

A—AXLES. B—WHEEL WHICH IS TURNED BY TREADING. C—TOOTHED WHEEL.  
D—DRUM MADE OF RUNDLES. E—DRUM TO WHICH ARE FIXED IRON CLAMPS.  
F—SECOND WHEEL. G—BALLS.

# Technological Learning

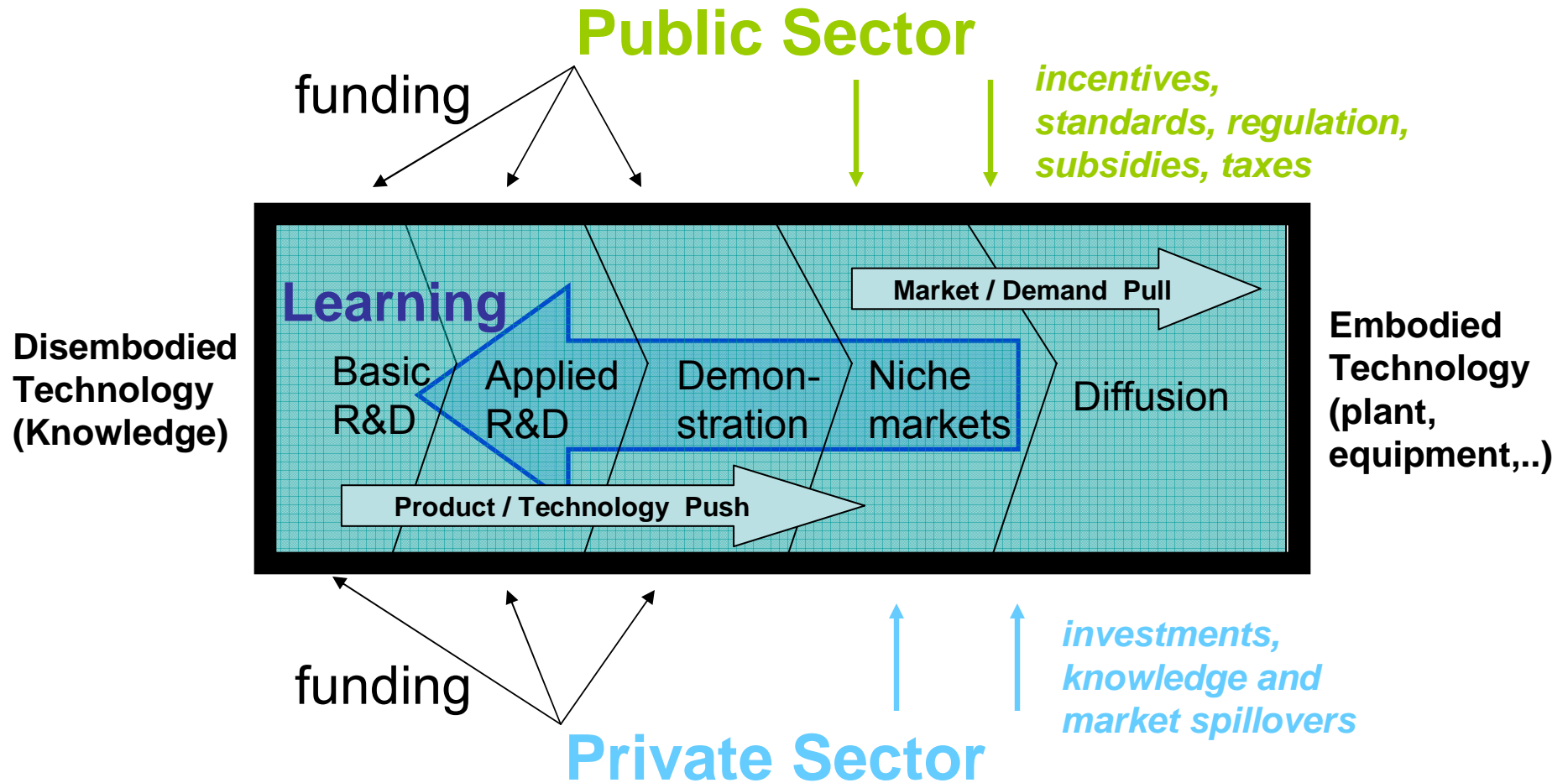
*Learning Conference  
IIASA April 10-11, 2006*

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# Learning about Technology

- Technological change is a process involving many steps and feedbacks. Hence multiple “learnings” about different things by different mechanisms.
- Technology = combination of disembodied and embodied knowledge. Embodied TC only via (costly) investments (by technology users  $\neq$  tech producers)
- Significant costs downstream “R” (research): “D” dominates “R&D”, investment dominates over R&D
- “Value” of technology increases downstream also:  
Value of patent < private RoR < social RoR of innovation
- Long tradition of Learning by Doing LbD (and using) or “experience curve” cost analysis in manufacturing (adding to terminological confusion: “Who learns what and how”  
©N. Rosenberg)
- Little exploration beyond aggregate, proxy drivers (e.g. knowledge stock, cum. production)

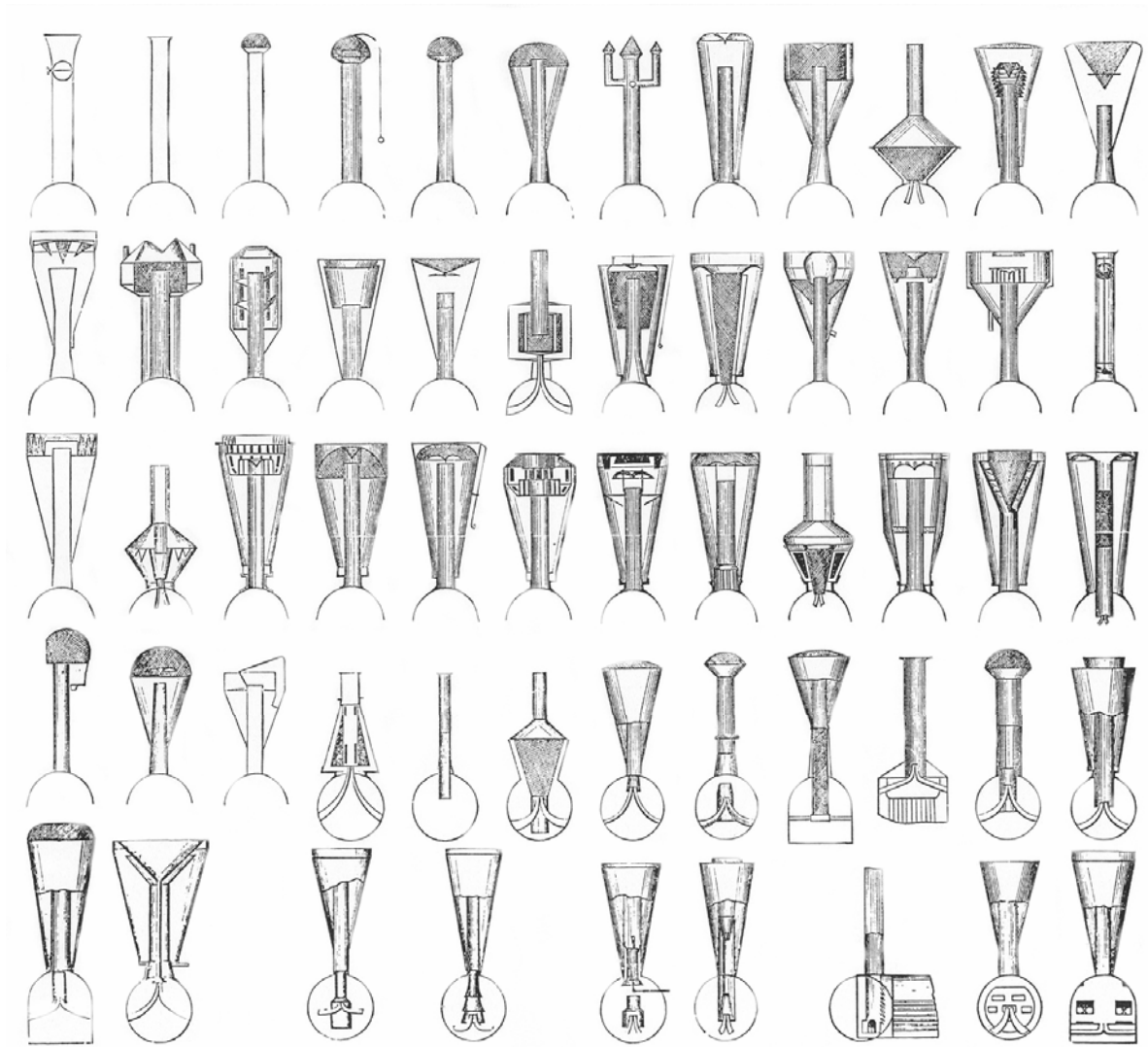
# The “black box” of Technology



# “Learning”: Resolving Technological Uncertainties

- Innovation: many are called, few are chosen
- Diffusion: multiple factors, e.g.
  - Technological “Figures of Merit”
  - Economics:  $Use = f(Costs)$ 
    - Static:  $C_t$
    - Dynamic: e.g.  $C_t = f(\sum_t U)$  (LbD)
- Feedbacks: e.g. spillovers, “take backs”
- Externalities: e.g. networks, knowledge,
- Impacts: nonlinear  $f(U)$  or “discovery by accident”

# Innovation Uncertainty: Patented but non-functional smoke-spark arrestors



Source: J. White, *American Locomotives*, 1968.

# Technology “Learning” = Knowledge Generation AND Depreciation

- *“Heavier-than-air flying machines are impossible.”* Lord Kelvin, 1895.
- *“I think there is a world market for maybe five computers.”* Tom Watson, IBM chair, 1943.
- *“But what ... is it good for?”* IBM engineer commenting on the microchip in 1968.
- *“There is no need for any individual to have a computer in their home.”* Ken Olson, President, Digital Equipment, 1977.
- More fun:  
<http://my.athenet.net/~jlindsay/SkepticQuotes.html>

# “Discovery by Accident”

©Tom Schelling

- Major nuclear weapons effects outside explosive force (radioactive fallout, retinal burn, tsunami waves, EM pulse)
- CFC's impact on stratospheric ozone
- Accumulation of DDT
- Lead poisoning
- Non-linear dose-response effect of acidification

# Scherer's Rule

(compounding uncertainties)

Probability an R&D project gets selected**	??
Probability of technical success (once selected)*	.57
Commercialization (given technical success)*	.67
Financial success (given commercialization)*	.74
Aggregate probability	.27
Magnitude of financial success (private AND social RoR)**	??

\* Based on Mansfield et al.'s empirical study of R&D project histories in US enterprises in chemical, pharmaceutical, electronics, and petroleum industries

\*\* **Largest uncertainties!**

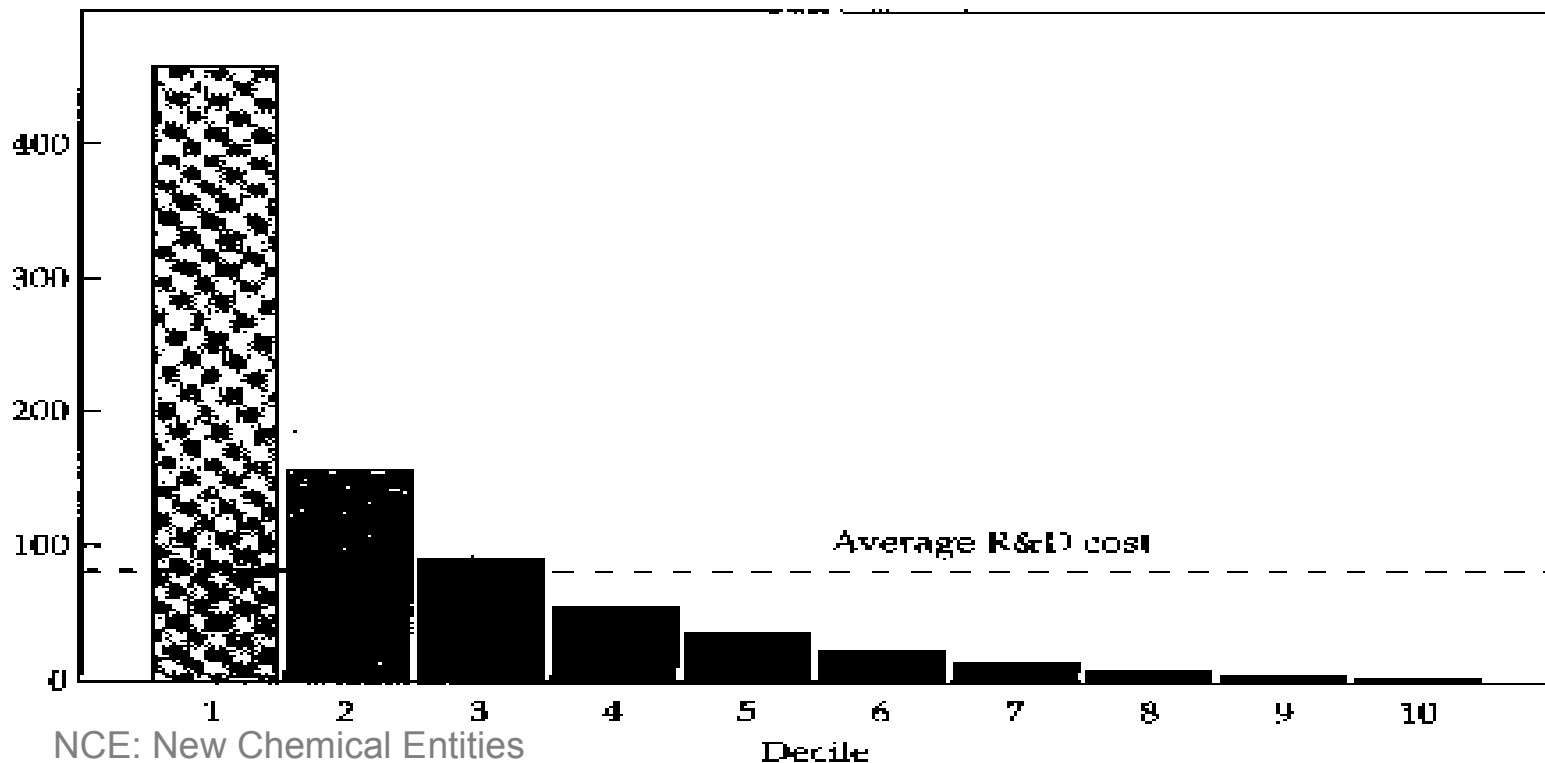
# On Probabilities

- Major components of technological life cycle defy probabilistic assessments:
  - upfront innovation feasibility
  - economic returns (from big hits)
  - application spillovers (lasers, internet,...)
  - impacts
- Many empirical “rules of thumb” available, but only for “routine” innovations
- Perhaps 90% of innovations could be modeled, but alas only the less interesting ones

# Fat tailed distributions:

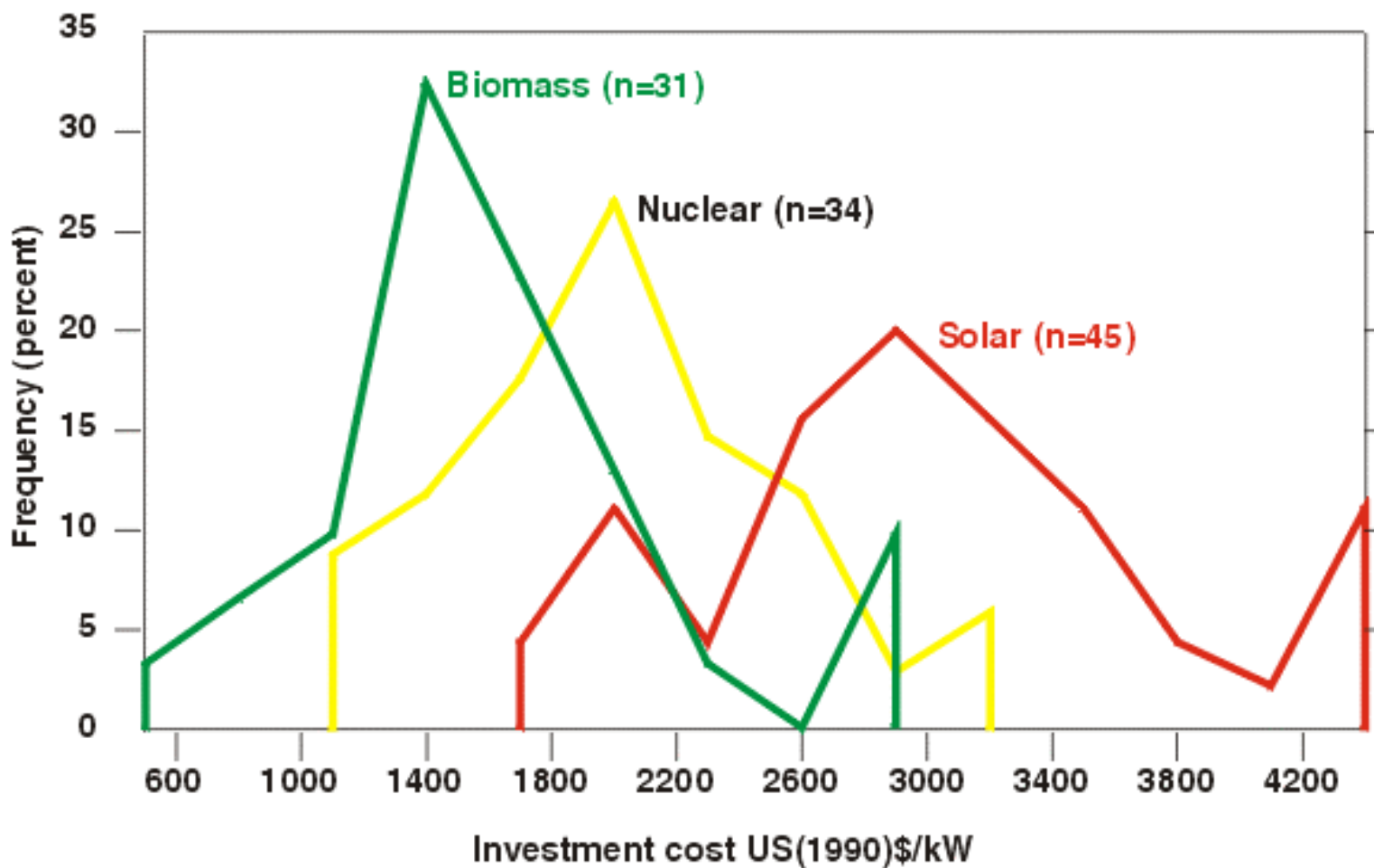
Pay-offs from US Pharmaceutical Innovations:  
(similar as in UK and EU “patent value” studies)

Discounted present value per NCE, millions of dollars



Source: Scherer, 2000.

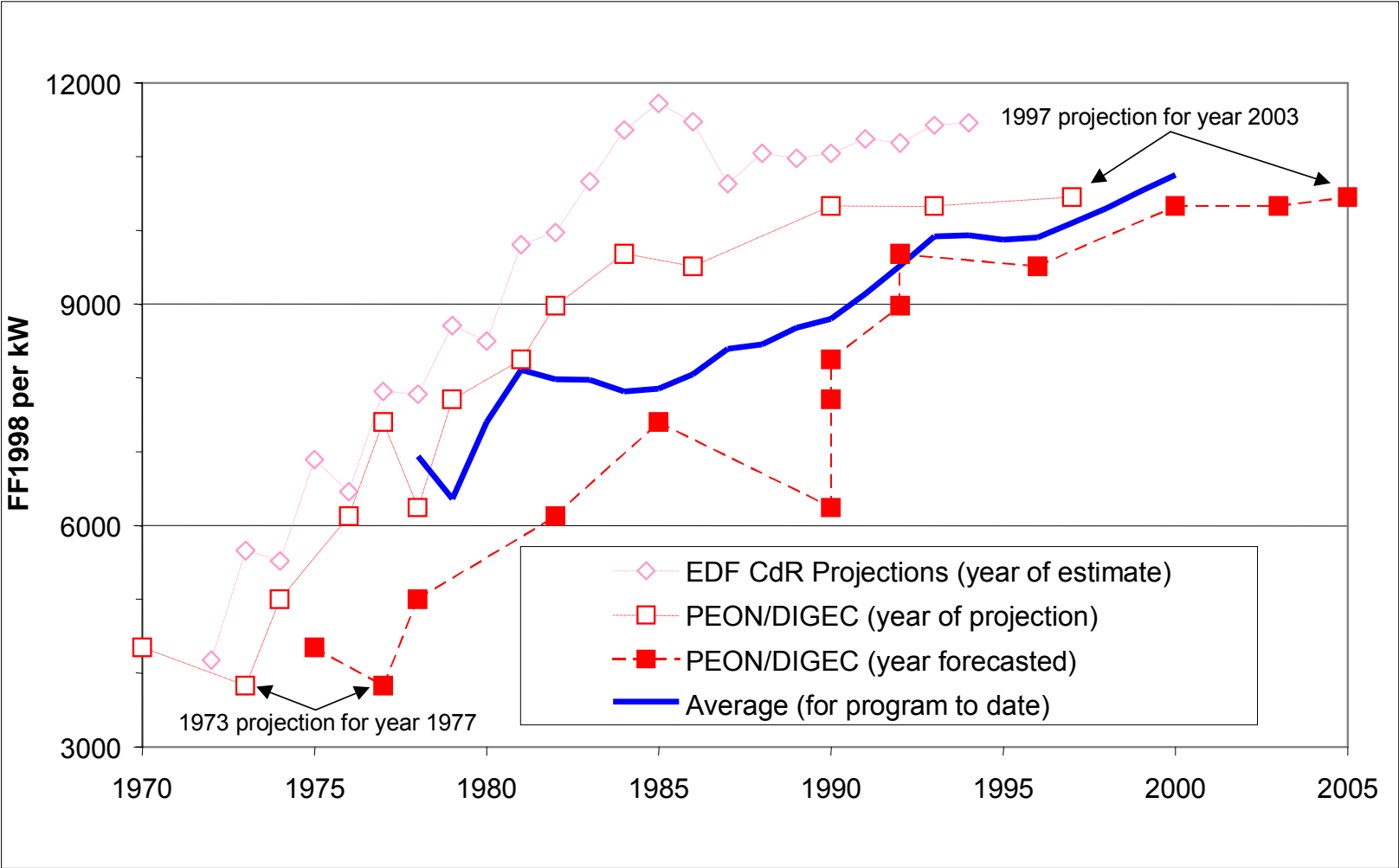
# Cost Uncertainty: Important Information in Tails!



Strubegger&Reitgruber 1995 analysis of near-term technology cost projections

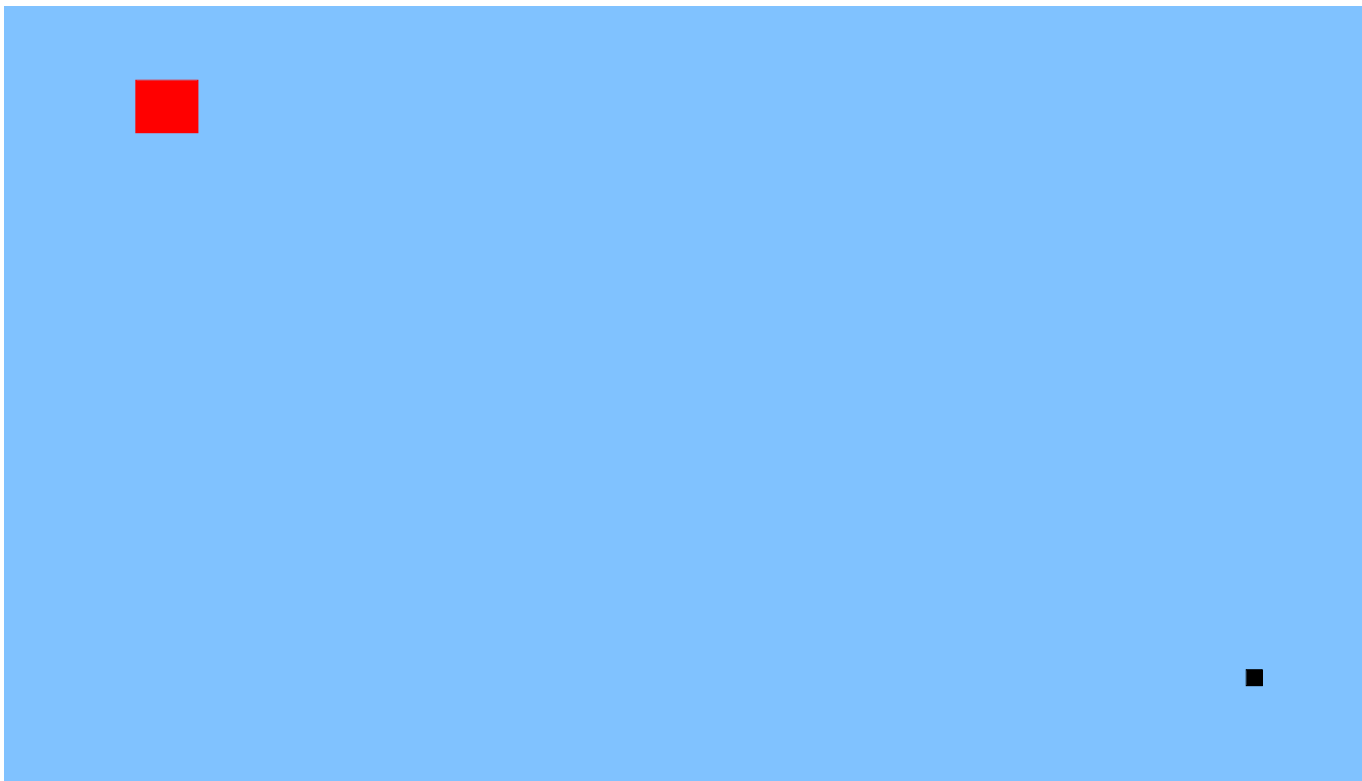
# France - Investment Costs of Nuclear

(cost forecasts of new technologies are always wrong!)



# AREA OF IGNORANCE

Relative proportions of  
chemicals known (6 million, blue),  
tested for carcinogenicity (7000, red), and  
related to human cancer (30, black)

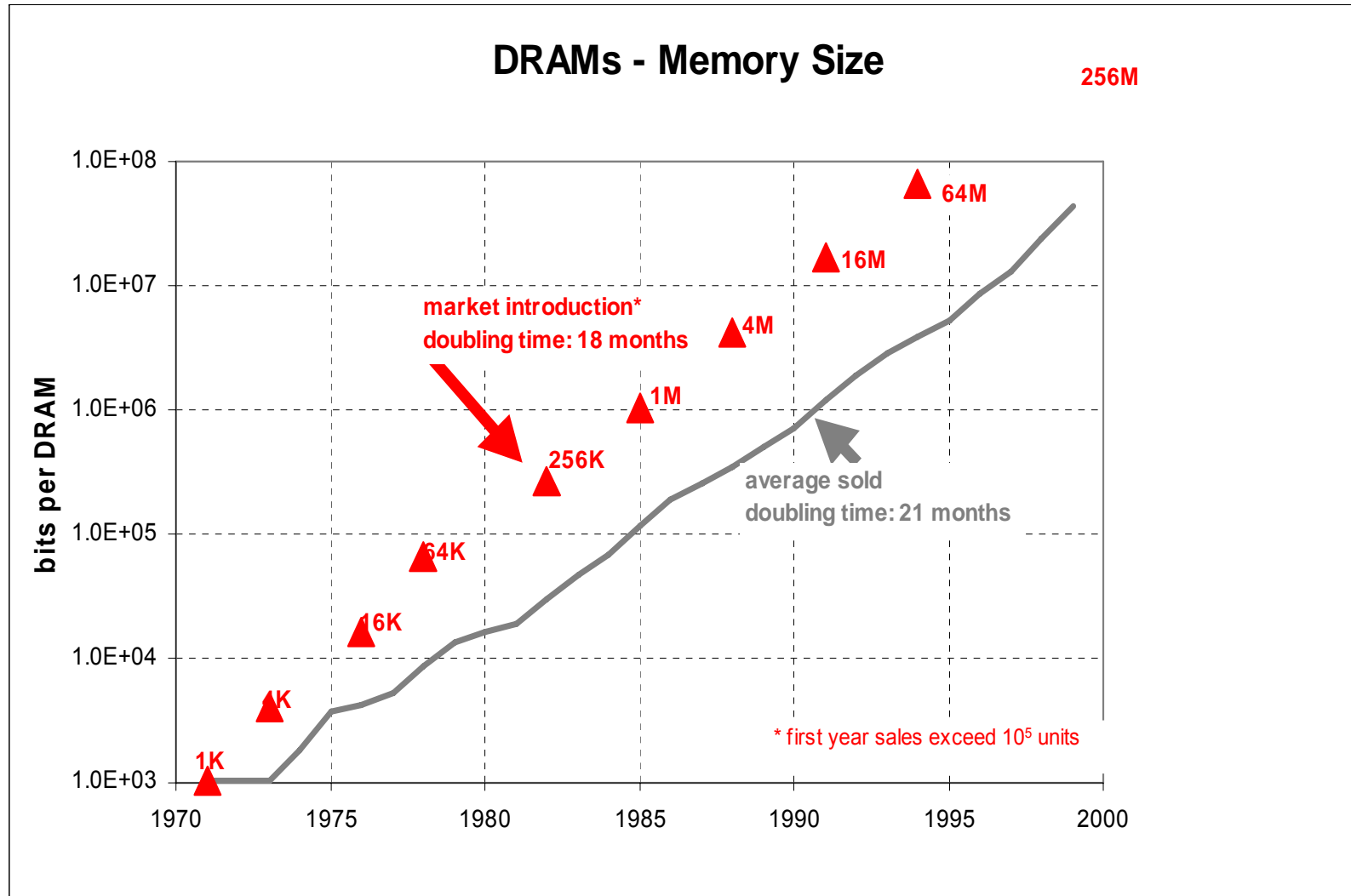


Source: Adams, 1995:46

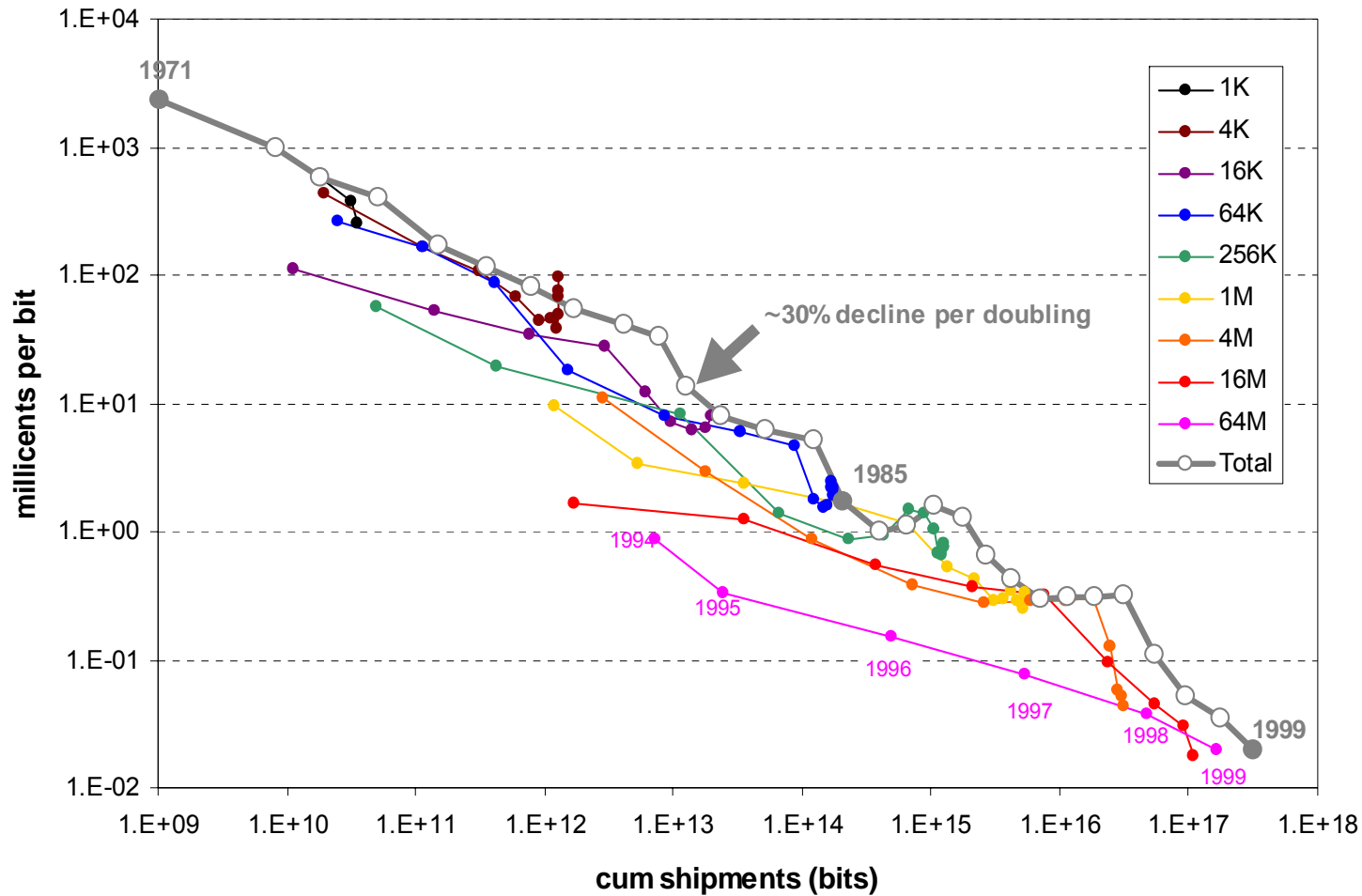
# LbD

- Vast case study literature (with possibilities of statistical interpretation, e.g. mean costs: -20% for 2x cumprod)
- Pro-innovation bias: mostly success stories (exceptions: Lockheed Tristar, French reactors)
- Quality improvements (+/-) largely ignored
- Impossibility to separate R&D (innovation) and learning in manufacturing (2-factor learning curves empirically vacuous and theoretically based on dismissed linear model of innovation)
- Intricate measurement challenges (costs vs. prices,...)
- Effects of spillovers important but difficult to measure (esp. for inter-industry and international spillovers, not to mention inter-technology spillovers)

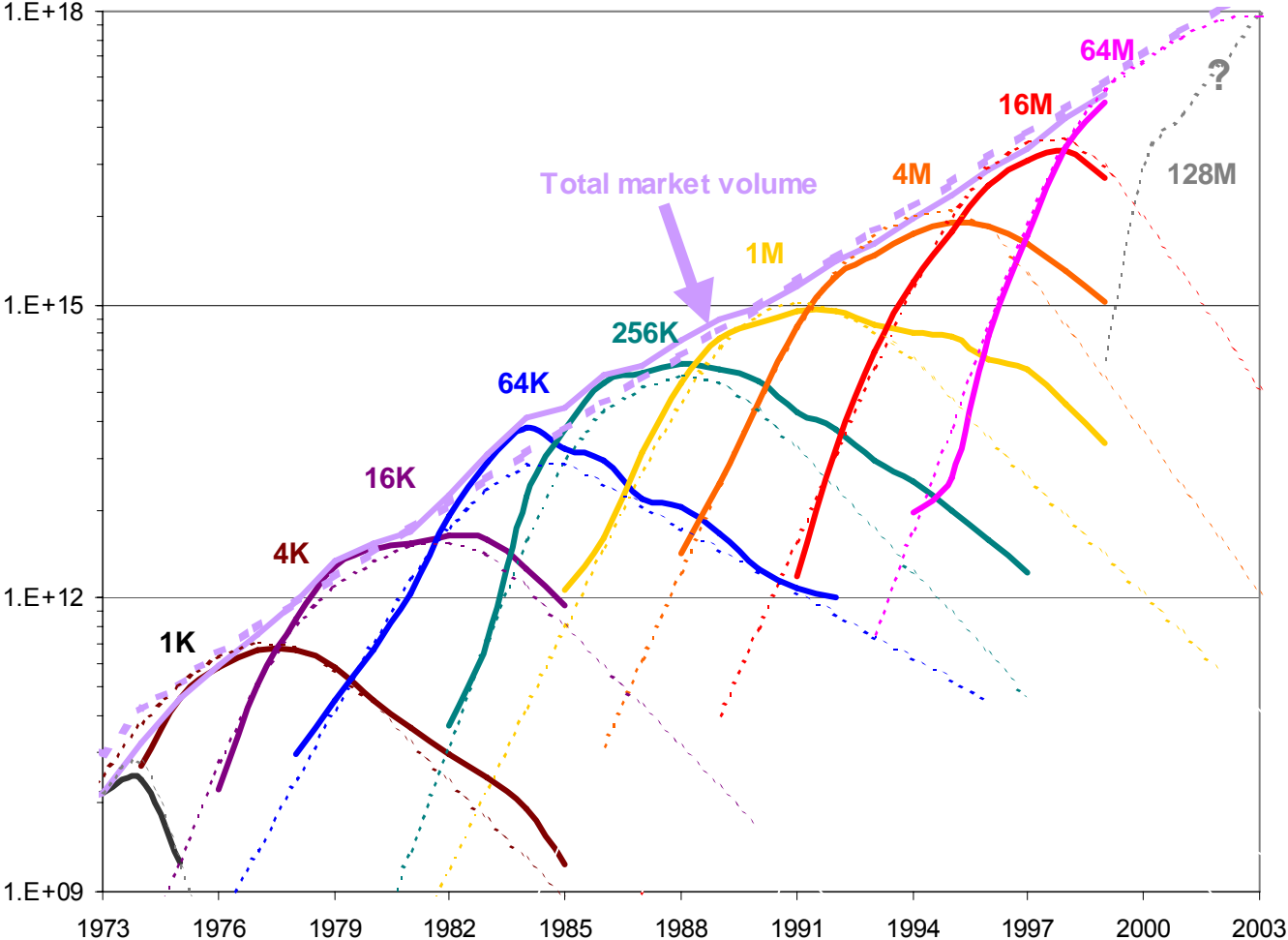
# DRAMs: Moore's Law



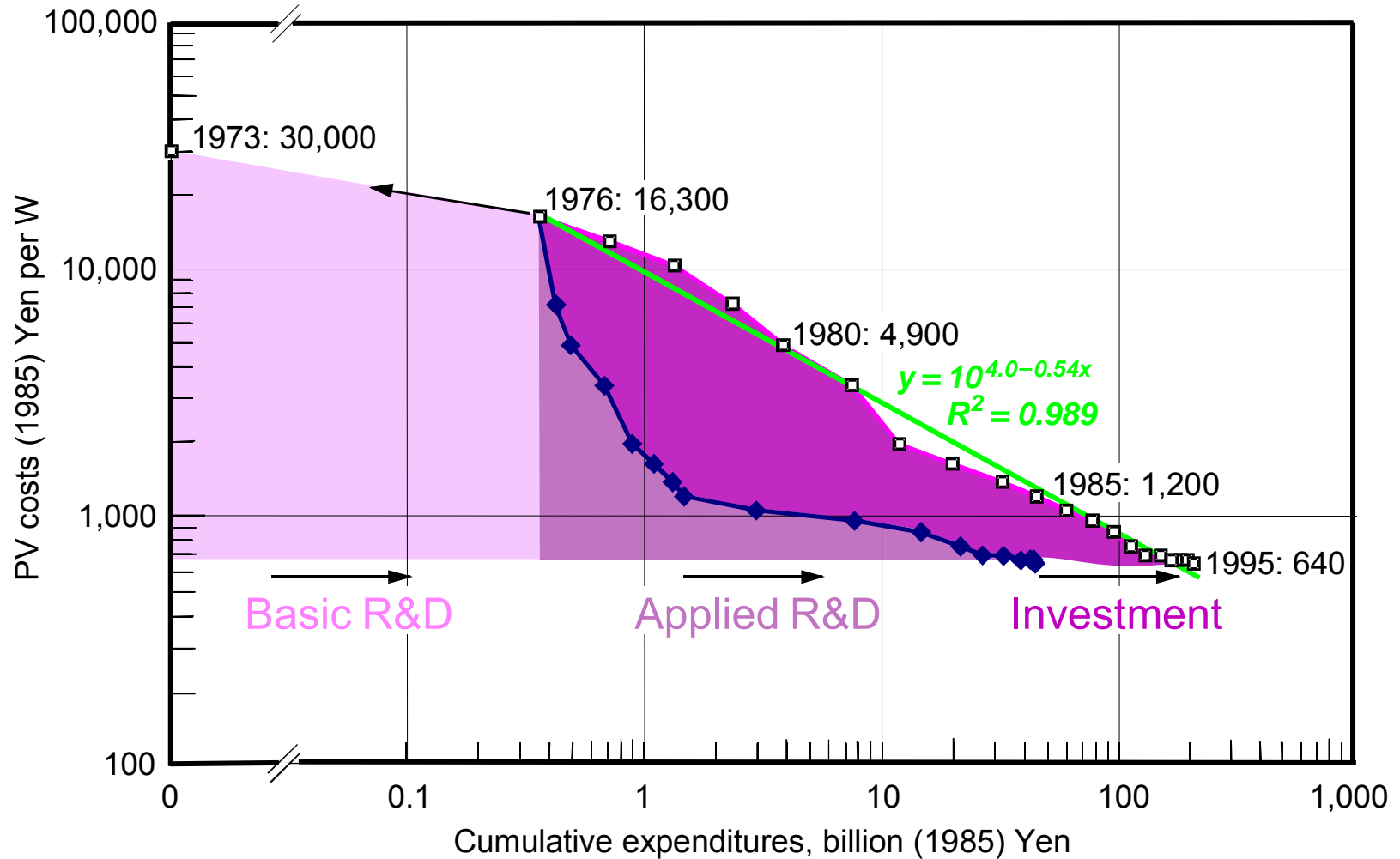
# DRAMS: Prices per bit (R&D, learning by doing, and spillovers)



# DRAM Diffusion (bits sold) as Cumulative Change

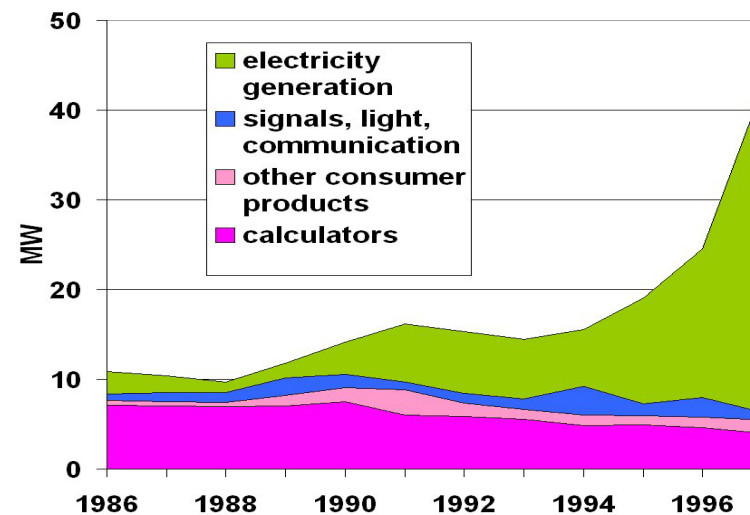
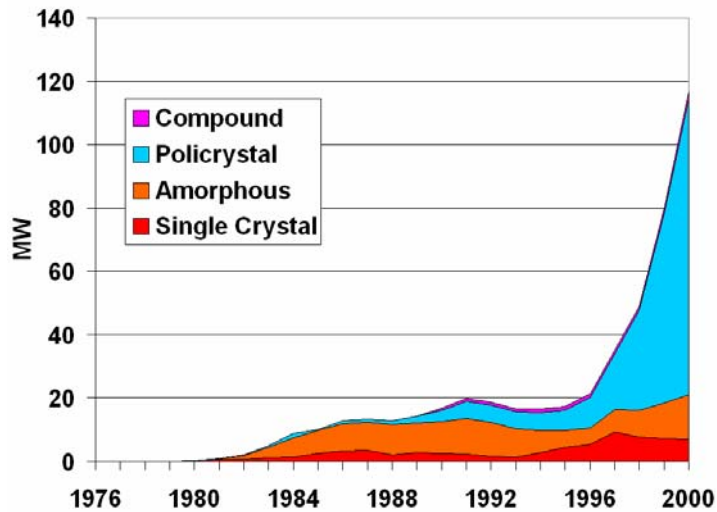


# Japan - PV Costs (improved knowledge) vs. Expenditures (effort)



# Japan PV: Importance of Supply Push AND Demand Pull

Data: Yuji, 2002



# Cost Dynamics of PVs: 2 Case Studies

<b>country</b>	<b>Japan</b>	<b>USA</b>
<b>author</b>	<b>C. Watanabe, 2002</b>	<b>G. Nemet, 2004</b>
<b>period</b>	<b>1976-1999</b>	<b>1975-2001</b>
<b>Cost decline factor</b>	<b>27</b>	<b>20</b>
<b>approach</b>	<b>Top-down, econometric</b>	<b>Bottom-up, engineering economics</b>
<b>Main explanatory variable</b>	<b>Knowledge stock (cum R&amp;D + depreciation + firm spillovers)</b>	<b>1. Innovation: Module efficiency, poly-crystals,...; 2. Economies of scale, 3. “Learning”</b>
<b>Other variables</b>	<b>Economies of scale, energy prices</b>	<b>Si-costs and use, wafer size and yield</b>
<b>Missing</b>	<b>International &amp; inter- industry spillovers, Demand response</b>	<b>Intra-, inter-industry, and international spillovers, Demand response</b>
<b>Role of institutions</b>	<b>Public&amp;private R&amp;D funding, intra-firm spillovers</b>	<b>n.a.</b>

# US PVs Factors of Cost Declines (in constant \$/W)

Source: G. Nemet, 2004

Factor/period	1975-1979	1980-2001	1975-2001
Module efficiency	- 9.9	- 7.1	- 17.0
Plant size	- 4.3	- 9.2	- 13.5
Si costs	- 5.0	- 2.7	- 7.7
Yield	- 0.4	- 0.5	- 0.9
Si consumption	- 0.4	- 0.6	- 1.0
Wafer size	0	- 0.7	- 0.7
Poly-crystal share	0	- 0.4	- 0.4
Sum	- 20.1	- 21.1	- 41.2
Residual	-28.6	- 0.6	-29.2
Total cost decline	-48.7	-21.7	- 70.4

Innovation (R&D) Economies of Scale Experience Other/total

# Summary

- Technologies have emergent properties that are constructed by “learning” processes
- Good empirical and theoretical understanding of “routine” innovations (e.g. incremental improvements via industrial R&D)
- Need to move beyond proxy drivers and black-box view of technology:  
**Who learns what, when, and how?**
- Need to move beyond pro-innovation bias in the empirical literature
- Technologies of greatest (economic, social, environmental) interest: low probability, extreme events which are difficult to anticipate or to model (scenario approach)