acid
CBS:	Columbia Broadcasting System
CERL:	Consumer Electronics Research Laboratory
CMOS:	Complementary metal-oxide-semiconductor
CRL:	Computer Research Laboratory
CRT(s):	cathode ray tube(s)
CSD:	Computer Systems Division
DHOBABB:	3-3'-dichloro-4,4'-di (p-n-heptyloxybenzylidene-amino) biphenyl
DSL:	David Sarnoff Library (Princeton, NJ/Wilmington, DE)
DSM:	Dynamic scattering mode
DSRC:	David Sarnoff Research Center
DTIC:	Defense Technical Information Center (http://www.dtic.mil/)
ECD:	Electronic Components Division
ERL:	Electronics Research Laboratory
FCC:	Federal Communications Commission
GE:	General Electric
HML:	Hagley Museum and Library (Wilmington, DE)
IEEE:	Institute of Electrical and Electronic Engineers

IRPCO:	Interim Research Planning Committee
KPA:	Klein Personal Archive (Richard Klein, Clifton, NJ)
KSU:	Kent State Univ. Libraries, Special Collections and Archives (Kent, OH)
LCD(s):	liquid crystal display(s)
LCI:	Liquid Crystal Institute (Kent, OH)
LED(s):	light-emitting diodes
MOCA:	p-methoxycinnamic acid
MOSFET:	metal-oxide-semiconductor field-effect transistor
MTS:	Member of the technical staff
NASA:	National Aeronautics and Space Administration
NBC:	National Broadcasting Company
NTSC:	National Television Standard Committee
PAA:	para-azoxyanisole
PEBAB:	p-ethoxybenzylidene-4-aminobenzonitrile
RCA:	Radio Corporation of America
SRL:	Systems Research Laboratory
SSD:	Solid State Division
TI:	Texas Instruments
TSA:	Technical staff associate
WNRC:	Washington National Records Center (Suitland, MD)
WPAFB:	Wright-Patterson Air Force Base (Dayton, OH)
ZPA:	Zanoni Personal Archive (Louis Zanoni, Ewing, NJ)

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