10-2023

Interfaces, modularity and ecosystem emergence: How DARPA modularized the semiconductor ecosystem

Jennifer Kuan
California State University, Monterey Bay

Joel West
Hildegard College

Recommended Citation

Kuan, Jennifer and West, Joel, "Interfaces, modularity and ecosystem emergence: How DARPA modularized the semiconductor ecosystem" (2023). *College of Business Faculty Publications and Presentations*. 16.
https://digitalcommons.csumb.edu/cob_fac/16

Research Policy 52 (2023) 104789

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Interfaces, modularity and ecosystem emergence: How DARPA modularized the semiconductor ecosystem

Jennifer Kuan[a,*], Joel West[b,c]

[a] California State University Monterey Bay, College of Business, Seaside, CA, United States
[b] Hildegard College, Costa Mesa, CA, United States
[c] Keck Graduate Institute, Claremont, CA, United States

ARTICLE INFO

Keywords:
Modularity
R&D policy
Open standards
Innovation ecosystems
Vertical disintegration
Fabless semiconductors

ABSTRACT

Scholars have identified the pivotal role that modularity plays in promoting innovation. Modularity affects industry structure by breaking up the value chain along technical interfaces, thereby allowing new entrants to specialize and innovate. Less well-understood is where modularity comes from. Firms seem to behave consistently with the theory in some settings, especially the information technology sector, but not in others, such as automobiles. Here we show how the government has a role to play in generating open interfaces needed for modularity, utilizing a case study of the semiconductor industry from 1970 to 1980. We show how the Defense Department's support for this effort aligned with its mission-based interest in semiconductors. We thus contribute a new source of open standards to the modularity literature, as well as a new analytical perspective to the public research funding literature.

1. Introduction

Modularity theory has connected the vertical structure of an industry to the rate of innovation (Baldwin, 2012; Baldwin and Woodard, 2009). The interfaces between modules enable firms to enter and specialize, such that the overall industry achieves diverse experimentation and rapid innovation (Baldwin, 2012, 2019; Baldwin and Clark, 2000; Brusoni and Fontana, 2005; Colfer and Baldwin, 2016). A classic example of the power of modularity is the information technology (IT) industry, where personal computers (PCs) were built from standardized modules, and semiconductor chips could be designed by one firm and produced by another (Baldwin and Clark, 2000). Empirically, design-only chip firms contributed to a substantial increase in semiconductor patenting (Hall and Ziedonis, 2001) and have since ushered in new technology and client-industries, placing computing technology into automobiles, smart phones, wearables, implants, cloud computing and more.

This industry effect of modularity is particularly important to understand given policy concerns about innovation and competitiveness (Macher and Mowery, 2008). Even where public research funding has been successful in the past, such as with the Department of Defense's (DoD) famous Defense Advanced Research Projects Agency (DARPA) (e.g., Mervis, 2016), questions persist about how to extend that success into the future (Khan et al., 2018; Whetsell et al., 2020) and across new domains (Azoulay et al., 2019; Rathje and Katila, 2021). Modularity theory suggests a way to leverage public funding.

However, as powerful as modularity has proven to be, open questions remain about *how* modularity arises. While Baldwin (2019) argues that firms will seek to earn rents by controlling the standardized interfaces between modules, firms more typically face trade-offs in deciding whether to pursue modularity (Pil and Cohen, 2006). Thus, scholars have observed multiple examples of firms that de-modularize their industry (Chesbrough and Kusunoki, 2001; Ernst, 2005; Fixson and Park, 2008; Schilling, 2000). More broadly, firms often lack the incentives to create the thin crossing points or technical interfaces that enable modularity, even backing away from innovations that would lead to a faster-paced modular structure (Jacobides et al., 2016; MacDuffie, 2013).

This paper suggests other potential actors with the incentive to create open interfaces: government agencies. We examine a familiar setting, the semiconductor industry, where the open interface Baldwin and Clark (2000) describe led to a de-integration into design-only "fabless" firms and production-only "foundries". This shift in industry structure was so straightforward as to be almost taken for granted. Indeed, Langlois and Steinmueller (1999, p. 50) characterize the "decoupling of design from

---

[*] Corresponding author.
E-mail addresses: jkuan@csumb.edu (J. Kuan), KGI@joelwest.org (J. West).

https://doi.org/10.1016/j.respol.2023.104789
Received 16 October 2020; Received in revised form 5 November 2022; Accepted 14 April 2023

production" as "a natural manifestation of the division of labor in growing markets." That is, they view de-integration as the natural result of greater scale.

However, our deeper examination of this case considers the DoD's interests in funding scientists who were tackling the technical bottlenecks of semiconductor design. The many coordinated components of the eventual technical interface and the resistance from industry incumbents encountered by the scientists suggest that industry-level de-integration was far from "natural" and straightforward. In addition, while the solution to scalability was a technical interface that also allowed for a partitioning of design from manufacture, organizational partitioning was far from predictable. Rather, the technical interface is a necessary but not sufficient condition for the organizational and market modularity that eventually, years later, gave rise to the innovative gains described by theory (Baldwin and Clark, 2000).

Our goal is thus to bring government agencies into modularity theory as a source of technical interfaces. Public agencies have an interest in making the interface open and available to all, whereas a private firm might keep an interface proprietary (Rathje and Katila, 2021). We also wish to bring modularity theory to policy makers, for whom a persistent policy question is how best to fund research and development (R&D) strategically (Azoulay et al., 2019; Bloom et al., 2019; Dosi, 1982). Modularity theory suggests a high-leverage strategy of creating technical interfaces that affect the speed and diversity of innovation through industry structure.

In the rest of the paper, we discuss the literatures on modularity and public R&D funding, then explain our historical sources and methods. We then lay out the backdrop and details of the focal five-year period during which many large and small pieces of the technical interface were created with the financial and institutional support of the DoD. We conclude with a discussion of implications and future research.

2. Connecting modularity to R&D policy

Modularity theory identifies a powerful role for industry structure in spurring rapid and diverse innovation. But the literature has languished even as the phenomenon itself, in its original focal industry of computing, has flourished. In part, this is due to challenges raised in the business literature on firms' incentives to create the open interfaces that would generate industry-level de-integration. Less scholarly attention has been paid to what public agencies might do. The public R&D funding literature has been dominated by the spillovers argument for public support for science research. However, a nascent literature is beginning to make headway studying the incentives of mission-oriented public agencies and their role in supporting scientific research.

2.1. Modularity and industry structure

Our starting point in the modularity literature is Baldwin and Clark (2000). Their study was inspired by the rapid technological growth of the computing industry:

> As the twentieth century draws to a close, we live in a dynamic economic and commercial world surrounded by objects of remarkable complexity, sophistication, and power. It is a world where the speed of business is rapid and accelerating, where new technologies create new products at once stunning and useful, and where the pace of change has created an environment that is fraught with risk and reward (p. 1) …we have chosen to study this phenomenon and its implications for firms and markets in a single context, albeit one where the underlying forces are especially salient. Our context for this work is an artifact of the second half of the twentieth century: the electronic computer (p. 3).

However, Baldwin and Clark (2000) were building on, and bringing together, existing scholarship on the subject of modularity. The literature addressed the growing complexity of creating new technology-based products and applications (Hobday, 1998; Malerba and Orsenigo, 1997). A potential solution for such complexity is modularity (Baldwin and Clark, 1997), when firms break down a problem into manageable modules (Sanchez and Mahoney, 1996).

This technical modularity also allows firms to organize tasks in modules, leading scholars to examine the organizational implications of modularity. Firms' internal organization might mirror the technical boundaries of problems (e.g., Colfer and Baldwin, 2016). And organizational modularity can extend to other firms, such that an ecosystem of firms specializing in different modules can create complex systems like airplanes and computers (Baldwin and Clark, 2000; Prencipe, 2000) — a process Chesbrough and Kusunoki (2001) term "market modularity". Partitioning technical and organizational complexity thus enables innovation to be decentralized (Baldwin, 2008, 2012, 2020; Baldwin and Clark, 2000; Colfer and Baldwin, 2016).

In order to partition tasks into modules, a thin crossing point is needed that allows a set of tasks to be performed by outside firms (Baldwin, 2008):

> If labor is divided between two domains and most task-relevant information hidden within each one, then only a few, relatively simple transfers of material, energy and information need to pass between the domains. The overall network will then have a *thin crossing point* at the juncture of the two subnetworks. Having few dependencies, the two domains will be modules within the larger system. In the task network, modules are separated from one another by thin crossing points and hide information. (Baldwin, 2020, p. 10, emphasis in original).

The interaction of modules at these crossing points is controlled by an interface (Baldwin and Clark, 2006). Such interfaces make possible a complex ecosystem of decentralized innovation and customer choice that Baldwin and Clark (2000) term *modularity in use*. Examples include computer platforms (Baldwin and Clark, 2000; Bresnahan and Greenstein, 1999; Garud and Kumaraswamy, 1993) and audio products (Langlois and Robertson, 1995).

2.2. Private incentives to create (open) technical interfaces

Existing research focuses on interfaces created by firms, such as proprietary standards (Langlois and Robertson, 1992), open standards promoted by a single firm (Kenney and Pon, 2011; West and Dedrick, 2000), or multi-lateral standards that reconcile various corporate interests (Bekkers et al., 2011; Leiponen, 2008; Simcoe, 2012). In these cases, standards are strategically created to coordinate economic activity, including the entry of new firms that will adhere to standards (Bresnahan and Greenstein, 1999; David and Greenstein, 1990) and invest in complementary goods (Farrell and Gallini, 1988). While firms sometimes promote open interfaces and open standards in an effort to change industry structure (Garud and Kumaraswamy, 1993; West and Dedrick, 2000), more often they seek to limit openness to retain control and imitation barriers that protect their core business model (Eisenmann et al., 2009; Garud et al., 2002; West, 2003).

While Baldwin and Clark (2000) emphasize the inherent advantages of technical and organizational modularity for the industry as a whole, other research has suggested that individual firms often have limited incentives to create technical interfaces or to make them open to outside firms. Pil and Cohen (2006) identify an important trade-off for modularity. While greater modularity makes radical component innovation easier, it also allows rivals to imitate more easily. Therefore, firms that have rapid-innovation capabilities gain an advantage by modularizing. This logic may well have driven automakers to *retreat* from modularization: Concerns about the competitive pressures that a modular industry would bring caused automakers to change their minds about modularization (Jacobides et al., 2016; MacDuffie, 2013).

This reverse logic—firms without rapid innovation capabilities would prefer a less-modular industry structure—also explains de-modularization. Fixson and Park (2008) describe the process in the bicycle component industry, which went from modular to re-integrated, resulting in dominance by a single firm. Studies therefore note the temporary, even cyclical nature of modularity at the industry level (Chesbrough and Kusunoki, 2001; Schilling, 2000) rather than as the inevitable outcome of industry evolution (Ernst, 2005). In the largest systematic review of empirical evidence, Colfer and Baldwin (2016) examine 142 studies and find that industry fragmentation is almost always preceded by technical modularity.

Even when technical interfaces are available, firms may choose to remain vertically integrated (Kapoor, 2013). In the semiconductor industry, de-integration at the industry level is led by the entry of design-only fabless firms rather than the de-integration of vertically-integrated incumbents (Funk and Luo, 2015). Remaining vertically integrated can confer innovative advantages: the broader scope of an integrated firm allows it to generate more complex (Macher, 2006) architectural innovations (Hoetker, 2006; Kapoor and Adner, 2012; Pil and Cohen, 2006) more quickly than specialized entrants.[1]

In the face of such inertia, there may be weak incentives (or strong disincentives) for firms to introduce interfaces and modularity. We therefore propose an alternative source: government funding.

2.3. Government funding of R&D

The literature on public funding of R&D has long been dominated by the rationale that knowledge spillovers lead to under-investment in R&D by private firms (Arrow, 1962; Nelson, 1959). Government funding therefore focuses on "basic science," which ostensibly generates the most spillovers. However, a newer literature has begun to consider institutional aspects of public R&D funding, including incentives. Dosi (1982, p. 160) observes that governments have "non-economic interests (such as, for example, military technological requirements and procurement…)," and cites agency mission as driving the translation of basic science into practice. Accordingly, scholars have identified mechanisms for the transfer of technology out of universities and into firms (e.g., Bercovitz and Feldman, 2005) which subsidies can promote (Feldman and Kelley, 2006). The importance of this translation of basic science to industry is captured by Sumney's (1982, p. 35) alarms about the lag time, or "technology insertion gap", that afflicts military implementation of new technologies. The "unconscionable delay between the creation of a new technology and its application in operational systems…has extended to 10 years or even longer". Thus, the question of how to spur innovative industry clusters is a matter of urgency for policy (Feldman et al., 2005).

Foray et al. (2012) have long called for more research on mission-orientation, observing that the literature is fractured into specialized domains, such as defense, health, and agriculture. Even now, "mission" is often taken to mean moonshots or politically motivated programs (Bloom et al., 2019). But agencies have missions that involve complex political and business motivations, which dictate budgets and allocations across research areas beyond just basic science (Sampat, 2012; Wright, 2012). One particularly important distinction is "between mission and science agencies" (Rathje and Katila, 2021, p. 8) developed by Ergas (1987). Mervis (2016) compares DARPA's funding process with the National Science Foundation's (NSF) process, noting differences in the amount of money awarded, methods for identifying recipients, decision-making authority, and oversight. More generally, Rathje and Katila (2021) theorize that mission-oriented agencies use centrally organized agency structure to promote radical innovations.

Of particular interest in the literature and our setting is DARPA, an agency formed in 1958 within the DoD to respond to the Sputnik crisis. DARPA has led basic research funding of technologies that are too risky, have no immediate application, or fall outside the scope of a single service (Van Atta et al., 1991). But DARPA's process has also been notable, creating networks across universities and firms with norms of open sharing of research (Fuchs, 2010) and connecting researchers with each other (Colatat, 2015). This role as research clearinghouse for the diffusion of expertise and diverse approaches (Fuchs, 2010; Colatat, 2015) arguably has far more impact on innovation (Holbrook, 1995) than the DoD's role as customer, which has been studied more extensively (e.g., Mowery, 2009). The creation of social networks to disseminate findings quickly and widely (Fuchs, 2010) is "more important to DARPA's function than the military's role as a customer" (Azoulay et al., 2019). In part, the DoD's role as a monopsony buyer yields a supplier base that avoids duplication but also locks in existing technology (Kaufman et al., 2003).

Despite the extensive research on successful agencies like DARPA, questions remain about how best to maintain that success and possibly extend it to other agencies. DARPA has served as a change agent by creating institutions and communities (Bonvillian, 2018) but questions remain about what is "ARPA-ble" (Azoulay et al., 2019). We suggest that, in addition to transferring features of DARPA's organizational practices, DARPA and other agencies can also consider the highly leveraged nature of modularity in public funding decisions.

3. Research design

We apply historical analysis to the semiconductor industry, a key example of modularity in Baldwin and Clark's (2000) theory. Historical analysis is particularly useful for explaining institutional change over time (Ingram et al., 2012); as Kahl et al. (2012, p. *x*) say, it "involves a deep dive into a small number of cases or phenomena… to explain what happened, and how and why it happened." But a deep dive into even a single case can also powerfully inform theory, another goal of this study. For this purpose, Eisenhardt (1989, p. 537) recommends selecting "extreme situations" or what Ingram et al. (2012, p. 255) refer to as "outlier observations" because these are likely to "extend the emergent theory" (Eisenhardt, 1989, p. 537).

We choose the semiconductor industry, and specifically the creation of an open technical interface, for its extreme importance to institutional change or industry evolution, but also as an episode in which details significantly inform theories about modularity and public R&D funding.

This industry's innovativeness and central position in the computing industry has long attracted scholarly attention. A literature on innovation has studied types of innovation (Henderson and Clark, 1990), industry structure (Macher, 2006; Macher and Mowery, 2004), and firm strategy (Kapoor, 2013; Kapoor and Adner, 2012) in the semiconductor industry.

But while popular and scholarly narratives have focused on innovation by private firms, the industry is built on the DoD's support of computing, which dates back to the inception of computer technology in World War II (Flamm, 1988). After establishing the basic von Neumann architecture of computers in the 1950s, government funding continued to support research in every important technology area introduced the following decade: "rotating magnetic storage, use of transistors, development of the magnetic core memory, and use of integrated circuits… all benefited from significant government-funded research support" (Flamm, 1988, p. 13).

We examine a narrow period of this long history, focusing on the creation of a technical interface that allowed firms to separate design from manufacturing. This eventually enabled modularity at the organization and industry level, permitting specialization by new entrants — thus transforming an industry once dominated by integrated firms into "an ecosystem of integrated and specialized firms transacting with each other through markets for manufacturing" (Kapoor, 2013, p. 1208).

---

[1] Some industries (such as telecommunications) require formal standardization of such interfaces. Recognizing that standards can promote de-integration (Langlois and Robertson, 1992), firms have collaborated to provide anticipatory standards that enable vertical (or horizontal) interoperability (Bar and Leiponen, 2014; Bekkers et al., 2011; Leiponen, 2008; Simcoe, 2012).

Table 1
Interviews.

Name	Role	Date
Academia		
Carver Mead	Coauthor of *Introduction to VLSI Systems;* Professor emeritus, Caltech	9/2020[a]
Lynn Conway	Coauthor of *Introduction to VLSI Systems;* Professor emeritus, University of Michigan	7/2021
Marina Chen	Carver Mead grad student, Chair emeritus, Boston University Computer Science Dept.	10/2020
Industry		
Douglas Fairbairn	Computer History Museum historian, founder of VLSI Technologies and *VLSI Design*	6/2020
Robert Garner	Engineer in Lynn Conway's group at PARC, later at Sun Microsystems	6/2020

[a] Supplemented by e-mail correspondence From Dec. 2020 to Jan. 2022.

However, this technical interface was but one necessary—and not sufficient—condition for a de-integrated industry structure, and the modularity literature is quite clear about the distinction between technical modularity and organizational or market modularity (Chesbrough and Kusunoki, 2001). So while the longer historical arc and the wide variety of specialized entrants motivates our interest, much of that arc is outside the scope of this study. Rather, we focus on the beginning of that transformation by examining the many components that were part of the new technical interface, as well as the incentives of public funders and private firms in creating or opposing that new interface.

Our historical evidence includes contemporaneous documentation such as technical publications and government reports, and oral histories, published scholarly research (Table 2) and interviews (Table 1). Of particular interest is the step-wise development of a new technology, sources of funding for each of these research activities, and the contact tracing of individuals and their ideas, i.e., the intellectual history of the new technology.

4. Interface development and public funding

In the 1960s and 1970s, firms producing semiconductor chips had to both design the chips and manufacture them. Together, these processes required cutting edge science in several domains: electron-device physics, material science, photolithography, solid-state chemistry, electronic circuits, digital logic, computer architecture, and software. The industry therefore came to be dominated by a few highly innovative, vertically integrated firms with the financial and human capital to manage this varied expertise.

In semiconductor design, integrating ever more circuits onto a single chip enabled higher performance in terms of speed and capabilities. Customers rewarded microprocessor designers who created faster, more complex chips and, in the 1970s, a new technology was emerging to massively increase this complexity, Very Large Scale Integration (VLSI). Meanwhile, the manufacturing of semiconductors was a separate technological feat of its own. To boost performance, firms shrank the dimensions of circuits and thus chips. Shortening the distance that electrons had to travel increased the speed with which chips perform instructions. Miniaturization depended upon ongoing improvements to the photolithography process (Adner and Kapoor, 2010; Henderson and Clark, 1990) and drove the biennial doubling of chip performance known as Moore's Law (Brock, 2006). By the early 1970s, the total value of US semiconductor sales exceeded $3 billion annually (Webbink, 1977, p. 11).

Amidst this technological and market success, a new technical interface was developed, permitting a separation of design from production. Industry observers recognized how the development of this interface transformed the industry. In bestowing their annual achievement award to the two primary inventors — Carver Mead and Lynn Conway — *Electronics* magazine described their effort as "bringing about a fundamental reassessment of how ICs are put together" and helping to "spawn a common design culture, so necessary in the VLSI era…" (Marshall et al., 1981, p. 103).

Academic researchers later noted that the interface enabled a shift in the industry structure by creating modularity and the opportunity for new entry:

> In the late 1970s and early 1980s many observers were predicting that the industry would consolidate into a small number of vertically integrated suppliers. Instead, the industry broke apart at a critical modular boundary—the design-to-fab interface. The potential for

Table 2
Oral histories, contemporary accounts.

Name	Material	Year
Carver Mead	• Computers that put the power where it belongs	Essay, 1972
	• ESP, A Distributed Architecture LSI Machine	Report, 1974
	• Basic limitations in microcircuit fabrication technology (with Sutherland, Everhart)	Report, 1976
	• The 1981 Achievement Award (by Marshall et al.)	
	• Silicon compilers and foundries will usher in user-designed VLSI (with Lewicki)	Essay, 1981
	• Caltech	Essay, 1982
	• Computer History Museum	
	• My First Chip	Oral history, 1996
		Oral history, 2009
		Memoir, 2017
Lynn Conway	• University Scene	Memoir, 1980
	• Documentation for participants in MPC580 (with Strollo, et al.)	Memo, 1980
	• The MPC adventures	
	• The 1981 Achievement Award (by Marshall et al.)	Memoir, 1981
	• Reminiscences of the VLSI Revolution	Essay, 1981
		Memoir, 2012
Morris Chang	• Computer History Museum	Oral history, 2007
Douglas Fairbairn	• The Silicon Foundry: Concepts and Reality	Essay, 1981
	• VLSI: A new Frontier for Systems Designers	Essay, 1982
	• Computer History Museum	Oral history, 2016
Cesar Piña	• Evolution of the MOSIS VLSI Educational Program	Memoir, 2002
Christine Tomovich	• MOSIS-A gateway to silicon	Memo, 1988

> this split was inherent in the pattern independence of the planar process, but Mead and Conway's insight and design rules were required to make the modular structure a reality. (Baldwin and Clark, 2000, p. 87).

But these three sentences make the transformation seem more deliberate and deterministic than it actually was. Below, we trace how this process unfolded. In the 1960s and 1970s, the DoD funded basic research at Caltech in hopes of accelerating the rate of semiconductor innovation. Against this backdrop, we focus on a ten-year period, 1970–1980, during which Caltech and Xerox scientists created a standardized process for partitioning the design and fabrication activities, and pilot-tested this process in the face of skepticism and even active opposition from industry incumbents. DARPA then funded a fabrication service that, since 1981, has allowed universities (and later, firms) to prototype their new designs. Finally, we note that once the partitioning and interface had proven feasible, new entrants exploited this open interface to create new organizational forms on both sides of that interface. Table 3 summarizes key events during this process.

Table 3
Timeline for creating semiconductor design/fabrication interface.

Date	Event
Prologue: Funding Basic Research	
1960	Carver Mead gets initial funding from Office of Naval Research
1964–1966	Ivan Sutherland heads ARPA's Information Processing Techniques Office (IPTO)
1967	Gordon Moore and Robert Noyce found Intel with Mead as Consultant
1968	Mead observes chip-making process while consulting for Moore at Intel
1971	Mead begins teaching LSI design class where students design, fabricate and test integrated-circuit projects
1974	Ivan Sutherland joins Caltech as founding chair of Computer Science department
Fall 1975	Bert and Ivan Sutherland introduce Mead and Lynn Conway
1976	Conway and Doug Fairbairn represent PARC in Caltech's industrial research consortium, the Silicon Structures Project
Phase I: Interface Development funded by DARPA	
1976	Mead's Caltech Integrated Circuit Design course is offered in both Computer Science and Electrical Engineering
1976	Ivan Sutherland and Ron Ayres create first draft of Caltech Interface Format (CIF)
November 1976	Sutherland, Mead and Thomas Everhart publish report for DARPA advocating government support for VLSI research
Fall 1977	Textbook drafts used by Mead (CalTech), Carlo Sequin (Berkeley)
Feb. 1978	Textbook draft used by Bob Sproull (CMU) and Fred Rosenberger (WUSTL) using ARPAnet for communication
Spring 1978	Bob Sproull and Dick Lyon (PARC) create CIF 2.0 spec
Summer 1978	Mead & Conway complete draft of full textbook
Fall 1978	Conway teaches class at MIT, with chips fabricated at HP, using ARPAnet for communication
Spring 1979	Mead & Conway's *VLSI Design* textbook published
Spring 1979	Doug Fairbairn and Dick Lyon teach and videotape internal course for PARC employees
Summer 1979	Courses to train faculty offered at PARC and U. Washington
Fall 1979	MPC79: Faculty at a dozen universities teach classes from draft textbook; 82 designs submitted by 124 participants via ARPAnet to PARC, masks made by Micro-Mask and fabricated at HP.
Spring 1980	MPC580 repeats MPC79 experiment, with 171 designs fabricated for 15 organizations
October 1981	Leading trade journal (*Electronics*) recognizes Mead & Conway with 1981 Achievement Award
Phase II: DARPA-funded fabrication service	
October 1979	DARPA awards first grant to Information Sciences Institute (USC) for MOSIS automated VLSI fabrication service
January 1981	MOSIS 1.0 completed, fabricates first projects for DARPA researchers using designs submitted via ARPAnet email interface
1981	MOSIS allows approved DoD contractors access to service.
1985	With NSF funding, MOSIS expands access to all US universities

Sources: Marshall et al. (1981), Conway (1981), Fairbairn (1982).

4.1. Prologue: fundamental research funded by defense department

As powerful and important as early integrated circuits were, their potential was far greater, according to a handful of far-sighted scholars. Prominent among them was Carver Mead, a Caltech professor who had been interested in semiconductors since at least 1959 when he began consulting for Gordon Moore, then at Fairchild Semiconductors. Moore was interested in Mead's work on electron tunneling which, in theory, would eventually interfere with transistors as they continued to miniaturize (Mead, 2017).

Research on electron tunneling and semiconductors was also of interest to the DoD. Mead received funding from the Office of Naval Research (ONR), a small agency that "serve(d) as a talent agency for ARPA"[2] (NRC, 1999, p. 100). It identified promising researchers and provided a "sandbox" for new ideas that, if successful, would merit subsequent DARPA funding (NRC, 1999, p. 121). Mead recalls that in 1960 he first encountered the person who would become his long-term benefactor, showing how quickly and easily the ONR could make decisions about financial support.

> This guy waltzed into my office, unannounced. And he said, "Hi. I'm Arnold Shostak from the Office of Naval Research. What are you doing?" …In those days at the ONR—there was a lot of personal freedom…to find the best people…They were really in search of the most original ideas and the highest energy people… And, so, this guy would hear about something somebody was doing and come around and…he did that every year. So, I told him what I was doing. It was the tunneling stuff at the time. And he said, "Oh, that's interesting. How would you like a contract? (Interview, Sept 24, 2020).

Mead strengthened his ties to DoD in 1976 when Ivan Sutherland joined Caltech as the founding chairman of the Computer Science Department. Prior to Caltech, in 1964–1966, Sutherland led ARPA's Information Processing Techniques Office (IPTO) — which became the DoD's primary source of funding for advancing computing research in the 1970s and 1980s (NRC, 1999, p. 99).

By the mid-1960s, Mead began encountering a concern in the industry about the limits to miniaturization; as devices became smaller, the heat from so many devices would become too great. Analyzing the problem, Mead concluded that as physical dimensions scaled down, so did voltages, so that power did not increase with speed. "What Mead had calculated was that…shrinking the sizes of the transistors on the chips would result in an exponential improvement in their performance. By making transistors smaller and cramming more and more of them onto a single chip, electronics would not only become cheaper, they would also become better" (Brock, 2006, p. 99). The skepticism that followed was met by Mead's "personal crusade, a barnstorming crisscrossing of the country" (Brock, 2006, p. 100), "to instill in the silicon community a belief in the long-term viability of Moore's law, and to motivate the silicon community to invest the effort required to make Moore's law a reality" (Brock, 2006, p. 97).

But if down-scaling did not create power and heat problems, it did create other bottlenecks, which Mead discovered at the newly founded Intel Corporation. Moore invited Mead to participate, as a consultant, in the founding of Intel in 1968, and Mead's visits to the company gave him insight into the time-consuming, manual process of integrated-circuit design and manufacture. This inspired him to develop a better way to make chips, by first making one himself. A chip design comprises lots of computational building blocks connected by metal connections or "traces". This design is implemented in a "mask", which is used to etch

---

[2] The agency was named ARPA from 1958 to 1972 and 1993–1995, and DARPA between those two periods and since 1995 (Fong, 2001).

or print the design onto silicon wafers using photolithography. To pack more elements into a small space, multiple layers, each with a different design, are stacked on top of each other.[3]

In the industry procedure of the 1970s, each step of the process was done by hand by a specialized expert. The design was drawn by hand on gridded Mylar at several hundred times the desired scale. Then the specialist traced the outline of shapes onto Rubylith, a sheet of Mylar coated with a thin red film, with the help of a Coordinograph that guided the cutting blade very precisely. Once the shapes were cut into the Rubylith, the colored "ruby" coating was peeled off by hand with a pair of sharp-pointed tweezers leaving a void in the shape of the desired design. A large fraction of the errors in final masks were due to "peeling errors"—small sections of ruby that had been cut but not removed. Mead saw immediately that there was simply no way, even with the help of his students, that he could accomplish even a modestly complex chip design using this "industry standard" method.

But he also had an important insight: memory chips were designed differently, as an array of cells, each containing the circuitry to store one bit of memory.[4] Mead realized that any digital function could be implemented using a small number of system building blocks designed as arrays.[5] This design paradigm turned out to be easy for students to learn. By the end of the quarter, each student had designed their own project using simple computer tools that Mead had developed for his own first chip. He used the same tools to place all eight of the individual student projects onto a single layout. The class multi-project chip was fabricated over the 1971 Christmas-New Year holiday.[6] When classes convened in January 1972, each student tested their own chip—some destroyed their project in the process and required a replacement be mounted and bonded. In the end all eight projects worked. This first LSI course became the model for the Mead-Conway book and the subsequent courses taught from it.

Sutherland and Mead described the shortcomings of the existing semiconductor process and industry division of labor in a RAND report advocating DARPA support for VLSI research. They argued that the cumbersome process Mead had witnessed at Intel, with its complex idiosyncratic designs and manual production process, would become a bottleneck; as Moore's Law miniaturized chips, it would accommodate exponentially more circuits onto a chip, but the existing process would be unable to grow exponentially more complex (Sutherland et al., 1976).

Their report led Bob Kahn, head of IPTO 1979–1986, to create the VLSI Project in 1978. During the first two years of the project, DARPA funded VLSI technology development at major universities, including Caltech. "Many, if not most, of the participants were early adopters of the Mead-Conway design methods and thus had a common basis on which to build their research explorations" (NRC, 1999, p. 117). The VLSI Project continued into the 1980s, funding university research into reduced instruction set computing (RISC) and graphics microprocessors, parallel computing, and electronic design automation (EDA) tools, which, in turn, enabled spinoff companies such as MIPS, Silicon Graphics, Sun Microsystems, and Thinking Machines (NRC, 1999).[7]

One solution to the bottleneck identified by Sutherland and Mead was to have customers help design chips for their own use (Sutherland and Mead, 1977), such as when Mead (1972) proposed creating a specialized chip for optically sequencing DNA. Having computer-maker customers involved would make the most of semiconductor technology and introduce the possibility of a wider set of applications. A prominent example of backward integration by a computer maker was IBM which, from the start, designed and manufactured computers *and* the chips that went into them.[8] Texas Instruments was a chip maker that later forward integrated into devices, including calculators (1972) and its Speak & Spell educational toy (1978). But a redrawing of the vertical structure of the industry could expand possibilities, as Douglas Fairbairn, founder of VLSI Technologies and *VLSI Design* magazine, explains:

> We needed new computer architectures to take advantage of the characteristics of ICs. To accomplish [this], we needed to create the concept of a "tall thin man (woman)" whose knowledge could span the whole process from architecture to IC layout. This would lead to true optimization… not the false optimization which was happening only at the transistor/layout level at the time. To make this happen, we needed to simplify design at the transistor and layout levels. In the process of doing that, we should make ICs which are not optimized for one fab, but can be run in multiple fabs… thus setting the groundwork for foundries. (Interview, June 1, 2020).

Fresh from Stanford, in 1971 Fairbairn had joined the System Science Laboratory (SSL) at the famed Xerox Palo Alto Research Center (PARC). He first met Mead in 1976, when the manager of the SSL — Ivan Sutherland's older brother Bert — assigned him to help represent PARC in collaborative research with Caltech.[9] The senior collaborator with Caltech was Lynn Conway, who joined PARC in 1973 after work at IBM and Memorex (Conway, 2012; Fairbairn, 2016; Hiltzik, 1999).

---

[3] For a complex chip, such as a microprocessor, designers first create a functional description, or instruction set. Instructions are implemented using system building blocks such as adders, registers, decoders, etc., which are themselves a diagram of logic operations made up of interconnected logic primitives such as NOR gates. The logic primitives are implemented as electronic circuits composed of interconnected primitives such as transistors, capacitors, etc. Each of those primitives, and the connections between them, are implemented as a set of inter-related shapes on the surface of the silicon wafer. Each physical layer is created by a photolithographic process from a mask. The totality of the shapes of all the mask layers for a chip is called its "layout".

[4] The cells also contained sections of wire that would run vertically or horizontally through the cell. These wires were used, e.g., to supply power, carry data to and from the cell, or command the cell to read or write. When the array was "tiled" with cells, these short sections of wire merged and formed all the wiring required to operate the entire memory array. In addition, specialized cells along the edges were "pitch-matched" to those in the array, so the entire memory block design was accomplished by designing optimized layouts for nine cells: a single memory cell, four special cells for providing power and signals to the four edges of the array, and a specialized cell for each corner. The selection of which rows and columns to activate on a given memory access could be accomplished by a pitch-matched decoder formed in a similar manner, with the number of cells to be designed scaling as the log2 of the number of lines to be distinguished.

[5] Mead's exploration of chip design and fabrication from this period is described in a documentary, My First Chip (Mead, 2017). The class he taught starting in the fall of 1971 as part of his ongoing learning process is documented in Mead (1972).

[6] Mead used Intel's fab for his class projects. His former graduate student, Gerry Parker, had joined Intel in 1973 and was in charge of reliability at the fab. As part of his job, he performed "engineering runs" of wafers to monitor reliability, and could run Mead's projects. When the wafers came out of fab, Gerry's assistant separated them into individual chips, each of which had copies of all student projects on it. Mead mounted enough chips in 16-pin packages so that each student could have their own, and used a bonder he had acquired to make connections to a different student project for each package. All of these steps were in place because they were debugged in the process of designing, fabricating, and testing Mead's first chip.

[7] Funding for many of the computing projects shifted from the VLSI Project to the Strategic Computing Initiative in 1983, at the beginning of Conway's two years at DARPA as Assistant Director for Strategic Computing (Conway, 2012; Roland, 2002).

[8] Langlois and Steinmueller (1999) note that transistors replaced vacuum tubes, the main producers of which were firms like IBM that used vacuum tubes in their products. Therefore, as innovative as transistors were, they were not architecturally disruptive: vacuum tube producers simply switched to producing transistors.

[9] PARC joined the Silicon Structures Project, an industrial research program created by Ivan Sutherland soon after arriving at Caltech. While NSF funded, its primary revenue came by charging computer firms (and Intel) $100,000/year to have their researchers collaborate with a Caltech faculty member and doctoral students (Mead, 2004).

At PARC, Conway experienced firsthand the challenges that Mead described for computer systems companies trying to develop custom semiconductors. She had built an optical character recognition (OCR) system for fax machines to make faxing more efficient. Using existing TTL technology from Texas Instruments, which she likened to Lego building blocks, the system "filled a full rack of circuit boards" (Conway, 2012, p. 12), making it commercially infeasible. But she felt certain that the whole thing could be implemented using the new semiconductor technology that was just beginning to emerge (Conway, 2012).

Even more than Mead, Conway also had access to ARPA and its research community. In 1970, PARC had hired Bob Taylor, Ivan Sutherland's former assistant and successor at IPTO; over the next decade, Taylor's role was to recruit top ARPA-funded researchers from around the country to staff PARC's R&D labs, internally termed the "ARPA Army" (Fong, 2001; Hiltzik, 1999). These ties were leveraged by Conway when she and Mead were transforming semiconductor design from 1976 to 1980, both to use ARPA resources to support their efforts, and to access ARPA-funded engineering and computer science departments that were, by then, the natural audience for their new process.

4.2. *Phase 1: interface development funded by DARPA*

In its role as talent agency, the ONR succeeded with its funding of Carver Mead.[10] Not only did Mead help to spur private investment in down-scaling semiconductor chips, but he and his colleagues identified bottlenecks—and solutions—that were aligned with DoD interests. Military procurement practices of second sourcing were meant to make supply chains more robust but often resulted in lower quality and effort.[11] An alternative to this practice was to make technology standards open because standards allow firms to make specific investments without fearing expropriation by the owner of the standard (Farrell and Gallini, 1988). Open standards would make possible vendor-independent semiconductor components, such that multiple vendors could produce the component regardless who designed the component. As one aerospace contractor later wrote:

> [A] benefit [of] vendor independent designs [is that they] can be processed at different foundries, using different feature sizes and different technologies to take advantage of electronic technology evolutions and guarantee continued availability of hardware as products are obsoleted or discontinued due to changes in economic conditions. (Hanna, 1989, p. 12).

However, while Farrell and Gallini (1988) show that firms can benefit from open licensing, Mead faced stiff resistance from the semiconductor industry, consistent with such resistance in other industry contexts (Fixson and Park, 2008; Jacobides et al., 2016; MacDuffie, 2013). Indeed, Mead's efforts to develop an open interface led to a personal rift with Andy Grove, then CEO of Intel.

> Andy Grove finally said, "Carver, we don't want anything to do with anything you're doing because you're undermining our position in the industry" …[F]ortunately, Andy and I got a chance to chat before he died, and by then he was friendly again. I think he realized that every custom chip creates a market for one of their chips. (Mead, C. 2021. Interview with authors).

Conway encountered negative reactions of her own. "The first sign you've been noticed is you get resistance. They start criticizing what you're doing" (Conway, L. 2021. Interview with authors). Her own experience of that resistance resembled what Mead recounted: A consultant to Texas Instruments warned managers that "Lynn Conway is crazy. You have to stop her" (Conway, L. 2021. Interview with authors).

Moreover, secrecy extended throughout the value chain. All of the tools and coding languages involved were proprietary. This helped perpetuate the industry structure, because only manufacturers could create new semiconductor designs.

> [D]esign rules in those days were proprietary. Nobody would let you see their design rules. So although they were all pretty much the same, nobody would let you see them, so nobody knew—what would you draw if you were going to draw an integrated circuit? (Mead, 2009, p. 17).

But Mead's experience creating his own chip convinced him that the industry needed design rules that were simpler and that freed design from the specifics of the fabrication process. For Mead, addressing this issue, again, revolved around teaching the LSI design class he began in 1971. By 1976, he and other Caltech researchers were collaborating with Conway and Fairbairn of PARC to develop processes and prototype software to simplify the design process (Conway, 2012).

As Mead and Conway developed material for their textbook, they continued to simplify and demystify the chip design process, and the ONR continued to provide financial support. The work involved four steps and an ever-widening set of collaborators.

First was a set of design rules (Conway, 2012). Conway viewed the design rules as a paradigm shift akin to movable type, and saw teaching students as an under-the-radar way to propagate that shift (Conway, 2021, interview). The design approach used proportional dimensions instead of actual measurements. This had the benefit of making designs "scalable": as dimensions shrank due to improved manufacturing technology, a designer could create a design that worked on any generation of manufacturing technology.

Second, in addition to design rules and methodology, the student designs had to be fabricated on an industrial fab. When Mead started teaching LSI design in 1971, the designs were tied to the Gerber plotter format he used. At that time, the Gerber plotter was the only computer-output device with the required resolution, and its format was freely available. Plotting the original chip layouts at several-hundred times final scale was an excellent solution because originals from semiconductor firms were Rubylith patterns at the same scale. But by 1976, the industry had caught on to computer-aided design (CAD), and mask suppliers were equipped with computer-driven pattern generators that produced originals at 10 times final size, saving an expensive reduction step in the mask-making process. Computer-aided design suites were available from several vendors that could interface directly with these pattern generators.

The leading industry standard was the proprietary GDSII system owned by Calma, which refused to share its file format with Caltech. So, Ivan Sutherland and two colleagues developed an open file format for specifying semiconductor mask layout called the Caltech Intermediate Form (CIF) (Ayres, 1998; Mead and Conway, 1980). This format remained in use for semiconductor fabrication for the next four decades. Both the availability of primary pattern generators at mask vendors and the ascendance of CAD system suppliers represented a large increase in industry modularity during the 1970s.

Third, the chips had to work properly, but that was not enough—-they also had to run fast enough. So any credible design approach needed a way to estimate the logic delay through various signal paths on the chip. Commercial analog simulators required vast computing resources and often produced misleading results. The approach adopted in Mead and Conway's textbook was based on first principles, was readily understood, and scaled easily to a new process. It was based on the fact that all delays in a digital system can be expressed as multiples of the transit time, *tau*, of a minimum-sized transistor.

---

[10] Although the largest funding overall came from ARPA, Mead later recalled that his overall effort "was [initially] funded by ONR and would not have been possible without that support" (Mead, e-mail, Jan. 27, 2022).

[11] Typically, the military buyer chooses a design from several competing proposals. The winning firm produces the design but must then transfer the technology to a second producer. Riordan and Sappington (1989) show that such policies reduce quality and effort by bidding firms as they anticipate reduced revenues after transferring technology to a second source.

> I think…the methodology…really demystified a lot of that. Just how a two-dimensional pattern created a circuit was made very clear, but that wasn't an obvious thing to people back then. The whole notion of, "Where did circuit performance come from?" The little *tau* model was a simplification, but without losing the essence of where the time went in an integrated circuit (Mead, 2009, p. 17).

Fourth, fabricating multiple student prototype designs on multi-project chips entailed its own set of technical challenges, some of which have already been described. When mass-producing semiconductor chips, a single design is arranged multiple times onto a standard silicon wafer. When the wafer is "diced" into separate chips, each chip is mounted into a "package" and the "bonding pads" for inputs and outputs to and from the chip are "bonded"—connected with fine wire to their respective pins on the package. For volume production, the bonding process is automated, controlled by a dedicated program that contains the "bonding pattern"—the description of which bonding pad on the chip is connected to which pin on the package. However, for student-designed prototypes on a multi-project chip, each chip included a range of designs from multiple designers. Instructions to a bonding service for this kind of chip are thus vastly more complex than those for a standard chip. A program must dictate how to bond each individual project (Conway et al., 1980). The Caltech LSI course never automated the packaging and bonding of individual projects on multi-project chips. Tools for automating these aspects of VLSI courses were essential for the course to be made available to a wider community. These tools and processes were key elements of the technical interface developed in the period after 1976.

The textbook was first piloted by Mead at Caltech in 1977, and then more broadly over the next two years at several universities. As a visiting faculty at M.I.T. in 1978, Conway used her PARC connections to fabricate projects created in her VLSI design class. To transmit the student designs from Boston to California, Conway got permission from Robert Kahn, Director of DARPA's IPTO, to send student designs over the ARPANET — the DARPA-funded research network that provided the only electronic mail network during that period. Conway also convinced Pat Castro, who was in charge of the Hewlett-Packard fab, to fabricate the designs so that when students came back from winter break, they had fabricated chips to work on (Conway, 1981). The success of the MIT class spurred considerable interest from other DARPA-funded universities:

> Word spread quickly on the ARPANET about the M.I.T. course, especially the news about Steele's LISP micro-processor. Many professors asked how to offer similar courses, and how to lead ambitious design projects (Conway, 2012, p. 19).

Mead, Conway and others taught their concepts to colleagues at firms and universities, including at a course for teachers held at the University of Washington. Conway (2021) describes the teaching guide as a complete how-to. "You didn't have to know anything about chip design to teach the class" (Conway, 2021, interview). And others did teach the class, in universities and in firms. Fairbairn recounts his experience teaching VLSI design at Xerox, Hewlett-Packard, and Evans and Sutherland Computer Corp. as "an instructor's delight" (Fairbairn, 1982).

In fall 1979, Conway led an effort called MPC79 in which 124 designs from 11 universities were fabricated by Hewlett-Packard and shipped back to their designers 29 days later (Conway, 1981). The enthusiasm for the course, its textbook, and teaching guide, was clear and demonstrated pent-up demand for simpler approaches to design and fabrication. The course also revealed a network of universities ready to disseminate that new approach. In May 1980, Conway's Xerox colleagues repeated these efforts one last time with MPC580, more than doubling the earlier MPC79 effort with 171 projects from 15 organizations submitted via ARPANET or GTE TELENET and fabricated at Hewlett-Packard (Strollo et al., 1980).

4.3. Phase 2: DARPA-funded fabrication service

With many of the technical hurdles addressed, growing interest from students fueled the need to move away from the use of fabs at Intel or Hewlett-Packard. Failure to address this need could doom the effort, with students unable to produce projects. A contemporary account of the industry process at the time points out the many process steps involved in designing and producing a chip, none of which were standardized; an ideal foundry would standardize them and make them transparent to a designer, much like getting photos developed (Jansen and Fairbairn, 1981). These steps included designing a chip, producing a mask that manufacturers use to print designs onto wafers, fabrication of wafers, packaging wafers into chips, and testing (Jansen and Fairbairn, 1981). Costs for various steps in the process, which also involved different vendors, were negotiated depending on complexity and projected volume, so pricing also lacked standards. And even finding a vendor could be a challenge. Jansen and Fairbairn (1981) assemble a short catalogue of firms, which illustrates the difficulties associated with the existing business models.

> AMI would like a minimum of $75,000 to $150,000 worth of annual business from a single customer, depending greatly on how much work AMI has to do in support of the job…Synertek is looking for a certain threshold of business in the form of follow-on production. For Synertek, this threshold is about $100,000… (Jansen and Fairbairn, 1981, p. 17).

A solution to these difficulties was a service that found capacity on a collection of participating industry fabs. That service was the Metal Oxide Silicon Implementation Service, MOSIS. In 1979 and 1980, DARPA awarded the first of a series of contracts to fund MOSIS (Roland, 2002, p. 356). The contracts were awarded to the Information Sciences Institute (ISI) at the University of Southern California.[12]

> …it was Ivan [Sutherland]'s inspiration, really, that we should start a silicon foundry to be available to the universities that were teaching these courses, and he was the one that convinced ARPA to sponsor the thing which later became called MOSIS. (Mead, 2009, p. 17)

Xerox transferred the prototype system developed for MPC79 and MPC580 to ISI (Strollo et al., 1980). In the first year of the contract, ISI programmers developed their own, more robust implementation of the fabrication service, which was debugged and operational in January 1981 (ISI, 1981). In the initial years, DARPA paid ISI less than $10 million annually to run the service.[13]

MOSIS was not a foundry but a broker that provided access to excess fabrication capacity — initially at integrated semiconductor manufacturers because there "were not dedicated foundries like TSMC," (Fairbairn, 2020, interview).[14] After it was founded in 1987, TSMC (Taiwan Semiconductor Manufacturing Corporation), a manufacturing-only foundry, became a contract manufacturer for MOSIS, as did GlobalFoundries, formed by the 2009 merger of the semiconductor production facilities of AMD, Chartered Semiconductor and later IBM (MOSIS, 2020; Tomovich, 1988).

Industry observers immediately recognized MOSIS as implementing

---

[12] The ISI was founded in 1972 by Keith Uncapher of the RAND Corporation and was best known for creating Internet domain names and hosting the Internet standardization process known as "Requests For Comments" (Snyder et al., 2016).

[13] Roland (2002, p. 356–357) estimates that DARPA paid ISI about $39 million from FY1982-1984 for all work. MOSIS was only a small part of that work; for example, ISI's 1983 annual report (ISI, 1984) lists 18 separate research projects, with MOSIS comprising a portion of the VLSI project.

[14] Piña (2002) reports the large firms participating in the MOSIS brokerage service — TSMC, Agilent Technologies, AMIS, IBM, and Peregrine Semiconductor — and all but the first were vertically integrated.

a standardized interface for fabricating semiconductor designs and the role of the DoD in supporting it as such (Jansen and Fairbairn, 1981).[15] This home within an academic institution, run by Danny Cohen (Ivan Sutherland's former student) and George Lewicki (Mead's former student), was consistent with MOSIS's educational goals:

> The main objective of [MOSIS] is to support the fast turnaround requirement of the ARPA VLSI community and of related programs. Another of our objectives is to help expand the VLSI design community by supporting research institutes and universities that are actively involved in VLSI. We hope to help MIT, Caltech, Berkeley and other universities train as many VLSI students as they can. (Cohen and Lewicki, 1981, p. 1).

MOSIS was an improved version of the prototype system developed by Xerox for MPC79 and MPC580. MOSIS implemented a standardized interface between semiconductor design and fabrication that fabless semiconductor designers used for the next four decades. That standardized interface included

- A methodology and set of design assumptions for how designers should conceive and specify their designs in a way that is independent of the fabrication technology. This process was prototyped by Mead in his Caltech LSI courses of the early-1970s, and then codified and validated by Mead and Conway's (1980) textbook and student beta testers from 1977 to 1980. From 1983 to 1985, the Mead-Conway design rules were supplemented with three new design rules from other sources (Roland, 2002).
- An open file format called the Caltech Intermediate Form (CIF). When Calma and Perkin-Elmer refused to divulge their proprietary semiconductor mask layout formats, Ivan Sutherland and his colleagues developed their own file format, which the MPC79 and MOSIS systems utilized. After MOSIS and CIF proved successful, Calma and Perkin-Elmer opened their file formats for external use (Ayres, 1998; Sproull et al., 1980; Tomovich, 1988).
- Email and underlying communications standards (TCP/IP) of the ARPANET (Crocker, 1982). MPC79 and MOSIS used the ARPANET, with DARPA's permission, to transmit designs from the designer to fabrication services.
- A set of rules and commands implemented by the MPC (later MOSIS) software. This allowed the designer to query and submit designs to an automated server that created fabrication jobs from the submitted designs.

In addition to fabricating the multiproject wafers, the MOSIS service also provided the remaining steps of dicing, packaging and bonding. ISI wrote its own software to create wafer masks and bond pins to the semiconductor package. As part of its service, it validated the quality of a multiproject wafer, then its suppliers cut multiple samples of a design's wafer from the multiproject wafer, packaged it, wire bonded it and shipped it to the customer one to two months after the original design was submitted (Ayres, 1998; ISI, 1981; Tomovich, 1988).[16]

While MOSIS was initially limited to organizations doing DARPA research, in 1981 it added DoD contractors and NSF-approved researchers (Roland, 2002, p. 135). In 1985, the NSF agreed to fund access to students (or non-sponsored research) at any accredited US institution. As a result, more than 50,000 students participated in MOSIS-enabled VLSI design classes from 1990 to 2000. However, those students went on to work at (and launch) fabless semiconductor firms, so that by 1994 commercial customers accounted for a majority of the designs fabricated by MOSIS. Beginning in 1994, DARPA and NSF began reducing their share of financial support, so that by 1998 MOSIS was no longer government funded (Piña, 2002; Weatherford, 1997).

4.4. *Epilogue: de-integration of industry*

MOSIS demonstrated the need for contract manufacturing of semiconductor designs, especially for small customers like students or entrepreneurs. Piña (2002) points out what Jansen and Fairbairn's (1981) survey of the industry showed, that even if a customer could afford to pay for an entire lot of a new chip, it would still be difficult to get the attention of a semiconductor firm. Aggregation of many small projects was thus the only way to access production technology. Meanwhile, Mead and Lewicki (1982, p. 107) promoted the commercial potential of the silicon foundry idea: "Clearly the silicon foundry, processing chips to order much as forges serve the machine industry, is inevitable." And new firms began to respond to the "Mead-and-Conway revolution," including Comdial, which resembled an ideal foundry in terms of its "willingness to do small jobs, the fact that it publishes a process data sheet and price list, and its stated commitment to fast turn-around." (Jansen and Fairbairn, 1981). Similarly, SynMos was founded by AMI employees to "streamlines the process" for designers (Jansen and Fairbairn, 1981, p. 26).

To support the use of MOSIS, DARPA's VLSI Project funded two generations of EDA tools developed at the University of California, Berkeley. First, software called Caesar produced CIF files for use with the MOSIS system and was used to design the RISC and MIPS processors at UC Berkeley and Stanford, respectively, that were commercialized by Sun Microsystems and MIPS Computer Systems. More advanced follow-on software, Magic, formed the basis of proprietary EDA tools from Cadence, Daisy, Mentor and VLSI Technology (NRC, 1999).

All of this was the logical extension of Mead's decade-long idea of separating design from fabrication, under which designers would concentrate on the novel features of a new chip, software would assist with key design steps, and specialized foundries would make the chip:

> This points to a new division of labor, where component designers become systems designers and manufacturing lines become … foundries that will fabricate chips starting with either masks, pattern-generator tapes, or higher-level commonly accepted descriptions of circuits. Foundry fabrication facilities will reflect the state of the art and be available at lower cost than the purchase and maintenance of private fabrication lines. Even firms with large internal facilities will benefit from the added capacity and resources of outside foundries. (Mead and Lewicki, 1982, p. 108–109).

But the industry reaction was mixed. On the one hand, industry incumbents saw Mead and Conway's success as a threat to the status quo. In awarding Mead and Conway their annual Award for Achievement in 1981, *Electronics* magazine described the "dismissal by most of a skeptical semiconductor industry" and the "implacable" semiconductor firms who ignored them (Marshall et al., 1981, p. 103). Conway's idea to disseminate knowledge through college courses proved to be essential in changing opinions. Notes Mead, "It was Lynn's idea to copy the first chapters to enable the schools to start their VLSI courses. She is particularly good at propagating knowledge," (Marshall et al., 1981, p. 103). But the "almost inevitable" resistance from industry was due to the "radical" changes to an existing practice.

> Still, the implications of the Mead-Conway concept disturbed semiconductor industry powers. For one thing, it advocates establishing many small groups to design custom proprietary circuits, attacking the concept of the standard IC, which was the bread and butter of the business. For another, in the mid-1970s Mead in particular began calling for what are called silicon foundries that would accept and fabricate independent design (Marshall et al., 1981, p. 103)

Another source of friction was Mead's prediction of a widespread restructuring of the semiconductor business to separate design and

---

[15] Jansen and Fairbairn (1981) also point out that the Norwegian Defense Research Establishment was similarly interested in promoting standards.

[16] By contrast, the chips fabricated at Intel for Mead in the late 1970s required Caltech to manually package and bond each design.

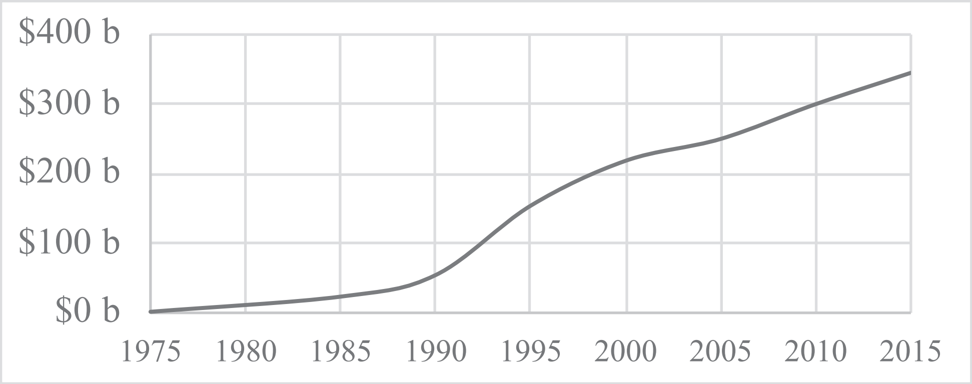

Fig. 1. Semiconductor global revenue growth, 1975–2015
Source: Webbink, 1977; IC Insights, 2011; VerWey, 2019.

fabrication functions. It is not surprising that industry officials who struggled to build their companies grumbled about "ivory tower academics" who offered economic advice (Marshall et al., 1981, p. 103).

On the other hand, some in the industry experimented with the concept of foundries. Jansen and Fairbairn (1981) describe some of the business models being tried, and a 1983 industry census by *VLSI Design* shows new semiconductor firms proliferating (Werner, 1983). All of the firms in that list were vertically integrated in the sense that they performed both design and manufacturing. Many performed some "foundry" work, meaning they would do some manufacturing for other firms. But this was a small part of each firm's business (Fairbairn, 2020, interview).

Even after MOSIS proved that design could be separated from manufacturing — and that there was a demand for such manufacturing services — making a business of a pure-play foundry remained a risky, chicken-and-egg problem. As the founder of TSMC recalled:

> There was no market because there was very little fabless industry, almost none. No fabless industry. So who are you going to sell these wafers to? Who are you going to manufacture the wafers for? (Chang, 2007, p. 13)

Another critical issue with the nascent foundry idea was the business model. As gatekeepers to fabrication services, manufacturers typically took ownership of the design IP, and sought to own some or all of the rights to the chips they fabricated. Fairbairn (1982) likens the model to writers and publishers:

> The best way to do this is probably to assign the rights to a semiconductor company that would then produce, test, market, and distribute the product. The relationship between the designer and the semiconductor company would be almost identical to that between writers and publishers today (Fairbairn, 1982, p. 96).

Eventually, with the support of the Taiwanese government, the first pure-play foundry was formed using a very different business model than that imagined by Fairbairn.[17] The net effect of industry growth (shown in Fig. 1) due to foundries and fabless firms is difficult to assess because the vertically integrated model might have produced new firms with new product ideas serving new customers, all without foundries, and this counterfactual is hard to model. However, the reduction of entry barriers via the new fabless business model meant that, by 1995, both the majority of semiconductor firms and the largest ones were new entrants rather than long-established incumbents (Funk, 2012).

On the other side of the scale, the indirect economic effect of entry by fabless firms is also hard to estimate. Fabless firms expanded the variety of products in the market and served new customers. Before TSMC, the main customers for semiconductors were computer makers and the military. After TSMC, new fabless entrants expanded into new markets to address ever more specialized niches.

5. Discussion

This paper traces the unexpected transformation of the semiconductor industry resulting from DoD support of a brief and relatively small-scale initiative by two scientists in the 1970s. The intervention was notable not for the size or scale of the investment, but rather for a series of ad hoc technical solutions that enabled university engineers to design new semiconductors without owning a factory. The effort succeeded because of a clever diffusion strategy (and strong word-of-mouth adoption) among key opinion leaders from leading engineering and computer science programs at American universities in the 1979–1980 academic year.

The legacy of this brief intervention was both a government-supported prototype manufacturing service, and an open interface that allowed any engineer to submit a design to be manufactured. The new interface had a significant impact on the modularization of industry structure, by de-integrating design and manufacturing, thus allowing entry by new firms on both sides of the interface.

Despite its rapid success and widespread impact, the result was neither expected nor widely supported by industry during its first decade — particularly by the incumbents, vertically-integrated semiconductor producers. A key example of this was vocal opposition by Intel's then-president, Andy Grove. In some ways, it parallels another de-integration that also surprised Grove — the shift from vertically integrated computer makers in 1982 to horizontally specialized component makers (Intel, Microsoft) and system integrators (IBM, Dell, HP) a decade later (Grove, 1996).[18] However, the latter shift was endorsed by Grove because the re-partitioning of computer systems generated economies of scale that cemented Intel's quasi-monopoly, while those for semiconductor production undercut Intel's ability to invest in new

---

[17] In a meeting arranged by his student, Marina Chen, Mead explained to Taiwan's Industrial Technology Research Institute (ITRI) his vision of a de-integrated industry structure, which featured a manufacturing-only foundry. Five years later, in 1986 TSMC was founded with investment from ITRI, Philips Electronics and four Taiwanese firms.

[18] Both are iconic examples of what Baldwin (2018) terms "open product platforms," respectively corresponding to a logistical (or supply-chain) platform and a standards-based platform. We thank the guest editor for calling our attention to this parallel.

production technologies, ultimately driving it seek the acquisition of a pure-play foundry.[19]

5.1. Mission orientation and public agencies

When considering the U.S. national innovation system, Mowery (2009, p. 470) reminds us of the central role that the defense industry and agencies have played since 1950:

> No discussion of the postwar U.S. national innovation system can ignore the role of defense-related R&D and procurement spending. To cite only one example, much of the growth of the postwar information technology sector in the United States, as well as the unusual industrial structure of this sector, reflects the influence of defense-related R&D and procurement spending. The transformation of U.S. research universities, including the postwar rise in prestige and wealth of institutions such as Stanford University, also is attributable in part to the effects of defense-related R&D spending in academia.

He identifies three levers of DoD influence on innovation: R&D funding of innovation, government procurement of these innovations, and civilian spinoffs. He predicts that spinoffs will happen early in a new technology before government and commercial requirements diverge.

Prior research has identified the impact of defense R&D funding and procurement in creating the U.S. software industry in the 1960s and 1970s (Mowery and Langlois, 1996), as well as an indirect role for large U.S. aerospace contractors, which were major customers for mainframe hardware and software (Steinmueller, 1996).[20] During that same period, before civilian applications were economically feasible, the aerospace industry also provided early R&D funding and procurement of communications equipment containing digital computing technology (West, 2008). Meanwhile, DARPA funding for the miniaturization of global positioning system (GPS) receivers laid the groundwork for GPS receivers in every smartphone today (Alexandrow, 2008).

But perhaps the best known and most celebrated (e.g., NRC, 1999) ARPA-funded technology was its eponymous national research network, ARPANET, forerunner of today's global Internet (Greenstein, 2015; Mowery and Simcoe, 2002). There are important parallels between DoD funding of the ARPANET and the Mead-Conway transformation of semiconductors, both before and during DARPA's VLSI Project. As a practical matter, the Mead-Conway design process was pilot tested at ARPANET-connected universities in 1979–1980, thus utilizing a subset of ARPANET users. Also, the initial research centers funded by the VLSI Project overlapped with ARPANET-connected universities. Both the ARPANET and the VLSI Project created open interfaces that were widely disseminated and that anchored collaboration by private firms for decades to come. And in both cases, these open interfaces enabled decentralized firm entry and innovation.

However, there were also important differences. DARPA's ongoing development and implementation of open interfaces over several decades established key enabling characteristics of the Internet (Fleming and Waguespack, 2007; Greenstein, 2009). By contrast, DARPA's financial support of Mead, Conway, and EDA tools development were mostly one-time interventions to partition the design and fabrication process. DoD and NSF support for MOSIS from 1980 to 1998 supported this partitioning and, within a decade, pure-play foundries emerged to satisfy commercial fabrication requirements.

More generally, with this case, we extend the fledgling and under-appreciated literature on mission-orientation in public funding (Foray et al., 2012; Rathje and Katila, 2021). Missions differ dramatically even within a single agency like the DoD; our study brings to light how a small investment nudged an industry to be more modular, diverse, and competitive, to ultimately benefit the funding agency. This narrative of public R&D funding is a significant departure from the existing literature, which focuses on basic science as the public good upon which innovation is built (Arrow, 1962; Nelson, 1959).

Government procurement has previously been identified as a tool for promoting competition and other changes to industry structure (Isaak, 2006). However, our study also illustrates why the literature on mission-oriented funding should move beyond procurement needs (Fabrizio and Mowery, 2005; Mowery, 2010, 2012). We show how ONR and DARPA decisions supported policies such as second sourcing and vendor-independent design (Farrell and Gallini, 1988; Hanna, 1989; Riordan and Sappington, 1989). This suggests the importance of *indirect* effects of agency funding and mission (e.g. enabling competition), which go beyond direct objectives such as funding technology development.

5.2. Leveraging modularity to strengthen policy outcomes

Our paper also links innovation policy to modularity theory. The application of modularity theory to our case demonstrates how technical interfaces are necessary (though not sufficient) for generating changes in industry structure, which in turn unleashed decentralized innovation.

This contribution is significant because even the government agencies that provided support did not formulate their funding strategy as affecting industry organization per se. Therefore, it is important to explain modularity theory's relevance: policymakers can identify opportunities to leverage industry structure.

Explaining the government's role in producing interfaces is also important because private firms may lack the incentives to create interfaces or standards. The extant research on interfaces and industry structure (Baldwin and Clark, 2000; Colfer and Baldwin, 2016; Langlois and Robertson, 1995) focuses on how a key goal of such interfaces is to enable firms to coordinate activity (David and Greenstein, 1990). Hence, we see research streams on firms creating proprietary de facto industry standards (Gawer and Cusumano, 2002), or open standards (West and Dedrick, 2000), as well as cooperative industry standards (Bar and Leiponen, 2014; Simcoe, 2012). Lead firms can sponsor an ecosystem (Gawer and Cusumano, 2002; Jacobides et al., 2018) by creating interfaces to enable modularity and complementary products (Baldwin, 2012; Bresnahan and Greenstein, 1999).

However, our study shows that lead firms may not pursue open interfaces, preferring secrecy instead. A theory of when firms will create an open interface and when they will not is beyond the scope of this study, but our case illustrates why such a theory is valuable; such a theory might also consider the potential competitive pressure of new interfaces that come from non-commercial sources. In our case, publicly funded open interfaces pressured owners of private interfaces to open them up; openness was a *consequence* of changes in industry structure (through entry) rather than an antecedent, as is often theorized (Cargill, 1997; Garud and Kumaraswamy, 1993).

We also contribute to modularity theory by providing a detailed account of the many components of a technical interface as well as the effort involved in promoting market modularity. Conway notes her own anthropological bent as motivating the development of a textbook and course (Conway, 2021), which the *Electronics* magazine award noted as instrumental to popularizing her ideas (Marshall et al., 1981).

And our study adds renewed emphasis on industry structure effects

---

[19] In July 2021, Intel proposed a $30 billion acquisition of GlobalFoundries; although the third largest foundry by market share, it had only 7 % of the global foundry market, compared to 56 % for TSMC and 18 % for Samsung (Aslop, 2021). Rather than accept the Intel offer, the firm raised $2.6 billion in its October 2021 IPO.

[20] Even ignoring the overlap between procurement of military aircraft and "civilian" space industry (e.g. Bell, Boeing, Douglas, Grumman, Lockheed as Apollo suppliers), to date government procurement of space technologies such as satellites and rocket boosters have largely been dual-use (Molas-Gallart, 1997; Pisano, 2006). After six decades, the nascent "space tourism" market, launched in 2021, may eventually create greater divergence between civilian and military technologies.

within modularity theory. What was not anticipated, even by Mead, was how the locus of semiconductor design would move to fabless firms, which in turn expanded the markets for semiconductors. Indeed, scholars studying the industry in the early 2000s described a "mature" industry with entry "slowed somewhat" (Macher and Mowery, 2004, p. 336). The primary shift that Mead had sought was to involve end-user product companies in chip design (because he considered it unlikely that a semiconductor company could design the optimal chip for any end product). Today, producers of low-tech mechanical products like refrigerators or cars have begun to design their own chips (e.g. Greenfield, 2010; Lyytinen and Yoo, 2002). The initial open interfaces spawned an ongoing trend that we term the "momentum of modularity." Once modularity spurs entry, firms innovate, reduce costs, and serve new customers.

5.3. *Future research*

As our epilogue suggests, a new technical interface is a necessary but not sufficient condition for organizational or industry-level modularity. The interface does not guarantee an industry response. Our research suggests that incumbents resisted de-integration, and research by Funk and Luo (2015) shows that de-integration was led by fabless entrants rather than the de-integration of vertically integrated incumbents. Thus, more research is needed to understand the full process of de-integration and industry modularity.

More generally, further research into how semiconductor industry structure eventually shifted will shed light on how government-sponsored interfaces differ from industry-sponsored ones. Prior research has considered both how industry structure affects interfaces (Bekkers et al., 2011) and how interfaces affect industry structure (David and Greenstein, 1990; Kenney and Pon, 2011; Steinmueller, 2003). But the practice of interface standardization over the past 30 years has focused on private economic actors creating interfaces that benefit their self-interest, as when a platform owner creates interfaces to attract third party complements (Gawer and Cusumano, 2002; Baldwin, 2020). Less is known about how this process differs for open interfaces from non-proprietary sponsors. Anecdotally, new entrants prefer open interfaces because they lack the resources to create a vertically integrated firm (Teece, 1986), while incumbents seek to stymie them (West, 2007). This case examines an interface created and used by academics that eventually enabled both fabless firms and foundries; such a trajectory has rarely been identified, let alone studied.

The mission-orientation of this interface is unmistakable and raises additional questions. On the one hand, DARPA had an interest in improving the performance of semiconductor devices. But might its practice of encouraging the publication of research findings (Fuchs, 2010) give strategic rivals access to the fruits of DARPA-funded research? The spread of manufacturing technology to Asian countries was raised as an issue more than two decades ago (Macher et al., 2002; Welling, 1987). One response was to develop technology more quickly than foreign rivals, as was the case in the 1990s when Japanese semiconductor firms surpassed American industry (Khan et al., 2018). But in our case, withholding certain components of the interface had some effect on slowing imitation. For example, Russians translated the Mead-Conway textbook almost immediately but were unable to develop a design industry because the US embargoed manufacturing technology. As a result, Soviet scientists could not fabricate their designs, a learning-by-doing process that is essential to applying the textbook's codified processes (Conway, 2021, interview).

Finally, a growing area of research examines the rate of innovation, especially in the emergence of nascent industries implementing new knowledge (Agarwal et al., 2017; Moeen and Agarwal, 2017). Our study brings mission-oriented public agencies together with academic and industry researchers to bring about rapid adoption. A literature on national innovation systems already cites this combination as critically important (Lundvall, 1992; Nelson, 1993). But future research should consider more broadly how even temporary, university-based, educational consortia can influence the speed and direction of a nation's technology adoption.

CRediT authorship contribution statement

Jennifer Kuan: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Joel West:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank five anonymous reviewers and especially Guest Editor Carliss Baldwin for their insightful suggestions. Early support and encouragement from Maryann Feldman and Erica Fuchs were also instrumental. The paper benefitted from suggestions and comments at the 2020 Special Issue Conference, the 2021 Wharton Conference on Technology and Innovation, and the 2021 Annual Meeting of the Southern Economic Association. This paper would not have been possible without the help of many interviewees, especially Carver Mead, Lynn Conway, and Doug Fairbairn.

References

Adner, R., Kapoor, R., 2010. Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations. Strateg. Manag. J. 31 (3), 306–333.

Agarwal, R., Moeen, M., Shah, S.K., 2017. Athena's birth: triggers, actors, and actions preceding industry inception. Strateg. Entrep. J. 11, 287–305.

Alexandrow, C., 2008. The story of GPS. In: DARPA: 50 Years of Bridging the Gap. Faircount Media, Tampa, FL. https://issuu.com/faircountmedia/docs/darpa50.

Arrow, K.J., 1962. Economic welfare and the allocation of resources for R&D. In: Nelson, R.R. (Ed.), The Rate & Direction of Inventive Activity. Princeton University Press, Princeton, NJ.

Aslop, T., 2021. Top semiconductor foundries ranked by global revenue from 2019 to 2021. July 26. Statista.com. https://www.statista.com/statistics/867223/worldwide-semiconductor-foundries-by-market-share/.

Ayres, R., 1998. A narrative history and description of MOSIS software. J. Syst. Softw. 43 (1), 67–82.

Azoulay, P., Fuchs, E., Goldstein, A.P., Kearney, M., 2019. Funding breakthrough research: promises and challenges of the "ARPA model". Innov. Policy Econ. 19 (1), 69–96.

Baldwin, C.Y., 2008. Where do transactions come from? Modularity, transactions, and the boundaries of firms. Ind. Corp. Chang. 17 (1), 155–195.

Baldwin, C.Y., 2012. Organization design for business ecosystems. J. Organ. Des. 1 (1), 20–23.

Baldwin, C.Y., 2019. Capturing Value by Controlling Bottlenecks in Open Platform Systems. draft Chapter 16 of *Design Rules, Volume 2: How Technology Shapes Organizations*. November 5. Available at SSRN. https://ssrn.com/abstract=3482538.

Baldwin, C.Y., 2020. Transactions in a Task Network. Draft Chapter 2 of *Design Rules, Volume 2: How Technology Shapes Organizations*. August 11. Available at SSRN. https://ssrn.com/abstract=3690565.

Baldwin, C.Y., Clark, K.B., 1997. Managing in an age of modularity. Harv. Bus. Rev. 75 (5), 84–93.

Baldwin, C.Y., Clark, K.B., 2000. Design rules. In: Volume 1: The Power of Modularity. MIT Press, Cambridge, Mass.

Baldwin, C.Y., Clark, K.B., 2006. Modularity in the design of complex engineering systems. In: Braha, D., Minai, A.A., Bar-Yam, Y. (Eds.), Complex Engineered Systems. Springer, Berlin, pp. 175–205.

Baldwin, C.Y., Woodard, C.J., 2009. The architecture of platforms: a unified view. In: Gawer, A. (Ed.), Platforms, Markets and Innovation. Elgar, Cheltenham, U.K., pp. 19–44

Bar, T., Leiponen, A., 2014. Committee composition and networking in standard setting: the case of wireless telecommunications. J. Econ. Manag. Strateg. 23 (1), 1–23.

Bekkers, R., Bongard, R., Nuvolari, A., 2011. An empirical study on the determinants of essential patent claims in compatibility standards. Res. Policy 40 (7), 1001–1015.

Bercovitz, J., Feldman, M., 2005. Entrepreneurial universities and technology transfer: a conceptual framework for understanding knowledge-based economic development. J. Technol. Transf. 31, 175–188.

Bloom, N., Van Reenen, J., Williams, H., 2019. A toolkit of policies to promote innovation. J. Econ. Perspect. 33 (3), 163–184.

Bonvillian, W.B., 2018. DARPA and its ARPA-E and IARPA clones: a unique innovation organization model. Ind. Corp. Chang. 27 (5), 897–914.

Bresnahan, T.F., Greenstein, S., 1999. Technological competition and the structure of the computer industry. J. Ind. Econ. 47 (1), 1–40.

Brock, D.C., 2006. Reflections on Moore's law. In: Brock, D.C. (Ed.), Understanding Moore's Law: Four Decades of Innovation. Chemical Heritage Foundation, pp. 87–108.

Brusoni, S., Fontana, R., 2005. Modularity as an entry strategy: the invasion of new niches in the LAN equipment industry. In: KITeS Working Papers 171. Centre for Knowledge, Internationalization and Technology Studies, Bocconi University, Milan.

Cargill, C.F., 1997. Open systems standardization: a business approach. Prentice Hall PTR, Upper Saddle River, NJ.

Chang, M., 2007. Oral History of Morris Chang. Interviewed by Alan Patterson, Recorded August 24. CHM Reference number: X4151.2008 Computer History Museum.

Chesbrough, H., Kusunoki, K., 2001. The modularity trap: innovation, technology phase shifts and the resulting limits of virtual organizations. In: Nonak, I., Teece, D.J. (Eds.), Managing Industrial Knowledge: Creation, Transfer and Utilization. Sage, London, pp. 202–230.

Cohen, D., Lewicki, G., 1981. MOSIS-the ARPA silicon broker. In: Proceedings of the Caltech Conference on VLSI, pp. 29–44.

Colatat, P., 2015. An organizational perspective to funding science: collaborator novelty at DARPA. Res. Policy 44, 874–887.

Colfer, L.J., Baldwin, C.Y., 2016. The mirroring hypothesis: theory, evidence, and exceptions. Ind. Corp. Chang. 25 (5), 709–738.

Conway, L.A., 1981. The MPC adventures: experiences with the generation of VLSI design and implementation methodologies. In: Proceedings of the Caltech Conference on VLSI, pp. 5–27.

Conway, L.A., 2012. Reminiscences of the VLSI revolution. IEEE Solid-State Circuits 4 (4), 8–31.

Conway, L., Bell, A., Newell, M., Lyon, R., Pasco, R., 1980. Implementation Documentation for the MPC79 Multi-University Multiproject Chip-Set. Internal report, Xerox Palo Alto Research Center. https://ai.eecs.umich.edu/people/conway/VLSI/MPC79/ImpDoc/ImpDoc79Front.html.

Crocker, D., 1982. Standard for the Format of ARPA Internet Text Messages. August 13, URL. https://www.ietf.org/rfc/rfc822.txt.

David, P.A., Greenstein, S., 1990. The economics of compatibility standards: an introduction to recent research. Econ. Innov. New Technol. 1 (1–2), 3–41.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Res. Policy 11, 147–162.

Eisenhardt, K.M., 1989. Building theories from case study research. Acad. Manag. Rev. 14, 532–550.

Eisenmann, T.R., Parker, G., Van Alstyne, M., 2009. Opening platforms: how, when and why? In: Gawer, A. (Ed.), Platforms, Markets and Innovation. Edward Elgar, Cheltenham UK, pp. 131–162.

Ergas, H., 1987. Does technology policy matter?. In: Technology and Global Industry: Companies and Nations in the World Economy. The National Academies Press, Washington, DC.

Ernst, D., 2005. Limits to modularity: reflections on recent developments in chip design. Ind. Innov. 12 (3), 303–335.

Fabrizio, K.R., Mowery, D.C., 2005. Defense-Related R&D and the growth of the postwar information technology industrial complex in the United States, revue d'économie industrielle, 112, 4e trimestre. Réseaux de connaissances, réseaux de defense 27–44.

Fairbairn, D., 1982. VLSI: a new frontier for systems designers. Computer January, 87–96.

Fairbairn, D., 2016. Oral History of Douglas Fairbairn. October 6. Computer History Museum, Mountain View, CA. Reference number: X7960.2017.

Fairbairn, D., 2020. Email Interview With Author.

Farrell, J., Gallini, N.T., 1988. Second-sourcing as a commitment: monopoly incentives to attract competition. Q. J. Econ. 103 (4), 673–694.

Feldman, M.P., Kelley, M.R., 2006. The ex ante assessment of knowledge spillovers: Government R&D policy, economic incentives and private firm behavior. Res. Policy 35, 1509–1521.

Feldman, M.P., Francis, J., Bercovitz, J., 2005. Creating a cluster while building a firm: entrepreneurs and the formation of industrial clusters. Reg. Stud. 39 (1), 129–141.

Fixson, S.K., Park, J.K., 2008. The power of integrality: linkages between product architecture, innovation, and industry structure. Res. Policy 37 (8), 1296–1316.

Flamm, K., 1988. Creating the Computer: Government, Industry, and High Technology. Brookings Institute Press.

Fleming, L., Waguespack, D.M., 2007. Brokerage, boundary spanning, and leadership in open innovation communities. Organ. Sci. 18 (2), 165–180.

Fong, G.R., 2001. ARPA does windows: the defense underpinning of the PC revolution. Bus. Polit. 3 (3), 213–237.

Foray, D., Mowery, D.C., Nelson, R.R., 2012. Public R&D and social challenges: what lessons from mission R&D programs? Res. Policy 41, 1697–1702.

Fuchs, E., 2010. Rethinking the role of the state in technology development: DARPA and the case for embedded network governance. Res. Policy 39, 1133–1147.

Funk, J.L., 2012. The unrecognized connection between vertical disintegration and entrepreneurial opportunities. Long Range Plan. 45 (1), 41–59.

Funk, J.L., Luo, J., 2015. Open standards, vertical disintegration and entrepreneurial opportunities: how vertically-specialized firms entered the U.S. Semiconductor industry. Technovation 45–46, 52–62.

Garud, R., Kumaraswamy, A., 1993. Changing competitive dynamics in network industries: an exploration of sun microsystems' open systems strategy. Strateg. Manag. J. 14 (5), 351–369.

Garud, R., Jain, S., Kumaraswamy, A., 2002. Institutional entrepreneurship in the sponsorship of common technological standards: the case of sun Microsystems and Java. Acad. Manag. J. 45 (1), 196–214.

Gawer, A., Cusumano, M.A., 2002. Platform Leadership: How Intel, Microsoft, and Cisco Drive Industry Innovation. Harvard Business School Press, Boston.

Greenfield, A., 2010. Everyware: The Dawning Age of Ubiquitous Computing. New Riders.

Greenstein, S., 2009. Open platform development and the commercial Internet. In: Gawer, A. (Ed.), Platforms, Markets and Innovation. Edward Elgar, Cheltenham, UK, pp. 219–248.

Greenstein, S., 2015. How the Internet became commercial: Innovation, privatization, and the birth of a new network. Princeton University Press.

Grove, A.S., 1996. Only the Paranoid Survive: How to Exploit the Crisis Points That Challenge Every Company and Career. Broadway Business.

Hall, B.H., Ziedonis, R.H., 2001. The patent paradox revisited: an empirical study of patenting in the US semiconductor industry, 1979–1995. RAND J. Econ. 32 (1), 101–128.

Hanna, W.A., 1989. Improvements in electronic hardware design productivity through design automation and the use of simulation. In: Proceedings of the IEEE National Aerospace and Electronics Conference, pp. 9–16.

Henderson, R.M., Clark, K.B., 1990. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. Adm. Sci. Q. 35 (1), 9–30.

Hiltzik, M., 1999. Dealers of Lightning: Xerox PARC and the Dawn of the Computer Age. HarperCollins, New York.

Hobday, M., 1998. Product complexity, innovation and industrial organisation. Res. Policy 26 (6), 689–710.

Hoetker, G., 2006. Do modular products lead to modular organizations? Strateg. Manag. J. 27, 501–518.

Holbrook, D., 1995. Government support of the semiconductor industry: diverse approaches and information flows. Bus. Econ. Hist. 24, 133–165.

IC Insights, 2011. Tracking the Top 10 Semiconductor Sales Leaders over 26 Years, Research Bulletin, December 19. https://web.archive.org/web/20120222035539/http://www.icinsights.com/news/bulletins/Tracking-The-Top-10-Semiconductor-Sales-Leaders-Over-26-Years/.

Ingram, P., Rao, H., Silverman, B.S., 2012. History in strategy research: what, why, and how? Adv. Strateg. Manag. 29, 241–273.

Isaak, J., 2006. The role of individuals and social capital in POSIX standardization. Int. J. IT Stand. Stand. Res. 4 (1), 1–23.

ISI, 1981. 1980 Annual Technical Report: A Research Program in Computer Technology. Report ISI/SR-81-20. USC Information Sciences Institute, Marina del Rey, Calif.

ISI, 1984. 1983 Annual Technical Report: A Research Program in Computer Technology. Report ISI/SR-84-138. USC Information Sciences Institute, Marina del Rey, Calif.

Jacobides, M.G., MacDuffie, J.P., Tae, C.J., 2016. Agency, structure, and the dominance of OEMs: change and stability in the automotive sector. Strateg. Manag. J. 37 (9), 1942–1967.

Jacobides, M.G., Cennamo, C., Gawer, A., 2018. Towards a theory of ecosystems. Strateg. Manag. J. 39 (8), 2255–2276.

Jansen, W.D., Fairbairn, D.G., 1981. In: The Silicon Foundry: Concepts and Reality, First Quarter. Lambda, pp. 16–26.

Kahl, S.J., Silverman, B.S., Cusumano, M.A., 2012. The integration of history and strategy research. Adv. Strateg. Manag. 29, ix–xxi.

Kapoor, R., 2013. Persistence of integration in the face of specialization: how firms navigated the winds of disintegration and shaped the architecture of the semiconductor industry. Organ. Sci. 24 (4), 1195–1213.

Kapoor, R., Adner, R., 2012. What firms make vs. what they know: how firms' production and knowledge boundaries affect competitive advantage in the face of technological change. Organ. Sci. 23 (5), 1227–1248.

Kaufman, A., Tucci, C.L., Brumer, M., 2003. Can creative destruction be destroyed? Military IR&D and destruction along the value-added chain. Res. Policy 32, 1537–1554.

Kenney, M., Pon, B., 2011. Structuring the smartphone industry: is the mobile internet OS platform the key? J. Ind. Compet. Trade 11 (3), 239–261.

Khan, H.N., Hounshell, D.A., Fuchs, E.R., 2018. Science and research policy at the end of Moore's law. Nat. Electron. 1 (1), 14–21.

Langlois, R.N., Robertson, P.L., 1992. Networks and innovation in a modular system: lessons from the microcomputer and stereo component industries. Res. Policy 21 (4), 297–313.

Langlois, R.N., Robertson, P.L., 1995. Firms, Markets and Economic Change: A Dynamic Theory of Business Institutions. Routledge, London.

Langlois, R.N., Steinmueller, W.E., 1999. The evolution of competitive advantage in the global semiconductor industry: 1947–1996. In: Mowery, D., Nelson, R. (Eds.), The Sources of Industrial Leadership. Cambridge University Press, Cambridge, UK, pp. 19–78.

Leiponen, A.E., 2008. Competing through cooperation: the organization of standard setting in wireless telecommunications. Manag. Sci. 54 (11), 1904–1919.

Lundvall, B. (Ed.), 1992. National Systems of Innovation: Toward a Theory of Innovation and Interactive Learning. St. Martin's Press, New York.

Lyytinen, K., Yoo, Y., 2002. Ubiquitous computing. Commun. ACM 45 (12), 63–96.

MacDuffie, J.P., 2013. Modularity-as-property, modularization-as-process, and “modularity”-as-frame: lessons from product architecture initiatives in the global automotive industry. Glob. Strateg. J. 3, 8–40.

Macher, J.T., 2006. Technological development and the boundaries of the firm: a knowledge-based examination in semiconductor manufacturing. Manag. Sci. 52 (6), 826–843.

Macher, J.T., Mowery, D.C., 2004. Vertical specialization and industry structure in high technology industries. Adv. Strateg. Manag. 21, 317–355.

Macher, J.T., Mowery, D.C., 2008. Introduction. In: Innovation in Global Industries: U.S. Firms Competing in a New World (Collected Studies), National Research Council. The National Academies Press, Washington, DC, pp. 1–18.

Macher, J.T., Mowery, D.C., Simcoe, T.S., 2002. E-business and disintegration of the semiconductor industry value chain. Ind. Innov. 9 (3), 155–181.

Malerba, F., Orsenigo, L., 1997. Technological regimes and sectoral patterns of innovative activities. Ind. Corp. Chang. 6 (1), 83–118.

Marshall, M., Waller, L., Wolff, H., 1981. The 1981 achievement award: Lynn Conway and Carver Mead. Electronics 54 (21), 102–105.

Mead, C., 1972. Computers that put the power where it belongs. Eng. Sci. 35 (4), 4–9.

Mead, C., 2009. Carver Mead Oral History. Recorded May 27. Computer History Museum, Mountain View, CA. Reference number: X4309.2008.

Mead, C., 2017. My First Chip [video]. YouTube. https://youtu.be/F5P5SAlEbo4.

Mead, C.A., Conway, L.A., 1980. Introduction to VLSI systems. Addison-Wesley, Reading, MA.

Mead, C.A., Lewicki, G., 1982. Silicon compilers and foundries will usher in user-designed VLSI: New design methodologies will exploit chip complexity with concurrent systems; architecture and algorithms will entwine on the chip. accessed October 8 Electronics 107–111.

Mervis, J., 2016. What makes DARPA tick? Science 351 (6273), 549–553.

Moeen, M., Agarwal, R., 2017. Incubation of an industry: heterogeneous knowledge bases and modes of value capture. Strateg. Manag. J. 38, 566–587.

Molas-Gallart, J., 1997. Which way to go? Defence technology and the diversity of ‘dual-use’ technology transfer. Res. Policy 26 (3), 367–385.

MOSIS, 2020. The MOSIS Services. accessed October 8. https://www.mosis.com/about.

Mowery, D.C., 2009. National security and national innovation systems. J. Technol. Transfer. 34 (5), 455–472.

Mowery, D.C., 2010. Military R&D and innovation. In: Hall, B., Rosenberg, N. (Eds.), Handbooks in Economics, Volume 01. Elsevier.

Mowery, D.C., 2012. Defense-related R&D as a model for “grand challenges” technology policies. Res. Policy 41, 1703–1715.

Mowery, D.C., Langlois, R.N., 1996. Spinning off and spinning on (?): the federal government role in the development of the US computer software industry. Res. Policy 25 (6), 947–966.

Mowery, D.C., Simcoe, T., 2002. Is the internet a US invention?—An economic and technological history of computer networking. Res. Policy 31, 1369–1387.

Nelson, R.R., 1959. The simple economics of basic research. J. Polit. Econ. 67, 297–306.

Nelson, R.R. (Ed.), 1993. National Innovation Systems: A Comparative Analysis. Oxford University Press, New York.

NRC, 1999. Funding a Revolution: Government Support for Computing Research. National Academy Press, Washington DC.

Pil, F.K., Cohen, S.K., 2006. Modularity: implications for imitation, innovation, and sustained advantage. Acad. Manag. Rev. 31 (4), 995–1011.

Piña, C.A., 2002. Evolution of the MOSIS VLSI educational program. In: Proceedings of the First IEEE International Workshop on Electronic Design, Test and Applications (DELTA ‘02).

Pisano, M., 2006. Moving Europe towards a more effective procurement of space-based assets. Space Policy 22 (3), 176–184.

Prencipe, A., 2000. Breadth and depth of technological capabilities in CoPS: the case of the aircraft engine control system. Res. Policy 29 (7–8), 895–911.

Rathje, J.M., Katila, R., 2021. Enabling technologies and the role of private firms: a machine learning matching analysis. Strateg. Sci. 6 (1), 5–21.

Riordan, M.H., Sappington, D.E.M., 1989. Second sourcing. RAND J. Econ. 20 (1), 41–58.

Roland, A., 2002. Strategic Computing. MIT Press, Cambridge.

Sampat, B.N., 2012. Mission-oriented biomedical research at the NIH. Res. Policy 41 (10), 1729–1741.

Sanchez, R., Mahoney, J.T., 1996. Modularity, flexibility, and knowledge management in product and organization design. Strateg. Manag. J. 17, 63–73.

Schilling, M.A., 2000. Toward a general modular systems theory and its application to interfirm product modularity. Acad. Manag. Rev. 25 (2), 312–334.

Simcoe, T., 2012. Standard setting committees: consensus governance for shared technology platforms. Am. Econ. Rev. 102 (1), 305–336.

Sproull, R., Lyon, R., Trimberger, S., 1980. The Caltech intermediate form for LSI layout description, silicon structures project technical report 2686. Caltech, Pasadena.

Steinmueller, W.E., 1996. The US software industry: an analysis and interpretive history. In: Mowery, D.C. (Ed.), The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure. Oxford University Press, New York, pp. 15–52.

Steinmueller, W.E., 2003. The role of technical standards in coordinating the division of labour in complex system industries. In: The Business of Systems Integration. Oxford University Press, Oxford, UK, pp. 133–151.

Strollo, T., Doughty, T., Krasner, G., Stone, M., Wilner, W., Cohen, D., Conway, L., Bell, A., Newell, M., Lyon, R., Pasco, R., 1980. Documentation for participants in the MPC580 Multiproject Chip-set. In: Xerox PARC Technical Memorandum.

Sumney, L.W., 1982. VHSIC: a status report. August 11. Available at SSRN. In: IEEE Spectrum, December, 34-39.

Sutherland, I.E., Mead, C.A., 1977. Microelectronics and computer science: microelectronics makes it possible to reconsider the design of computers. Sci. Am. 237 (1), 210–228.

Sutherland, I.E., Mead, C.A., Everhart, T.E., 1976. Basic limitations in microcircuit fabrication technology. In: DARPA Report R-1956-ARPA. RAND Corporation, Santa Monica, CA.

Teece, D.J., 1986. Profiting from technological innovation: implications for integration, collaboration, licensing and public policy. Res. Policy 15 (6), 285–305.

Tomovich, C., 1988. MOSIS-A gateway to silicon. IEEE Circuits Devices Mag. 4 (2), 22–23.

Van Atta, R.H., Reed, S., Deitchman, S.J., 1991. DARPA Technical Accomplishments, Volume 2. Institute for Defense Analyses, Alexandria, VA https://apps.dtic.mil/sti/citations/ADA241725.

VerWey, J., 2019. The Health and Competitiveness of the U.S. Semiconductor Manufacturing Equipment Industry. In: Working Paper ID-058. Office of Industries, U.S. International Trade Commission.

Weatherford, M., 1997. MOSIS eyes the future. IEEE Micro 17 (2), 79–80.

Webbink, D.W., 1977. The semiconductor industry: A survey of structure, conduct, and performance. In: Staff Report to the Federal Trade Commission, January.

Welling, K.M., 1987. Play by the Same Rules — Intel’s Andy Grove Says That’s What Semiconductor Makers Must Do. Barron’s. June 29.

Werner, J., 1983. Silicon foundries forge ahead. In: VLSI Design Magazine, July/August, pp. 51–63.

West, J., 2003. How open is open enough? Melding proprietary and open source platform strategies. Res. Policy 32 (7), 1259–1285.

West, J., 2007. The economic realities of open standards: Black, White and many shades of gray. In: Greenstein, S., Stango, V. (Eds.), Standards and Public Policy. Cambridge University Press, Cambridge, pp. 87–122.

West, J., 2008. Commercializing open science: deep space communications as the lead market for Shannon Theory, 1960–73. J. Manag. Stud. 45 (8), 1506–1532.

West, J., Dedrick, J., 2000. Innovation and control in standards architectures: the rise and fall of Japan’s PC-98. Inf. Syst. Res. 11 (2), 197–216.

Whetsell, T.A., Siciliano, M.D., Witkowski, K.G., Leiblein, M.J., 2020. Government as network catalyst: accelerating self-organization in a strategic industry. J. Public Adm. Res. Theory 30 (3), 448–464.

Wright, B.D., 2012. Grand missions of agricultural innovation. Res. Policy 41, 1716–1728.