Patterns of technological evolution

SFI complex systems summer school
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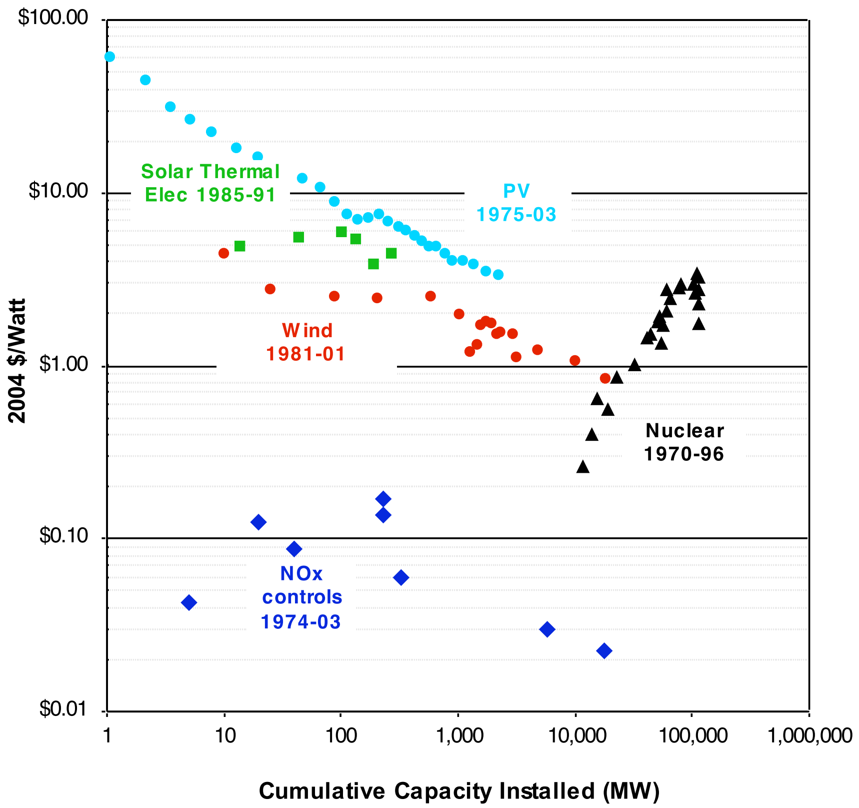
J. Doyne Farmer
Santa Fe Institute
LUISS Guido Carli

Outline

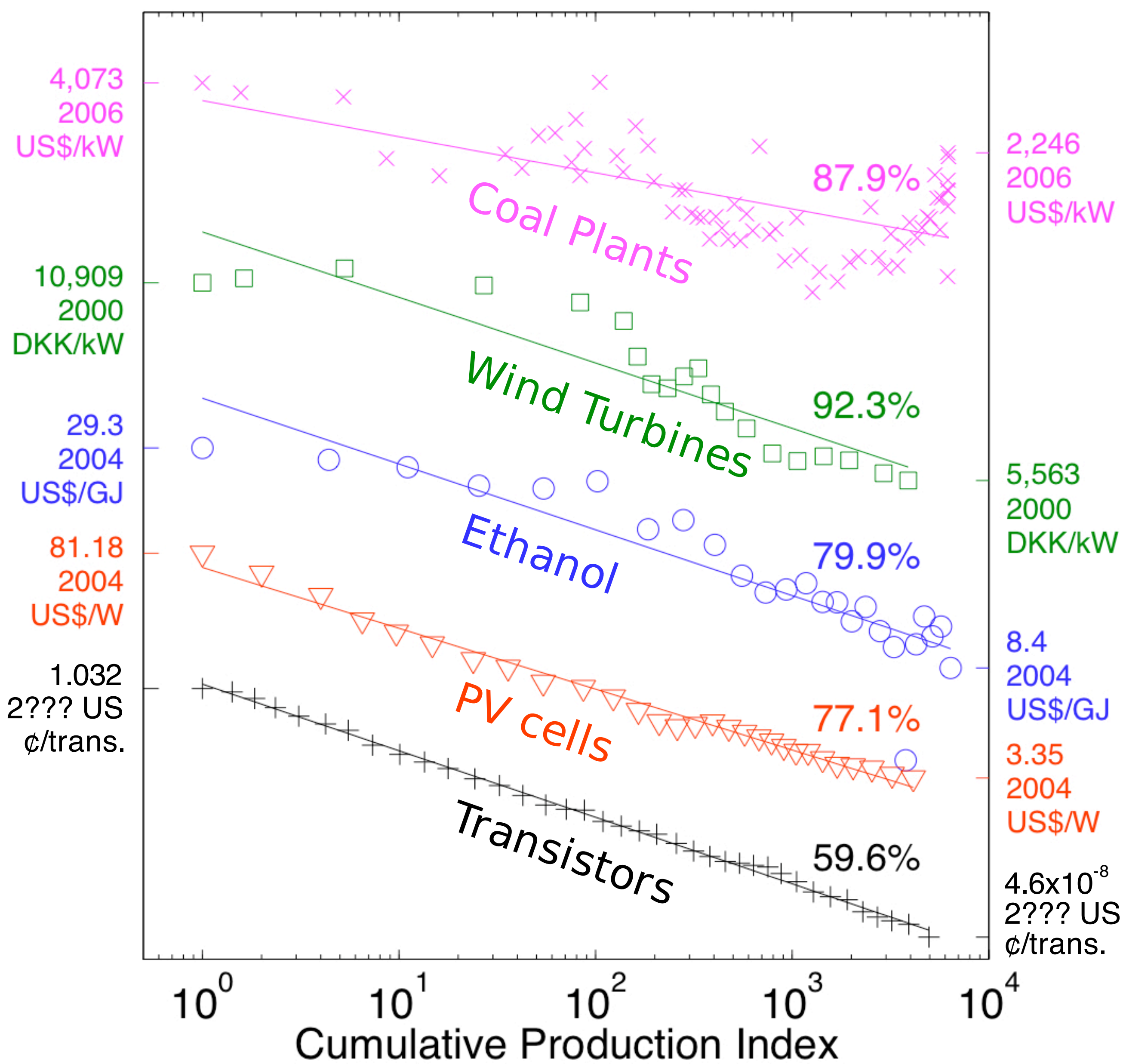
- Are there patterns in technological evolution and improvement?
- Can they be used to forecast technological trajectories?
- What might cause these patterns?

Performance curves

- Worker output in airplane manufacturing (Wright, 1936)
- Cost of a technology across entire industry (BCG, 1968)
- Observed for aggregates of technologies and diverse metrics
- Functional form assumed: $y=ax^{-b}$ and *Progress ratio* $= 2^{-b}$
- Used to predict future costs
- How reliable are projections?
- How to design portfolios?

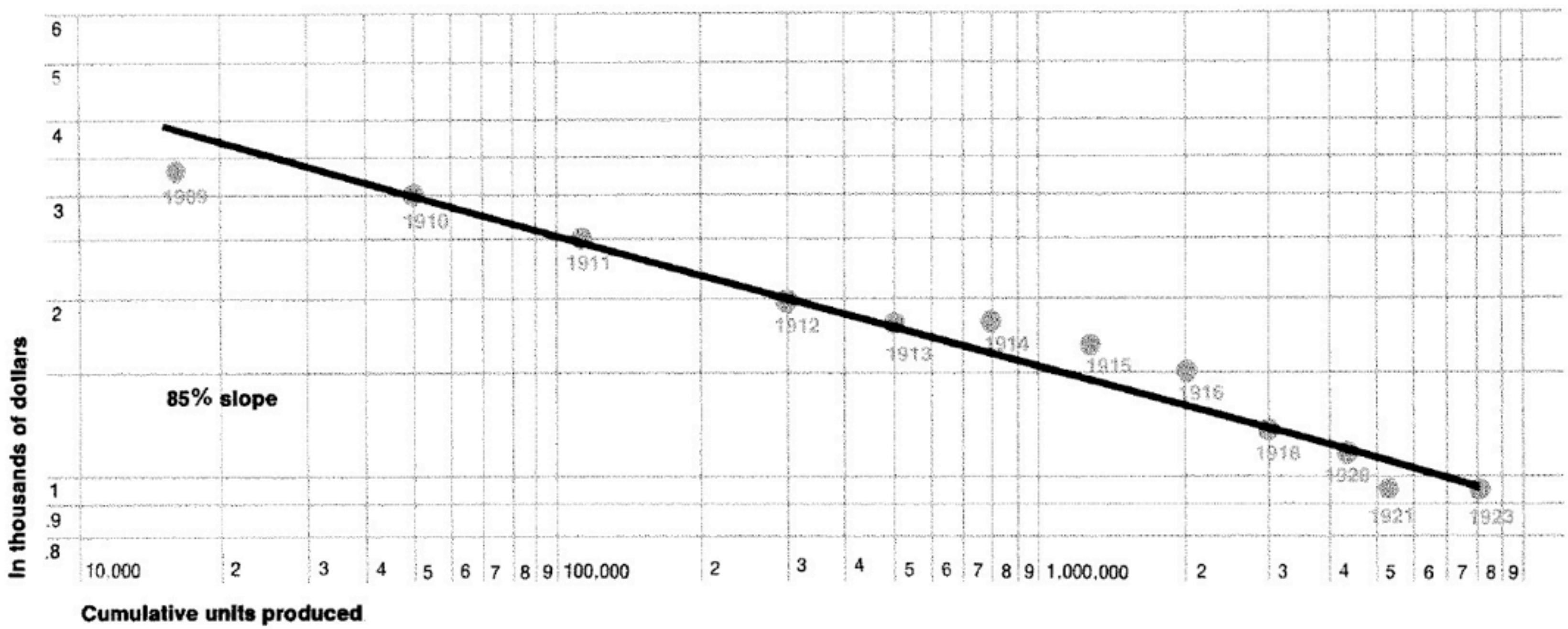


(Nemet, *Energy Policy*, 2007)

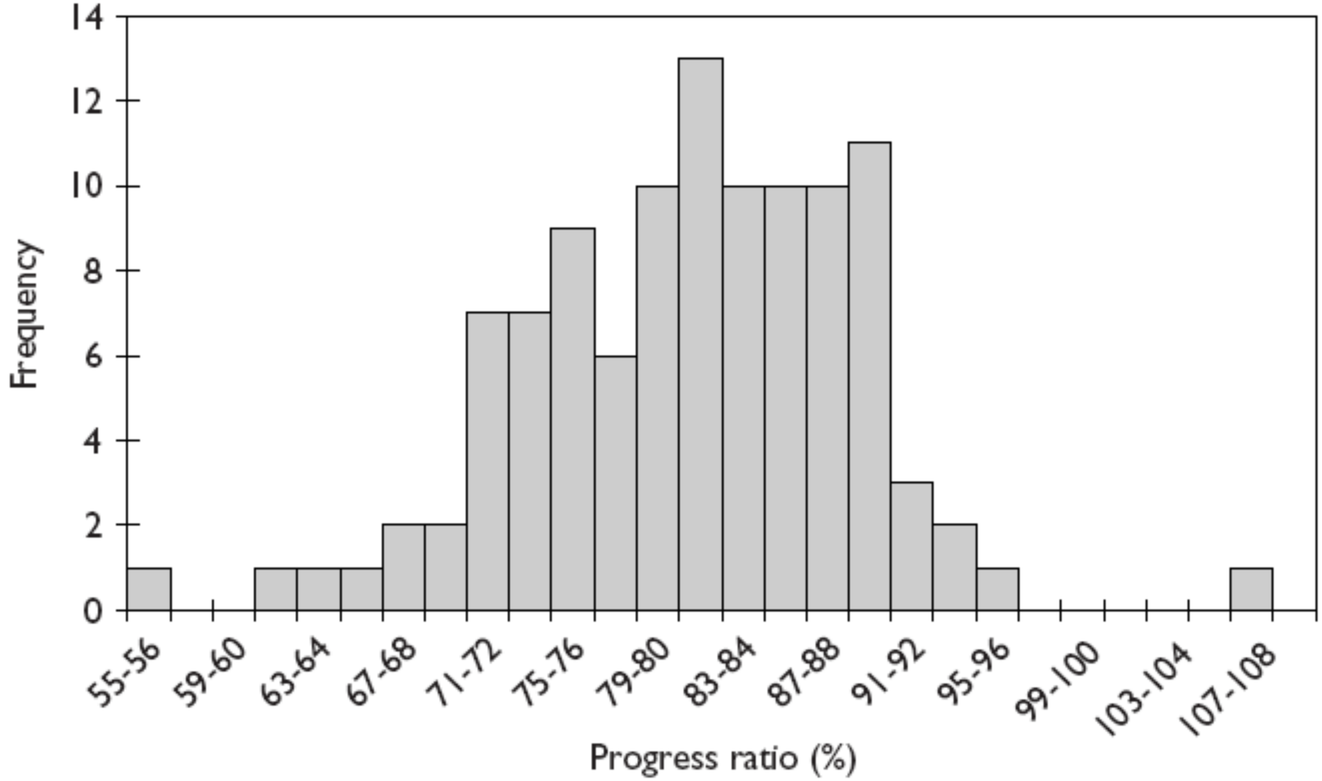


4,073
2006
US$/kW
10,909
2000
DKK/kW
29.3
2004
US$/GJ
81.18
2004
US$/W
1.032
2??? US
¢/trans.
2,246
2006
US$/kW
5,563
2000
DKK/kW
8.4
2004
US$/GJ
3.35
2004
US$/W
4.6x10-8
2??? US
¢/trans.
Coal Plants
87.9%
Wind Turbines
92.3%
Ethanol
79.9%
PV cells
77.1%
Transistors
59.6%
10^0
10^1
10^2
10^3
10^4
Cumulative Production Index

Exhibit I
Price of Model T, 1909-1923 (Average list price in 1958 dollars)



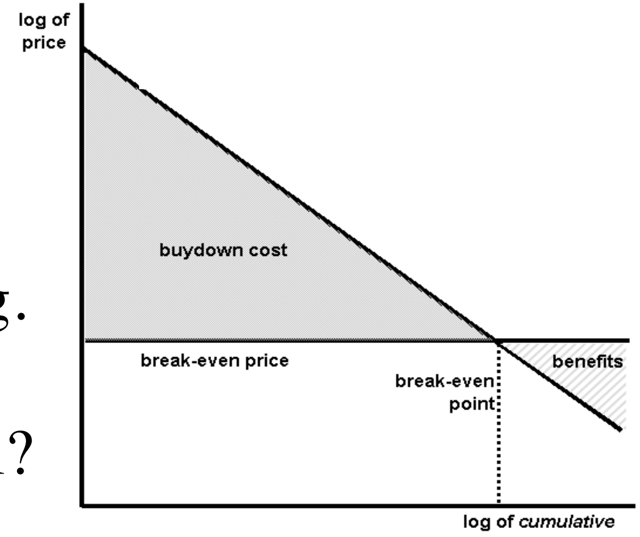
Diversity of performance ratios



Progress ratios 108 cases, 22 field studies, electronics, machine tools, system components for electronic data processing, papermaking, aircraft, steel, apparel, and automobiles (Dutton and Thomas, 1984)

Cross-over sensitively depends on progress ratio

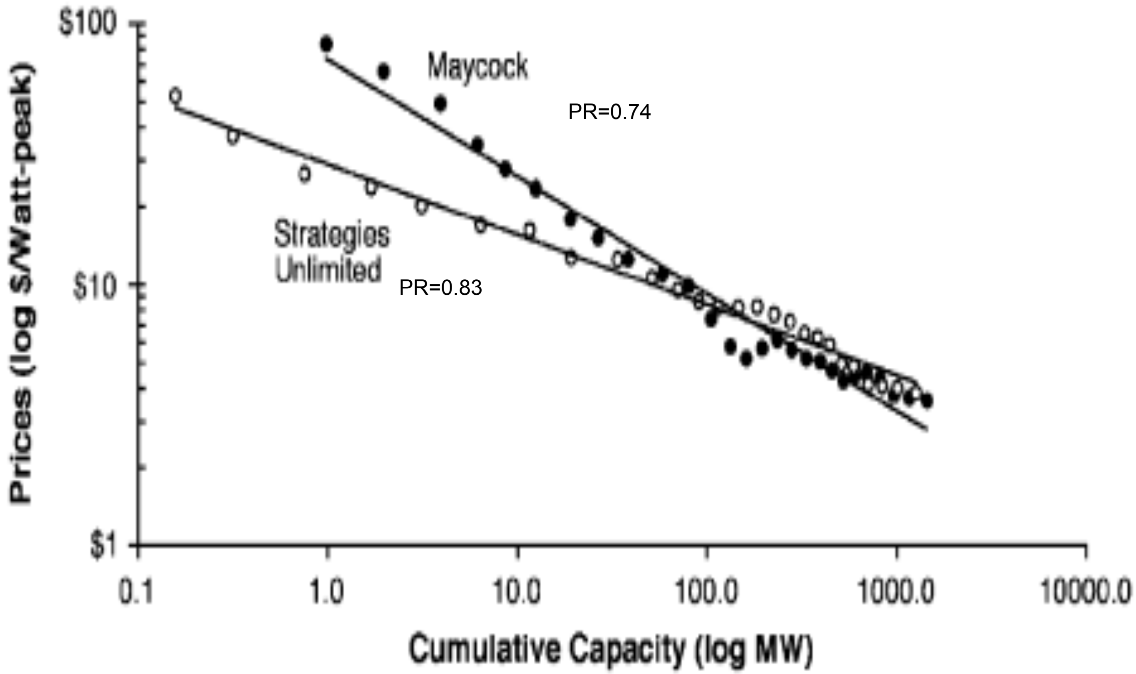
- Under assumptions about progress ratios, can estimate cost of achieving parity between two technologies. E.g. what is capacity increase needed to break even with coal?
- Very sensitive to PR:
    - 0.75 => 30B
    - 0.8 => $60B
    - 0.85 => $300B



(Duke, RFF presentation, 2003)

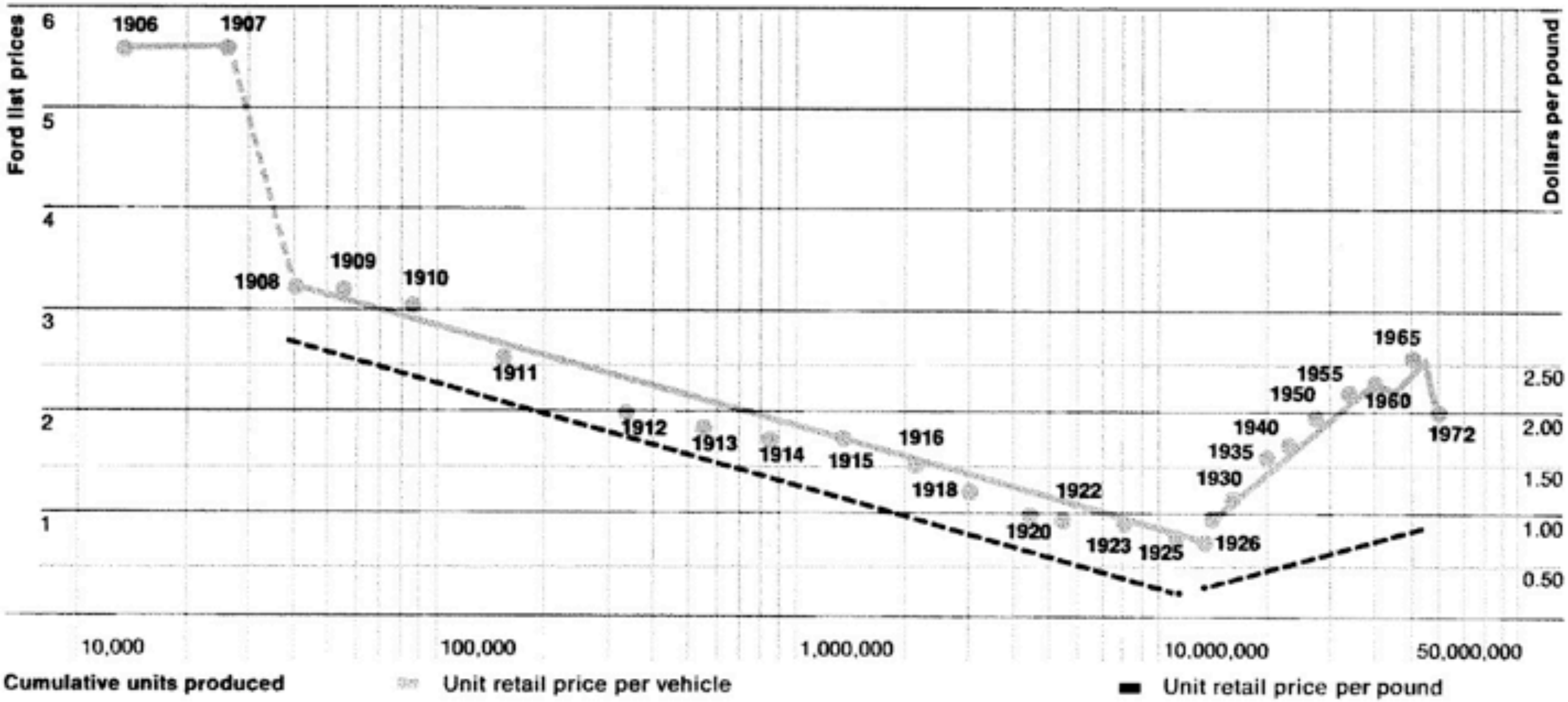
Performance curves -data problems

- Data discrepancies / curve fitting (lack of out-of-sample testing)
- Price data vs. cost data



Photovoltaics performance curves (Nemet, *Energy Policy*, 2006)

Models	ABCNRSK	T	A	Annual model changes
Engines (H.P.)	2 (15 & 50)	1 (20)	1 (24)	2 or more (50 & more)
Wheel bases	2	1	1	2 or more
Weights	Up to 1800	1100-1820	2312 (average)	2335 and up (average)



Is technological progress predictable?

- Joint work with Bela Nagy and Jessika Trancik

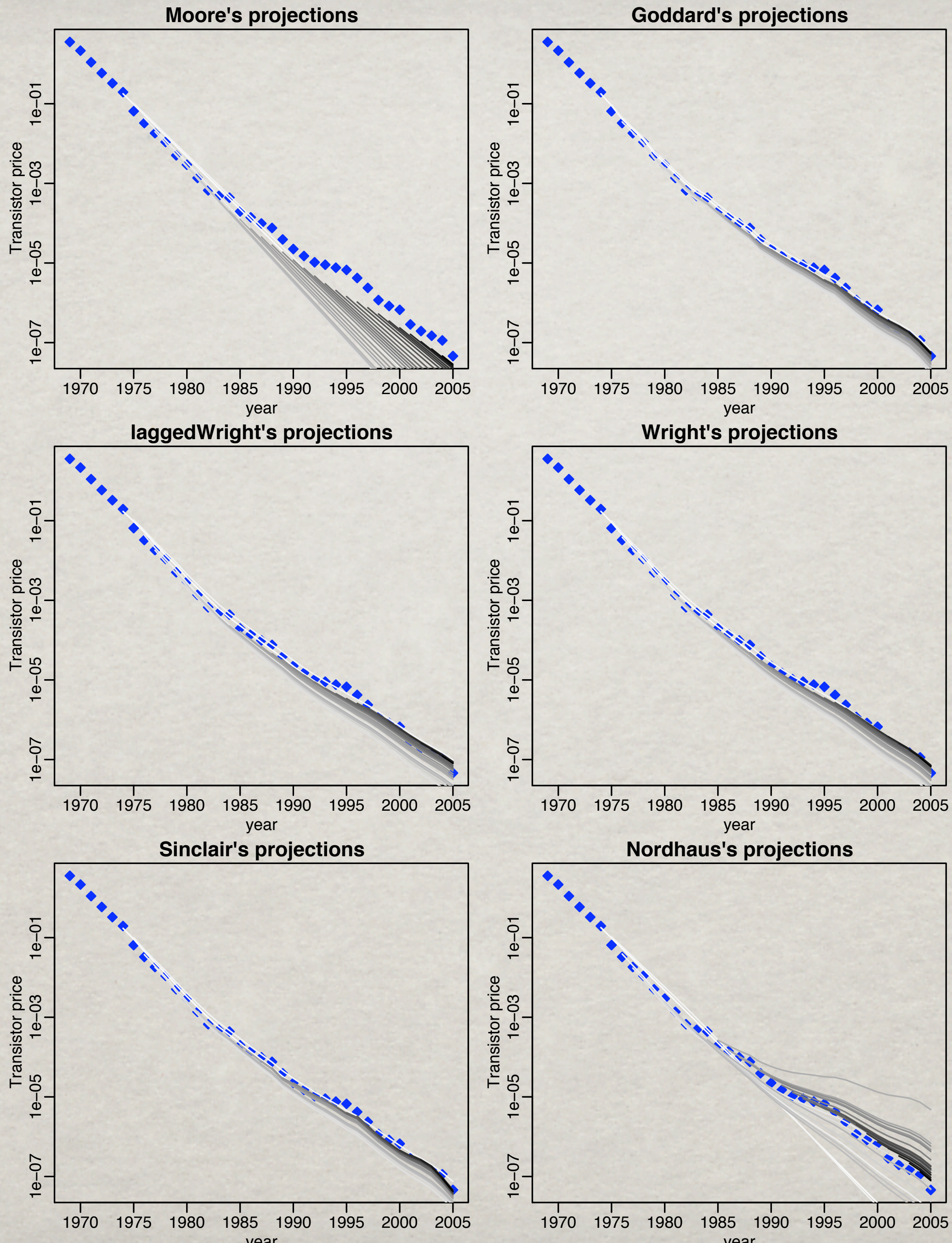
Is technological progress predictable?

$$
\begin{aligned}
y_t &= \text{price in year t} \\
q_t &= \text{number of units produced in year t} \\
e_t &= \text{number of units produced prior to year t} \\
\text{Moore:}\quad \log y_t &= \text{intercept} + \text{slope}\, t + \text{random error} \\
\text{Goddard:}\quad \log y_t &= \text{intercept} + \text{slope}\ \log q_t + \text{random error} \\
\text{Wright:}\quad \log y_t &= \text{intercept} + \text{slope}\ \log(e_t + q_t) + \text{random error} \\
\text{Sinclair:}\quad \log y_t &= \text{intercept} + \text{slope}_1\ \log e_t + \text{slope}_2\ \log q_t + \text{random erro} \\
\text{Nordhaus:}\quad \log y_t &= \text{intercept} + \text{slope}_1\ t + \text{slope}_2\ \log(e_t + q_t) + \text{random err}
\end{aligned}
$$

- Double exponentials

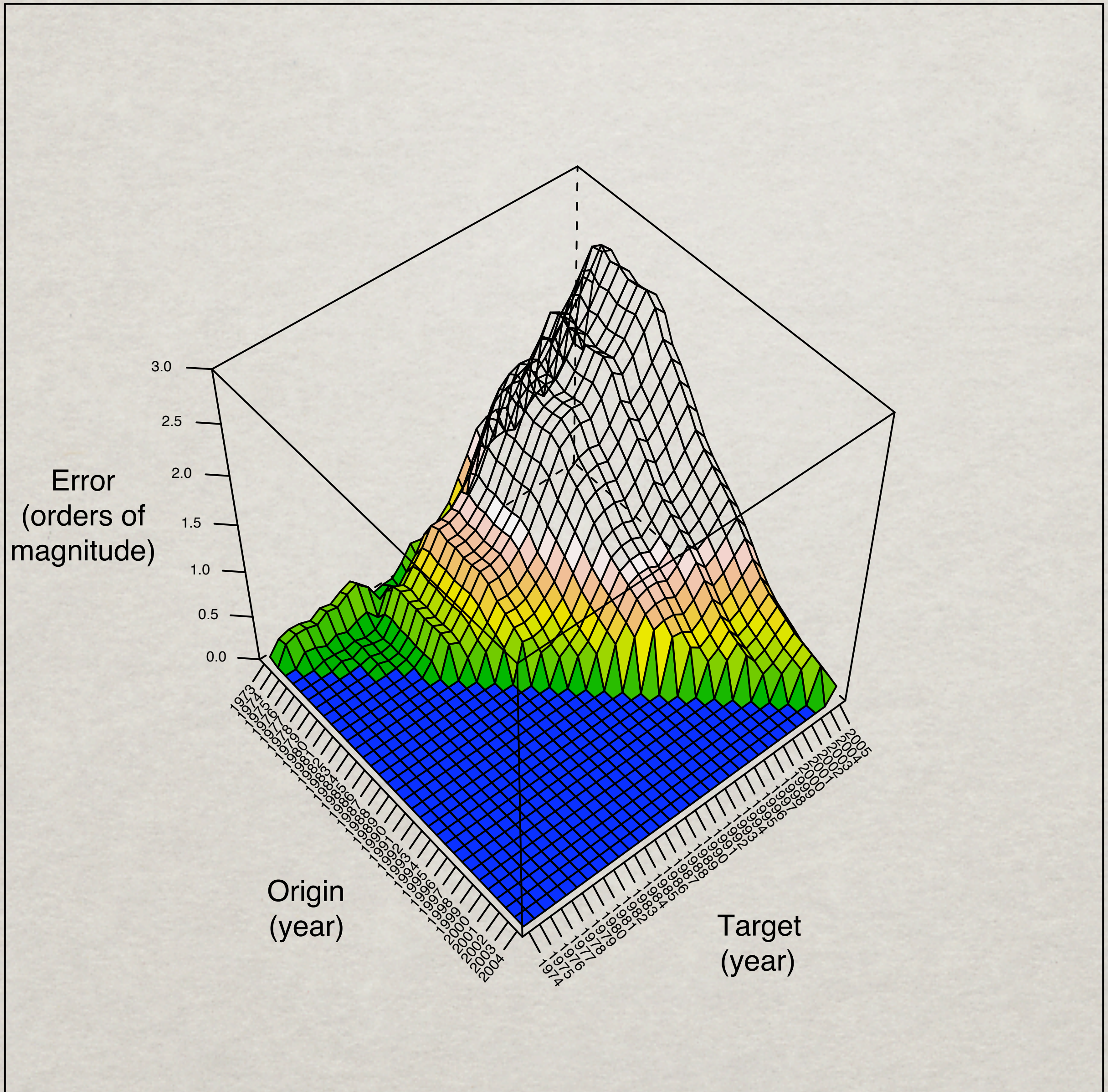
$$
\begin{aligned}
x(t) &= \exp(at) \\
y(t) &= \exp(-bt) \\
y(x) &= x^{-b/a}
\end{aligned}
$$

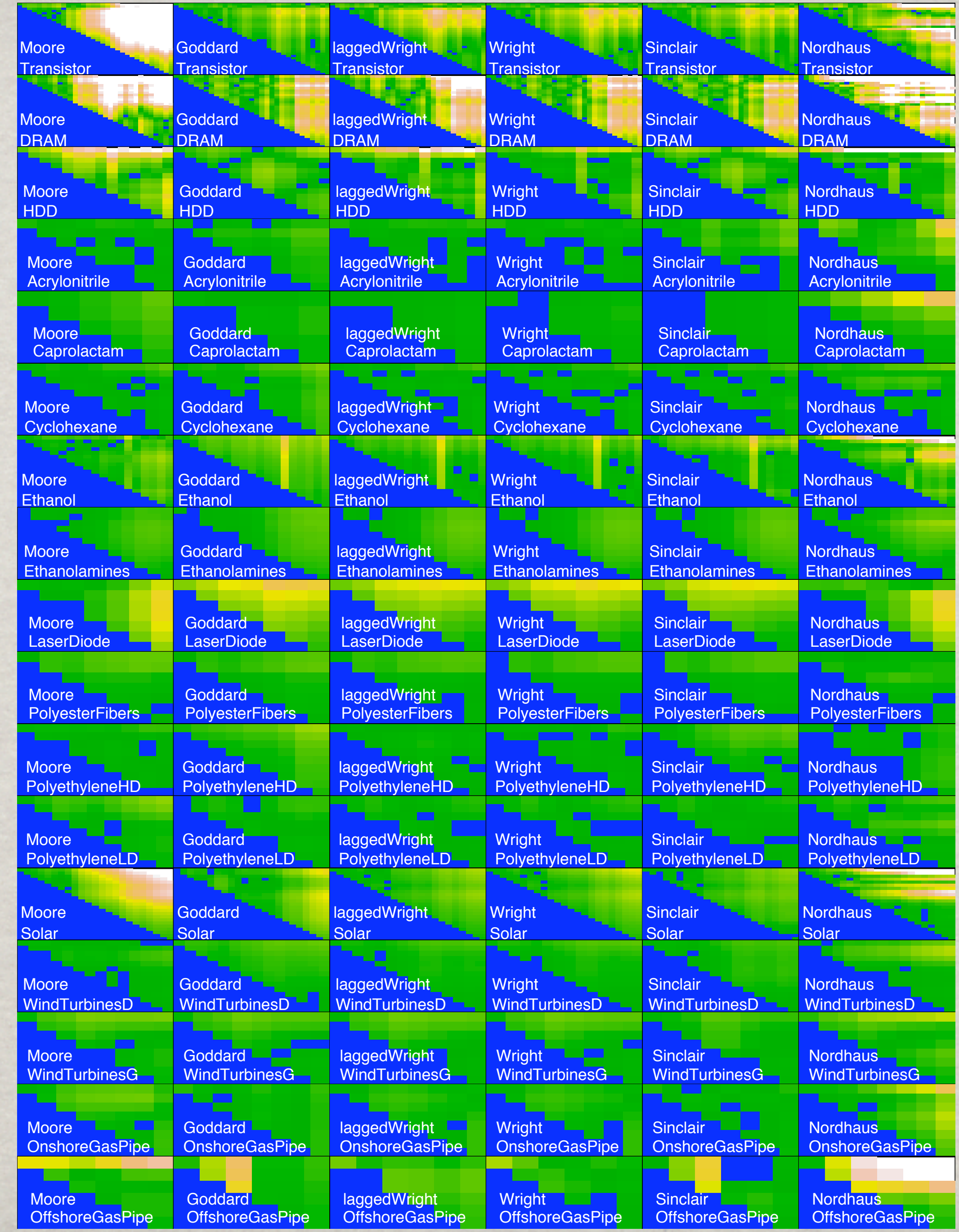
-



Moore's projections
Goddard's projections
laggedWright's projections
Wright's projections
Sinclair's projections
Nordhaus's projections
Transistor price
1e−01
1e−03
1e−05
1e−07
1970
1975
1980
1985
1990
1995
2000
2005
year

Moore's error mountain




Moore Transistor
Goddard Transistor
laggedWright Transistor
Wright Transistor
Sinclair Transistor
Nordhaus Transistor
Moore DRAM
Goddard DRAM
laggedWright DRAM
Wright DRAM
Sinclair DRAM
Nordhaus DRAM
Moore HDD
Goddard HDD
laggedWright HDD
Wright HDD
Sinclair HDD
Nordhaus HDD
Moore Acrylonitrile
Goddard Acrylonitrile
laggedWright Acrylonitrile
Wright Acrylonitrile
Sinclair Acrylonitrile
Nordhaus Acrylonitrile
Moore Caprolactam
Goddard Caprolactam
laggedWright Caprolactam
Wright Caprolactam
Sinclair Caprolactam
Nordhaus Caprolactam
Moore Cyclohexane
Goddard Cyclohexane
laggedWright Cyclohexane
Wright Cyclohexane
Sinclair Cyclohexane
Nordhaus Cyclohexane
Moore Ethanol
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Sinclair Ethanol
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Moore Ethanolamines
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Sinclair Ethanolamines
Nordhaus Ethanolamines
Moore LaserDiode
Goddard LaserDiode
laggedWright LaserDiode
Wright LaserDiode
Sinclair LaserDiode
Nordhaus LaserDiode
Moore PolyesterFibers
Goddard PolyesterFibers
laggedWright PolyesterFibers
Wright PolyesterFibers
Sinclair PolyesterFibers
Nordhaus PolyesterFibers
Moore PolyethyleneHD
Goddard PolyethyleneHD
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Sinclair PolyethyleneHD
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Moore PolyethyleneLD
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Sinclair PolyethyleneLD
Nordhaus PolyethyleneLD
Moore Solar
Goddard Solar
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Wright Solar
Sinclair Solar
Nordhaus Solar
Moore WindTurbinesD
Goddard WindTurbinesD
laggedWright WindTurbinesD
Wright WindTurbinesD
Sinclair WindTurbinesD
Nordhaus WindTurbinesD
Moore WindTurbinesG
Goddard WindTurbinesG
laggedWright WindTurbinesG
Wright WindTurbinesG
Sinclair WindTurbinesG
Nordhaus WindTurbinesG
Moore OnshoreGasPipe
Goddard OnshoreGasPipe
laggedWright OnshoreGasPipe
Wright OnshoreGasPipe
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Moore OffshoreGasPipe
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Error analysis

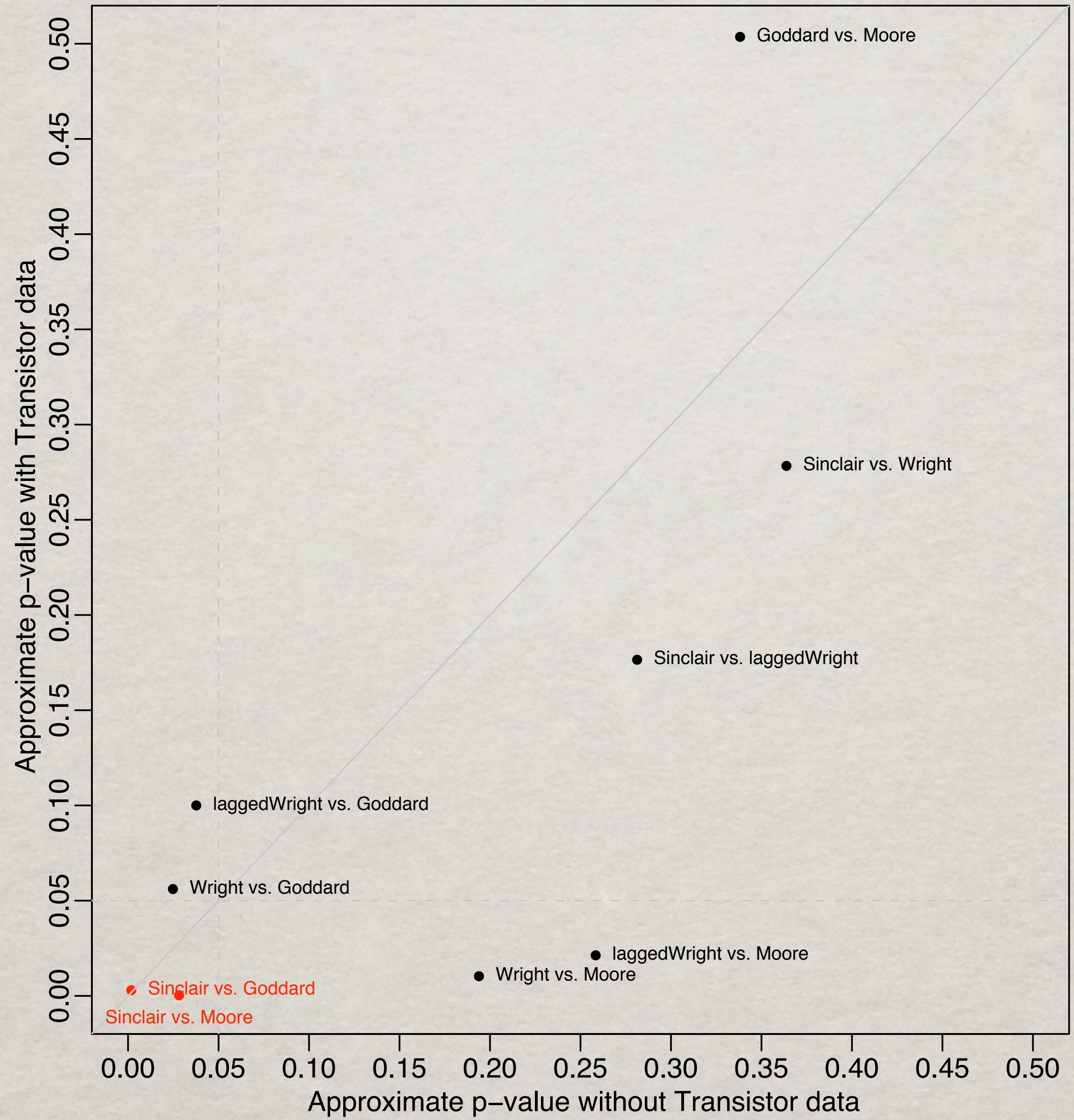
$$r_{fdij} = \left| \log y_j^{(d)} - \log \hat{y}_j^{(f,d,i)} \right|^{0.5},$$

$$r_{fdij} = \alpha_f + \beta(j-i) + a_d + b_d(j-i) + \varepsilon_{fdij}$$

Fixed effect parameters	*Estimates with Transistor data*	*Estimates without Transistor*
α_{Moore}	0.241	0.219
$\alpha_{\mathrm{Goddard}}$	0.230	0.234
$\alpha_{\mathrm{laggedWright}}$	0.205	0.202
α_{Wright}	0.202	0.199
$\alpha_{\mathrm{Sinclair}}$	0.188	0.187
β	0.025	0.026

Table 1: Parameter estimates for the fixed effects with and without the Transistor data set (rounded to three digits).

Testing the differences between the functional form effects



Results

- Sinclair consistently beats Moore and Goddard
- Sinclair is slightly better than Wright, but this is not statistically significant.
- Economic interpretation:
  - Learning: More production implies more demand, implies more effort to improve.
  - Economy of scale may also be important.

Model of learning

- Joint work with James McNerney, Sid Redner, and Jessika Trancik

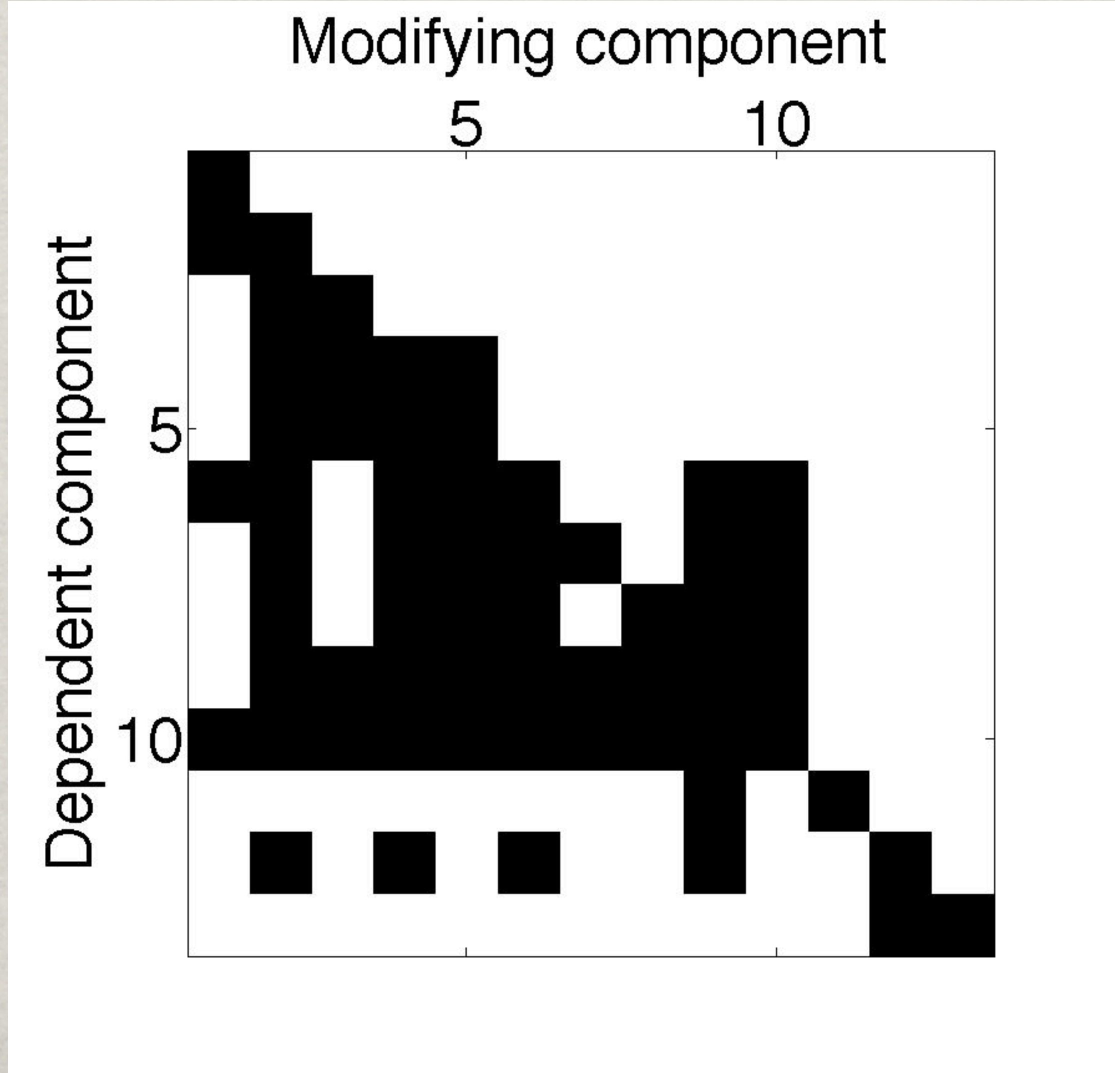
Auerswald et al.

$$\omega = (\omega_1, \ldots, \omega_n)$$

$$\phi(\omega) = \sum_{i=1}^{n} \phi^i(\omega)$$

- Production recipe
- Production costs are additive
- Each operation is affected by d operations.
- Innovation proceeds through a series of trials in which d operations omega_i are altered.

Design structure matrix for automobile brake system



- Pick a component i
- Randomly change its cost and all the costs of the d components that it affects.
- If the total cost decreases, accept the change.

Analysis

1 dependency:

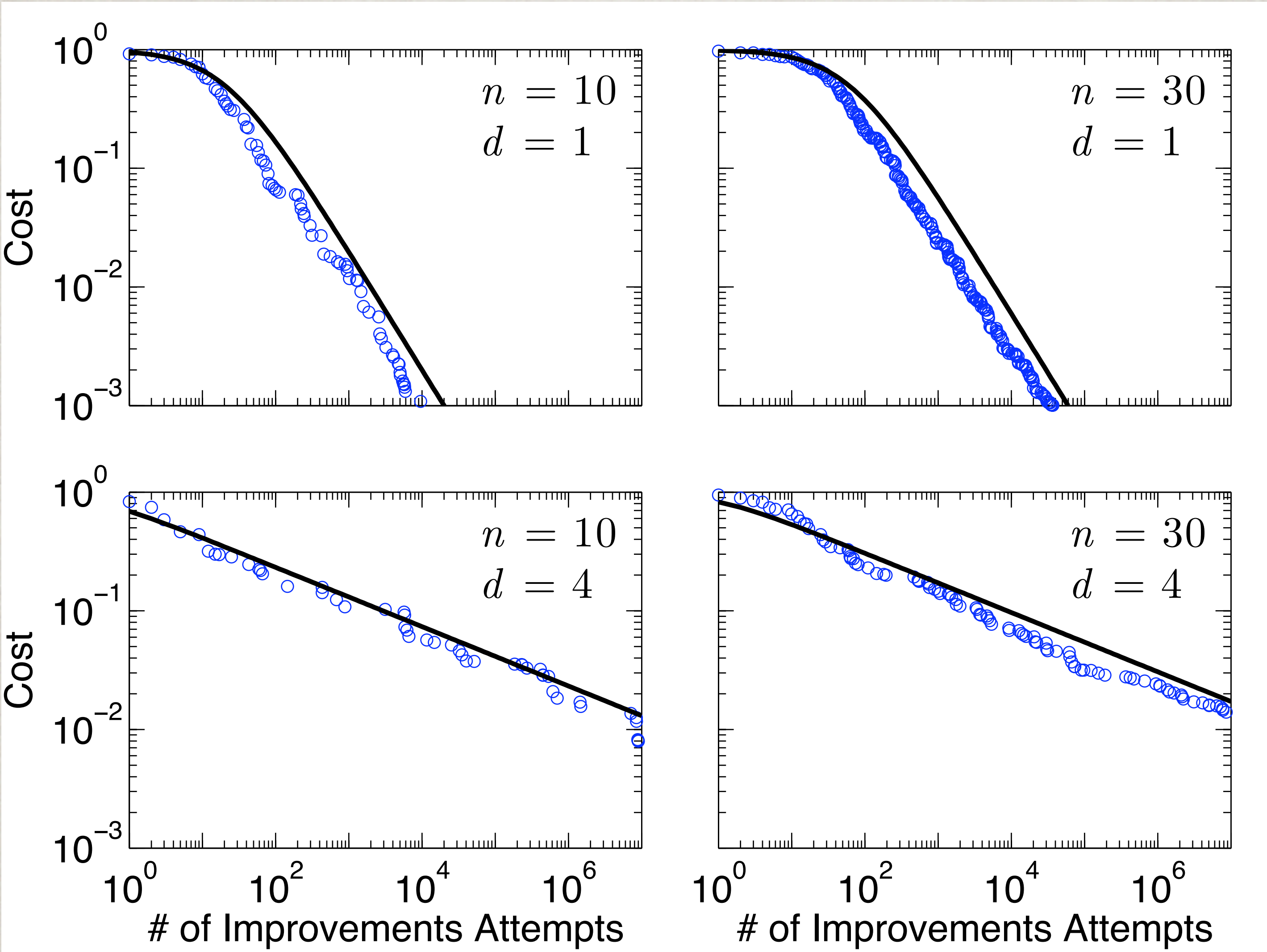
$$\frac{d\phi}{dy} \propto -\phi\left(\frac{\phi}{2}\right) \quad \Rightarrow \quad \phi(y) \sim y^{-1}$$

- Size of reductions decreases exponentially, and it takes exponentially more time to reach reductions

d dependencies:

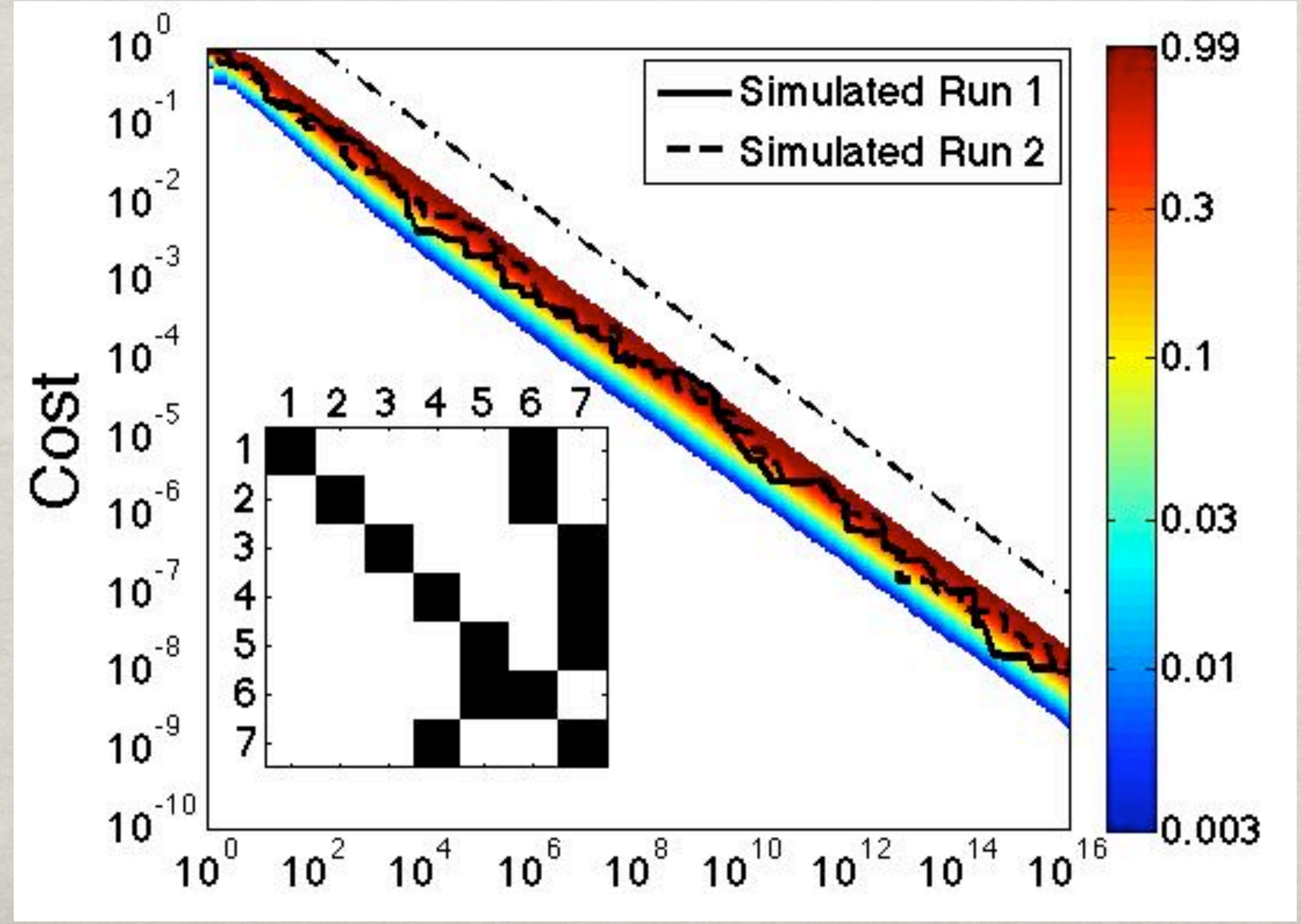
$$\frac{d\phi}{dy} \propto -p(\phi' < \phi)\left(\frac{\phi}{2}\right) \quad \Rightarrow \quad \phi(y) \sim y^{-\frac{1}{d}}$$

$$p(\phi' < \phi) \sim \phi^d$$

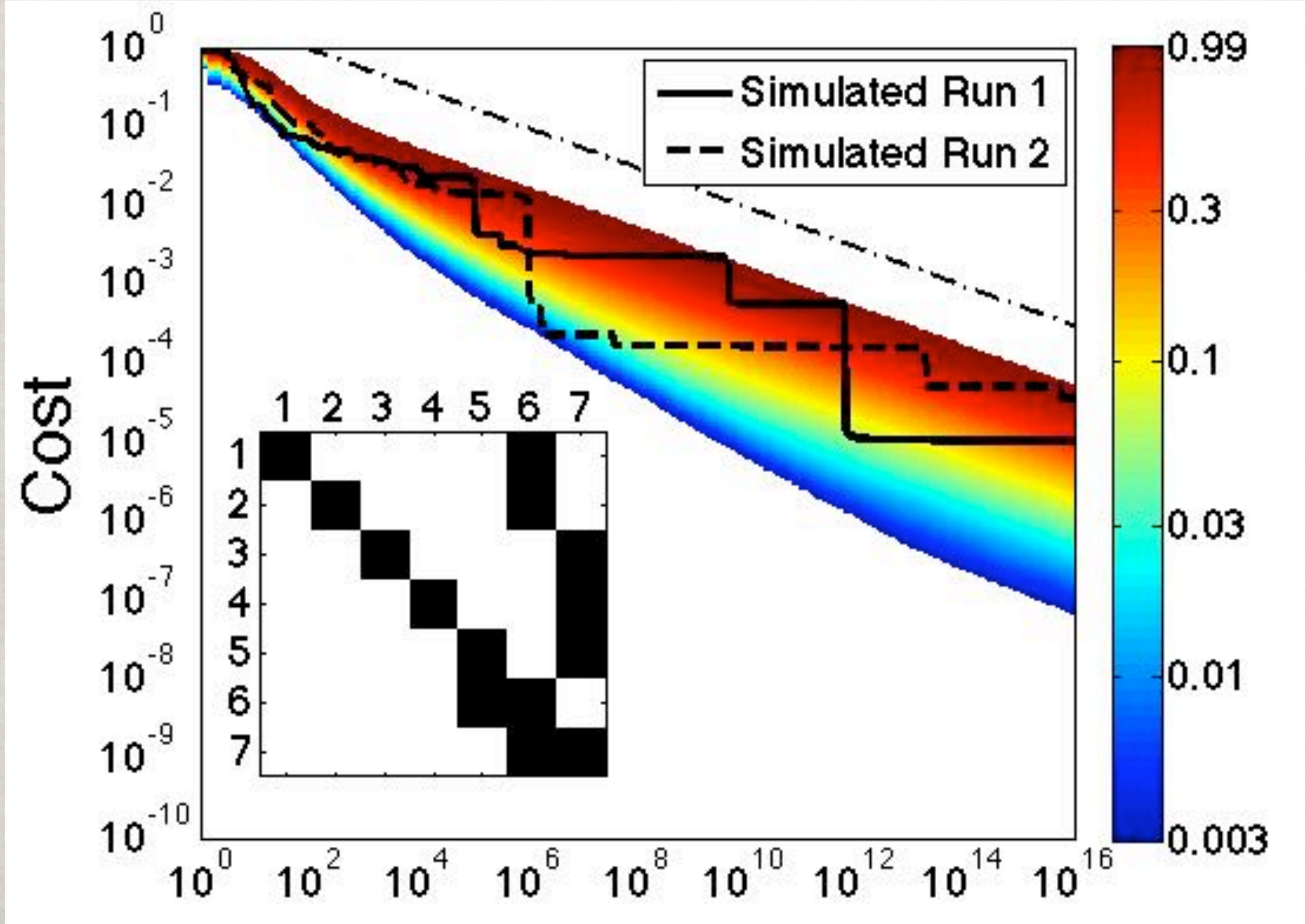


$n = 10$
$d = 1$
$n = 30$
$d = 1$
$n = 10$
$d = 4$
$n = 30$
$d = 4$
Cost
Cost
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^2
10^4
10^6
# of Improvements Attempts
# of Improvements Attempts

Constant out-degree



VARIABLE OUT-DEGREE



Predictions of model

- Rate of improvement depends on interconnectness of components, not on total number.
- Variable interconnectness can cause punctuated equilibria in performance curve.

Overall conclusions

- Improvement of existing technologies is predictable.
- How to deal with new technologies?
- Need better learning models.
- Better economy of scale models.