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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 examine 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.

Key words: R&D; Sematech; Semiconductor; Consortium; Subsidies

JEL classification: H2; L1; L6; O3

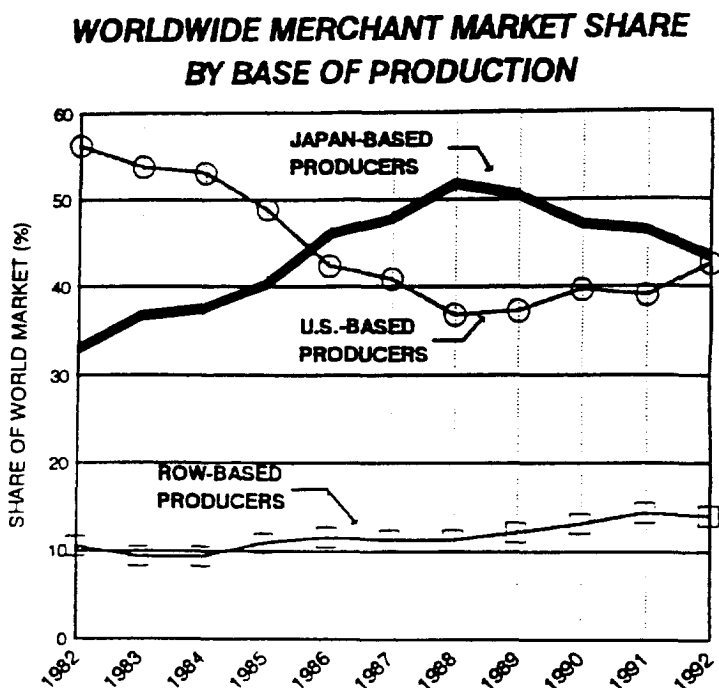
1. Introduction

As Japanese semiconductor producers dramatically increased their world market share in the early 1980s, the U.S. government responded by undertaking policies to support U.S. semiconductor producers. Among these policies was the provision of R&D subsidies. In 1987, the government joined with 14 U.S. semiconductor firms to form an R&D consortium called Sematech – SEMiconductor MANufactur-

ing 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.

Sematech has sometimes been given part of the credit for the rebound of the U.S. semiconductor industry vis-a-vis its Japanese rivals since the mid-1980s, as depicted in Fig. 1. Testing this proposition, of course, is exceedingly difficult. Rather than try to trace out all the effects of Sematech's activities relative to what otherwise would have occurred, we seek to determine only how Sematech members' overall R&D spending, profitability, investment, and productivity have behaved as a result of Sematech's existence. We use Compustat panel data on U.S. semiconductor firms to try to disentangle the effects of the consortium from the effects of other factors such as exchange rate movements.

Section 2 provides some background about the organization and activities of Sematech. Section 3 considers the impact of Sematech on R&D spending. After discussing the R&D objectives of Sematech and providing a framework for



Source: Semiconductor Industry Association

Fig. 1. Worldwide merchant market share by base of production (source: Semiconductor Industry Association).

interpreting our results, we compare the R&D spending of member and non-member firms, controlling for firm, year, and age effects. We find that Sematech members reduced their R&D spending compared with non-members. Section 4 Section 5 Section 6 go on to consider the effects of Sematech membership on firms's profitability, investment, and productivity with much less informative results.

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% of net sales on R&D, compared with 3.1% for U.S. industry overall, according to the National Science Foundation (1992, p. 77). The semiconductor industry (SIC 3674) is even more R&D intensive: merchant firms devoted 12.3% of their sales to R&D in 1989, according to the Semiconductor Industry Association (1993, p. 41).

Since the early 1980s, the U.S. government has taken several steps to reduce the cost of semiconductor R&D and improve the ability of firms to appropriate the benefits of their semiconductor research.¹ One of these steps was the government's involvement in the creation of Sematech. Sematech was incorporated in August 1987 with 14 founding members (listed on Table 1) and 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 support in the form of an ongoing government subsidy. Government assistance was formalized in the National Defense Authorization Act (fiscal year 1988–1989), which allowed the Department of Defense to contribute (through ARPA) up to \$100 million annually in matching funds to Sematech.² The government initially committed funding for only five years, but legislation renewing these expenditures was passed in 1993. In mid-1994, Sematech announced that it would end its reliance on ARPA funds by fiscal year 1997.

¹For example, the Semiconductor Chip Protection Act of 1984 enhanced the protection of intellectual property rights for the industry, and the National Cooperative Research Act of 1984 loosened antitrust restrictions on collaborative R&D and other joint ventures.

²The Department of Defense had raised concerns about the national security implications of dependence on foreign sources of semiconductors in the mid-1980s.

Table 1
Sematech member companies

| |
|-----------------------------------|
| AT&T Microelectronics |
| Advanced Micro Devices |
| International Business Machines |
| Digital Equipment |
| Harris Semiconductor ^a |
| Hewlett-Packard |
| Intel |
| LSI Logic ^b |
| Micron Technology ^b |
| Motorola |
| NCR |
| National Semiconductor |
| Rockwell International |
| Texas Instruments |

^aLeft Sematech in 1993.^bLeft Sematech in 1992.

Sematech members contribute financial resources and personnel to the consortium.³ They are required to contribute 1% of their semiconductor sales revenue, with a minimum contribution of \$1 million and a maximum of \$15 million. Of the 400 technical staff at Sematech, about 220 are assignees from member firms who stay at Sematech's facility in Austin, Texas for anywhere from 6 to 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 turned down), although no restrictions are placed on joint ventures between Sematech members and foreign partners.

According to a General Accounting Office (1991) survey of executives from Sematech members, most firms have been generally satisfied with their participation in the consortium. Burrows (1992) reports that Intel believes it has saved \$200–\$300 million from improved yields and 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

³This section draws heavily on Spencer and Grindley (1993). William Spencer is the current chairman of Sematech. See also Grindley et al. (1994).

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.

Sematech's apparent success has prompted some to embrace it as a successful 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.” Romer (1993) has argued for the creation of industry technology boards to fund high-spillover R&D, citing Sematech as a prototype.

Others are more critical of such government participation in joint ventures. Cohen (1994) argues that government-supported research joint ventures concentrate more on appropriable than generic R&D and that consortia that are less than industry-wide impose negative externalities on non-member firms. One widely 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% of their semiconductor sales revenue to the consortium, with a minimum contribution of \$1 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. Executives from 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.

Since its formation, Sematech's membership has declined. Three firms have left the consortium, dropping its membership to 11, and another has reserved its option to 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. All of the former members questioned the new direction of Sematech's research effort, complaining that Sematech had strayed from its original objective of developing processes for making more advanced chips toward giving cash grants to equipment companies.

In mid-1994, Sematech announced that it would forgo ARPA subsidies after fiscal year 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 ten years. That is, ARPA funding may end 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.

3. Effect of Sematech on R&D spending

We first address whether Sematech induces member firms to alter their total R&D spending, inclusive of their contributions to the consortium. Before presenting our empirical results, we consider Sematech's R&D goals within a simple theoretical framework.⁴

3.1. Interpreting Sematech's R&D goals

One purpose of Sematech is to encourage firms to do more high-spillover R&D. To discourage the free-riding associated with such R&D spillovers, Sematech by-laws initially prohibited equipment manufacturers developing products with Sematech's assistance from selling that equipment to non-member companies for one year. This equipment holdback 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 six to nine 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.⁵

A second goal of Sematech is to enhance the effectiveness of members' R&D spending by eliminating overlapping and duplicative R&D. One of Sematech's first priorities, for example, was to reduce sequentially 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

⁴The theoretical literature on the impact of joint ventures and cooperation on R&D spending is examined in Tirole (1988), Reinganum (1989), and Katz and Ordover (1990), and extended by d'Aspremont and Jacquemin (1988), Kamien et al. (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. Dixit (1985) provides a very useful discussion of the theoretical issues in the context of international competition.

⁵Since 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.

“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.”

These two motivations have different implications for members’ R&D spending.

Under the first motivation, Sematech induces members jointly to spend more on high-spillover types of R&D. We call this the ‘commitment’ hypothesis. One problem with this 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% government subsidy and the equipment holdback provisions are crucial for Sematech’s existence. The ‘commitment’ hypothesis both justifies these features and requires them 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. 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 Under the second motivation for Sematech – sharing of R&D within the consortium to reduce duplicative R&D – the consortium allows members to spend less on 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% government subsidy.

One can view the consortium as raising ‘effective R&D’, a sufficient statistic for the knowledge created by R&D. 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

$$RE_i = RI_i + (1 + \lambda)\theta_i RS,$$

where RI_i is firm i ’s independent R&D spending, RS is the sum of member contributions to Sematech, λ is the government subsidy rate ($\lambda=1$ if the government matches firm contributions dollar for dollar), and θ_i is a firm-specific

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

parameter indicating the usefulness of Sematech's R&D to member firm i . 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 . 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,

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

Since Sematech members continue to spend on R&D independently, their mandated contributions to RS are infra-marginal and Sematech does not affect the marginal cost of RE . If Sematech also does not affect the marginal benefit of RE , say because its research perfectly substitutes for the type of research firms do independently, then 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 $(1 + \lambda)\theta N(RS/Sales)$. Using $\lambda = 1$, $N = 14$, and $RS/Sales = 1\%$, firms should cut their independent R&D spending by $(28\theta - 1)\%$ of sales. Their total R&D spending (inclusive of contributions to Sematech) should fall by $\theta^* = 28(\theta - 1)\%$ of sales. The intuition is that Sematech reduces duplication of infra-marginal 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.⁷ 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. However, 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. Combining the hypotheses, in theory Sematech may change total member firm R&D anywhere from $-\theta^*$ to $+1\%$ 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 lower R&D spending also could have resulted.

⁷Since, prior to Sematech, R&D/sales was about 10% for Sematech firms, independent R&D should cease if $\theta > 10/(2N) = 10/28 = 0.36$. Since, as noted, the bulk of R&D is still conducted independently, θ would have to be substantially below 0.36.

3.2. Empirical approach

Our approach is to compare the R&D intensity of Sematech member firms against those of non-members, controlling for past R&D intensity, firm fixed effects, year effects, and firm age effects.⁸ 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 71 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 1993 (or the available subset), reaching a total of 689 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 in 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 3674.⁹ R&D intensity and size are 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,

⁸As 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, and these responses could be affected by selection bias. Of these, three said 'no impact' (meaning a dollar contributed to Sematech came out of an unchanged R&D budget) and two indicated that Sematech allowed them to lower their R&D spending by increasing the efficiency of their R&D spending.

⁹We avoided cyclical measures of size such as sales and employees since they are correlated with R&D/sales in the period prior to Sematech.

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.¹⁰ Unfortunately, although arguably exogenous, this instrument did not prove very relevant.

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 (we treat this as 1988, since Sematech opened in August 1987). Sematech members exhibit higher R&D intensity than non-members both before and after 1988. The mean R&D/sales ratio rose 0.9 percentage points for Sematech members after 1988, 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 1988. Fig. 2 plots the movements in R&D intensity of Sematech member firms and non-members from 1971 to 1993.

Table 2 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 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 those they replaced. For this reason, we wish to control for firm fixed effects.

Beyond firm fixed effects, the empirical literature seeking to explain firm R&D-intensity has focused on firm size and market power. As surveyed by Cohen and Levin (1989), the results of these studies have been inconclusive, so we follow Hall (1990) in adopting a parsimonious specification that controls only for past R&D intensity, year effects (to adjust for industry-wide cycles), and firm effects. The motivation for including lagged R&D is the belief that the cost of adjusting R&D intensity may be considerable. Firm age dummies are included in the specification because R&D has a delayed impact on sales, and younger firms may

Table 2
Sample means (in percentage terms)

| Sematech status | R&D/sales | | R&D/assets | |
|-----------------|-----------|------------|------------|------------|
| | Pre-1988 | Post-1988 | Pre-1988 | Post-1988 |
| Non-member | 7.4 (355) | 11.3 (230) | 7.9 (355) | 11.9 (230) |
| Member | 10.5 (72) | 11.4 (32) | 12.2 (72) | 11.4 (32) |
| Full sample | 8.0 (427) | 11.3 (262) | 8.6 (427) | 11.8 (262) |

Note: number of observations in parentheses.

¹⁰Another 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.

R&D Intensity of Semiconductor Firms

Source: COMPUSTAT

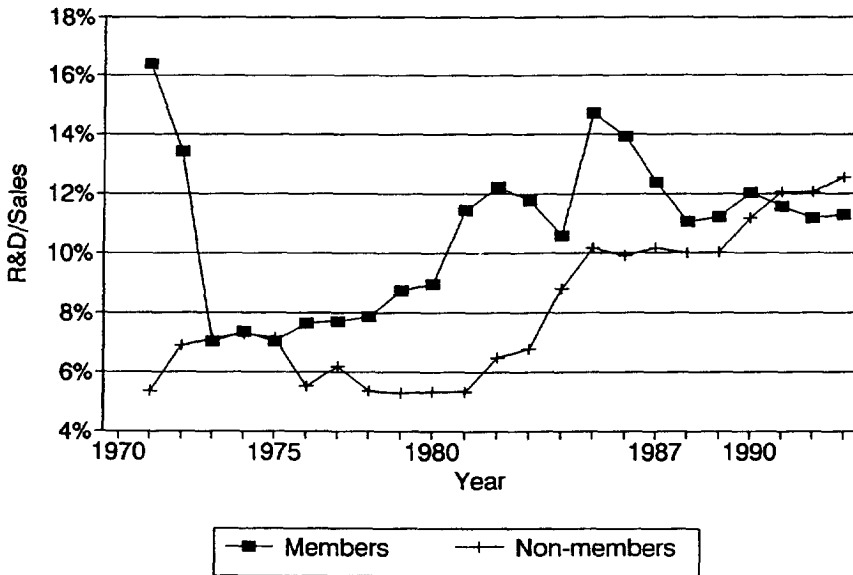


Fig. 2. R&D intensity of semiconductor firms (source: Compustat).

have yet to realize some of the sales stemming from their initial R&D expenditures.

Therefore, our econometric approach is to estimate variations on the following equation:

$$(R\&D/Sales) = \beta_1 Sematech + \beta_2 (R\&D/Sales)_{-1} + \beta_3^* dummies + \varepsilon.$$

Sematech is a dummy variable set to unity if the firm-year observation is of a firm that was a member of Sematech in that year (1988–1993 for member firms; LSI Logic and Micron Technology were treated as members through 1991, and Harris Semiconductor through 1992). *R&D/Sales* is the ratio of total R&D expenditures to net sales. The dummies include firm dummies, year dummies, and age dummies (one for firms aged 2 or less, one for firms aged 3 to 5, and one for firms aged 6 or more).

Table 3 presents results of ordinary least squares (OLS) and weighted least squares (WLS) estimation for two time periods: 1970–1993 and 1980–1993.¹¹ The weights used for WLS were firm-year assets. The OLS and WLS results for the

¹¹The firm and time dummy coefficients and their standard errors are available upon request.

Table 3
Sematech membership and R&D expenditures

| | Dependent variable: R&D/sales | | | Dependent variable: R&D/assets | | |
|--|-------------------------------|--------------------|--------------------|--------------------------------|--------------------|--------------------|
| | OLS (1970-1993) | WLS (1970-1993) | OLS (1980-1993) | OLS (1970-1993) | WLS (1970-1993) | WLS (1980-1993) |
| Sematech | -1.30 (0.49) | -1.02 (0.33) | -1.83 (0.60) | -1.04 (0.56) | -1.53 (0.45) | -1.51 (0.49) |
| Lagged R&D/sales | 0.43 (0.06) | 0.57 (0.05) | 0.20 (0.07) | 0.26 (0.06) | 0.36 (0.06) | 0.39 (0.07) |
| Age ≤ 2 | 7.0 (2.4) | 3.6 (2.4) | 5.3 (1.2) | 7.8 (1.5) | 6.4 (1.9) | 0.5 (1.8) |
| 3 ≤ age ≤ 5 | 9.8 (2.3) | 5.8 (1.9) | 7.8 (1.4) | 9.3 (1.3) | 5.0 (1.2) | 5.3 (1.0) |
| Age ≤ 6 | 10.5 (2.2) | 6.5 (1.9) | 8.6 (1.4) | 9.7 (1.3) | 8.2 (1.1) | 7.0 (1.1) |
| Unweighted R ² | 0.78 | 0.75 | 0.77 | 0.75 | 0.73 | 0.79 |
| Mean of dependent variable | 9.8 | 9.8 | 10.4 | 9.2 | 9.2 | 10.4 |
| Standard deviation of dependent variable | 6.8 | 6.8 | 6.6 | 6.2 | 6.2 | 7.3 |
| N | 689 | 689 | 487 | 689 | 689 | 487 |

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

longer period show a statistically significant -1.3 and -1.0 percentage point decline, respectively, on Sematech member firms' R&D intensity. In the shorter sample period, the OLS and WLS results indicate a -1.8 percentage point reduction. As shown, the results are similar when R&D intensity is measured relative to assets. In results we do not report (here or for the subsequent regressions), our findings were robust to the following: shifting the Sematech dummy from 1988 to 1987 and 1989, respectively; using a continuous age variable or variations on the three age categories; throwing out Intel; using an earlier edition of Compustat (through only 1992, and with a slightly different mix of firms).

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%). 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%. If Sematech reduced this ratio by 1.4 percentage points, roughly the magnitude indicated by the results above, then in the absence of the consortium firms would have spent 12% 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% rather than 10.3 in 1991. Under this interpretation, Sematech reduced the industry's R&D spending by 9%. (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 $+1\%$ of sales under the commitment hypothesis. Although we did not explicitly test the sharing and the commitment hypotheses, our results are clearly more consistent with the sharing 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.

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% to other U.S. firms in the industry. Even if competition between member firms lowers 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 more to 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^* % 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 heterogeneity in firm θ s to explain the limited Sematech membership.

For investigating profitability, our Compustat sample consists of 80 firms over some subset of 1970 to 1993. We have the necessary data for a total of 824 firm-years. Our measure of profitability, a standard one in the corporate finance literature, is a gross rate of return on assets:

$$\text{Return on assets} = (\text{Sales} - (\text{Labor and material expenses})) / (\text{Book value of assets}).$$

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 1988 under the sharing hypothesis. Since the results are not sensitive to moving the dummy variable from 1987 to 1990, we report only 1988 results. Table 4 shows the return on sales going from 24% before 1988 to 31% since 1988 for Sematech members, while it went from 16 to 19% for non-member firms. A different story emerges, however, when profits are scaled by assets rather than sales. There is little change in the return on assets for member and non-member firms before and after the formation of Sematech.

Fig. 3 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. Was Sematech 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

Table 4
Sample means (in percentage terms)

| Sematech status | Return/sales | | Return/assets | |
|-----------------|--------------|------------|---------------|------------|
| | Pre-1988 | Post-1988 | Pre-1988 | Post-1988 |
| Non-member | 15.6 (464) | 18.6 (254) | 17.6 (468) | 19.0 (250) |
| Member | 23.7 (74) | 30.6 (32) | 28.3 (74) | 28.1 (32) |
| Full sample | 16.7 (538) | 20.0 (286) | 19.1 (542) | 20.0 (282) |

Note: number of observations in parentheses.

Profitability of Semiconductor Firms

Source: COMPUSTAT

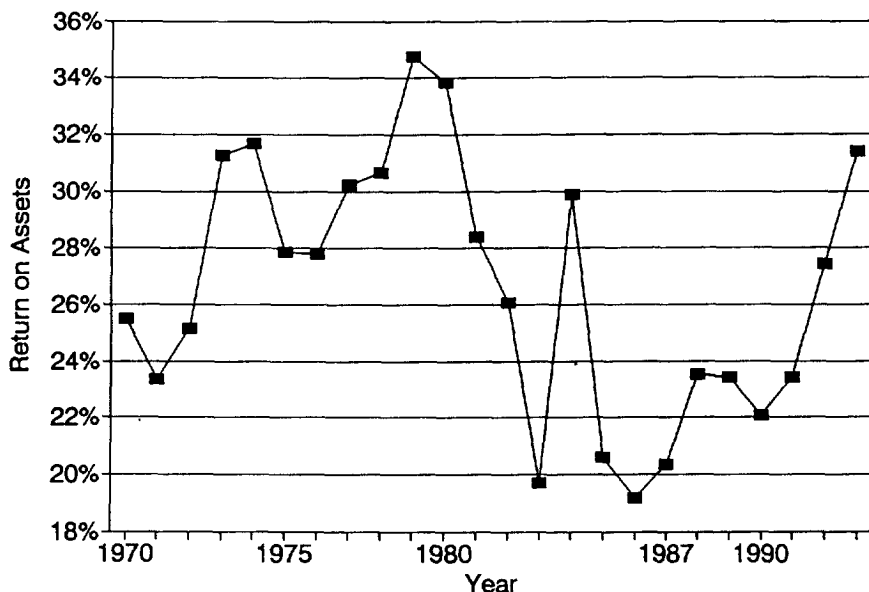


Fig. 3. Profitability of semiconductor firms (source: Compustat).

U.S. industry’)? There are several 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 Fig. 1 and Fig. 3. Moreover, the commitment hypothesis implies a more delayed response of profitability than seen in Fig. 3. 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. OLS and WLS estimates suggest Sematech raised member firms’ return on sales 5–7 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 to 2–5%, however, when profitability is measured by return on

Table 5
Sematech membership and profitability

| | Dependent variable: return on sales | | | Dependent variable: return on assets | | |
|--|-------------------------------------|--------------------|--------------------|--------------------------------------|--------------------|--------------------|
| | OLS (1970–1993) | WLS (1970–1993) | WLS (1980–1993) | OLS (1970–1993) | WLS (1970–1993) | WLS (1980–1993) |
| Sematech | 6.28 (1.56) | 5.44 (1.38) | 5.89 (1.53) | 2.01 (1.66) | 3.63 (1.63) | 4.11 (1.90) |
| Lagged R&D/sales | 0.26 (0.05) | 0.42 (0.08) | 0.46 (0.09) | 0.38 (0.07) | 0.44 (0.07) | 0.39 (0.11) |
| Age ≤ 2 | 13.1 (3.1) | 18.4 (5.6) | 26.0 (8.0) | 14.7 (3.9) | 16.1 (4.4) | 13.4 (5.7) |
| 3 ≤ age ≤ 5 | 9.6 (2.0) | 12.9 (2.9) | 14.2 (3.6) | 15.1 (3.0) | 15.3 (3.6) | 12.4 (3.5) |
| Age ≥ 6 | 8.9 (1.8) | 11.9 (2.7) | 11.4 (3.0) | 15.2 (3.0) | 16.7 (3.5) | 15.7 (4.1) |
| Unweighted R ² | 0.54 | 0.49 | 0.54 | 0.44 | 0.40 | 0.40 |
| Mean of dependent variable | 17.9 | 17.9 | 18.6 | 19.4 | 19.4 | 18.4 |
| Standard deviation of dependent variable | 13.1 | 13.1 | 14.0 | 14.1 | 14.1 | 14.0 |
| N | 824 | 824 | 561 | 830 | 830 | 566 |

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

assets rather than sales. Taken together, these results are broadly consistent with the prediction of the sharing hypothesis 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 822 firm-years, with 81 firms. Table 6 indicates the investment/sales and investment/assets ratios for the firms in our sample. These ratios decline after 1988 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 strong 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

Table 6
Sample means (in percentage terms)

| Sematech status | Investment/sales | | Investment/assets | |
|-----------------|------------------|-----------|-------------------|-----------|
| | Pre-1988 | Post-1988 | Pre-1988 | Post-1988 |
| Non-member | 10.0 (463) | 7.3 (254) | 9.5 (463) | 7.1 (254) |
| Member | 17.1 (73) | 15.6 (32) | 17.7 (73) | 14.2 (32) |
| Full sample | 11.0 (536) | 8.2 (286) | 10.6 (536) | 7.9 (286) |

Note: number of observations in parentheses.

Table 7
Sematech membership and investment

| | Dependent variable: investment/sales | | | Dependent variable: investment/assets | | | |
|--|--------------------------------------|--------------------|--------------------|---------------------------------------|--------------------|--------------------|--------------------|
| | OLS (1970–1993) | WLS (1970–1993) | OLS (1980–1993) | OLS (1970–1993) | WLS (1970–1993) | OLS (1980–1993) | WLS (1980–1993) |
| Sematech | 1.15 (1.46) | 1.83 (1.36) | 0.74 (2.29) | -0.26 (1.23) | 1.22 (1.02) | 1.17 (1.43) | 1.76 (1.07) |
| Lagged R&D/sales | 0.25 (0.06) | 0.34 (0.09) | 0.25 (0.07) | 0.167 (0.043) | 0.235 (0.64) | 0.174 (0.054) | 0.195 (0.071) |
| Age ≤ 2 | 6.6 (2.6) | 10.0 (4.8) | 16.7 (6.0) | 6.8 (1.9) | 8.1 (3.9) | 11.3 (4.0) | 15.6 (5.5) |
| 3 ≤ Age ≤ 5 | 2.3 (1.4) | 4.4 (2.5) | 4.9 (2.2) | 4.0 (1.2) | 3.7 (1.6) | 4.9 (1.5) | 6.4 (2.1) |
| Age ≥ 6 | 0.78 (1.1) | 1.4 (1.3) | 1.7 (1.2) | 3.5 (1.0) | 3.6 (1.3) | 3.9 (1.1) | 4.3 (1.5) |
| Unweighted R ² | 0.46 | 0.42 | 0.56 | 0.47 | 0.41 | 0.47 | 0.43 |
| Mean of dependent variable | 10.0 | 10.0 | 11.1 | 9.7 | 9.7 | 9.7 | 9.7 |
| Standard deviation of dependent variable | 10.6 | 10.6 | 12.0 | 7.5 | 7.5 | 7.7 | 7.7 |
| N | 822 | 822 | 558 | 822 | 822 | 558 | 558 |

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

Table 8
Sample means (in percentage terms)

| Sematech status | Labor productivity growth | |
|-----------------|---------------------------|-----------|
| | Pre-1988 | Post-1988 |
| Non-member | 9.2 (390) | 8.9 (223) |
| Member | 9.6 (67) | 13.1 (32) |
| Full sample | 9.2 (457) | 9.4 (255) |

Note: number of observations in parentheses.

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 75 firms and 712 total observations with the necessary data. We again denote the Sematech period as beginning in 1988; 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 1988 for non-member firms, but not for 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. The adjusted R^2 is always very low. In sum, our results are uninformative about whether Sematech had any appreciable impact on productivity. Labor productivity growth at the firm level is simply too volatile to attribute the pattern in Table 8 to Sematech with any precision.

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 identify only its relative impact.

Table 9
Sematech membership and productivity

| | Dependent variable: labor productivity growth | | | |
|--|---|-----------------|-----------------|-----------------|
| | OLS (1970-1993) | WLS (1970-1993) | OLS (1980-1993) | WLS (1980-1993) |
| Sematech | 5.8 (4.4) | 1.0 (3.6) | 4.92 (5.45) | -0.357 (3.923) |
| Lagged labor productivity | -0.20 (0.07) | -0.09 (0.06) | -0.24 (0.08) | -0.08 (0.07) |
| Age ≤ 2 | n.a. | n.a. | n.a. | n.a. |
| 3 ≤ Age ≤ 5 | 9.8 (5.4) | 17.2 (6.5) | 6.7 (7.3) | 11.5 (8.1) |
| Age ≥ 6 | 8.7 (4.3) | 14.8 (4.2) | 11.6 (4.4) | 7.1 (4.3) |
| R ² | 0.07 | 0.00 | 0.10 | 0.02 |
| Mean of dependent variable | 9.3 | 9.3 | 9.4 | 9.4 |
| Standard deviation of dependent variable | 25.4 | 25.4 | 26.5 | 26.5 |
| N | 712 | 712 | 467 | 467 |

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

We view our results as a small step towards the important task of estimating the social rate of return to Sematech. This would require much more detailed evidence on the effects of Sematech on consumer and producer surplus (of firms both inside and outside the consortium). The task is essential for evaluating whether to continue government funding of the consortium (through non-ARPA sources after financial year 1997), whether to found and fund similar consortia in other high-technology industries, and whether to further relax antitrust restrictions on private consortia.

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