# Economic Impacts of International R&D Coordination:

## SEMATECH, the International Technology Roadmap, and Innovation in Microprocessors

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# 1990s Were An Important and Dynamic Period for the Semiconductor Industry

- New US R&D Strategy in Semiconductors
- Acceleration in rate of innovation in semiconductors
- Increasing global dispersion of technology & production
- This presentation analyzes how these events were linked
  - Focus on microprocessors
- Trace links between details of tech change and economic impacts of innovation

# Why Look at Microprocessors?

- Has come to dominate US (geographic) industry
  - In 2004, 46+% of US IC shipments
    - Compare to 29% in 1995, 37+% in 2002
    - Compare with DRAMs:
      - Approx 14% in 1995, 7% 2001, 11% 2004
- In 90s, highest rate of tech innovation
- Largest value type of semi input to computers
  - Big impact on tech improvement in computers
  - Productivity in downstream IT-using industries
  - Return to this theme at end of talk
- Rich data set

# New US R&D Strategy

- SEMATECH formed in late 1980s
  - Spencer strategic plan, 1992+
  - Focus on manufacturing, accelerate introduction of new tech nodes
    - From 3 years to 2 years
  - Apparent success, inspires imitation elsewhere
- National Semiconductor Technology Roadmap
  - Started as MicroTech 2000, on behalf of NACS
    - 1992 workshop and report
  - SEMATECH provided technical leadership for effort
  - First National Technology Roadmap in 1994
  - Update in 1997, codified 2-year tech nodes

# Roadmap Evolved Into International Effort in Late 1990s

- Now called ISTR
- Recognized that leading edge players in semis were multinational, scattered around globe
- Common belief that closer coordination among specialized suppliers, users, has worked to accelerate innovation in industry
- Has worked to keep 2 year nodes coming
  - Not all think is a good thing
  - To date, have been unable to slow it down!
- Unique and interesting structure of great economic interest
  - Unaware of any other high tech industry with similar degree of R&D coordination
  - Coordination– lawyers' ears perk up!
  - But US law passed in 1980s that granted limited antitrust immunity for registered consortia like SEMATECH

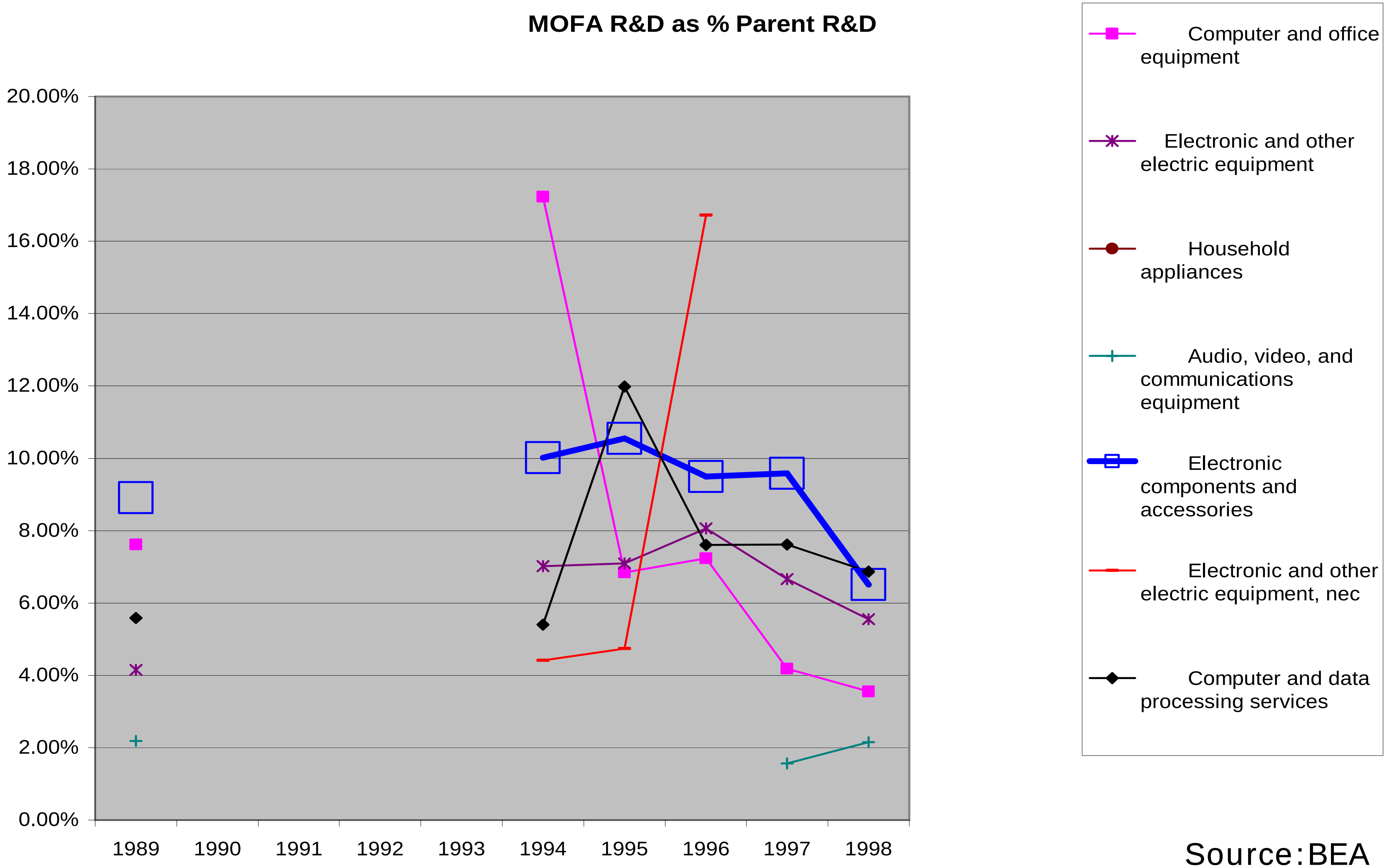
# International SEMATECH

- SEMATECH also went international in late 1990s
  - Recognized that tech capability, best technology now dispersed globally
  - Another Bill Spencer initiative
    - Encouraged by USG (including KF@DoD)
  - Prior recovery, stabilization of health of US semi industrial base
    - Critical to decision by all parties
- Began with international partnership to work on 300mm wafer tech (I300I)
- Continued with non-US companies as full members of IST
  - No continuing USG subsidy after 1997
- Today, share of world semi output accounted for by members exceeds share when formed in late 1980s

# ~~International~~ SEMATECH

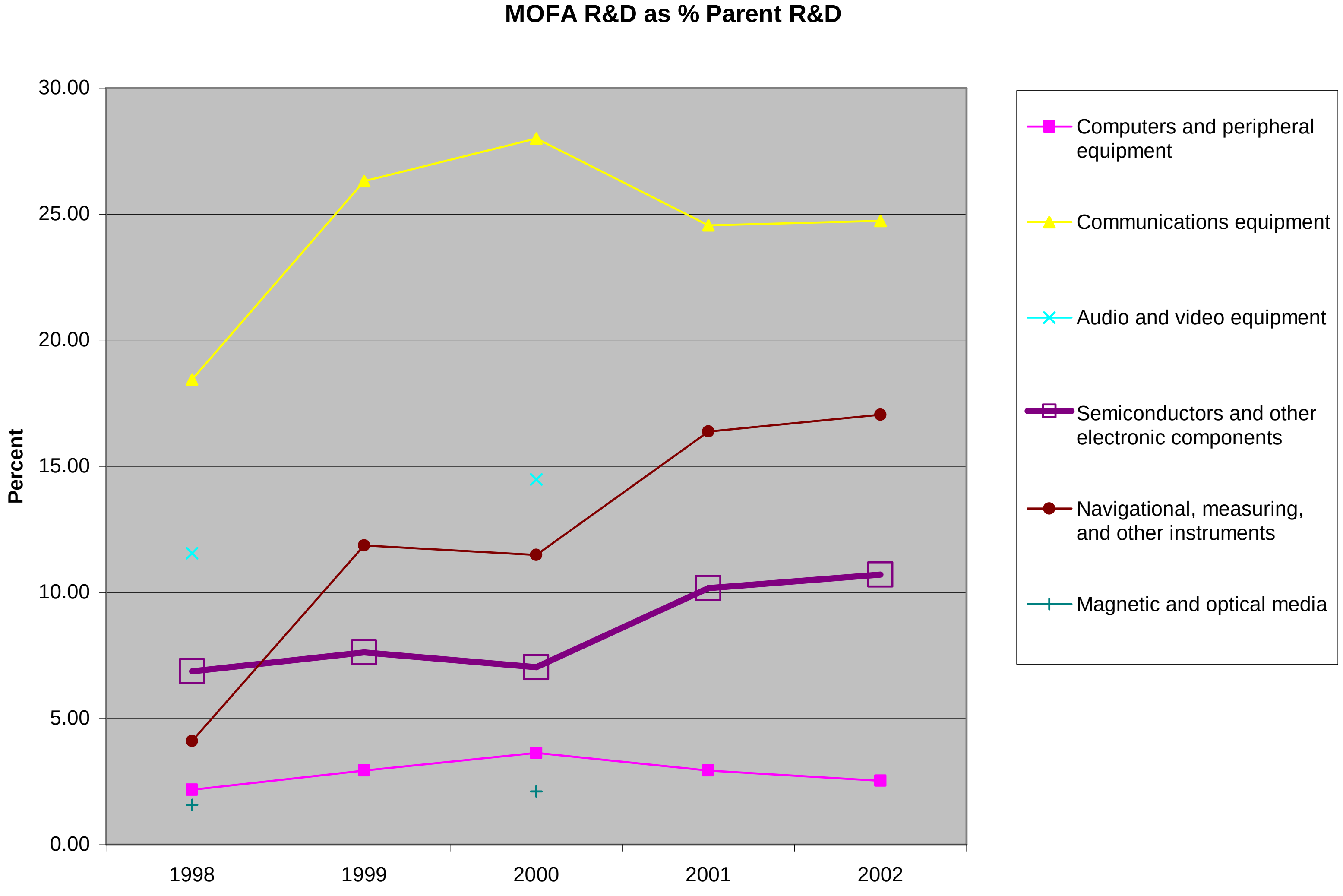
- SEMATECH dropped the I-word in 2004
- What does this mean?
  - ?... a “branding” issue
  - Still has many international members
    - (including Samsung, most recently)
- Also, spun off subset of R&D activities into ISMI
  - Walled off from access to “highest tech” (e.g., litho) R&D in main SEMATECH organization
  - All 9 “full” SEMATECH members also get membership in ISMI
    - AMD, Freescale, Hewlett-Packard, IBM, Infineon, Intel, Philips, Samsung, Texas Instruments
  - 3 ISMI-only members are do not get access to full SEMATECH information set
    - TSMC, Panasonic/Matsushita Electric, Spansion
    - First Japanese membership in SEMATECH consortia

# But…Even as SEMATECH internationalized, US semi industry did less of R&D globally

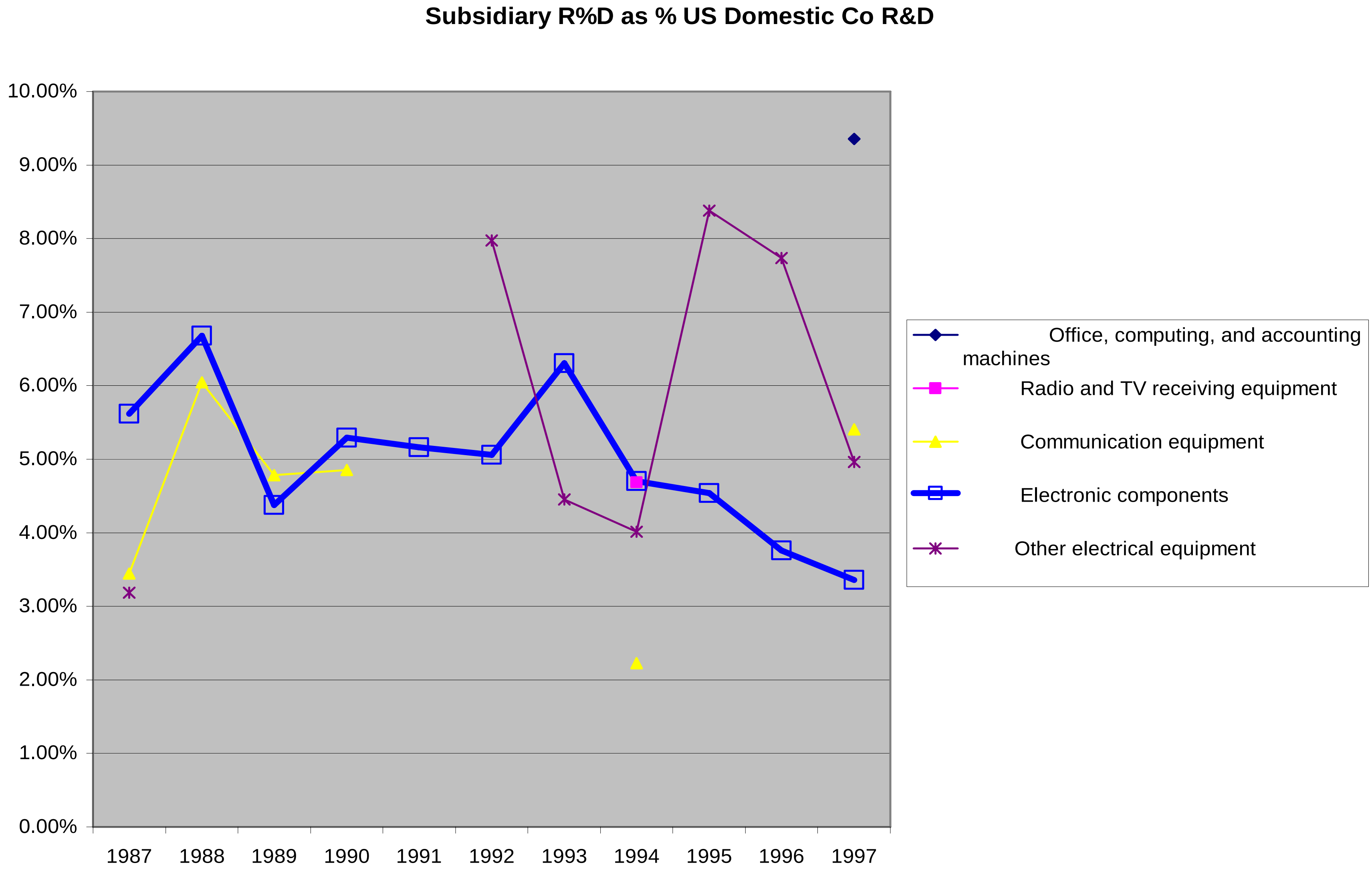



Source: BEA

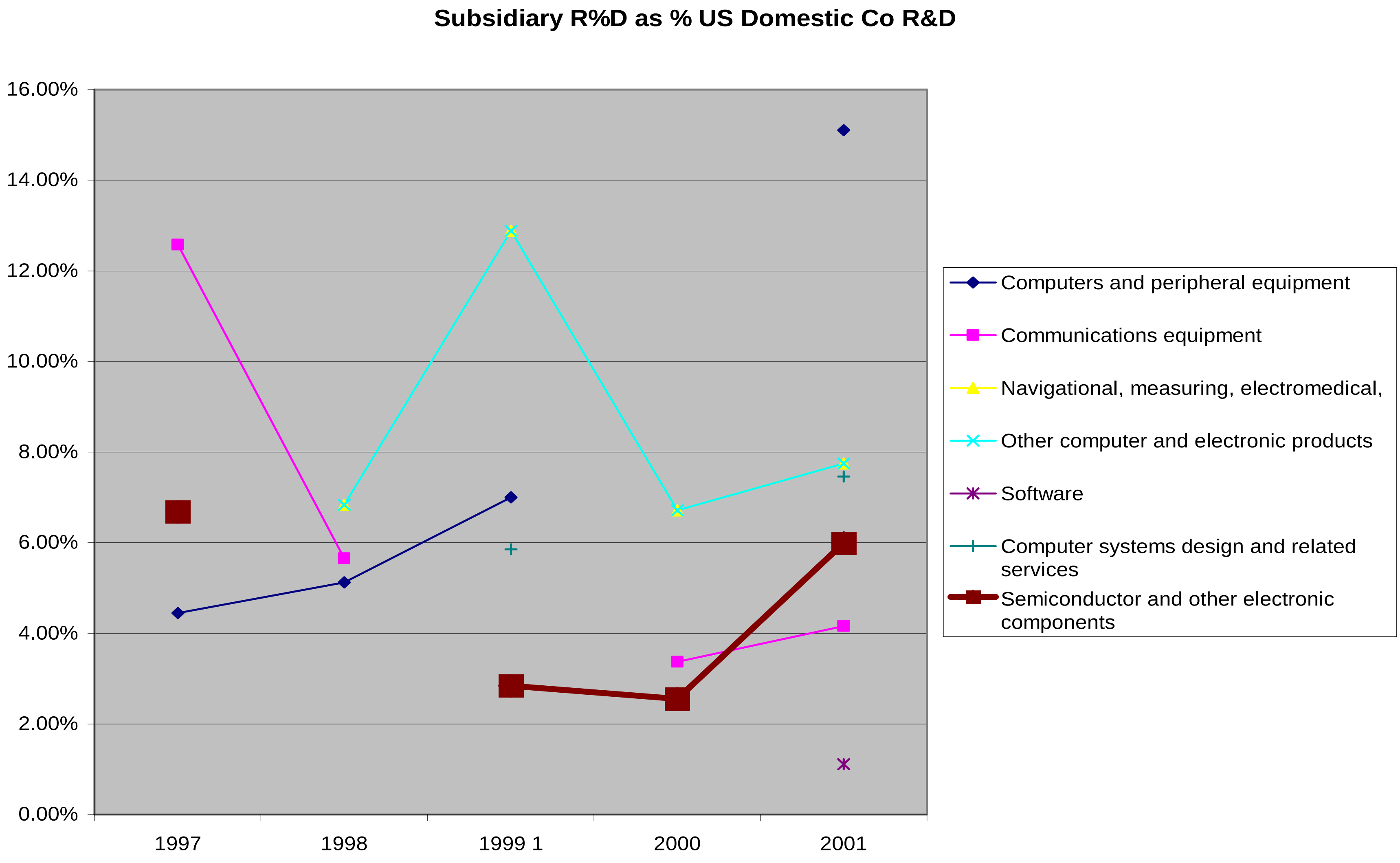
# Very Recent Trend Toward Increased Offshore R&D in US Semi Industry



# NSF Data Verify 1990s Trend



# And Subsequent Turnaround



# What to Make of This?

- Speculation
- US Semi Firms Best at What They Were Doing
  - US the place to be for R&D in these areas?
- R&D Cooperation Thru Roadmap in 1990s a Way to Coordinate with Suppliers in Areas Where Best of Breed Not in US
- Increasing Offshore Competence led to Some Increase in Offshore in R&D by US Firms After Millenium

# Back to Possible Impacts of Coordination….

**Acceleration in rate of innovation in semiconductors!**

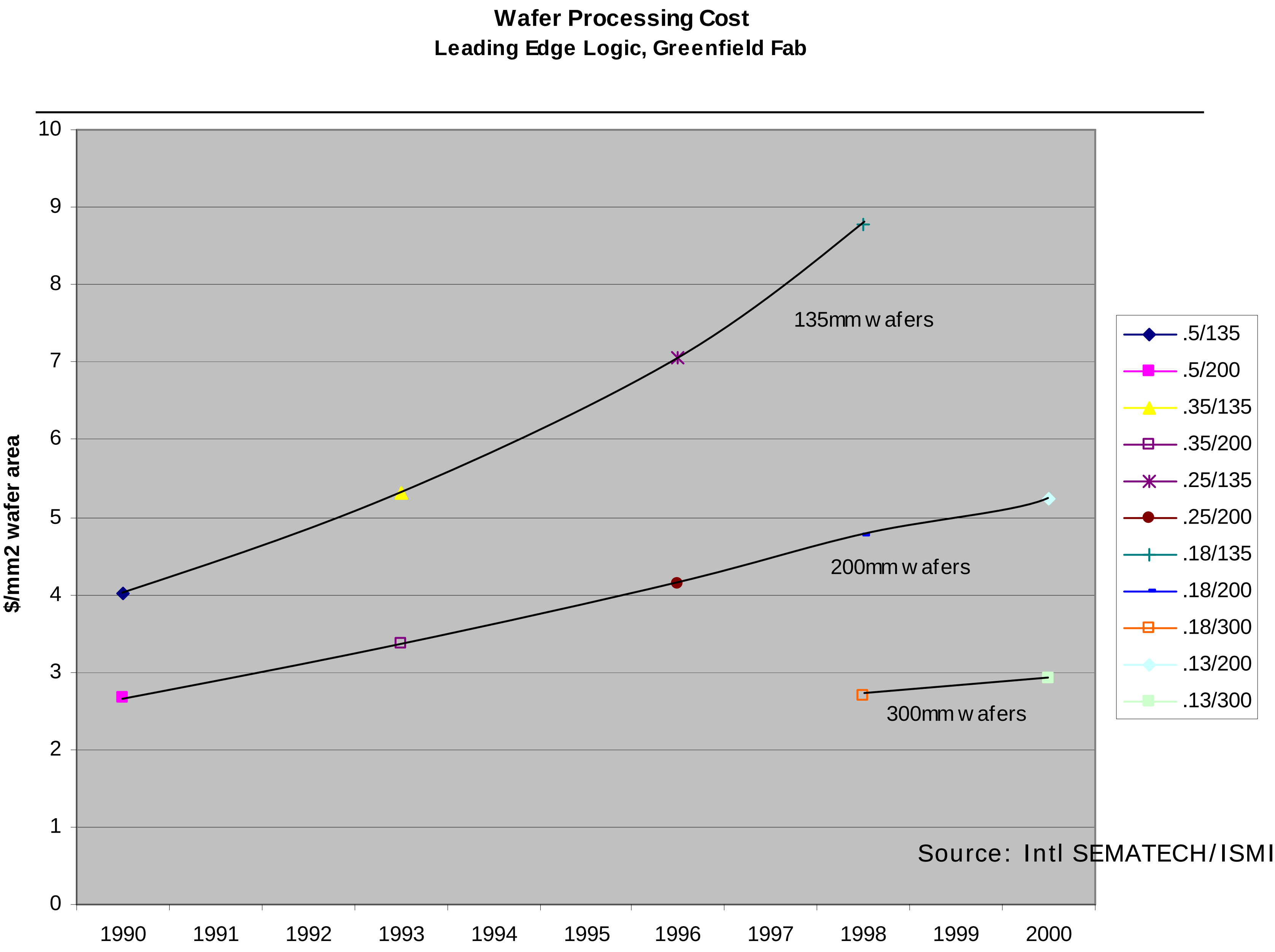
# Two Sources of Improvements in Price-Performance

- Declines in manufacturing cost lead to lower price for given quality / functionality
- Improved capabilities / performance / quality of functions provided by IC
- Both happen, are not independent
  - Design innovation may be needed to use lower cost components productively
  - Improved manufacturing techniques may bring quality improvement
    - Example: smaller features, faster gates
  - But will analyze separately

# Declines in Manufacturing Cost

- Linked to intro of new tech nodes
  - Process innovation ➔ smaller feature sizes
  - New tech node organized around 50% reduction in silicon area
    - (30% reduction in feature size)
    - On 2D plane, twice as many devices (transistors, logic gates, DRAM cells) in given area
    - All other things equal, would expect 2x as many devices in given area
      - i.e., ***device density*** would double with new node
    - To rough order of approximation, IC manufacturing cost per area of silicon has remained roughly constant
      - (more accurately, risen slowly)

# Microprocessor Wafer Processing Costs



# Simplest model

$$\text{Mfg Cost/device} = \frac{\dfrac{\underline{\text{\$ processing cost}}}{\text{area silicon}}}{\text{devices/Area silicon}} \quad \begin{matrix} \color{red}{c} \\ \\ \color{red}{t} \end{matrix}$$

- t is what is improved w/innovation in semi lithography
- feature size reduced 30%, device area 50% w/new node
  - so t doubles when this happens
- if we assume
  - no quality change (i.e., simply producing same chip in smaller area)
  - c remains constant
  - new t = "technology node" (an approximation) every 3 years
- Then...

# Result:

- Manufacturing cost drops by half every new technology node
  - every 3 years
- Works out to cost declining by
  - -21 % CADR

# Compare to Historical Reality at the Leading Edge

Decline Rates in Price-Performance

| | | Percent/Year |
|---|---|---|
| Microprocessors, | 1975-85 | -37.5 |
| Hedonic Index | 1985-94 | -26.7 |
| | | |
| DRAM Memory, | 1975-85 | -40.4 |
| Fisher Matched Model | 1985-94 | -19.9 |
| | | |
| DRAMs, Fisher Matched Model, Quarterly Data | | |
| | 91:2-95:4 | -11.9 |
| | 95:4-98:4 | -64.0 |
| Intel Microprocessors, Fisher Matched Model, Quarterly Data | | |
| | 93:1-95:4 | -47.0 |
| | 95:4-99:4 | -61.6 |

Prices generally exceeded prediction about costs!

Slowed down over time, then speeded up in mid-90s

# Why?

- Improvement in device density exceeded 2-dimensional impact of smaller feature size
- Ingenuity, innovation in feature design made this possible:
  - For example, building structures/transistors vertically, in 3-D
  - Using additional layers, in 3-D, to interconnect devices, instead of using up 2-D real estate to wire things together
- What happened:
  - In memory chips (DRAMs), density historically increased by about 2.9x (> 2X) with each new technology node

# Result:

- New tech node every 3 years
- + historical additional ingenuity (2.9x density increase at new tech node instead of 2x)
- ➔ density increases at 43% per year
- ➔ cost decline of -30% per year
- = approximate long run average rate of decline for both DRAM and microprocessor prices in 1975-95 period

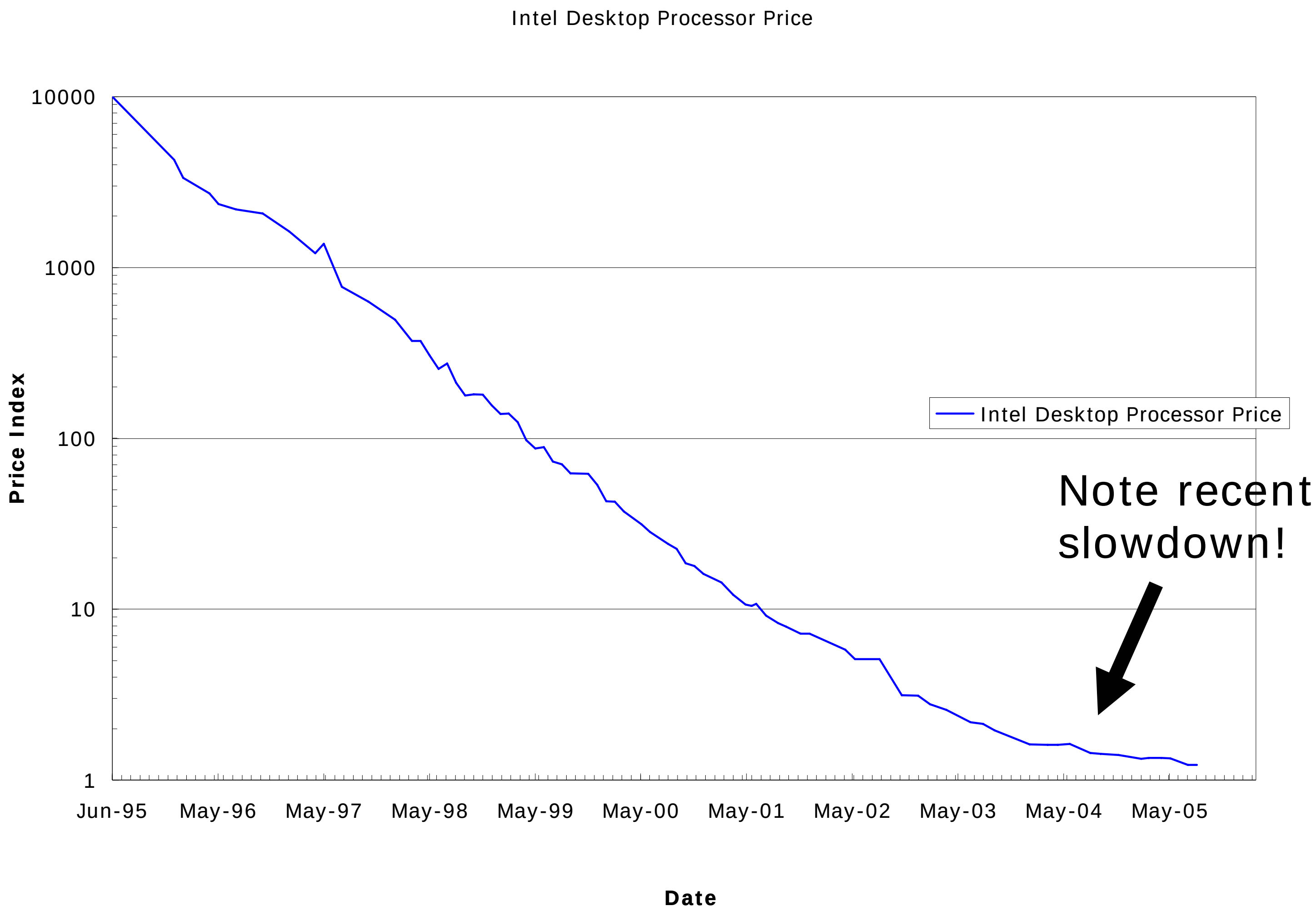
# Impact of 2 Year Technology Cycle (R&D Coordination) on Cost

- Now tech node every 2 years
- Maintain historical additional ingenuity (2.9x density increase at new tech node instead of 2x)
- ➔ density now increases at 70% per year
- ➔ cost decline of -41% per year
- Big increase in rate of decline in price, but still less than what measured in late 1990s (60%+ annual decline in prices in late 1960s)
- So let’s look at other candidate explanations (beyond manufacturing cost decline) for the rest of the story

# First, Analysis of Impact of Different Attributes of Improvement in Microprocessors on Price

- Constructed "hedonic" price indexes for Intel desktop microprocessors
  - Used detailed Intel price sheet data
  - Estimated over one year time periods
  - Price-characteristics relationship allowed to vary over time
  - Linked using common month in both periods
- Used regression analysis to links prices of microprocessors to measured characteristics
- Would expect other methods (price indexes) of constructing quality-adjusted prices to somewhat underestimate true decline in price
- Covered period 6/95-9/05
- Very detailed microprocessor characteristics
  - Processor clock speeds, bus speeds, L1, L2, L3 cache sizes, chip archtecture (Pentium, Celeron, P2, P3, P4), Instruction set features, voltage levels

# Hedonic Price Index for Intel Desktop Processors



# Example of Hedonic Regression Output

Dependent Variable: lp

| | |
|---|---|
| Number of Observations Read | 484 |
| Number of Observations Used | 484 |

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 25 | 306.69959 | 12.26798 | 510.94 | <.0001 |
| Error | 458 | 10.99687 | 0.02401 | | |
| Corrected Total | 483 | 317.69647 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0.15495 | R-Square | 0.9654 |
| Dependent Mean | 5.21507 | Adj R-Sq | 0.9635 |
| Coeff Var | 2.97127 | | |

Parameter Estimates

| Variable | Label | DF | Parameter Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|---|
| Intercept | Intercept | 1 | -16.77791 | 1.50892 | -11.12 | <.0001 |
| lproc | | 1 | 3.25134 | 0.09312 | 34.91 | <.0001 |
| p4 | p4 | 1 | 0.18154 | 0.04648 | 3.91 | 0.0001 |
| l1c16cel | | 1 | -0.38673 | 0.12118 | -3.19 | 0.0015 |
| l1c16p | | 1 | -0.20458 | 0.13991 | -1.46 | 0.1444 |
| L2C2000 | | 1 | 0.11858 | 0.06139 | 1.93 | 0.0540 |
| L3C2000 | | 1 | 1.33076 | 0.05024 | 26.49 | <.0001 |
| B800 | | 1 | -0.01174 | 0.04525 | -0.26 | 0.7955 |
| B1066 | | 1 | 0.44815 | 0.07751 | 5.78 | <.0001 |
| hvolt | hvolt | 1 | -0.90918 | 1.09809 | -0.83 | 0.4081 |
| lvolt | lvolt | 1 | -1.89787 | 0.64063 | -2.96 | 0.0032 |
| HT | HT | 1 | 0.18346 | 0.04849 | 3.78 | 0.0002 |
| LGA775 | LGA775 | 1 | 0.01850 | 0.02095 | 0.88 | 0.3777 |
| dualcore | dualcore | 1 | 1.06352 | 0.08021 | 13.26 | <.0001 |
| EIST | EIST | 1 | 0.08066 | 0.05672 | 1.42 | 0.1556 |
| EM64T | EM64T | 1 | 0.03341 | 0.03791 | 0.88 | 0.3785 |
| D200406 | | 1 | 0.00968 | 0.03208 | 0.30 | 0.7630 |
| D200408 | | 1 | -0.11177 | 0.03764 | -2.97 | 0.0031 |
| D200410 | | 1 | -0.12228 | 0.03199 | -3.82 | 0.0002 |
| D200412 | | 1 | -0.13788 | 0.03674 | -3.75 | 0.0002 |
| D200502 | | 1 | -0.18498 | 0.03749 | -4.93 | <.0001 |
| D200503 | | 1 | -0.17653 | 0.03665 | -4.82 | <.0001 |
| D200505 | | 1 | -0.17474 | 0.03634 | -4.81 | <.0001 |
| D200506 | | 1 | -0.18078 | 0.03792 | -4.77 | <.0001 |
| D200508 | | 1 | -0.27205 | 0.04038 | -6.74 | <.0001 |
| D200509 | | 1 | -0.26966 | 0.04004 | -6.74 | <.0001 |

# Results Consistent with Other Non-Hedonic Studies

| Aizcorbe, Corrado, Doms<br>Matched Model<br>Fisher Ideal Price Index | | Flamm<br>Hedonic<br>Annualized Rates | |
|---|---|---|---|
| Q2/93-Q2/94 | -28.27% | | |
| Q2/94-Q2/95 | -57.39% | | |
| Q2/95-Q2/96 | -66.22% | | |
| Q2/96-Q2/97 | -48.54% | May96-May97 | -55.52% |
| Q2/97-Q2/98 | -71.82% | May97-May98 | -69.27% |
| Q2/98-Q2/99 | -68.06% | May98-May99 | -73.77% |
| | | May99-Apr00 | -65.02% |
| | | Apr00-May01 | -74.56% |
| | | May01-May02 | -45.46% |
| | | May02-Apr03 | -58.80% |
| | | Apr03-May04 | -40.07% |
| | | May04-May05 | -16.03% |

# Hedonic Analysis Suggests Large Big Role for Processor Speed in Price

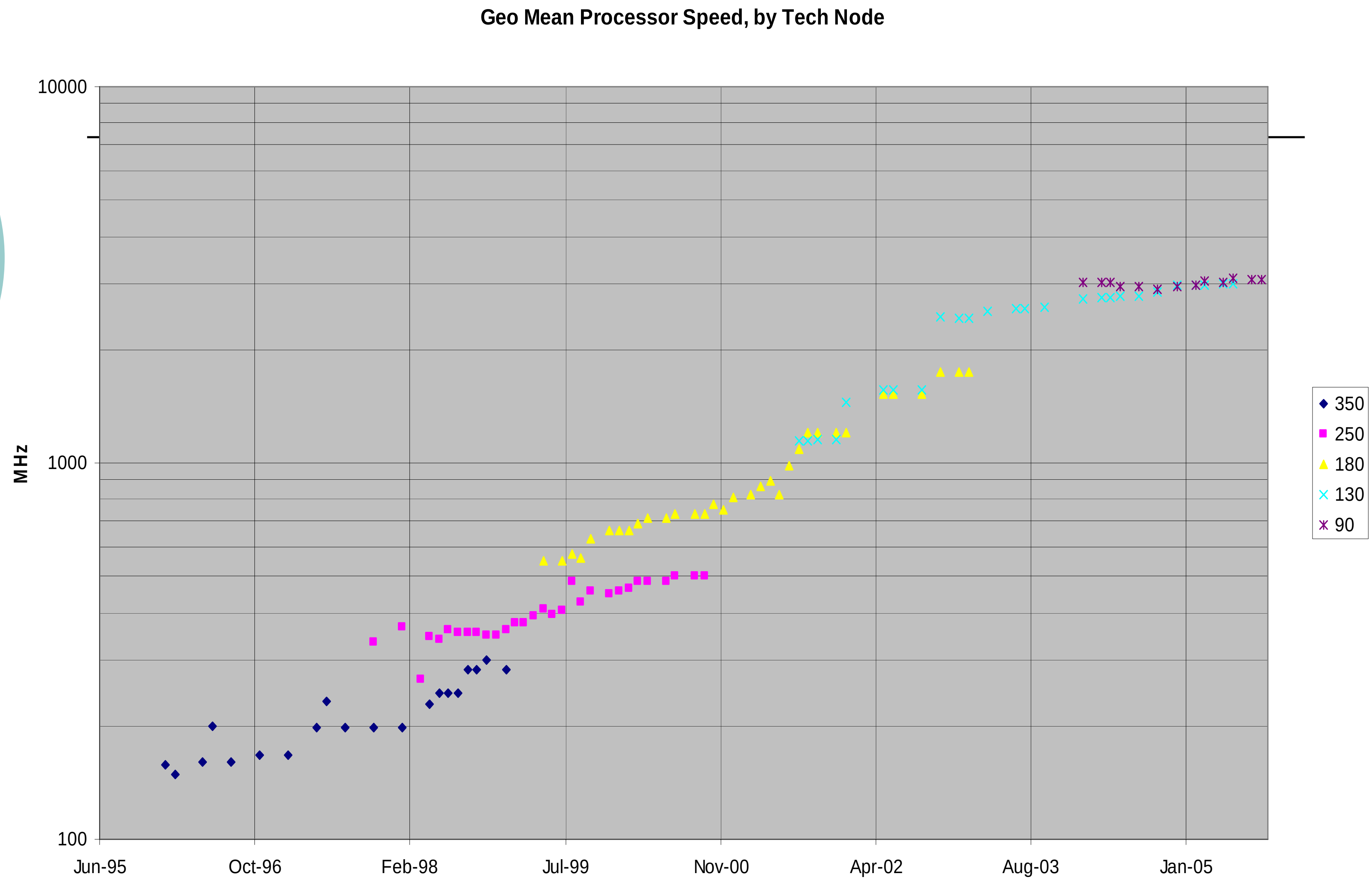
- Elasticity in range of 2 to 3 in regressions for all years from 1996 on
- 10% increase in processor speed associated with 20-30% increase in price, at any moment in time

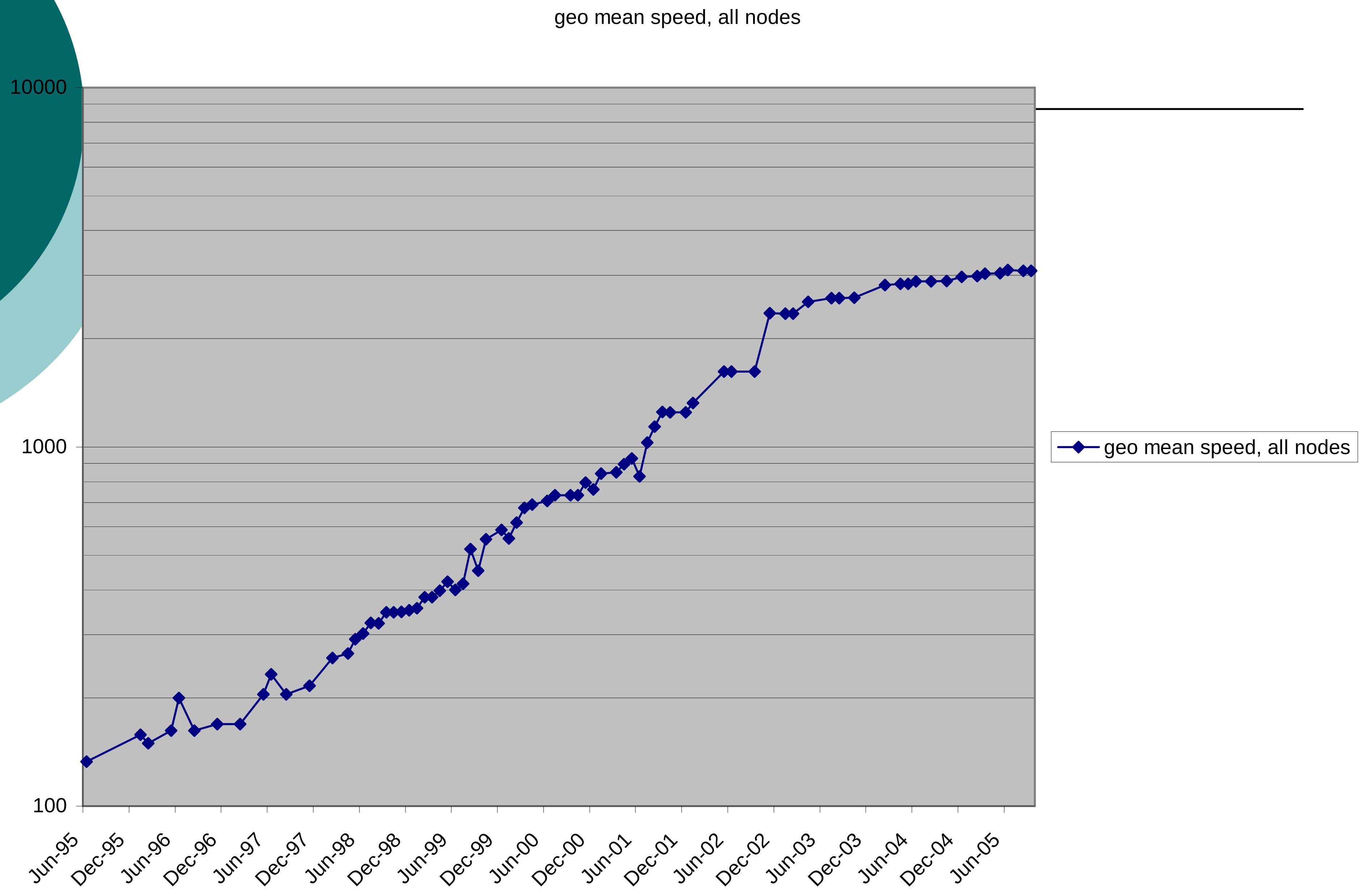
# Acceleration in technology nodes also led to acceleration in processor speed improvement!

- New technology node historically led to discontinuous increase in processor speed
- Byproduct of smaller feature sizes is shorter distances between features, potentially faster chips
  - Design innovation needed to make use of greater switching speeds
- Another benefit of roadmap-led acceleration in nodes beyond merely reducing manufacturing cost

# Crisis in Microprocessors?

- Hit "brick wall" related to power and heat dissipation in 2004-2005
- Processor speed no longer increasing significantly
- Processor speed now increasing very slowly if at all
- Processor speed slowdown in 2003-04, halt in 2004-05 coincide with big declines in rate of price performance improvement
- Feature proliferation going on in new microprocessors, hedonics suggest relative small enhancement to value of new processors
- Slowdown in new node intro at Intel may also explain slowdown in price decline rate


Geo Mean Processor Speed, by Tech Node
MHz
10000
1000
100
Jun-95
Oct-96
Feb-98
Jul-99
Nov-00
Apr-02
Aug-03
Jan-05
350
250
180
130
90



geo mean speed, all nodes
10000
1000
100
Jun-95
Dec-95
Jun-96
Dec-96
Jun-97
Dec-97
Jun-98
Dec-98
Jun-99
Dec-99
Jun-00
Dec-00
Jun-01
Dec-01
Jun-02
Dec-02
Jun-03
Dec-03
Jun-04
Dec-04
Jun-05
geo mean speed, all nodes

# New Tech Node Introduction at Intel (Using Intro of 1st Commercial Product)

| Year | Month | Tech Node (nm) | Years since last Node Introduction |
|---|---|---|---|
| 1974 | 4 | 6000 | |
| 1976 | 3 | 3000 | |
| 1982 | 2 | 1500 | 5.92 |
| 1989 | 4 | 1000 | 7.17 |
| 1991 | 6 | 800 | 2.17 |
| 1994 | 3 | 600 | 2.75 |
| 1995 | 3 | 350 | 1.00 |
| 1997 | 9 | 250 | 2.50 |
| 1999 | 6 | 180 | 1.75 |
| 2001 | 1 | 130 | 1.58 |
| 2004 | 2 | 90 | 3.08 |

# Big Trouble?

- Rapid improvement in price performance for processors and memory→ rapid improvement in PC price-performance
- Rapid improvement in PC price-performance→ widespread use of IT, productivity improvements in entire economy
- Likely to significantly reduce incentive to purchase new computers
- Slowdown in purchases of PCs, application of IT, likely to have significant ripple effects throughout global economy

# Microprocessor Industry Response

- Dual and multi-core processors
  - Unlike faster processors (with higher clock rates), do nothing to improve performance of applications written as single threads
    - As opposed to running multiple instances of a single app on a server
  - Rewriting existing applications to "parallelize" and divide work into parallel threads difficult and expensive—lesson from supercomputer industry
  - But it is possible to do it with appropriate investment—another lesson from recent history of supercomputer industry
  - Suggests that increased investments in high end computing ultimately likely to be generating new wave of "spillover" benefits to IT users—and broader economy
- New feature proliferation
  - Verdict out on how worthwhile

# Feature proliferation

**Processor Number Feature Table**

| Type | Intel® Brand or Processor Family | Processor Name | Architecture | Cache (MB/KB) | Clock Speed (GHz/MHz) | Front Side Bus (MHz) | Dual-core | Intel® Virtualization Technology‡ | Hyper-Threading Technology‡ | Enhanced Intel SpeedStep® Technology | EM64T‡ | Execute Disable‡ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Desktop | Intel® Pentium® Processor Extreme Edition | Intel® Pentium® Processor Extreme Edition 840 | 90nm, LGA775 | 2 x 1 MB L2 Cache | 3.20 GHz | 800 MHz | Yes | No | Yes | No | Yes | Yes |
| | Intel® Pentium® D processor | Intel® Pentium® D processor 840 | 90nm, LGA775 | 2 x 1 MB L2 Cache | 3.20 GHz | 800 MHz | Yes | No | No | Yes | Yes | Yes |
| | Intel® Pentium® D processor | Intel® Pentium® D processor 830 | 90nm, LGA775 | 2 x 1 MB L2 Cache | 3 GHz | 800 MHz | Yes | No | No | Yes | Yes | Yes |
| | Intel® Pentium® D processor | Intel® Pentium® D processor 820 | 90nm, LGA775 | 2 x 1 MB L2 Cache | 2.80 GHz | 800 MHz | Yes | No | No | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 672 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3.80 GHz | 800 MHz | No | Yes | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 670 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3.80 GHz | 800 MHz | No | No | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 662 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3.60 GHz | 800 MHz | No | Yes | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 660 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3.60 GHz | 800 MHz | No | No | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 650 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3.40 GHz | 800 MHz | No | No | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 640 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3.20 GHz | 800 MHz | No | No | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 630 supporting Hyper-Threading Technology | 90nm, LGA775 | 2 MB L2 Cache | 3 GHz | 800 MHz | No | No | Yes | Yes | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 571 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.80 GHz | 800 MHz | No | No | Yes | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 570J supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.80 GHz | 800 MHz | No | No | Yes | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 561 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.60 GHz | 800 MHz | No | No | Yes | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 560J supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.60 GHz | 800 MHz | No | No | Yes | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 560 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.60 GHz | 800 MHz | No | No | Yes | No | No | No |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 551 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.40 GHz | 800 MHz | No | No | Yes | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 550J supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.40 GHz | 800 MHz | No | No | Yes | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 550 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.40 GHz | 800 MHz | No | No | Yes | No | No | No |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 541 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.20 GHz | 800 MHz | No | No | Yes | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 540J supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.20 GHz | 800 MHz | No | No | Yes | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 540 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3.20 GHz | 800 MHz | No | No | Yes | No | No | No |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 531 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3 GHz | 800 MHz | No | No | Yes | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 530J supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3 GHz | 800 MHz | No | No | Yes | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 530 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 3 GHz | 800 MHz | No | No | Yes | No | No | No |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 521 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 2.80 GHz | 800 MHz | No | No | Yes | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 520J supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 2.80 GHz | 800 MHz | No | No | Yes | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 520 supporting Hyper-Threading Technology | 90nm, LGA775 | 1 MB L2 Cache | 2.80 GHz | 800 MHz | No | No | Yes | No | No | No |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 519K | 90nm, LGA775 | 1 MB L2 Cache | 3.06 GHz | 533 MHz | No | No | No | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 519J | 90nm, LGA775 | 1 MB L2 Cache | 3.06 GHz | 533 MHz | No | No | No | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 518 | 90nm, LGA775 | 1 MB L2 Cache | 2.93 GHz | 533 MHz | No | No | No | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 515J | 90nm, LGA775 | 1 MB L2 Cache | 2.93 GHz | 533 MHz | No | No | No | No | No | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 515 | 90nm, LGA775 | 1 MB L2 Cache | 2.93 GHz | 533 MHz | No | No | No | No | No | No |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 511 | 90nm, LGA775 | 1 MB L2 Cache | 2.80GHz | 533 MHz | No | No | No | No | Yes | Yes |
| | Intel® Pentium® 4 processor | Intel® Pentium® 4 processor 505J | 90nm, LGA775 | 1 MB L2 Cache | 2.66 GHz | 533 MHz | No | No | No | No | No | Yes |

# Conclusions

- R&D coordination effort started with SEMATECH and continuing through ISTR appears to have created significant benefits over last decade
- Technology node acceleration has big impact on manufacturing costs, quite apart from any other benefits
- Examination of microprocessors suggest additional important benefits
- Microprocessor analysis also suggests new technical barriers seem to have at least temporarily slowed down creation of additional benefits
  - Significantly slowing declines in quality-adjusted microprocessor prices
- Investment in advancing software technology may be needed to capitalize on continuing advance in semiconductor manufacturing
- Implication- in long run, supercomputer software R&D investment is likely to be as or more economically important than new supercomputer hardware– where $ are now going