TECHNOLOGICAL INNOVATION IN THE SEMICONDUCTOR INDUSTRY: A CASE STUDY OF THE INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS (ITRS)

by

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ABSTRACT

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This dissertation is an historical and evaluative study of the Semiconductor Industry Association's (SIA) Technology Roadmap, now referred to as the *International Technology Roadmap for Semiconductors (ITRS)* or simply, the "Roadmap." Technology roadmaps and roadmapping practices comprise new and emerging tools in technology strategy, planning and management that have gained increasing attention by researchers. This study addresses how technology roadmaps affect technological innovation, corporate strategies, and public policies in the semiconductor industry.

This inquiry is accomplished through an examination of the technology roadmap 'landscape' more generally and a case-based analysis of the ITRS in particular. Several hypotheses were formulated to help seek greater and deeper understanding of not just the Roadmap but the surrounding context within which it emerged and has since evolved. This unique approach will demonstrate the overall thesis that the Roadmap is part of a continuing tradition wedded to the goal of sustaining historical industrial productivity—also referred to as "Moore's Law."

In support of this, an important contribution of the study is substantial historical research of key developments within the semiconductor industry. The findings depart from more widelyaccepted interpretations of technological innovation advanced by much previous research. Specifically, this research is concerned with the industry's heritage of incremental or evolutionary technological change following a *normal* innovation pattern, particularly involving manufacturing *process* innovations in semiconductors.

The findings also suggest that the Roadmap continues the decades-long heritage of normal innovation, now conducted at an international level and reaching across a wide and complex supply chain network. Finally, the analysis supports a new structural approach to technological innovation, one that is more coordinated with the help of a global industry roadmap. Thus a theory of *organized innovation* is advanced that helps explain how the increasingly fragmented semiconductor innovation community is able to continue working in cadence to address the daunting technical and economic challenges facing the industry 'down the road'.

Topical Chapter Outline

Preface

1. Introduction

This chapter sets up the thesis as an historical and evaluative study of the ITRS—its origin, evolution, and future role in influencing industry strategies and public policies. The overall research question is posed: *How have technology roadmaps affected innovation, strategy, and policy in the semiconductor industry?* This is followed by a review of nine hypotheses that guided the research.

Part One: Theory

2. Technology roadmaps and roadmapping for strategic planning

This chapter introduces the emerging field of technology roadmaps and roadmapping in an increasingly "hi-tech" environment. Technology roadmapping is briefly compared with other technology planning methods such as technological forecasting and technology assessment. Various types, uses, benefits, and other characteristics of technology roadmaps are discussed. This provides the necessary context for subsequent discussion and analysis.

3. The complexity challenge of industrial innovation in semiconductors

The purpose of this chapter is to begin to provide the conceptual framework for the research into the Roadmap and the Roadmap process. Important concepts from Complexity Science have been selected to inform this study. The chapter provides detailed description and application of complexity science concepts that draws heavily on *The Complexity Challenge: Technological Innovation for the 21st Century* by Rycroft and Kash (1999).

4. Emerging pattern of organized innovation

This chapter introduces a theory of a distinct pattern called "Organized Innovation" that helps explain the evolutionary behavior of the semiconductor industry. As background it provides an in-depth review of evolutionary theory including application of additional topics from *The Complexity Challenge.* Taken together, this and the previous chapter form the conceptual framework for this study. The Roadmap process is viewed within a normal innovation pattern that extends across international borders.

5. Research design

This chapter describes the qualitative research design used in this investigation. The research design is a two-pronged strategy: (1) historiography and (2) case study method. The research type is inductive within the tradition of grounded theory, which affords an opportunity to build theory that offers significant explanatory power from the evidence gathered. Each of these three approaches—historiography (the past), case study (the present), and grounded theory (implications for the future)—is complementary to the overall research design and intended to help establish face validity of the study.

Part Two: History

6. History and evolution of the integrated circuit industry

Chapters 6, 7 and 8 provide background and context to help support the concepts put forth in Chapters 2 and 3. These three chapters review important elements of industrial history that have shaped the innovation process. The Roadmap is derived from innovation practices and patterns that formed early on. Chapter 6 provides a brief history of innovation in the IC industry. By no means an exhaustive historical treatment of the IC industry, particular elements are highlighted and discussed (e.g., MOS technology) that would become critical to the success of the industry.

7. The *invention* of the microprocessor, *revisited*

The purpose of this analysis is to underscore the incremental (or normal) innovation pattern built upon accumulated knowledge that so characterizes this industry, in contrast with what many have since referred to as a revolutionary or discontinuous innovation. This writing looks back to the late 1960s and early 1970s with a perspective that draws on a variety of sources and is organized in a way that offers new insight into the innovation process.

8. Moore's Law: basis for industrial cadence

This chapter explores one factor—perhaps the most significant factor—from the previous chapters that determines the pace of innovation in semiconductors. Based originally on a simple observation of a few data points, this early extrapolation has been elevated to a meta-law that must continue to be validated by the semiconductor community. Reflecting its universal appeal, a much broader interpretation of Moore's Law has evolved.

9. Early history and evolution of semiconductor roadmaps

This chapter is concerned with the early history and evolution of semiconductor technology roadmaps and includes a significant amount of original research findings of a practice that dates back much earlier than what is commonly understood. This covers a fifteen-year span of roughly the mid 1970s through Micro Tech 2000 developed in 1991. Elements of a successful roadmap—long-range view, multi-disciplinary participation, and consensus-based methodology—are evident throughout the progressive expansion of scope from individual firm, to supply chain, and eventually to industry, national, international levels.

Part Three: ITRS Case Study

10. ITRS: A decade of industry roadmapping

This chapter picks up with the events immediately following Micro Tech 2000 that led to the first official industry roadmap developed by the SIA in 1992. This chapter is an historical thematic examination of published industry roadmap editions beginning with the 1992 Roadmap. A form of content analysis is used to study the major topics, considerations, and other salient features of each Roadmap edition to better understand its evolving nature.

11. Summary findings (ITRS assessment)

This chapter summarizes the major findings of extensive research into the ITRS process based primarily on a survey administered to fifty Roadmap participants. Note that this chapter is of primary interest to Sematech as part of a joint research project.

12. Implications for industry strategies and public policies

This chapter examines macro level effects of the Roadmap in both private and public arenas. Regarding industry strategies, the Roadmap plays a central role in helping prioritize resource investments from research to semiconductor equipment and materials suppliers. From a public policy standpoint, similar benefits are derived from mission agencies and national labs engaged in semiconductor R&D. In both cases, however, a more general question concerns the traditional industry-government connection that has diminished over the years in this "critical technology" area. The Roadmap, in many ways, represents this linkage, but in a far different manner.

13. Conclusions

'What would the industry be like without a roadmap?' is a question that elicits a wide range of answers from interviewees. The consensus is, however, that the roadmap is not only useful, but increasingly vital to the continued technological advance, and thus industrial growth of the industry. As the industry—and supporting processes like the Roadmap—fully adjust to international involvement, the former CEO of Sematech has stated, "For the next 10 years, there's a different crisis. It's no longer 'beat Japan', but to stay on the productivity curve."[1] The purpose of the Roadmap is to 'show the way'—at least technically—to this end. Additional conclusions are discussed.

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[1] C. Mark Melliar-Smith, quoted in Jeff Dorsch, "*Sematech*: and then there were nine," *Electronic News*, Vol. 44, Iss. 2227, July 13, 1998, 38.

PREFACE

The U.S. semiconductor industry is one of the industrial success stories of the past fifty years. Semiconductor devices (or "chips") drive our modern electronics era and are the basis of the technology-based *knowledge* economy. One recent study reports that the semiconductor industry is now the leading manufacturing industry in America, producing 20 percent more value added than any other manufacturing industry.[2] This success is attributable to the industry's ability to continuously deliver new technological innovations at a phenomenal rate. The semiconductor industry is now truly global and easily a contemporary model of today's dynamic, high-tech environment.

As expected, market forces have played a significant role in the industry's growth and development as scholars and investors alike have discovered in studying the behavior of this dynamic industry. Another part of the explanation, however, rests on the cooperative nature of the semiconductor community (i.e., industry, universities, research consortia, and government agencies and labs) as evidenced by the important role played by research consortia such as Sematech, SRC, IMEC, Selete, and many others. These developments have also been studied by industrial researchers.

One particular outcome of this unique industrial arrangement is an industry-wide *Technology Roadmap*. Interestingly, this development has not received much attention from researchers (aside from the practitioners who develop and use this Roadmap).

This dissertation is an historical and evaluative study of the Semiconductor Industry Association's (SIA) Technology Roadmap, now referred to as the *International Technology*

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[2] Robert J. Damuth, *America's Semiconductor Industry: Turbocharging the U.S. Economy*, report for the Semiconductor Industry Association, San Jose, CA, 1998.

Roadmap for Semiconductors (ITRS) or simply, the "Roadmap."[3] It is a comprehensive case study of not just the Roadmap but the surrounding context within which it emerged and has since evolved. Past and future roles in influencing industry strategies and public policies are addressed. The ITRS, accessible online at http://public.itrs.net/, is a cooperative effort of global industry manufacturers and suppliers, government organizations, consortia, and universities that identifies the technological challenges and needs facing the semiconductor industry over the next 15 years. The Roadmap plays a vital role in research and industrial planning throughout the semiconductor community. Increasingly, it serves as a guide which individual organizations in industry, research consortia, government, and academic communities reference in strategic decision making including the multi-billions in capital investments needed for plant and equipment. The scope has broadened substantially over time; the Roadmap process is now international, including representation from the five largest producing regions of the world: the U.S., Japan, Taiwan, Korea, and Europe.

The ITRS provides a reference document of technology requirements, potential solutions, and their timing. It is a collaborative planning process that involves all parts of the semiconductor value chain from raw materials suppliers, to semiconductor equipment manufacturers who make sophisticated photolithography and other tools, to device makers who produce microprocessors, DRAMs, and other types of chips. Research consortia, academic, and government representatives also participate in the technology roadmapping process. Interestingly, the process is entirely voluntary.

Perceived by some as a novel—even unusual or unnatural—activity in such a highly dynamic industry, the Roadmap is actually one important element of a broader industrial arrangement that has evolved from the convergence of technological, economic, institutional, and cultural factors, all hinged on the goal of sustaining historical industrial productivity—also referred to as "Moore's Law."

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[3] The terms *SIA Roadmap*, *ITRS*, and *Roadmap* are used interchangeably throughout this document.

Technology roadmaps and roadmapping practices have emerged recently as new forms of strategic technology planning in a wide variety of settings, most notably in semiconductors. One reason for this is the pervasiveness of semiconductor technology in today's industrial environment. Another reason for the widespread adoption is that roadmapping was advanced within industry and thus differs from other, more academic methods like technological forecasting. The ITRS has been on the forefront of this trend as an industry-wide compilation of future technology needs. As such, it is often cited as the exemplar, model, or "mother" roadmap as other industry roadmapping efforts have been patterned after the ITRS.[4] The reasons for its success are many and complex, but central to the answer is that, as Bob Burger, former research executive at the SRC, states "the Roadmap is one of the building blocks to a comprehensive process" that distinguishes the collaborative, yet competitive nature of this industry.[5]

Thus, the Roadmap has become an integral part of the industry, publicly capturing the best available knowledge of future needs and requirements for the bulk planar CMOS technological trajectory to continue unabated.[6] At the same time, the pace of progress moves so rapidly in semiconductor technology that as soon as the Roadmap is published it is out of date. As a result, the Roadmap process is now, for all practical purposes, on-going. Asked what life would be like without a Roadmap, informants for this research from throughout the semiconductor community consistently have difficulty answering the question.

The role of the Roadmap is explained in the Foreword of the *2001 ITRS* as follows:

> It is the purpose of this *2001 ITRS* to provide a reference document of requirements, potential solutions, and their timing for the semiconductor industry. This objective has been accomplished by providing a forum for international discussion, cooperation, and agreement among the leading semiconductor manufacturers and the leading suppliers of equipment, materials, and software, as well as researchers from university and government labs. It is hoped that in the future—starting with this document as a common reference and through *cooperative efforts among the various ITRS participants*—the challenge of R&D investments will be cooperatively and more uniformly *shared by the*

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[4] David Probert and Michael Radnor, "Frontier Experiences from Industry-Academia Consortia," *Research Technology Management*, Vol. 46, No. 2, Mar/Apr 2003, 29.

[5] Robert M. Burger, personal interview, January 14, 2000. By 'building blocks' Burger is referring to the incremental approach the industry has taken toward collaboration: the 5yr cycle starting with SIA (1977), then SRC (1982), then Sematech (1987); also NACS (1988) that spawned Micro Tech 2000 (1991), the forerunner to the SIA Roadmap (1992, 1994, 1997) and ITRS (1999, 2001 and continuing). Also included are the MARCO Focus Centers initiated in 1998 to address long-term research needs.

[6] CMOS (complementary metal-oxide semiconductor) has been the dominant IC technology since 1980.

> *whole industry* while, at the same time, *the fundamental elements that foster innovation will continue to be valued and cultivated by individual companies*.[7]

The most recent *2003 ITRS* comprises 646 pages that comprehensively address the technology needs and challenges over the next 15 years (through 2018). To do this, the ITRS pulls together individual requirements from a broad spectrum of a dozen technology areas that reflect the complexity of semiconductor manufacturing, arguably one of the most complex manufacturing processes today.

This dissertation attempts to explain the Roadmap in a manner that provides broader context and meaning. It is argued that the Roadmap is the culmination of a series of important events along a rich, but short history of a dynamic technology and equally dynamic community involved in the research, development, and commercialization of semiconductor devices. With this deeper understanding, implications for industry strategies and public policies can more readily be understood. To accomplish this important topics are examined, beginning with the general area of technology roadmaps. This is followed by a review of relevant theoretical concepts drawn from Complexity Science and Evolutionary Theory where a model of the Roadmap as a distinguishable pattern of "organized innovation" is proposed. To place the background, evolution, and assessment of the ITRS in context, the history of the semiconductor industry is reviewed, with emphasis on the IC, the microprocessor, and Moore's Law as the basis for the technological innovation "cadence" that the Roadmap intends to sustain. The final part of the dissertation is a comprehensive case study of the ITRS where industry strategy and public policy implications of the Roadmap are explored.

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[7] Semiconductor Industry Association, *International Technology Roadmap for Semiconductors: 2001*, San Jose, CA: SIA, 2001, ii, emphasis in original.

CHAPTER 13
Conclusions

"As the human mind becomes more developed, more enlightened, as new discoveries are made, new truths discovered and manners and opinions change, with the change of circumstances, institutions must advance also to keep pace with the times."

- Thomas Jefferson[8]

"All generalisations are dangerous, but without them the intellect is starved."

- Ernest Braun & Stuart Macdonald[9]

"It's a better bet to be optimistic about technology rather than pessimistic. History is on the side of the optimists."

- Dirk Bruere[10]

"For the next 10 years, there's a different crisis. It's no longer 'beat Japan', but to stay on the productivity curve."

- C. Mark Melliar-Smith[11]

Probably the most striking finding of this research was one not initially sought: the legacy of semiconductor roadmaps dates back at least into the 1970s and perhaps implicitly to the early days of the IC industry in the 1960s. This historical point is significant because the continued success of the Roadmap is attributable in large part to the formative roadmapping efforts that helped shape it (see Figure 13-1). Moreover, an increasing number of interrelated industry-level and firm-level roadmaps reach both horizontally across and vertically deeper into the semiconductor supply chain, thus broaden the web of roadmapping behavior and further

8 Thomas Jefferson, 1816; also inscribed in the wall of the Jefferson Memorial, Washington, DC.
9 Ernest Braun & Stuart Macdonald, *Revolution in Miniature*, Cambridge: Cambridge University Press, 1982, 181.
10 Dirk Bruere, newsgroup posting: From dirk@neopax.com, Subject: Re: Noise threatens Moore's Law, Newsgroups: sci.physics, Date: 2002-12-19 13:39:33 PST.
11 C. Mark Melliar-Smith, quoted in Jeff Dorsch, "*Sematech*: and then there were nine," *Electronic News*, Vol. 44, Iss. 2227, July 13, 1998, 38.

reinforcing the importance of the "mother" Roadmap. In this sense the linear presentation of Figure 13-1 is insufficient.

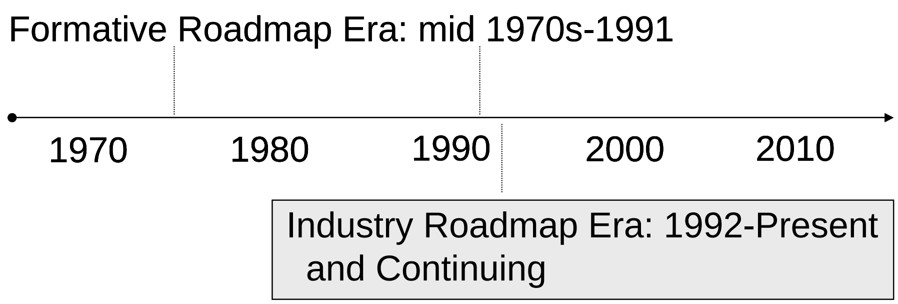

Figure 13-1. Evolution of Semiconductor Roadmaps

Retrospective

This dissertation began as an attempt to study Moore's Law. While unique, interesting and important, this topic soon proved difficult to research in a practical way. After repeated but unsuccessful attempts at making the topic researchable, my advisor finally suggested an examination of the Roadmap, in many ways Moore's Law *operationalized* or as Sonny Maynard referred to earlier as "heavily decorated." Indeed, when I first opened up *The National Technology Roadmap for Semiconductors*, I noted how thoroughly semiconductor technology was examined in a *forward-looking* fashion. This approach stood in contrast to many treatments of Moore's Law which were mostly historical curve-fitting exercises with some simple future extrapolations. On the other hand, the Roadmap's purpose of anticipating, and deliberately sustaining or even perpetuating Moore's Law carried with it profound strategy and policy implications and thus seemed a much more appropriate topic to study. One early informant musingly referred to the Roadmap as Moore's Law "insurance." That interpretation stuck.

My idea was to study this technology "road map" to better understand its role in a broader innovation context. Like any research the path to discovery is rarely straight, however the Roadmap seemed to run counter to this view. What became apparent upon examining preceding

Roadmaps is that there did not appear to be a great deal of difference among the documents. However, upon closer examination small changes were noticed, which begged questions that could not be answered by simply looking at Roadmaps. It became evident that studying the Roadmap meant much more than reviewing publications—these were outcomes of a methodical *roadmapping process* that typically involved a wide range of knowledge, skills, and interests. Roadmapping is a social process applied, in this particular case, to a technological challenge: how to advance semiconductor technology, and do so continuously. The economic benefits from such an effort, whether accrued to a single firm or entire industry, were clear and compelling.

With the Roadmap (not just the document but the process behind it) as the unit of analysis this dissertation covered a broad theoretical base in economics, sociology, and public policy. Numerous studies, reports, books, articles, and other publications covering the semiconductor industry informed the research on all these fronts. A more focused review of the innovation studies literature within the framework of complexity science and especially evolutionary theory provided the conceptual basis. Specialized topics in the areas of technical and engineering knowledge, network and organizational learning, collaboration, industrial organization, and strategic behavior along with contemporary practices in research consortia, technology assessment and forecasting, and management of technology were also surveyed. An academic interest in the phenomenon of Moore's Law along with a former technical background in the computer industry helped translate curiosity into meaningful inquiry. An historical bent ensured that loose ends were carefully tied while context was purposely considered. The richness of the primary data on everything from simple facts to deep insights obtained in interviews of several dozen semiconductor industry representatives afforded the benefit of a more complete understanding and articulation of findings. Finally, a penchant for detail, completeness, and rigor guided a thorough treatment of all data sources.

The net result of all these research considerations is the capacity to now look at a particular figure, table, or statement in the ITRS and perhaps not understand its technical merits, but appreciate and articulate how it was arrived at, how it will be used, and its overall significance to semiconductor innovation, strategy, and policy.

As with any research more questions are produced than answers. These questions are for future study. For now, the answers to the initial research questions are addressed.

The Research Question

How have technology roadmaps affected innovation, strategy, and policy in the semiconductor industry?

Roadmaps and Innovation

I have argued that technological innovation in semiconductors follows a normal innovation pattern. By itself, this is not a new finding. However what has been demonstrated is that evolutionary change best describes the vast majority of semiconductor innovations including the microprocessor, considered by most conventional accounts as a revolutionary change. At a different level, advances in lithography, historically the most critical chip fabrication tool, have followed a very distinct normal pattern. As attempts have been made to introduce revolutionary methods (e.g., x-ray), incremental advancements in optical methods have stretched its utilization far beyond forecasted limits. Even EUV lithography, the industry's apparent current choice of next-generation lithography, is an extension of the present DUV (optical exposure) technology.

Underneath this pattern is a roadmap, whether explicit or implicit, that has predetermined the path of innovation. What makes these roadmaps credible is the collective, accumulated knowledge captured within them. This is most evident in the case of the ITRS due to its public nature. But in earlier pre-Roadmap times the innovation network shared this understanding in large part through the unique scaling properties of IC technology. Moore's Law has become legacy because the industry has made it so through day-in, day-out engineering practice that continues to expand technical knowledge and thus capability at an exponential rate.

Without initially intending, industrial innovation has increasingly become *organized*—actually *self-organized*—because designing and building semiconductors is very complex and requires considerable coordination and alignment of a wide variety of elements. Thus, organized innovation has benefited greatly from a roadmap. As collective knowledge is made more explicit and codified in ever finer detail in an *International* Roadmap, this awareness allows the innovation network to, in turn, affect the nature and pace of innovation as has become so evident in the SIA Roadmap era. This give-and-take process ensures the primary purpose of the Roadmap: to perpetuate Moore's Law.

Therefore, roadmaps and innovation in semiconductors have become almost inseparable.

Roadmaps and Strategy

The semiconductor industry is unique in many ways, not the least of which is in the sheer diversity of organizations that make it up, whether large or small, private or public, chip maker, tool maker, OEM, materials provider, research consortium, etc. In contrast with the common properties of the technology, very disparate organizations participate in such a way that benefits each while assisting the broader interest. At a top level, "beating the Roadmap" is akin to Adam Smith's *invisible hand* of competition theory of market forces. This helps explain the evolutionary nature of roadmapping from firm to industry to national to international levels.

At a lower level it has been demonstrated how roadmaps can be used to gain competitive advantage. In some organizations the roadmap is the strategy, or at least a large part of it.

In the area of research, one unique factor of this industry is the noticeable 15yr outlook (i.e., research and development time line) that distinguishes research responsibilities among members of the innovation network, from semiconductor equipment supplier to university researcher. Throughout the semiconductor infrastructure exists a roadmapping mentality, (i.e., "it's on somebody's roadmap"). This is the broader impact of the Roadmap; it really does foster a broad-based, coordinated strategy.

Roadmaps and Policy

Policy, especially public policy, is about crafting and instituting some action that corrects, remedies, or otherwise improves a situation that needs attention. The relationship between roadmaps and policy has varied considerably over time as the situation has changed. Initially a byproduct of policy the Roadmap became an instrument for policy, and has since become an activity almost in *lieu* of policy. Of the three attributes, policy is probably the one least influenced by the Roadmap at the present. This is evident in the reduced levels of Roadmap participation by Government representatives as shown in Figure 13-2.

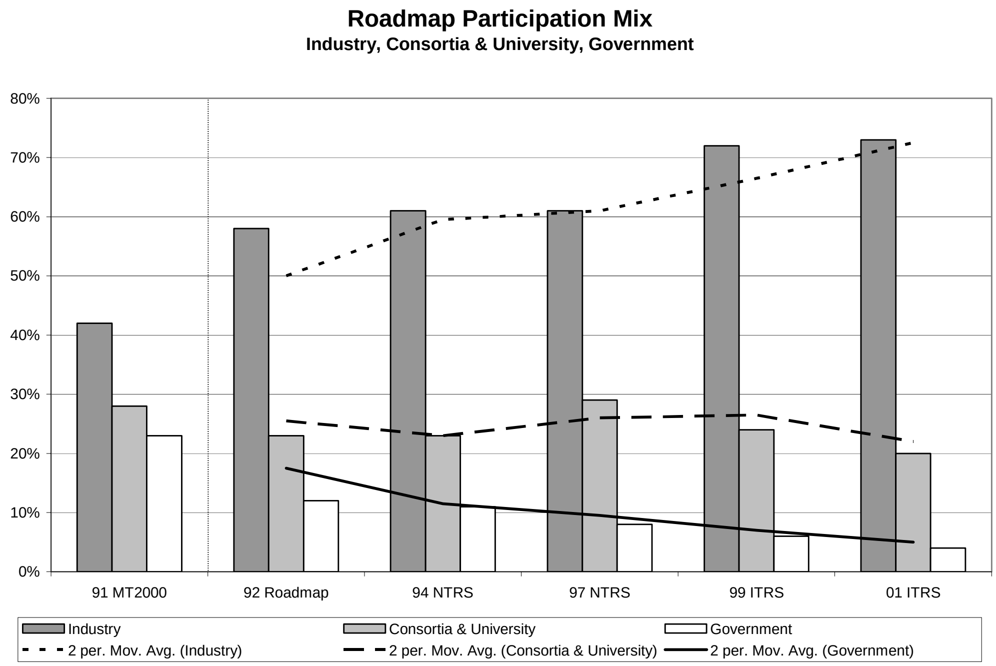

Figure 13-2. Roadmap Participation Mix by Industry, Consortia & University, and Government[12]

Source: SIA Roadmaps, Sematech Archives

One particular policy lesson is in the area of research. The U.S. Government has traditionally supported advanced applied research in technologies deemed as replacement technologies. Major examples include non-silicon substrate materials and non-optical lithography. In the vast majority of cases these programs were not successful because they were incompatible with the needs of industry. It has only been recently when industry has essentially chosen the research topic (increasingly from the Roadmap) that Government support has been more useful. Examples include EUV lithography and the MARCO Focus Center Research Program.

[12] Note that data for the 2003 ITRS did not distinguish Government as a single category but was combined into a single category of Consortia, Research Institutes, and Universities which totals 20%. Total industry participation for 2003 increased to 78%.

Thus both strategic and policy-oriented decisions are best made on the Roadmap or on technologies that do not veer too far from it.

Other Conclusions and Observations

Studying the Roadmap in the context of a broader industry analysis leaves one with many impressions. A couple of points are noteworthy. The first is the very noticeable technology acceleration or "beat the Roadmap" behavior. This suggests strongly that non-technical factors are at play and offer a fertile area for future research. The second is the relatively easy, almost natural flow of roadmapping to increasingly higher levels of participation and use. Another is the ready acceptance and credibility of the Roadmap. Yet another is the all-volunteer nature of Roadmap participation. Since these particular points have already been addressed elsewhere in the thesis, the following paragraphs offer comments on other aspects of the Roadmap that may not have been addressed previously.

Assessing the first SIA Roadmap

Having had the opportunity to examine the 1992 Roadmap over the span of its initial projection (through 0.10 um) allows a researcher to assess it in many ways. Technically, the 1992 Roadmap out-year technology node was achieved in 2003, four years ahead of forecast, as discussed in Chapter 10. So was it successful or not? Secondly, the future has not unfolded as it was supposed to. For example, we do not have 16G DRAMs and die sizes are not monster 1000 mm^2 as the 1992 Roadmap projected. At the same time, device feature sizes are actually smaller than anticipated and on-chip performance far exceeds 1GHz. Again, what does this say about the Roadmap? As discussed in Chapter 2 forecast accuracy is *not* the only—and perhaps only a minor—success measure for a roadmap. One major factor that contributed to these deviations is that other technology drivers have emerged that required different capabilities than the narrow DRAM and logic/microprocessor assumptions used in the first Roadmap. What seems more important is that successive Roadmaps adjusted for the variances to reflect the best collective judgment at the time. But each required adjustment upon renewal, sometimes major change. Thus is the iterative nature of the roadmapping process: a continual reassessment that becomes obsolete as soon as it is published. Perhaps the best example of this (that also predates industry roadmaps) is the projected end of optical lithography. Yes, the industry still uses optical lithography, and plans to continue for the foreseeable future.

Why is the Roadmap successful?

If forecast accuracy is not the proper success metric, then what is? And what explains this success? This research uncovered a wide variety of success measures. While these have been discussed at various points in this dissertation, the following general proposition is offered.

The Roadmap is "successful" because it is still going, six editions later.

Tens of thousands of hardcopy Roadmaps have been purchased while the public website records more than 5,000 visits per day. Total participation is approaching 1,000 and now consists of more non-U.S. participants than U.S. participants. Users include chip makers, tool makers, materials suppliers, OEMs and other customers, researchers, faculty, government agencies, investors, etc. Iteration (or renewal) is now an annual event. But how long can this continue? Gordon Moore himself suspects that the Roadmap and even Sematech might "peter out" after a while. His experience is that things like this usually last no more than a decade.[13] For now, though, the Roadmap shows no immediate sign of petering out.

If anything it continues to grow in size, scope, and complexity. The 2003 ITRS is almost 650 pages, single-space, 10pt font, and loaded with more than 200 intricate figures and tables. In comparison the 1992 Roadmap (Workshop Working Group Reports) was 154 pages.[14] Yet, as pointed out in Chapter 10, the first and most recent "bookend" Roadmaps share much in common in large part because the underpinning need has not changed. One informant provides an historical perspective to make this point evident while adding a bit of levity:

> "Today's industry is fragmented, vertically disintegrated, etc., but the "whole thing" hasn't changed much. It's just divided differently on the inside. The same level of R&D needs to go on with equipment suppliers, formerly device makers, in process development. Remember that the Roadmap was always to provide a tool to guide *research*, to identify

[13] Gordon Moore, telephone interview, February 11, 2002.
[14] A second 60pg volume (Workshop Conclusions) summarized the Workshop Reports for a non-technical audience.

> gaps… thus a "roadmap" to identify needs. The Roadmap has expanded in character over time, but it's still the same issue. The first Roadmap looks very much like the current Roadmap. We're now down to nuances—in ITWG workshops we're arguing over the definition of dimensions (i.e., gate length, half-pitch, etc) or semantics. The discussion is almost, 'How many angels can dance on the head of a pin?' "

The last comment, though facetious, does capture the delicate balance the Roadmap attempts to strike between the forest and trees of research in semiconductor technology. Returning to the original question, exactly *why* the Roadmap is successful has many possible answers. One certainly is the unique scaling nature of the technology and the normal innovation pattern that seems to coincide with it. The existence of "Moore's Law" is a short-hand way of describing this. Another factor is that the Roadmap has been rationalized by industry, not government, academia, or other institution that lacks a market incentive. At the same time, the role of research consortia such as the SRC and especially Sematech in providing the model for industry collaboration has been of critical importance. Additionally, the evolutionary nature of the Roadmap correlates with the industry's evolution. For example, the disintegration, specialization, and globalization of industry necessitate a common reference, which the Roadmap seems to provide. This is especially true between device makers and tool and materials suppliers as hinted in the caption above.

Related to this and perhaps the most important reason that the Roadmap continues to be useful and credible is because it is a continual process that must evolve along with the industry. It has become an almanac, an atlas (i.e., collection of maps), a compendium that is reviewed, assessed, and updated (i.e., made current) on a regular basis. At the same time, it changes as needs change. “Renewal” is a very appropriate term. The ITRS has become an ongoing process. Like cartography (i.e., the art of map-making), successive Roadmaps have become more granular. Similarly, the author has noted that a *Rand-McNally Road Atlas* states as its purpose, "keeping the *Road Atlas* up-to-date is job #1." Below is a brief passage from the document that aptly parallels the work embodied in the renewal process of the semiconductor industry Roadmap:

> Every year there are thousands of changes, updates, and additions to the Rand McNally *Road Atlas*. And they have real impact. For example, roads are built, interchanges are

> constructed, and highways and byways are newly named and numbered. The importance of these changes lies in knowing that you'll reach your destination as planned.[15]

Along with increased granularity, the Roadmap has simultaneously become broader in scope (e.g., international, addressing different devices/drivers, even new status categories like “interim solutions exist”).

The pull-in or technology acceleration is a broader bias reflected in the Roadmap over time. The Roadmap served initially as a research instrument to see what was possible down the road. Thus it was not that concerned with the current state-of-the-art. If anything, the purpose of an early research roadmap like Micro Tech 2000 was to deliberately *change* or disrupt the current state. As such, this was (per Chapter 2) a *requirements-pull prospective* roadmapping approach (i.e., start with a future goal like a 1G SRAM and work backwards). The newer emphasis—starting actually at Sematech—is to fully understand the current state and how to project it forward (i.e., a *technology-push prospective* roadmapping approach). As Government research interest in the Roadmap began to wane in the 1994 and particularly 1997 Roadmaps, the supplier community became a much more significant user which started a shortened view of research. The 1997 Roadmap reflected 2yr technology nodes through N+3 and by 1999 the Roadmap went to two timings: near-term (annual for next 6 yrs) and long-term (last 3 generations over 9 yrs). Most recently (2003), the inclusion of *interim solutions known* status color formally acknowledges a form of "temporary research."

The combined effect of these adjustments is a collapsing research horizon. In other words the Roadmap is now noticeably biased to the front-end. Similarly, the goal-driven roadmapping process runs the risk of path dependency, potentially missing important technological opportunities. While the Roadmap fosters organized innovation, the opportunity cost of roadmapping is some degree of curiosity-driven inventiveness. The very framework that brings about consensus and collaboration is also delimiting of nonconforming views. The extent of this consequence deserves greater attention.

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[15] Preface, *Rand McNally Road Atlas: 2000 Millennium Atlas*, A1, 2000.

Finally, the Roadmap is but a piece of a larger puzzle that is the uniqueness of the semiconductor industry. All the other pieces or elements (e.g., Moore's Law, industry consortia, standards, etc.) are required to complete the industrial pattern. While the Roadmap works well for the semiconductor industry, it would not necessarily fit within other sectors with distinct needs. Thus the Roadmap, by itself, is not replicable. This finding is consistent with other assessments of industry roadmaps:

> …*there is no one best way* to define the optimal level at which to carry out [technology roadmapping]… Hence a general definition of the best application level cannot—and *should not*—be given. Technology Road Mapping is typically needs-oriented and the definition of the level to which it should apply depends on the specific needs defined by those who participate in the exercise.[16]

In sum, the Roadmap is "successful" as evident by the hundreds of people who volunteer their time and energy routinely. As one respondent stated:

> "We have learned very simply that if you provide your customer with more capability for the same dollar, year after year, then you'll be able to grow your markets. That's a real simple idea - that's what we've done. Each year we give you more for the same amount of money - more functionality, etc. We do this exponentially - we've been able to do this for two decades now. That's what Moore's Law says: well, surprise, surprise, it really works. And so this industry is *determined* to keep doing that - it sees that as a way of success, growth. My opinion is that we will find a way to push the Roadmap - I'm guessing - at least the CMOS era - maybe ten or fifteen more years."

Prospective

While many questions were addressed in this dissertation, several important questions remain. What is the future role of the Roadmap, especially as the industry approaches the limits of CMOS technology and possibly industrial maturity? What changes must be made to prepare the Roadmap for the second decade of practice? For example, how much longer will a single Roadmap be able to sustain the weight of so many constituents? Should it be broken up into more manageable “volumes” (i.e., more like an atlas) by device type, thrust area, etc.? One respondent offered the idea of two Roadmaps to serve distinct audiences: 1) for suppliers yrs 1-6, 2) for research yrs 6-15. As inter-consortia (and inter-industry) collaboration increases, will the Roadmap become even more important as the common denominator for discussion and debate?

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[16] Bastiaan de Laat and Shonie McKibbin (Technopolis), "The Effectiveness of Technology Road Mapping: Building a strategic vision," a study for the Dutch Ministry of Economic Affairs, est. 2002, 7, emphasis in original.

Finally, asked about the future role of Roadmap, respondents consistently viewed it as an important institution within the global semiconductor innovation community. The industry plans to continue Roadmap activity, essentially now a continuous process. When Juri Matisoo, SIA VP of Technology Programs was asked the question, "do you see a time when a roadmap is no longer needed?" he replied by rephrasing the question: "will there be a time when collective research in semiconductor technology will not be required?" His answer: "I don't think so."[17]

In a recent special issue of *Business Week* that examines the changing U.S. position in world science and technology leadership, the authors conclude, "History's powerful lesson: When it comes to a nation as a whole, the best system to foster innovation is disorganized and chaotic."[18] The rationale for this statement is that "no central authority in government or industry should decide what the future ought to hold," as entrepreneurial spirit within a market system has proven a better driver of innovation.

In the same issue is an interview with Craig Mundie, chief technologist at Microsoft. Mundie describes innovation more fully as a "symbiotic cycle" that needed balanced attention:

> You have to think of this [innovation] as a symbiotic cycle in which the government funds research and trains people, and businesses create the opportunity for these people to turn their ideas into products. Our great concern is that if you don't pay careful attention to each element of the cycle, you end up with a broken machine.[19]

The concern Mundie is referring to is the diminished investment in fundamental, long-term research that has occurred since the end of the Cold War. This claim has been raised often.

For its part, the semiconductor industry has chosen a much more *organized system of innovation*—greatly assisted by the Roadmap—that seems more aligned with Mundie's symbiotic view than the preceding disorganized and chaotic view. To date it has proven successful for the key reason suggested by Jefferson in the opening quote of this chapter: the Roadmap as an institution has evolved alongside the industry it reflects and supports.

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[17] Juri Matisoo, telephone interview, August 10, 2000.
[18] John Carey, Otis Port, and Adam Aston, "America's Enduring Tech Edge," *Business Week Online* (Special Report: America's Tech Might: Slipping?), March 16, 2004, http://www.businessweek.com/technology/content/mar2004/tc20040316_2875_tc166.htm
[19] Craig Mundie, quoted in Alex Salkever, "Innovation Is a "'Symbiotic Cycle'," *Business Week Online* (Special Report: America's Tech Might: Slipping?), March 16, 2004, http://www.businessweek.com/technology/content/mar2004/tc20040316_9616_tc166.htm