Engineering determinants of cost trends in energy systems

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MIT LGO Operating Committee

Trancik Lab: Energy Systems

research areas:
- technology assessment
  - dynamics of change and influence of engineering characteristics
- technology design
  - for rapid improvement and scaling

domains:
- electricity (e.g. solar, coal, wind)
- transportation (e.g. fuels, electrification)
- materials design

methods:
- statistical analysis of large datasets
- theory and modeling
  - device physics
  - networks
  - optimization
  - ...

goal: accelerate the discovery and scaling of clean energy technologies.

Outline

technology assessment

- **coal-fired electricity**

technology/system design

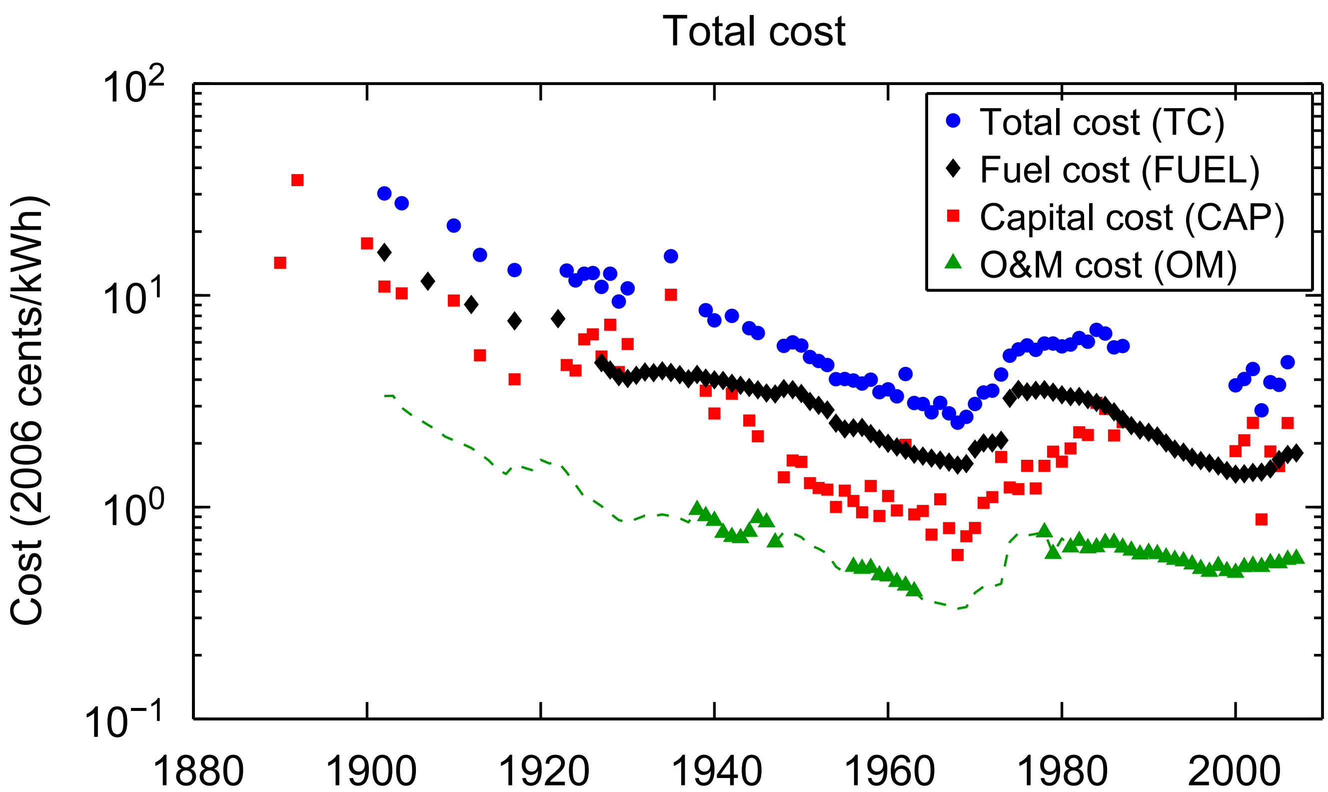
- **role of design complexity in rate of improvement**

Historical costs of coal-fired electricity and implications for the future

- why study coal?
  - basis of comparison for new technologies
- why a historical perspective (rather than make projections)?
  - valuable information on dynamics (as compared to static estimate of future best performance)
- why focus on decomposed costs?
  - cost determines adoption of energy technologies
  - different cost components may evolve differently

McNerney, Farmer, Trancik, *Energy Policy,* 2011

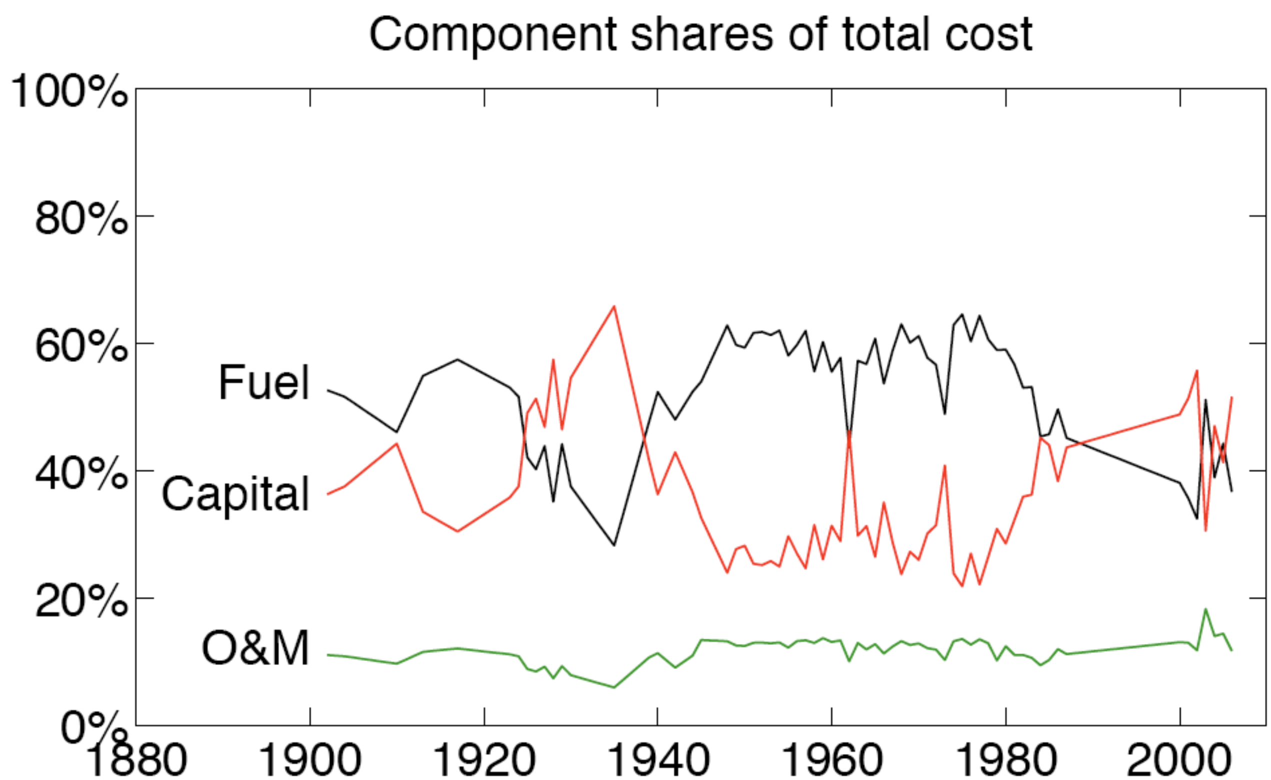
US coal-fired electricity: the last 125 years...



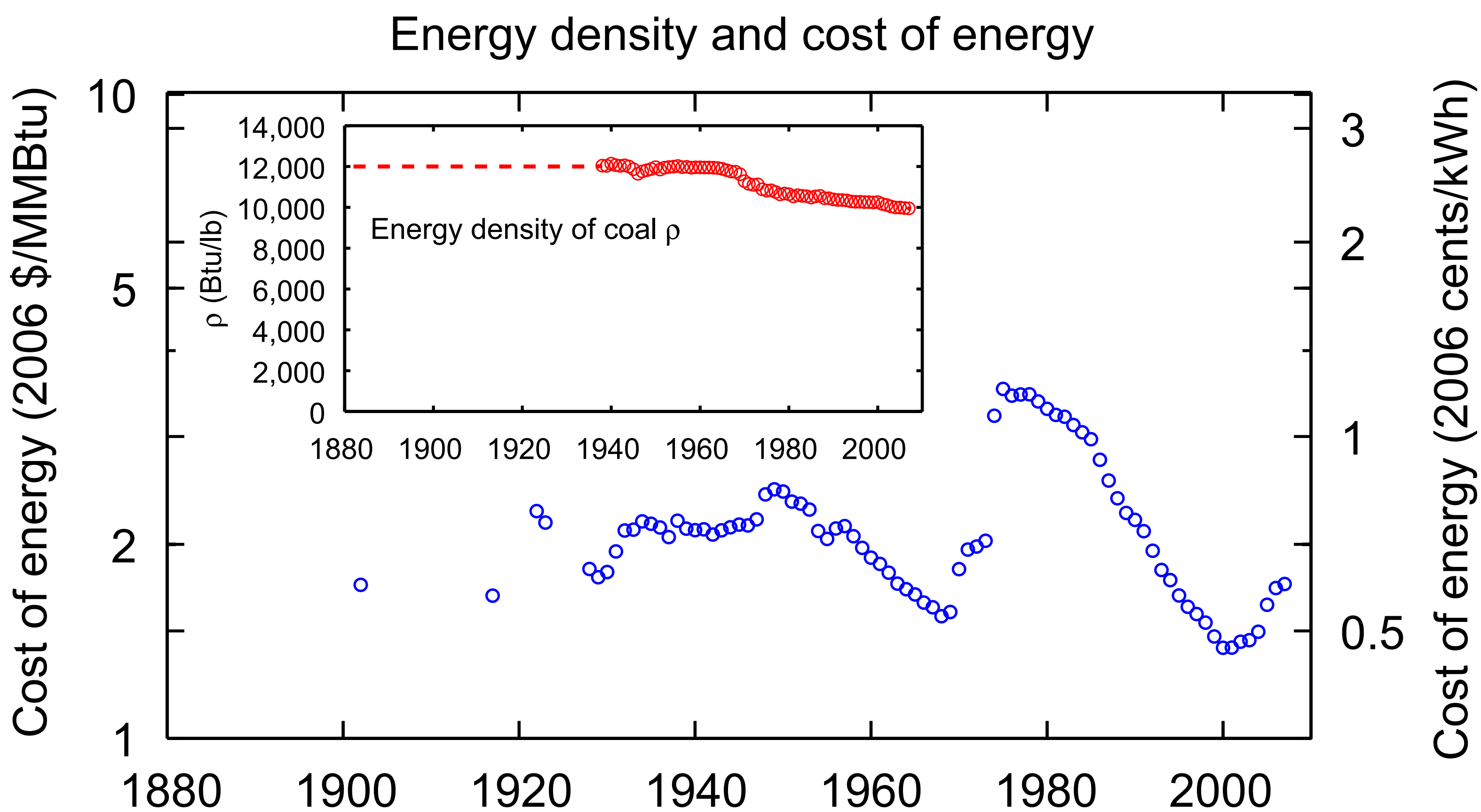
$$\begin{aligned} \mathrm{TC}_t &= \mathrm{OM}_t + \mathrm{FUEL}_t + \mathrm{CAP}_t \\ &= \mathrm{OM}_t + \frac{\mathrm{COAL}_t + \mathrm{TRANS}_t}{\rho_t \eta_t} + \frac{\mathrm{SC}_t \times \mathrm{CRF}(r_t, n)}{\mathrm{CF}_t \times 8760\ \mathrm{h}}. \end{aligned} \tag{1}$$

McNerney, Farmer, Trancik, *Energy Policy*, 2011

Shares of total cost: fuel and capital dominate

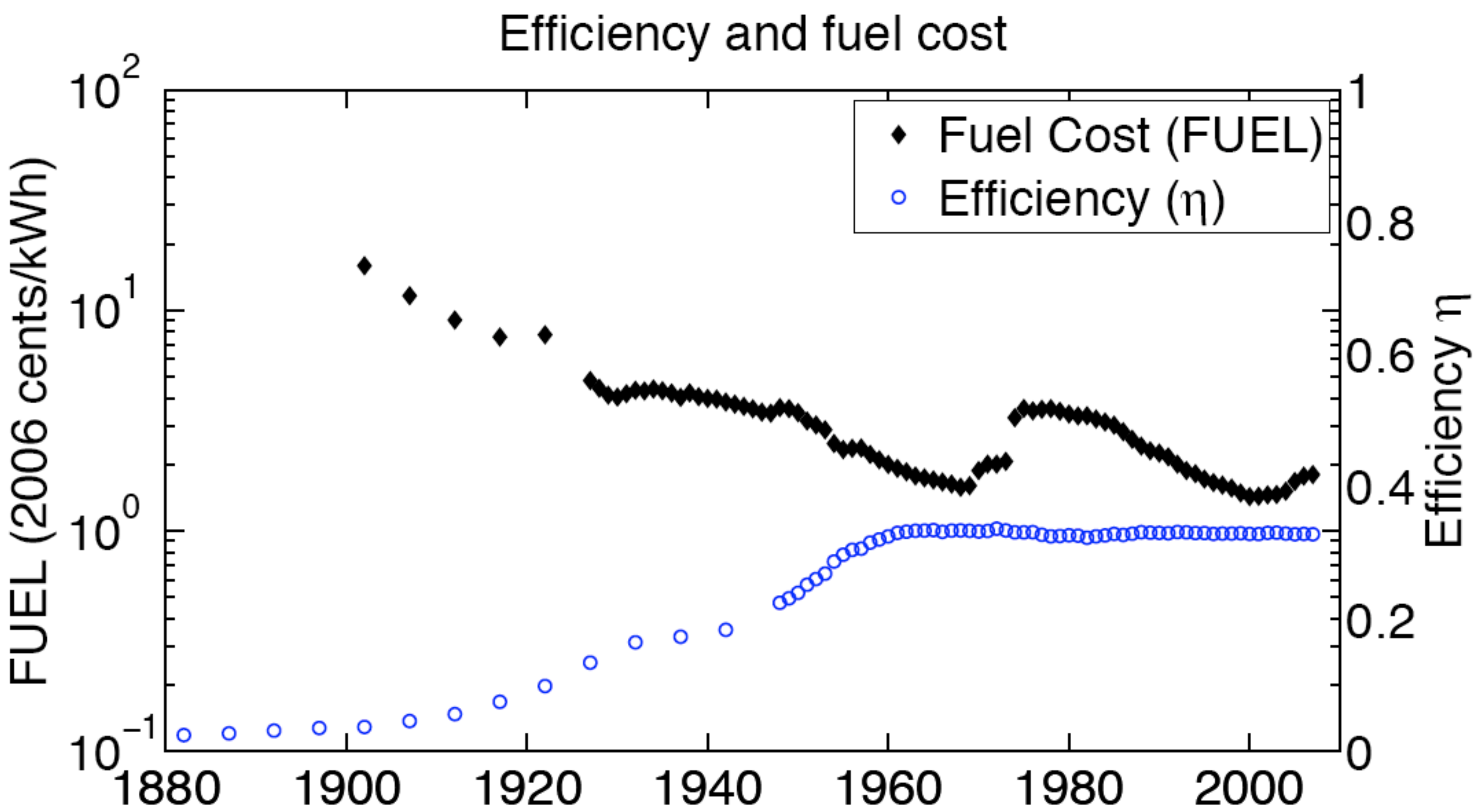


Cost of coal-stored energy



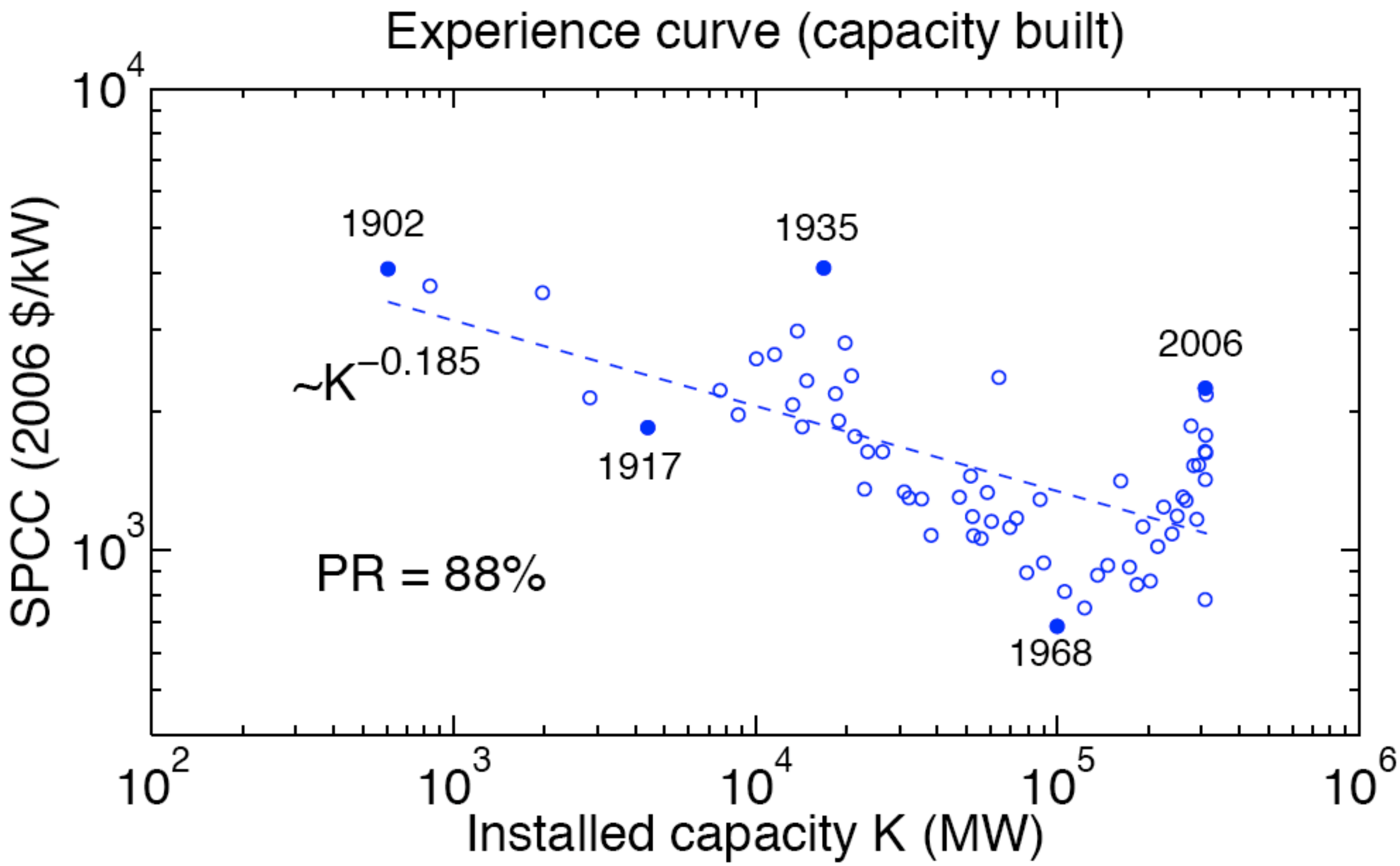
- Coal prices have fluctuated and shown no overall trend up or down
- We cannot rule out a random walk model
- This is consistent with expected behavior of a traded commodity (should not be possible to make easy arbitrage profits by trading it)

Fuel cost



$$
\begin{aligned}
\mathrm{TC}_t &= \mathrm{OM}_t + \mathrm{FUEL}_t + \mathrm{CAP}_t \\
&= \mathrm{OM}_t + \frac{\mathrm{COAL}_t + \mathrm{TRANS}_t}{\rho_t \eta_t} + \frac{\mathrm{SC}_t \times \mathrm{CRF}(r_t, n)}{\mathrm{CF}_t \times 8760\ \mathrm{h}}.
\end{aligned}
\tag{1}
$$

Construction costs



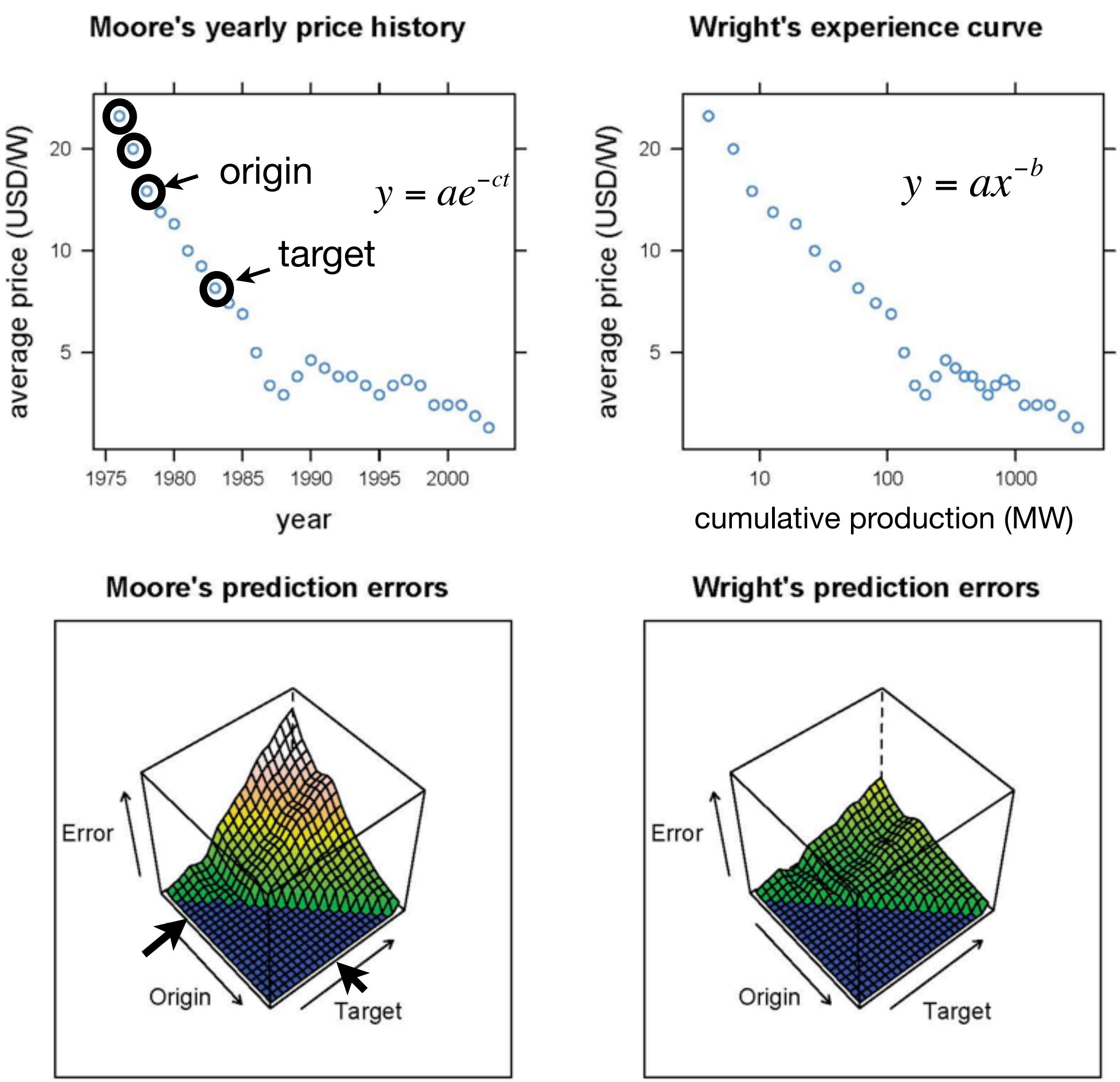
- Plant construction costs follow long term trends (with noise)
- Decreasing until 1970
- Turning point in 1970 (in part due to pollution controls)

Historical costs of coal-fired electricity and implications for the future: conclusions

- fuel cost imposes a fluctuating floor on total cost of coal electricity
  - greater variability in total costs over time
- qualitatively different behavior between coal (and other fossil fuels) and other energy technologies
  - should be considered in integrated assessment models
- technology versus commodity: effect on innovation dynamics

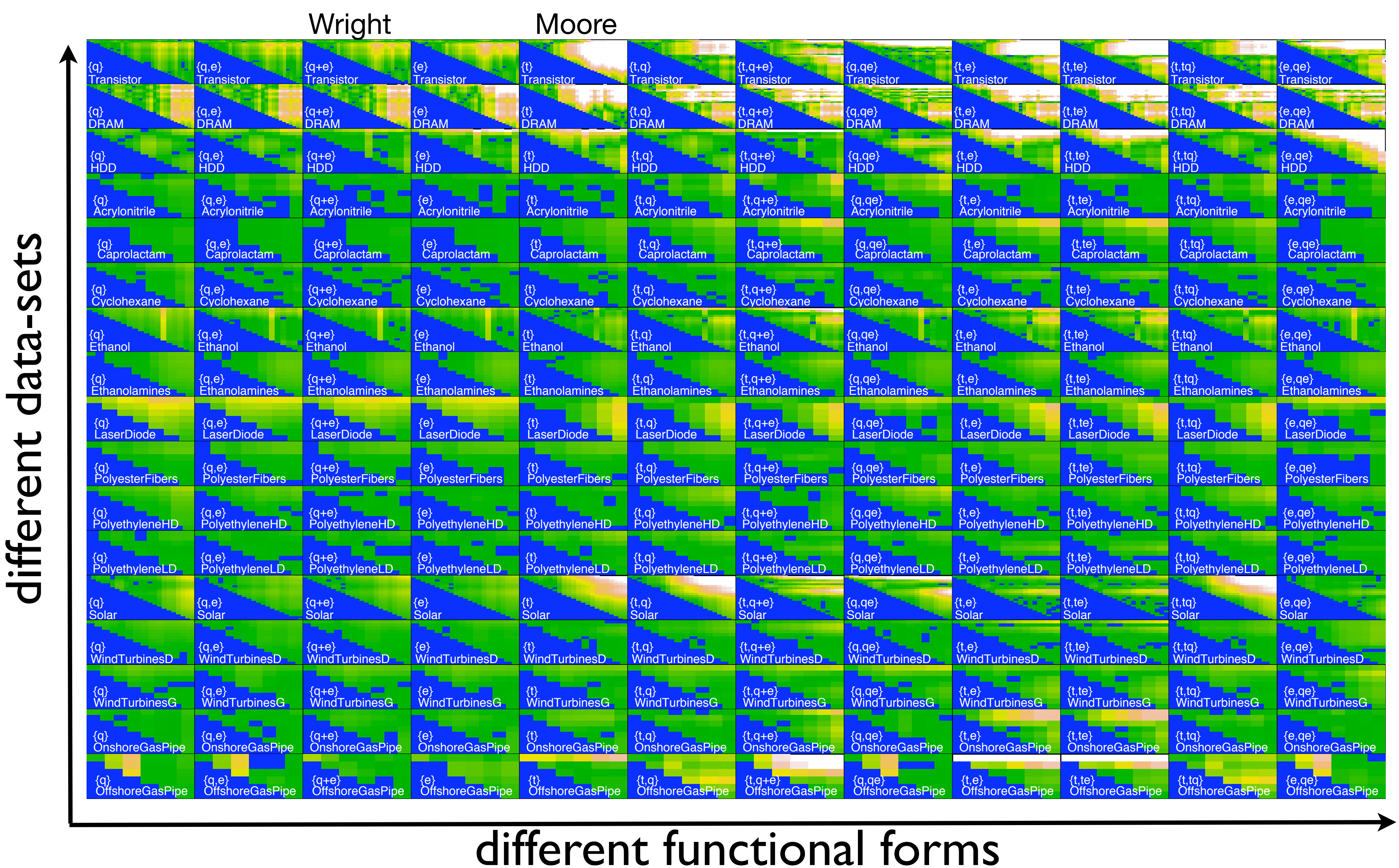
McNerney, Farmer, Trancik, *Energy Policy,* 2011

Comparison of (predictive ability) of functional forms for performance curves



- prediction is uncomfortable but sometimes necessary
  - e.g. cost of mitigating climate change
- many proposals for predicting the future evolution of technologies
- which one performs best? how can we capture uncertainty?
- ~60 datasets (from energy and hardware to beer and chemicals)
- ~15 fcn forms, compared using a mixed effects statistical model...
- **main conclusion:** a tie between Moore and Wright (the two are indistinguishable because of exponential growth)

Nagy, Farmer, Bui, Trancik, in review


Wright
Moore
different data-sets
different functional forms
{q}
{q,e}
{q+e}
{e}
{t}
{t,q}
{t,q+e}
{q,qe}
{t,e}
{t,te}
{t,tq}
{e,qe}
Transistor
DRAM
HDD
Acrylonitrile
Caprolactam
Cyclohexane
Ethanol
Ethanolamines
LaserDiode
PolyesterFibers
PolyethyleneHD
PolyethyleneLD
Solar
WindTurbinesD
WindTurbinesG
OnshoreGasPipe
OffshoreGasPipe

performance curve database: pcdb.santafe.edu

Outline

technology assessment

- **coal-fired electricity**

technology/system design

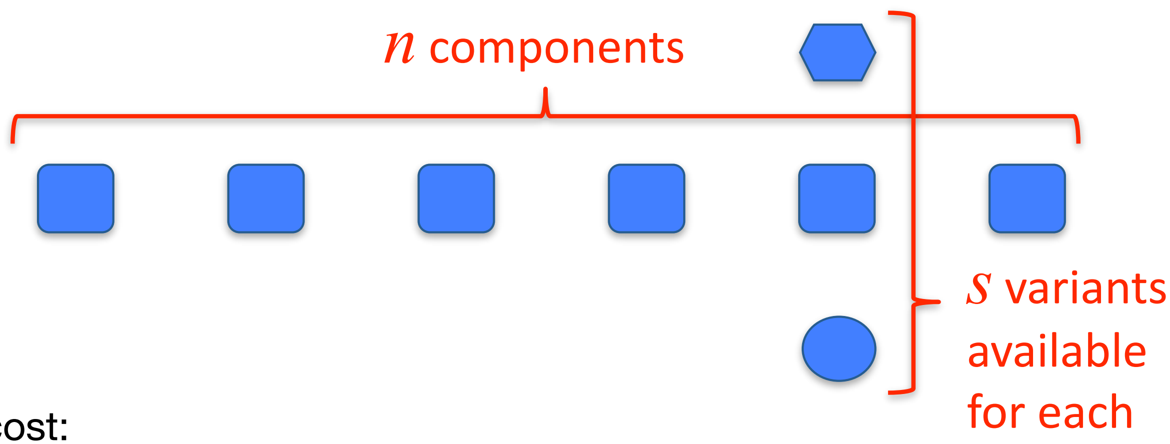
- **role of design complexity in rate of improvement**

Role of design complexity in technology improvement

- simple model of innovation process
- incorporate effect of engineering design characteristics

McNerney, Farmer, Redner, Trancik, *PNAS,* 2011

Simple model of design or production



Total cost:

$$c = c_1 + c_2 + c_3 + c_4 + c_5 + c_6$$

Simplification:

$$s \longrightarrow \infty$$

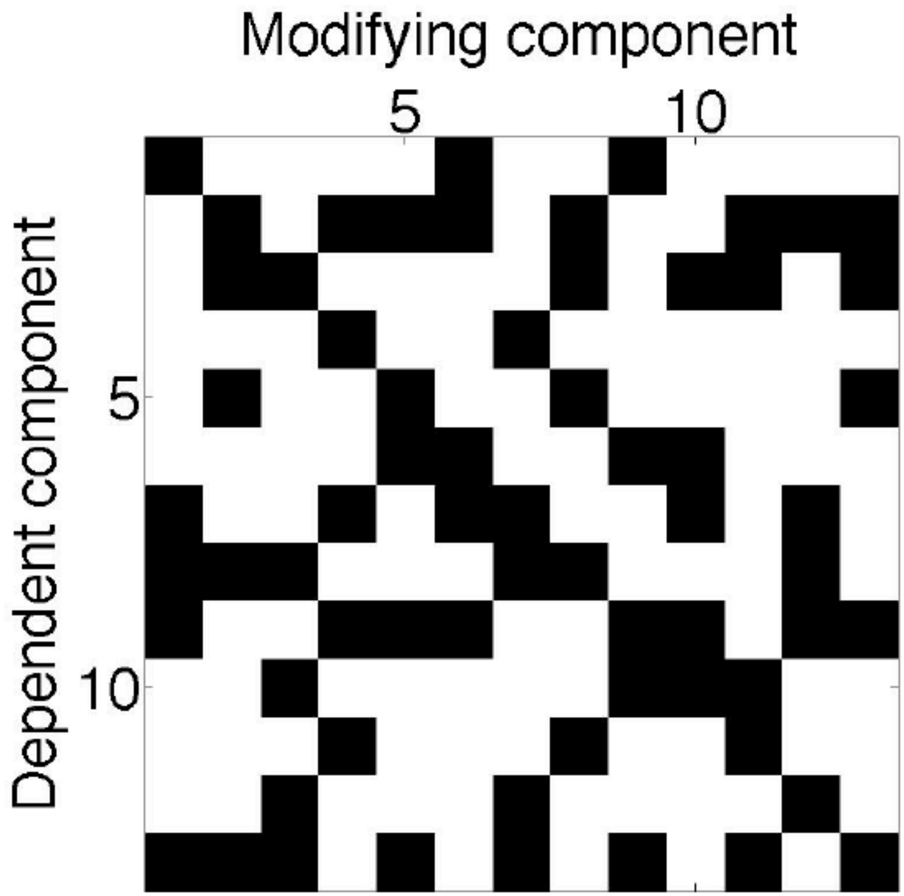
In addition, components depend on one another...

Inspiration from Muth, 1986 and Auerswald et al., 2000

McNerney, Farmer, Redner, Trancik, *PNAS,* 2011

Design structure matrix: fixed out-degree

d dependencies per component



Simulations

1. Pick a random component i.
2. Use the DSM to identify the set of components $\mathscr{A}_i = \{j\}$ whose costs depend on i (the outset of i).
3. Determine a new cost c'_j for each component $j \in \mathscr{A}_i$ from a fixed probability distribution f.
4. If the sum of the new costs, $a'_i = \sum_{j \in \mathscr{A}_i} c'_j$, is less than the current sum, a_i, then each c_j is changed to c'_j. Otherwise, the new cost set is rejected.

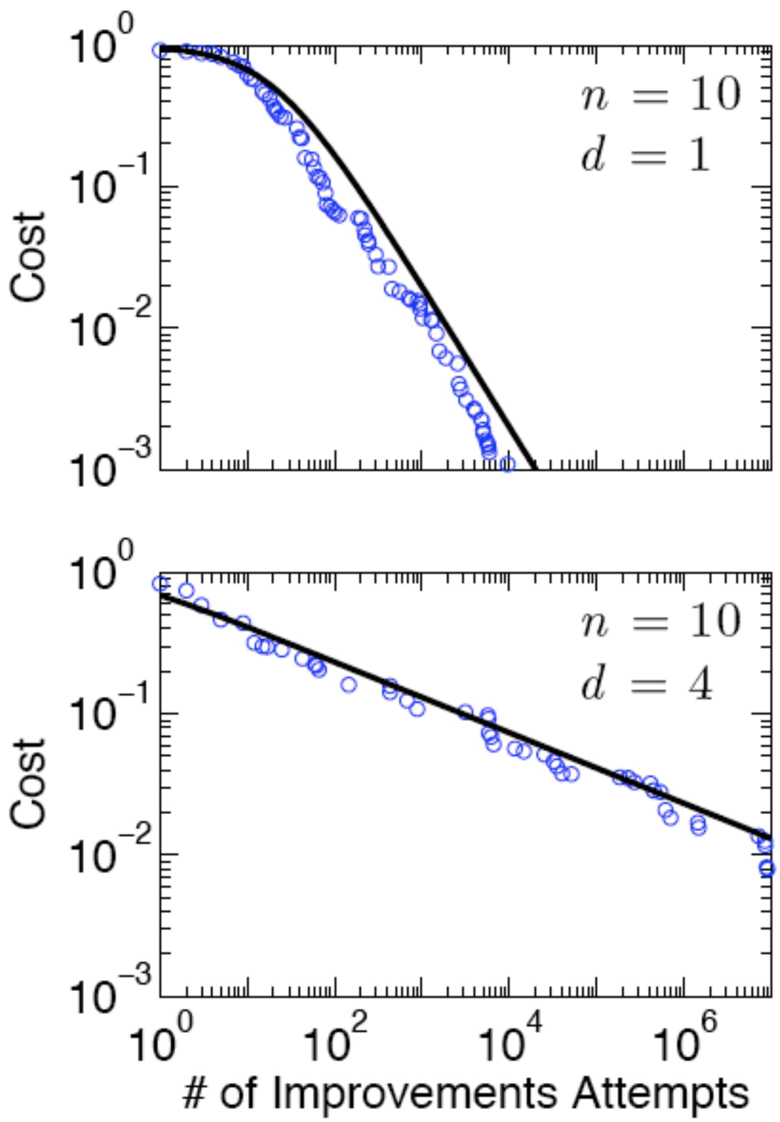
$$c = \boxed{c_1} + c_2 + c_3 + \boxed{c_4} + c_5 + c_6$$

$$c' = \boxed{c_1'} + c_2 + c_3' + \boxed{c_4'} + c_5 + c_6$$

$$c' < c \rightarrow \text{accept changes}$$
$$c' > c \rightarrow \text{keep old recipe}$$

Design complexity and rate of improvement

Increasing complexity

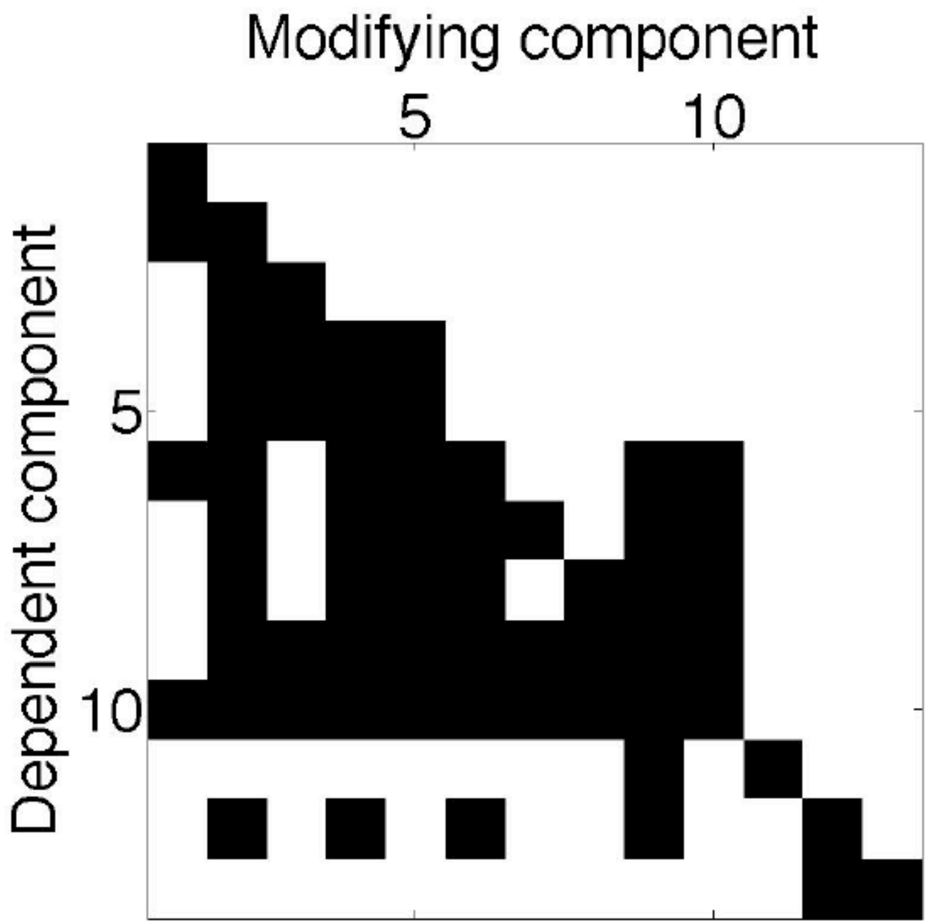


$$c(x) \sim x^{-\alpha}$$

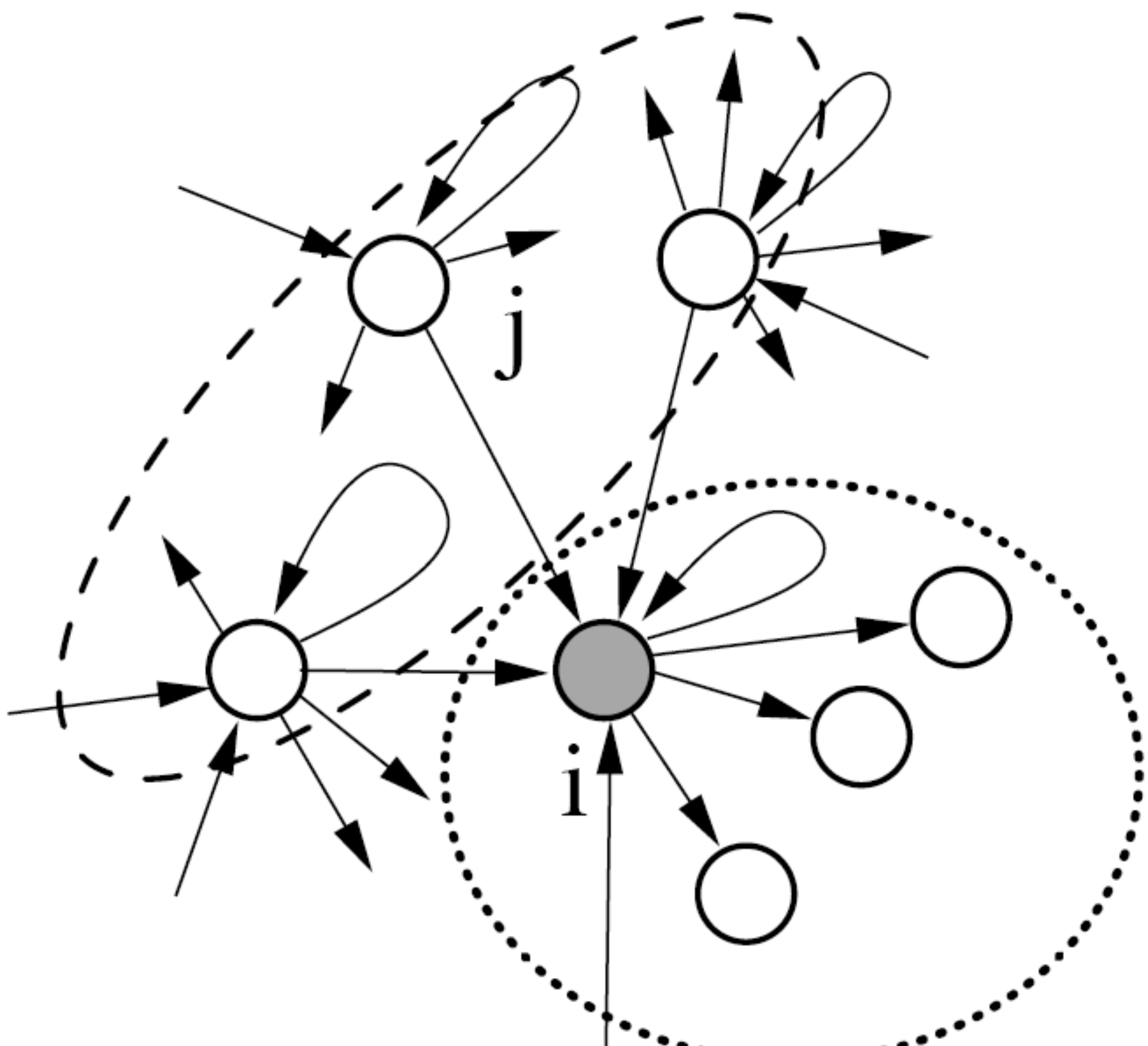
$$\alpha \sim \frac{1}{d}$$

Design structure matrix: variable out-degree

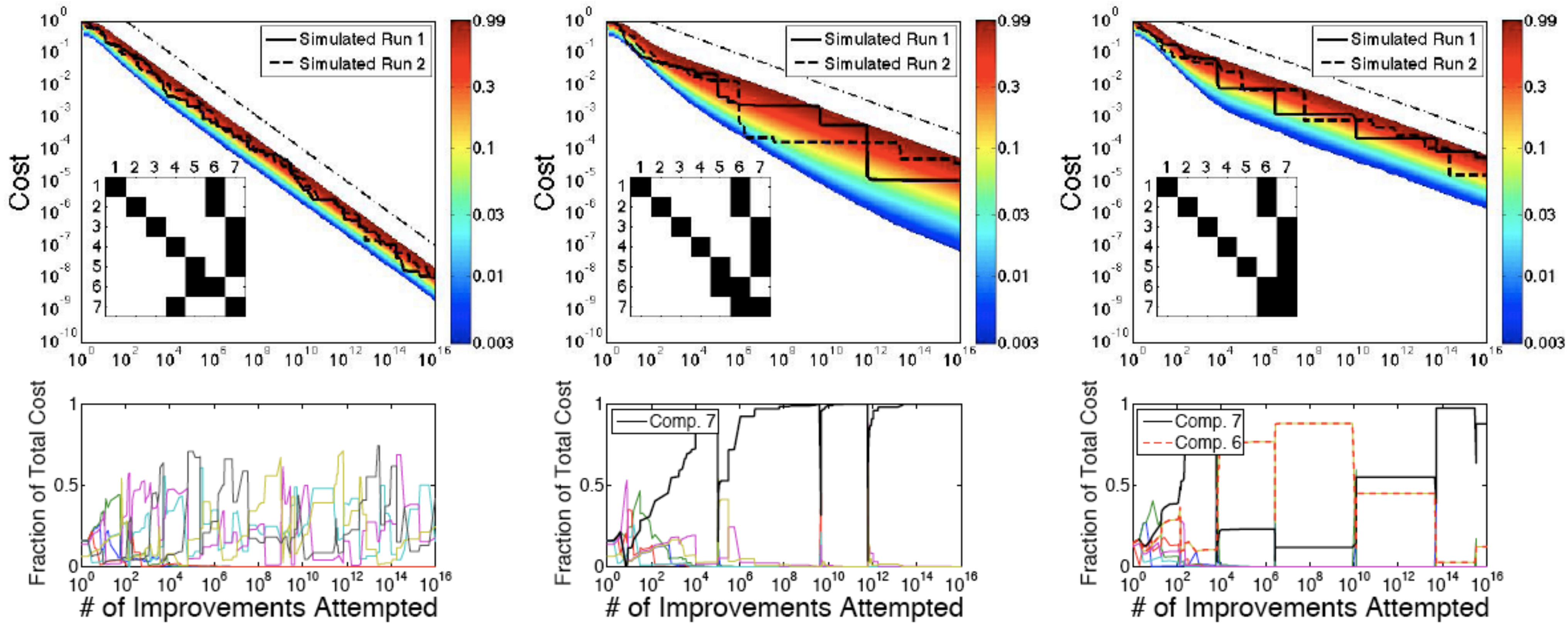
d - average number of dependencies per component



Bottlenecks form - d_i^{min}



Bottlenecks determine rate of improvement



component i	1	2	3	4	5	6	7
out-degree of i	1	1	1	2	2	3	4
$d_i^{\min}$	**1**	**1**	**1**	**2**	**2**	**2**	**2**

component i	1	2	3	4	5	6	7
out-degree of i	1	1	1	1	2	4	4
$d_i^{\min}$	**1**	**1**	**1**	**1**	**2**	**2**	**4**

component i	1	2	3	4	5	6	7
out-degree of i	1	1	1	1	1	4	5
$d_i^{\min}$	**1**	**1**	**1**	**1**	**1**	**4**	**4**

$d^* = \max(d_i^{\min})$

Next step - empirical relationships

$$c(x) \sim x^{-\alpha} \qquad \alpha \sim \frac{1}{d^*}$$

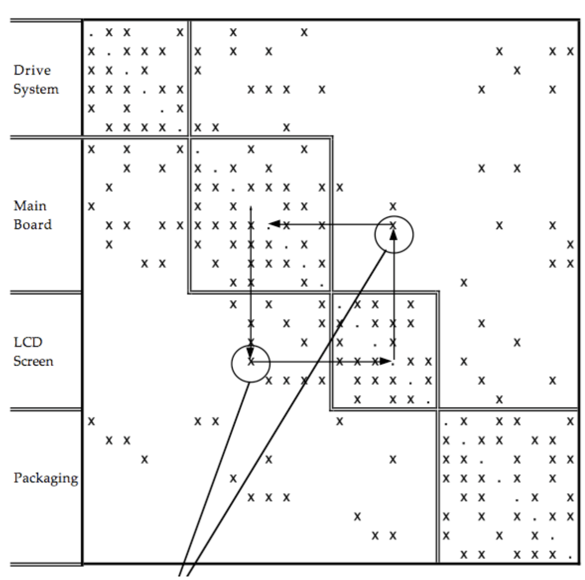
- Testable prediction:

  Component decoupling →faster cost reduction

- Design structure matrices (DSM)

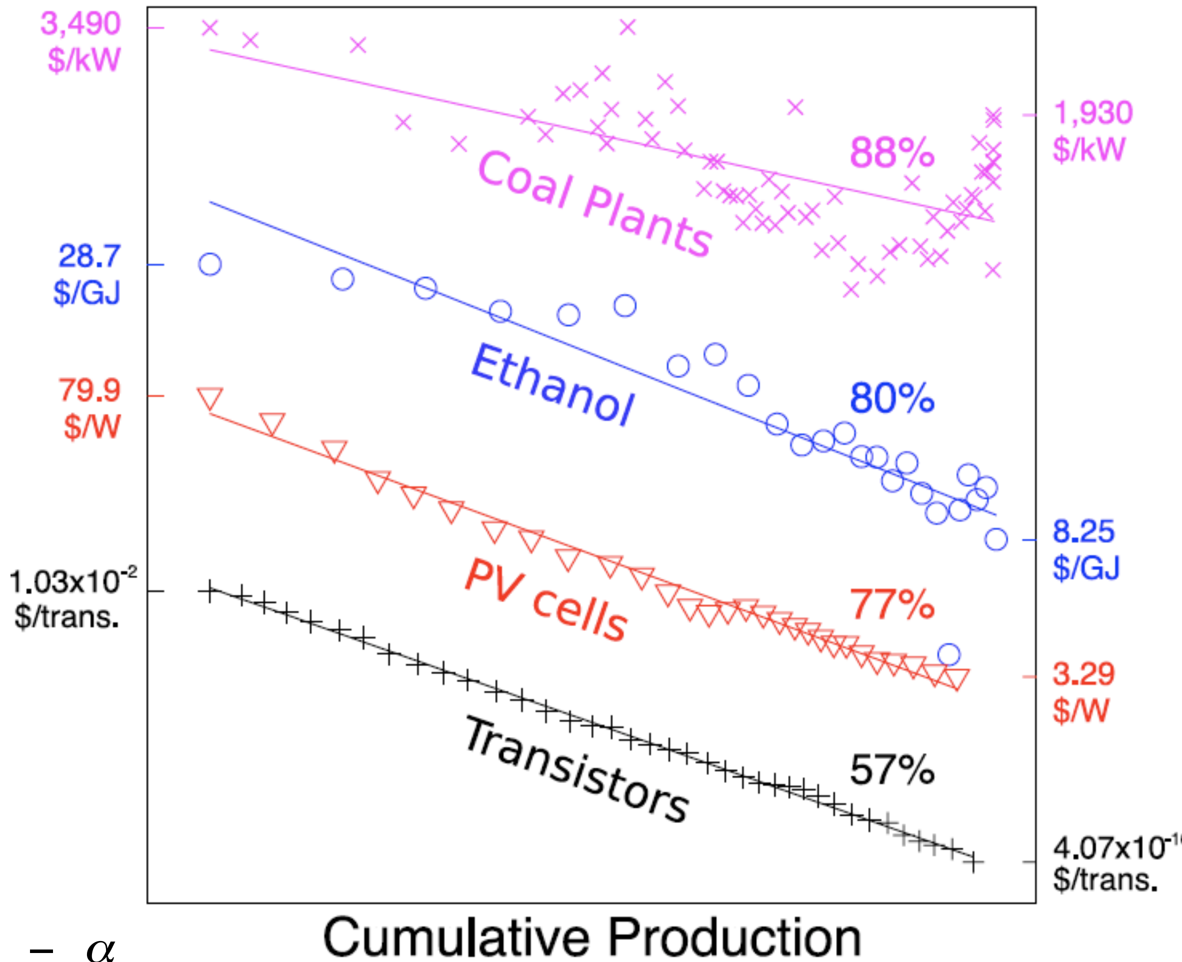
DSM of a laptop computer:

Design Structure Matrix Map of a Laptop Computer



d	Progress Ratio 2^ (-1/d*)
1	50.0%
2	70.7%
3	79.4%
4	84.1%
5	87.1%
10	93.3%
20	96.6%
40	98.3%

Performance curves



$$c(x) \sim x^{-\alpha}$$

$$PR = 2^{-\alpha}$$

Series	Years	Range
Coal plants	1902–2006	$6.1\times10^5 - 3.1\times10^8$ kW
Ethanol	1980–2004	$3.4\times10^6 - 2.7\times10^8$ m³
PV cells	1975–2003	$5.4\times10^2 - 2.2\times10^6$ kW
Transistors	1968–2005	$2.0\times10^9 - 1.1\times10^{19}$

Conclusions

- we can reproduce power function performance curve with a simple model
- relationships between components greatly affect rate of improvement
- bottlenecks can form, determining whether progress is steady

McNerney, Farmer, Redner, Trancik, *PNAS,* 2011

Interpretation of theory and future directions

- what does the theory tell us?
  - an effort-based model gives rise to an empirically observed regularity
  - lessons for technology investment
  - lessons for technology and engineering system design
- future developments applications?
  - design technologies for rapid *future* development
    - materials selection and design
  - model of networks of networks
    - infrastructure
    - supply chains

Materials optimization map: example photovoltaics

processing temperature

materials resource size

equipment capital cost

select materials and processing costs ($/m²)

estimate specific construction cost (SC_t)

maximize efficiency=η=$(J_{sc}V_{oc}FF)/P_s$

materials structuring at nano and mesoscale
(automated discovery)
(robust optimization)

$$TC_t = OM_t + CAP_t$$

$$TC_t = OM_t + \frac{SC_t \times CRF(r_t, n)}{CF_t \times 8760 hrs/year}$$

$$SC_t(\$/W) = \frac{1}{\eta} \times (\$/m^2) \times (m^2/W)$$

Trancik, Barton, Hone, *Nano Letters*, 2008
Trancik and Hone, US Patent App. 2008
Trancik, in preparation

future extensions:
- consider device lifetime: SC_t x CRF(r,n)
- design complexity: design for rapid innovation
- other performance metrics
- other devices

Students and postdocs

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