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HIGH TECH R&D SUBSIDIES: ESTIMATING THE EFFECTS OF SEMATECH

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ABSTRACT

Sparked by concerns about their shrinking market share, 14 leading U.S. semiconductor producers, with the financial assistance of the U.S. government in the form of $100 million in annual subsidies, formed a joint R&D consortium -- Sematech -- in 1987. Using Compustat data on all U.S. semiconductor firms, we estimate the effects of Sematech on members' R&D spending, profitability, investment, and productivity. In so doing we test two hypotheses: the "commitment" hypothesis that Sematech obligates member firms to spend more on high-spillover R&D, and the "sharing" hypothesis that Sematech reduces duplication of member R&D spending. Whereas the commitment hypothesis provides a rationale for the government subsidies, the sharing hypothesis does not. We find that Sematech induced members to cut their overall R&D spending on the order of $300 million per year, providing support for the sharing hypothesis.

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1. Introduction

The potentially adverse impact of international competition from Japan on U.S. producers is nowhere more hotly debated than in the high technology sector. Foreign trade and industrial policies are widely alleged to have targeted specific high technology industries for promotion in an effort to capture world markets. These policies are said to operate to the detriment of U.S. firms which do not have the benefit of such government support. Concern is particularly acute in the case of the semiconductor industry. Foreign industrial policies are believed to have undermined U.S. semiconductor producers, denying the economy potential spillovers that emanate from this R&D-intensive industry. Many analysts, such as Tyson (1992), have urged the U.S. government to undertake a more aggressive response to such foreign industrial targeting.

The theoretical rationales for government intervention to assist high technology industries were developed extensively in recent years. The international trade literature on strategic trade policy, such as Brander and Spencer (1983), examined international competition in R&D-intensive industries and found a role for government R&D subsidies to enable domestic firms to capture rents from their foreign rivals. Recent work linking R&D to economic growth, such as Romer (1990) and Grossman and Helpman (1991), reinforces these rationales to the extent that knowledge spillovers are geographically local.

Fearing a dramatic shrinkage in the U.S. semiconductor industry as a result of Japanese competition, the U.S. government responded in part by subsidizing the R&D efforts of certain semiconductor producers beginning in the mid-1980s. In 1987, the government agreed to match the financial contributions of private firms in sponsoring the formation of an industry R&D consortium called Sematech -- SEmiconductor MAnufacturing TECHnology. Since then, the Advanced Research Projects Agency (ARPA) of the Department of Defense has contributed just under one-half of Sematech's roughly $200 million annual budget. The rebound of the U.S. semiconductor industry vis-a-vis their Japanese rivals since the mid-1980s is sometimes attributed to Sematech. Figure 1, which depicts a slight rebound in the world market share of U.S. producers after 1987, provides circumstantial support for this claim.

Sematech's apparent success has prompted those concerned about the impact of international competition on the fate of U.S. high technology industries to embrace it as a model of government-industry cooperation. The General Accounting Office (1992, p. 2) has stated that "Sematech has demonstrated that a government-industry R&D consortium on manufacturing technology can help improve a U.S. industry's technological position while protecting the government's interest that the consortium be managed well and public funds spent appropriately." Others are more critical of such government participation in joint ventures. Cohen (1994) argues that government-supported research joint ventures will concentrate more on appropriable than generic R&D and that consortia that are less than industry-wide impose negative externalities on non-member firms.

Despite the ongoing controversy over government industrial policies for high technology industries, little is known about the actual effects of programs such as Sematech. Using panel data on U.S. semiconductor firms (including both members and non-members of Sematech), we try to disentangle the effects of the consortium on U.S. firms' R&D spending, profitability, investment, and productivity. Before attempting this task in sections 3-6, we briefly discuss Sematech's organization and activities since its formation.

2. The Origin and Purpose of Sematech

The semiconductor industry is one of the largest high-technology industries in the United States and provides a key input to other high technology industries. It also ranks among the most R&D-intensive of all industries: in 1989, for example, the electronic components industry (SIC 367) spent 8.3 percent of net sales on R&D, compared with 3.1 percent for U.S industry overall, according to the National Science Foundation.[1] The semiconductor industry (SIC 3674) is even more R&D intensive: merchant firms devoted 12.3 percent of their sales to R&D in 1989, according to the Semiconductor Industry Association.[2]

A common presumption holds that the social returns to these R&D investments cannot be fully appropriated by the firms undertaking the expenditures. R&D results arguably have the attributes of a public good, "spilling over" to the benefit of other firms in the industry and to consumers downstream. To the extent that R&D spillovers exist and give rise to a free-rider problem, firms will devote insufficient resources to R&D compared with the social optimum. Countervailing "business stealing" effects push firms to devote too many resources to R&D. By business stealing we mean quasi-rents of other firms destroyed by R&D.[3]

With the support of the U.S. semiconductor industry, the U.S. government has taken several steps to reduce the cost of R&D expenditures and improve the ability of firms to appropriate the benefits of their research.[4] The Semiconductor Chip Protection Act of 1984 enhanced the protection of intellectual property rights for the industry, and the economy-wide R&D tax credit was renewed in 1986. Perhaps more importantly, the National Cooperative Research Act of 1984 loosened antitrust restrictions on collaborative R&D and other joint ventures. Such ventures among semiconductor producers have proliferated since that time, and the cooperative pooling of resources could enable firms to boost the efficiency of their R&D spending as well as better internalize R&D spillovers.

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[1] National Science Foundation, Research and Development in Industry, 1989, NSF 92-307, p. 77.

[2] Semiconductor Industry Association, 1993 Databook, p. 41.

[3] Dixit (1985) provides an excellent discussion of these theoretical issues in international R&D competition.

[4] A host of government trade-related policies were designed to support the semiconductor industry in the mid-1980s, as described in Irwin (1994).

Partly as a result of this legislation, Sematech was incorporated in August 1987 with 14 founding members, listed on Table 1. Sematech was primarily designed to help improve U.S. semiconductor production technology. Under its by-laws, Sematech is prohibited from engaging in the sale of semiconductor products. Sematech also does not produce or design semiconductors itself, nor does it restrict member firms' R&D spending outside the consortium.

The establishment of Sematech received critical support in the form of an ongoing government subsidy. When the U.S. semiconductor industry faced severe competition from Japanese producers in the mid-1980s, the Department of Defense raised concerns about the national security implications of dependence on foreign sources of semiconductors. Government assistance to help revitalize the industry was formalized in the National Defense Authorization Act (FY 88 - 89), which allowed the Department of Defense to contribute (through ARPA) up to $100 million in matching funds to Sematech. ARPA has been a relatively passive financial provider, although it does play an advisory role in the consortium and encourages projects related to national defense. The government initially committed funding for only five years, but legislation renewing these expenditures passed in 1993. In mid-1994, Sematech announced that it would end its reliance on ARPA funds by FY 1997.

Sematech members contribute financial resources and personnel to the consortium.[5] They are required to contribute 1 percent of their semiconductor sales revenue, with a minimum contribution of $1 million and a maximum of $15 million. Of the 400 technical staff of Sematech, about 220 are assignees from member firms who stay at Sematech's facility in Austin, Texas for anywhere from 6 - 30 months. Because the objective has been to bolster the domestic semiconductor industry, membership has been limited to U.S.-owned semiconductor firms. U.S. affiliates of foreign firms are not allowed to enter (a bid by the U.S. subsidiary of Hitachi to join the consortium in 1988 was

[5] This section draws heavily on Spencer and Grindley (1993). William Spencer is the current chairman of Sematech.

turned down), although this policy is now under review. However, no restrictions are placed on joint ventures between Sematech members and foreign partners.

To discourage free-riding and to encourage firms to join the consortium, Sematech originally discriminated against non-members through policies that were designed to allow members to reap most of the benefits of the collaborative research. Efforts to prevent spillovers and to internalize the knowledge generated by Sematech's R&D have been relaxed in recent years. Sematech bylaws initially prohibited equipment manufacturers developing products with Sematech's assistance from selling that equipment to non-members companies for one year. This equipment hold-back provision was vehemently criticized by non-members and equipment manufacturers, and this exclusivity was suspended in late 1991. Sematech members still have the "right of first acceptance" on Sematech-funded equipment, effectively giving them the option of acquiring new equipment 6 - 9 months in advance of non-members. Regarding intellectual property, Sematech originally licensed its knowledge exclusively to members for two years, after which it would become available to all other U.S. firms at nominal royalty charges. This provision has been eliminated.

To try to ensure that the collaborative research is useful to all of Sematech's members, the consortium originally focused on generic, pre-competitive process (not product) R&D. According to Spencer and Grindley (1993, p. 16), "this agenda potentially benefits all members without threatening their core proprietary capabilities, and the emphasis on technology that is generic to the manufacturing industry reduces appropriability problems in the treatment of research output." One of Sematech's first priorities, for example, was to sequentially reduce the width of circuit lines etched onto silicon wafers from 0.80 to 0.25 microns -- allowing more circuits to be put on a given chip. To this end, Sematech purchased and experimented with semiconductor manufacturing equipment and transferred the technological knowledge to its member companies. Spencer and Grindley (1993, p. 15) state that "central funding and testing can lower the costs of equipment development and introduction by reducing the duplication of firms' efforts to develop and qualify new tools."

Since about 1990, however, Sematech's direction has shifted toward "subcontracted R&D" in the form of grants to semiconductor equipment manufacturers to develop better equipment. In 1991, for example, as reported in Burrows (1992), about $130 million of Sematech's $233 million budget went into projects with equipment makers, whereas this figure had been under $30 million just two years earlier. By contrast, Katz and Ordover (1990, p. 183) report that Sematech's equipment purchases for experimentation on its own fabrication lines declined from $119 million in 1989 to $45 million in 1990. This new approach aims to establish a stronger domestic supplier base and strengthening the vertical links between the equipment and semiconductor manufacturers.

By improving the technology of semiconductor equipment manufacturers and relaxing the exclusivity policies, Sematech has arguably increased the spillovers it generates for non-members. Indeed, Spencer and Grindley (1993, p. 25) argue that

> "the spillovers from these Sematech efforts constitute a further justification for government support. The equipment developed from Sematech programs is shared with all U.S. corporations, whether they are members or not."

These spillovers may be international in scope: Sematech members are free to enter into joint ventures with foreign partners, and equipment manufacturers are free to sell to foreign firms.[6]

Has Sematech been a success? According to a Government Accounting Office (1991) survey of executives from Sematech members, most firms have been generally satisfied with their participation in the consortium. A number of executives noted that Sematech's research had not been incorporated into their own firms' operations until about 1991, indicating that a payoff is just starting. Burrows (1992) reports that Intel believes it has saved $200-$300 million from improved yields and

[6] For evidence of international learning-by-doing spillovers in the semiconductor industry, see Irwin and Klenow (1994).

production efficiencies in return for annual Sematech investments of about $17 million. The GAO survey indicated that the Sematech research most useful to members includes methods of improving and evaluating equipment performance and machine capabilities, fabrication factory design and construction activities, and yield management through defect control. Several executives maintained that Sematech technology had been disseminated most easily through "people-to-people interaction," and that the assignee program of sending personnel to Austin has been useful. These executives also noted that, as a result of Sematech, they had begun to purchase more semiconductor equipment from U.S. manufacturers.

However, Sematech has also drawn extensive criticism from non-members and from those opposed to government subsidies for the industry. According to Jerry Rogers, president of Cyrix semiconductor, "Sematech has spent five years and $1 billion, but there are still no measurable benefits to the industry." T. J. Rodgers, the president and CEO of Cypress Semiconductor, has argued that the group just allows large corporations ("the losers" in his words) to sop up government subsidies for themselves while excluding smaller, more entrepreneurial firms.[7] The most controversial aspect of Sematech has been its initial policy of preventing non-members from gaining quick access to the equipment it helped develop. These restrictions raised questions about whether research undertaken with public funds was benefiting one segment of the domestic semiconductor industry at the expense of another. Adversely affected were smaller firms that were (financially) unable to join Sematech, and equipment producers that could initially sell only to Sematech members and thus found a limited market for their new products.

Another heavily criticized feature of Sematech has been its membership fee schedule, which discriminates against small firms. Sematech members, as noted earlier, are required to contribute 1 percent of their semiconductor sales revenue to the consortium, with a minimum contribution of $1

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[7] See Burrows (1992).

million and a maximum of $15 million. This fee schedule places heavier financial burdens on firms with sales of less than $100 million and lighter burdens on firms with sales of more than $1.5 billion. Many smaller firms such as Cypress Semiconductor say they cannot afford to pay the steep membership dues or to send their best engineers to Sematech's Austin facility for a year or more. Even if these companies joined, moreover, they might have a limited impact on Sematech's research agenda: the consortium is reputed to operate on a "one dollar - one vote" basis.

Sematech's membership has also declined. Three firms have left the consortium, dropping its membership to 11, and another has reserved its option of leave. (Any firm can leave Sematech after giving two-years notice.) In January 1992, LSI Logic and Micron Technology announced their withdrawal from Sematech, followed by Harris Corporation in January 1993. Press reports in February 1994 indicated that AT&T Microelectronics notified Sematech of its option to leave the consortium in two years, although a spokesman denied the company had definite plans to leave. All of the former members questioned the new direction of Sematech's research effort, complaining that Sematech strayed from its original objective of developing processes for making more advanced chips toward just giving cash grants to equipment companies. Departing firms have also stated that their own internal R&D spending has been more productive than investments in Sematech.

In mid-1994, Sematech announced that it would forgo ARPA subsidies after FY 1997. Reports indicate that there was an implicit agreement between Sematech and the government in 1987 that, if Sematech was a success, ARPA funding would cease after 10 years. That is, ARPA funding may have ended in 1997 even without Sematech's declaration of independence. Sematech remains free to apply for competitive grants from government agencies such as the National Science Foundation.

Whatever the future of Sematech, it is vitally important to learn from its experience to date. The consortium has been hailed by the Clinton Administration and others as a successful model of government-industry cooperation in support of high-tech R&D. Romer (1993), arguing for the creation of industry-specific technology boards to fund high-spillover R&D, cites Sematech as a prototype. Has Sematech been a good investment for the United States? To date there has been no empirical study of its social return. Given that history cannot be re-run without Sematech, estimating its social return is a daunting task. We address several more modest questions, the answers to which could contribute to eventually estimating the social return to Sematech. These questions fall under the rubric, "Did Sematech affect member firms' behavior?"

3. Effect of Sematech on R&D Spending

We first address whether Sematech induces member firms to alter their R&D spending. The theoretical literature on the impact of joint ventures and cooperation on R&D spending has been summarized by Tirole (1988), Reinganum (1989), Katz and Ordover (1990), and Cohen (1994), and extended by d'Aspremont and Jacquemin (1988), Kamien, Muller, and Zang (1992) and Suzumura (1992). Not surprisingly, the predictions from theory depend heavily on the particular assumptions made. The crucial details include: (1) the extent of spillovers in the absence of the joint venture; (2) the extent of "business stealing" in the absence of the joint venture; (3) whether the joint venture restricts firms' independent R&D spending; (4) whether the venture allows firms to contribute as little as they want; and (5) whether the joint venture strengthens spillovers among venture partners.

As noted earlier, Sematech places no restrictions on firms' independent R&D spending. Thus Sematech could not curtail R&D for the sake of internalizing business stealing. Sematech could internalize knowledge spillovers, however, by committing members to contribute sufficiently to the consortium. But then the mandatory contributions would have to exceed what firms would spend without Sematech, and independent programs would cease. This is clearly not the case for Sematech since every member continues to spend independently.

Still, Sematech could internalize spillovers to certain *kinds* of R&D. Sematech's stated purpose is to improve *generic* manufacturing technology and, more recently, to improve the quality of U.S. equipment, which can be bought by non-members and members alike. Sematech may committed firms to jointly spend more on high-spillover R&D. We call this the "commitment" hypothesis. Suppose member firms would spend ρ percent of sales on high-spillover R&D in the absence of Sematech, where $\rho < 1$. Under Sematech they contribute roughly 1 percent of sales, so Sematech stimulates R&D spending by $(1-\rho)$ percent of member sales.[8] One problem with the "commitment" hypothesis is that firms need not join Sematech, and those that do can leave after giving two years' notice. Firms should be tempted to let others fund high-spillover R&D. Under this hypothesis, then, the 50 percent government subsidy is crucial for Sematech's existence. The "commitment" hypothesis both justifies a government subsidy and requires one to explain Sematech's membership. A government subsidy could also be justified on the grounds that not all U.S. semiconductor firms have joined Sematech, and that some spillovers extend to non-members. This hypothetical role of Sematech is behind Romer's (1993) support.

Another hypothesis is that, rather than internalizing spillovers, Sematech promotes sharing of R&D within the consortium (but not necessarily of results from independent R&D programs), thereby reducing duplicative R&D. Since Sematech firms are free to carry out independent R&D, this "sharing" hypothesis requires a floor on member contributions. Without a floor firms would contribute nothing (or next to it) and free ride off the contributions of others. The "sharing" hypothesis implies greater efficiency of consortium R&D than of independent R&D. From a private standpoint Sematech contributions are all the more efficient because of the 50 percent government subsidy.

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[8] Spending on high-spillover R&D could, of course, substitute for or complement other types of member firm R&D. If they are substitutes, the impact on firms' R&D spending would be lower than $(1-\rho)$ percent; if they are complements then it would be higher.

One can view the consortium as raising "effective R&D," a sufficient statistic for the knowledge created by R&D. That is, R&D spending affects productivity, sales, etc, only through effective R&D. Suppose that effective R&D for member firm i, denoted RE_i, can be expressed as

$$RE_i = RI_i + (1+\lambda)\cdot\theta_i\cdot[RS_i + \sum RS_j]$$

where RI_i is firm i's independent R&D spending, RS_i is firm i's contribution to Sematech (and RS_j the contributions of all other members to Sematech), λ is the government subsidy rate (where $\lambda = 1$ indicates the government matches firm contributions dollar for dollar), and θ_i is firm i's firm-specific parameter indicating the usefulness of Sematech's R&D to member firm i, where $\theta_i \geq 0$. If larger firms exert greater control over the types of R&D conducted by Sematech, then θ_i may be higher for such firms. One might interpret exiting firms as having low values of θ_i, perhaps after Sematech shifted its emphasis toward grants to equipment producers. Our specification of effective R&D assumes that the R&D conducted independently and by Sematech are perfect substitutes up to a multiplicative constant.

To fix ideas, suppose Sematech members are symmetric. In this case,

$$\frac{RE}{Sales} = \frac{RI}{Sales} + (1+\lambda)\cdot\theta\cdot N\cdot\frac{RS}{Sales}$$

Since Sematech members continue to spend on R&D independently, their mandated contributions to RS are infra-marginal. And since Sematech does not affect the marginal cost or benefit of RE, each member firm's choice of RE will be unaffected by RS. As a result, Sematech should induce members to cut their independent R&D spending by $(1+\lambda)\cdot\theta\cdot N\cdot(RS/Sales)$. Using $\lambda = 1$, $N = 14$, and $RS/Sales = 1$ percent, firms should cut their independent R&D spending by $(28\cdot\theta)$ percent of sales. Their total R&D spending (inclusive of contributions to Sematech) should fall by $\theta^* = (28\cdot\theta - 1)$ percent of sales. The intuition is that Sematech reduces duplication of inframarginal R&D, allowing firms to do the same amount of effective R&D with less spending. The more successful is Sematech

R&D (the higher is θ), the more member firms are able to cut their total R&D spending.[9] The analysis is more complicated if, instead of being perfect substitutes, independent and Sematech R&D are imperfect substitutes or even complements.

Unlike the "commitment" hypothesis, the "sharing" hypothesis does not provide a rationale for government funding. Firms should have every private incentive to form joint ventures to raise their R&D efficiency. Perhaps fears of antitrust prosecution, even in the wake of the National Cooperative Research Act of 1984, deter semiconductor firms from forming such ventures. The stamp of government approval may provide crucial assurance for Sematech participants such as IBM and AT&T.

The commitment and sharing hypotheses are not mutually exclusive. Sematech may both commit firms to spend more on high-spillover R&D *and* boost R&D efficiency. High-spillover R&D may inherently be more likely to be duplicated. Combining the hypotheses, in theory Sematech may change total member firm R&D anywhere from $-\theta^*$ to $+1$ percent of sales. Given Sematech's roughly $200 million annual budget, half contributed by member firms, this means Sematech could have induced no more than $100 million in higher spending, but also could have triggered R&D reductions.

Does this Sematech theory match Sematech reality? As a first pass at answering this question, we polled all 14 current and past members of Sematech. We asked each firm whether participation in Sematech had increased, decreased, or had no effect on their total R&D spending (including Sematech contributions). We received responses from 5 of the 14 firms.[10] Of these, three said "no impact" (meaning that a dollar contributed to Sematech came out of an unchanged R&D budget) and two

[9] Since prior to Sematech R&D/Sales was about 10 percent for Sematech firms, independent R&D should cease if $\theta \geq 10/(2N) = 10/28 = 0.36$. Since, as noted, the bulk of R&D is still conducted independently, θ would have to be substantially below 0.36.

[10] There may be selection bias in the firms that chose to respond.

indicated that Sematech *lowered* their overall R&D spending by increasing R&D efficiency. These responses are more consistent with the "sharing" hypothesis, which predicts a reduction in R&D spending, than with the "commitment" hypothesis, which predicts higher R&D spending.

To address the question more systematically, we collected financial data from Compustat on all U.S. firms whose principal business is semiconductors and related devices (SIC 3674). Our sample consists of 69 firms reporting R&D expenditures, including 6 of the original 14 members of Sematech -- Advanced Micro Devices, National Semiconductor, Texas Instruments, Intel, Micron Technology, and LSI Logic, the last two of which left the consortium early in 1992. We use annual observations from 1970 to 1992 (or the available subset), reaching a total of 675 firm-years.

Since we cannot observe the behavior of Sematech firms in the absence of the consortium, we estimate Sematech's effects by comparing the R&D spending of members to that of non-members. This strategy has two drawbacks. First, our approach only identifies Sematech's effect on members *relative* to non-members. Sematech may have raised or lowered the R&D spending of non-members. The impact on non-members will be absorbed in the year effects in our panel estimation. Exactly how non-member firms' R&D should be affected by Sematech depends on whether the "commitment" and/or the "sharing" hypothesis holds, and on whether firms' R&D spending levels are strategic substitutes or complements.

A second drawback to our estimation strategy is that firms were not randomly selected to join Sematech. If a firms' expected R&D intensity affected its decision to join, then the results may be biased. We address this endogenous selection into Sematech by accounting for firm fixed-effects in our estimation. We also tried firm size as an instrument for Sematech membership, using the book value of assets divided by a capital goods deflator for all of SIC 3674.[11] R&D intensity and size are

[11] We avoided cyclical measures of size such as sales and employees since they are correlated with R&D/Sales in the period prior to Sematech.

uncorrelated during the pre-Sematech sample, consistent with size being exogenous with respect to R&D intensity. Our logic for using size as an instrument is that larger firms gain more in absolute terms from high-spillover R&D and from R&D knowledge gleaned from inside the consortium, even conditional on their R&D intensity. That is, larger firms have more to gain under both of the hypotheses outlined above. Of course, if required contributions to Sematech were proportional to size, larger firms would also have to contribute more to secure their greater gains. But contributions rise less steeply than sales, and larger firms reputedly have more say over the direction of the consortium's spending.[12] Unfortunately, although arguably exogenous, this instrument did not prove very powerful as the standard errors of the estimates rose substantially.

Table 2 presents summary statistics for R&D/Sales and R&D/Assets. In this table, we divide the sample into firms that were (at some point) members of Sematech and those that never were, and into the period prior to and after the formation of Sematech in 1987. Sematech members exhibit higher R&D intensity than non-members both before and after 1987. The mean R&D/Sales ratio rose 1.3 percentage points for Sematech members after 1987, although the ratio rose even more for non-member firms. Recall that the higher average ratio for Sematech firms does not reflect the fact that larger firms tend to be members of Sematech since size and R&D intensity were uncorrelated before 1987.

At first glance this table makes it hard to imagine that Sematech raised member firms' R&D intensity relative to what it otherwise would have been, given that non-member firms' ratio rose even more. But part of the dramatic rise in the R&D/Sales ratio of non-members may merely reflect the shifting composition of firms: new firms in the mid-1980s may exhibit greater R&D intensity than

[12] Another candidate instrument would be diversification. Jovanovic (1993) argues that more diversified firms can better exploit serendipitous results from R&D. Similarly, they might have more to gain from being exposed to other firms' R&D personnel. Unfortunately, we could not find a suitable measure of firm diversification.

those they replaced. Firm age and lagged R&D/Sales could also explain a bigger jump in the ratio for non-members.

Given these considerations, our econometric approach is to estimate variations on the following equation:

$$(R\&D/Sales) = \alpha + \beta_1 \text{ Age} + \beta_2 (R\&D/Sales)_{-1} + \beta_3 (\text{Sematech}) + \varepsilon,$$

where R&D/Sales is the ratio of total R&D expenditures to net sales, Age is the number of years the company exists on the Compustat file, and Sematech is a dummy variable set to unity if the firm is a member of Sematech in a given year (starting in 1987). Because firms differ in their average R&D/Sales ratio, we include firm fixed-effects. We include year dummies to adjust for industry-wide cycles.

Table 3 presents results of weighted least squares (WLS) estimation for two time periods: 1970-92 and 1980-92. Firm years are weighted by firm assets. The age and lagged dependent variable coefficients are very similar when estimated without using the Sematech dummy. The WLS results for the longer period show a -1.4 percentage point, statistically significant effect of Sematech on member firms' R&D intensity. The table shows that this result carries over to the shorter time sample and when R&D intensity is measured relative to assets. These effects are also robust to shifting the Sematech dummy from 1987 to 1988.

How much does our coefficient imply that the industry's total R&D effort was reduced as a result of Sematech? In 1991, our sample of firms had sales of $31.1 billion with $3.2 billion in R&D expenditures (a ratio of 10.3 percent). In that year, Sematech members accounted for two-thirds of sales ($20.7 billion) and R&D ($2.2 billion) in our sample, for a ratio of 10.6 percent. If Sematech reduced this ratio by 1.4 percentage points, then in the absence of the consortium firms would have spent 12.0 percent of sales on R&D, or $2.5 billion, or $300 million more. In the absence of Sematech, according to this exercise, the overall R&D/Sales ratio of the industry would have been 11.2 percent rather than 10.3 in 1991. Under this interpretation, Sematech reduced the industry's R&D spending by 9 percent. (This whole exercise, of course, presumes that Sematech had no overall impact on semiconductor sales or on other firms.)

Recall the predicted impact of Sematech ranged from $-\theta^*$ of sales under the "sharing" hypothesis to +1 percent of sales under the "commitment" hypothesis. Our results are clearly more consistent with the sharing hypothesis than with the commitment hypothesis. Under the "sharing" hypothesis, this reduction in R&D spending is efficient. Firms have acquired knowledge more cheaply by sharing the results of the joint R&D effort. It is not clear, however, just how much of the cost savings comes from the government subsidy as opposed to true knowledge-sharing.

4. Effect of Sematech on Profitability

The commitment hypothesis implies that Sematech raises members' profitability relative to non-members so long as Sematech R&D results do not spill over 100 percent to other U.S. firms in the industry. Even if member firms compete down the price of semiconductors with the knowledge they jointly acquire, their profitability should rise *relative* to that of other U.S. firms. Since Sematech focuses on process technology and equipment, member firms' rising relative profitability should owe to more rapidly rising productivity than otherwise. According to a Bureau of Labor Statistics (1989) survey of the literature relating R&D to productivity growth, the productivity gains should lag the R&D outlays by at least one year. Hence the initial impact on profitability should be negative, then should turn positive in 1989 or 1990.

Under the sharing hypothesis, member firm profitability should rise immediately by θ^* percent of sales. The intuition is that members are conducting the same amount of effective R&D while spending θ^* percentage points of sales less. Since effective R&D is unchanged, there should be no impact on the profitability of non-member firms. Under this hypothesis, the predicted jump in profitability is equal in magnitude to the predicted fall in R&D spending. It should be noted that if all firms have the same θ, all but the smallest firms should seek to join Sematech and reap the R&D savings. The sharing hypothesis therefore requires hetergeneity in firm θ's to explain the limited Sematech membership.

For investigating profitability, our Compustat sample consists of 79 firms over some subset of 1970 to 1992. We have the necessary data for a total of 820 firm-years. Our measure of profitability, a standard one in the corporate finance literature, is a gross rate of return on assets:

Return on Assets = (Sales - (Labor and Material Expenses))/(Book Value of Assets).

Given that Sematech mandates contributions relative to firms' sales, and for comparability with the R&D estimates, we consider the return on sales as well as on assets.

Table 4 gives summary statistics on profitability. According to the theory, the positive impact of Sematech on profitability should begin in 1989 under the commitment hypothesis and in 1987 under the sharing hypothesis. Since the results are not sensitive to moving the dummy variable from 1987 to 1990, we only report 1989 results. Table 4 shows the return on sales going from 24 percent before 1989 to 30 percent since 1989 for Sematech members, while it went from 16 to 18 for non-member firms. A different story emerges, however, when profits are scaled by assets rather than sales. There is virtually no changes in the return on assets for member and non-members firms before and after the formation of Sematech.

Figure 2 shows the return on assets for all U.S. semiconductor firms year by year, however, and a recovery in industry profitability clearly begins in 1988. Suppose Sematech was indeed responsible for the revival of the U.S. industry (in our survey of members, one referred to Sematech as "a key ingredient in the resurgence of the U.S. industry"). Relative to the 1987 return on assets, the higher return on assets over 1988 to 1992 translates to about $1.3 billion a year. This implies a return on the government's $100 million annual contribution of 1300 percent![13] If one assigns a healthy but more modest 100 percent return to the government's investment, Sematech explains only one-eighth of the rise in industry fortunes.

There are several other reasons to be cautious about attributing the revival of the U.S. semiconductor industry to Sematech. The formation of Sematech coincides with a substantial depreciation in the foreign exchange value of the dollar, a semiconductor trade agreement with Japan that blunted foreign competition, and the declining importance of memory chips compared with microprocessors in the semiconductor market. These factors may explain the bulk of the turnaround depicted in figures 1 and 2. Moreover, the commitment hypothesis implies a more delayed response of profitability than seen in figure 2. The sharing hypothesis implies an immediate response, but of a smaller magnitude in line with the estimated R&D savings.

To investigate the impact of Sematech more systematically, we carried out panel regressions including the lagged return, firm age, the Sematech dummy, firm fixed effects, and year dummies. Our findings are reported in Table 5. WLS estimates suggest Sematech raised member firms' return on sales 4 percentage points relative to non-member firms. This coefficient is similar to the jump in member firm returns relative to non-member firms seen in the raw data, suggesting the difference cannot be traced to firm age, firm fixed effects, etc. The coefficient falls below 2 percent and is no longer statistically significant, however, when profitability is measured by return on assets rather than sales. Taken together, these results as broadly consistent with the prediction of the sharing hypothesis

[13] This ignores any impact on consumer surplus, profits of firms outside of Sematech, or rents to labor. Also, if we take the rebound in profits after 1987 vis-a-vis the 1980-86 period, the rate of return of the government investment is a more modest 5.2 percent.

that profitability will rise due to R&D savings.

5. Effect of Sematech on Investment

Recall that Sematech shifted away from on-site R&D toward grants to U.S. semiconductor equipment manufacturers in the early 1990s. Such grants could easily fall under the rubric of "commitment" to high-spillover R&D. It is harder to see that they disseminate knowledge among members, as in the "sharing" hypothesis. In any case, improved equipment for members (and, with some delay, non-members) is now a primary focus of Sematech. One can interpret improved, more reliable equipment as a fall in the relative price of equipment. Since this better equipment becomes available to non-member firms after a delay of up to two years, Sematech firms should have shifted away from other inputs toward capital.

We consider Sematech's impact on investment expenditures relative to sales and assets. Our Compustat sample with the required data comes to 816 firm-years, with 79 different firms. Table 6 indicates the investment-sales and investment-assets ratio for the firms in our sample. These ratios decline after 1989 for members and non-members alike. The regression results presented in Table 7 depict a positive but statistically insignificant effect of Sematech on investment. Thus, we cannot find any evidence that Sematech changed investment patterns in the semiconductor industry.

6. Effect of Sematech on Productivity

Under the "commitment" hypothesis, Sematech boosts member spending on high-spillover R&D. Jointly-conducted high-spillover R&D should generate faster productivity growth among members. If the knowledge does not spill over entirely to non-member firms, then Sematech should generate faster productivity growth even relative to non-member firms. Under the "sharing" hypothesis, in contrast, Sematech leaves effective R&D and hence productivity growth unaffected.

Did Sematech firms' productivity rise more than their history and the experience of the U.S. industry as a whole would predict? Here our sample consists of 74 firms and 712 total observations with the necessary data. We again denote the Sematech period from 1989 (the sharing hypothesis predicts no effect over any interval, whereas the commitment hypothesis predicts a delay in seeing the yield of higher R&D). We use labor productivity growth as our measure, defined as

$$\Delta \text{ Labor Productivity} = \Delta(\text{Real Sales}) - \Delta(\text{No. of Employees})$$

where Δ denotes the log first difference. Firm-level nominal sales were deflated by an industry (SIC 3674) output deflator obtained from the NBER's Productivity Database.

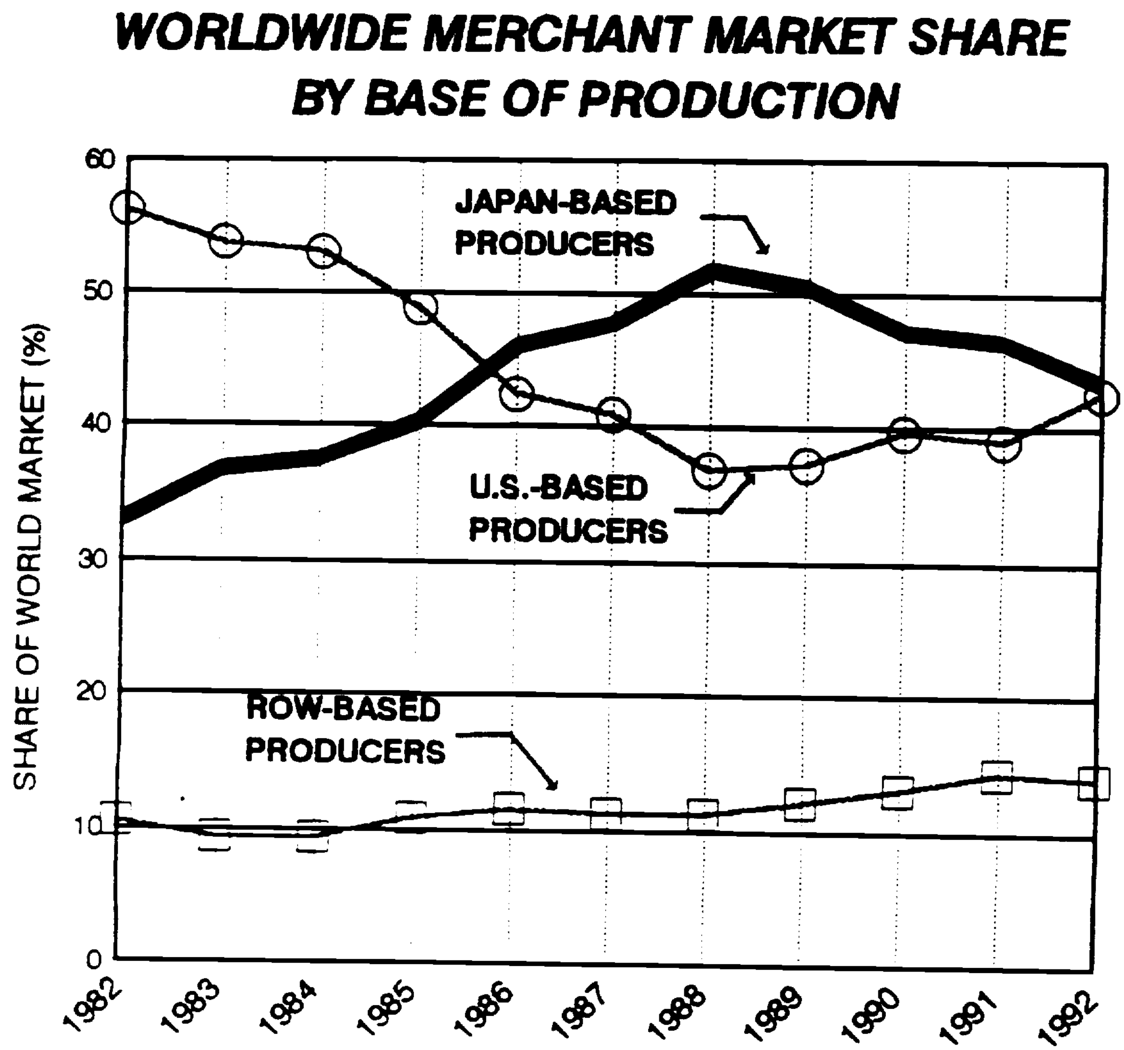
Table 8 reports the mean values of labor productivity growth across firms and time. Labor productivity growth declined after 1989 for member and non-member firms alike, but declined much more for non-member firms. Table 9 shows estimates adjusting for firm age, firm lagged productivity growth, firm fixed-effects, and year effects. The coefficients on Sematech are dwarfed by their standard errors. More generally, the adjusted R^2 is zero, indicating that firm labor productivity growth is hard to explain. In sum, our results are uninformative about whether Sematech had any appreciable impact on productivity.

7. Conclusions

Our principal finding is that Sematech induced members to cut their overall R&D spending on the order of $300 million per year, providing support for the sharing hypothesis over the commitment hypothesis. Our estimates of Sematech's impact on profitability, investment, and productivity are much less precise. We emphasize that our methodology of comparing members of Sematech to non-members means that we could only identify its relative impact.

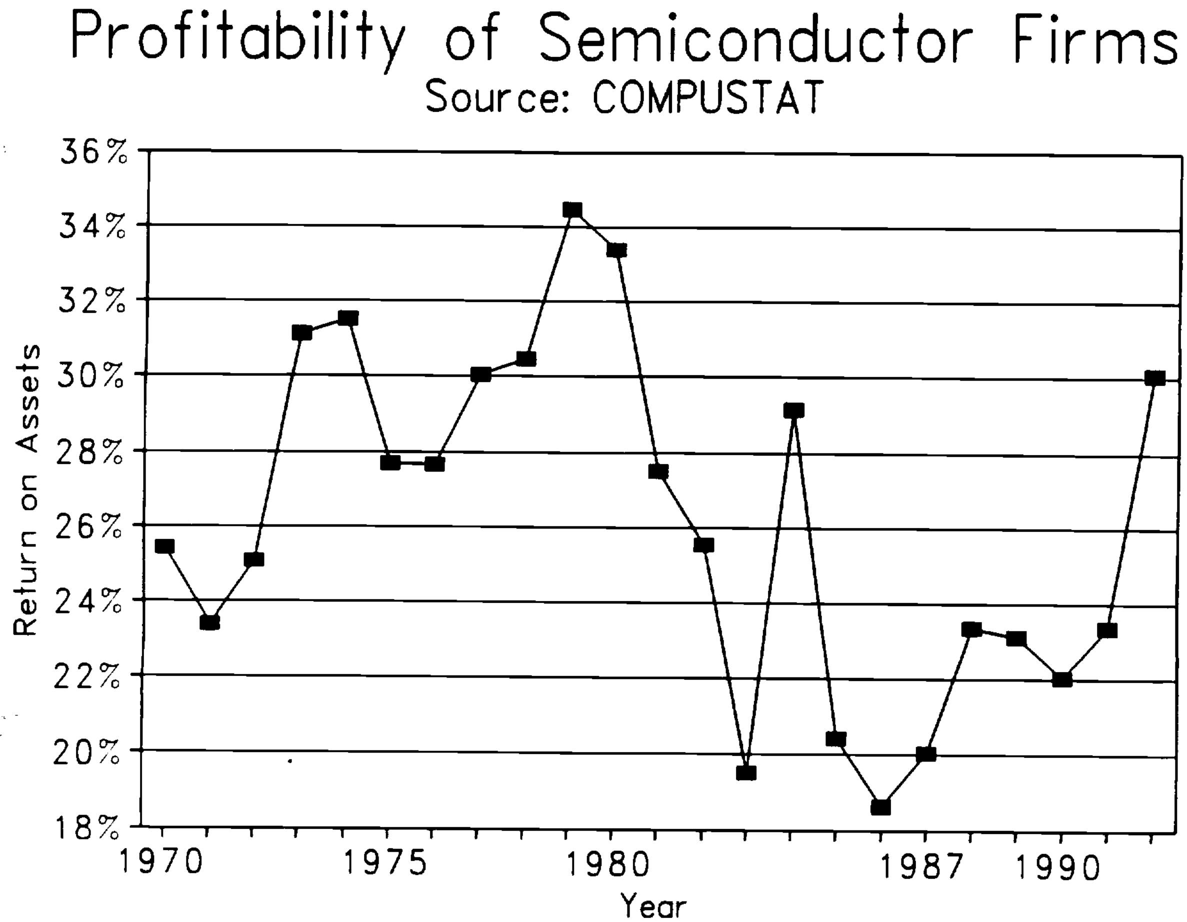
We view our results as a small step towards the important task of estimating the social rate of return to Sematech. The task is essential for evaluating whether to continue government funding of the consortium (through non-ARPA sources after FY 1997), whether to found and fund similar consortia in other high technology industries, and whether to further relax antitrust restrictions on private consortia.

Figure 1



Source: Semiconductor Industry Association

Figure 2



Profitability of Semiconductor Firms
Source: COMPUSTAT
36%
34%
32%
30%
28%
26%
24%
22%
20%
18%
Return on Assets
1970
1975
1980
1987
1990
Year

Table 1

Sematech Member Companies

AT&T Microelectronics

Advanced Micro Devices

International Business Machines

Digital Equipment

Harris Semiconductor**

Hewlett-Packard

Intel

LSI Logic*

Micron Technology*

Motorola

NCR

National Semiconductor

Rockwell International

Texas Instruments

* Left Sematech in 1992

** Left Sematech in 1993

Table 2

Sample Means of R&D/Sales

(in percentage terms)

Sematech Status	Pre-1987	Post-1987
Non-Member	7.0 (340)	10.6 (233)
Member	10.3 (66)	11.6 (36)
Full Sample	7.5 (406)	10.7 (269)

Note: Number of Observations in parentheses.

Sample Means of R&D/Assets

(in percentage terms)

Sematech Status	Pre-1987	Post-1987
Non-Member	7.6 (340)	10.9 (233)
Member	12.3 (66)	11.1 (36)
Full Sample	8.4 (406)	11.0 (269)

Note: Number of Observations in parentheses.

Table 3: Sematech Membership and R&D Expenditures

Dependent Variable: R&D/Sales

	WLS (1970-92)	WLS (1980-92)
Age	0.46 (.07)	0.68 (.14)
Lagged R&D/Sales	0.37 (.08)	0.33 (.08)
Sematech	-1.4 (0.5)	-1.8 (0.5)
Unweighted R^2	0.77	0.81
Mean of Dependent Var.	8.8	9.9
St. Dev. of Dependent Var.	5.9	6.3
N	675	464

Note: standard errors in parentheses, results in percentage terms, firm and year effects included.

Dependent Variable: R&D/Assets

	WLS (1970-92)	WLS (1980-92)
Age	0.34 (.11)	0.34 (.09)
Lagged R&D/Sales	0.59 (.05)	0.54 (.07)
Sematech	-1.1 (0.3)	-1.3 (0.4)
Unweighted R^2	0.75	0.77
Mean of Dependent Var.	9.4	9.8
St. Dev. of Dependent Var.	6.6	7.1
N	675	464

Note: standard errors in parentheses, results in percentage terms, firm and year effects included.

Table 4

Sample Means of Return on Sales

(in percentage terms)

Sematech Status	Pre-1989	Post-1989
Non-Member	15.7 (542)	17.7 (174)
Member	24.3 (80)	29.9 (24)
Full Sample	16.8 (622)	19.2 (198)

Note: Number of Observations in parentheses.

Sample Means of Return on Assets

(in percentage terms)

Sematech Status	Pre-1989	Post-1989
Non-Member	17.9 (542)	18.4 (174)
Member	28.2 (80)	27.0 (24)
Full Sample	19.3 (622)	19.5 (198)

Note: Number of Observations in parentheses.

Table 5: Sematech Membership and Profitability

Dependent Variable: Return on Sales

	WLS (1970-92)	WLS (1980-92)
Age	0.62 (.11)	0.59 (.13)
Lagged R&D/Sales	0.30 (.07)	0.31 (.08)
Sematech	4.2 (1.3)	4.6 (1.4)
Unweighted R^2	0.50	0.55
Mean of Dependent Var.	17.4	18.0
St. Dev. of Dependent Var.	12.6	13.6
N	820	544

Note: standard errors in parentheses, results in percentage terms, firm and year effects included.

Dependent Variable: Return on Assets

	WLS (1970-92)	WLS (1980-92)
Age	0.90 (.15)	0.85 (.18)
Lagged R&D/Sales	0.39 (.07)	0.39 (.09)
Sematech	1.3 (1.6)	1.9 (1.7)
Unweighted R^2	0.37	0.32
Mean of Dependent Var.	19.3	18.1
St. Dev. of Dependent Var.	13.2	13.1
N	820	544

Note: standard errors in parentheses, results in percentage terms, firm and year effects included.

Table 6

Sample Means of Investment/Sales

(in percentage terms)

Sematech Status	Pre-1989	Post-1989
Non-Member	9.7 (541)	6.2 (172)
Member	17.0 (79)	15.6 (24)
Full Sample	10.7 (620)	7.3 (196)

Note: Number of Observations in parentheses.

Sample Means of Investment/Assets

(in percentage terms)

Sematech Status	Pre-1987	Post-1987
Non-Member	9.2 (541)	6.2 (172)
Member	17.4 (79)	14.0 (24)
Full Sample	10.3 (620)	7.2 (196)

Note: Number of Observations in parentheses.

Table 7: Sematech Membership and Investment

Dependent Variable: Investment/Sales

	WLS (1970-92)	WLS (1980-92)
Age	0.06 (.09)	0.05 (.09)
Lagged R&D/Sales	0.34 (.10)	0.34 (.11)
Sematech	1.2 (1.5)	1.5 (1.6)
Unweighted R^2	0.40	0.41
Mean of Dependent Var.	9.8	11.0
St. Dev. of Dependent Var.	10.8	12.3
N	816	539

Note: standard errors in parentheses, results in percentage terms, firm and year effects included.

Dependent Variable: Investment/Assets

	WLS (1970-92)	WLS (1980-92)
Age	0.14 (.09)	0.15 (.09)
Lagged R&D/Sales	0.21 (.07)	0.17 (.08)
Sematech	.8 (1.2)	1.5 (1.2)
Unweighted R^2	0.39	0.40
Mean of Dependent Var.	9.5	9.6
St. Dev. of Dependent Var.	7.6	8.0
N	816	539

Note: standard errors in parentheses, results in percentage terms, firm and year effects included.

Table 8

Sample Means of Labor Productivity Growth

(in percentage terms)

Sematech Status	Pre-1989	Post-1989
Non-Member	9.0 (459)	6.8 (156)
Member	10.6 (73)	10.0 (24)
Full Sample	9.2 (532)	7.2 (180)

Note: Number of Observations in parenthesis.

Table 9: Sematech Membership and Productivity

Dependent Variable: Labor Productivity Growth

	WLS (1970-92)	WLS (1980-92)
Age	0.46 (.21)	0.40 (.21)
Lagged Labor Prod	- 0.08 (.06)	-0.06 (.06)
Sematech	.4 (3.1)	-1.3 (3.3)
R^2	.00	.00
Mean of Dependent Var.	8.7	8.1
St. Dev. of Dependent Var.	25.1	25.4
N	712	454

Note: standard errors in parenthesis, results in percentage terms, firm and year effects included.

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