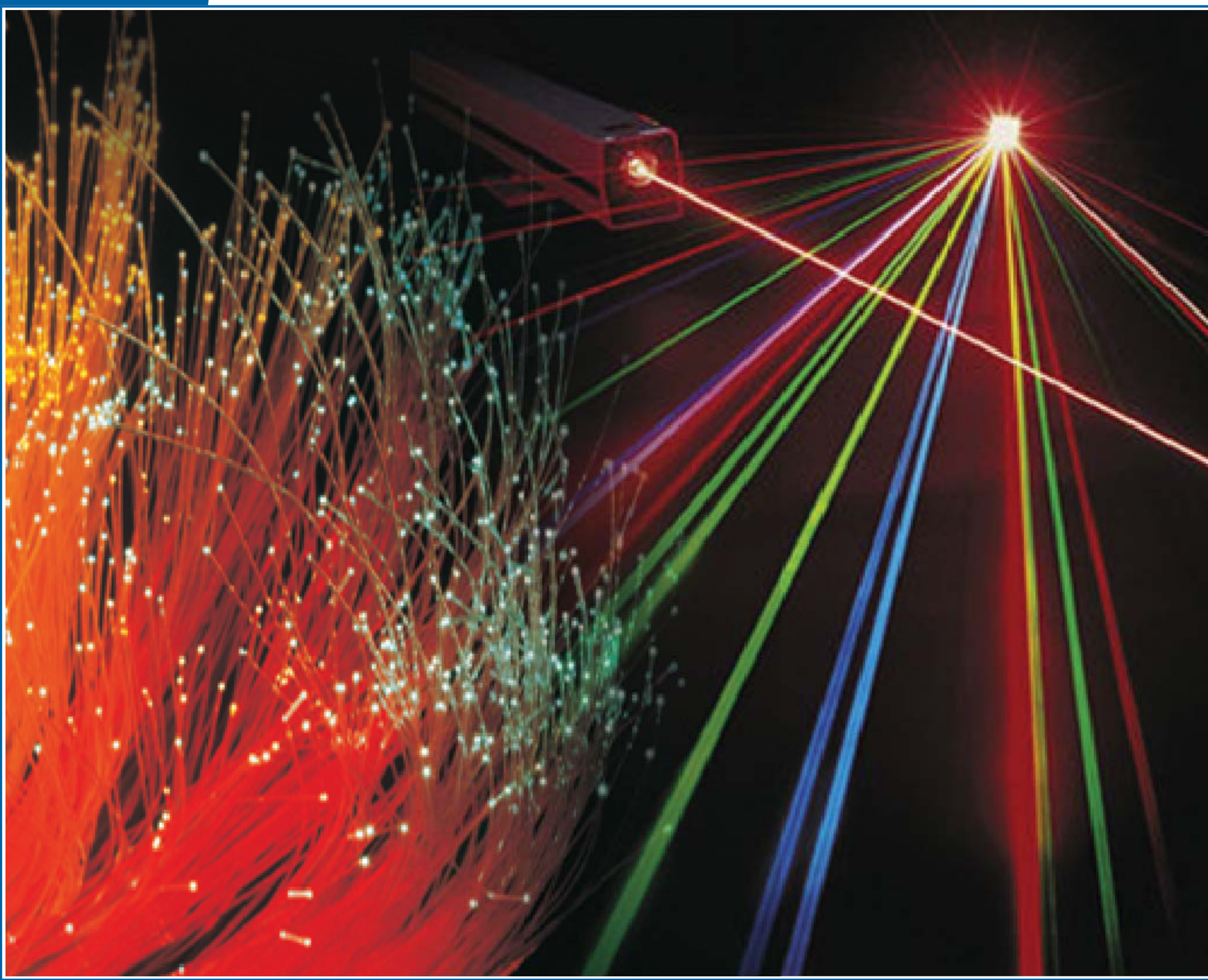
NIST GCR 06-893

Direct and Spillover Effects of ATP-Funded Photonics Technologies

Todd A. Watkins
Theodore W. Schlie



December 2006

National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce

ABOUT ATP'S ECONOMIC ASSESSMENT OFFICE

The Advanced Technology Program (ATP) is a partnership between government and private industry to conduct high-risk research to develop enabling technologies that promise significant commercial payoffs and widespread benefits for the economy.

Since the inception of ATP in 1990, ATP's Economic Assessment Office (EAO) has performed rigorous and multifaceted evaluations to assess the impact of the program and estimate the returns to the taxpayer. To evaluate whether the program is meeting its stated objectives, EAO employs statistical analyses and other methodological approaches to measure program effectiveness in terms of:

- Inputs (program funding and staffing necessary to carry out the ATP mission)
- Outputs (research outputs from ATP supported projects)
- Outcomes (innovation in products, processes, and services from ATP supported projects)
- Impacts (long-term impacts on U.S. industry, society, and economy)

Key features of ATP's evaluation program include:

- Business Reporting System, a unique online survey of ATP project participants that gathers regular data on indicators of business progress and to enable estimation of economic impact of ATP projects.
- Special Surveys, including the Survey of Applicants and the Survey of Joint Ventures.
- Status Reports, mini case studies that assess ATP projects on several years after project completion, and rate projects on a scale of zero to four stars to represent a range of project outcomes.
- Benefit-cost analysis studies, which identify and quantify the private, public, and social returns and benefits from ATP projects
- Economic and policy studies that assess the role and impact of the program in the U.S. innovation system
- Data Enclave to allow for analysis of innovation and entrepreneurship (Spring 2007)

EAO measures against ATP's mission.

The findings from ATP surveys and reports demonstrate that ATP is meeting its mission:

- Nine out of 10 organizations indicate that ATP funding accelerated their R&D cycle.
- The existence of a "halo effect." As revealed by EAO surveys, shows that an ATP award establishes or enhances the expected value in the eyes of potential investors.
- ATP stresses the importance of partnerships and collaborations in its projects. About 85 percent of project participants had collaborated with others in research on their ATP projects.

Contact ATP's Economic Assessment Office for more information:

- On the Internet: www.atp.nist.gov/eao/eao_main.htm
- By e-mail: atp-eao@nist.gov
- By phone: 301-975-8978, Stephanie Shipp, Director, Economic Assessment Office, Advanced Technology Program
- By writing: Economic Assessment Office, Advanced Technology Program, National Institute of Standards and Technology, 100 Bureau Drive, Stop 4710, Gaithersburg, MD 20899-4710

NIST GCR 06-893

Direct and Spillover Effects of ATP-Funded Photonics Technologies

Prepared for
Economic Assessment Office
Advanced Technology Program
National Institute of Standards and Technology
Gaithersburg, MD 20899-4710

By
Todd A. Watkins
Theodore W. Schlie
Lehigh University
Bethlehem, PA 18049

Contract 50SBNB9C1092

December 2006

U.S. DEPARTMENT OF COMMERCE
Carlos M. Gutierrez, Secretary

TECHNOLOGY ADMINISTRATION
Robert Cresanti, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
William Jeffrey, Director

ADVANCED TECHNOLOGY PROGRAM
Marc G. Stanley, Director

Abstract

To evaluate the impact of the Advanced Technology Program (ATP) relative to what might have happened without it, this study compares Displaytech, a 1994 ATP awardee, with Uniax, a matched case nonawardee that was a semifinalist from the same application round in the same microdisplays niche of photonics technologies. A novel methodology combines "snowball" interviewing with patent and publication citation analysis and a dynamic analysis of defender technologies to investigate ATP's incremental effects on its goals of promoting scientific and technical knowledge, U.S. competitiveness, and economic spillovers to the broader economy. The methodology attempts to better account for both market spillovers and knowledge spillovers and to explore what market and technological factors promote larger spillovers.

The main findings are that ATP funding accelerated technology development at Displaytech by about two years, leading to earlier mass-commercialization that significantly enabled the firm to weather the technology downturn in 2000–2002. Comparison case Uniax lagged by about two years in technology patenting and in fully commercializing its technology. Estimated measurable net economic gains to the nation from ATP's role in accelerating Displaytech's technical and competitive position is on the order of $5–7 million through 2006, mostly through the market effects directly to Displaytech, its employees, and its customers. This is an attractive 30-35% annualized rate of return to the $1.75 million ATP award. The paired comparison case Uniax evidences economic value of similar magnitude without the ATP award, but with a time lag in both technology and commercial impact. In both cases, economic spillover value came largely in the form of market spillover. The value of knowledge spillovers to the broader U.S. economy outside of the microdisplay market from these relatively small scale (<$5 million) projects were below the thresholds measurable by the methodology.

The cases suggest that key spillover-value-enhancing mechanisms include larger market scale, unique enabling technologies, lower price elasticities, closer social ties and technological similarity, high-profile researchers and a collaborative university culture, advances in complementary technologies, and the resources and absorptive capacity of larger firms. Spillover-value-limiting delays in commercialization in both cases were in part due to the failure of complementary supply-side or demand-side technologies to advance as rapidly as anticipated. This suggests that evaluation of the likelihood of advances in necessary complementary technologies is a potential project selection criterion for programs like ATP that aim to enhance spillovers. Similarly, a statistical analysis comparing citations to 30 ATP awardees and semifinalists in photonics suggests the rate of publication citations prior to application might be a useful, and readily obtainable indicator of knowledge spillover potential in evaluating project proposals. The cases also show that compared with a static defender methodology, using a dynamic defender technology methodology is feasible, easier, and produces estimates of downstream consumer value that are smaller, and hence less likely to overestimate the social value of new technologies. Finally, the snowball interviews with individuals named on citing patents and publications indicate that patent citations are a noisy, weak indicator of knowledge spillover. In contrast, publication citations by corporations were cleaner in terms of signaling true information flows. Future technology diffusion and spillover research might usefully apply techniques used in the large patent citation literature to the analysis of publication citations by corporations.

Keywords: Advanced Technology Program; research and development; innovation; technology policy; technology diffusion; social returns; economic spillovers; externalities; evaluation methodology; patents; citation analysis; case studies.

Acknowledgments

This research would not have been possible but for the dedicated help of several outstanding research assistants at Lehigh University. Lolita Paff did remarkable work tracing social networks for the Displaytech case and, together with Michael Margitich and Joleen Codner, was instrumental in reading and screening original ATP proposals in our process of selecting ATP cases and in assisting with citation analyses. Michael Metcalf was particularly valuable in tackling the complex technical issues in optical switching, the related marketplace, and citation analyses. Timothy Doherty also assisted with citation analyses.

During the initial planning stages of the project, EAO and ATP staff were exceptionally helpful working with us in developing the methodologies, accessing ATP records and documents, guiding case study selection, and contacting and getting participation approval from case study companies. In particular, EAO and ATP staff who provided guidance and support include Maryellen Kelley, former Economist, EAO; Rosalie Ruegg, former Director, EAO; Jeanne Powell, Economist, EAO; Richard Spivack, Economist, EAO; Thomas Lettieri, Program Manager, ATP. Andrew Wang, Economist, EAO, provided input throughout the project and writing of the report.

Stephanie Shipp, Director, EAO, Brian Belanger, former ATP Deputy Director, and Lorel Wisniewski, ATP Deputy Director, reviewed the final versions. Robert Sienkiewicz, supervisor in EAO, and Janet Brumby, Business Liaison Specialist in EAO, oversaw the publication of the report. Jo Ann Brooks, Information Resources Group, ATP, designed the cover.

Finally, we are grateful to company officers at Displaytech and Uniax who were generous with their time in cooperating with our interviews for this study.

Executive Summary

The Advanced Technology Program (ATP) aims to stimulate the development of high-risk technologies with potential, broad national economic benefits. ATP seeks to support research projects that otherwise would not be undertaken by the private sector, or carried out as quickly with the necessary scale or scope, because of the high technical risk associated with the research. In evaluating ATP as a program, the key issue is the impact of ATP relative to what would have happened without it. The research methodology of the present study is to compare an ATP awardee project with a nonawardee proposed project that was not funded by ATP, but was a semifinalist in the final selection round in the same technology area and ATP award competition as the awardee project. Both market and knowledge spillovers are tracked into the network of customers, competitors, suppliers, and even others outside of the originally conceived markets. To explicitly investigate market spillovers and knowledge spillovers, a novel methodology of combining "snowball" interviewing with patent and publication citation analysis is developed. In addition, a dynamic analysis of the defender technologies displaced by the ATP awardee technology is used. The main research work for this study was carried out during 2001-2004.

Methodology Definitions

- Snowball interview methodology: Interviews with key customers, suppliers, and competitors to measure market spillovers.
- Static defender methodology: Estimating the value of a new technology by comparing to an existing technology already in the market, while assuming that the existing technology remains static and unchanging.
- Dynamic defender methodology: Estimating the value of a new technology by comparing to competitor technologies being developed in the market, while assuming the competitor technologies are dynamic and changing.

This report presents the findings from a paired-comparison case study in photonics, comparing ATP awardee Displaytech (1994 awardee) with a semifinalist nonawardee firm that proposed a project in the same year and technology area as Displaytech. Due in part to manufacturing process and materials improvements supported by the 1994 ATP award, Displaytech today designs and sells microdisplays based on its patented ferroelectric liquid crystal (FLC) on silicon (FLCOS) integrated circuit technology. The firm remains the world's leading supplier of FLCOS microdisplays and is the first firm to bring FLC devices successfully to mass-market commercialization. The microdisplays have so far been sold mainly for viewfinders in digital cameras and digital camcorders, where they have displaced miniature cathode ray tubes (CRTs). The main market effects to date have been, first, in slightly increasing price competition in the fiercely competitive microdisplays market, saving U.S. consumers several million dollars, and second in expanding U.S. market share by roughly 2 percentage points and adding several million dollars to labor force earnings in the Boulder area. In the longer term, the capabilities of FLCOS microdisplays show promise in enabling the emerging area of holographic storage devices. While multiple sources of simultaneous federal funding to Displaytech make it difficult to isolate an ATP-only effect, the combined federal funding impact has been large; in all probability, in our view, this company and these microdisplays otherwise would not exist. Furthermore, ATP funding was the most relevant to commercialization because it was not tied to specific proposed applications, but rather to develop the technology to scale up to high-volume manufacturing.

The study estimates ATP's incremental impact, with respect to the particular technology, by exploring seven related questions:

Question 1: Has ATP advanced scientific and technological knowledge?

Question 2: Has ATP increased the economic and competitive performance of U.S. companies?

Question 3: Has ATP generated net benefits that spill over to the broader economy?

Question 4: Does ATP succeed in identifying high spillover projects, relative to what would happen without ATP?

Question 5: How might case study methodologies be improved to better account for both market spillovers and knowledge spillovers?

Question 6: What are principal spillover mechanisms, and what market and technological factors promote larger spillovers?

Question 7: How might methodologies for estimating the value of displaced technologies be improved?

The main findings on these questions from the paired-comparison case study are as follows:

1. **ATP support accelerated technology development for Displaytech.** A comparison of ATP awardee Displaytech with nonawardee Uniax finds that ATP support helped accelerate technology development. The impact of ATP support on awardee Displaytech is reflected in an increase in the number of Displaytech patents and citations to Displaytech patents. In contrast, without ATP support, nonawardee Uniax shows a patent citation pattern that indicates a lag of about two years in technology development. Furthermore, Displaytech advanced to commercial production, to the benefit of consumers.

2. **ATP increased U.S. economic and competitive performance in the display market.** In the absence of ATP support, ATP awardee Displaytech may not have been able to survive the technology downturn in 2000-2002. Specifically, ATP funding support and the ATP project focus on manufacturing processes helped reduce time-to-commercialization by about two years. By comparison, through 2004, nonawardee Uniax had yet to fully commercialize a cost-effective process.

3. **Measurable net economic gains from ATP investment in Displaytech include direct benefits to Displaytech as well as market spillover benefits to downstream customers.** Measurable net economic benefits from the ATP investment in Displaytech is estimated to be on the order of $5-7 million, accruing to Displaytech, its employees, and its customers. This represents a 30-35 percent annualized internal rate of return (IRR) to the nation on the $1.75 million ATP funding investment. This estimate does not include future value beyond 2006 that may accrue. Spillover benefits measured in this study are mainly market spillovers to consumers, while the value of knowledge spillovers measured is limited.

4. **The paired-comparison case study provides mixed evidence on whether ATP identified a high spillover project relative to what would happen without ATP.** ATP identified a high value project in the Displaytech technology, but the value from nonawardee Uniax technology has been similar in magnitude. Our snowball interviewing procedure produced little evidence of a measurable value in knowledge spillovers from either Displaytech or Uniax. However, in terms of a broader view of the overall economic spillover value from the two firms, both have been similar in employment and revenues, and both have generated substantive but diffuse value in terms of scientific impact. This suggests rough parity in the economic measures of value from the two projects.

5. **In this case study, the value of economic spillovers is largely measured in the form of market spillovers, while the value of knowledge spillovers may not be measurable with the present methodology.** The value of knowledge spillovers from the technologies analyzed in this case study was below the measurement threshold of the methodology. Measurement noise and uncertainty in techno-socioeconomic systems make it difficult to estimate the value of knowledge spillovers in relatively small ($1-5 million) projects. On the other hand, the methodology was able to estimate the value of market spillovers on this scale.

6. **This case study suggests that key spillover value-enhancing mechanisms include: larger market scale, unique enabling capabilities, lower price elasticities, closer social and technological distance, high-profile researchers and a collaborative university culture, advances in complementary technologies, and the resources and absorptive capacity of larger firms.** In the case of Displaytech, limited advances in complementary technologies was a principal impediment to broader technology spillover. This suggests the possibility of identifying spillover potential of projects by evaluating the likelihood of advances in necessary complementary demand-side and supply-side technologies.

7. **This case study shows that comparing a proposed new technology to a dynamic defender technology is methodologically feasible and easier than comparing it to a static displaced technology. The method of dynamic defender technologies is less likely to overestimate economic value from a new technology.** Over the 10-year time-to-market horizons of the studied projects, the actual technology trajectories were characterized by fundamental uncertainty: changing dynamic industries, new unforeseen substitute and complementary technologies, strategic moves by previously nonexistent competitors and suppliers, or entirely new potential customers. In the Displaytech case, several of the uncertain, unforeseen opportunities turned out to be significant for the firm. This study finds that using a dynamic defender methodology produces estimates of downstream consumer value that are smaller by a rough order of magnitude than that from a static defender methodology.

We make three final observations and conclusions:

First, ATP awards are relatively small in funding amount, and participating firms often leverage a broad portfolio of other federal, state, and local programs. So we cannot fully identify any single program's impact on a firm's competitiveness and technical success over long time horizons.

Second, statistical analysis of a sample of ATP awardees and nonawardees in the photonics technology area shows that ATP awardees have higher publication and citation rates than do nonawardees. This is true both before and after the date of ATP application. We suggest that prior publication citations by corporations might be a useful and readily available indicator of spillover potential.

Finally, our interviews with individuals named on citing patents and publications indicate that patents are a noisy, weak indicator of actual knowledge spillover, while corporate publication citations are a cleaner measure of true information flows. Much of the non-case study empirical literature on technology diffusion and knowledge spillovers has relied on patents. We suggest applying similar techniques to corporate publications.

Contents

Abstract iii

Acknowledgments v

Executive Summary vii

1. Introduction and Background 1

Why Are Economic Spillovers of Policy Interest? 1
ATP's Mission 3
Expanding Assessment Methodologies 4
Overview of Photonics Industries 6
Methodology 8
Case Selection 10
Snowball Interviewing 11
Citation Analysis 12

2. Displaytech 13

Introduction 13
Technical and Company Background 14
Proposed Research and Product under ATP 15
Proposed Applications 16
Competing Alternatives 18
Results 20
Unexpected Main Commercial Application 24
Direct Economic Effects 24
Producer Surplus and Employment 25
Consumer Surplus 29
Total Direct Economic Effect 32
Indirect Knowledge Effects 33
Patent Citations Analysis 34
Publications Citation Analysis 44

3. Comparison of Displaytech and Uniax 53
Comparison Case: Uniax 53
Technical and Company Background 53
Competing Alternatives and Applications 54
Results without ATP 55
Direct Economic Benefits 57
Patent Citation Analysis 58
High-Profile Scientists as Technology Diffusion Nodes 65
Publication Citation Analysis 67

4. Findings and Observations 75
Findings and Implications 75
General Observations on Technology Development and Evaluation Methodologies 82

5. Conclusions 87

Appendix 89
Semistructured Interview Instrument 89

References 91

About the Authors 97

About EAO . . . . inside front cover

About the ATP . . . . inside back cover

Figures

1. Value Creation and Spillovers 5
2. Worldwide Photonics Components Revenues, 2000 (Total $73 Billion) 9
3. Cross-Section of a Ferroelectric Liquid Crystal on Silicon Display 17
4. Competing Electronic Display Technologies 21
5. Within-Market Increase in Economic Surplus 25
6. Estimated ATP Employment Effect at Displaytech, 1995–2005 27
7. Monte Carlo Cumulative Probability for Employment Compensation Effect Through 2006 (ATP Award to Displaytech) 30
8. Historic Display Price-Quantity Trends 31
9. Within-Market Increase in Economic Surplus for a Highly Competitive Market 32
10. Monte Carlo Cumulative Probability for Consumer Surplus Effect Through 2006 (ATP Award to Displaytech) 34
11. Patents Citing Displaytech by Industry and Country 36
12. Patent Citations to Displaytech Patents 37
13. ColorLink Single-Panel Architecture for Microdisplay Projection System 38
14. Geographic Distribution of Citations to Displaytech Patents 41
15. Social Links to Organizations Citing Displaytech Patents 42
16. Citations to Displaytech Publications by Country 45
17. Citations to Displaytech Publications by U.S. Region 46
18. Corporate Citations to Displaytech Publications by Corporate Location 48

19. Corporate Citations to Displaytech Publications by Industry and Location 49
20. Timing of Displaytech and Uniax Patents 59
21. Timing of Citations to Displaytech and Uniax Patents 59
22. Patents Citing Uniax by Industry and Country 62
23. Patent Citations to Uniax Patents 63
24. Geographic Distribution of Citations to Uniax Patents 66
25. Citations to Uniax Publications by Country 68
26. Corporate Citations to Uniax Publications by Corporate Location 69
27. Citations to Uniax Patents and Publications by Chemical Industry Market Share 72
28. Corporate Citations to Uniax Publications by Industry and Location 73
29. Post-ATP Date Publication Citation Counts of ATP Awardees and Nonawardee Semifinalists 78
30. Flowchart of ATP Technology Development and Economic Benefit Generation Process 83

Tables

1. Photonics Technologies Enable Many Industries 8
2. Comparative Industry Scale, Growth, and Academic Research 10
3. Matched Case Study Firms by ATP Proposal Competition and Technology Area 11
4. Crowded Display Competition: Manufacturers and Developers of Non-CRT Electronic Display Technologies 19
5. Estimated Employment Compensation Effect Through 2006 (ATP Award to Displaytech) 28
6. Estimated Consumer Surplus Effect Through 2006 (ATP Award to Displaytech) 33
7. Organizations and Groups Most Frequently Citing Displaytech Patents 35
8. OLS Regression Results on Time Lag to Citation of Displaytech Patents 44
9. Top Organizations and Individuals Citing Displaytech Publications 47
10. Corporations Citing Post-1994 Displaytech Publications 51
11. Organizations and Groups Most Frequently Citing Uniax Patents 61
12. OLS Regression Results on Time Lag to Citation of Uniax Patents 67
13. Top Organizations and Individuals Citing Uniax Publications 70
14. Top 20 Corporations Citing Uniax Publications 74
15. Publication and Citation Rates of ATP Awardees and Nonawardee Semifinalists in Photonics 79
16. OLS Regression of Post-ATP Publication Citation Rates by ATP Awardees and Nonawardees in Photonics 80

1. Introduction and Background

The Advanced Technology Program (ATP) aims to stimulate the development of technologies with potential broad national economic benefits. ATP seeks to support research projects that otherwise would not be undertaken by the private sector, or carried out as quickly with the necessary scale or scope, because of the high technical risk associated with the research. When ATP was authorized in the Omnibus Trade and Competitiveness Act of 1988, its goals were “to assist U.S. business in creating and applying the generic technology and research results to (1) commercialize significant new scientific discoveries and technologies rapidly and (2) refine manufacturing technologies” (Public Law 100–418). ATP seeks to foster economic growth and the competitiveness of U.S. firms by advancing technologies with potentially large net social value for the nation, but that would not otherwise emerge in time to maximize their competitive value or realize first-mover advantages. By supporting specific commercially relevant, high-risk technology development projects, ATP aims, among other things, to accelerate the benefits of emerging technologies, to widen potential application areas, and to increase the likelihood of technical success and hence commercial success. The economic rationale for ATP is an R&D market failure argument relating to risk and uncertainty, imperfect information, externalities and spillovers, and incomplete markets. Therefore, a central issue for program evaluation is whether ATP is successful at fostering and enabling economic spillovers.

WHY ARE ECONOMIC SPILLOVERS OF POLICY INTEREST?

The links between competitiveness and technology, and the questions those links raise for technology policy or, more broadly, industrial policy, have major implications for a nation’s wealth, living standards, and national security. Policymakers and economists have long understood that technological innovation is important for economic growth. Francis Bacon (1626) fantasized about a utopian civilization, New Atlantis, which flourished through the application of science to understanding nature in a learned society he called Solomon’s House. In 17th century Britain, the society served as the model for the Royal Society, the origin of today’s National Academies of Science. Bacon’s proclamation that “knowledge is power” became, in *The Wealth of Nations* (1776), Adam Smith’s pin factory that embodied productive technology. Joseph Schumpeter (1942) saw innovation as the dynamic engine of competition and economic growth. Empirical work by Robert Solow (1957) and later extensions [Denison (1985), Terleckyj (1974), Griliches (1964, 1986), Scherer (1982, 1984)] made it clear that technological innovation indeed has been a major contributor to increases in economic productivity.

It is also well understood that, under some circumstances, competitive markets will fail to generate adequate incentives to innovate. The market failure justifications for government support of R&D are well established and widely discussed in the innovation economics and technology policy literature [see reviews in Geroski (1995), Metcliff (1995), Jaffe (1996), and Tassey (1997)]. Main sources of market failure in case of R&D include uncertainty and externalities. In economics, an "externality" is a side effect, a cost or benefit affecting others that is not reflected fully in market prices.

Richard Nelson (1959) and Kenneth Arrow (1962), among others, have argued persuasively that because of the *public good* characteristics of scientific and technological information, from the national perspective, private competitive firms will invest in suboptimal levels of R&D activity because they are unable to capture enough of the benefits that will accrue to society. This *appropriability* problem fundamentally distinguishes R&D from other sorts of investment options by firms. One company's use of technical information does not necessarily preclude another from use of the same information. Zvi Griliches (1979) and Paul Romer (1990) further formalized the national underinvestment implications of this external spillover of R&D results.

Empirical evidence from a wide variety of studies, industries, and methodologies supports the view that the social benefits of R&D are consistently high and, importantly for policymaking, higher than the private benefits by factors typically ranging from 30 to 80 percent, and sometimes as much as 300 percent [Griliches (1958, 1964), Leonard (1971), Mansfield et al. (1977), Evenson and Kislev (1973), Tewksbury et al. (1980), Jaffe (1986), Bernstein (1989), Bernstein and Nadiri (1989)]. The persistence of high social rates of return on R&D is an indication that not enough is being invested in R&D from a social optimization point of view. Otherwise, returns on R&D would return to rates that are more normal.

Despite the relative consistency of (at least the positive sign of) the empirical evidence, there remain significant disagreements in both the U.S. political arena and the economic literature about the appropriate policy response to the underinvestment in R&D. In particular, there is little consensus about the extent to which the federal government should subsidize technology development geared toward commercial markets.

The U.S. federal government, in fact, uses a broad portfolio of mechanisms for fostering technical innovation: direct and indirect R&D tax credits; capital gains incentives; patents and other intellectual property policies; antitrust exemptions; manufacturing extension programs; cost-shared funding (such as those in ATP); small business grants and loans; science parks; technology transfer initiatives; and government-industry partnerships. To all this we can add the mission-oriented technology development spending by agencies such as the Department of Defense (DOD), National Institutes of Health (NIH), National Aeronautics and Space Administration (NASA), Department of Energy (DOE), and many others. This portfolio diversification approach reflects to a significant degree both our U.S. tradition of decentralized power and resources and the great diversity of markets and technologies, with attendant variation in the proportion of the characteristics of public and private goods.

ATP'S MISSION

ATP emerged during the late 1980s amid national concern over the competitiveness of U.S. companies and their ability to commercialize new technologies effectively relative to foreign competitors. Since World War II, U.S. science and technology policy had largely been mission-driven or focused on basic research. Major international trading competitors such as Japan, the European Union, and rapidly emerging South Korea, however, were employing policies more directly supporting the commercial development and application of technologies. High-profile commercial technology policies from Japan's Ministry of International Trade and Industry (MITI) and the European Commission's "precompetitive" Framework Program reinforced the U.S. political response that included the establishment of the ATP.

Hence, one public document from ATP aimed at attracting industry participation explains ATP's goals:

> to foster the development and broad dissemination of challenging, high-risk technologies that offer the potential for significant, broad-based economic benefits for the nation. Such a unique government-industry research partnership fosters the acceleration not only of dramatic gains in existing industries, but also acceleration of the development of emerging or enabling technologies leading to revolutionary new products, industrial processes and services for the world's markets.... (ATP Proposal Preparation Kit, November 1998, p. 1)

Another ATP publication, targeted more toward economists and policy analysts, suggests that ATP:

> selects only those projects for awards for which it thinks the potential social rate of return (the return to the nation) far exceeds the potential private rate of return on investment, and for which it thinks the private sector will either not do the project at all, or not within the critical time, or in the scale/scope, necessary to realize the potential societal benefits.... A successful ATP will in the long run result in net societal benefits greater than would have resulted without it. (Ruegg, 1996)

In other words, as pointed out earlier, the economic rationale for ATP is an R&D market failure argument squarely within the Bacon-Schumpeter-Nelson-Arrow-Solow-Griliches-Romer theoretical tradition outlined above. Thus, a central issue for program evaluation is whether ATP is successful at fostering and enabling economic spillovers.

A body of research evidence demonstrates that ATP projects do indeed generate positive spillovers. However, empirical studies of privately funded industrial R&D indicate that R&D in general generates spillovers, whether funded by the government or not. It is insufficient for ATP evaluation, then, as Jaffe (1996) points out, "simply to cite the existence of spillovers. The ATP must be able to show that the government policy portfolio including the ATP is more effective at correcting the R&D market failure problem than the portfolio without the ATP would be." He adds, "If the ATP can succeed in targeting projects with better-than-average spillover potential, then it will generate large social returns that would not otherwise have been achieved."

EXPANDING ASSESSMENT METHODOLOGIES

Four questions have been central in ATP evaluation research:

Question 1: Has ATP advanced scientific and technological knowledge?

Question 2: Has ATP increased the economic and competitive performance of U.S. companies?

Question 3: Has ATP generated net benefits that spillover to the broader economy?

Question 4: Does ATP succeed in identifying big spillover projects, relative to what would happen without ATP?

Existing evaluation methods begin by estimating the direct effects of ATP on its participants, gathering data through interviews, surveys, document reviews, and expert forecasts and using metrics such as revenues, productivity gains, resource savings, decreased product maintenance costs, improved product quality, and reduced time required to launch new products. This value to participants is represented conceptually below as the center circle in Figure 1. Evaluating the incremental effect of ATP is a counterfactual (or counter-temporal) exercise of comparing the current (or estimated future) state to what might have been (or was before) without ATP.

Evaluating the impact on nonparticipants is more difficult. Part of the methodological problem is that spillover benefits come in two main flavors: a) value or benefits to customers, competitors, and suppliers of the technology innovator (market spillovers); and b) knowledge to others not in the same markets, perhaps even completely unrelated to the developer (knowledge spillovers). Most ATP case studies focus on the value to participants and the value of market spillovers, especially to customers/users. This is shown by the shaded regions of Figure 1. The value of knowledge spillovers to other players outside the target market (the lower right quadrant in Figure 1) has not been directly or explicitly measured.

Hence, we consider two additional study questions where we hope to contribute:

Question 5: How might case study methodologies be improved to better account for both market spillovers and knowledge spillovers?

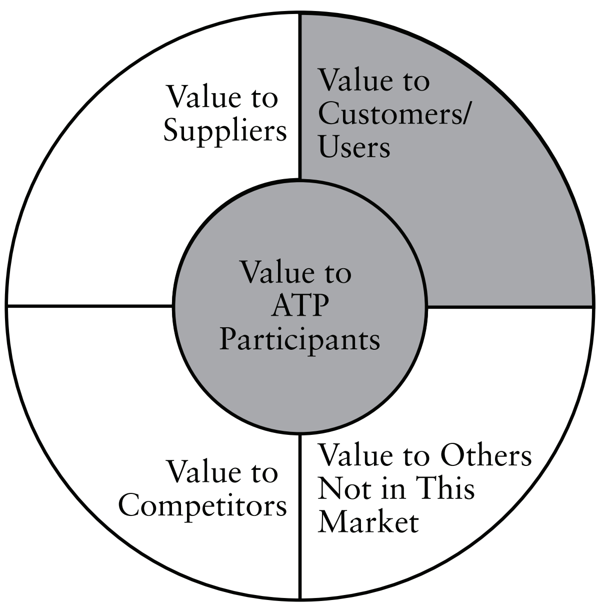
Question 6: What are the principal spillover mechanisms, and what market and technological factors promote larger spillovers?

Our methodology extends program evaluation of ATP in three ways. First, by including a quasi-control comparison case, we aim to address questions that previous ATP evaluations have not been able to deal with. We include in our case study both an ATP awardee and a nonawardee semifinalist in the same technological field and from the same proposal competition. Tracking the nonawardee allows us to explore the extent to which an ATP awardee generates larger spillovers than projects that do not receive ATP funding.

The second and third methodological improvements extend the case study methodology of Mansfield et al. (1977) in two significant ways. Case study methods to date have implicitly focused on market spillovers. Knowledge spillovers, on the other hand, have generally been the focus of analytical studies using patent statistics, or aggregate industry statistics.

FIGURE 1

Value Creation and Spillovers



To investigate explicitly both market spillovers and knowledge spillovers through case studies, a methodological extension we implement is a combination of a snowball interviewing process, in which we identify key customers, suppliers, and competitors and include them in our interviewing in order to measure market spillovers, and patent and publication citation analyses to identify organizations outside the initial target markets in order to investigate knowledge spillovers. We are thereby mapping the technology diffusion process by including nonparticipating customers, competitors, suppliers, and other organizations in the study.

The third methodological contribution is framed in our question:

Question 7: How might methodologies for estimating the value of displaced technologies be improved?

This relates to accounting for the economic value of technologies displaced from the market by technologies emerging from ATP-supported development projects. In theory, the incremental economic value attributable to a new technology (and, by extension, to the policies that supported its development) should net out the economic value that would have existed had the new technology not been created. This is either (or both) a forecasting or historical counterfactual exercise, subject to large uncertainties and subjectivity.

In empirical practice, this has meant subtracting the forecast value of the displaced "defender technologies" already in the market. Note, however, that this counterfactual compared-to-what valuation of a new technology takes a static view of the "old" market. It essentially ignores the potential value of parallel development projects that may have occurred elsewhere in the market, the results of which were not yet in the market. However, parallel development projects among competitors in markets characterized by dynamic strategic interactions and rapidly moving technologies are possible, and even likely. When a new technology enters a market, it might not only displace the existing defender in the market but also preempt a second, third, or more also-rans that would have otherwise emerged. We call this process "dynamic displacement" and believe it is a theoretically superior construct to the forecast of a single defender technology and, in the context of counterfactual estimation, no more subject to error empirically.

Where counterfactual analysis is called for, we utilize a dynamic interpretation of the defender technology for estimating the economic value displaced by a new technology, comparing both a static and dynamic defender interpretation in order to evaluate the difference between the two approaches in terms of their estimates of net social value, as well as their empirical feasibility.

OVERVIEW OF PHOTONICS INDUSTRIES

This study focuses on evaluating ATP projects in the photonics industries. Photonics involves the joint application of optics and electronics (i.e., generating, controlling, manipulating, applying, and detecting photons and electrons). ATP supports technology development in this area because many photonics technologies are in an emerging stage characterized by high risk, are seen as enabling technologies for many industrial sectors, and are based on such a broad interdisciplinary science platform. Development of photonics technologies has the potential to lead to significant spillover and market opportunities.

At the intersection of optics and electronics, photonics often draws on and informs multiple science and technology disciplines, including:

- optical physics and chemistry
- materials science, materials processing, and thin films
- integrated optics, micro-optics, and adaptive optics
- information processing, holography, optical storage, and pattern recognition
- quantum electronics, semiconductors, and lasers

Moreover, fields across this base are progressing rapidly. Our ability to control photons has surpassed our ability to control electrons. We can control not only light's energy better, but also its wavelength and its temporal dimensions. For example, scientists have made pulses of light that are femtoseconds (10–15) long, a millionth of a billionth of a second.

Today, photonics plays a key enabling role in applied technologies such as telecommunications, information storage, imaging, and signal processing. The invention of lasers, semiconductor materials, optical fibers, and other waveguides and discoveries in photonics materials and of nonlinear optical phenomena have enabled the development of many new optical systems and devices with far-reaching impact on our everyday lives (see Table 1).

This study of photonics and optoelectronics adds to the set of field-focused ATP evaluations. The vast diversity in technologies, market structures, relative U.S. competitive positions, methods for appropriating value from technology development, degrees of collaboration, spillover mechanisms, and so on almost certainly mean that ATP's impact will vary widely across sectors. Sector diversity in evaluation studies should lead to a better understanding of spillover mechanisms and the relative importance of various market and technological factors. Such increased insight, in turn, may improve program design and project selection not only for ATP, but also for other science and technology funding programs.

Few studies of this increasingly important industry have been conducted. According to the Optoelectronics Industry Development Association, total revenues for photonics components worldwide were more than $73 billion in 2000 (see Figure 2). Photonics is rapidly becoming one of the largest high-technology sectors. It is already roughly half as large worldwide as semiconductors or aircraft and growing more rapidly (see Table 2). Curiously, despite the importance of photonics in absolute terms, and the central role it plays in enabling other key sectors, very few academic studies exist. Using a simple metric, shown in Table 2, a keyword search on abstracts in the academic literature database EconLit turned up hundreds of studies on semiconductors, aircraft, and pharmaceuticals, but only a handful on either photonics (2 abstracts) or optoelectronics (8 abstracts). Even "optics" generated very few (15), and several

TABLE 1

Photonics Technologies Enable Many Industries

Communication
- Fiber optic networks
- Optical Internet

Computer/office
- Displays, CD, DVD, storage
- Scanners, fax, printers

Entertainment
- Audio/video disk players
- Digital cameras, HDTV

Lighting and illumination

Military
- Laser weapons, displays
- Range finding, sensors

Material processing
- Laser machining and processing
- Test and evaluation
- Sensors

Medical
- Laser surgery and dentistry
- Imaging
- Biophotonics

Signs and signals
- Traffic signals
- Advertising displays
- Indicator lights

Solar Power

of those related to optometry. By this metric, even “zinc,” an industry one-eighth the size, generated considerably more academic interest than photonics, with 27 abstracts.

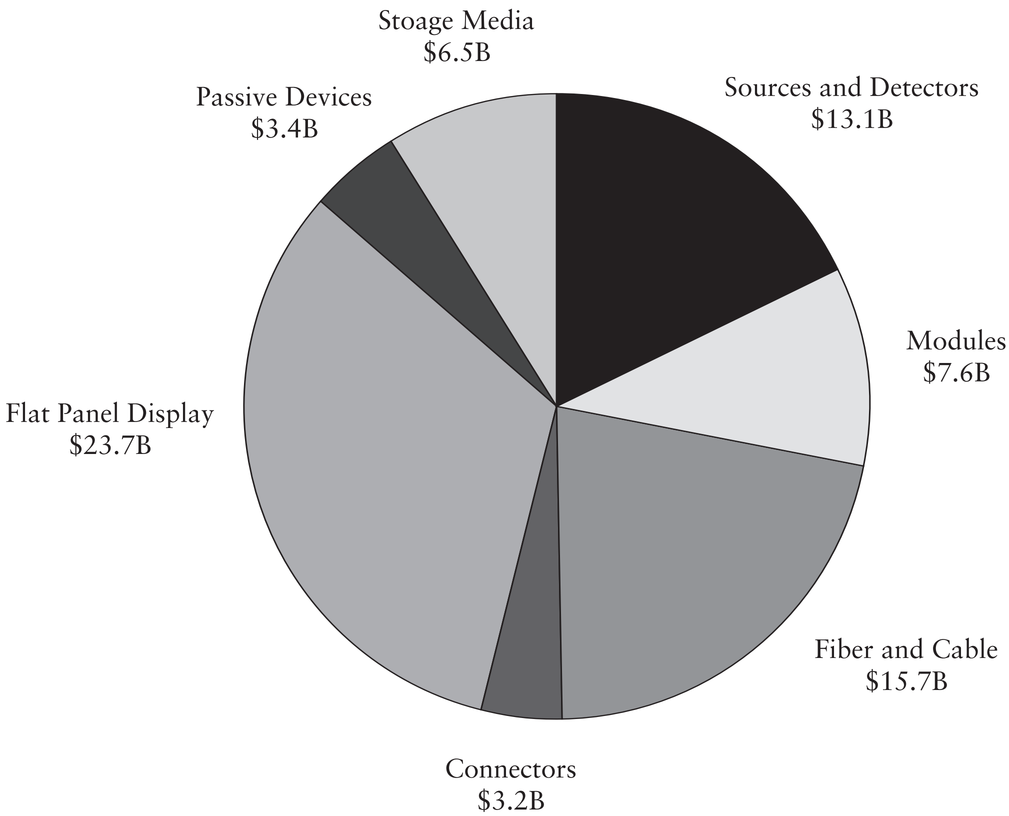
METHODOLOGY

In evaluating whether ATP’s benefits outweigh its costs, the relevant issue for economic evaluation is ATP’s impact compared to what would have happened without it. The research methodology here makes a contribution in that direction compared with previous ATP evaluations by including a quasi-control comparison case—a project not funded by ATP, but which made it to the final selection round in the same field in the same proposal cycle—and explicitly tracking both market and knowledge spillovers into the network of customers, competitors, suppliers, and others outside of the originally conceived markets. To investigate both market spillovers and knowledge spillovers through a case study approach, we developed and used a novel methodology: a combination of a snowball interviewing process coupled with patent and publication citation analyses. We also incorporated a dynamic interpretation of displaced defender technologies.

We compare an ATP awardee with a nonawardee semifinalist that acts as a quasi-control case, matched by technological area and ATP proposal competition, in order to estimate ATP’s incremental impact along three key dimensions of net social value creation: 1) advances in scientific and technological knowledge; 2) increases in the competitiveness of U.S. companies; and 3) benefits that spill over to the broader economy. We also investigate spillover mechanisms, and identify market and technological factors that might promote larger spillovers.

FIGURE 2

Worldwide Photonics Components Revenues, 2000 (Total $73 Billion)



Source: Optoelectronics Industry Development Association, www.oida.org

Methodology Definitions

- Snowball interview methodology: Interviews with key customers, suppliers, and competitors to measure market spillovers.
- Static defender methodology: Estimating the value of a new technology by comparing to an existing technology already in the market, while assuming that the existing technology remains static and unchanging.
- Dynamic defender methodology: Estimating the value of a new technology by comparing to competitor technologies being developed in the market, while assuming the competitor technologies are dynamic and changing.

TABLE 2

Comparative Industry Scale, Growth, and Academic Research

Industry	Worldwide Sales ($ billions)	Growth/Year (1990s)	EconLit Abstracts (2000)
Photonics/Optoelectronics Components (1)	$73 B (2000)	19%	"Photonics" 2 "Optoelectronics" 8 "Optics" 15
Semiconductor Components (2)	$140 B (2001)	13.5%	"Semiconductor" 226
Aircraft, including Engines and Parts (3)	~$175 B (2000)	1.2%	"Aircraft" 267
Pharmaceuticals (4)	$317 B (2000)	9.2%	"Pharmaceuticals" 289

Sources: 1. Optoelectronics Industry Development Association, www.oida.org
2. Semiconductor Industry Association, www.sia-online.org
3. Aerospace Industries Association, www.aia-aerospace.org, and European Association of Aerospace Industries, www.aecma.org
4. IMS Health, www.imshealth.com

CASE SELECTION

We worked with ATP staff to identify all photonics-related projects started in or after 1992 and completed by 1998. We identified 19 ATP awardee projects that satisfied these broad constraints. We then met with the ATP project managers responsible for those photonics projects to narrow the potential ATP cases while maintaining a range of technical fields within photonics. One key selection criterion was a willingness of the project organizations to cooperate in this study. A second criterion was that there be other applicants from the same ATP funding competition and in the same technical field that could qualify as our quasi-control comparison case. A third criterion was that the company be small enough to enable reasonable clarity in tracking technology flows and ATP impacts. Through this process, we selected Displaytech in the microdisplays technology area.

We then worked with ATP personnel to identify all proposals from the same competitions that were evaluated highly by the reviewers and became semifinalists (i.e., invited to the final selection round to make an oral presentation), but did not win an ATP award. These "near winners" were used to derive a quasi-control comparison case that would enable us to better assess the incremental impacts of ATP support. From the 1991–1994 ATP funding competitions, there were 30 nonawardee semifinalists whose proposal titles appeared to be in the photonics technology area, broadly interpreted.

We sought to match a nonawardee semifinalist proposal to our ATP case study target. First, we looked at apparent technological proximity. Based on the proposal titles, we identified 10 potential matches in the technology area of displays. Second, we looked at the ATP

TABLE 3.

Matched Case Study Firms by ATP Proposal Competition and Technology Area

ATP Awardee	ATP Semifinalist Nonawardee
Displaytech • 1993 and 1994 proposal competitions • Microdisplays	Uniax • 1993 proposal competition • Microdisplays

competition year of the proposals. Some of the semifinalist proposals were ATP awardees in later years, and thus eliminated as possible controls for the case study. Through ATP's Economic Assessment Office (EAO), we sent letters requesting participation to the top several candidates. Finally, we narrowed the pool to the one closest, willing semifinalist match for the case study target, as shown in Table 3. In this case, discussed in detail in the next chapter, we are quite satisfied that we have a reasonable match.

SNOWBALL INTERVIEWING

We undertook in-depth semistructured interviews with the two or three people most familiar with the project and its target markets. Based on these interviews, we expanded the list of interviewees in snowball fashion by asking the ATP participant to identify, among non-participating firms, several customers and several suppliers judged to have gained the most value from the ATP technology. We also asked for competitors, those most likely to gain by learning and borrowing ideas and those most likely to have been preempted, if any, in a technology race. To explore market spillovers, we then contacted these nonparticipating organizations to identify the people within each of these organizations thought most likely to be knowledgeable about the technology and markets in question, and we then did semistructured interviews with them, in most instances by telephone.

We designed two semistructured interview instruments, one for in-person interviews of the ATP participants (see Appendix) and a very slightly modified one for the nonparticipant spillover recipients. The instruments targeted specific metrics that technology managers could be reasonably expected to answer concretely and with reasonable accuracy.

We explored the effect of the ATP technology on metrics along the following concrete and specific lines, though the relevant metrics differed from case to case: increases in sales, employment and market share; cost savings and yield improvements; numbers of new or significantly improved products introduced; enhanced quality control (process variance, time-to-failure); lowered maintenance and operating costs; increased speed of new product development completion/time-to-market; expansion in the scope of technology applications (e.g., number of new technology projects/products enabled or undertaken); decreased additional costs, such as equipment and marketing costs normally incurred in commercial ramp-up; greater use of mechanisms to capture value from technology (e.g., patents, trade secrets, first-mover advantages, customer loyalty, learning curves, and economies of scale); and enhanced position in requisite complementary assets (what they cost and who owns them).

Because we are interested in tracing the spillover flows into the broader network, we specifically asked for outputs from the ATP project, such as papers published, conference presentations, patent applications, and awards. We also asked about information-sharing metrics such as resulting alliances with customers, subcontractors, and competitors.

We also specifically explored whether the technology in question drove out or lost to promising close alternatives through questions such as: Who are the organizations that you believe were closest to introducing similar technologies? How many more months or years longer might it have taken them to introduce them? What were the quantities and prices of displaced/cannibalized products/processes?

CITATION ANALYSIS

Finally, we attempted to identify knowledge spillovers to completely unrelated organizations through analyses of external patents and publications citing the patents and publications emerging directly from the ATP project. Based on citation counts, we identified and interviewed by telephone citing individuals at the top five other nonparticipant U.S. firms that were apparently gaining the highest value from the ATP-sponsored technology.

For patents, we used full-text patent citation indexing available online from the U.S. Patent and Trademark Office to identify all subsequent patents that cited the case project outputs. These patents, in turn, identified firms and individuals who had not collaborated in any way with the case firm, but had used its results, perhaps in other fields or applications.

Similarly, we used a publication citation analysis data service, the Science Citation Index available from the Institute for Scientific Information (ISI). With ISI's Research Services Group, we identified all papers in the ISI database authored by investigators associated with the case study firm and all subsequent publications and authors that cite them. Again from citation counts, we identified and interviewed by telephone citing individuals at U.S. firms that appeared to be the top receivers of knowledge spillovers.

2. Displaytech

INTRODUCTION

In June 1994, Displaytech, Inc. submitted a proposal entitled *FLC/VLSI High-Definition Image Generators* to the Advanced Technology Program. The proposal won federal funding of $1.75 million in the ATP General Competition of November 1994, and lasted two years. The 1994 proposal was a revised submission from a well-received, but not awarded, proposal in the 1993 competition.

The company, founded in 1985, today designs and sells microdisplays based on its patented ferroelectric liquid crystal (FLC) on silicon (FLCOS) integrated circuit technology. The microdisplays have been sold mainly for viewfinders in digital cameras and digital camcorders, where they have displaced miniature cathode ray tubes (CRTs). Interestingly, these mass-market applications that dominate Displaytech revenues today were not those envisioned in the 1994 proposal. The microdisplays also have large, near-term market applications in digital projectors, cellular telephones, and other mobile devices, as well as in large-format computer monitors and televisions. All these areas were foreseen in the 1994 proposal, but have yet to develop fully as mass-market outlets for Displaytech. In the longer term, the capabilities of FLCOS microdisplays show promise in the emerging area of holographic storage devices. The military has also shown continued interest in and funding for applications to displays, as well as applications in fast optical correlators for real-time image processing, pattern recognition, and guidance systems.[1]

Located in Longmont, Colorado, the firm remains the world's leading supplier of FLCOS microdisplays and the first firm to bring FLC devices successfully to mass-market

1. Note also that Displaytech also won a DARPA SBIR award in July 1994 to pursue optical architectures for head mounted displays, using these same microdisplays. See http://www.darpa.mil/MTO/Displays/HMD/Factsheets/MiniLCD.html. Both awards came shortly after the Clinton administration in April 1994 launched the separate, but related, $587 million Flat Panel Display Initiative intended to create a reliable domestic supply base of displays for the military. These microdisplays are clearly a classic dual-use technology.

commercialization. In 2001, Displaytech produced more than 1 million FLCOS microdisplays. This mass-market application took 27 years from the first theory proposing that FLCs exist and 22 from the first discovery of bistable switching behavior in FLC thin films. ATP funding in 1994–1996, coupled with previous federal funding under Small Business Innovation Research (SBIR) contracts from the Defense Advanced Research Projects Agency (ARPA/DARPA), the Naval Surface Warfare Center, Air Force Rome Labs, and NASA and prior PhD research support from the Army, played a very significant role enabling that commercial success by 2001. While the multiple sources of simultaneous federal funding make it impossible to isolate an ATP-only effect, the combined federal funding impact has been large: in all probability, in our view, this company and these microdisplays otherwise would not exist. ATP funding, however, was the most relevant to commercialization because it was not tied to specific proposed applications, but rather to develop the technology to scale up to high-volume manufacturing.

TECHNICAL AND COMPANY BACKGROUND

Displaytech and the ATP-supported FLCOS technology trace roots directly back to faculty at the University of Colorado, Boulder. As we will see below, this connection continues to be an important nexus for the diffusion of ATP-supported technology. In 1974, Robert Meyer of Harvard University first theorized and then demonstrated that ferroelectric liquid crystals exist.[2] Physicist Noel Clark was an assistant professor working in the same liquid crystal group at Harvard at the time, so knew closely about Meyer's work. Clark moved to the University of Colorado in 1977, and spent the next two summers investigating smectic liquid crystal films with Sven Lagerwall at Chalmers University of Technology in Sweden.

In 1979, while waiting in Sweden for some dismantled research equipment to be rebuilt for other purposes, Clark and Lagerwall undertook what they intended to be "a few quick experiments to explore FLC switching…to investigate what would happen when the liquid crystal layer was made very thin."[3] In thicker films, the properties of the crystals would create stripes in transparent capacitor FLC cells, but the stripes would disappear under an applied electric field. However, this was not stable if the field was turned off. The behavior of the thinner layers was unexpectedly different. A checkerboard-like pattern appeared, with boundaries that changed with applied voltage. As Clark put it: "I knew within about 30 seconds what I had seen. The dark and bright regions were ferroelectric domains, which could be controlled with the field. It was a bistable switch…. We showed that you could have these very fast, bistable electro-optic devices. People got very excited."[4]

Clark and Lagerwall shortly thereafter applied for a patent (US4367924), and then in 1980 published an article on their discovery in *Applied Physics Letters*.[5] The work stimulated

2. The following history based on Paul (2000) and personal interviews by the authors with Noel Clark.
3. Paul (2000), p. 9.
4. Paul (2000), p. 9.
5. Clark and Lagerwall (1980).

significant interest worldwide. The article is now among the most often cited in liquid crystal research, with thousands of citations. By 1990, there were more than 1,000 other FLC-related patents from a wide range of researchers and companies.[6] But, given the complexity of the technology, bringing it to commercial mass-market reality took until 2001, when Displaytech had solved enough materials, manufacturing process, and cost issues. Manufacturing process and materials design issues were the core of the 1994 ATP proposal, and today's Displaytech microdisplays are produced by a contractor in Japan using a fundamental manufacturing process and some materials ingredients Displaytech developed using the ATP funding.

Displaytech itself took shape in 1984, founded by Clark and one of his PhD physics students, Mark A. Handschy. In 1983, Handschy completed his dissertation on surface-stabilized FLC electro-optic devices (with PhD research support from the Army Research Office).[7] They invited Michael Wand, another recent University of Colorado PhD, in the field of organic chemistry, to help direct Displaytech's research into the properties and formulations of FLC materials. In 1987, the company introduced its first commercial product, a high-speed shutter that took advantage of the very fast switching capabilities of FLCs. With some commercial sales and a regular string of federal SBIR contracts related to military applications, the firm grew to about 25 employees by 1991 and remained there through the time of the 1994 ATP award. After several rounds of venture capital, which ATP's funding award helped attract,[8] employment then grew to 100 by 1998 and 140 by 2000. Plans were well in place to ramp up mass-manufacturing capacity in Longmont and bring employment up to 200–250 by the end of 2001. However, by 2003, hit by the technology-sector downturn, Displaytech instead had gone through several layoffs, decided to outsource all its high-volume manufacturing to Japan, and had only 50 employees in Longmont. The firm is a very nice case study for a study in technology diffusion and spillover, because it is essentially a one-technology company: all its revenues continue to be related to FLC devices enabled by co-founder Clark's patented discovery of fast, bistable FLC switching.

PROPOSED RESEARCH AND PRODUCT UNDER ATP

Displaytech's 1994 ATP proposal aimed to enable mass manufacturing of miniature active-matrix pixel arrays using FLC directly on silicon integrated circuits—tiny imagers on microchips. Displaytech invented and first demonstrated the high-resolution FLCOS microdisplays, but had made only laboratory grade samples, one at a time. Specifically, the proposed work involved high-volume manufacturing process techniques, methods for maintaining direct current (DC) balance, and research toward stable FLC materials that were commercial device grade. The goal was a market-ready, high-resolution (2000 x 2000 pixels), full-color and grey-scale capable display on silicon chips in the same size range as microprocessors (e.g., the 17mm^2 Intel Pentium).

6. Paul (2000).

7. See Army Research Office (1999).

8. Authors' personal interviews with Displaytech co-founder Mark Handschy. See discussion below.

On the manufacturing process side, a major challenge was to reduce manufacturing costs to the point where commercial applications were economically attractive. The lab-scale processes were labor intensive and had quite high failure rates. The proposed process was "wafer-scale," that is, manufacturing 50 to 100 or more devices on a single silicon wafer, processed as one unit. However, as shown in Figure 3, the displays have glass, which cover a gap in the FLC material, enclosed over a silicon integrated circuit (IC). One major problem was how to scribe or dice both glass and silicon in order to separate—"singulate" in industry jargon—the multiple microdisplays on the wafer. Traditional liquid crystal display (LCD) manufacturing involved only scribing glass, and traditional microchips involve just silicon. Displaytech wanted to investigate several alternative methods using equipment from various vendors.

Another process focus was improving the edge sealing method for depositing adhesives in the tiny gap between silicon and glass, the "perimeter seal" in Figure 3. Technically, to get bistable behavior, the gap needed to be 1 micron, 10 times smaller than in typical liquid crystal (LC) displays. So, the sealing process needed to deposit far smaller amounts of adhesive. Reliably depositing glue for 1-micron spaces, in a repeatable process for high-yield, high-volume manufacturing, turned out to be a significant technical challenge.

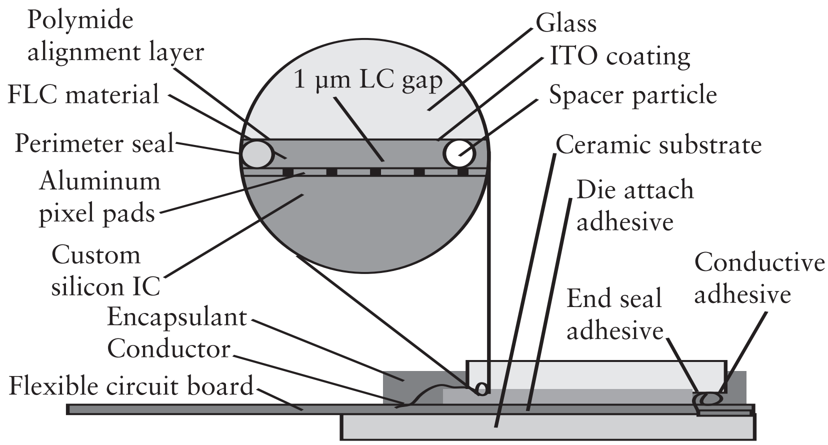
On the materials side, they hoped to improve the effective lifetime of the FLC materials, in part through composition and characterization research to overcome electrolytic degradation problems of FLCs. The bistable property of FLC materials eliminates the need to apply DC voltage constantly. This has commercial advantages in power consumption, for example. However, in the original composition of the FLC materials, it was difficult to maintain good bistability over time and wide temperature ranges. Bistable formulations tended to reduce either switching speed or contrast, both important in commercial applications. Displaytech investigated various compounds as components of FLC compositions to improve these properties. While the complete multi-ingredient FLC composition developed under ATP funding is now only used in minor market applications, several of the individual compounds identified remain in use in Displaytech's current commercial applications.

PROPOSED APPLICATIONS

In the 1994 proposal, Displaytech envisioned selling the microdisplays to a variety of markets. The hope was that the small-scale, fast-switching characteristics would not only displace conventional CRT tubes in some display markets, but also enable other market applications where CRTs and standard LC displays were less than adequate. The most attractive markets for displacing CRTs, one of the last bastions of vacuum tube technology, were in televisions and computer monitors. Displaytech believed the FLC microdisplays could be combined with light sources and optics to make relatively thin, light, yet high-resolution front- or rear-projection displays, including high-definition televisions in size ranges up to 60 inches and office projectors for computer presentations. They also hoped to enable a major market in head-mounted goggles for virtual reality, portable computing, stereo computer aided design (CAD) workstations, medical and industrial hands-free visualization, and 3D

FIGURE 3

Cross-Section of a Ferroelectric Liquid Crystal on Silicon Display



Source: Displaytech

video games. Other potential applications Displaytech hoped for their miniature displays included portable wireless communication devices (e.g., cell phones, PDAs, and fax pagers), pocket electronic books, low-cost instant film printers for consumers, fast ultra-high-resolution line-scan medical imaging, and digital pre-press equipment. They also believed the speed and size advantages of FLC would be useful as input devices in high-capacity, fast-access optical (holographic) computer memories. Note that the proposal mentions in passing, but does not envision a major emphasis on, camera or camcorder viewfinders, which turned out to be the major revenue generator by 2003. Note also that, because the microdisplays would be only one part of larger complex systems, commercial success in each of these applications required parallel innovation, very largely beyond Displaytech's control, in complementary technologies. For example, projectors and monitors required longer-life, higher-brightness light sources and lower-loss, lower-distortion optical magnification systems, visual signal processing and addressing microelectronics, and so forth. Holographic memory needed, and still needs, better and lower costs along several key fronts: materials for the holographic recording media; information processing algorithms and storage architectures; highly coherent laser sources; and high-speed output detectors.[9]

9. Wilson (2002).

COMPETING ALTERNATIVES

Display and imaging markets are diverse and huge, attracting significant investment in a broad range of competing alternatives. Displaytech proposed to enter markets remarkable for the depth and breadth of both technological alternatives and corporate competitors. In 1994, traditional CRTs and flat-panel LC screens dominated display markets. CRTs for television and computer monitors, however, suffered from issues of size and weight and limits on the pixel resolution. Miniature CRTs also dominated in camcorders and goggles. Yet they remained relatively low resolution, limiting the information the user could see, tended to be dim, and used more battery power than was ideal. LC screens for laptops, etc., were generally quite costly to manufacture, and LC panel manufacturing facilities were increasingly complex and began to approach the prohibitive costs of semiconductor “fabs.” These weaknesses of both technologies were particularly problematic as demand increased for larger and larger screen dimensions. Using either approach, 30- to 60-inch displays were simply cost- and/or size-prohibitive. From the U.S. point of view, another weakness of both was that nearly all manufacturing was outside of the United States. In this context, Displaytech’s ATP award in 1994 helped support a broader federal effort to bolster the domestic display supply base.

Given these weaknesses and the very large worldwide consumer markets for displays (almost $60 billion in 2003[10]), the range of technical exploration in alternative display technologies was and remains impressive indeed. Table 4 shows more than 220 companies that have or are competing in various non-CRT electronic display markets, and yet the list is still not exhaustive. Figure 4 illustrates only some of the various competing technical approaches. Many of the competing technologies shown in Figure 4 have also been funded in part by the many various federal programs aimed at improving the U.S. display industry. The approach has been to fund a wide variety of alternatives and hope that some will emerge to challenge the dominance of foreign display producers.

Microdisplays, to the left of the figure, are attractive alternatives because they can display large numbers of pixels in a very small package and use relatively compact optics to magnify the image, either in front- or rear-projection systems for large displays or in a small optical viewer system for “near-to-eye” viewfinders and goggle-like applications. However, microdisplays remain a minor market with worldwide sales of about $850 million in 2002,[11] compared to the more than $30 billion in liquid crystal flat-panel markets and similar size CRT markets. Displaytech’s FLCOS microdisplay technology is shown at the bottommost left of Figure 4.

Yet even within this narrower niche for microdisplays, the competition is fierce. In 1994, the most mature microdisplay alternatives to miniature CRTs were the reflective digital micromirror displays (DMD) developed (with significant federal subsidy) by Texas Instruments,

10. According to forecasts by iSupply/Stanford Resources reported in Chin (2003).
11 Allen (2003).

TABLE 4.

Crowded Display Competition: Manufacturers and Developers of Non-CRT Electronic Display Technologies

MICRODISPLAYS	FLAT-PANEL DISPLAYS			
EMISSIVE	OLED	LIQUID CRYSTAL		OTHER FLAT PANEL
OLED				PLASMA
Cambridge Display Technology	Adeon	Acer	Matsushita	Acer
eMagin	Agilent (was Hewlett Packard)	ADI	Mitsubishi	AU Optronics
MircoEmissive	Asahi Glass	Advanced Display Systems	Nam Tai Electronics	Central China Display Laboratories
TFS	AU Optronics	Alps Electric	Nan Ya Plastics	Chunghwa Picture Tubes (CPT)
	Beijing Visionox	Anshan YES Optoelectronics Display	Nanox	Daewoo
AMEL	Cambridge Display Technologies	Arima Display	NEC	FHP
Kopin	Chi Mei Optoelectronics	Asahi Glass	Nemoptic	Formosa Plastics
Planar Systems	Chunghwa Picture Tubes (CPT)	AU Optronics	Optical Imaging Systems (until 2000)	Fujitsu
	Covion	A-Z Displays	Optrex	Hitachi
SCANNED	Delta Optoelectronics	BOE-Hydis	Orient Display	LG Electronics
Microvision	Denso (was Nippondenso)	Cannon	Orion Display Technology	Matsushita
Reflection Technology	DNP	CASIL Optoelectronic	PCI	Mitsubishi
	DORA	Casio	Philips	NEC
PHOSPHORS	Dow Chemical	Chang Yih Technology	Picvue	Okaya
Display Research Laboratories (DRL)	DuPont Displays	Changzhou Dongnan LCD	PrimeView International	Oki
FED Corp. (now eMagin)	Eastman Kodak	Chi Mei Optoelectronics	Quanta Display	Orion PDP
PixTech (was Micron Display)	Elia Tech	Chunghwa Picture Tubes (CPT)	RCL Display	Philips
	eMagin	Chunlan	Rohm	Pioneer
	Hitachi	Citizen	Samsung	Planar Systems
TRANSMISSIVE	Hoechst (now Clariant)	Clover Display	Sanyo	Samsung
CRL Opto	Hoya Continuum	CMO	Seiko Epson	Sharp
Hitachi	Hydis	CPT	Seiko Instruments	Sony
Kopin	Hyundai	CPT	Shanghai General Electronics (SVA)	Thompson
NEC	IBM	Crystaloid Technologies (acq. by DCI)	Shanghai Hai Jing Electron	Toshiba
Opsis	Idemitsu-Kosan	Dalian Dongfu Color Display	Shantou Goworld Display	Ultra Plasma Display (was Hyundai)
Radiant Images	IDTech	Dalian Eastern Display	Sharp	
Sanyo	LG Electronics	Display Technology (DTI)	Shenzhen Jinghua Displays	FIELD EMISSIVE
Seiko Epson	Lightronik Technology	dpiX (until 2001)	Shenzhen Shenhui Technology	AU Optronics
Serif Display	Lite Array	Fordic Component	Shenzhen STD Display Technology	Candescent Technologies
Sharp	Luxell Technologies	Fujitsu	Shenzhen Tianma Microelectronics	Futaba
Sony	Matsushita	Genda Microelectronics	Shing Yih Technology	Micron Displays (acq. by PixTech)
Xerox	Mitsui Toatsu Chemicals	Giantplus Technology	Smart Display	Orion Electric
	Nan Ya	Grand Pacific Optoelectronics	Solomon Goldentek Display	PixTech
	NEC	Hainan Ocular Electronic	Sony	Printable Field Emitters (PFE)
REFLECTIVE	NESS Display	HannStar Display	ST Liquid Crystal Display	Raytheon
LCOS	Nippon Denyo	Hebei Jiya Electronics	Stanley Electric	SI Diamond Technology
Aurora Systems	Nippon Seiki	Hitachi	Sunway International	
Boulder Nonlinear Systems (BNS)	Opsys	Hosiden	Tecdis	EL & OTHER EMISSIVE
Cannon	Opto Tech	Hunet	Three-Five Systems	A-Z Displays
Colorado MicroDisplay/Zight (acq. by Three-Five)	Optrex	Hydis (was Hyundai Electronics)	Tianma Microelectronics	Central China Display Laboratories
Digital Reflection (closed 2001)	Orion Electric	Hyundai LCD	TMDisplay	Denso
Displaytech	Osram Opto Semiconductors	IBM	Toppoly Optoelectronics	iFire
eLCOS Microdisplay Technology	Philips	IDTech	Toshiba	Kingbright Electronic
Hitachi	Pioneer	ImageQuest (until 1997)	Tottori Sanyo	Lumex
IBM	Planar Systems	Info (was Chang Yih)	TQL Technology	Luxell
Integrated Microdisplay	RiTdisplay (was Ritek)	InnoLux Display	Truly Semiconductors	Noritake
Inviso (was Siliscape, acq. by Three-Five)	Rohm	Jiandu	Unipac	Opto Tech
JVC	Samsung	JIC Technology	United Radiant Technology (URT)	Planar Systems
MicroDisplay Corp.	Sanyo	Jilin Caijing Digital High-Tech Panels	Vbest Electronics	Rohm
MicroPix Technologies (now CRL Opto)	Seiko Epson	Kent Displays	Vikay Industry	Samsung SDI
MicroPixel	Semiconductor Energy Laboratories	Kyocera	Vision Display System	Sharp
MicroVue	Sharp	LC-Tec Sweden	Wintek	Stellar Micro Devices (was Stellar Display)
National Semiconductor (acq. by Three-Five)	SK Displays	LG.Philips	Xiamen Ocular LCD Devices	Telegen
Philips	SNMD	Litton (until 1997)	Yeebo LCD	ZEC
Pioneer	SoftPixel	Lumex	ZBD Displays	
Samsung	Sony			
Silicon Display	Stanley Electric			
Sony	Sumitomo Chemical			
SpatiaLight	TDK			
S-Vision (now Hana Microdisplay)	Teco Optronics		OTHER ALTERNATIVE DISPLAYS	
Taiwan Microdisplay (TMDC)	Three-Five Systems		Actuality Systems	Gyricon (was Xerox)
Three-Five Systems (Brillian spinoff in 2003)	Tohoku Pioneer		Alien Technology	NGK Insulators
United Microdisplay Optronics	Toppan Print		CamFPD (was Cam3D)	Philips
Varitronix	Toppoly Optoelectronics		Citala	Picvue
	Toshiba Matsushita Display (TMD)		DuPont Displays	Uni-Pixel Displays
MEMS	Tottori Sanyo		E-Ink	
Daewoo	ULVAC			
Iridigm Display	Uniax (acquired by Dupont)			
Microvision	United Radiant Technology (URT)			
Reflectivity	Universal Display Corp (UDC)			
Silicon Light Machines (was Echelle)	Univision Technology			
Sony	Varitronix			
Texas Instruments	Windell			
	Xerox			
	Zhejiang Beijing Orient Vacuum Electronic (ZEC)			

the emissive active-matrix electroluminescent (AMEL) approach followed at the time by U.S. firms Kopin and Planar Systems (both also ATP awardees), and the transmissive transferred-silicon active-matrix liquid crystal display (AMLCD) also pursued by Kopin. ATP also funded early microdisplay work in the area of field emission displays (FED) by FED Corp., now called eMagin Corp., but eMagin has since switched to an alternative technology, organic light-emitting diodes (OLED) on silicon, shown at the top of the leftmost column of Figure 4.

By 2003, U.S.-based Texas Instruments, Kopin, Three-Five Systems (now Brillian), and Displaytech joined Seiko Epson, Sony, JVC, Hitachi, and Sanyo in dominating high-volume microdisplay markets. In this still small, but rapidly growing, niche, helped by a decade of federal investments widely dispersed across many alternatives, U.S. firms are now indeed winning significant display market share, which we estimate on the order of about 30 percent (an estimated \$200 million for Texas Instruments, \$40 million for Kopin, \$16 million for Displaytech, and \$1 million for Three-Five Systems/Brillian).

RESULTS

In overall terms, the ATP funding enabled Displaytech, as proposed, to move from lab-scale one-by-one assembly toward mass manufacturing by solving glue deposition and wafer singulation problems and moving them down the road toward an eventually effective contrast compensator and materials reliability. The company believes the funding helped attract venture capital and enabled work that cut their time to mass market by roughly two years.[12] Although Displaytech has not yet turned a profit, given the technology-sector downturn in 2000–2002, during which many of Displaytech's emerging potential competitors failed,[13] the cash flow enabled by accelerating the ramp-up to mass-market sales probably saved the company. However, the primary market they eventually entered, viewfinders, was not their main target in the 1994 proposal.

The most critical manufacturing process breakthrough that Displaytech's ATP funding enabled, and which is specifically in use today, is the method of depositing adhesive seals in the very small gap between the silicon and glass. Displaytech sees this glue deposition manufacturing technology as critical to its current competitiveness. Because it is so central to device performance and cost-competitiveness, they fiercely guard it as a trade secret and have not patented or otherwise made details known outside of transferring it to their contract manufacturer, the Japanese firm Miyota.

A second valuable outcome of the ATP funding, though less concrete or specifically identifiable in current products, was in developing a structured methodology for FLC

12 This rough estimate by Displaytech principals is corroborated by the status of another company independently pursuing FLCOS microdisplays, MicroVue in Scotland. In 2003, MicroVue was making demonstration production models available to potential developers. This is roughly where Displaytech was in 1999.

13 U.S.-based microdisplay firms included Zight (formerly Colorado Microdisplay) and InViso (formerly Siliscape), which both closed in 2001, with assets acquired by Three-Five Systems. S-Vision also closed, with assets acquired by contract-manufacturer Hana Microdisplay. Digital Reflection also closed in 2001.

FIGURE 4.

Competing Electronic Display Technologies

Competing Electronic Display Technologies

- Microdisplays
  - *Emissive*
    - Organic (OLED)
      - on Silicon
      - Poly-Silicon TFT
      - Soluble
      - ....
    - Electroluminescent
      - Active Matrix (AMEL)
      - ....
    - Scanned
      - LED
      - Semiconductor Laser
      - ....
    - Phosphors
      - Vacuum Fluorescent (VFD)
        - VF on Silicon (VFOS)
      - Field Emission (FED)
      - Miniature CRT
      - ....
    - ....
  - *Transmissive*
    - Poly-Crystalline Silicon Liquid Crystal
      - Active Matrix (AMLCD)
        - High Temperature (HTPS)
        - Low Temperature (LTPS)
      - Passive
    - Single Crystal Silicon Liquid Crystal
      - Active Matrix Silicon on Glass
      - ....
    - ....
  - *Reflective*
    - Micro Electrical Mechanical Systems (MEMS)
      - Digital Micromirrors (DMD)
      - Grating Light Valve (GLV)
      - Thin-Film Micromirror Array (TMA)
      - ....
    - Liquid Crystal (RLCD)
      - on Silicon (LCOS)
        - Nematic
          - Reflective
          - Diffractive
        - Polymer Dispersed (PDLCOS)
          - Scattering
          - Diffractive
        - Homeotropic
        - Ferroelectric (FLCOS)
          - ....
        - ....
      - ....
    - ....
  - ....
- Other Displays
  - Electrophoretic (EPID)
    - Active Matrix Plastic
    - Segmented
    - ....
  - Organic TFT on Plastic
  - ....
- Flat-Panel Displays
  - Plasma
    - AC
    - DC
  - Liquid Crystal (LCD)
    - Passive Matrix
      - Nematic
        - Twisted (TN)
        - Super-Twisted (STN)
          - Film Compensated (FSTN)
          - Double Layer (DSTN)
          - Reflective (RSTN)
          - ....
        - Vertically Aligned (VAN)
        - ....
      - Ferroelectric (FLC)
      - ....
    - Active Matrix (AMLCD)
      - Amorphous Silicon TFT (a-Si)
      - Poly-Crystalline Silicon TFT (p-Si)
        - High Temperature (HTPS)
        - Low Temperature (LTPS)
      - Cadmium Selenide TFT
      - Polymer Dispersed (PDLC)
      - Metal-Insulator-Metal (MIM)
      - Amorphous Silicon Pin Diodes
      - ....
  - Electroluminescent (ELD)
    - AC Thin Film (ACTFEL)
    - AC Powder
    - Thick Film Dielectric (TDEL)
    - DC Thin Film
    - ....
  - Organic LED (OLED)
    - Active Matrix (AMOLED)
      - Small Molecule
      - Polymer
    - Passive
  - Field Emission (FED)
  - Vacuum Fluorescent (VFD)
  - Inorganic LED
  - ....
- CRT Displays
  - ....

material reliability issues. The speed and contrast performance of laboratory device LC and FLC chemical materials tends to decay rapidly with repeated use over time, which would be unacceptable in commercial products. Displaytech tackled this in two ways, with a materials formulation and a contrast compensator. Materials formulation involved developing a better mix of ingredients. Narrowly, the specific mixture developed under ATP funding is used now only in minor products, so has quite limited measurable value. More broadly, several core components identified under ATP funds in that mix are now in use in improved mixes to help stabilize Displaytech's proprietary FLC materials.

Most importantly, though, Displaytech principals believe the ATP funding enabled them to develop a methodical discipline for developing FLC materials reliability. "We'd never gone through the discipline," said one. "Though we were doing interesting chemistry, we'd never made the transition to device grade materials…. What are all the parameters that matter? How do you build a metrology around those parameters?" Another added, "We'd never done reliability qualifications of FLC material before then. In fact, no one had." Displaytech has since investigated more than 5,000 different formulations and transitioned into commercial-grade compositions. Without the disciplinary approach, they believe, they could not now be mass manufacturing. Although the original Displaytech proposal to ATP discussed the need for improved materials reliability, the broader formalization of the discipline was a more important lasting result, perhaps inevitable given the goal, but unforeseen nonetheless. In contrast to the trade secret glue deposition process, Displaytech has since been patenting FLC material formulations. This patenting behavior is typical in the chemical industries, as chemicals are more straightforward for competitors to learn through reverse engineering of products in the market than are manufacturing processes.[14]

A related area of work begun under ATP to improve the commercial lifetime of the FLC materials and devices involved a so-called contrast compensator. This was related to the issue that the LC materials tend to degrade chemically if the net drive voltage across them is not zero.[15] Because these devices use DC power to drive them, the "on" voltages need counterbalance from an opposite signal to net to zero. The traditional method in an FLC display would be to show a positive image frame, and then electrically send the negative of the same frame, but visually black it out with a fast shutter so the visual result is not a contrastless, neutral gray wash. The trouble with this shuttering approach is it reduces the brightness and effective frame rate in the visual signal. Displaytech, under ATP, instead started developing an additional active optical element that selectively reverses the polarization, turning each negative frame positive, while leaving positive frames. This contrast compensator eliminates the need to shutter out the negative signal. It is separate from the microdisplay itself, but it also uses an FLC layer because it has to switch just as fast. Displaytech has patented their technique.

A final important technical result was an improved manufacturing process for singulation—scribing and separating—of the multiple microdisplays that are manufactured on a single

14. See, for example, Mansfield (1986).
15. Underwood (1997).

wafer. For FLC-on-silicon microdisplays, the glass needs to be cut in a slightly different place than the silicon. This offset exposes the wire-bond pads needed to connect the silicon chips electronically to the systems they operate in. Displaytech proved the process ideas and identified equipment and process steps that were more repeatable, higher-yield, and cost-effective. The process has been improved and altered somewhat since. Yet, the early work under ATP was significantly useful in reducing the high uncertainty about the then-unproven possibilities of doing high-volume offset singulation of both glass and silicon in a wafer sandwich at the same time. Again, because this is a competitively important proprietary manufacturing process, Displaytech has not pursued patents or otherwise disclosed details along these lines.

Beyond the technical outcomes, another very critical result of the ATP funding was Displaytech's subsequent ability to raise venture capital. Before the award in 1994, Displaytech had not attracted any venture capital. Its first round of venture capital investors came aboard in 1995, and by 2001 the firm had attracted about $100 million. The ATP award had two related effects. The first was a halo effect. The principals believe it gave Displaytech a recognized stamp of approval: "[The venture capital community looks] for outside endorsement as part of the due diligence process. Who else thinks this is going to work? We were able to use the logic on our investors that the ATP program was highly competitive….So we said, you have the expertise of this body of experts at NIST looking over these proposals….That adds credibility to Displaytech." The second effect was leverage for new investors, who could buy equity in in-process R&D without dilution from previous investors. Displaytech went to potential first-round venture capital investors and said, "Look at this ATP award as a million and three-quarters of seed money, with no points, no equity attached." This venture capital attracting effect is consistent with the statistical findings from surveys of ATP awardees (Feldman and Kelley, 2001; ATP, 2003).

The combination of technical progress and substantial additional investment enabled Displaytech eventually to land and announce in late 1999 what it hoped would be its first major product. Displaytech's microdisplays were designed into lightweight and slim Samsung 43- and 50-inch, rear-projection, high-definition televisions, one of the principal markets identified in the ATP proposal. The product launch, Displaytech hoped, would also help prove to other companies that Displaytech had graduated from an R&D operation, into a mass-market capable supplier. Samsung introduced the sets at trade shows beginning in early 2000 and went into very limited distribution, but pulled them from the market by fall 2001. Thomson did the same thing, withdrawing an early high-definition television (HDTV) based on liquid crystal on silicon (LCOS) microdisplays from Displaytech competitor Three-Five Systems. Referring to the whole microdisplay industry, not Displaytech in particular, Samsung's Technology Display Director Ian Miller explained in 2001, "The performance isn't good enough for the cost yet. Nobody has yet been able to close that cost/performance equation."[16] By 2002, though, Samsung tried again: it announced second-generation, rear-

16. Displays Cut Prices, *Consumer Electronics* 41(52), December 24, 2002.

projection, large-screen HDTV versions based on Texas Instruments' micromirror microdisplays. The displacement was direct indeed: the new versions actually used the same cabinets designed for the Displaytech versions.[17]

The combination of the technology-sector downturn and a major product being discontinued led Displaytech to exit the rear-projection market. In short, the major market Displaytech foresaw in the 1994 ATP proposal had, for now, evaporated. By late 2001, Displaytech restructured, with major layoffs, shifting all microdisplay manufacturing (though not the liquid crystal materials production) to its contract manufacturing partner Miyota in Japan. So too, another major market that Displaytech hoped for in the original ATP proposal has yet to emerge. High-resolution near-to-eye goggles and eyeglasses for computers or portable film viewers remain small niche markets or at the application prototype stage.

UNEXPECTED MAIN COMMERCIAL APPLICATION

Fortunately, digital cameras and camcorders were a rapidly expanding consumer market with proven cash flow potential. Displaytech landed large viewfinder contracts from JVC for camcorders (JVC's own microdisplay activities notwithstanding) and from both Minolta and Concord Camera for digital cameras. So, by early 2002 the firm announced it would "focus exclusively on the emerging microdisplay-based viewfinder" markets and return work on projection systems to "research status."[18] The major markets foreseen in the 1994 ATP proposal had not yet materialized, and a market mentioned only in passing became the firm's mass-market lifeblood.

The downside of the decision was that prices for viewfinder microdisplays, because they are smaller and lower resolution, tend to be in the tens of dollars compared to roughly 10 times that for HDTV rear-projection television microdisplays. Still, the volumes were high enough to enable Displaytech to survive, albeit not yet profitably, and in 2003 to continue to employ about 50 people in the United States. In this viewfinder segment, main competitors include U.S.-based Kopin, with about three times the volume of Displaytech's sales,[19] and Three-Five Systems. Indeed, Kopin supplied JVC before Displaytech landed the contract with them. So, in a sense, one ATP awardee (Displaytech) is directly taking market share from a second ATP awardee (Kopin). Yet on net, both have gained market share from Asian competitors. The Texas Instruments micromirror technology is not competitive in this viewfinder niche.

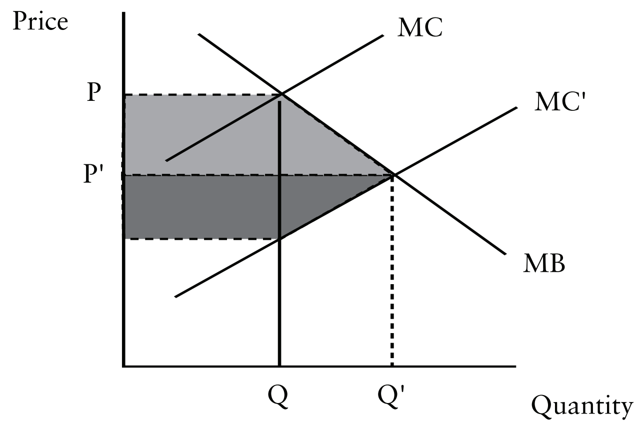
DIRECT ECONOMIC EFFECTS

In this section, we estimate the direct economic value to the nation in several very different ways. Because of the significant uncertainties involved, we investigate how sensitive our estimates of direct effects are to assumptions and methodology. In later sections, we address broader indirect effects.

17. Notebook, *Consumer Electronics* 42(10), March 11, 2002.
18. Displaytech press release, March 8, 2002.
19. Forgrieve (2002).

FIGURE 5.

Within-Market Increase in Economic Surplus



The direct economic benefits to the nation from the ATP funding to Displaytech come from several sources. There are direct effects to Displaytech owners and employees. Beyond the firm itself, but still within the microdisplay market, there are economic surplus effects—higher value to users and/or lower prices in the market. From an overall national perspective, the positive impacts may be mitigated somewhat, to the extent that Displaytech sales displace sales by other U.S. firms and/or drive down the prices other U.S. firms might have received.

The net effects in their simplest economic form are the two shaded areas in Figure 5. In the figure, MC represents the marginal cost or market supply curve, and MB represents the marginal benefit or market demand curve. The shift from MC to MC' represents the increase in available supply, raising the quantities exchanged in the market from Q to Q' and driving prices down from P to P'. The shaded upper area represents gains to consumers from lower prices and more availability, and the darker lower area represents net gains to the sellers from those increased sales. The sizes of these gains in consumer and producer surplus, which we estimate separately below, depend on the scale of the change and the demand and supply elasticities.

PRODUCER SURPLUS AND EMPLOYMENT

Moving from the theory to empirical estimation, for producer surplus, as indicated in the lower shaded region in Figure 5, the primary direct effect is that ATP funding accelerated the research and development cycle by about two years, and the resulting earlier cash flow likely enabled Displaytech to survive the technology downturn. Displaytech is not yet profitable, so there is no economic surplus for the investor-owners of the firm.

Nevertheless, employees have increased from roughly 25 at the time of the 1994 proposal, to 35 in 1996, 58 in 1997, 89 in 1998, 100 in 1999, 150 in 2000, and then falling to 50 after 2002 following a series of cutbacks.

Given various other income sources, including multiple other federal contracts, and the subsequent $100 million in venture capital invested, it is impossible to allocate the fraction of this employment ramp-up exclusively to the $1.75 million ATP award. However, since the other contracts were largely product-driven (e.g., specific NASA or Pentagon applications), not manufacturing processes or materials reliability, the ATP award was the most critical early enabler for mass commercialization. Second, it also was critical for attracting the venture capital, which significantly increased Displaytech's scale and likelihood of commercial success.

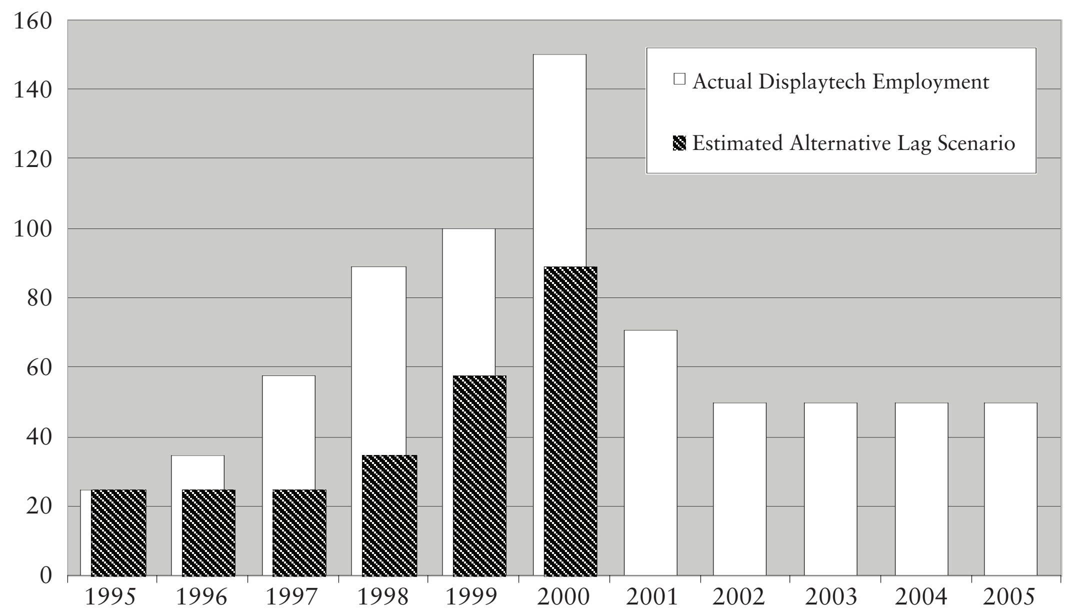
How to value this? Based on our analysis of Displaytech and the technology sector downturn in 2000, we believe that Displaytech would not exist today without the ATP. The technology development might have continued through an acquisition by another display or liquid crystal firm, but Displaytech and the existing jobs would have disappeared. Attributing all of the value of Displaytech today to ATP is extreme, but provides a useful upper-bound assumption for estimating value created, which can then be scaled according to any alternative assumed fraction attributable to ATP.

Figure 6 shows Displaytech's actual employment trend over time, and also a non-ATP counterfactual estimated employment trend based on a two-year delay in commercialization, which is the lead time that Displaytech believes it gained from ATP funding. After 2000, our alternative estimated employment falls to zero under the assumption that without the accelerated ramp-up, Displaytech would have been a victim of the technology-sector downturn. The difference between the white and shaded bars represents an upper-bound estimate of the direct employment effect from ATP.

It is an upper bound, but probably not too much of an overestimate if we look only within the microdisplay sector. If Displaytech did not exist, a significant fraction of the increase shown in Figure 6 for employment in U.S.-based high-technology jobs would not exist either. Foreign firms, because they dominate microdisplay markets, would likely have made up the bulk of sales now displaced by Displaytech. U.S.-based Kopin in particular, as an existing JVC camcorder supplier, and perhaps Three-Five Systems, would likely pick up some of the business in their existing product lines. Because of the contract manufacturing alliance with Miyota, Displaytech's main manufacturing employment is overseas, so few U.S. manufacturing jobs would be lost. However, the management, engineering, and research jobs, the majority of U.S. employment at Displaytech, would likely be lost altogether from U.S. microdisplay sector employment. Kopin's and Three-Five Systems' R&D and engineering activities would not expand much, but their sales of existing microdisplays would. In our interviews with management at Three-Five Systems, for example, they estimated that, without Displaytech, their microdisplay sales, currently small to begin with, might expand only about 5 percent. On the other hand, the manufacturing output at the two likely would expand by several million dollars per year if Displaytech did not exist. These jobs would be

FIGURE 6.

Estimated ATP Employment Effect at Displaytech, 1995–2005



net gains for the United States, since both Kopin and Three-Five Systems were manufacturing at U.S. facilities, while Displaytech was using a Japanese contractor.

So on net, how much were these Displaytech jobs worth? We make estimates under various assumptions shown in Table 5. As a privately held firm, Displaytech does not make financial or wage information available, and we had no access to it. We can estimate, however, based on industry norms. Average white-collar technical professional wages ranged from about $40,000–70,000 annually in the Boulder area in 2003.[20] Photonics industry employment in the Boulder area was about 30,000, so the 50–150 working at Displaytech, even in regional economy, had negligible impact on wage levels. So Displaytech's 50 jobs after 2002 represented a total wage bill of about $2–3 million annually, and the 150 in 2000 about $6–9 million.

However, counting the entire differential wage bill between the two scenarios in Figure 6 would overstate the economic impact because these extra employees were not free to the economy. They could have been doing other things—their opportunity cost—although perhaps less valuable things. The Boulder-Longmont region had an unemployment rate of

20. U.S. Department of Labor (2003b).

TABLE 5.

Estimated Employment Compensation Effect Through 2006 (ATP Award to Displaytech)

Model Variables	Best-Guess Scenario	Worst-Case Scenario	Best-Case Scenario
Average 2003 Compensation	$55,000	$40,000	$70,000
Opportunity Cost (%)	75%	65%	85%
U.S. Share of Displaced Business	30%	50%	20%
RESULTS (FOR EMPLOYMENT COMPENSATION EFFECT ONLY)			
IRR (%)	19.4%	-2.71%	40.2%
7% Social Discount Rate			
NPV (millions 2005 dollars)	$1.85	-$1.03	$6.20
Discounted Benefit Cost Ratio	1.79	0.56	3.65
All-Scenario Monte Carlo Simulation @ 7%: Probability NPV>0, p>0.98			
5% Social Discount Rate			
NPV (millions 2005 dollars)	$2.36	-$0.89	$7.26
Discounted Benefit Cost Ratio	2.00	0.62	4.08
All-Scenario Monte Carlo Simulation @ 5%: Probability NPV>0, p>0.99			
3% Social Discount Rate			
NPV (millions 2005 dollars)	$2.97	-$0.72	$8.51
Discounted Benefit Cost Ratio	2.25	0.70	4.57
All-Scenario Monte Carlo Simulation @ 3%: Probability NPV>0, p>0.99			

5–6 percent through 2002–2003, and there was 6–8 percent unemployment nationwide in durable goods manufacturing.[21] Had Displaytech not hired them, many of these people would have eventually been employed elsewhere, perhaps with a lag period in finding work (the average duration of unemployment among white-collar technical workers was three to six months). Moreover, U.S. Department of Labor studies on workers displaced in 1999–2001 showed that, when they did find other jobs, on average they made roughly 65–85 percent of their previous wages, with significant variation by industry and region.[22] Finally, some U.S. firms, namely Kopin and Three-Five Systems, would gain market share without Displaytech. As we mention above, the U.S. share of the overall microdisplay market is about 30 percent, and we use various estimates from 20–50 percent as the U.S. share of the sales displaced by Displaytech.

Taking these alternative opportunities for the employees into account, we took the average wage levels (varying from $40,000–70,000 in 2003, per Department of Labor ranges),

21. U.S. Department of Labor (2003a).
22. U.S. Department of Labor (2002).

subtracted the opportunity value of those employees doing other things (varying from 65–85 percent), and subtracted what might have been the U.S. share (varying from 20–50 percent). Given the employment trends in Figure 6, and assuming Displaytech continues to employ at least 50 people through 2006, then adjusting for technology-sector wage inflation, using the Office of Management and Budget's (OMB) statutory social discount rate of 7 percent, and netting out the $1.75 million ATP grant, we estimate the net present value (NPV) of the difference over the period 1995–2006 between Displaytech with and without ATP as $1.85 million (2005 dollars), our best-guess scenario point estimate. The OMB's 7 percent comes from the historical average return for private investments. However, there is compelling theoretic support (e.g., Caplin and Leahy, 2004) that social planners should use lower discount rates than private returns. Indeed, the United Kingdom (HM Treasury, 2003) standard is 3.5 percent in evaluations for time periods up to 30 years, and lower rates for even longer periods. So, we also explored two alternative social discount rates. At a 5 percent social discount rate, the best-guess scenario NPV is $2.36 million, and at 3 percent it rises to $4.04 million.

Discount rate notwithstanding, if we count only this employment effect, this represents a decent, though not spectacular, 19.4 percent internal rate of return (IRR) from the ATP investment and discounted benefit to cost ratios ranging from 1.79 to 2.25. (Note that these values are only for the direct economic effects on Displaytech, its employees, and competitors and do not include direct effects on downstream consumers or indirect knowledge spillover effects outside of the market.) Our NPV estimate of the direct employment compensation effect ranges from -$1.03 million in the worst-case scenario at the 7 percent discount rate to $8.51 million in the best-case scenario at the 3 percent discount rate. Assuming simple triangular probability functions on the low, best-guess, and high values for the various parameters, we used Monte Carlo simulation to generate probability distributions, shown in Figure 7, for the additive value of the ATP award. The award has positive net value to the nation in more than 98 percent of the Monte Carlo variations under each of the three discount rates, with mean values of $1.63 million at 7 percent, $2.17 million at 5 percent and $2.66 million at 3 percent. The internal rate of return averaged about 18 percent. These figures for employment compensation are less speculative than the estimates that follow for the consumer surplus and knowledge spillover effects, and, as such, they represent a most conservative set of estimates.

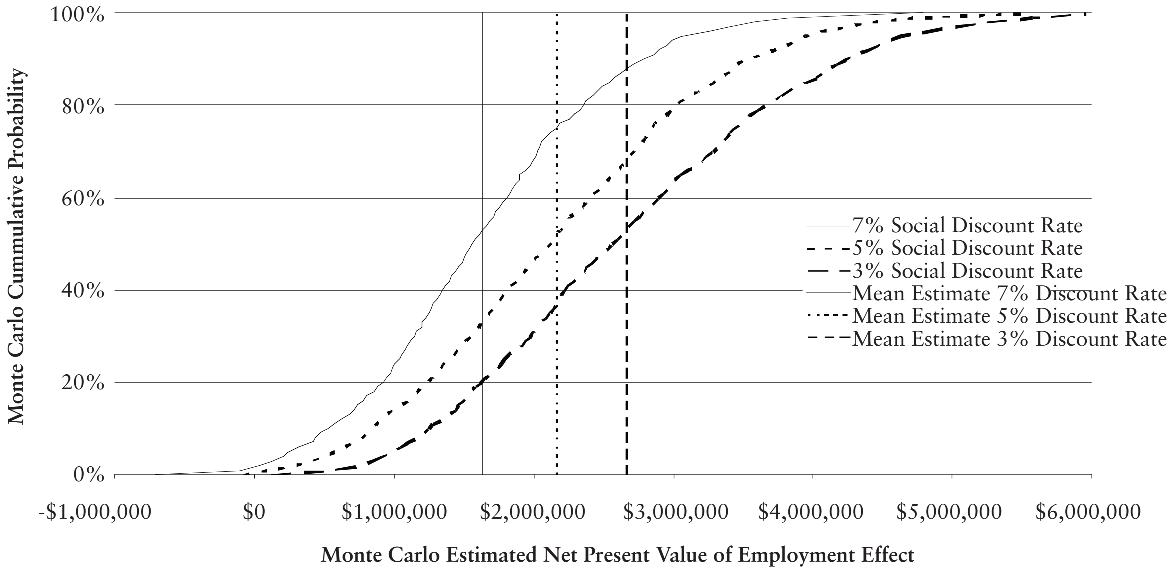
CONSUMER SURPLUS

For the impact of Displaytech on consumer surplus in the market, as indicated by the upper shaded region in Figure 5, we estimate the net increase in the value of sales, accounting for potential price and quantity effects to consumers and competitors and for some displaced sales volume from U.S.-based competitors.

In the current main application of Displaytech microdisplays, viewfinders, the advantages of their specific ferroelectric liquid crystal technology are not yet enabling anything that alternative microdisplay approaches cannot. As one impartial industry observer we interviewed put it, the performance difference for the end users from FLC in viewfinders

FIGURE 7.

Monte Carlo Cumulative Probability for Employment Compensation Effect Through 2006 (ATP Award to Displaytech)



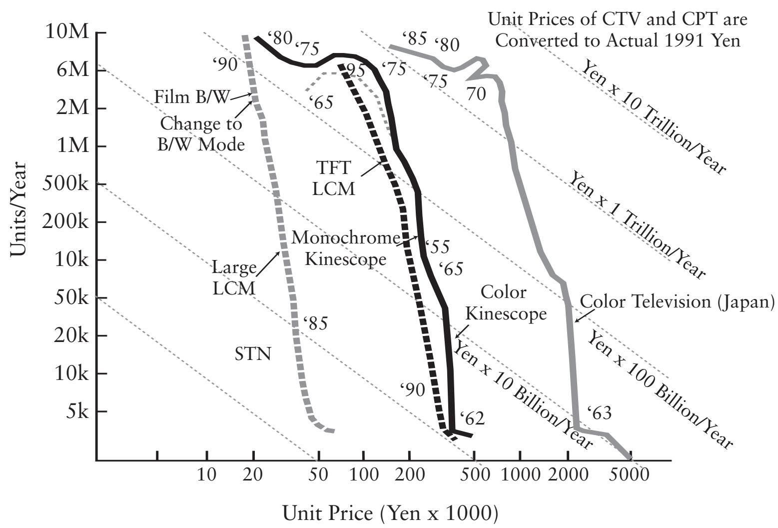
is "qualitative rather than quantitative." Given the stiff competition illustrated in Table 4, the industry is very price competitive and the major customers, original equipment manufacturers (OEMs), are unwilling to pay much extra for qualitative performance differential, except where the performance edge enables new applications, such as with Texas Instruments' micromirrors in HDTV.

In economic terms, microdisplay price elasticities are high. This is consistent with the history of other display technologies. As Figure 8 shows, sales quantities have been remarkably and repeatedly sensitive to falling prices across several generations of displays (monochrome kinescope, color kinescope, color television, monochrome STN LCDs, color TFT LCDs). In all cases in Figure 8, the rates of change in quantities exceed the rate of change in prices by factors well over 100.

The combination of price sensitivity, lack of real enabling differential performance from Displaytech viewfinders, and Displaytech's small (roughly 2 percent) microdisplay market share means that the effects of economic surplus expansion are likely to look more like Figure 9 than Figure 5. Our interviews and analysis lead us to believe it unlikely that the price differential due to Displaytech's existence, the distance from P to P' in Figure 9, is more than a few percent of the $10–20 per viewfinder OEM price. (Indeed, if price elasticities are above 2, which we believe they are, the loss of a supplier of 2 percent market share translates into lower than 1 percent price changes). According to the consulting firm iSupply/Stanford

FIGURE 8.

Historic Display Price-Quantity Trends



Source: Firester (1992).

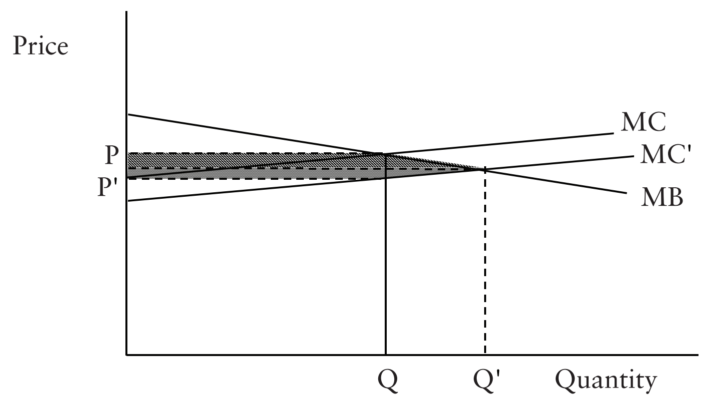
Resources, the world market for viewfinders of all types (in their jargon “near-eye microdisplays”) may grow to 30 million by 2008.[23]

Assuming Displaytech remains a factor affecting prices in the market through 2006, we take price change estimates from 0.5 to 2 percent across the cumulative 75–150 million units sold worldwide in 2000–2006 at $10–20. There was little consumer impact before those dates, since Displaytech had not yet ramped up manufacturing volumes. The added economic surplus to consumers due to lower prices in viewfinders from Displaytech’s effect, then, is in the neighborhood of $5–20 million worldwide. Only about 35 percent of digital cameras and camcorders sell to U.S. consumers. Thus, depending on assumptions, the net impact on U.S. consumers would be $2–12 million, if OEMs pass the entire price effect on to consumers. The fraction of this attributable to the ATP award is not possible to disentangle, but we repeat our belief that Displaytech would not exist without the ATP award and other federal contracts. Attributing all of it to ATP, our rough point estimate from our best-guess scenario would be nearly $6 million in (undiscounted) cumulative added U.S. consumer surplus during 2000–2006 in viewfinder end-user markets stemming from the 1995–1996 ATP investment of $1.75 million. As Table 6 shows, considering only the consumer surplus effect, the best-

23. Allen (2003).

FIGURE 9.

Within-Market Increase in Economic Surplus for a Highly Competitive Market



guess scenario at the 7 percent social discount rate amounts to an NPV of $2.33 million through 2006, and an IRR of 17.2 percent. (Note that these figures do not include the value of the employment compensation effect discussed above.) The NPV estimates rise to $3.11 million and $4.04 million at 5 percent and 3 percent, respectively.

Monte Carlo simulations adjusting the various parameters using simple triangular probability functions between the low, best-guess, and high values in Table 6 yield NPV estimates of $3.31 million (7 percent social discount rate), $4.39 million (5 percent) and $5.49 million (3 percent), and near-zero probabilities that the NPV might be negative. The cumulative probability distributions of the NPV estimates from these simulations appear in Figure 10.

TOTAL DIRECT ECONOMIC EFFECT

Combining the best-guess scenarios through 2006 from the employment compensation effect and the consumer surplus effect yields, at a 7 percent social discount rate, an overall estimated NPV of $4.73 million, and an IRR of 33.2 percent on the ATP funding investment. The combined NPV estimate rises to $5.67 million using a 5 percent social discount rate and $6.80 million using 3 percent. These are upper-bound estimates in the sense that the entire Displaytech effect is attributed to ATP. On the other hand, we note that these estimates derive entirely from direct effects within the market, including Displaytech, its employees, competitors, and customers. We have so far not addressed indirect, knowledge spillover effects, as discussed below.

TABLE 6.

Estimated Consumer Surplus Effect Through 2006 (ATP Award to Displaytech)

Model Variables	Best-Guess Scenario	Worst-Case Scenario	Best-Case Scenario
Price Change Effect Due to Displaytech	-1%	-0.5%	-2%
Viewfinder Price With Displaytech	$15	$10	$20
Market Unit Sales 2004 (millions)	18	10	25
Market Sales Growth	15%	0%	35%
U.S. Share of Viewfinder Consumers	35%	30%	45%
RESULTS (FOR CONSUMER SURPLUS EFFECT ONLY)			
IRR (%)	17.2%	?6.5%	41.0%
7% Social Discount Rate			
NPV (millions 2005 dollars)	$2.33	-$1.49	$18.51
Discounted Benefit-Cost Ratio	2.00	0.36	8.92
All-Scenario Monte Carlo Simulation @ 7%: Probability NPV>0, p>0.98			
5% Social Discount Rate			
NPV (millions 2005 dollars)	$3.11	-$1.37	$22.32
Discounted Benefit-Cost Ratio	2.32	0.42	10.46
All-Scenario Monte Carlo Simulation @ 5%: Probability NPV>0, p>0.99			
3% Social Discount Rate			
NPV (millions 2005 dollars)	$4.04	-$1.24	$26.95
Discounted Benefit-Cost Ratio	2.70	0.48	12.31
All-Scenario Monte Carlo Simulation @ 3%: Probability NPV>0, p>0.99			

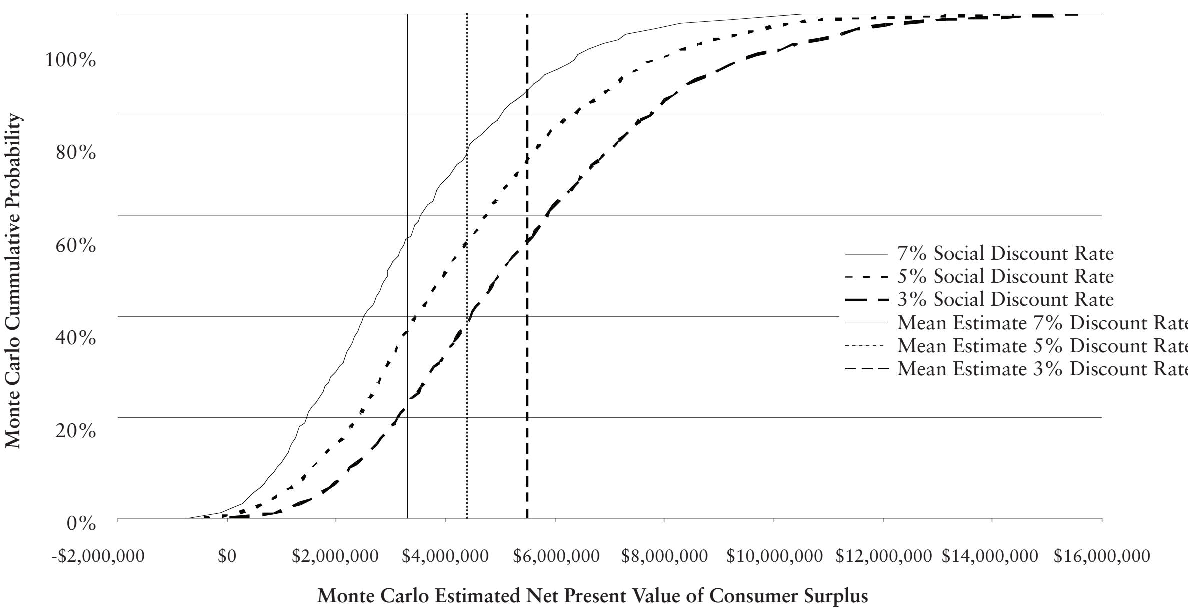
We also have not attempted to value potential future options that may emerge from the continued existence and improvement in FLC microdisplays. These may be significant in the areas of holographic storage and image processing. One indication of the market's perception of that significant future value is that Displaytech received $20 million from a private investment firm in May 2005 in exchange for minority equity ownership. Presumably this is, at minimum, the risk-adjusted value the investment firm placed on that equity fraction of those future returns.

INDIRECT KNOWLEDGE EFFECTS

The next step in our evaluation of the value enabled by ATP support of Displaytech involves identifying potential sources of value created outside of the market impact of Displaytech's products. Our method, as described above, involved tracking the spillover of technical information to others through patent and publication citations. Following Scherer (1984),

FIGURE 10.

Monte Carlo Cumulative Probability for Consumer Surplus Effect Through 2006 (ATP Award to Displaytech)



Jaffe (1986), and others, we identified the most likely major recipients of spillover value from Displaytech's technical activities as those commercial organizations most actively citing Displaytech patents or publications. We then interviewed representatives at those U.S.-based organizations to explore the extent to which that information created value. Because we focus on market value creation, that is, economic surplus, we did not pursue those main citing organizations that were universities or other nonprofit research organizations.

PATENT CITATIONS ANALYSIS

We turn first to the diffusion of information from Displaytech patents. We used the U.S. Patent and Trademark Office's online full-text patent database to identify patents assigned to Displaytech. The database includes inventor name, organization, location, date of patent application, date of patent issue, and subsequent citing patents. Among those citing, we identified citing individuals, organizations, and locations and counted the number of citations each organization made to Displaytech patents.

Through the end of 2003, Displaytech received 48 U.S. patents as assignee. Because of the significant lag in awarding patents, none of the 11 patents received after June 2001 had yet been cited by others. Among the remaining patents, we identified 137 citations by 54 different organizations and research groups, with the top citing organizations and groups shown in Table 7. To track the potential value creation from the diffusion of the Displaytech

TABLE 7.

Organizations and Groups Most Frequently Citing Displaytech Patents

Citing Organization	Location	Citations	Citing Organization	Location	Citations
Gemfire/Deacon Research*	U.S.	24	Rockwell	U.S.	3
ColorLink/KAJ, Inc.+	U.S.	11	Semiconductor Energy Laboratory Co.*	Japan	3
N. Clark & S. Lagerwall+	U.S.	9	Takeda Chemical	Japan	3
Sharp*	Japan	7	Hewlett-Packard+	U.S.	2
Chorum/MacroVision+	U.S.	6	Industrial Research Institute	Taiwan	2
InViso*/Siliscape+	U.S.	5	MicroOptical	U.S.	2
Sony*	Japan	4	Molex	U.S.	2
Fujitsu*	Japan	3	Rolic	Switzerland	2
Hoechst+	Germany	3	Silicon Light Machines*	U.S.	2
Kopin*	U.S.	3	Thomson-CSF	France	2
Matsushita*	Japan	3	Optical Imaging Systems	U.S.	1
Philips*	NDL	3			

Others of Interest: International Business Machines (IBM)*, Canon*, NEC*, Lucent, Nortel, France Telecom, Tektronix, Polaroid+, Owens Corning, Citizen, Delco, Mitsui Petrochemical, Nippon Oil, Merck GmbH, Takasago International

Notes: + known links to Displaytech; * competing display manufacturer

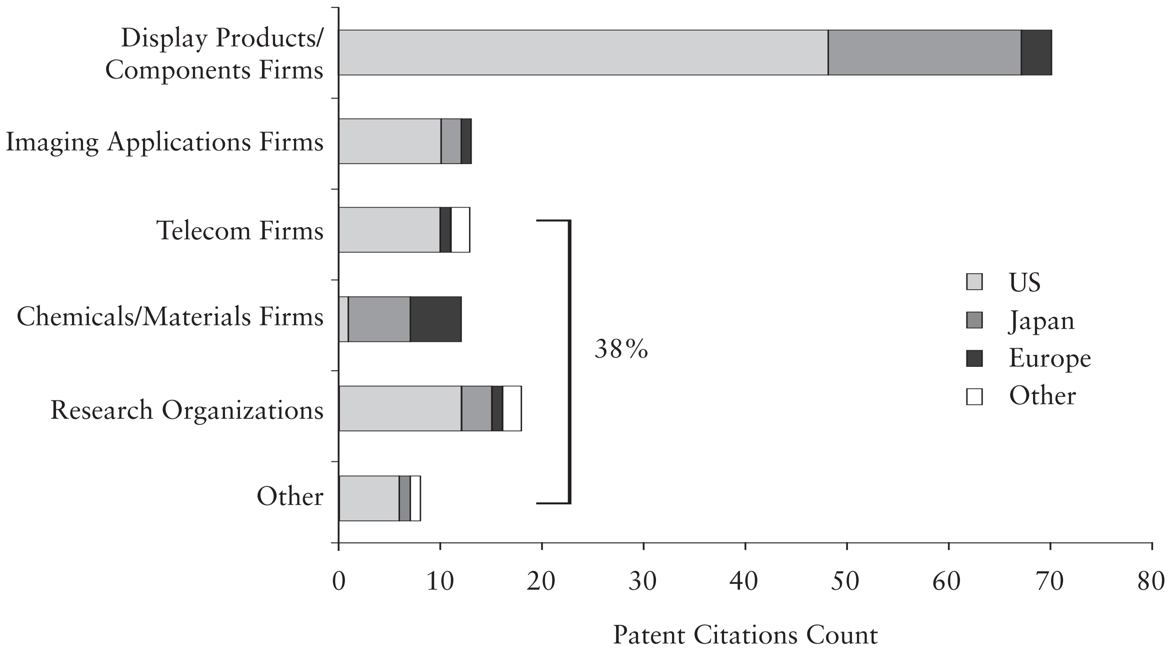
technologies, we contacted and interviewed the principals at the top four U.S.-based groups: Gemfire Corporation (formerly Deacon Research), ColorLink, Chorum, and Clark's group.

In Figure 11, we categorize the citing patents by the main industry of the research group involved and home country of the 54 assignees. Note that more than three-fifths of the citations are by organizations within the markets of display or other imaging applications. Of the remaining, universities and other independent research organizations comprise the largest number. Firms in telecommunications areas (e.g., Chorum, Lucent, and France Telecom) tend to investigate optical switching for fiber optic networks, and those in chemical/materials areas generally are working on liquid crystal properties or production processes (e.g., Hoechst GmbH, Takeda Chemical, Nippon Oil, and Merck GmbH). This does indicate that nearly all the citing organizations tend to have technological "closeness" to Displaytech activities.

However, social and geographical closeness appear to be even more important. As noted in Table 7, we identified a large number of groups that either have known professional collaborative ties to Displaytech (e.g., have co-authored papers or other significant research interaction through the University of Colorado) or are competitors in display markets. In Figure 12, we graphically show the fraction of citations by each of the top groups, as well the geographic distribution of citations. Fully one-quarter of the citations are from collaborators, and 43 percent of the citations are from potential competitors, firms who have some

FIGURE 11.

Patents Citing Displaytech by Industry and Country



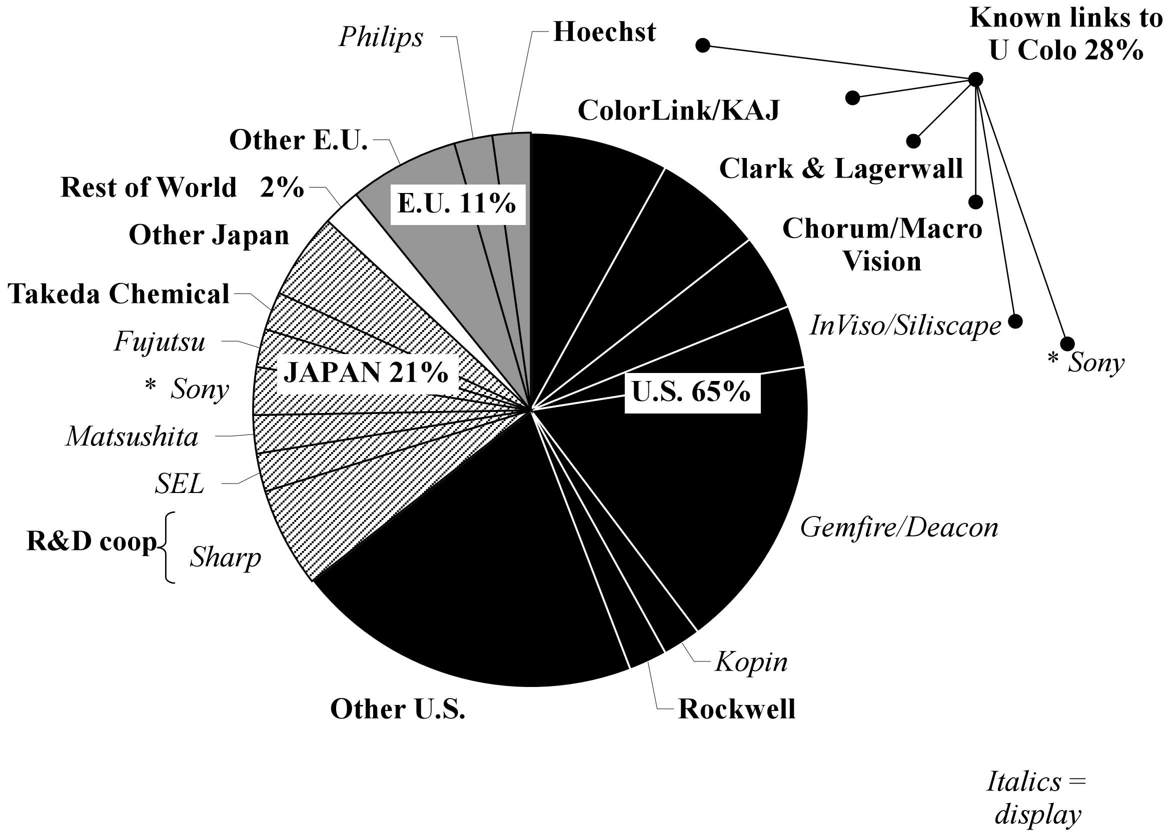
commercial display activities. Geographically, 65 percent of patent citations to Displaytech are from U.S.-based researchers, 21 percent from Japan, and 11 percent from Europe.

The top single citing organization, Gemfire Corporation of Fremont, California, mainly develops and manufactures components for optical networking and devices that integrate multiple optical components on semiconductor chips. Some applications have been in highly integrated display devices. Given the large number of citations, 18 percent of all citations to Displaytech, we were eager to identify how the Displaytech information had been useful to Gemfire. The principals at Displaytech were surprised that Gemfire had cited them so much, thinking of them as being in relatively unrelated semiconductor laser and integrated optical circuit businesses.

In fact, the principal researcher on the Gemfire patents could not recall using any particular information from Displaytech, or from the specific research scientists involved, and was surprised Gemfire was a primary Displaytech-citing group. He recalled that patent attorneys and patent examiners had suggested additional citations to prior art for various reasons. He speculated the citations were added for legal rather than technical reasons. Given this, he did not believe the specific technical information in the patent citations had any value to Gemfire. This was a first indication that patent citations are, at best, a very noisy indicator of technology diffusion and spillover. The patent citations we tracked in our interviews were regularly not indicators of any direct learning, but artifacts of the legal process in obtaining a patent.

FIGURE 12.

Patent Citations to Displaytech Patents

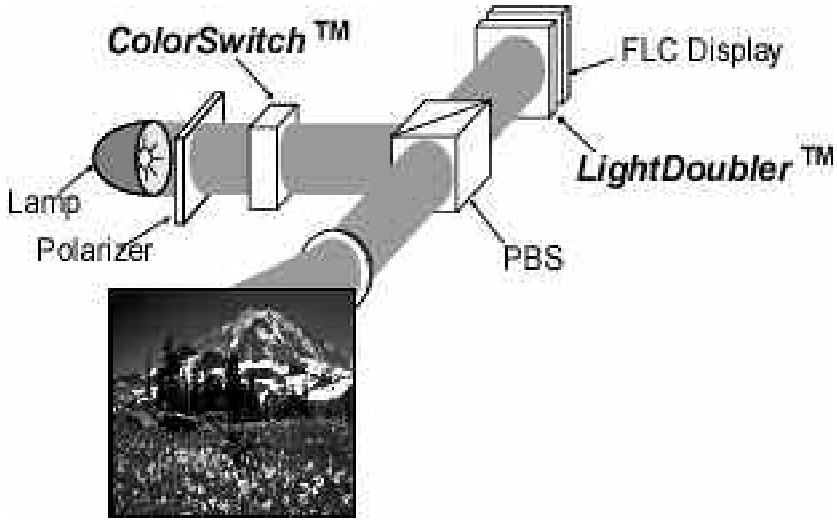


The second most frequent citing organization was ColorLink, Inc., of Boulder, Colorado. It turns out that ColorLink, coincidently, also received a three-year ATP grant in 1997–2000.[24] ColorLink develops component optical technologies that enable color control (color separation, combination, and modulation) in display systems, particularly those based on LCOS microdisplays similar to Displaytech's FLCOS devices. One of ColorLink's founders was Kristina M. Johnson, at the time a faculty member at the University of Colorado and colleague of Clark, one of the co-founders of Displaytech.

24. While ColorLink was not a target case study for us, we note here that they also told us that ColorLink was unlikely to have survived the technology downturn without the ATP funding. Just as for Displaytech, the grant provided not only helpful cash flow, but also visibility and credibility with angel and venture capital investors. We quote: "It [the ATP grant] gave us very early financing and research that allowed us to bring our products to commercialization stage. Without them we would have had trouble attracting angel investors or VCs. Very, very instrumental to our success."

FIGURE 13.

ColorLink Single-Panel Architecture for Microdisplay Projection System



Source: www.colorlink.com/products/products.html

Indeed, because their products are potentially complementary in projection display systems, ColorLink and Displaytech have collaborated. One of the potential advantages of FLC microdisplays in projection and monitor applications is the ability to cycle through three colors—so-called field sequential—with a single microdisplay panel, rather than the usual three panels needed in systems using slower switching LCOS microdisplays. As shown in Figure 13, ColorLink has developed fast switching color filters (ColorSwitch™) and polarization switch inverters (LightDoubler™) for these single-panel systems, but also has systems (ColorQuad™) for three panels for use with Displaytech competitors' panels.

In investigating methods to achieve the fast switching speeds needed, some earlier work at ColorLink was on using FLC materials. The initial work was based on FLC technologies coming out of the University of Colorado. This explains ColorLink citations to Displaytech's FLC-based frame-sequential switching patents. However, according to our interviews with the principals, ColorLink moved away from using ferroelectric techniques and migrated to alternative electro-optic effects (nematic and pi-cell) to achieve what they see as a more attractive commercial balance of switching speed, cost, and performance. Their current main frame-sequential color switch products use pi-cells, and the switching speeds, though not quite as fast as FLC, are adequate for single-panel microdisplay applications.[25] Indeed, Displaytech itself has demonstrated a single-panel FLC microdisplay system using

25. See Sharp et al. (2000) for technical discussion of ColorLink's pi-cell frame-sequential color switch.

ColorLink's pi-cell color switches and driver electronics. Thus, while ColorLink did use Displaytech patent-related technical information in early investigations, no significant commercial value has emerged from the spillover of technical information.

That said, the fact that Displaytech exists and is selling FLC microdisplays has slightly increased ColorLink's sales. The sales are not based on the spillover technical information, but due to sales of fast-switching pi-cell ColorSwitches with associated driver electronics for occasional demonstration kits with Displaytech microdisplays going out to potential OEMs. The demonstration kits are generally used by display system designers who are evaluating performance characteristics of various alternative components in the early phases of product development. ColorLink principals estimate that these sales related to Displaytech represent only about 1 percent of their business, but that these sales would not occur if Displaytech did not exist.

While we were not privy to ColorLink sales figures, based on their 25 employees and a rough industry norm of $150,000 revenue per employee, we estimate that the Displaytech-stimulated 1 percent represents about $30,000–40,000 of ColorLink revenues per year. After including costs, it is unlikely that the economic surplus generated by these extra sales, simply from Displaytech's existence, is more than $5,000–15,000 annually. Total resulting economic surplus through 2006 will almost certainly be less than $100,000. This is easily within the estimation error of the millions of dollars in direct economic surplus estimated above. So again, we conclude that the indirect spillover value of the patent technology is negligible and that even the direct market value to ColorLink as a supplier is quite limited compared to the customer and competitor effects discussed above. If Displaytech ever successfully reenters the HDTV or desktop monitor businesses, then ColorLink might significantly benefit in the future. But, as we discussed above, there is no evidence yet that Displaytech will be successful in those large markets.

The third highest number of citations to Displaytech patents came from the research team of Clark and Lagerwall, listed as inventors without an associated organization. Recall from above that Clark and Lagerwall discovered and patented the FLC bistable switching effect to begin with. Their subsequent nine references to Displaytech are on nine different subsequent Clark and Lagerwall patents, but all reference the same single Displaytech patent, a fundamental patent for electro-optic switching using FLC materials. While Displaytech is the assignee on this patent, the two inventors listed are Displaytech co-founder and Chief Scientist Handschy and Clark himself. These citations turn out to be simply Clark referencing himself. So, we see no spillover value here, which we confirmed by interviewing Clark.

The next highest U.S.-based group citing Displaytech was from Chorum Technologies of Richardson, Texas. Chorum was formerly MacroVision Communications LLC based in Boulder, Colorado. Yet again, there are social networking ties through the University of Colorado. One of the two founders of Chorum/MacroVision received his PhD there in 1995 studying acousto-optic photonic switches for telecommunications. The other founder was a researcher at the university's Optoelectronic Computing Systems Center. They moved the company from Boulder to Richardson in 1998. Our interviews with Chorum indicated, again, little demonstrable value from technology spillover. Chorum's core business is in optical filters, optical switches, optical signal processors, and related electro-optical components for telecommunication networks. Their six citations were to Displaytech's patent on an electro-optical polarizing switch. When interviewed, Chorum said they had experimented with FLCs to perform fast optical routing and switching, but had not pursued the idea past the early lab bench phase. None of their current products utilizes the Displaytech ideas, and they have no plans to pursue them further. Since Chorum and Displaytech are in different lines of business, Chorum saw no competitive impact either.

InViso Corp. of Sunnyvale, California (formerly Siliscape Corp. of Palo Alto, California) was the fifth U.S.-based organization most frequently citing Displaytech. It was formed in 1994 and co-founded by Gregory Kintz, who got his MS in physics in 1985 from, again, the University of Colorado. InViso was developing optics and electronic driver circuits for miniature image generators appropriate for use in head-mounted displays, goggles, and other near-to-eye applications. These were complete systems, including compact magnification optics. InViso patents that cited Displaytech patents had to do with InViso's novel techniques for reducing the size of the optical path and the magnification optics to display images like those generated by microdisplays. However, InViso struggled with cash flow problems, never achieved profitability, and folded in 2001. Three-Five Systems acquired InViso's 40 patents, some equipment, and other assets for $780,000 in 2002, after writing off an earlier $3.8 million equity investment for a minority stake in InViso.[26] When Three-Five Systems subsequently spun off its microdisplay activities as Brillian Corporation in 2003, the division had yet to be profitable.

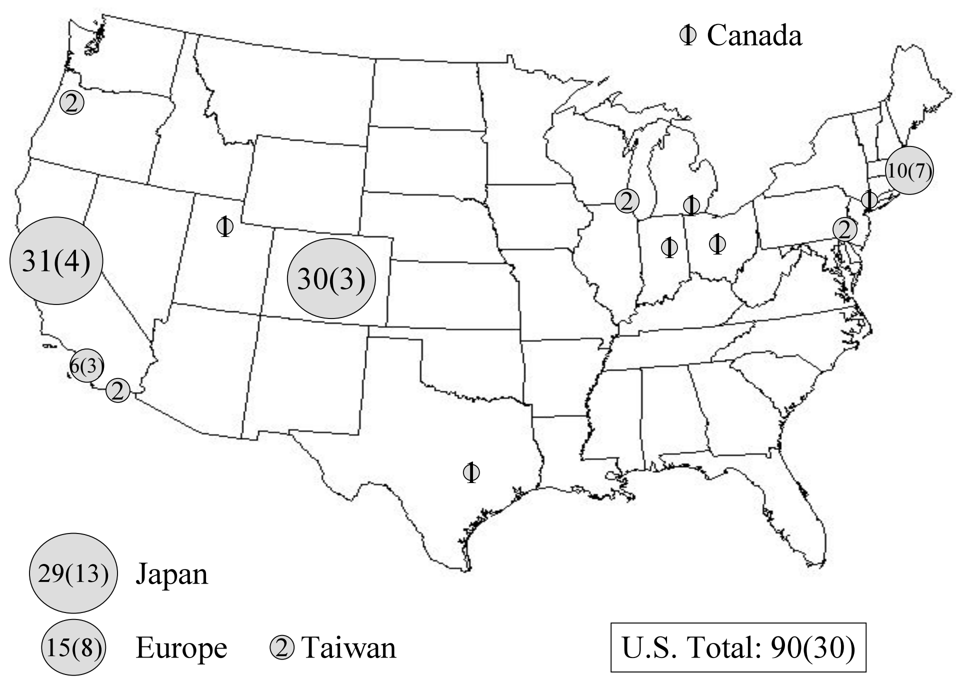
Thus, after interviews with technology management personnel at Three-Five Systems/Brillian, we estimate the value of knowledge spillovers to InViso from Displaytech's patents or products to be on the order of tens of thousands of dollars. This value is limited because of: 1) InViso's failure; 2) the limited total market value of InViso assets in the end, only a small fraction of which were related specifically to Displaytech patents; 3) the continued unprofitability under Three-Five Systems/Brillian; and 4) the fact that Three-Five Systems/Brillian makes (and had been supplying to InViso) its own alternative LCOS microdisplays that most likely would be used in any near-eye systems that Three-Five Systems/Brillian might produce using the acquired InViso intellectual property.

In summary, together with the Japanese firm Sharp, patents from these top six organizations accounted for nearly half the total citations to Displaytech patents. Despite this, we found little evidence among these patent-citing organizations of significant economic value created within the United States through the direct spillover of technical information either to potential competitors such as Three-Five Systems/InViso or to those in unrelated markets such as Chorum in telecommunications. Moreover, the citations from the top-citing organization, Gemfire, were not indicative of any sharing or diffusion of technology at all. Three of the others, ColorLink, Lagerwall, and Chorum, all had existing personal social ties

26. *The Business Journal of Phoenix* (2002) and Securities and Exchange Commission (SEC).

FIGURE 14.

Geographic Distribution of Citations to Displaytech Patents



Note: values indicate number of citations (number of citing organizations).

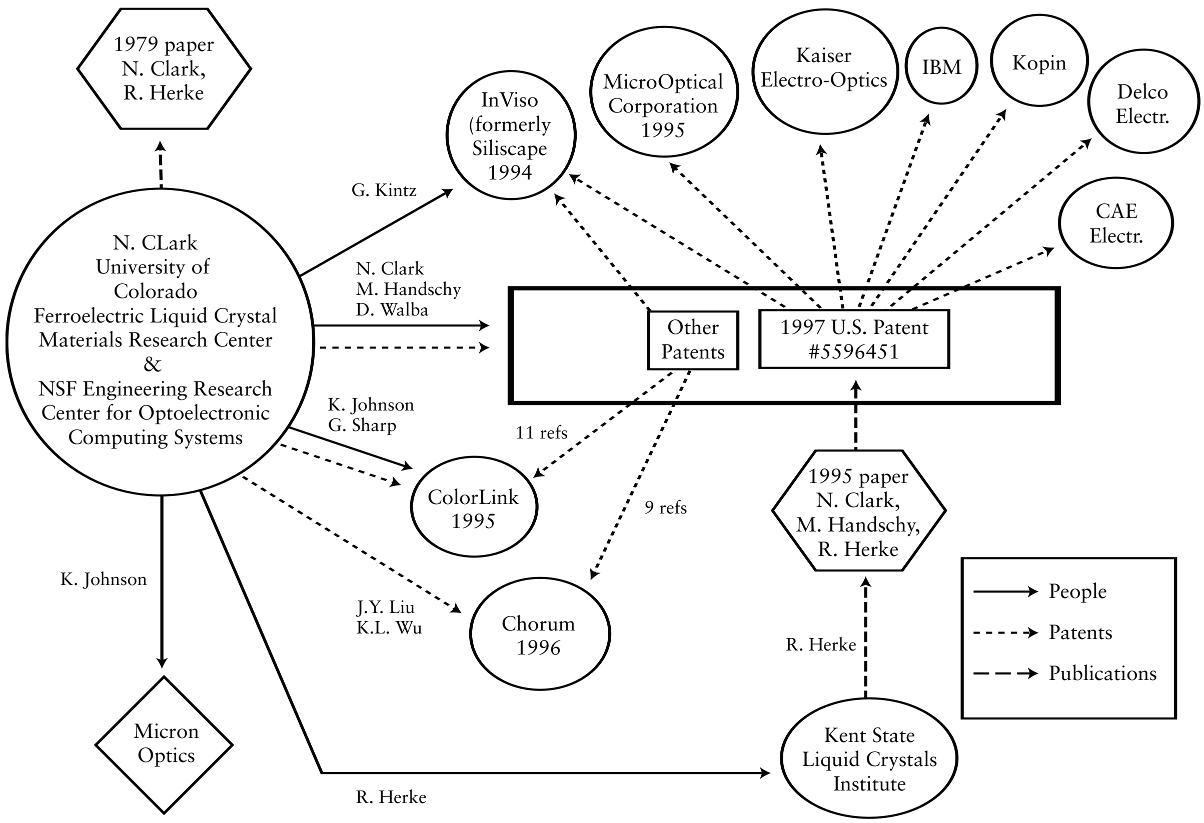
with Displaytech through the University of Colorado. The social network centered on a star researcher, Clark, who was the mechanism for technology flows, and our analysis shows the flows to those outside Displaytech have yet to create much economic spillover value. Our conclusion is that patent citations are, at best, a very noisy indicator of technology spillover.

One of the questions motivating our study relates to the social and geographic characteristics of technology diffusion mechanisms. Technology flows through geographically clustered social ties are clearly very strong in the Displaytech case. Figure 14 shows a schematic of this geographic clustering among the citing patents by location (region or country) of the assignee. Silicon Valley, California, had the highest number, 31 citations by four groups, followed by the Boulder area and Japan. The U.S. total was 90 citations by 30 groups. The concentration in Displaytech's home state of Colorado is consistent with findings by Hicks (2002) that patents by U.S. companies tend to be more likely to cite in-state public sector science.

Yet, as an indicator of geographic clustering or social networks, this picture of patents would send misleading signals. Without detailed case investigation, Gemfire in Silicon Valley, with 24 citations, would look like a significant receiver of technological information, as would Chorum in Texas and InViso in Silicon Valley. Yet Gemfire was not a receiver, and Chorum's links actually emerged when it was started in Boulder by researchers associated with

FIGURE 15.

Social Links to Organizations Citing Displaytech Patents



University of Colorado. So too, InViso's founder was also a student there. Even the German firm Hoechst had collaborated with Displaytech and researchers at the University of Colorado on liquid crystals and had supplied them with early compounds. The real information flows were significantly more concentrated in social links through the University of Colorado than the geographic clustering of patent citations would indicate.

We illustrate the importance of this social network stemming from the University of Colorado in Figure 15. It shows, for illustrative purposes, Displaytech's 1997 U.S. patent number US05596451 for "Miniature image generator including optics arrangement" and the citing organizations, including InViso, as well as several other significantly related major citing groups, such as ColorLink and Chorum that cite other patents. The figure also shows the people out of the university that founded the various companies and the dates those firms began.

Beyond patent citations underrepresenting the social clustering, we also suspect, but have not further investigated, that a reasonably large fraction of the citations, particularly by display competitors, were added by patent examiners and attorneys (as in the case of Gemfire), rather than because the inventors had actually learned something from the cited patent. Patent citation analysis in the technology diffusion and spillover literatures is increasingly popular, perhaps because it is a readily available source of data. Given the scope of the task and the main purpose of our analysis to track main avenues of economic value creation, we only tracked about half of the patent citations. To gauge the level of false signals in more macro-level patent citation analyses, we believe a series of detailed cases that track every patent citation and whether or not each indicated real or spurious information flows, would be a valuable addition to the literature. We also believe, as we discuss in the next section, that publication citations by industry might be a fruitful alternative.

We performed one final analysis on these patent citation data in order to begin exploring our emerging conclusion that social and technological “closeness” was driving the pattern of patent citations to Displaytech. We measured the time lag in days between the issue date for each Displaytech patent and the filing date for the citing patents. Using these lag days as the dependent variable, we ran a simple ordinary least squares (OLS) regression to see if there was evidence that organizations who were socially, technically, or geographically closer to Displaytech were faster to citation than others. Our crude measure of social closeness was a Yes/No dummy variable for whether they had known collaborative or university ties. Our measure of technical closeness was a series of sector dummy variables for whether the citing group was a direct competitor in displays or more broadly in imaging, telecommunications, chemicals, or other industry. The base-case group was university and other research organizations. Since large firms tend to have regular patent filing processes and legal staff, which might help speed the process compared to smaller firms without such resources, we used a dummy variable for firms that had more than 1,000 employees. We also included a geographic indicator of whether the citing organization was based in the United States. Finally, citations to more recent patents would tend to have, on average, shorter lag times. So, we included the patent issue date to control partially for this bias. Table 8 shows the results of this modeling on the 137 patent citations to Displaytech patents.

We see that firms with social ties to Displaytech are on average more than 250 days faster to citation than others, controlling for the other variables in the model. We also see that large firms are almost 300 days faster on average. Industry sector also seems to matter. Chemicals/materials firms are almost two years faster to citation than the base-case research organizations. Next fastest, with an almost 400 day lead, are imaging firms (not in direct display competition). Telecommunications firms and, surprisingly, direct display competitors show no statistically significant differences. We attribute these differences in part to industry patenting norms, particularly in chemical industries, where patenting is particularly important strategically.[27] In the chemicals/materials industry, for example, molecular structure is both competitively critical and relatively straightforward for competitors to reverse engineer. We find that once we control for industry and links to Displaytech, U.S. firms are no different from foreign firms. Geographical clustering per se, measured in this crude way,

27. Mansfield (1986).

TABLE 8.

OLS Regression Results on Time Lag to Citation of Displaytech Patents

Dependent Variable: Lag Days	Coefficient	Std. Err	p>|t|			
Patent Date in Days	-0.623	0.050	0.000	***	n	137
Links to Displaytech Dummy	-250.7	140.8	0.077	*	F(9, 127)	22.48
Large Firm Dummy	-299.2	173.5	0.087	*	Prob > F	0.000
U.S. Dummy	21.6	165.3	0.896		R2	0.6144
Imaging Applications Firm	-392.9	235.8	0.098	*	Adj R2	0.5871
Telecommunications	-73.6	220.3	0.739		Root MSE	549.4
Chemicals/Materials	-639.1	247.0	0.011	**		
Other	-416.7	192.9	0.033	**		
Direct Competitors	-166.2	188.8	0.380			
Constant	8857.4	693.0	0.000	***		

Two-Tailed Significance Levels: *p<0.10, **p<0.05, ***p<0.01.

does not seem to explain the speed of technology flows as measured by citation lag time. Indeed, without controlling for other variables, U.S. firms are actually statistically significantly slower, 1,019 days to 609 days (p=.0073). This difference goes away once we include the other variables. This suggests that social ties, large firm resources, and industrial sector practices are more important mechanisms than geography per se for explaining Displaytech-related technology flows.

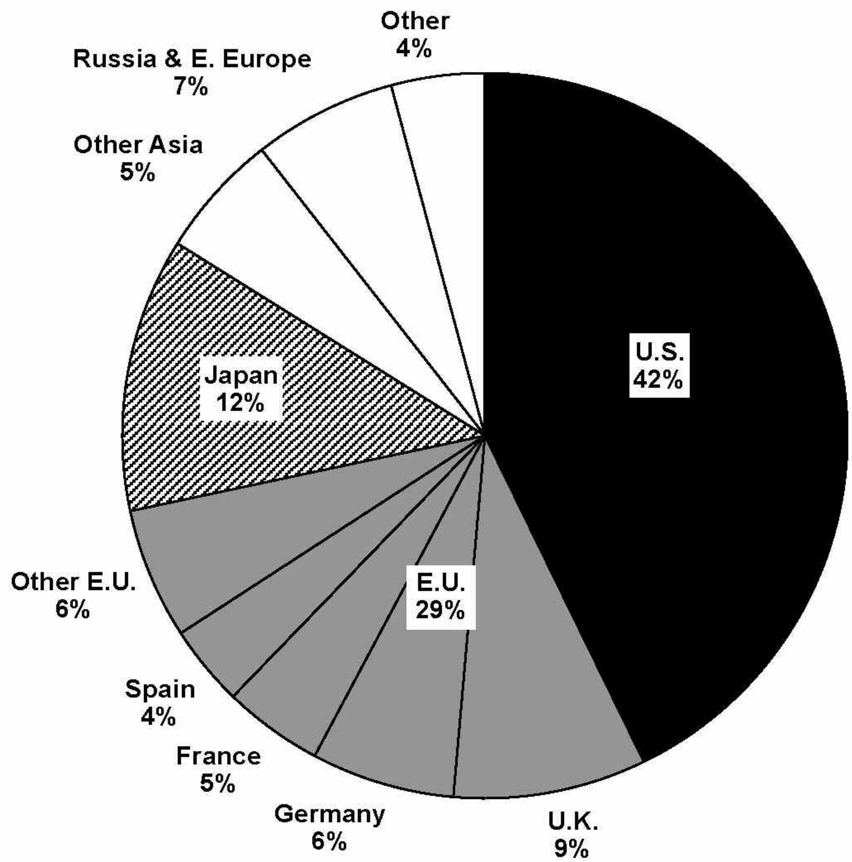
PUBLICATIONS CITATION ANALYSIS

Another approach we used to track potential spillover of technical information used publication citations. Using the Thomson Scientific's Institutional Citation Report database, we identified 75 scientific, technical, and professional trade publications through June 2001 (the latest available data set) that listed Displaytech among the authors' affiliations. There were 904 citations to those articles, 99 of which were self-citations from papers with Displaytech authors. This left 805 citations from 255 different external organizations and 862 different authors.

The distribution of those citations by the country of the authors is shown in Figure 16. The distribution is considerably less U.S.-centric than for patents in Figure 12. This is, in part, explained by the role of the U.S. patent in protecting intellectual property in the United States, but not elsewhere. Yet it is also suggests that Displaytech has had an international impact on the field of liquid crystal materials research and that any value creation is likely to be more international than U.S. patent citation analysis would imply. In particular, Western European researchers play a much larger role citing Displaytech publications (29 percent of citations) compared to citing Displaytech patents (11 percent). Except Japan, the same pattern emerges for the rest of the world, which accounts for 16 percent of publication citations compared to only 3 percent of patent citations. The relative lack of multinational

FIGURE 16.

Citations to Displaytech Publications by Country

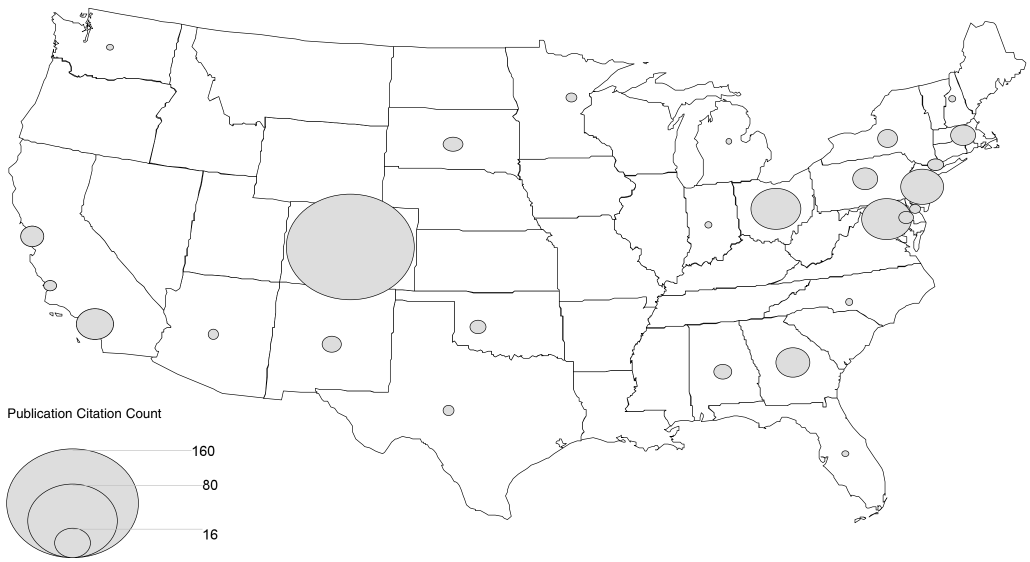


commercial industries in Russia and Eastern Europe that would likely patent in the United States, coupled with strong traditional academic research groups, probably accounts for the citation difference there. Conversely, the comparative international strength in liquid crystals lies in Japanese multinational electronics firms, who, together with South Korean firms, dominate LCD markets. This explains the large Japanese share (21 percent) of patent citations, but not of publication citations (12 percent). This bias toward commercial applications in Japan becomes even clearer below when we remove nonprofit research groups from the publication citation data.

Figure 17 shows the geographic distribution of publication citations within the United States. Like the patent citations, there is significant concentration within the Boulder area, but less concentration than the patents in the high-tech commercial corridors of Silicon Valley or the Route 128/Boston area. By contrast, there are publication citation clusters around Washington, D.C. (30 citations by nine organizations, including the U.S. Naval Research Laboratory, George Mason University, and GeoCenters, Inc.), New Jersey (22 citations

FIGURE 17.

Citations to Displaytech Publications by U.S. Region



among seven organizations, including Bell Labs and Princeton University), and Ohio (29 citations by six organizations, including Case Western Reserve University and Kent State University's Liquid Crystal Institute).

The top-citing organization and individual authors (including Displaytech itself) are shown in Table 9. It is immediately clear that a large majority are universities and similar noncommercial research groups. Clear, too, is the close affiliation of authors from Displaytech and the University of Colorado. Personal ties are also significant: our analysis of co-authoring showed that at least 11 of the top 25 citing organizations have had collaborative co-authoring ties with one or more Displaytech authors. Though economic value creation might occur through science and technology diffusion to the academic researchers, the large majority (and even Clark himself) is doing fundamental science considerably removed from applications. For example, the main citing researcher at Case Western Reserve University, Displaytech's top external citing organization besides the University of Colorado, was working on the "fundamental principles that govern rational design and synthesis of complex molecular, macromolecular, and supramolecular nonbiological systems that exhibit biological functions."[28] Only two industrial firms besides Displaytech make this list anywhere: Nippon Telegraph and Telephone (NTT) and Lockheed

28. Percec (2004).

TABLE 9.

Top Organizations and Individuals Citing Displaytech Publications

Top Organizations Citing Displaytech Publications

Cites	Citing Organization	Collab	Location	Industry
145	U Colorado	Yes	U.S.-CO	Research Org.
99	Displaytech, Inc.	Self	Self	Self
18	Case Western Reserve U		U.S.-OH	Research Org.
16	Tech U Berlin	Yes	Germany	Research Org.
16	U.S. Naval Research Lab		U.S.-DC	Research Org.
15	Georgia Inst Technology	Yes	U.S.-GA	Research Org.
13	NTT Optoelectric Labs		Japan	Telecom
13	Tokyo Inst Technology		Japan	Research Org.
12	Chalmers U Technology	Yes	Sweden	Research Org.
12	U Oxford		U.K.	Research Org.
10	U Cambridge		U.K.	Research Org.
10	U Dublin Trinity Coll	Yes	Ireland	Research Org.
10	U Exeter		U.K.	Research Org.
10	U Zaragoza	Yes	Spain	Research Org.
9	U Hull		U.K.	Research Org.
9	U Pais Vasco		Spain	Research Org.
8	Caltech		U.S.-SV	Research Org.
8	Queens Univ	Yes	Canada	Research Org.
8	U Mainz	Yes	Germany	Research Org.
7	Tech U Clausthal		Germany	Research Org.
6	6 Organizations each with 6 Citations	3 Yes	6 Nations	5 Research 1 Def & Space

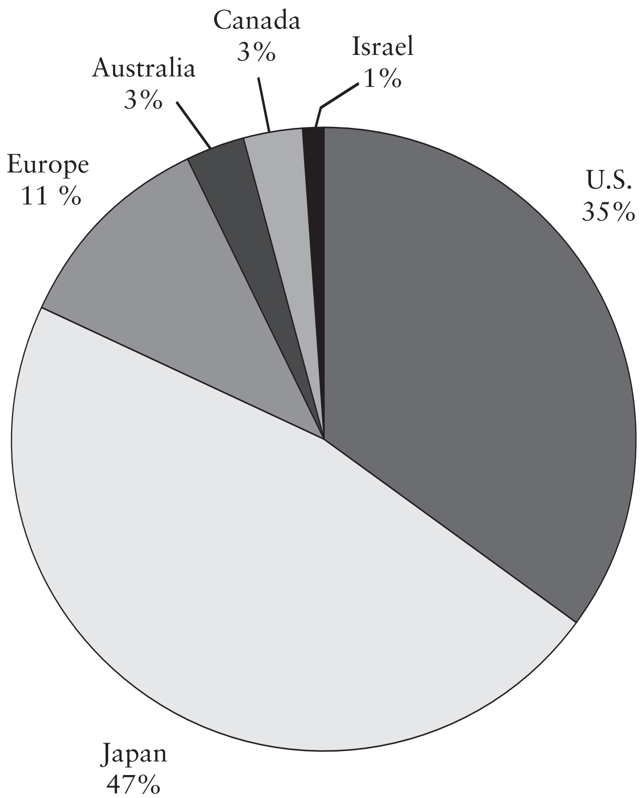
Top Individual Authors Citing Displaytech Publications

Cites	Name	Affiliation	Location
39	Clark, N.A.	Displaytech & U Colorado	U.S.-CO
32	Walba, D.M.	Displaytech & U Colorado	U.S.-CO
30	Johnson, K.M.	U Colorado	U.S.-CO
21	Moddel, G.	U Colorado	U.S.-CO
12	Handschy, M.A.	Displaytech	U.S.-CO
12	Shashidhar, R.	U.S. Naval Research Lab	U.S.-DC
11	Elston, S.J.	U Exeter	U.K.
11	Heppke, G.	Tech U Berlin	Germany
10	Maclennan, J.E.	U Colorado	U.S.-CO
10	Mao, C.C.	U Colorado	U.S.-CO
10	Percec, V.	Case Western Reserve U	U.S.-OH
10	Ros, M.B.	U Colorado & U Zaragoza	Spain
10	Wand, M.D.	Displaytech	U.S.-CO
9	Goodby, J.W.	U Hull	U.K.
9	Shao, R.F.	U Colorado	U.S.-CO
8	Doroski, D.	U Colorado	U.S.-CO
8	Dyer, D.J.	U Colorado	U.S.-CO
8	Lemieux, R.P.	Queens U	Canada
8	Naciri, J.	U.S. Naval Research Lab	U.S.-DC
8	Ratna, B.R.	U.S. Naval Research Lab	U.S.-DC
8	Robinson, M.G.	U Colorado	U.S.-CO

Source: Authors' analysis based on data from Thomson Scientific's ISI Institutional Citation Report database.

FIGURE 18.

Corporate Citations to Displaytech Publications by Corporate Location

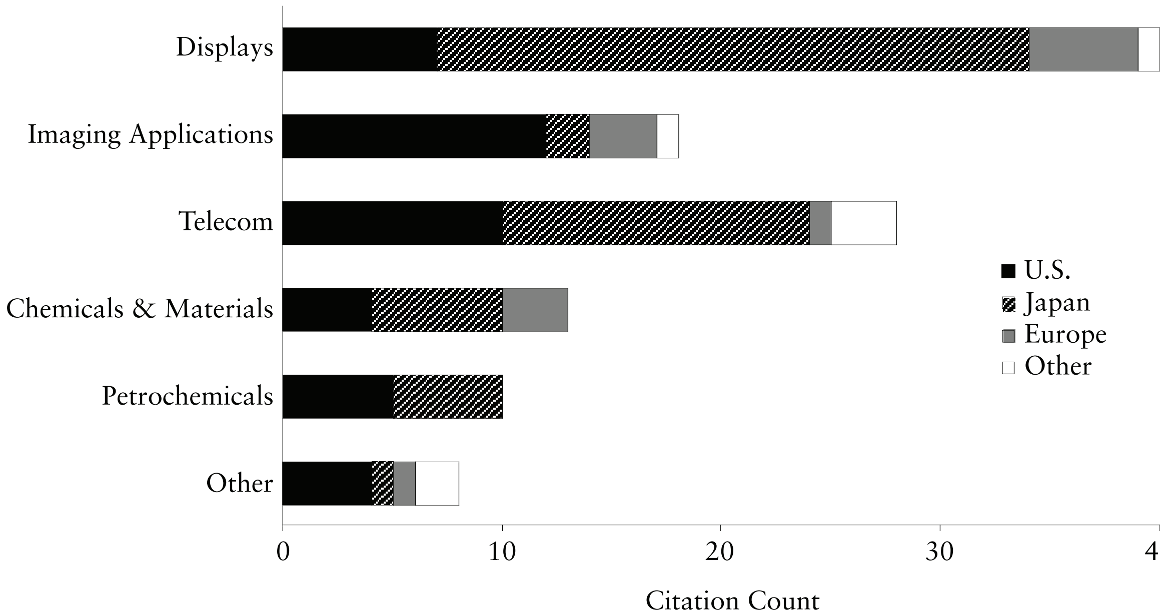


(now Lockheed-Martin). The latter is among the six organizations with six citations. Publication citations to Displaytech per se are clearly even noisier and diffuse than patent citations as a metric of economic value spillover. On the other hand, since no patent lawyer suggests what citations the researchers include, the publication citations are, we believe, cleaner in terms of the learning occurring.

Given the potential for cleaner tracking of learning pathways, and because we focus on economic value creation rather than value to academic basic science, we then took an additional step. We looked only at those citing organizations that were corporations. A total of 117 (14.5 percent) of the 805 citations were from authors associated with corporations. Figure 18 shows these corporate citations to Displaytech publications by the corporate location. The distribution is quite different than before we exclude the academic research organizations. Corporate citations to Displaytech publications are far more concentrated among Japanese corporate researchers, who account for 47 percent of the corporate citations, compared to the 12 percent Japanese rate among all organizations. Europeans

FIGURE 19.

Corporate Citations to Displaytech Publications by Industry and Location



account for only 11 percent of corporate citations, but 29 percent of all citations to Displaytech publications.

Figure 19 shows the distribution of these corporate citations by industry sector. Since some citing organizations are large multisector conglomerates, we categorize the sector related to the liquid crystal research work. Almost exactly half (58 of 117) of the corporate citations are from companies that are in competing display markets or in related markets as potential customers in imaging applications. The remaining half is from sectors we would categorize as potential knowledge spillovers, such as telecommunications, chemicals, or petrochemicals. This compares to the 38 percent knowledge spillover measure in the patent citations. In particular, a much higher fraction (20 percent) of corporate publication citations is from chemicals and materials or petrochemical firms than was true for patent citations (9 percent).

We believe this pattern is consistent with our findings that the patents are noisy as spillover indicators, for legal reasons. Because citations help define the boundaries of the intellectual property, direct or near competitors and users are more likely to cite Displaytech patents than are patentees in more tangential industries. On the other hand, those tangential industries may in fact be learning too, as evidenced by their voluntary citations in publications. Because of the legal peculiarities of patent citations, they give here a narrower measure of technical spillover than do the publication citations.

To pursue more narrowly the question of whether the corporate publications were providing a useful measure of ATP-related spillover, we focused on interviews with those whose corporate citations were specifically to Displaytech publications after the ATP grant. Articles that Displaytech published before the award in late 1994 presumably did not benefit from ATP. Of Displaytech's 79 papers in our database, 34 appeared after 1994. There were 145 citations to Displaytech articles that followed the ATP award. Of those, 16 citations were from authors listing a corporate affiliation.

Table 10 lists all the corporate citing organizations that might have benefited from the ATP-funded research at Displaytech, based on appropriate publication dates. Notably, 10 of the 16 citations are from researchers working in foreign companies. We tracked down the remaining six in the United States.

The first U.S.-based citation shown in the table, Computer Optics, Inc., turned out to be a researcher who, though listed on the publication as at Computer Optics, told us he had actually done the research in question while a doctoral student working with funding from the U.S. Air Force. He was working on optical image recognition and tracking technologies and used one of Displaytech's early devices as a spatial light modulator in an optical correlator. In fact, the Air Force funded Displaytech, through an SBIR contract, to develop the system used. The project at the Air Force was later discontinued and the technology not pursued further. The firm he currently works with does not use related technologies. In this case, then, the citation was clean, in the sense of being an indication of direct information flow, but was through the collaborative direct funding relationship via the Air Force as a paying Displaytech customer/funding organization, a within-market transaction. The economic value beyond the market transaction and employment of this doctoral student was negligible.

Litton Data Systems' (now part of Northrop Grumman) citation in 1997 also had to do with work they were doing on real-time image recognition systems for targeting and guidance systems, primarily for military and space applications. Their "miniature ruggedized optical correlator module," they said, took advantage of the fast-switching capabilities of Displaytech FLC microdisplays to speed up the system's image processing. The citation is again clean in terms of being a signal of technology diffusion, and the FLC technology was enabling a processing speed capability that most other microdisplay alternatives did not. Although applied at Litton to military target identification, the technology also has potential applications in automated automobile traffic road-sign recognition, digital facial recognition, robot vision, medical image processing, as well as manufacturing applications such as quality control. One member of the Litton team later founded a startup company, DataVision, which explains the DataVision citation. This application of the Displaytech FLC was work done at Litton, and not directly related to his startup.

According to our discussions with the IBM Watson Research Center authors, they were investigating technical options for and advances in solving various challenges in designing projection display systems that use reflective microdisplays, like Displaytech's. Were there value here, it would be within-market and captured in the analysis above, as designers of these projection systems are potential customers. As of 2003, IBM was selling portable front-

TABLE 10.

Corporations Citing Post-1994 Displaytech Publications

Citations	Citing Corporation	Location	Industry
2	Clariant	Japan	Displays
2	Mitsubishi Gas Chemical	Japan	Chemicals and materials
2	Toshiba	Japan	Displays
1	Samsung Display Devices	Japan	Displays
2	Thomson-CSF (now Thales)	France	Imaging applications/defense
1	Philips	Netherlands	Displays
1	Computer Optics	U.S.-NH	Optical design and consulting
1	DataVision	U.S.-NJ	Imaging applications
1	IBM Watson Research Center	U.S.-NYC area	Displays
1	McLaughlin Consulting Group	U.S.-Silicon Val	Display market review article
1	Litton Data Systems	U.S.-CA (L.A.)	Imaging applications/defense
1	Rockwell Research Center	U.S.-CA (L.A.)	Micro-optics review article

projection displays, but using Texas Instruments' Digital Light Processing (DLP) microdisplays. This 1999 article citing Displaytech discusses a range of theoretical and practical optimization issues of overall projection system design. These include, among others: alternative projector configurations, illumination sources, transmission and focusing lenses, optical coatings, methods for improving light collection and reflection, thermal effects in optical components, and imaging screens. The authors refer to Displaytech in an illustrative table listing 19 examples of "reflection light valve technologies." The table also includes some major competitors such as Texas Instruments, Three-Five Systems, JVC, and Hitachi. The enabling speed of the FLC and DLP microdisplays was pushing the research need for improvements in single-path, color-sequential systems, which the authors address briefly, as opposed to the standard three-path, color-combining systems, particularly in solving illumination brightness and contrast issues. Economic spillover value from Displaytech in this case is limited, however, by lack of commercialization in projection displays. Indeed, slow progress in these complementary technologies is one reason Displaytech exited the projection and desktop display sides of microdisplay markets. Beyond this, there is no mention or analysis of any differentiation among these various microdisplays, so there is no evidence of additional spillover market value from Displaytech-specific technologies. So this citation is again clean in terms of being evidence of technology flow, but the value, if any, depends on any future commercialization of FLC-based projection systems.

The citation from the McLaughlin Consulting Group was in a trade journal review article about various emerging display technologies. The principal of the McLaughlin Consulting Group, whom we spoke with, makes a living consulting, writing, and speaking about trends in the display industries. The group follows, analyzes, and reports on new developments industrywide. The specific technologies are of interest to him from the point of view of an industry analyst, not in the sense of technical learning and beneficial economic spillover effects, which we are interested in here. If the specific technologies Displaytech was developing did not exist, his industry analysis would change slightly (i.e., Displaytech would not be included in the industry and technology analysis), but it would be unlikely to affect the overall value or output of his activities. Presumably, the buyers of his consulting services (including display manufacturers, suppliers, and OEM customers) are getting some value out of the information he provides, so there may be a tertiary spillover value of his reports on Displaytech activities back into the display market competitors, suppliers, or customers. However, we did not attempt to track these tertiary effects.

The Rockwell Research Center citation was in another, even broader, review article in 2000 about "Microoptics Development in the Past Decade." The article overviews the historical evolution of microlens technologies, then discusses, among other things, design rules, materials issues, fabrication techniques (e.g., resists, photomasks, inkjet, vapor deposition, and laser ablation), testing and characterization processes, and mass-manufacturing issues and then reviews a large number of application areas. The authors reference, among 149 total references, a 1995 Displaytech article on microlens arrays, an option that Displaytech and multiple other firms investigated for improving the input/output light efficiency of microdisplay-based optical systems. Indeed in 2003, several commercially available microdisplay-based digital projection systems (e.g., Sony, NEC, Toshiba, Mistubishi, and Proxima) were using microlens arrays. Because we found no other industry-related citations to Displaytech's article, there is no citation evidence that Displaytech microlens work specifically influenced commercialization efforts more broadly. In any event, microlens work was not part of the ATP-funded activities at Displaytech, so we see no spillover value from ATP funding here.

In summary, although the value we managed to track though these six U.S. citations was limited, what emerges from tracking publication citations by industrial organizations is, we believe, a potentially crisper and less noise-prone approach to tracking technology flows. The list very narrowly focuses on display manufacturing firms or those applying display technologies to other sectors (e.g., military imaging systems). Only four of the 18 post-ATP citations listed are not in the display or display applications sectors, and three of those are related review articles in trade publications. The fourth, attributed to the firm Computer Optics, Inc., turned out to be by a researcher previously doing imaging-related dissertation work using Displaytech microdisplays. Since these researchers voluntarily cite Displaytech work, each one we contacted uniformly confirmed that they had learned something. The flip side to publication citations is that the citing authors tend to be in the more fundamental research groups within these firms, rather than commercialization-oriented groups who might create more value. Patents, although noisy, do signal some expected commercial value. A blend of the two citation analysis approaches seems appropriate.

3. Comparison of Displaytech and Uniax

COMPARISON CASE: UNIAX

Uniax is nearly ideal as a comparison case to Displaytech. Like Displaytech, Uniax pursued a single principal technology, conductive polymer light-emitting diode (poly-OLED). This focus on a single technology allows a more accurate tracking of technology diffusion and spillover. Uniax also applied for ATP funding in the same 1993 competition as Displaytech's first proposal application to ATP. Although a semifinalist, Uniax did not receive an ATP award in 1993. Like Displaytech, Uniax was developing a novel technology for competing in display markets and, like Displaytech, was focusing on materials and processing issues for moving a laboratory-phase proof of concept into—a decade later in both cases—a cost- and performance-competitive, mass-manufacturable commercial product. Also like Displaytech, Uniax maintained strong university ties and its technology emerged from critical basic scientific discoveries by a world famous university researcher, Alan Heeger, who—like Clark at Displaytech—became one of Uniax's founders.

TECHNICAL AND COMPANY BACKGROUND

Uniax started in 1990 as a spinoff from the University of California, Santa Barbara (UCSB). It was founded by Heeger and UCSB colleague Paul Smith to commercialize technologies related to electronically conducting polymers, which Heeger discovered with Alan MacDiarmid and Hideki Shirakawa in 1977. Their discovery of "electronic plastics" was so important and revolutionary that Heeger, MacDiarmid, and Shirakawa shared the 2000 Nobel Prize in Chemistry. One indication of the economic spillover potential of the discovery comes from the Nobel Prize Committee's press release announcing the award, calling conductive polymers "one of the great chemical discoveries of our time." Potential practical applications are widespread (e.g., in electronics, photonics, holographic memories, telecommunications, textiles, paints, lighting, smartcards, batteries, medical devices, and automobiles), and the field rapidly attracted billions of dollars in R&D. Market growth for conductive polymers has been led early on by applications in electrostatic coating and shielding and in OLED displays. Enabling commercially competitive OLED displays formed the basis for Uniax's proposal application to ATP in 1993.

COMPETING ALTERNATIVES AND APPLICATIONS

The late 1980s saw two different discoveries of the light-emitting potential of electronic plastics, building on Heeger et al.'s initial discovery. One, published in 1987 by Ching Tang, a researcher at Eastman Kodak in Rochester, New York, was of the electroluminescent capabilities of some types of small organic molecules. Kodak has since licensed this technology to several firms, including the current OLED market leaders, Pioneer and RiTdisplay. The second, discovered a year later by Jeremy Burroughs, a doctoral student at the University of Cambridge, was of light emission from large molecule polymers. Burroughs and his faculty advisor, Richard Friend, then founded Cambridge Display Technology (CDT) in 1992. CDT now licenses large molecule poly-OLED technologies to Philips, Seiko Epson, DuPont, and others.

Pioneer introduced the first commercial OLED display, a small monochrome version for car stereos, in 1997. Ten years after Tang's discovery, it relied on Kodak-licensed technology. The market has expanded rapidly since, following progress in manufacturing and materials performance and on longevity issues, and competition is as fierce as in Displaytech's microdisplay markets. According to *The Wall Street Journal,* by 2001 there were over 100 firms pursuing OLED display markets, including heavy hitters such as Samsung, NEC, Sanyo, and Sony.[29] Many of these appear in the OLED column on Table 4. Collectively, more than $1 billion had been invested in OLED manufacturing capacity by 2001.[30] This capacity expansion allowed worldwide markets for OLED displays to grow from about $3 million in 1999 to $27 million in 2000,[31] and then reached $263 million in 2003, with over 17 million units shipped, with projections up to $3.5 billion by 2008.[32] Cell phones and automobile stereos are the largest current applications. The Kodak and CDT technologies remain the leading competing approaches in the OLED display marketplace, with Kodak-licensed small-molecule approaches from Pioneer, Samsung, and RiTdisplay currently quite dominant. Their 2003 combined market share approached 98 percent.[33] Market observers believe competition could intensify in the next several years as Kodak's fundamental patents expire.[34]

Although the broad commercialization of poly-OLED displays is several years behind small-molecule ones, they potentially are less costly to manufacture because their underlying physical structure can be simpler than the small-molecule crystalline films. Moreover, poly-OLEDs can be fabricated on flexible plastic substrates, rather than the rigid and breakable glass now used for the market-dominant LCDs and for the small-molecule OLEDs. Because they generate their own light, OLEDs do not need the costly, thicker, and power-hungry

29. Clark (2001).
30. Grant et al. (2002).
31. 1999 and 2000 OLED market data attributed to Stanford Resources, as reported in *Consumer Electronics,* March 20, 2000, and June 1, 2001.
32. DisplaySearch (2004).
33. DisplaySearch (2004).
34. According to display research firm iSupply/Stanford Resources, as reported in *Electronics Weekly,* June 16, 2004.

backlights of LCDs; and they are brighter. This combination of flexibility, performance, size, and efficiency compared to LCDs could open up wide ranges of new, more convenient, more energy efficient display applications. It also has brought into display markets competitors such as DuPont, Dow Chemical, Sumitomo, and Kodak whose main expertise is in chemicals and related manufacturing processes, particularly automated rolling flexible sheet processing, rather than in electronics. These roll processes would be considerably less costly, involve many fewer processing steps, and be more environmentally friendly than current caustic-chemical-intensive semiconductor-on-glass LCD processing. As a result, competitive interest has been high. These poly-OLED flexible displays have been Uniax's main commercialization focus.

RESULTS WITHOUT ATP

Without an ATP award, Uniax has nonetheless prospered, and by 2004 was nearing large-scale commercialization, about two years behind Displaytech. Given the different investment and cash flow patterns of the two firms, this lag is consistent with statements by Displaytech principals that the ATP award cut their time-to-market by about two years.

Founded in 1985, Displaytech took 10 years to attract its first round of venture capital, stimulated in part by the ATP award. Uniax, by contrast, had early equity investment from the Finnish firm Neste, which took a 50 percent stake by 1994, though terms were undisclosed. Founded in 1990, Uniax's main work before their ATP proposal application was on developing conducting polymer materials that would enable cost-effective manufacturing processes. This led to several fundamental patents in the early to mid-1990s on processing technologies for what are called intrinsically conductive polymers (ICP), which Heeger and his team developed, a materials blend and doping technique that enables melt or liquid solution processing, rather than the vacuum-deposition-on-glass methods used for other OLEDs. Melt or liquid solution processing allows the mixing of ICP materials with conventional plastic materials, leveraging the processing and mechanical properties of the conventional materials for fabrication in desired shapes and flexibility and using well-known plastic processing techniques. At the same time, the resulting compound materials have electrical and optical properties that can be manipulated, ranging from insulating to semiconducting in the range of silicon or germanium. Later research also showed that the ability to suspend these molecules in liquid solutions made inkjet application onto flexible sheets possible, potentially (though not yet) a very cost-effective mass-manufacturing technique.

The obvious potential advantages attracted early equity investment from Neste, which also acquired an exclusive license from Uniax to these ICP processes in nondisplay applications. Neste later spun this off into a company called Panipol, which markets melt-processible ICP materials primarily for use in electrostatic coatings.[35] Future ICP applications may be in conductive fabrics and all-polymer integrated circuits, a 326 transistor prototype of which

35. See www.panipol.com.

Philips successfully demonstrated in 2000.[36] Indeed, these so-called organic thin film transistors (OTFT) might enable flexible integrated circuits that could be combined with flexible OLED displays for future radical new product categories, both the OLED and OTFT stemming in part from Heeger's and Uniax's pioneering work.

Uniax survived with cash flow from these processing technology licenses, combined with later limited industry contracts, related sales of pilot demonstration prototypes, and, significantly, government contracts. Before the ATP award, Displaytech also had the latter two sources of cash flow, but no licensing revenues. Like Displaytech, Uniax was well plugged into and got substantial cash flow sustenance from other non-ATP federal funding sources. In the years following Uniax's 1993 ATP proposal application, they did manage to win a series of federal contracts, mainly through SBIR awards from the Office of Naval Research (ONR) and the Air Force, and related to DARPA and the Ballistic Missile Defense Office. Between 1994 and early 1999, these totaled at least $2.3 million across at least nine different awards.[37]

Another large equity infusion came in February 1996 when Philips and Hoechst each invested $1.5 million for minority equity stakes in Uniax. This investment enabled Uniax to install a $2 million clean room and pilot production line. Uniax believes this funding significantly accelerated their development of "medium information content emissive displays," which they successfully demonstrated in 1997. Uniax succeeded in producing the world's first poly-OLED flexible plastic displays. Again, such a demonstration and steps toward commercialization were the basis for the ATP proposal application. Uniax managed to proceed using private equity funding instead. Thereafter, with a proven demonstration in hand and the availability of a pilot production capability, Uniax was able to win at least six large government contracts between late 1996 and 1999, with a combined value of $2 million.

Finally, in March 2000, DuPont agreed to acquire Uniax and its patent portfolio. Uniax became and continues as a division of DuPont Displays. While terms of the acquisition were not publicly disclosed, detailed perusal of DuPont's 10K and 10Q SEC filings after the acquisition place the value in the neighborhood of $15–20 million. DuPont added Uniax's poly-OLED and melt- and solution-processing technologies to its portfolio of new display technologies. It shortly thereafter invested an additional $15 million in a poly-OLED marketing group associated with Uniax, while at the same time hedging its technological bets with $27.6 million for an 8 percent stake in Ritek (and its display subsidiary RiTdisplay) in Taiwan.[38] Under the agreement, Ritek built an automated poly-OLED production line, with a monthly capacity of 35,000 small (sub-4-inch) passive-matrix displays. RiTdisplay also hedged its bets and, in parallel, continued to produce small-molecule OLED displays under license from Kodak. DuPont agreed to outsource 80 percent of its orders to RiTdisplay,

---

36. Pesala et al. (2001).

37. *Commerce Business Daily,* several editions: October 17, 1994; August 24, 1995; March 28, 1996; August 21, 1996; December 2, 1996; July 9, 1998; September 17, 1998; September 14, 1999; October 4, 1999.

38. Contractual details reported in *Consumer Electronics,* May 21, 2001.

which was to give DuPont access to market entry-level, commercial-scale poly-OLED manufacturing capacity. However, these displays were based on glass substrates because techniques for fabricating flexible poly-OLED displays based on Uniax technology were not yet commercially viable.

As it turned out, neither were the passive-matrix glass OLED displays. DuPont and RiTdisplay were unable to get high enough production yields or the 2,000–3,000 hour display lifetimes needed to be attractive in cell phone applications.[39] Compounding the competitiveness problem, DuPont's target prices were reportedly in the $9–10 range for small cell phone displays, while prices for comparable LCDs fell to about $2.50.[40] DuPont eventually dropped these passive OLEDs from its planned line entirely, withdrawing from the manufacturing agreement with RiTdisplay. Instead, in 2004, DuPont began focusing exclusively on bringing active-matrix OLED glass-based displays to market and continued to pursue R&D at the Uniax subsidiary for flexible poly-OLED displays. Uniax licensee Philips also has continued pursuing solution-based processing of flexible poly-OLEDs. In early 2004, the company demonstrated a 13-inch inkjet-printed flexible poly-OLED television.[41] They believe flexible displays are attractive enough that Philips is no longer pursuing R&D on glass-based displays.

So far, however, flexible poly-OLED displays cannot be made cost-effectively using roll-to-roll processing and, until that occurs, are unlikely to achieve large-scale commercial volumes. A major hurdle is that the complementary manufacturing equipment is not yet standardized, and so the equipment supply base has not achieved the scale and efficiency economies to rival the 100-times-larger LCD industry.[42]

DIRECT ECONOMIC BENEFITS

To summarize the economic value story so far, presumably the $15–20 million Uniax acquisition price from DuPont represents the risk-adjusted market value of the overall technology and patent portfolio, including potential licensing fees, accumulated by Uniax by that point in time. As such, it also is a lower bound on the forecasted future economic value created by Uniax technology overall. Even as a lower bound, it is well in excess of the $2.3 million in federal funding and $3 million reported in private funding (beyond Neste's original stake) to that point and, as such, represents an impressive social return for the combined federal and private investment. Ideally, we would add in past and future employment effects and past licensing revenues, but we were not privy to this private financial information. We note that press reports[43] suggest that Uniax employment peaked at about 150 in 2002, which is the same level as Displaytech's employment peak two years earlier, and fell about 20

39. Reported in Warren's *Consumer Electronics Daily,* May 26, 2004.
40. Reported in Warren's *Consumer Electronics Daily,* May 26, 2004.
41. Yoshida (2004).
42. Yoshida (2004).
43. Van De Kamp (2003).

percent thereafter. The pattern suggests that the net social value employment effect of both firms is in the same order of magnitude, with a two-year lag for Uniax.

Because Uniax technology has not yet entered mass commercial markets, lacking efficient complementary manufacturing equipment technologies, and because of the existing fierce competition among the 100 or so firms in those markets, there is little additional economic surplus yet from either price or quantity effects directly stemming from Uniax activities. Future economic surplus directly in these markets, however, may be significant if the potential discussed above is ever realized, particularly for radical product categories that flexible displays could enable. We address the broader knowledge spillover effects below while discussing the patent and publication citation analysis.

Comparing the two cases, then, both Uniax and Displaytech have created roughly the same order of magnitude (low tens of millions of dollars) in total direct economic value from their technologies, well in excess of the federal investments, resulting in similar magnitude NPVs (mid-millions). In both cases, the time-to-mass-market horizon was eight or more years, consistent with ATP's stated high-risk, long-term mission. ATP investment in Displaytech, based on a proposal from the same award competition as Uniax, accelerated Displaytech's market entry by about two years, attracted venture capital, and, along with other federal contracts in our view, allowed the firm to weather the technology downturn. Uniax survived with private equity investments and licensing revenue from large firms and non-ATP federal contracts. Yet even now, despite DuPont's resources, mass-market entry for the technology proposed to ATP remains elusive and lags at least two years behind Displaytech. As a counterfactual exercise, it is difficult to know whether an ATP award would have further accelerated Uniax's learning curve to commercialization or whether Uniax would have been able to attract additional equity earlier or in greater volumes.

PATENT CITATION ANALYSIS

Counterfactual problems notwithstanding, a similar time lag between the two cases arises when we turn to patent citations. As shown in Figures 20 and 21, the timing of Uniax patents and patent citations follows a remarkably parallel course to Displaytech's, with about a two-year delay. The graphs show cumulative patent counts (by patent issue date) and patent citation counts (by filing date) over time. The rate of Displaytech patenting picks up significantly around the time of the 1994 $1.75 million ATP award, and Uniax patenting accelerates around the time of the 1996 $3 million equity investments by Hoechst and Philips. Because of the delay between patent filing and issue, in both cases it appears that the investments followed successful early technological progress.

Turning to the timing of the citations to each firm's patents, a similar two-year lag appears, as does the pattern of investment following technical progress. With striking similarity in both cases, the rate of citation picks up well in advance of the cash infusions. The technologies of both firms began attracting notice as revealed through citation by others, which indicates a growing interest in their commercial potential. The revealed technical success and increasing notoriety precedes (and it seems reasonable to assume is causally

FIGURE 20.

Timing of Displaytech and Uniax Patents

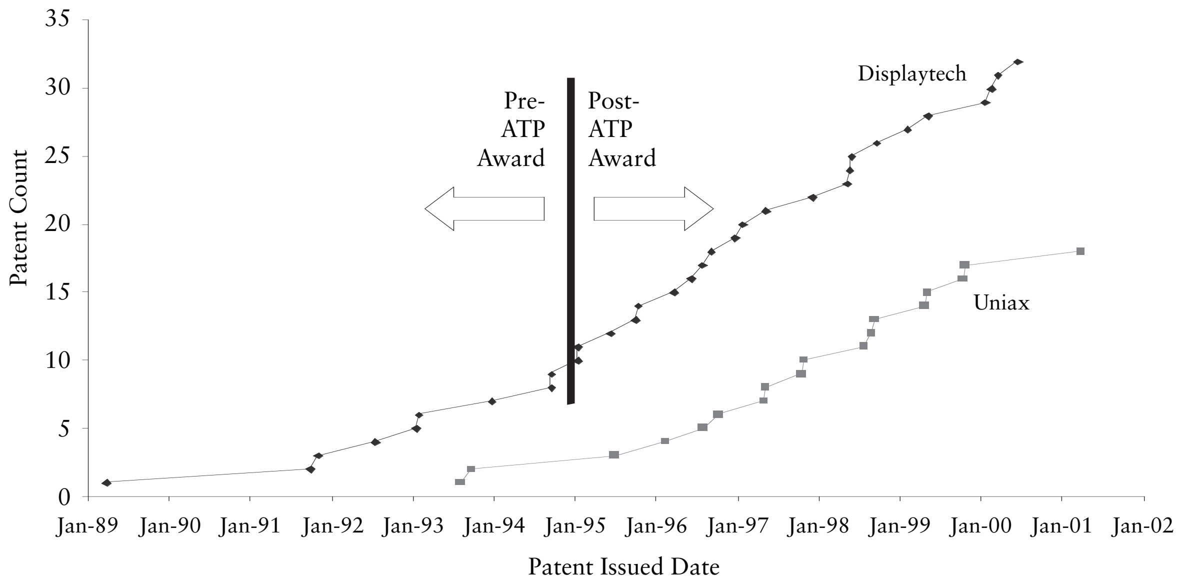
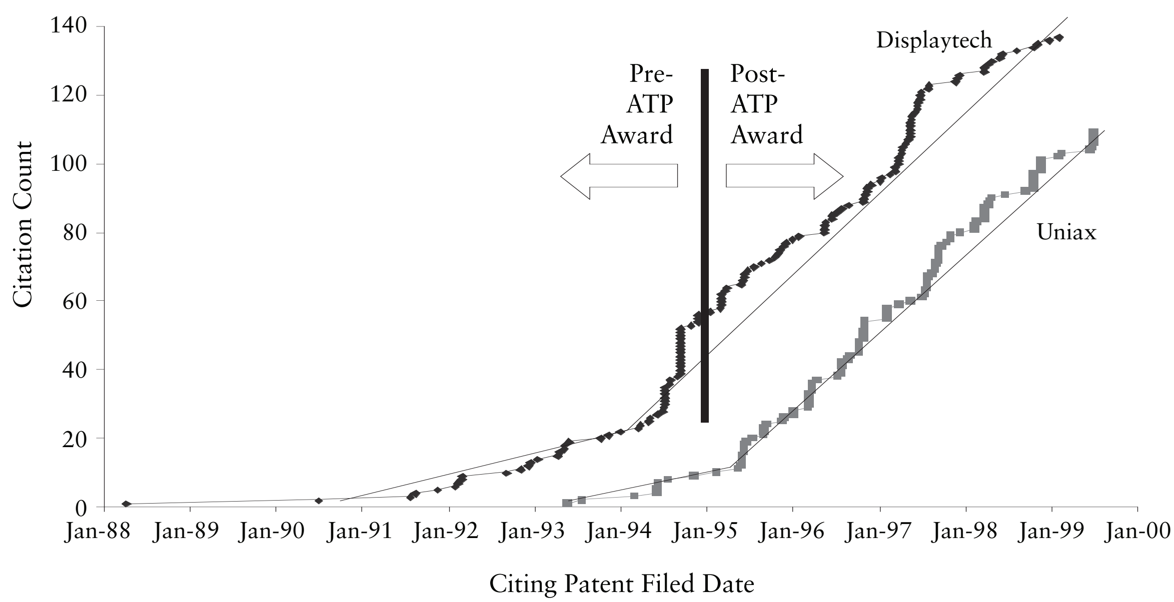


FIGURE 21.

Timing of Citations to Displaytech and Uniax Patents



related to) the subsequent attraction of investment capital, which in turn accelerates the commercial development and economic return to the technology. Indeed, the rate of citations might be a useful and readily obtainable a priori metric for evaluating applications for future ATP grants, as not only an indication of the spillover potential from the scientific importance of the work, but also as a proxy for the potential for attracting required capital.

Moving on to evidence about the diffusion of information from Uniax patents, we find a somewhat different picture than when looking at Displaytech. We identified 18 patents issued through 2001 assigned to Uniax, which attracted 110 citations from 38 different organizations or groups. The top-citing organizations appear in Table 11. To track the potential value creation in the United States from the diffusion of the Uniax technologies, we contacted and interviewed the principals at the top four U.S.-based groups: Thermo-Chem, IBM, Monsanto, and Eveready. The other top five citing group was the Finnish firm Neste (now Panipol), the early Uniax investor and licensee.

Figure 22 shows the citing patents categorized by the main industry of the research group involved and the home country of that group or organization. Compared with the Displaytech patent citations (see Figures 11 and 12), the citations to Uniax are slightly more concentrated in the United States (77 percent versus 65 percent), but significantly more diverse in terms of applications outside of displays and imaging (69 percent versus 38 percent). Both the greater U.S. focus and industry breadth would indicate higher spillover value potential for the United States from Uniax than from Displaytech. This industry diversity is driven by chemical and materials companies such as Monsanto, Dow Chemical, and early Uniax investor Neste/Panipol, all of whom are interested as potential suppliers across a broad range of applications of the attractive characteristics of ICPs. Another top-citing industry, batteries, at first blush may seem a surprise, but it turns out that the charge storage capacity of conductive polymers might eventually make cost-effective, more environmentally friendly replacements for battery materials. More immediately, Eveready was working on using conductive plastics and flexible printed plastic electronic circuits in battery charge-remaining indicator labels. The other significant citing industry is in electronic components, where conductive plastic coatings have advantages for thermal sensing switches, for anticorrosion applications, and for antistatic shielding and discharge. Clearly, the range of possible applications of Uniax's technology is broader than Displaytech's.

Social collaborative ties appear similarly important as a diffusion mechanism among the Uniax patents as in the Displaytech case. This appears in Figure 23, which charts the collaborative links as well as the fraction of citations by each of the top groups and their geographic distribution. Compared to Displaytech (see Figure 12), a lower fraction of citing organizations has known collaborative ties to Uniax (19 percent compared to 28 percent). Among those collaborative ties, Uniax's are more international than Displaytech's. Nevertheless, the overall U.S. concentration of patent citations is higher (77 percent compared to 65 percent), and the Japanese fraction is far lower (6 percent compared to 21 percent). In part, this reflects the competitive strengths of U.S. firms in plastics-related materials and chemicals compared with Japanese strengths in LCDs. We address this competitive strength again below when discussing the publication citations.

Table 11. Organizations and Groups Most Frequently Citing Uniax Patents

Citing Organization or Group	Location	Citations
Therm-O-Disc	U.S.-Ohio	16
IBM *	U.S.-Metro NYC & Silicon Valley	14
Neste (now Panipol) +	Finland	9
Monsanto	U.S.-St. Louis	8
Eveready Battery	U.S.-Ohio	6
Eastman Kodak *	U.S.-Rochester NY	4
Dow Chemical	U.S.-Michigan	4
Heeger et al. +	U.S.-Southern CA	4
Cambridge Display Technology + *	U.K.	3
Kemet Electronics	U.S.-South Carolina	3
Lynntech	U.S.-Texas	3
P. Kinlen et al. (had been at Monsanto)	U.S.-St. Louis	3
Philips + *	Netherlands	3

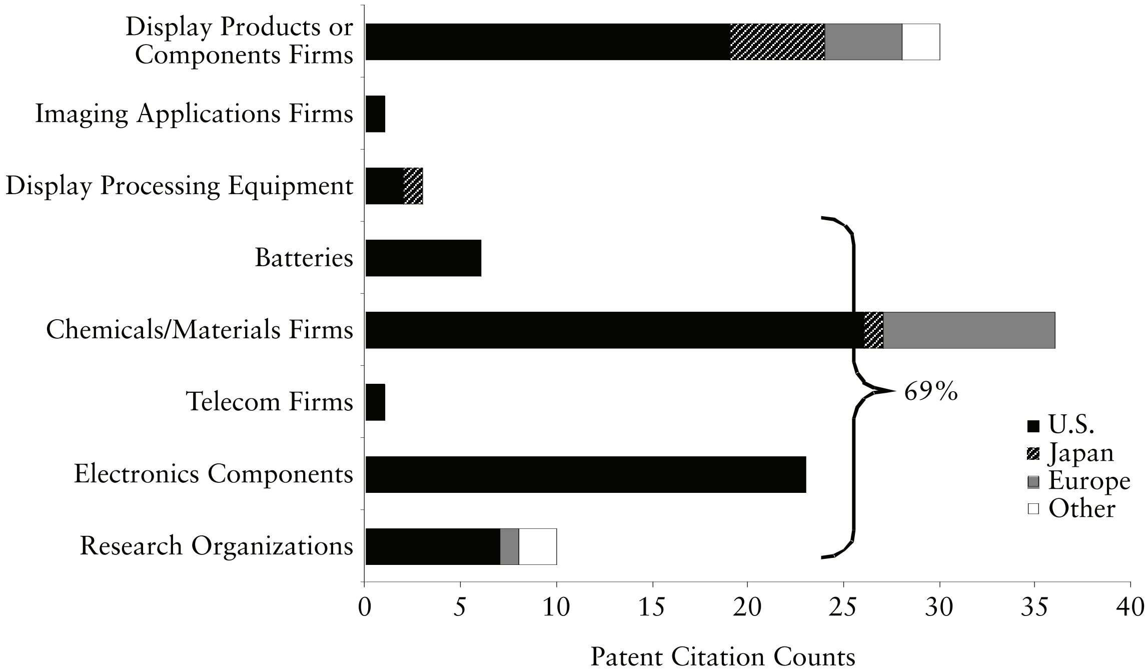
Notes: + known cooperative links to Uniax; * competing in display markets

The top single citing organization, Therm-O-Disc, Inc., of Mansfield, Ohio, a subsidiary of Emerson Electric Co., is a major supplier of temperature sensors, temperature controls, and temperature-sensitive electrical switches. A principal application of billions of their temperature switches is in protective cutoff switches that protect against appliance motors and circuits overheating. Their main products use strips made from two different metals with different thermal expansion rates bonded together. They mechanically switch on and off in response to temperature changes. For solid-state electrical applications (rather than mechanical) their research group developed techniques for using conductive polymer materials as resistors that increase their resistance with temperature (called positive temperature coefficient—PTC) and can withstand high temperature and high voltage environments. Therm-O-Disc sells these polymer-based PTC circuit protectors in large quantities for high temperature electronic circuits in automobile motors.

Specifically, Thermo-O-Disc patents related to high temperature and high voltage PTCs cite various Uniax patents related to processing technologies for ICPs. Liren Zhao, whose name appears on all the Uniax-citing patents, led the research group. Zhao has since left the firm, and, despite repeated attempts, we unfortunately were unable to find him for first hand verification. But our conversations with current Thermo-O-Disc technical personnel who worked with him indicate that Thermo-O-Disc processing technologies have not changed significantly over the past five years and that most of their effort has concentrated on chemical formulation improvements. They were unaware of any relationship to the Uniax patents. There may have been learning value here, but not apparently embodied in corporate learning or large enough to attract the notice of technical colleagues. If the spillover value were large and economically of high value, we would expect some echo would remain after the original researcher left.

FIGURE 22.

Patents Citing Uniax by Industry and Country

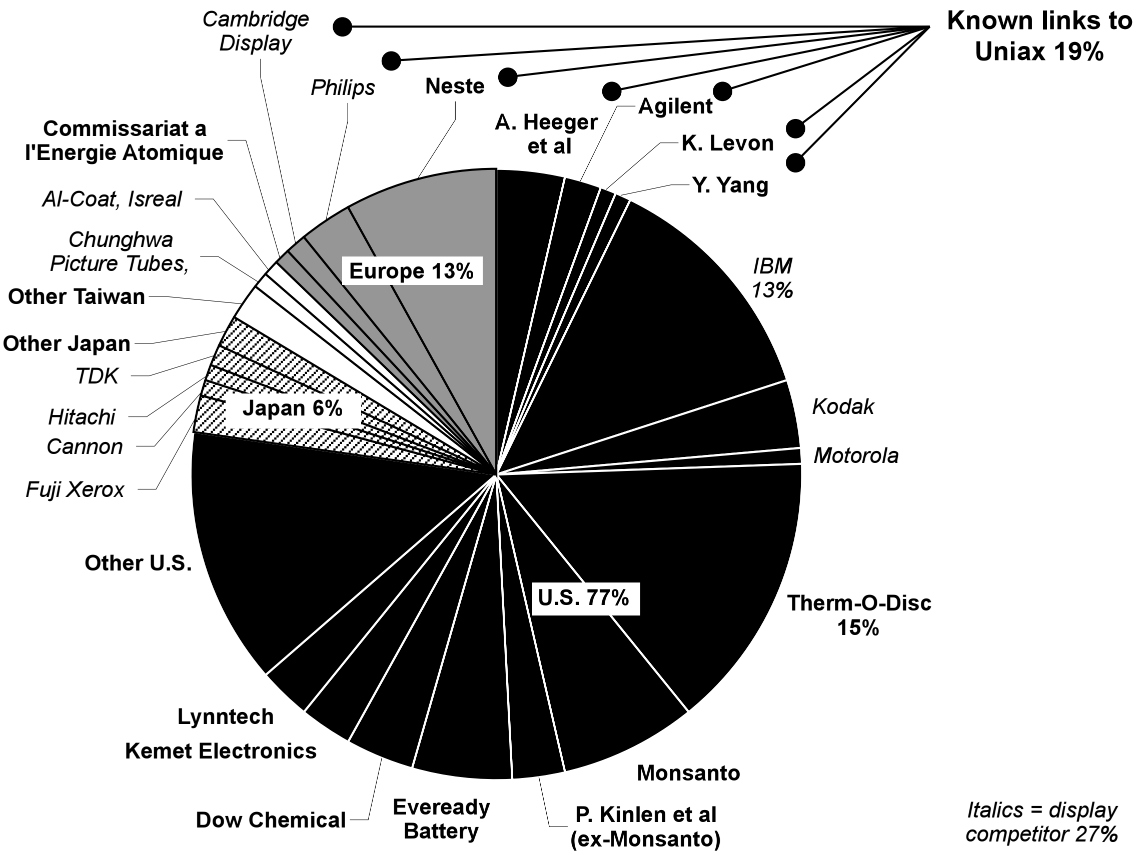


The second organization frequently citing Uniax patents was IBM, where three different research groups were patenting in three different areas: water-soluble conductive polymers; conductive lubricants for magnetic disc drives; and plastic thin film transistors. However, 11 of IBM's 14 citations came from the water-soluble conductive polymer team at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York, near New York City. We contacted this group. IBM is also at the top of the corporate list for citing Uniax publications, as shown below.

The spillover story from the IBM patent citations is mixed. The measurable direct economic impact on IBM was, according to the interviewees, negligible. Their citations in both their water-soluble conductive polymer patents and their related publications were an acknowledgement that alternative approaches to soluble conducting polymer technologies existed. However, because IBM was investigating a different approach, in technology diffusion terms, the researchers claim there was no real direct influence on the trajectory, pace, or insight of the IBM research work. IBM has, in fact, recently commercially licensed a water-soluble conducting polymer technology, but one not at all based on the Uniax work. Any economic spillover impact here would be through market competitive price and quantity

FIGURE 23.

Patent Citations to Uniax Patents



effects rather than through knowledge spillovers. On the other hand, they acknowledge that Uniax's soluble polymer technology work had significant enabling impact on the broad field: "It was very valid work. It enabled a lot in the field." These comments are consistent with the breadth and enormous number of citations to Uniax publications that we discuss below (e.g., a Uniax article is the second most highly cited article in the world in the whole field of conducting polymers, second only to a Heeger article, which he wrote as a UCSB faculty member)[44] and with Heeger's Nobel Prize.

The third most frequent citing U.S.-based organization was Monsanto, where researchers were studying corrosion resistant paints and investigating improving various performance

44. See the *Conducting Polymers Top 25 Papers* special topics page at ISI Essential Science Indicators, www.esi-topics.com/conducting-polymers/papers/a1.html.

characteristics of conducting polymers. In addition to the eight Monsanto citations, as Table 11 shows, three more citations were from Patrick Kinlen, listed on three patents without organizational affiliation, but who, as the research team leader, was also the single most active citer of Uniax among the Monsanto scientists. He has since moved to a small startup business in conducting polymers, Crosslink Polymer Research, a 25-employee firm in Fenton, Missouri, with a host of Department of Defense and aerospace contracts.

In our discussions with Crosslink, they indicated—like IBM—that the Uniax technology has not influenced Crosslink at all, and, although Kinlen was no longer at Monsanto, they did not believe it had much, if any, impact at Monsanto either. Like IBM, the citations were acknowledgement, early in the cycle of developing commercial viability, of an alternative approach to soluble conductive polymers. In filing patents, we were told, "you have to cite things, otherwise the examiners will question you." In the mid-1990s, there was a limited circle of groups working on problems of commercially efficient processing, so cross-citations were natural, we were told. However, the groups tended to pursue different avenues and operate "in silos," they said, where they "did not learn a lot" from each other. Occasionally, they would get competitive intelligence from a consulting report, from McKinsey or a similar organization, or from internal patent monitoring, that other firms had new patents or related research activities; but because the Monsanto and Crosslink approaches were different than the Uniax effort the direct influence was reported to us as minimal.

So again, any economic spillover would come through competitive price and quantity effects in the commercial markets, rather than through technology transfer. Moreover, since the conductive polymers outside of displays remain largely precommercialized, and neither Monsanto nor Crosslink are directly in display markets, those price and quantity effects remain largely in the future and speculative. Patent citations, though accurately identifying active R&D competition, once more appear, at best, a noisy indicator of knowledge spillover.

The fourth most frequent U.S.-based organization citing Uniax was Eveready Battery. The six citations, on six patents between 1997 and 2001, all relate to various approaches of using conductive polymers in battery charge-remaining indicators. Since Eveready and Uniax are in entirely different markets, any value creation here would be through knowledge spillovers. However, so far, implementation remains speculative. Eveready and competitor Duracell each introduced their first on-label battery charge indicators nearly simultaneously in 1995, based on heat-sensitive color-changing chemicals (thermochromic). Each company licensed independently patented, but similar, technologies and immediately got into patent and licensing disputes.[45] The Uniax citations by Eveready were in later patents related to research into potential future alternatives to those first-generation indicators, including both electrochromic (rather than thermochromic) polymers and liquid crystals. The melt- or solution-processible polymers that Uniax pioneered were, according to the researchers at Eveready, among the options for electrode layers in these alternative charge indicators.

45. Fox (1996).

In summary, together with Uniax early investor and collaborator Neste/Panipol, patents from Therm-O-Disc, IBM, Monsanto (plus the related citations attributed to Crosslink principals), and Eveready counted for more than half (56 of 110) of the total citations to Uniax patents. Nonetheless, as in the Displaytech case, our interviews again found little evidence among these main citing groups of significant economic value through the spillover of technical information. In contrast with the Gemfire citations in the Displaytech case, these citing scientists were uniformly aware of the Uniax research, though in some cases not the details. As indicators, these patent citations were slightly more useful in tracking diffusion of Uniax technology than for Displaytech. However the citations were not really indicators of strong idea flows, but rather acknowledgements of alternative approaches and prior art in the patent literature. None of these top-citing organizations, except collaborating partner Neste/Panipol, had directly used or were yet commercially pursuing Uniax-influenced technologies. Under licence from Uniax/DuPont, Neste's spinoff company Panipol is selling related polymer technologies. The economic value created from that licencing is directly within-market, and presumably was already accounted for above as part of the price DuPont paid to acquire Uniax. Moreover, Neste was half owner of Uniax in the early to mid-1990s period in which their Uniax citations occurred. A significant question arises here, then, of how to classify the boundaries of the firm in studying technology diffusion: is it technology diffusion when the flow is to an owner?

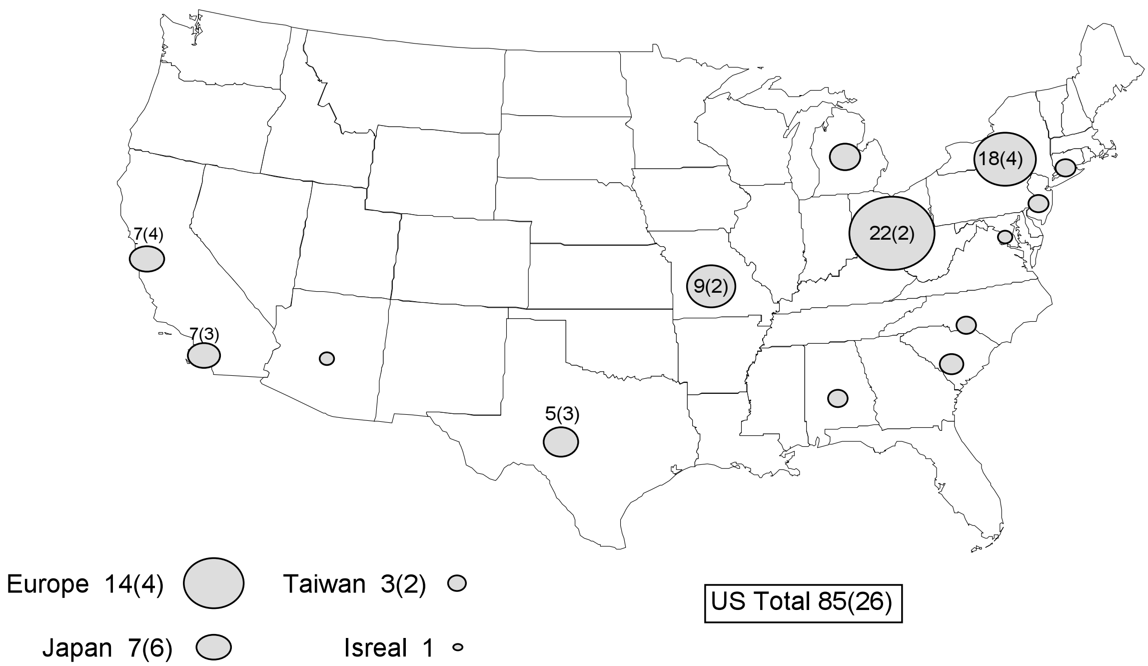
That said, even if we classify Neste as external diffusion, we again conclude that patent citations are at best, quite a noisy proxy for technology diffusion because there was essentially no substantive flow to any of the other top-citing organizations, except Eveready, where there was not yet measurable value because research remained exploratory. In the other cases, the citations simply helped identify research teams pursuing neighboring technical domains, but not those directly learning or deriving benefit.

HIGH-PROFILE SCIENTISTS AS TECHNOLOGY DIFFUSION NODES

In the Displaytech case, to explore technology diffusion mechanisms we also investigated technology flows through geographically and technologically clustered social ties. We repeated this analysis for Uniax. Figure 24 is a schematic of the geographic clustering by region or nation of the patent assignee. Ohio had the highest number of citations, 22 between two different firms (Therm-O-Disc and Eveready), followed by New York, with 18 among four groups (IBM, Kodak, AlliedSignal, and one unaffiliated). IBM labs are near New York City and Kodak is in western New York in Rochester. In first-blush contrast to Displaytech's diffusion nexus through the University of Colorado, these Uniax-citing organizations were generally unrelated organizations in very different industries and the geographic clustering apparently coincidental. What is not coincidental, however, is these Uniax-citing researchers were nearly all clustered around the general technical area of conductive polymers, an entire field stimulated by Uniax founder and Nobel laureate Heeger's work, and several citing groups had collaborative ties to him. So, although the citations are geographically more diffuse than Displaytech's, they still were clustering technologically and socially around Heeger, who played a role very similar to Displaytech founder and ferroelectric liquid crystal pioneer Clark. The high-profile scientist provided the

FIGURE 24.

Geographic Distribution of Citations to Uniax Patents



Note: values indicate number of citations (number of citing organizations).

central node and stimulus for the communication network. This is consistent with Lynne Zucker and Michael Darby's (1995, 1999) work on the importance of star researchers and collaboration on knowledge flows.

To analyze further this pattern of social and technological closeness driving patent citations, we ran an OLS regression using the time lag to citation to Uniax patents. The regression approach was identical to that used in the Displaytech case, and the results remarkably consistent. Using lag days as the dependent variable, we explored whether there is statistical evidence that organizations that were closer socially (measured by a collaborative ties dummy variable), technically (by industry dummies), or geographically were faster to cite Uniax patents than others. Our base-case group was university and other research organizations. We also included a dummy variable for large firms and controlled for patent issue date. Table 12 shows the regression results of this modeling on the 110 citations to Uniax patents.

Firms with collaborative social ties to Uniax are, on average, 290 days faster to citation than others, controlling for other variables in the model. For Displaytech, the collaborative advantage was surprisingly similar: 250 days. Here, too, industry sector matters, and again chemical/materials firms are generally much faster to citation, by 444 days for Uniax compared with 639 days for Displaytech. Also similar, imaging applications firms are also

TABLE 12.

OLS Regression Results on Time Lag to Citation of Uniax Patents

Dependent Variable: Lag Days	Coefficient	Std. Err	p>|t|			
Patent Date in Days	-0.709	0.063	0.000	***	n	110
Links to Uniax Dummy	-289.7	135.8	0.035	**	F(8, 101)	22.11
Large Firm Dummy	189.3	116.9	0.109		Prob > F	0.000
U.S. Dummy	44.4	118.3	0.708		R2	0.6366
Imaging Applications Firm	-500.8	239.7	0.039	**	Adj R2	0.6078
Telecom/Electronics	42.6	188.2	0.821		Root MSE	437.9
Chemicals/Materials	-443.7	165.0	0.008	***		
Display Competitor	-334.1	182.2	0.070	*		
Constant	9911.1	835.3	0.000	***		

Two-Tailed Significance Levels: *p<0.10, **p<0.05, ***p<0.01.

quick to cite, beating the base-case research organizations by 500 days for Uniax citations and nearly 400 days for Displaytech. And again, telecommunications and electronics firms are not different from the base case. The parallel findings continue: without controls, U.S. firms, on average, cite more slowly than international firms by 725 days to 419 (p=0.054), but, just like in the Displaytech case, that geography-related difference disappears once we add the control variables. Direct competitors in the display industry are nearly a year quicker to cite Uniax.

We conclude from the citation mapping and regression analyses in these two cases that social ties, technological proximity, and industry sector practices are more important mechanisms than geography in explaining both Uniax and Displaytech patent-related technology flows. That said, our interviews lead us to believe, in both cases, that the flows suggested by the patent citation data are weak beyond the direct commercial market relationships.

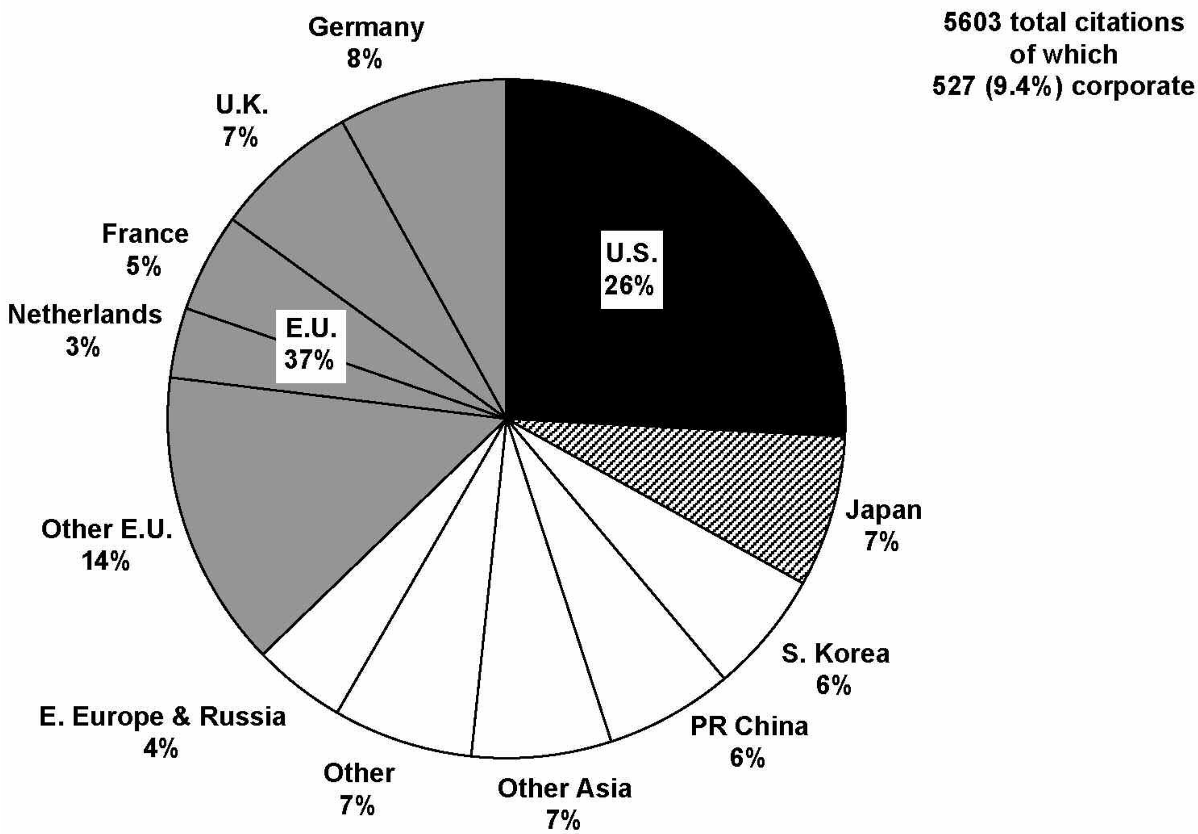
PUBLICATION CITATION ANALYSIS

Moving on to citations of Uniax publications, in purely scientific terms, the Uniax work has had substantially more impact than has Displaytech's. We identified 172 publications listing Uniax among the authors' affiliations (2.3 times as many as Displaytech), which attracted a remarkable total of 5,603 citations in 3,254 citing articles from 5,193 individuals at 1,071 organizations, excluding self-citations. This is seven times the number of citations that Displaytech enjoyed, and a citation rate of nearly 33 citations per paper, compared to 12 for Displaytech. By this metric then, knowledge spillover potential from nonawardee Uniax is significantly higher than from the ATP awardee.

We show the distribution of those citations by the geographic location of the authors in Figure 25. Like Displaytech, the distribution is much less U.S.-centric than for patents, with only 26 percent of citations to Uniax publications coming from the United States, compared

FIGURE 25.

Citations to Uniax Publications by Country

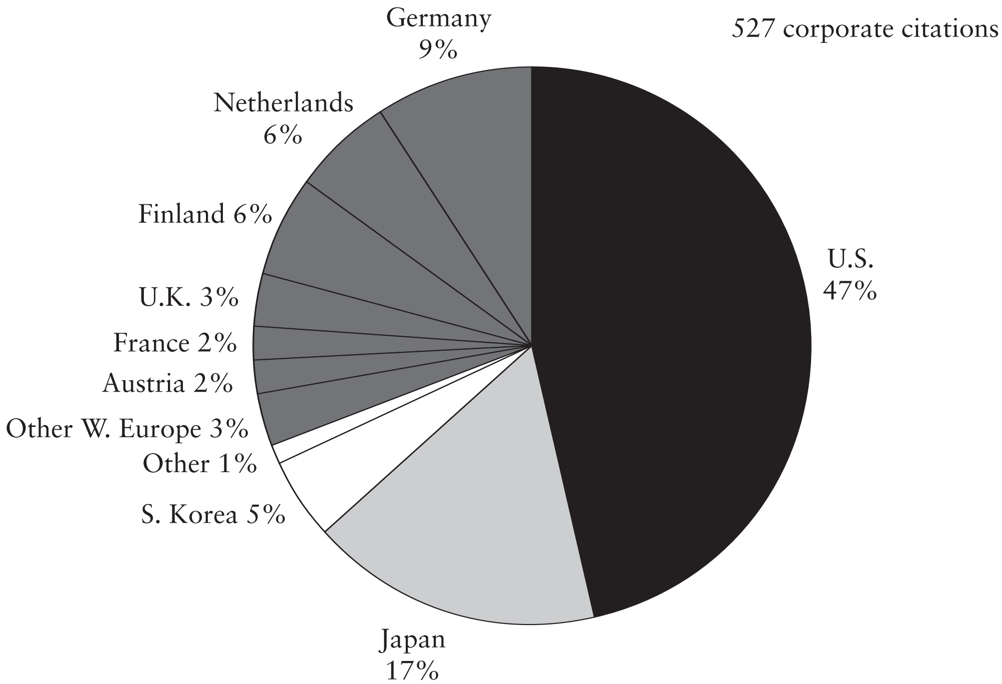


to 77 percent of patent citations. This indicates that, to a degree even higher than for the similar pattern for Displaytech, Uniax's international impact and value creation outside the United States would be substantially greater than patent citations would suggest. Indeed, Western European researchers nearly triple their share of publication citations (37 percent) compared to patents (13 percent), and the rest of the world besides Japan grows to 30 percent of publication citations from 4 percent for patents. In contrast to the strong Japanese presence in citing Displaytech patents (21 percent), here Japan represents a limited share in citing both publications (7 percent) and patents (6 percent). The relative strength of Europe in publication citations to Uniax conducting polymer research reflects a strong competitive position in chemistry and materials science among both European industry and universities. In 2002, for example, European firms accounted for an estimated 48.3 percent of world chemical market revenues, compared to 32.5 for the United States and only 12.6 for Japan.[46] For Displaytech, the industry advantage favored Japan in liquid crystals patenting, while, in both cases, publications from Japan fall short, particularly in comparison to industry market

46. *Chemical Engineering News* 82(29), 11–13, July 19, 2004.

FIGURE 26.

Corporate Citations to Uniax Publications by Corporate Location



shares, presumably because of the combination of language and a more limited forefront research tradition.

Table 13 lists the 25 top-citing organizations and individuals. Seventeen of the top 25 organizations, including all of the top nine, are groups with known social collaborative coauthoring ties, an even higher fraction than the 11 of 25 for Displaytech. Heeger alone has coauthored papers with more than 100 people. This reinforces our conclusions above about the critical role social collaborative ties associated with high-profile scientists appear to play in diffusion.

Like with Displaytech, the vast majority of the organizations citing Uniax work are universities or similar research institutes, with only two firms among the top 25 citing organizations, IBM and Bell Labs. Focusing on organizations where the economic value creation would be more likely than with academic institutions, we identified those citations that were from authors associated with corporations. A total of 527 (9.4 percent) of the 5,603 papers citing Uniax came from corporate-affiliated authors. This is about fivefold more than the corporate citation rate for Displaytech, again a metric indicating significantly greater knowledge spillover potential from nonawardee Uniax than from ATP awardee Displaytech. Figure 26 shows the geographic distribution of those corporate citations. Compared to overall citations, the U.S. share of corporate citations rises to 47 percent from

TABLE 13.

Top Organizations and Individuals Citing Uniax Publications

Top 25 Organizations Citing Uniax Publications

Cites	Citing Organization	Collab	Location	Industry
192	U Cal Santa Barbara	Yes	U.S.-CA	Research Org
144	U Cambridge	Yes	U.K.	Research Org
99	Linkoping U	Yes	Sweden	Research Org
91	Chinese Academy of Sci	Yes	China	Research Org
89	Max Plank Institute for Polymer Research Mainz	Yes	Germany	Research Org
78	U Groningen	Yes	Netherlands	Research Org
75	National U Singapore	Yes	Singapore	Research Org
72	Korea Advanced Institute of Science & Technology	Yes	S. Korea	Research Org
69	U Mons	Yes	Belgium	Research Org
67	Osaka U		Japan	Research Org
59	Technical U Graz	Yes	Austria	Research Org
59	U Rochester		U.S.-NY	Research Org
58	Ohio State U		U.S.-OH	Research Org
56	U Durham		U.K.	Research Org
53	U Penn	Yes	U.S.-PA	Research Org
48	IBM		U.S.-NY & CA	Displays
46	Los Alamos National Lab	Yes	U.S.-NM	Research Org
45	U Sheffield		U.K.	Research Org
43	Bell Labs (AT&T/Lucent)	Yes	U.S.-NJ	Displays
43	MIT	Yes	U.S.-MA	Research Org
40	Chalmers U Technology	Yes	Sweden	Research Org
40	Princeton U		U.S.-NJ	Research Org
39	UCLA	Yes	U.S.-CA	Research Org
38	CNRS	Yes	France	Research Org
38	U Marburg		Germany	Research Org

continued

26 percent, the Japanese share rises to 17 percent from 7 percent, and the Western European share falls slightly from 37 percent to 31 percent. In the Displaytech liquid crystal case, the Japanese share jumped and the European share fell far more dramatically when focusing only on corporate patents.

As Figure 27 shows, the result is that the distribution of citations roughly correlates with world market shares in chemicals and plastics, with some bias in favor of U.S. authors. Clearly, corporations already strong in related fields are more likely to support related research, and the authors in turn are much more likely to absorb and to cite technical information. The scatter also shows that U.S. patent citations deviate significantly more

TABLE 13.

Continued

Top 25 Individual Authors Citing Uniax Publications

Cites	Name	Affiliation	Location
194	Heeger, A.J.	Uniax & U Cal Santa Barbara	U.S.-CA
123	Friend, R.H.	CDT & U Cambridge	U.K.
87	Bredas, J.L.	U Mons	Belgium
77	Holmes. A.B.	U Cambridge	U.K.
69	Cao, Y.	Uniax & U Cal Santa Barbara	U.S.-CA
58	Leising, G.	Technical U Graz	Austria
56	Epstein, A.J.	Ohio State U	U.S. OH
55	Bradley, D.D.C	U Cambridge & U Sheffield	U.K.
50	Inganas, O.	Linkoping U	Sweden
49	MacDiarmid, A.G.	U Pennsylvania	U.S.-PA
49	Sariciftci, N.S.	U Cal Santa Barbara	U.S.-CA
48	Salaneck, W.R.	Linkoping U	Sweden
47	Scherf, U.	Max Plank Institute for Polymer Research Mainz	Germany
47	Yu, G.	Uniax & U Cal Santa Barbara	U.S.-CA
44	Moratti, S.C.	U Cambridge	UK
44	Yoshino, K.	Osaka U	Japan
43	Cacialli, F.	U Cambridge	U.K.
40	Mullen, K.	Max Plank Institute for Polymer Research Mainz	Germany
38	Andersson, M.R.	Chalmers U Technology	Sweden
38	Yang, Y.	Uniax	U.S.-CA
37	Moses, D.	U Cal Santa Barbara	U.S.-CA
36	Pron, A.	Technical U Warsaw	Poland
35	Huang, W.	National U Singapore	Singapore
35	Hummelen, J.C.	U Groningen	Netherlands
35	Hwang, D.H.	Korea Advanced Institute of Science & Technology	S. Korea

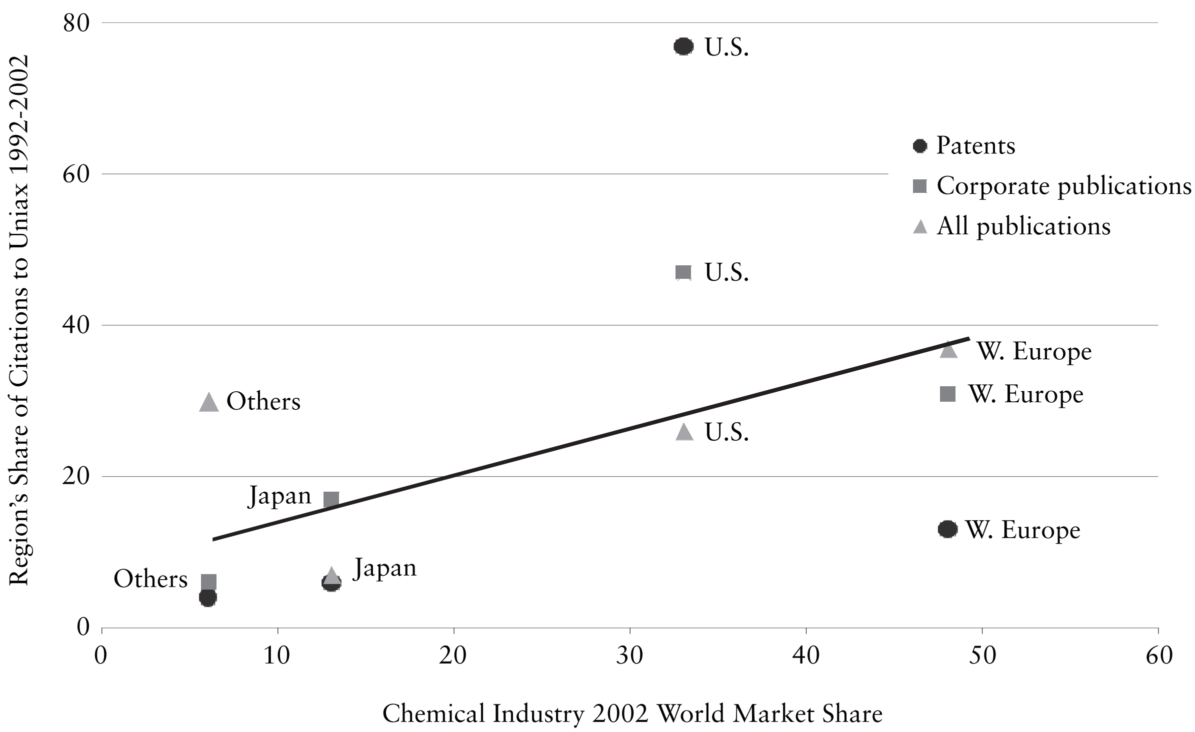
Source: Authors' analysis based on data from Thomson Scientific's ISI Institutional Citation Report database.

from this pattern than do publication citations, again suggesting patents are noisier indicators of knowledge spillovers.

To the extent that publications, then, are indicators of the diffusion of technical information, this pattern suggests a metric indicating the potential to capture value from spillover from federal technology funding. It appears—from the Uniax and Displaytech cases at least—that the spillover potential for the United States from technology funding is higher in those industries where the United States has relative strengths in strongly complementary areas. This illustrates a significant tension between, on one hand, those policies aimed at improving competitiveness in industries where the United States is relatively weak, but where the resulting spillover values might be lower, and, on the other hand, those policies where the

FIGURE 27.

Citations to Uniax Patents and Publications by Chemical Industry Market Share

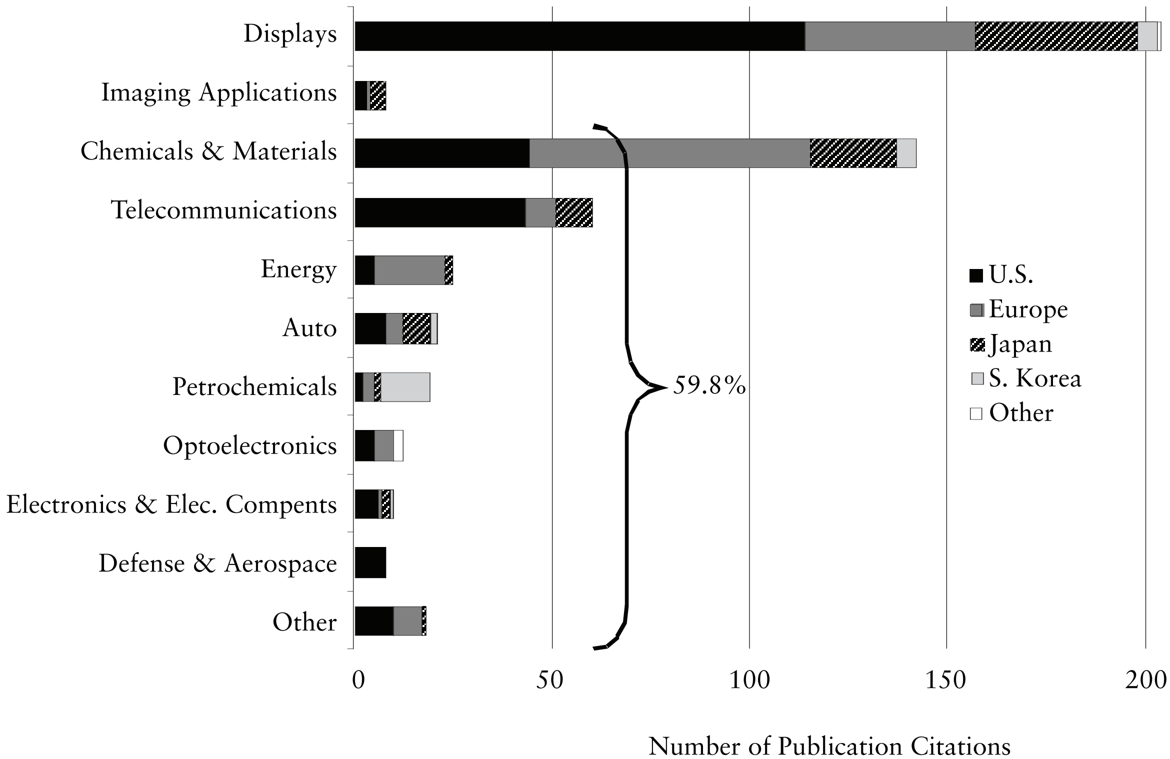


goal is to maximize public good technology diffusion and spillovers in the United States, which would target those where complementary technologies are relatively strong.

Figure 28 breaks down the corporate citations to Uniax publications by industry sector and location of the citing group, and Table 14 lists the top 20 most active citing firms. About 40 percent of the citations are from display or related imaging applications firms that would be potential direct market competitors or customers of Uniax. This share from within-market is somewhat higher than the 31 percent for Uniax patents. U.S. firms account for the majority of these within-market corporate citations, driven by the display interests and research prowess of IBM, Bell Labs, Kodak, and Xerox. Another 27 percent are in chemical and materials firms, similar to that sector's 29 percent for Uniax patent citations. Specifically, most of the top-citing chemicals and materials firms are actively pursuing variations on light emissive polymers.

FIGURE 28.

Corporate Citations to Uniax Publications by Industry and Location



The most substantial difference between the publication and patent citations is in the electronics components sector, which has few citations to publications, but represents 21 percent of patent citations. This is explained largely by the high patent citation count from Therm-O-Disc, a firm which is entirely absent from citing Uniax publications and where we were unable to find evidence of economic spillover value. Yet again, we see this as a signal that the patent citations are a noisier indicator of technology flows. Compare this to IBM, which was the highest citing organization on both lists, and whose scientists indicated to us that they were following, although not directly learning from, the developments at Uniax and citing them willingly because of the interesting alternative approach. For IBM, either patents or publications would indicate the same flow, albeit weak, of technical information. In contrast, for top-citing Therm-O-Disc in the Uniax case and Gemfire in the Displaytech case (where we know directly from interviews that there were patent-examiner-induced false signals), neither firm showed up in the publication citations at all, suggesting publication citations were a cleaner metric of the flows, however weak.

TABLE 14.

Top 20 Corporations Citing Uniax Publications

Citations	Company	Collab	Location	Industry
48	IBM		U.S.-Metro NYC & Silicon Valley	Displays
43	Bell Labs (AT&T/Lucent)	Yes	U.S.-Metro NYC	Displays (via e-ink)
30	Xerox		U.S.-Rochester, NY	Displays
26	Philips	Yes	Netherlands	Displays
25	Neste (now Panipol)	Yes	Finland	Light-emitting polymers
19	Dow Chemical		Michigan	Light-emitting polymers
16	Eastman Kodak		U.S.-Rochester, NY	Displays
16	Samsung		S. Korea	Displays
12	Korea Kumho Petrochemical		S. Korea	Conducting polymers
11	Hewlett-Packard		U.S.-Silicon Valley	Displays
9	Cambridge Display Technology	Yes	U.K.	Displays
9	Quantum Solar Energy Linz		Austria	Photovoltaics
8	Covion Organic Semiconductors	Yes	Germany	Light-emitting polymers
8	General Motors		U.S.-Michigan	Automobiles
8	Hoechst	Yes	Germany	Light-emitting polymers
8	Sumitomo Chemical	Yes	Japan	Displays
7	NTT		Japan	Telecommunications
6	Bayer		Germany	Light-emitting polymers
6	Toyota		Japan	Automobiles
6	Zipperling Kessler & Co.		Germany	Conducting polymers

4. Findings and Observations

FINDINGS AND IMPLICATIONS

We summarize this paired-comparison case study by reviewing how it illuminates the main questions relating to ATP and evaluation methodology that were posed in Chapter 1. We finish by exploring several more general observations about technology policy design.

We first address the seven specific questions that motivated our case analysis:

1. Has ATP advanced scientific and technological knowledge?

Unquestionably, Displaytech's work has advanced scientific and technological knowledge in microdisplays. Displaytech has also advanced their technology to commercial production, to the benefit of consumers. Patent citation patterns for the comparison case Uniax, without ATP support, lagged roughly by one to two years. So, indeed, ATP support accelerated technology development for Displaytech.

2. Has ATP increased the economic and competitive performance of U.S. companies?

With regard to Displaytech, ATP increased U.S. economic and competitive performance in the microdisplay market. In particular, Displaytech may not have been able to survive the technology downturn in 2000–2002 without the ATP-related R&D acceleration and funding support. Specifically, the R&D project focus on manufacturing processes boosted competitive performance by reducing time-to-commercialization. By comparison, through 2004, nonawardee Uniax/DuPont had yet to fully commercialize a cost-effective process, in part because of limited progress in complementary manufacturing technologies.

A related observation is that Displaytech had repeated success over many years in winning federal grants and contracts from multiple programs, in part because of the dual-use nature of display and laser technologies. No single program or award can claim full responsibility for enabling Displaytech's success. But dollar for dollar, when compared to specific mission-or product-oriented contracts, the ATP support for Displaytech was the most commercially helpful because of its manufacturing focus (and the timing vis-à-vis the technology stock crash). The firm succeeded in part because it was successful at getting government grants, which provided cash flow that enabled it to bridge the gap between invention and commercialization and attract venture capital. Lewis Branscomb and Philip Auerswald have called this gap the investment "Darwinian Sea,"[47] and others refer to it as a "Valley of Death." This relates to another point for Displaytech: small, interim market niches other than the main target markets were important for maintaining life-sustaining cash flow.

3. Has ATP generated net benefits that spill over to the broader economy?

We estimate that the measurable net benefits from the ATP investment in Displaytech are on the rough order of \$5–7 million. This represents an attractive 30–35 percent annualized internal rate of return (IRR) to the nation on the \$1.75 million ATP funded investment and does not include any future options value that may accrue. Most of that value is evidenced in direct effects to Displaytech employees, and market spillovers effects to microdisplay consumers. We found limited measurable value in knowledge spillovers to the United States outside of the market, although the scientific interest was high, indicating that value may expand in the future.

One reason for this limited knowledge spillover from Displaytech ATP-related work may be because of the focus on manufacturing process improvements, which were more locally specialized and appropriable (and explicitly kept proprietary) than if Displaytech were in the business of selling process equipment. By comparison, Uniax had seven times the citations to its patents than did Displaytech. On the other hand, the focus on manufacturing problems was central to Displaytech's successful commercialization.

Commercializing the microdisplay technology was directly valuable to consumers and indirectly helped cut market prices and expand user options via competition with alternative approaches. Moreover, the high-speed potential of FLC may enable several larger untapped markets of significant future value. But the sheer size of those display markets has attracted fierce worldwide competition, billions of dollars in private investment, and many alternative technical approaches. This results in high economic price elasticities. In turn, high economic price elasticities limit market spillover value for any single technology, whether ATP-supported or not, in the competitive mix.

When combined with the uncertainties always associated with long-term research, this suggests the importance of a portfolio approach for policy design and evaluation, not picking any single technology, but pursuing several alternatives within any key sector. With multiple federal programs supporting a wide range of display technologies over many years, U.S. firms such as Texas Instruments, Displaytech, Kopin, Three-Five/Brillan, Kodak, DuPont, and others have begun to win back display markets, including a roughly 30 percent share in

47. Branscomb and Auerswald (2002), p. 36.

microdisplays. We cannot fully disentangle the ATP effect from other federal programs, but the portfolio as a whole has succeeded in advancing microdisplay technology. In this context, we also note that the time-to-commercialization (and thus to significant measurable market spillover value) was a decade, suggesting the need for patience in gauging success in ATP and similar programs with explicit spillover goals.

4. Does ATP succeed in identifying high spillover projects, relative to what would happen without ATP?

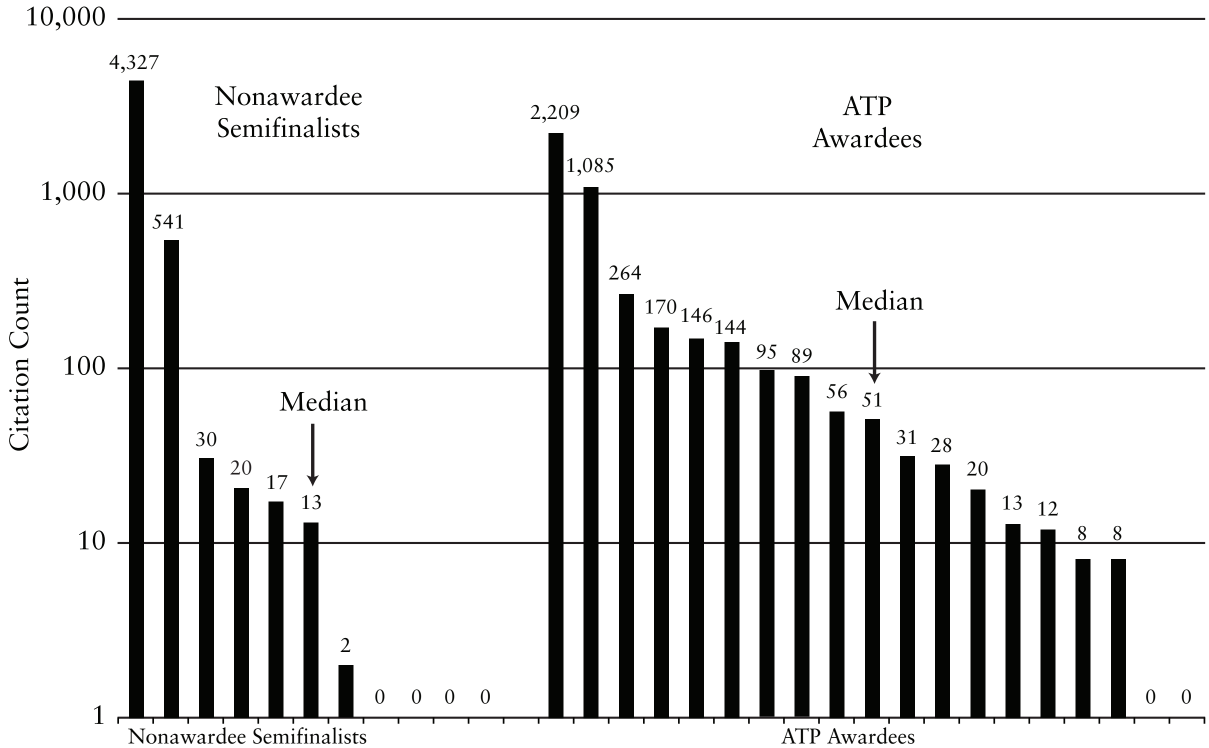
Our study yields mixed evidence on this question. With Displaytech, ATP identified a project with reasonably high payoff. Yet the payoff from nonawardee Uniax may have been similar in magnitude, if we use its acquisition value as a market measure of potential. Moreover, our snowball interviewing procedure turned up little evidence of substantial measurable value in knowledge spillovers from either Displaytech or Uniax. That said, beyond measurable economic value, the evidence suggests that Uniax has broader, although so-far unrealized, spillover potential. We noted that a Uniax article is the second most highly cited article in conducting polymers. Displaytech is not in the same league in terms of international recognition of the importance of their technical work. Similarly, but admittedly forward looking and speculative, Uniax strikes us as having a higher long-term enabling potential, given the radically new product categories that flexible displays could someday enable. But Uniax has not yet reached commercialization. In contrast, Displaytech has microdisplays on the market and that provide value.

One study finding, which we believe potentially useful in improving spillover methodologies, is that patents are a noisy indicator of spillovers and that publication citations are cleaner, at least in terms of whether they indicate true information flows. Neither approach identified economically measurable knowledge spillover value, but there were fewer false signals in the publication citations. Much of the noncase study empirical literature on technology diffusion and spillovers has relied on patents. We suggest trying similar methodologies applied to corporate publications.

To illustrate, we took one step in that direction, moving beyond our detailed case studies. Because our case-matching methodology required identifying more photonics-related nonawardee ATP semifinalists than those we studied in detail for comparison purposes, we were able to get some broader comparative citation data to illuminate the relative spillover question. Figure 29 compares the distributions of publication citation counts of all ATP awardees and nonawardee semifinalists in photonics as listed in the Science Citation Index available from ISI-Thomson Scientific. Similarly, Table 15 shows several statistical tests for differences in publication and citation rates between the two groups, both before and after ATP-application dates. The highly cited nonawardee semifinalist Uniax skews the nonawardee distribution, making comparison of means t-tests insignificant. However, statistical tests on equality of medians (chi-squared tests) and equality of distributions (Kolmogorov-Smirnov tests) indicate that, among this group of photonics firms, ATP awardees have statistically significant higher publication and citation rates than nonawardees. This is true both before and after the date of ATP application.

FIGURE 29.

Post-ATP Date Publication Citation Counts of ATP Awardees and Nonawardee Semifinalists



This suggests, and the regressions in Table 16 confirm, that publication citations and citation rates preceding the ATP application date correlate strongly to post-ATP citations, whereas ATP awardee status itself does not. Combining this with our case study finding that corporate publication citations are reasonably clean indicators of information flows, we conclude that, if knowledge spillovers are an important goal, prior publication citations by corporations might be a useful and readily available screening metric for spillover potential. We also note that both Uniax and Displaytech were not only highly cited, but also both able to attract regular streams of additional outside investment after the ATP award—the upticks in funding following upticks in citations. While more exploration of this idea would be necessary to verify the correlative hint here, publication citations might also, then, serve in the selection process as a rough quality proxy for the proposing firm's potential for attracting additional capital required for eventual commercialization.

TABLE 15.

Publication and Citation Rates of ATP Awardees and Nonawardee Semifinalists in Photonics

Metric	Nonawardee Semifinalists Mean	Nonawardee Semifinalists Median	ATP Awardees Mean	ATP Awardees Median	P-Value: Diff of Means (t-test)[a]	P-Value: Equality of Medians (chi^2 test)[b]	P-Value: Equality of Distributions (KS test)[c]
Total Papers	30.5	13	51.3	27	.42	.06*	.17
Total Citations	592.6	13	400.8	108	.67	.06*	.02**
Papers Pre-ATP Application Date	4.5	0	14.9	4	.29	.06*	.05**
Citations Pre-ATP Application Date	142.6	0	167.7	52	.86	.06*	.06*
Papers Post-ATP Application Date	26.1	7	36.4	18	.61	.11	.11
Citations Post-ATP Application Date	450.0	13	233.1	51	.52	.06*	.11
Citations Per Post-ATP Paper	3.81	1.25	3.75	2.64	.97	.06*	.14
Number of Firms	11		19				

Notes: *significant at .10, **significant at .05, ***significant at 0.01
a. difference of means t-tests (two-tailed)
b. non-parametric, two-sample, equality of medians chi^2 tests
c. equality of distributions Kolmogorov-Smirnov tests that ATP awardees distribution contains larger values

5. How might case study methodologies be improved to better account for both market spillovers and knowledge spillovers?

We hypothesized that both market and knowledge spillovers exist, so methodologies focusing on only one type of spillovers might underestimate the net social value of technology development projects. The evidence in these cases, for both the ATP-funded and the comparison cases, suggests that measurable economic value lies nearly exclusively in market value. Market spillovers very substantially dominate measurable knowledge spillovers. Knowledge spillovers through publications and patents exist, particularly for Uniax and to some extent for Displaytech, because people are clearly learning, but scientific value did not translate into measurable economic value in the cases studied here. Knowledge spillover recipients from Displaytech and Uniax acknowledged there was some value—they learned things—but uniformly reported no direct commercial value.

In the cases here, it appears that the translation into commercial products of bits of knowledge flowing through social networks and scientific publication involves so much deeper a set of activities, investments, and combinations of technologies that measurable knowledge spillover value from any narrow technology is below the noise thresholds of our methodology's ability to measure it. Most obviously, given how important conducting polymers are—based on Uniax citation counts—the knowledge spillovers should be high relative to large fractions of technical activities on the scale of ATP projects. If the knowledge

Table 16.

OLS Regression of Post-ATP Publication Citation Rates by ATP Awardees and Nonawardees in Photonics

	Model 1		Model 2		Model 3		Model 4		Model 5	
Citations Post-ATP Application Date	**Coef. Std.**	**Err. Sig.**	**Coef. Std.**	**Err. Sig.**	**Coef. Std.**	**Err. Sig.**	**Coef. Std.**	**Err. Sig.**	**Coef. Std.**	**Err. Sig.**
Citations Pre-ATP Application Date			1.74	0.33***			0.44	0.19**	0.43	0.19**
Citations Per Pre-ATP Paper					14.24	0.96***	12.51	1.15***	12.68	1.17***
ATP Application Year									-42.42	47.93
ATP Winner Dummy	-216.9	335.7	-260.5	241.6	53.4	114.3	9.5	107.2	45.2	115.0
Constant	450.0	267.1	201.7	198.0	29.1	94.1	17.0	87.1	84,513.7	95,469.4
Number of Obs.	30		30		30		30		30	
F	0.42		13.95		112.31		89.53		66.79	
Prob. > F	0.524		0.000		0.000		0.000		0.000	
R-Squared	0.015		0.508		0.893		0.912		0.914	
Adj. R-Squared	-0.021		0.472		0.885		0.902		0.901	

Note: *significant at .10, **significant at .05, ***significant at 0.01

spillover signal from Uniax, the largest potential signal among our particular cases, is lost in the noise, the implications are troubling for the power of the methodology to track value from knowledge spillovers from small-scale projects. We conclude that the measurement noise and uncertainty in techno-socioeconomic systems may make it unreasonable to expect tracking value from knowledge spillovers from small ($1–5 million) projects. On the other hand, the methodology was able to identify value from market spillovers at this scale.

Although unable to confirm the hypothesis, we believe finding ways to track explicitly both types of spillovers remains a worthwhile pursuit. Further research on case or microeconomic methodologies might attempt to track significantly larger-scale research programs, which may have impact discernable above the complexity-related noise. Macroeconomic and systemic approaches may also prove more fruitful.

6. What are principal spillover mechanisms, and what market and technological factors promote larger spillovers?

Beyond the obvious conclusion that larger markets make for larger consumer and producer surpluses, and that market spillover value is driven more powerfully by unique enabling capabilities like those of Uniax, we found in these cases that social collaborative ties were a principal mechanism for diffusion beyond direct markets. In both the Displaytech and Uniax cases these social ties clustered around a high-profile researcher—in Uniax's case a Nobel Prize winner—and diffusion mechanisms were rooted in the university culture of collaboration and openly sharing ideas. The much more geographically diffuse pattern in the Uniax case suggests that closeness of social ties is more important than closeness in geography per se. Indeed, the regression analyses indicated that, in addition to closeness of social ties, distance in the sense of technological proximity and industry sector practices are more important mechanisms than geographic distance in explaining technology flows. Corporations already strong in related fields are more likely to support related research, and the authors in turn are much more likely to absorb and cite technical information. That said, our interviews lead us to believe, in both cases, that the flows suggested by the patent citation data are weak beyond the direct commercial market relationships.

One policy implication is that the spillover diffusion potential for the United States is higher in those industries where the United States already has relative strengths in strongly complementary areas. Our regression analyses of patent citation rates also suggested that large firms were much quicker to citing behavior, an indication of the advantages of large firm resources. We conclude that external absorptive capacity is another important mechanism helping foster economic spillovers.

This illustrates a significant tension between policies aimed at improving competitiveness in industries where the United States is relatively weak, but where the resulting spillover values might be lower, and policies where the goal is to maximize public good technology diffusion and spillovers in the United States, which would target those where complementary technologies are relatively strong.

The importance of complementary technologies in fostering spillover value is evident too. Part of the reason for long lag times between ATP application and commercialization—for Displaytech, and Uniax alike—was the failure of complementary technologies to advance as rapidly as anticipated. Neither of Displaytech's original two anticipated major markets materialized, in part because of weakness in the commercialization of complementary demand-side technologies: illumination sources and optical path technologies remained problematic for projection television applications, and optical systems too costly and bulky for commercially attractive head-mounted displays. Instead, Displaytech took advantage of alternative complementary advances in digital cameras on the demand side of the value creation, light-emitting diodes for illumination on the optical system side, and silicon wafer planarization on the manufacturing process supply side. All three were necessary for enabling the current market value from ATP's investments. Uniax lacked complementary manufacturing equipment to enable cost-effective roll-to-roll processing of flexible OLEDs to challenge LCDs for mainstream commercialization.

This suggests a potential criterion for policies aimed at enhancing spillover: explicit identification and evaluation of the likelihood of advances in necessary complementary demand-side and supply-side technologies.

7. How can methodologies for estimating of the value of displaced technologies be improved?

We suggested in Chapter 1 that accounting for dynamic displacement was theoretically more attractive as a counterfactual benchmark than static defenders for estimating the social value from new technologies. Although the citation and snowball interviewing methodologies were unable to discern knowledge spillover value, we were able to estimate market spillovers. Given the 10-year-plus delay between both Displaytech and Uniax's ATP applications and volume commercialization (notably in line with ATP's stated target of funding pre-competitive research), display markets and technologies evolved considerably. Indeed, Displaytech's main application in digital viewfinders was not among the main markets identified in their ATP proposal. Nor was microdisplays the primary competition a decade ago from U.S. firms like TI, Kopin, and Brillan. Or plasma displays. Or organic displays. Instead, it was the LCDs and CRT displays of several generations ago, markets wholly dominated by foreign firms. Our interviewing experience in these cases convinces us that it is, in fact, easier for respondents to estimate value relative to current competitors—dynamic defender technologies—rather than static defender options available a decade ago. The clarity of the conversations was aided considerably by the narrowness of the Uniax and Displaytech technology portfolios, essentially single-technology firms that industry insiders knew well. Confirming our hypothesis that use of static defender technologies would tend to lead to overestimates of social value, competition and price elasticities have increased in display markets while current price levels are fractions what they were a decade ago. We estimate that our consumer surplus estimates using dynamic defenders are smaller by a rough order of magnitude than they might have been using static defenders.

The analysis supports our view that the dynamic defender technology approach to spillover evaluation is methodologically superior. Indeed, the Displaytech and Uniax cases suggest expanding the methodological approach beyond the displaced defender technology, to include dynamic complementary technologies and dynamic application areas as well.

GENERAL OBSERVATIONS ON TECHNOLOGY DEVELOPMENT AND EVALUATION METHODOLOGIES

ATP's mission is to fund high-risk advanced technology developments with the potential for significant economic and social payback for the nation. The extensive and complex nature of this technology development process is pictured in the flowchart in Figure 30.

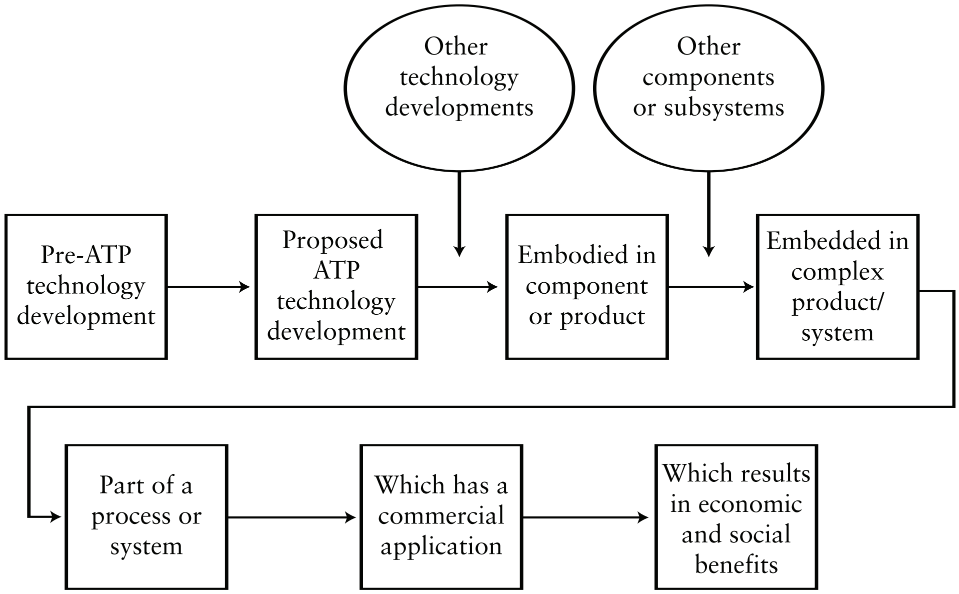
In an ATP-funded technology, there may be a stage prior to the ATP proposal where initial technology development occurs, pre-ATP technology development. These developments may occur in a variety of ways: through university research funded by the NSF; through SBIR grants from various federal agencies; through DOD contracts; through large corporation research subsequently spun off into an independent company; and through a robust array of other public and private mechanisms.

ATP enters the picture when a technology appears to have significant commercial potential, at the proposed ATP technology development stage. ATP funds the development of technologies, not products, in this stage of technology development.

If an ATP-funded technology is successfully developed, it, along with other necessary technology developments, likely gets embodied in a component or product that is only one

FIGURE 30.

Flowchart of ATP Technology Development and Economic Benefit Generation Process



piece of a system that actually results in a commercial application. In order for that higher-order product to work, however, other components or subsystems are also needed, some of which may also require significant technology development. If all of the pieces become available, they can be integrated and the ATP technology will now be embedded in a complex product or system that delivers the functionality required for the envisioned commercial application. But often the complex product or system does not deliver the functionality by itself, but only as part of a yet-larger process or system in which other complementary products and services are integrally involved. It is this larger system that generates the ultimate commercial value and economic and social benefits for the nation.

So, it is important to recognize that, in addition to the technical risk inherent in the development of the ATP technology itself—for example, it may fail to perform cost-effectively—there are significant uncertainties, both risks and opportunities, downstream that may affect the perceived success of the outcome. These uncertainties are inherent in the fact that many of the downstream applications—not only substitute products and systems, but also complementary products and systems—also tend to involve technologies in the early dynamic stages of their own development life cycles. This dynamic complementary technology uncertainty is compounded by the risk of market failure that can also occur—for example, the commercial application perceived at the time of the ATP proposal may fail to materialize or may have been satisfied by an emerging competing technology, the dynamic defender, by the time the ATP technology is ready for commercialization.

If the market (the proposed commercial application) for the ATP technology is changing just as dynamically as the technology being developed, then the developer is trying to hit a moving target and may find that performance and cost-effectiveness thought to be superior or satisfactory at the time the proposal was submitted is inadequate by the time the technology is developed. The other side of this coin, however, is the opportunity that may be presented by other commercial applications, not foreseen at the time the proposal was submitted, which emerge just as dynamically during the time the technology is being developed.

Thus, the fact of high risk and uncertainty that is present in ATP proposals is much more complex and extensive than simply the technology to be developed. This presents both problems and opportunities for understanding what "success" may mean when evaluating ATP projects. To summarize the evaluation problem:

- if a single technology is to be embodied with other technologies in a product or component and the other technologies are also in the early stages of their life cycle; and
- if the product or component needs to be bundled with other products or components to have a complex product or system that can provide the commercial application and the other products or components are dependent upon technologies that are also in the early stages of their life cycles; and
- if this product or system that provides the commercial application is a substitute for a different technology-based product or system and that different technology is also in the early stage of its life cycle; and
- if the commercial application—the market—is also technology-driven and those technologies are also in the early stages of their life cycles;

then the uncertainty regarding the outcome of the ATP project is greater, even given the successful development of the proposed technology. The greater this uncertainty, the less a proposal will be able to predict technical, commercial, and socioeconomic outcomes. Evaluating success based on earlier static benchmarks is bound to misrepresent a project's value, because even as problems occur and expected outcomes go unrealized, unexpected opportunities also appear in this dynamic environment for the observant and flexible developer.

One rationale for government programs like ATP in the funding of commercial technology development projects is that these high-risk projects would not be undertaken at all or would occur only at a later point in time—perhaps too late to establish a leadership first-mover position—absent government funding. Moreover, the size of what's at stake in taking the risk (the investment required) needs to be compared to the resources available to the proposed developers (particularly small, entrepreneurial startups) in establishing a government support role. This argument and justification are squarely within the historical tradition of U.S.

government policies, which established federal research laboratories and funding programs for the family farmer in the U.S. Department of Agriculture and for miners in the U.S. Geological Survey and Bureau of Mines without significant controversy a century ago and more.

While the term *high risk* has appeal, from our case study examination we find that the term *high uncertainty* may be a somewhat more accurate description of the kinds of projects ATP funds. Understanding programs such as ATP depends, in part, in expanding the language used to justify federal funding of commercially relevant new technologies. Over the 10-year horizons of the ATP projects studied here, the actual trajectories involved not predictable risk, but the uncertainty of real unknowables: changing and dynamic industries; new unforeseen substitute and complementary technologies; strategic moves by previously nonexistent competitors and suppliers; or entirely new potential customers.

More broadly, complexity suggests the value of a diverse, flexible technology base—able to take advantage of whatever positive outcomes of uncertainty that might appear. The uncertain complexity also highlights the value of robustness in a variety of technology policy approaches, funding mechanisms, target participants, and structures in the base of supporting programs. The decentralization and complexity of the U.S. system of government support for technology development may be duplicative in a static sense—funding the similar things several different ways. However, dynamic uncertainty may reward robust policy diversity, as particularly evident in the high returns in the microdisplay industry cases studied here. Generic approaches like ATP, open to a variety of technical areas and types of participating firms and organizations, are inherently more flexible and more robust than targeted programs and are, therefore, likely to be of particular long-term value in budding new industries—like microdisplays—where both markets and technical uncertainty abound, in part because no dominant technical paradigms have yet emerged.

5. Conclusions

From our comparative case analysis of Displaytech and Uniax, we conclude that:

- ATP funding creates national value and, given high uncertainty, supports projects with market spillover potential and accelerates development and commercialization of technology.
- With regard to currently measurable economic value, market spillover value significantly dominates knowledge spillover value.
- Key spillover value-enhancing mechanisms include: larger market scale; unique enabling capabilities; lower price elasticities; closer social ties and technological similarity; high-profile researchers and a collaborative university culture; advancing complementary technologies; and the resources and absorptive capacity of large firms.
- The time-to-market in the cases studied was more than six years, quite consistent with ATP's target time horizons. Interim niches other than the main target markets sustained cash flow. Consistent with ATP's goals, the cases exhibited high-risk, high-uncertainty technologies.
- High uncertainty extends beyond the proposed new technologies themselves, so evaluation methodologies may be further improved by considering dynamic complementary technologies and dynamic application areas as well.
- Patent citations are a noisy proxy for measuring actual knowledge spillover.
- Universities dominate publication citations, but corporate publication citations appear to be better than patent citations as an indicator of actual knowledge spillovers.
- The rate of publication citations might be a useful and readily obtainable a priori metric for evaluating project proposals, as an indicator of knowledge spillover potential from the scientific work, and also, tentatively, as a rough quality proxy for the firm's potential for attracting capital investment.
- Identification of dynamic defender technologies is feasible and methodologically easier than using static displaced technologies—although both approaches are empirical counterfactual exercises. The dynamic defender methodology is less likely to overestimate social value (particularly where emerging strong competition increases price elasticities, thus limiting market spillover value).

- ATP goals inherently involve several key tensions, which make evaluation challenging:
  - High uncertainty and long time horizons of targeted projects may limit the utility of traditional evaluation methods.
  - High market spillover and knowledge diffusion may run counter to commercial potential and the ability of participating firms to capture value from new technologies, but successful commercial implementation is necessary for large-scale value creation.
  - Evaluation may tend to have a bias toward measurement of private returns, because spillover value is broadly dispersed and significantly harder to measure than private returns.
  - High potential value areas will attract private capital investment over time, which dynamically increases competition and price elasticities, thereby reducing realized private and market spillover value.
  - ATP awards are relatively small in funding amount, and participating firms often leverage a broad portfolio of other federal, state, and local programs. This limits the possibility of identifying the individual impact of any single program on a firm's competitiveness and technical success over long time horizons.

Appendix

SEMISTRUCTURED INTERVIEW INSTRUMENT

I. Introductions. Brief **overview** of Lehigh University research and then of case company (employees, major markets, growth since ATP project).

II. Query **major results** from ATP project.
   i. **Technical,** most valuable innovations/solutions?
   ii. Would these have **occurred without ATP**? If so, when?
   iii. **How embodied?**
      a. Patents (issued or pending?)
      b. Published articles?
      c. Trade secrets?
      d. Products?

III. Query **extensions and uses** of these technical advances.
      a. Direct: In target markets?
      b. Spillover: In other areas?
   i. **Company.**
      a. Later technical extensions of ATP-related advances enabled?
      b. Past or current products using ATP-related results?
      c. Estimated (rough OK) net value to company of the ATP-related advances?
   ii. **Customers.** Consider the three or four customers getting the most value created by ATP-related technical advances.
      a. Who are those customers?
      b. What has it enabled them to do? How valuable?
      c. What alternatives did they have? Why is your company's product better?
   iii. **Competitors.** Three or four on whom ATP-related advance had the largest impact (positive or negative) on their market or technical positions.
      a. Who?
      b. How did they adjust? What did they do differently?
      c. Estimated value?

iv. **Suppliers.** Three or four on whom there was the most valuable impact.
  a. Who?
  b. What must they, or have these advances enabled them to, do differently?
  c. Estimated value?
v. **Cooperating.** Were there any other organizations, companies, or universities whose work was integral to your ATP work?
  a. Who?
  b. How did that cooperation take place (alliances, formal agreements, informal meetings)?
  c. Advances they made based on this joint work?
  d. Estimated value?
vi. Others. (University researchers, other industries, etc.)?

IV. **Counterfactual Scenario:** What would have happened without the ATP award?
  a. In general, in market, and in technical field?
  b. What would the **company** have done differently?
  c. **Customers:** three or four getting the most value? Alternatives without ATP-related advances?
  d. **Competitors:** three or four on whom ATP advances had the most impact?
  e. **Suppliers:** three or four on whom ATP advance had the most impact?
  f. Other cooperating organizations?
  g. Any others?

References

Advanced Technology Program (1998), *ATP Proposal Preparation Kit,* November 1998, National Institute of Standards and Technology, Gaithersburg, MD.

Advanced Technology Program (2003), *Survey of ATP Applicants 2000,* NIST GCR–03–847, National Institute of Standards and Technology, Gaithersburg, MD.

Allen, K. (2003), Microdisplays, *Emerging Display Technologies—2003,* Stanford Resources Display Insight. Available online at www.isuppli.com/catalog/L2_edts.asp.

Army Research Office (1999), *1999 ARO in Review: Physics.* Available online at www.aro.army.mil/arorev99/phy99.htm.

Arrow, K.E. (1962), Economic Welfare and the Allocation of Resources for Invention, in R.R. Nelson, ed., *The Rate and Direction of Inventive Activity,* Princeton University Press.

Bacon, F. (1626), *New Atlantis.* Available online at Project Gutenberg, www.gutenberg.org/etext/2434.

Bernstein, J.I. (1989), The Structure of Canadian Inter-industry R&D Spillovers, and the Rates of Return to R&D, *The Journal of Industrial Economics* 37, 315–28.

Bernstein, J.I. and M.I. Nadiri (1989), Research and Development and Intra-industry Spillovers: An Empirical Application of Dynamic Duality, *The Review of Economic Studies* 56, 249–67.

Branscomb, L.M. and P.E. Auerswald (2002), *Between Invention and Innovation: An Analysis of Funding for Early-Stage Technology Development,* NIST GCR–02–841, National Institute of Standards and Technology, Gaithersburg, MD.

Business Journal of Phoenix, The (2002), Three-Five Buys InViso Assets, April 29, 2002.

Caplin, A. and J. Leahy (2004), The Social Discount Rate, *Journal of Political Economy* 112, 1257–68.

Chin, S. (2003), Small Display Makers Face Cash Crisis: Start-Ups Fight for Survival Despite Booming Market, *Planet Analog,* March 25, 2003. Available online at www.planetanalog.com/news/OEG20030325S0047.

Clark, D. (2001), What's Ahead for Display Screens, *Wall Street Journal,* June 6, 2001, R18.

Clark, N.A. and S.T. Lagerwall (1980), Submicrosecond Bistable Electro-Optic Switching in Liquid Crystals, *Applied Physics Letters* 36, 899–901.

Denison, E.F. (1985), *Trends in American Economic Growth, 1929–1982,* The Brookings Institution, Washington, DC.

DisplaySearch (2004), *DisplaySearch Annual OLED and FPD Equipment Reports,* Insight Media, Norwalk, CT.

Evenson, R.E. and Y. Kislev (1973), Research and Productivity in Wheat and Maize, *Journal of Political Economy* 81, 1309–29.

Feldman, M.P. and M.R. Kelley (2001), *Winning an Award From the Advanced Technology Program: Pursuing R&D Strategies in the Public Interest and Benefiting From a Halo Effect,* NISTIR-6577, National Institute of Standards and Technology, Gaithersburg, MD.

Firester, A.H. (1992), Active Matrix Technology, *Display Technologies in Japan,* Japanese Technology Evaluation Center, June 1992. Available online at http://www.wtec.org/loyola/dsply_jp/toc.htm.

Forgrieve, J. (2002), Survival on Display: Displaytech of Longmont Fights to Stay Afloat With Its Microdisplay Technology, *Rocky Mountain News,* January 28, 2002, 1B.

Fox, B. (1996), Battery Giants Ready for Battle Over Patent, *New Scientist,* March 16, 1996, 2626.

Geroski, P. (1995), Markets for Technology: Knowledge, Innovation, and Appropriability, in P. Stoneman, ed., *Handbook of the Economics of Innovation and Technological Change,* Blackwell, Oxford, U.K.

Grant, E., P. Nolan, and D. Pinner (2002), Chips Off a New Block (Organic Thin Film Transistors), *McKinsey Quarterly,* January 1, 2002.

Griliches, Z. (1958), Research Cost and Social Returns: Hybrid Corn and Related Innovations, *Journal of Political Economy* 66, 419–31.

Griliches, Z. (1964), Research Expenditures, Education, and the Aggregate Agricultural Production Function, *American Economic Review* 44, 961–74.

Griliches, Z. (1979), Issues in Assessing the Contribution of R&D to Productivity, *Bell Journal of Economics* 10, 92–116.

Griliches, Z. (1986), Productivity, R&D, and Basic Research at the Firm Level in the 1970s, *American Economic Review* 76, 141–54.

Hicks, D. (2002), Indicators of Knowledge Value, *Conference on Estimating the Benefits of Government Sponsored Energy R&D,* U.S. Department of Energy, March 4–5, 2002. Available online at www.esd.ornl.gov/benefits_conference/hicks.ppt.

HM Treasury (2003), Annex 6: Discount Rate, *The Green Book: Appraisal and Evaluation in Central Government,* HM Treasury, London. Available online at greenbook.treasury.gov.uk/annex06.htm.

Jaffe, A.B. (1986), Technological Opportunity and Spillovers of R&D: Evidence From Firms' Patents, Profits, and Market Value, *American Economic Review* 76, 984–1001.

Jaffe, A.B. (1996). *Economic Analysis of Research Spillovers: Implications for the Advanced Technology Program,* NIST GCR–97–708, National Institute of Standards and Technology, Gaithersburg, MD.

Leonard, W.N. (1971), Research and Development in Industrial Growth, *Journal of Political Economy* 79, 232–56.

Mansfield, E. (1986), Patents and Innovation: An Empirical Study, *Management Science* 32, 173–81.

Mansfield, E., J. Rapoport, A. Romeo, S. Wagner, and G. Beardsley (1977), Social and Private Rates of Return From Industrial Innovations, *Quarterly Journal of Economics* 91, 221–40.

Metcliff, S. (1995), The Economic Foundations of Technology Policy: Equilibrium and Evolutionary Perspectives, in P. Stoneman, ed., *Handbook of the Economics of Innovation and Technological Change,* Blackwell, Oxford, U.K.

Nelson, R.R. (1959), The Simple Economics of Basic Scientific Research, *Journal of Political Economy* 67, 297–306.

Paul, J. (2000), A Brief History of Ferroelectric Liquid Crystals: Research Explores Chirality, *The Liquid Crystal Observer* 2(2), 8–11, Ferroelectric Liquid Crystal Research Center, University of Colorado, Boulder.

Percec, V. (2004), Professor Virgil Percec's Research Interests. Available online at http://perceco2.chem.upenn.edu/~percec/research.html.

Pesala, J., S. Peltonen, and J. Perento (2001), Polyaniline: A Conductive Polymer, *Industrial Horizons Magazine,* April 2001.

Photo Industry Reporter (2002), InfoTrends: Digital Camera Sales to Reach $11.8 Billion in 2007, November 18, 2002.

Romer, P. (1990), Endogenous Technical Change, *Journal of Political Economy* 98, S71–S102.

Ruegg, R. (1996), *Guidelines for Proposing Economic Evaluation Studies to the Advanced Technology Program (ATP),* NISTIR-5896, National Institute of Standards and Technology, Gaithersburg, MD.

Scherer, F.M. (1982), Interindustry Technology Flows and Productivity Growth, *Review of Economics and Statistics,* 627–34.

Scherer, F.M. (1984), Using Linked Patent and R&D Data to Measure Interindustry Technology Flows, in Z. Griliches, ed., *R&D Patents and Productivity,* University of Chicago Press, Chicago.

Schumpeter, J.A. (1942), *Capitalism, Socialism, and Democracy,* Harper, New York.

Sharp, G.D., J.R. Birge, J. Chen, and M.G. Robinson (2000), High Throughput Color Switch for Sequential Color Projection, *SID '00 Digest* 31, 92–5.

Solow, R. (1957), Technical Change and the Aggregate Production Function, *Review of Economic Statistics* 39, 312–20.

Tassey, G. (1997), *The Economics of R&D Policy,* Quorum Books, Westport, CT.

Teece, D.J. (1986), Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing, and Public Policy, *Research Policy* 15, 285–305.

Terleckyj, N.E. (1974), *Effects of R&D on the Productivity Growth of Industries: An Exploratory Study,* National Planning Association, Washington, DC.

Tewksbury, J., M. Crandall, and W. Crane (1980), Measuring the Societal Benefits of Innovation, *Science* 209, 658–62.

Underwood, I. (1997), Ferroelectric Liquid Crystal over Silicon Spatial Light Modulators: Principles, Practice, and Prospects, in G. Burdge and S.C. Esener, eds., *Spatial Light Modulators, O.S.A. Trends in Optics and Photonics* v14, Optical Society of America, Washington, DC.

United States Department of Labor (2002), *Worker Displacement, 1999–2001,* USDL 02–483, Bureau of Labor Statistics, Washington, DC.

United States Department of Labor (2003a), *Data Series: Unemployment Rate,* (PMSA Boulder-Longmont, CO), Bureau of Labor Statistics, Washington, DC.

United States Department of Labor (2003b), *Highlights of Denver-Boulder-Greeley, CO. National Compensation Survey June 2000.* Available online at www.bls.gov/ro7/den00ncs.htm.

Van De Kamp, M. (2003), Goleta Calif. Flat-Panel Display Screen Technology Maker Downsizes, *Knight Ridder Tribune Business News,* November 15, 2003, 1.

Wilson, W. (2002), The Holographic Holy Grail, *Computer Technology Review* 22, 26–7.

Yoshida, J. (2004), Plastic, Not Glass, to Spawn New Breed of Thin, Flexible Displays, *EE Times* 24.

Zucker, L.G. and M.R. Darby (1995), Virtuous Circles of Productivity: Star Bioscientists and the Institutional Transformation of Industry, NBER Working Paper No. W5342, National Bureau of Economic Research, Cambridge, MA. Available online at www.nber.org/papers/w5342.

Zucker, L.G., M.R. Darby, and J. Armstrong (1999), Intellectual Capital and the Firm: The Technology of Geographically Localized Knowledge Spillovers, NBER Working Paper No. W4946. Available online at www.ssrn.com/abstract=226546.

ABOUT THE AUTHORS

Todd A. Watkins is an Associate Professor in the College of Business and Economics at Lehigh University and Director of the Institute for the Study of Regional Political Economy. He holds Ph.D. and M.P.P. degrees in Public Policy from Harvard University, and a B.S. in Optics from the University of Rochester. His research and teaching focuses on the intersection of technology, public policy, business and economics, and he's authored more than 50 publications. His research on technology policy, photonics industries, defense industries, dual-use manufacturing, and the economics of innovation has been published in various journals, including *Science, Technology Review, IEEE Engineering Management Review, Defence & Peace Economics, Technovation, Governance,* and *Research Policy.* He has been a consultant to the U.S. Congressional Office of Technology Assessment, Arthur D. Little, the Semiconductor Research Corporation, and was a research team member of the M.I.T. Lean Aircraft Initiative, a consortium of 20 major aerospace companies. He has worked as a technology policy analyst for the Commission of the European Communities, and also for the U.S. General Accounting Office. Prior to graduate studies, he worked in Optical Design and Optical Manufacturing Engineering for the Eastman Kodak Company. Dr. Watkins serves on the editorial boards of *Technovation, The International Journal of Technological Innovation and Entrepreneurship*, and the *International Journal of e-Collaboration.* He has served on the faculty of the National Technological University's Management of Technology Program; and has been a Visiting Scholar at the Centre for Defence Economics, University of York, England; a Center Associate of the Center for Trade & Commercial Diplomacy, Monterey Institute of International Studies; and a Research Fellow in the Center for Science and International Affairs, Harvard University. During 2004–2006, he served as a member of The National Academies' Committee on Innovation Models for Aerospace Technologies, advising NASA on improving their innovation processes.

Theodore W. (Ted) Schlie is an Associate Professor of Technology Management in the College of Business and Economics at Lehigh University where he teaches and conducts research in innovation management and policy, production/operations management, science and technology policy, business strategy and policy, R&D management, and international competitiveness. Previously, Dr. Schlie has been Associate Director of Research at the Center for Innovation Management Studies, now at North Carolina State University, and Director of Field Research Projects for the National Technological University's Management of Technology Program. He has been a consultant to a number of industrial, university, and government institutions. Before arriving at Lehigh in 1989, Dr. Schlie was Associate Professor of Business Administration at the Illinois Institute of Technology (IIT) in Chicago, where he also served as Executive Director of the IIT-Midwest Manufacturing Roundtable. From 1978 to 1985, Dr. Schlie was with the U.S. Department of Commerce in a number of positions. During 1983–85, he was Director of the Industry Analysis Division in the International Trade Administration, directing a research program on competitiveness issues across industry sectors. As the Director of the Office of Competitive Assessment in 1982–83, Dr. Schlie established the Competitive Assessment Program to study the long-term competitiveness of sectors of U.S. industry. Prior to 1982, he served as Deputy Director of the Office of Technology, Strategy, and Evaluation; Acting Director of the Experimental Technology Incentives Program (on detail to the National Bureau of Standards); and Senior Policy Specialist to the Assistant Secretary for Science and Technology. Before joining the government in 1978, Dr. Schlie was a Senior Research Economist with the Office of International Programs of the Denver Research Institute, where he developed and managed cooperative, institution-building programs with industrial research institutes in developing countries. He also conducted and supervised technology policy studies for the National Science Foundation, the U.S. Department of State, the Agency for International Development, the United Nations, and other governmental agencies. Dr. Schlie received both his M.S. (1969) and Ph.D. (1973) degrees from the Department of Industrial Engineering and Management Sciences at Northwestern University. He is a Fellow of the American Association for the Advancement of Science, and a member of numerous profession associations and societies.

ABOUT THE ADVANCED TECHNOLOGY PROGRAM

The Advanced Technology Program (ATP) is a partnership between government and private industry to conduct high-risk research to develop enabling technologies that promise significant commercial payoffs and widespread benefits for the economy. ATP provides a mechanism for industry to extend its technological reach and push the envelope beyond what it otherwise would attempt.

Promising future technologies are the domain of ATP:

- Enabling or platform technologies essential to development of future new products, processes, or services across diverse application areas
- Technologies where challenging technical issues stand in the way of success
- Technologies that involve complex systems problems requiring a collaborative effort by multiple organizations
- Technologies that will remain undeveloped, or proceed too slowly to be competitive in global markets, in the absence of ATP support

ATP funds technical research, but does not fund product development—that is the responsibility of the company participants. ATP is industry driven, and is grounded in real-world needs. Company participants conceive, propose, co-fund, and execute all of the projects cost-shared by ATP. Most projects also include participation by universities and other nonprofit organizations.

Each project has specific goals, funding allocations, and completion dates established at the outset. All projects are selected in rigorous competitions that use peer review to identify those that score highest on technical and economic criteria. Single-company projects can last up to three years; joint venture projects involving two or more companies can last up to five years.

Small firms on single-company projects cover at least all indirect costs associated with the project. Large firms on single-company projects cover at least 60 percent of total project costs. Participants in joint venture projects cover at least half of total project costs. Companies of all sizes participate in ATP-funded projects. To date, nearly two out of three ATP project awards have gone to individual small businesses or to joint ventures led by a small business.

Contact ATP for more information:

- On the Internet: www.atp.nist.gov
- By e-mail: atp@nist.gov
- By phone: 1-800-ATP-FUND (1-800-287-3863)
- By writing: Advanced Technology Program, National Institute of Standards and Technology, 100 Bureau Drive, Stop 4701, Gaithersburg, MD 20899-4701