Interfaces, Modularity and Ecosystem Emergence:

How DARPA Modularized the Semiconductor Ecosystem

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Abstract:

Scholars have identified the pivotal role that modularity plays in creating innovation ecosystems—complex arrangements of buyers, suppliers, and complementors. In large part, this is due to modularity's effect on industry structure, breaking up the value chain along interfaces, thus allowing specialized firms to enter, compete, and innovate. Less well-understood is where modularity comes from. While modularity theory is heavily influenced by the information technology sector, other industries (such as automobiles) suggest a potential conflict between firm incentives and the creation of modular interfaces. We demonstrate the role for government funding in generating modularity using an historical case study of the semiconductor industry and shifts in industry structure enabled by public R&D funding in the 1970s. We argue that this funding was mission-oriented with an interest in changing the semiconductor industry structure from a vertically-integrated oligopoly to a competitive, de-integrated industry. A subsequent shift, to an ecosystem encompassing an ever-expanding variety of customer industries, further increases the long-term economic value of modularity-as-policy.

Key words: modularity, public R&D funding, semiconductor, ecosystem, fabless, foundry

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1. Introduction

A core function of an innovation ecosystem is to promote cooperative value creation (Hannah & Eisenhardt, 2018; Bogers et al, 2019). But this cooperation depends on interfaces and coordination rules that allow firms to develop complementary modules in the value creation process (Jacobides, Cennamo & Gawer, 2018). Thus, modularity plays a mediating role for a broad range of innovations through its impact on industry structure (Baldwin & Woodard, 2009; Baldwin, 2012). The interfaces between modules enable innovation, specialization and entry, and influence the appropriation of returns to innovation (Baldwin & Clark, 2000; Baldwin, 2012, 2019; Brusoni & Fontana, 2005; Colfer & Baldwin, 2016).

However, the issue of where this modularity comes from remains an important question. While some firms seek to extract rents by controlling interfaces at the "thin crossing points" between modules (Baldwin, 2019) — private incentives for their creation are often weak. MacDuffie (2013) and Jacobides, MacDuffie & Tae (2016) document the strategic reversal of automotive firms exploring a modularity strategy, which chose the existing vertically integrated structure over a faster-paced modular structure. Indeed, even where de-integration is possible, some firms remain vertically integrated (Kapoor, 2013) and generate more complex (Macher, 2006) architectural innovations (Hoetker, 2006; Kapoor & Adner, 2012) more quickly than specialized entrants.[1]

Instead of looking to firms to introduce modularity into their industries, Dosi (1982: 160) argues for a government role: because governments have "non-economic interests (such as, for

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

example, military technological requirements and procurement…etc.),” This idea departs significantly from the Arrow (1962) and Nelson (1959) view that government research funding is justified by spillover externalities: when many applications can be commercialized from basic science, firms underinvest because they cannot capture all of the returns to the research. Dosi highlights the incentives of mission-oriented agencies, the implications of which are still relatively understudied and fractured into specialized domains, such as defense, health, or agriculture (Foray, Mowery & Nelson, 2012).

In this paper, we focus on the role of mission-oriented government funding of modularity. We present a case study of the semiconductor industry and show how DARPA (Defense Advanced Research Projects Agency) had an interest in promoting modularity and thus changing industry structure. Using economic history methods, including the intellectual history of the scientific evolution, interviews, oral histories and statistics on industry structure, we trace the origins of a pivotal interface conceived and implemented in the late 1970s. We then describe the policy effects on subsequent industry structure and innovation.

Specifically, before the pivotal innovation, the industry was organized as an oligopoly of vertically-integrated semiconductor firms that designed and manufactured devices using proprietary methods. Each firm created design files that only its own unique manufacturing process could read. DARPA-funded research at Caltech decoupled design and fabrication of semiconductors. Further government-supported research led to a textbook, university courses across the country, and a fabrication brokerage service for students’ designs.

To boost defense capabilities, DARPA had a vested interest in accelerating improvements in semiconductor technology. However, the vertical structure of the industry was unable to cope with the exponential growth in complexity of semiconductor devices. Large vertically-integrated firms utilized manual design processes that would be unable to keep up with manufacturing processes that continued to miniaturize rapidly. In addition, DARPA was wary of the oligopoly supply of semiconductors, instead hoping for vendor-independent designs.

Beginning in 1981, the DARPA-funded MOSIS service demonstrated the technological effect of creating a new interface and new modularity: sophisticated semiconductor designs were created quickly by researchers, students and small companies, using the first vendor-independent, state-of-the-art fabrication service (Piña, 2002). By the late 1980s, the industry effect was manifest: new "silicon foundries" had been launched with a new business model of contract manufacturing for other firms (Mead & Lewicki, 1982, Shin et al, 2017). These foundries led to the entry of fabless firms in droves, enabling today's complex, dynamic, and innovative semiconductor ecosystem.

We argue that focusing solely on the effects of government research funding on technology overlooks how innovation can be accelerated through changes in industry structure. Foundries ushered in a veritable Cambrian explosion of fabless firms, technology, and new client-industries that has taken computing technology out of the computer and into automobiles, smart phones, wearables, implants, cloud computing and more. We thus contribute to two literatures. For the literature on modularity, we identify public funding as an important source of modularity. And we extend research on public R&D funding, especially on mission-oriented programs, which shape the supply of technology inputs for public agencies. Finally, we conclude by identifying future research opportunities in modularity and R&D policy.

2. Connecting Modularity to R&D Policy

Because of government's role in the modularization of the semiconductor industry, we discuss how these two perspectives can join to address the gaps and opportunities in joining these literatures. First, we consider two models of government innovation policy: the market failure model, and mission-oriented investment. Second, we review the literature on modularity and how interfaces enable task partition and decentralized innovation.

2.1. Government funding of R&D

The literature on public funding of research and development (R&D) has been dominated by the idea that externalities lead to under-investment by private firms. This literature includes both a theoretical rationale for such funding, and empirical tests of that rationale which measure the effectiveness of funding — typically by studying technological or economic impacts. Largely overlooked is how this funding aligns to the mission and incentives of the funding agency, which may include a broader perspective on success. Thus, if this broader perspective is ignored, then other outcomes — such as changes to industry structure — will never even be considered in measures of funding effectiveness, despite the outsized effects of industry structure on innovation.

2.1.1. Theoretical rationale for public funding

The broad case for government funding of R&D argues that knowledge leaks out of firms to competitors despite their best efforts at maintaining secrecy. This spillover externality results in firms underinvesting in innovation and a justification for government funded R&D (Arrow, 1962; Nelson, 1959). More specifically, government funding is best applied toward the fundamental science, or “basic research,” which underlies the commercial applications that firms would be willing to fund.

While Arrow and Nelson focus on basic science, it is but one of three perquisites for technological change (Dosi, 1982). Also needed are translation of basic science into applications by entrepreneurs and government investment. Thus, Foray, Mowery & Nelson (2012) urge a closer look at mission-oriented public funding. 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).

The Department of Defense (DoD) is perhaps the largest, most extensively studied, government funder of R&D, and employs multiple strategies. Formed to respond to the Sputnik crisis, DARPA has, since 1958, been the lead agency for funding basic research, creating networks across universities and firms with norms of open sharing of research (Fuchs, 2010) and connecting researchers with each other (Colatat, 2015). DARPA funds technologies that individual DoD branches will not fund — either because they are too risky, have no immediate application, or fall outside the scope of a single service (Van Atta, 1990).

At the same time, the DoD must also procure equipment in the near or intermediate term, leading to procurement strategies that prevent disruptive innovation. As a monopsony buyer, the agency can find it very tempting to structure its supplier base to eliminate duplication but also lock in existing technology (Kaufman, Tucci & Brumer, 2003).

Other government agencies vary in their missions and their ability to transfer research into the market. The Department of Energy (DoE), which manages a system of national labs, is a stark contrast and counterfactual to DARPA. The DoE is closely overseen by Congress and interacts with industry via contracts known as Cooperative Research and Development

Agreements (CRADAs), which were enabled through the Technology Transfer Act of 1986. Case studies show how the labs' own rules and incentives can hinder the successful hand-off of new technology, although projects that were closely related to the lab's mission did best (Ham and Mowery, 1998) and CRADAs were successful in the biotech sector, helping establish an industry cluster near Washington DC (Feldman, 2001).

2.1.2. Empirical assessments of publicly funded R&D

The effectiveness of publicly funded R&D should be assessed against the goals of the funding. A straightforward spillover model of innovation, in which research begets research, measures research productivity in terms of patents. By these measures, government funding has a consistently positive impact. Patenting at national labs grew to match patents per research dollar at universities after incentives to create more application-oriented research were implemented in the 1980s (Jaffe and Lerner, 2001). Industry labs with CRADAs saw increased patenting after partnering with national labs (Adams, Chiang & Jensen, 2003). Scholars have also traced patents to federally-funded research, and find that government funding generates more breakthrough innovation than firm-based research (Corredoira, Goldfarb & Shi, 2018). Moreover, a third of total patents were based on publicly funded science, as firms increasingly pull back on performing and publishing basic research (Fleming et al., 2019). Government can also directly support private R&D, through R&D subsidies, and subsidized projects are also shown to have positive follow-on effects, like research collaborations and outside funding (Feldman and Kelley, 2006).

When an agency's mission is taken into account, funding can have a variety of effects on innovation. For example, the economic effects of military funding are three-fold. In addition to research spillovers discussed above, two commercialization effects include startups that spin-off from DoD projects and incumbents who develop new technology with the support of a procurement contract (Fabrizio & Mowery, 2005; Mowery, 2010; Mowery, 2012). Regarding the first group, national labs (run by the Department of Energy) are found to be the source of a significant number of spinoffs, but organizational and policy issues hinder many of these entrepreneurs from commercializing research from the lab (Mowery and Ziedonis, 2001). In the second group, procurement can be a powerful driver of innovation and can work through a variety of channels. Edquist and Zabala-Iturriagagoitia (2012) discuss several categories of government funding, including direct procurement versus “catalytic” procurement, in which the agency procures innovation such as low-energy lighting, on behalf of consumers outside the agency. On a second dimension, innovation can be pre-commercial, adaptive (i.e., localized), or developmental (involving radical innovation). Empirically, mission orientation adds a level of complexity for assessing funding.

An example of where such mission funding is often studied empirically (due to centralized data availability) is the Small Business Innovative Research (SBIR) program, where U.S. government agencies allocate a portion of their R&D budgets to small firms. Studies find such funding increases revenues (Siegel & Wessner, 2012) and firm growth (Lerner, 1996), especially benefitting new and inexperienced firms (Lanahan and Feldman, 2018). Although SBIR funding helps attract more venture funding (Lerner, 1996; Cox-Pahnke et al, 2015), it may also substitute for private investment that can help firms in other ways (Wallsten, 2000).

This empirical literature demonstrates the challenges of assessing public R&D funding. Much of the literature takes a narrow phenomenon and attempts to measure direct effects of research funding. Our case suggests the importance of identifying the incentives or goals of funders before attempting to assess the effectiveness of public R&D spending. We highlight a hitherto overlooked outcome driven by agency goals: shifts in industry structure that affect innovation through entry, specialization, variety, and competition.

2.2. Modularity and Industry Structure

In technology-based industries, firm, industry and overall economic growth depend on developing and commercializing new technologies and applications. A frequent challenge to such growth is innovating in the face of increasing complexity of technology and products (Malerba & Orsenigo, 1997; Hobday, 1998).

A potential solution for such complexity is modularity (Baldwin & Clark, 1997). Within a firm, modularity allows a firm to break down a problem into manageable pieces (Sanchez & Mahoney, 1996). Such modularity also allows firms to cooperatively develop complex large-scale systems such as airplanes and computers (Prencipe, 2000; Baldwin & Clark, 2000). Baldwin & Clark (2000) term such modularity to manage organizational complexity "modularity in production".

But industry-level innovation and economic growth typically require decentralized innovation efforts. Within an ecosystem, such decentralized innovation requires task partitioning between organizations, which in turn is made possible by modularity of technology, intellectual property (IP) and organizational boundaries (Henkel et al, 2013; Parker et al, 2017).

Baldwin (2008, 2012, 2020; Baldwin & Clark, 2000; Colfer & Baldwin, 2016) has studied how partitioning of the technical and organizational complexity enables such decentralized innovation. Key to that is her concept of a "thin crossing point":

> 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: 10).

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

Research has long shown that the creation of interfaces impacts firm boundaries and industry structure via vertical specialization, which can also enable new entry (Langlois & Robertson, 1995; Baldwin & Clark, 2000; Langlois, 2002; Colfer & Baldwin, 2016). Previous research has tended to focus on the industry impact of interfaces created by firms, such as proprietary standards (Langlois & Robertson, 1992), open standards promoted by a single firm (West & Dedrick, 2000; Kenney & Pon, 2011), or multi-lateral standards that reconcile various corporate interests (Leiponen, 2008; Bekkers et al, 2011; Simcoe, 2012). In these cases, standards are strategically created to coordinate economic activity including the entry of new firms that will adhere to standards (David & Greenstein, 1990; Bresnahan & Greenstein, 1999).

While Baldwin & Clark (2000) emphasize the inherent advantages of technical and organizational modularity, subsequent has suggested conditions where an integral strategy may provide superior innovation and financial results. Beyond the technical opportunities for partitioning the design efforts, other moderators of modularity include competencies, the business model of the firm and its complementors, and firm strategy (Fixson & Park, 2008; Cabigiosu et al, 2013; MacDuffie, 2013; Jacobides et al, 2016). In a review of 142 empirical studies of the linkage of technical and organizational modularity, Colfer & Baldwin (2016) concluded such organizational modularity was most common and efficient in industries with slowly-changing technologies and complexity. Thus, incumbents may rationally resist efforts at modularization — either because such modularization provides no advantages over an integral approach, or for those cases where the resulting entry is more competitive than complementary.

In the face of such inertia, there may be weak firm incentives (or strong disincentives) for introducing interfaces and modularity. In this study we identify a possible alternative: the potential for government-funded R&D to overcome such collective action problems.

3. Research Design and Context

We situate our study of modularity and ecosystem development in the semiconductor industry. Because of its innovativeness and central position in the computing industry, the semiconductor industry has attracted significant attention from social scientists. That literature has focused on types of innovation (Henderson and Clark, 1990), industry structure (Macher, 2006; Macher and Mowery, 2004), and firm strategy (Kapoor, 2013; Kapoor and Adner, 2012).

For more than 50 years, the industry has been organized around an ongoing process of technological change referred to as "Moore's Law" (Moore 1995), which both enabled miniaturization, lowered cost, and increased variety and encouraged new uses for semiconductors. Less often remarked has been the emergence of a dramatically different industry structure.

3.1 Research Design

To understand the emergence of this new structure, we began by tracing the historical origins of this organizational modularity back to the creation of new interfaces; we then followed forward the implications of such interfaces and modularity upon industry structure. We used an exploratory research design with a wide range of historical evidence. This included early technical publications, oral histories, government reports and published scholarly research that described the antecedents and expected consequence of this inflection point, supplemented by interviews with key participants (Table 1).

<<Table 1 about here>>

To trace the impacts of these changes upon industry structure, we combined industry reports with the (private) archives of the trade association at the center of this transformation, the Fabless Semiconductor Association, founded in 1994 (Cataldo 1994). By supporting the interests of the new entrants separate from (and sometimes contrary to) that of the integrated semiconductor incumbents, this association helped orchestrate and coordinate the proliferation and variegation of semiconductor entrants. It also facilitated the latest phase in the industry shift as downstream customers became fabless designers, prompting a broadening of the association's scope and membership symbolized by its 2007 rebranding as the "Global Semiconductor Alliance".

We therefore take an ecosystem view of the industry, including the emergence of customer-design efforts leveraging the selection and customization activities of the semiconductor ecosystem. We map the industry structure before, during, and after a key inflection period, showing how the vertical specialization created by the industry's new thin crossing point helped fuel evolution to an ecosystem as defined by prior research (Adner & Kapoor, 2010; Jacobides, Cennamo & Gawer, 2018).

3.2. Industry Structure Before 1979: Vertical Integration and Looming Bottlenecks

In the 1960s and 1970s, firms producing semiconductor chips, firms had to both design them and then manufacture them. Together, these aspects of the process required command of cutting edge science in several domains: physics, material science, digital logic, and software. Hence, the industry came to be dominated by competitive, highly innovative, vertically integrated firms that had the financial and human capital to manage all of this varied expertise under one roof.

In semiconductor design, integrating ever more circuits onto a single chip enabled higher performance in terms of speed and capabilities. Customers could always use faster, more complex chips, and rewarded microprocessor designers who pushed the bounds of technology. In the 1970s, a new technology was emerging to massively increase this complexity: Very Large Scale Integration (VLSI).

Meanwhile, manufacturing semiconductors was a separate technological feat of its own. To boost performance, the manufacturing side of the company would shrink the dimensions of circuits and thus chips. Shortening the distance electrons must travel increases the speed with which chips perform instructions. This miniaturization process involves the photolithography process described in Henderson and Clark (1990) and has driven the regular doubling of chip capacity known as Moore's Law.

Miniaturization, in addition to increasing chip speed, also created opportunities to increase the complexity of chips. More circuits, and more-complex circuits, gave chips more capabilities all in the same package as a last-generation chip a few years earlier. But arranging ever more logic onto a chip created a growing challenge for the designer. As Caltech professor Carver Mead and Xerox PARC scientist Lynn Conway concluded in July 1979:

> VLSI electronics presents a challenge not only to those involved in the development of fabrication technology, but also to computer scientists and computer architects. The ways in which digital systems are structured, the procedures used to design them, the trade-offs between hardware and software, and the design of computational algorithms will all be greatly affected by the coming changes in integrated electronics. We believe this will be a major area of activity in computer science on through the 1980s (Mead & Conway, 1980: vi).

In this period, chip design was a proprietary process that was laborious and shrouded in mystery. Mead later recalled:

> That period was one where...the integrated circuits were created by "wizards." They were people who had extremely deep knowledge of the process and of the transistor physics, and it was a very mysterious process by which an integrated circuit was created. (Mead, 2009: 17).

In terms of the wider value chain in this period, upstream firms supplied manufacturing equipment, and downstream firms consisted of computer firms and defense contractors. Some firms, including IBM, produced both chips and computers. By the early 1970s, the total value of US semiconductor sales exceeded $3 billion annually (Webbink, 1977: 11).

4. Emergent Interfaces and Organizational Modularity

What was the process by which industry structure changed, thereby ushering in new innovation and new sources of innovation? The phase process involved creating new interfaces that allowed shifts in the organizational boundaries of innovation. First came problem identification. Next, participants had an opportunity to attempt to solve the problem. Finally, participants got the chance to implement their solution. We describe how DAPRA (and other government funding) aligned with agency mission and provided flexible support for breakthrough ideas that had the potential to reshape entire industries. [2]

4.1. Problem identification

As powerful and important as early integrated circuits were, the potential for greater performance and capability was becoming clear, at least to a handful of visionaries. Principal 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 interfere with transistors if transistors continued to shrink (Mead, 2017). By the mid-1960s, the pace of miniaturization, had become established and new applications made semiconductors a fascinating topic for the young physicist.

In 1968, to better understand the technology, Mead undertook to make his own semiconductor chip. To learn how a chip was fabricated, he visited Moore at Intel, which he had

[2] While our study focuses on the role of DARPA, we don't claim omniscience in its vision for the future of the semiconductor industry. For example, in response to a Defense Science Board prediction, DARPA helped found (and was for years the largest funder) of SEMATECH, a consortium of large, vertically-integrated semiconductor firms in the US, created to combat low-price competition from Japanese firms (Grindley et al, 1994).

founded earlier that year with fellow Fairchild veteran Robert Noyce. The time-consuming manual process, involving Mylar and X-Acto knives, was but one set of problems Mead identified. Another problem was the approach to designing chips itself: specific functionality was hardwired into the chip via the arrangement of various logic gates and wires or "traces" (thin metal wires embedded into a plastic board). A documentary of Mead's exploration of the chip design and fabrication process describes the process of this period, his solution to problems he identified in the process, and the class he taught as part of his own learning process (Mead, 2017).

What emerged was a mechanized fabrication process using a digital Gerber plotter, then being used by defense contractors to make printed circuit boards (early versions of computer boards on which metal traces were embedded or "printed" and onto which transistors were affixed). Mead designed a neat, repeating pattern of traces and semiconductor transistors to create a generic grid or "array". His teaching assistant created code for the logical functions the chip would perform. In class, they programmed the chip to function as a clock, attaching the chip to a simple digital display. In short, they produced a general purpose computer: a generic array that could be programmed later to perform tasks. Documented in an eerily prescient article, Mead (1971) imagines a world in which computing is embedded in a wide variety of devices and are intuitive and easy to use.

The shortcomings of the existing semiconductor process—and industry structure—were also described in a series of articles. First, the cumbersome process he witnessed at Intel, with its complex idiosyncratic designs and manual production process would become a bottleneck (Sutherland, Mead and Everhardt, 1976). As Moore's Law miniaturized chips, it also accommodated exponentially more circuits onto a chip. The existing process would be unable to grow exponentially more complex. Thus, in their RAND report for DARPA, they argued that something would have to change. One solution to both the bottleneck and to the wider application of semiconductors was to integrate design with the semiconductor customer (Sutherland and Mead, 1977). By involving computer-maker customers in chip design, computers could take full advantage of what semiconductor devices had to offer. This meant redrawing the vertical structure of the industry. 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).

During much of this period, Mead's research was supported by the Office of Naval Research (ONR). While DARPA is better known as a funder of cutting edge technology, the smaller ONR would "serve as a talent agency for ARPA,"[3] (National Research Council, 1999: 100), identifying promising researchers and providing a "sandbox" for new ideas that, if successful, would merit subsequent DARPA funding (National Research Council. 1999: 121).

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

Mead's own recollection of his first interaction in 1960 with his long-time benefactor shows how quickly and easily the ONR could provide 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).

This flexibility and far-sightedness would prove crucial to the next phases of the industry change process. Armed with the experience of creating his own semiconductor chip and using it as a programmable computer, Mead identified the critical bottleneck in the semiconductor industry that would prevent it from exploiting miniaturization and from deploying diverse applications.

As electronics became increasingly important for military equipment, DoD policy and investments during the 1970s and 1980s sought to promote vendor independence in semiconductor components (analogous to supplier redundancy for other equipment). 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: 12).

4.2. Partitioning semiconductor design through curriculum and interfaces

The next step toward re-configuring the industry required the creation of a new interface. One aspect of the industry organization at the time was secretiveness in the process designing the physical layout of a working chip. All of the tools and coding languages involved in producing designs were proprietary. This helped perpetuate the industry structure, because only manufacturers would be able to 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: 17)

Mead's experience creating his own chip convinced him that the industry needed simpler design rules and to free design from the specifics of the fabrication process. For Mead, addressing this issue, again, revolved around teaching the VLSI design class he began teaching in 1976. But this time, a wider cast of characters was needed. Mead's co-author on his articles about the industry structure was also his department head at Caltech, Ivan Sutherland headed ARPA's Information Processing Techniques Office (IPTO) from 1964-1966 and thus had connections to that source of funding (National Research Council, 1999: 99). Ivan Sutherland also had connections to industry; his brother Bert was a manager at Xerox PARC, the famed Palo Alto Research Center. Bert Sutherland introduced Mead to a scientist on his staff, Lynn Conway.

Mead and Conway worked to simplify and demystify the chip design process, and the ONR continued to provide financial support. The work involved three steps and an ever-widening set of collaborators. First was a set of design rules that Conway thought they should publish as a textbook. 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.

> 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: 17).

Second, in addition to design rules and methodology, Mead wanted students to get real experience; he wanted to implement their designs. When he started teaching VLSI design in 1976, the designs were tied to the specific Gerber plotter format. The leading industry standard was the proprietary GDSII system owned by Calma, which refused to share its file format with Caltech. Instead, Sutherland and two colleagues developed an open file format for specifying semiconductor mask layout called the Caltech Intermediate Form (CIF) (Mead & Conway, 1980: 115-127; Ayres, 1998); this format remained in used for semiconductor fabrication for the next three decades.

Third, to fabricate multiple student prototype designs entailed a whole set of technical challenges. When mass-producing semiconductor chips, a single design is arranged multiple times onto a standard silicon "wafer," a flat, round disc of silicon material onto which designs were printed. After the designs are printed or etched onto the wafer, the designs are cut out of the wafer and then "packaged" into protective plastic outer housing with metal leads in a process called a "multi-project chip" (Conway, 1981). The tools and processes created were key prerequisites to a new industry structure.

The textbook was first piloted by Mead at Caltech in 1977, and then more broadly over the next two years at several universities. As 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, DARPA's early incarnation of the Internet. She also lined up a fab at Hewlett-Packard to fabricate the designs so that when students came back from winter break, they had fabricated chips to work on (Conway, 1981).

The ideas and the course were wildly successful. Mead and Conway taught colleagues at other universities their concepts, including a course for teachers at University of Washington. In fall 1979, Conway led an effort called MPC79 in which 124 designs from 11 universities were fabricated and shipped back to their designers 29 days later (Conway, 1981). The enthusiasm for the course, its textbook, and for student designs was clear — demonstrating the need for a new solution for fabrication.

4.3. Proof of concept of modularity: From lab to scale

With many of the technical hurdles addressed, the growing interest from students fueled the need to move away from the use of fabs at Xerox or Hewlett Packard. Failures to address this need could, in principle, doom the effort, with students unable to produce projects. The long-term solution would be a service that took student projects and found capacity on a collection of participating industry fabs:

> …it was Ivan's [Sutherland] 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: 17)

MOSIS — the Metal Oxide Silicon Implementation Service — was announced in 1980, and would be housed at the Information Sciences Institute (ISI) of the University of Southern California.[4] The service would be run by two of Mead's former students: Danny Cohen and George Lewicki (Cohen & Lewicki ,1981). In May 1980, Xerox repeated its MPC79 efforts one last time with 171 projects from 15 organizations, and Cohen joined in the effort to aid the transition to the longer-term solution, MOSIS (Strollo et al, 1980).

MOSIS was not a foundry, but a broker that provided access to excess fabrication capacity — initially at integrated semiconductor manufacturers, but eventually from leading foundries such as TSMC and GlobalFoundries (Cohen & Lewicki, 1981; Tomovich, 1988; MOSIS, 2020). When it launched in 1981, the service required design files to be expressed using the Caltech Intermediate Format and emailed using the ARPANET (Cohen & Lewicki, 1981). MOSIS demonstrated the need for contract manufacturing of semiconductor designs. However, by 1988 it was also accepting designs using the proprietary (but no longer secret) file formats from Calma and Perkin-Elmer (Tomovich, 1988).

Meanwhile, Mead and Lewicki sought to promote 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" (Mead and Lewicki, 1982: 107). This was the logical extension

[4] 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).

of Mead's decade-long idea of separating design from fabrication, under which designers would concentrate on the novelty aspects of their 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 foundry services. … 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: 108-109).

Industry took incremental notice of the concept of foundries. In the early 1980s, new semiconductor firms proliferated, as shown in a 1983 industry census by *VLSI Design* (Werner, 1983). All 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 the business. According to VLSI Design Magazine founder and editor, Douglas Fairbairn, "these were not dedicated foundries like TSMC," (Interview, June 5, 2020).

Another critical issue with the nascent foundry idea was the business model. Manufacturers connected the design, and the IP of the design, to fabrication. Thus, manufacturing firms considered themselves to be the owner of the design IP, and sought to own some or all of the rights to the chips they fabricated.

With vertically integrated semiconductor firms pursuing a different business model, the leap to the first pure-play foundry would have to involve a completely different set of participants, leveraging the economic growth ambitions and capital availability of the Taiwanese government. Mead's doctoral student, Marina Chen, repeatedly heard Mead's complaint that Silicon Valley firms were not interested in the foundry model. An immigrant from Taiwan, she decided to write to an official in Taiwan's national Industrial Technology Research Institute (ITRI). They invited her and Mead for a visit in the winter of 1981-2 and held a series of meetings at the newly established Hsinchu Science Park to discuss the foundry idea (Interview, Oct. 5, 2020). These meetings, in which Mead made his case for a foundry model for the semiconductor industry, proved reinvigorating for Mead because he found, for the first time, a receptive audience for the idea (Interview, Sept. 24, 2020).

The Taiwanese continued to pursue efforts to start an industry. In 1985, ITRI convinced a long-time Texas Instruments executive, Morris Chang, to return to Taiwan to head ITRI. Chang found a country eager to start its technology industries but saddled with old technology that was rapidly losing ground on the leaders in the industry (Chang, 2007: 11). Almost immediately, Chang was charged with a new challenge, to start a technology company.

> A few weeks after I arrived in Taiwan, and became the President of ITRI, I was called in by Mr. K.T. Lee (a government minister) …I paused and thought about the task that Mr. K.T. Lee gave to me. He wanted me to present a business plan, he wanted me to start a semiconductor company. (Chang, 2007: 11-12)

Two years later, in 1987, Chang founded the world's first pure-play foundry, Taiwan Semiconductor Manufacturing Corporation (TSMC), jointly funded by the Taiwan government, Dutch multinational Philips N.V. and other private investors. While Chang credits his reading of Mead's ideas on foundries as the basis of his company, he points out that Mead never actually articulated the idea of a pure-play foundry, one that *only* manufactured other firms' designs.

“[Mead] didn't advocate the advent of pure-play foundries, but he did make the point which would lead to the conclusion that you could start up a pure-play foundry” (Chang, 2007: 12).

Indeed, even after MOSIS proved 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.

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

Fortunately, Chang understood the industry where he had worked in for decades, and he had observed latent demand for a foundry. Existing foundry capacity was inadequate. A service like MOSIS was appropriate for research, but not for production even of specialized products. And existing foundry capacity, from incumbents, was insecure. Foundry work was a sideline for these firms, as a way to use up excess capacity. That capacity would disappear when the incumbent saw an increase in demand for its own products. In addition, the question of who would own IP was also problematic for fabless startups.

> I saw a lot of IC designers wanting to leave and set up their own business, but the … biggest thing that stopped them from leaving those companies was that they couldn't raise enough money to form their own company…at that time it was thought that every company needed … wafer manufacturing, and that was the most capital intensive part of … an IC company. And I saw all those people wanting to leave, but being stopped by the lack of ability to raise a lot of money to build a wafer fab. So I thought that maybe TSMC, a pure-play foundry, could remedy that… then those designers would

> successfully form their own companies, and they will become our customers, and they will constitute a stable and growing market for us. (Chang, 2007: 13)

The founding of TSMC ushered in fabless entrants, just as Chang had hoped. With a reliable source of manufacturing capacity, inventive chip designers could leave their jobs at an incumbent and strike out on their own. Venture capital followed, especially because foundries made fabless firms less risky. On his own calculated risk, Chang remarked, “I can't tell you that I saw the rise of the fabless industry, I only hoped for it,” (Chang, 2007: 13).

Although capital intensive, TSMC’s success attracted competitors. The Taiwan-based United Microelectronics Corporation (UMC) was founded in 1980 and originally sought to sell its own chip designs, but soon imitated TSMC by implementing the foundry model. However, its role as a foundry was later eclipsed by the foundry business of two leading chipmakers

In 2020, the world’s second largest foundry (by revenues) was Samsung, the world’s largest semiconductor maker (Aslop, 2020); the company had long offered manufacturing services to leading fabless semiconductor designers — such as Apple and Qualcomm — to help pay the R&D and capital costs for manufacturing its own proprietary semiconductors (Park & Lee, 2015). The third largest foundry (and second largest pure-play foundry) is GlobalFoundries, which was created in 2009 via spinoff of the fabrication facilities of AMD, Intel’s largest microprocessor competitor; in 2014, it acquired IBM’s semiconductor fabrication facilities, which manufactured chips both for its own and external fabless designers.

5. Impact on Industry Structure

The effect of these foundries on industry structure was two-fold. First, foundries allowed for a variety of new entrants including fabless firms that performed design only, customer firms creating their own designs, and combinations of the two. Second, the entrants generated a *variety* of new applications that have continued to proliferate and that have exceeded even the predictions of visionaries like Carver Mead.

5.1. Entry and success of new types of firms

Baldwin and Clark (2000) summarize how these new interfaces 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 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 & Clark, 2000: 87).

The direct economic impact of TSMC and other pure-play foundries is evident from the list of the largest semiconductor firms from 1985 to 2018. Table 2 shows big, vertically-integrated firms jockeying for position until TSMC enters the top ten in 2006, followed in the next period by fabless Qualcomm in 2011 and by Broadcom and Nvidia in 2018. Note, however, that time is needed for the industry to transition. Macher and Mowery's (2004) description of the vertical structure acknowledges entry by fabless and foundry firms but still characterizes the industry as "mature" with entry "slowed somewhat," (p. 336). In other words, more than a decade after the first foundry, the eventual effects on industry structure were not fully visible.

<<Table 2 about here>>

5.2. Fractalization of designs and designer firms

The indirect economic effect of entry by fabless firms is much harder to estimate. While fabless firms, now among the giants of the industry, contributed to the overall growth of the market (see Figure 1), from $1.5 billion in 1975 (Webbink, 1977) to $345 billion in 2015 (VerWey, 2019),[5] they did so by expanding the variety of product offerings in the market and serving new customers. Before TSMC, the main customers for semiconductors were computer makers and the military. After TSMC, the number and types of customers has exploded. In a Schumpeterian way, fabless firms were founded to serve underserved markets, a process of addressing ever-specialized niches that Moore (2005) terms “fractalization”. Broadcom was formed to serve networking equipment makers. Nvidia specialized in graphics processors for video gamers. And Qualcomm provided digital radio chips for mobile phones and other cellular network communications. All of these customers were, and continue to be, underserved by vertically integrated incumbents. In fact, fabless entrants have entered the incumbents’ main market, the computer market, which now incorporates Internet connectivity and high-quality graphics in its products.

<<Figure 1 about here>>

As a measure of how thoroughly the foundry-fabless model has come to dominate the industry, the Fabless Semiconductor Association (FSA), founded in 1994 with 35 members (four of which were investment banks) changed its name to the Global Semiconductor Association

[5] The growth of the industry paused at the beginning of the 20th century, when the puncturing of the dot-com bubble in March 2000 brought with it a crash in telecom equipment manufacturers that had grown rapidly to supply infrastructure and equipment for this market (Endlich, 2004).

(GSA) in 2008. Founder Jodi Shelton observes that the boundaries of the "semiconductor industry" have become utterly blurred. "Software engineers make up 40% of employment at semiconductor firms…and Tesla is now on our board…Alibaba is on our advisory board," (Interview, Aug. 11, 2020). In a sense, Mead's (1972) idea that break points in the computing value chain were in the wrong place—that computer makers should be more closely integrated with chip designers, while manufacturing should be separated from design—is consistent with the direction of the industry's latest phase.

The explosion of variety and the thick market for that variety underpins semiconductors' conceptual shift from vertical value chain to ecosystem. Customers, from computer makers to automakers, now pick and choose from a smorgasbord of options to customize their products. And customers themselves hail from a growing set of industries, far beyond the traditional computing industry.

5.3. Government funding strategy

Through generous, flexible, discretionary spending at ONR, the long-term vision of a far-sighted researcher led to the creation of the open interfaces needed to alter industry structure and, in turn, innovation. The ONR and DARPA had clear mission-oriented goals, including a robust competitive industry capable of innovation and growth. Vendor-independent design was one feature of such an industry outcome, and military funders supported efforts in that direction.

This approach to mission-oriented funding is part of a broader pattern at DARPA. Indeed, DARPA has a long record of funding transformative research that creates open interfaces. It is best known for its funding of the key technologies of the Internet — including TCP/IP and domain names — along with enabling institutions such as the Internet Engineering Task Force (Mowery & Simcoe, 2002; Fleming & Waguespack, 2007); together these open processes and interfaces made possible widespread deployment and adoption of the commercial Internet (Greenstein, 2009, 2015). Similarly, GPS technology — originally for military targeting and now a mainstay of every smartphone — was created by DARPA and made available through open interfaces (Alexandrow, 2008).

6. Theoretical Implications

Our study of an early-stage, government-funded research project has several implications for theory. By connecting the elements of the story across the entire period of evolution, we establish the effects of new interfaces on modularity, industry structure and innovation— as a fractalized, dynamic ecosystem. We have the opportunity to observe an industry's transition, via the momentum spawned from a central, modularizing innovation. And finally, we articulate a long-term innovation strategy for public agencies that goes far beyond a simple, high-level approach to addressing spillover externalities.

6.1 Interfaces, Modularity and Fractalization

Prior research has shown how creating interfaces can impact industry structure (Langlois & Robertson, 1995; Baldwin & Clark, 2000; Colfer & Baldwin, 2016). A common source of such interfaces is the creation of *de facto* industry standards, whether proprietary (Gawer & Cusumano, 2002), open standards from a single firm (West & Dedrick, 2000) or cooperative industry standards (Simcoe, 2012; Bar & Leiponen, 2014). A key goal of such interfaces is to enable and coordinate firm activity (David & Greenstein, 1990).

This study examines interfaces from another source: government R&D funding. A group of scientists led by a U.S. Navy-supported professor partitioned the task of design and manufacturing of semiconductors. In the late 1970s, this led to a new semiconductor design methodology, the widely adopted textbook on VLSI design, open interfaces for sending designs to a remote foundry, and a proof of concept using the decade-old ARPANET. By the 1980s, DARPA promoted adoption of this task partitioning by funding a fabrication service for researchers and small businesses.

Unlike more complex interfaces — as with the recent litigation between Oracle and Google over Java interfaces (Menell, 2016) — the importance and impact of these new open interfaces was not due to their control. The particular interface, the Caltech Intermediate Format 2.0, was a particularly simple file format.[6] Instead, its outsized impact came from providing a proof of concept for the task partitioning and organizational modularity needed to allow semiconductor design to be practiced by those who did not own a semiconductor fab. This widely available open interface enabled fabless designers, foundry services, and design tools, but there was no impact a decade later when other previously proprietary interfaces were opened up and adopted by users.

The proof of concept had a significant impact on industry structure, enabling computer makers to integrate backward into chip design as Mead had advocated and predicted. What was not anticipated, either by Mead or scholars studying the industry in the early 2000s (Baldwin and Clark, 2000; Macher and Mowery, 2004), was the fractalization that would later ensue. With successful foundries enabling countless fabless firms to enter, niches were explored and developed, producing a level of variety that was unanticipated decades earlier. Only by following the story forward is it possible to discern the proliferation of new semiconductor applications. Thus, the past decade suggests major changes in the locus of semiconductor design. Whereas the primary shift that Mead had sought was to involve computer makers in design, because he

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[6] If complexity is linearly proportional to page count, then the CIF 2.0 was less than 1/3 the complexity of the Rich Text Format, a simple word processing format of the mid-1980s (Library of Congress, 2017).

considered it unlikely that a semiconductor company could design the optimal chip for a computer, now producers of low-tech mechanical products like refrigerators or cars have begun to design their own chips (e.g. Lyytinen & Yoo, 2002; Greenfield, 2010). Meanwhile, computer makers have expanded the boundaries of their industry into new areas such as wearables, cloud computing, and more.

6.2 Ecosystems and the momentum of modularity

As Jacobides and his colleagues (2018) observed, modularity is an inherent organizing principle for many ecosystems. However, here we suggest two departures from previous conceptions.

First, the emergence of the semiconductor ecosystem is unlike most previously studied ecosystems, which tend to focus on coordination by a lead firm that sponsors the ecosystem (Gawer & Cusumano, 2002; Jacobides et al 2018). Such lead firms create interfaces to enable modularity and complementary product creation, as has been true since the earliest proprietary ecosystems (Bresnahan & Greenstein, 1999; Baldwin, 2012).

Many of these same benefits of modularity accrue from open interfaces created through publicly funded R&D. However, this study suggests some key differences. Here, the open interfaces pressured owners of private interfaces to open them up. While a vertically-integrated industry could carry on with proprietary interfaces, open interfaces were an essential input to a flourishing ecosystem. This additional openness was a consequence of changes in industry structure, rather than an antecedent of such changes, as sometimes theorized (Garud & Kumaraswamy, 1993; Cargill, 1997).

Second, the break with vertical integration created by these initial open interfaces spawned an ongoing trend that we term the “momentum of modularity.” Once modularity spurred entry, the ordinary forces of competition propel firms to innovate, ultimately lowering cost and increasing availability to new customers. For example, fabless firms created simple graphics processors that now power cloud computing, artificial intelligence and self-driving cars.

6.3 Research Policy

The role of mission-oriented government research funding is vastly understudied and long overdue (Foray, Mowery and Nelson, 2012). Departments differ dramatically in their missions, even within a single agency like the Department of Defense. This case brings to light the profound effect of an agency's mission, organization, and strategy on innovation. A small investment in long-term vision has the ability to nudge an industry structure to be more modular, more diverse, and more competitive. All of this makes for a robust and innovative industry that benefits the agency.

In our case, agency incentives were paired with an effective organization. Funders at the ONR and DARPA had the flexibility and discretion to support researchers like Mead, Conway, and others. In addition, their role in maintaining openness and in bringing people together, well-documented by Fuchs (2010), was in evidence as well. Not only did the cast of characters continue to widen as needed, but in a 2020 interview, Mead recalled DARPA's help in making introductions, opening doors, and connecting him to other researchers.

This study details a model of government R&D funding that differs from the standard model, which imagines research in basic science drifting into private hands to be commercialized (Figure 2). The literature on public R&D funding views government's role as preceding firms' commercialization activity.

<<Figure 2 about here>>

We instead show how government agencies can strategically nudge key elements in the technology value chain. Interfaces that have the potential to generate modularity are funded with the goal of making them open to new firms. Thus, in this alternative model, government agencies have goals or missions that create incentives for funding particular types of innovation. For example, as a large buyer of certain technologies, the government seeks to promote a robust, commercial market for those technologies. A public-funding strategy that focuses on modularity, i.e., innovations that create interfaces, generates an innovation ecosystem with rapid entry, competition, and variety (Figure 3).

<<Figure 3 about here>>

This focus on mission-oriented public funding contributes to the literature on public R&D funding. Even the literature that considers mission-oriented funding omits the possibility that a government agency might have an incentive to promote a robust commercial market. The literature currently considers government's procurement needs (Fabrizio & Mowery, 2005; Mowery, 2010; Mowery, 2012) but not the indirect goal of an innovative commercial market. And while we have explained a single highly technical and impactful case, DARPA has made a practice of this type of intervention, investing in TCP-IP and other key Internet technologies, and GPS, which has been deployed in countless applications, both military and civilian.

6.4 Future Research

While this study highlights the linkages between interfaces, modularity and industry structure, further research opportunities remain. Both for unilateral and multilateral industry standardization, prior research has considered both how industry structure affects interfaces (Bekkers et al, 2011) and how interfaces affect industry structure (David & Greenstein, 1990; Kenney & Pon, 2011; Steinmueller, 2013). However, the practice of interface standardization of the past 30 years has emphasized economic actors creating interfaces that benefit their self-interest, as when a platform owner creates interfaces to attract third party complements (Gawer & Cusumano, 2002).

But less is known about how this process is different for open interfaces from non-proprietary sponsors. New entrants benefit from organizational modularity because they lack the resources to make a fully integral firm (Teece, 1986). Anecdotally, new entrants and other challenges prefer open interfaces while incumbents seek to stymie them (West, 2007). Yet this case points to the successful adoption (and widespread effect) of an interface created and used by academics — not sponsored by any firm — that eventually enabled both fabless and foundry semiconductor firms. But such a trajectory has rarely been identified, let alone studied.[7]

We also highlight an opportunity to extend the typology of Baldwin & Clark (2000) that distinguishes between two types of modularity: "modularity-in-use" and "modularity-in production".[8] The semiconductor industry suggests yet another form of modularity, "modularity in production processes". Future research could examine features of this form of modularity compared with the other two types of modularity, such as two-sided market benefits (cf. Boudreau & Hagiu, 2009) or network effects from installed base (Saloner, 1990).

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[7] While it is tempting to draw a parallel to TCP/IP and the Internet, the parallel is inexact because the government funded decades of procurement of products and services that conformed to this standard.

[8] The latter might more precisely termed "modularity in product assembly" or (per Mikkola & Gassman, 2004) "modularity in product architecture." While the economic effects of these two are different (because in the latter, the modules are not separately traded), the technical roles are nearly identical: for example, per Saloner (1990), the standardized interfaces of the IBM S/360 allowed IBM to share peripherals across the product family (modularity-in-product) even if IBM (unsuccessfully) sought to discourage other firms from using these same interfaces to provide competing peripherals (modularity-in-use).

On the policy side, the relationship between government-funded research and industry structure merits further research. For example, the vast array of niches spurred by modularity and the shift toward a rich ecosystem suggests new ideas for measuring the effects of government-funded research. In our study, indirect industry-structure effects on value creation that arise through modularity contributed to and may have exceeded the direct effects of the publicly funded research. This is important for policy makers to understand because as economically important as we argue MOSIS was, its budget was regularly under threat, especially when it became successful (Roland, 2002: 139). More generally, we demonstrate the importance of understanding an agency's mission in assessing innovation outcomes. While in our case, an agency had industry-structure goals, there may be instances in which the agency has much more limited goals. Again, assessing funding outcomes against those limited goals is important to understanding the performance of public R&D.

Table 1: Primary Data

Name	Role	Date
Carver Mead	Coauthor of *Introduction to VLSI Systems;* Professor emeritus, Caltech	Interview 3 oral histories Published works
Lynn Conway	Coauthor of *Introduction to VLSI Systems;* Professor emeritus, University of Michigan	Published works
Marina Chen	Carver Mead grad student, Chair emeritus, Boston University Computer Science Dept.	Interview
Morris Chang	Founder, TSMC	Oral history
Douglas Fairbairn	Computer History Museum historian, founder of VLSI Technologies and *VLSI Design*	Interview
Robert Garner	Engineer in Lynn Conway's group at PARC, later at Sun	Interview
Peter Tong	Early Nvidia engineer	Interview
Rick Whitacre	Early Nvidia operations engineer	Interview
Jodi Shelton	Founder and Chair, Fabless Semiconductor Association	Interview
Gina Gloski	Early board member, Fabless Semiconductor Association	Interview

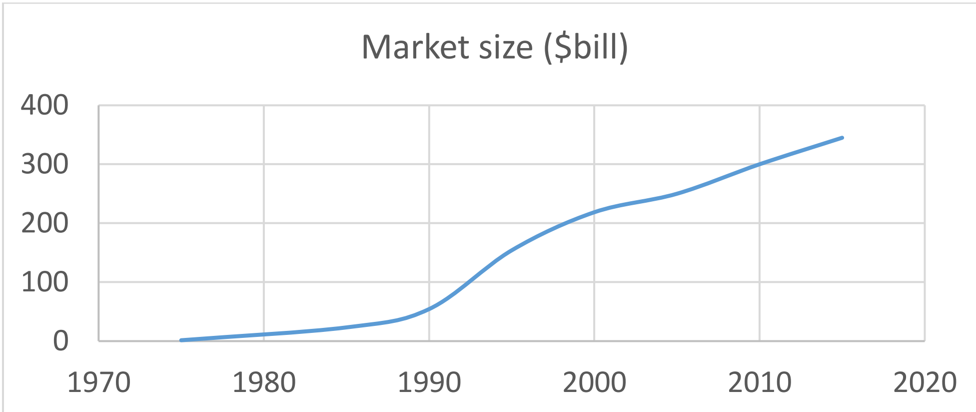
Table 2: Top 20 Semiconductor firms (Source: IC Insights, 2011; VerWey, 2019)

1985	1990	1995	2000	2006	2011	2018
NEC	NEC	Intel	Intel	Intel	Intel	Samsung
TI	Toshiba	NEC	Toshiba	Samsung	Samsung	Intel
Motorola	Hitachi	Toshiba	NEC	TI	TSMC*	TSMC*
Hitachi	Intel	Hitachi	Samsung	Toshiba	Toshiba	Hynix
Toshiba	Motorola	Motorola	TI	ST	TI	Micron
Fujitsu	Fujitsu	Samsung	Motorola	TSMC*	Renesas	Broadcom**
Philips	Mitsubishi	TI	ST	Renesas	ST	Qualcomm**
Intel	TI	IBM	Hitachi	Hynix	Qualcomm**	TI
National	Philips	Mitsubishi	Infineon	Freescale	Hynix	Toshiba
Matsushita	Matsushita	Hyundai	Philips	NXP	Micron	Nvidia**

* Foundry   ** Fabless

Semiconductor spinoffs during this period include: Renesas (Hitachi + Mitsubishi); Freescale (Motorola); NXP (Philips); Hynix (Hyundai + LG)

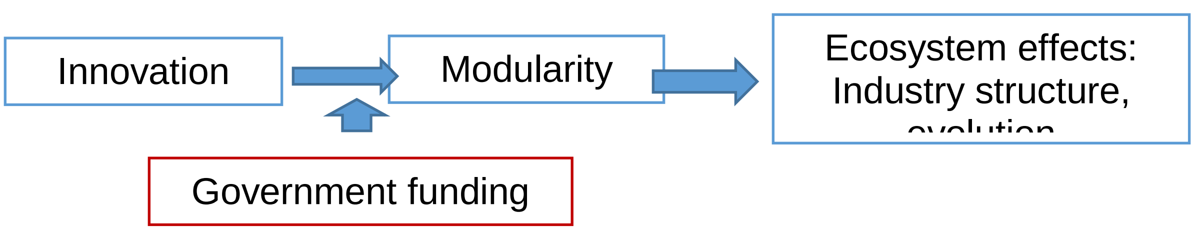
Figure 1: Semiconductor market growth, 1975-2015



Source: Webbink, 1977; IC Insights, 2011; VerWey, 2019

Figure 2: Existing model of government R&D funding

Figure 3: Model of the effect of a modularizing innovation on the ecosystem



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