Massively Parallel Infrastructures

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Small Modular Infrastructure

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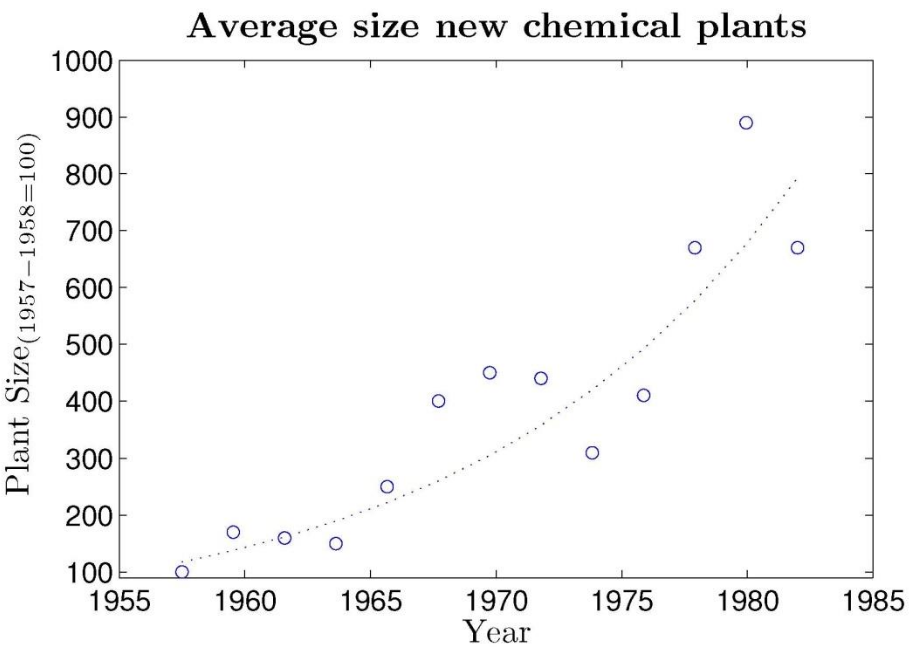
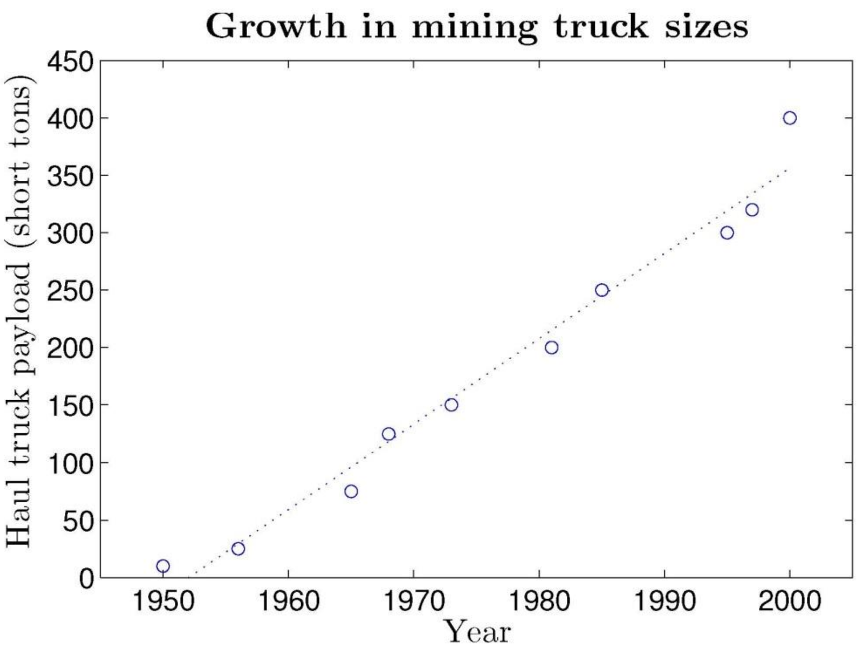
In this article we argue that advances made in automation, communication, and manufacturing portend a dramatic reversal of the "bigger is better" approach to cost reductions prevalent in many basic infrastructure industries; for example, transportation,

Historic Data on Scaling





Evolution of unit size in the chemical processing industry
data adapted from Lieberman (1987)

Size of mining trucks
data adapted from Koellner et al. (2004)

Eric Dahlgren, 2013 Ph. D. Thesis

Spot the low cost power plant

stock image

Per unit of power, the cost of a car engine is about 100 times lower than that of a power plant

wikipedia

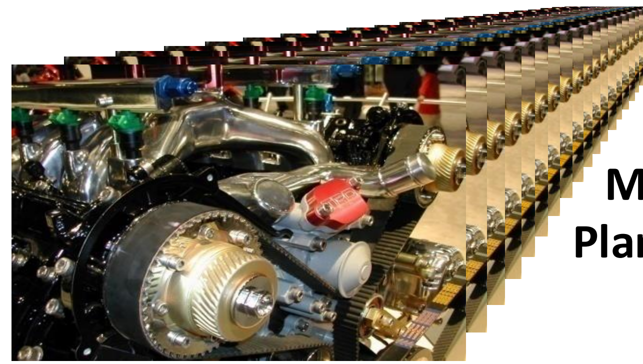
Economies of Scale

$$\text{Cost} = C_0 \cdot (\text{size})^{\alpha}, \quad \alpha < 1$$

Economies of Mass Manufacturing

Unit cost drops with production: $\frac{c_{2n}}{c_n} = \varepsilon$

Cost of n-th unit: $c_n = c_1 \varepsilon^{\log_2 n} = c_1 n^{\log_2 \varepsilon}$



Modular Plant

Cost of N units $= \frac{c_1}{1+\log_2 \varepsilon} \cdot N^{1+\log_2 \varepsilon}$

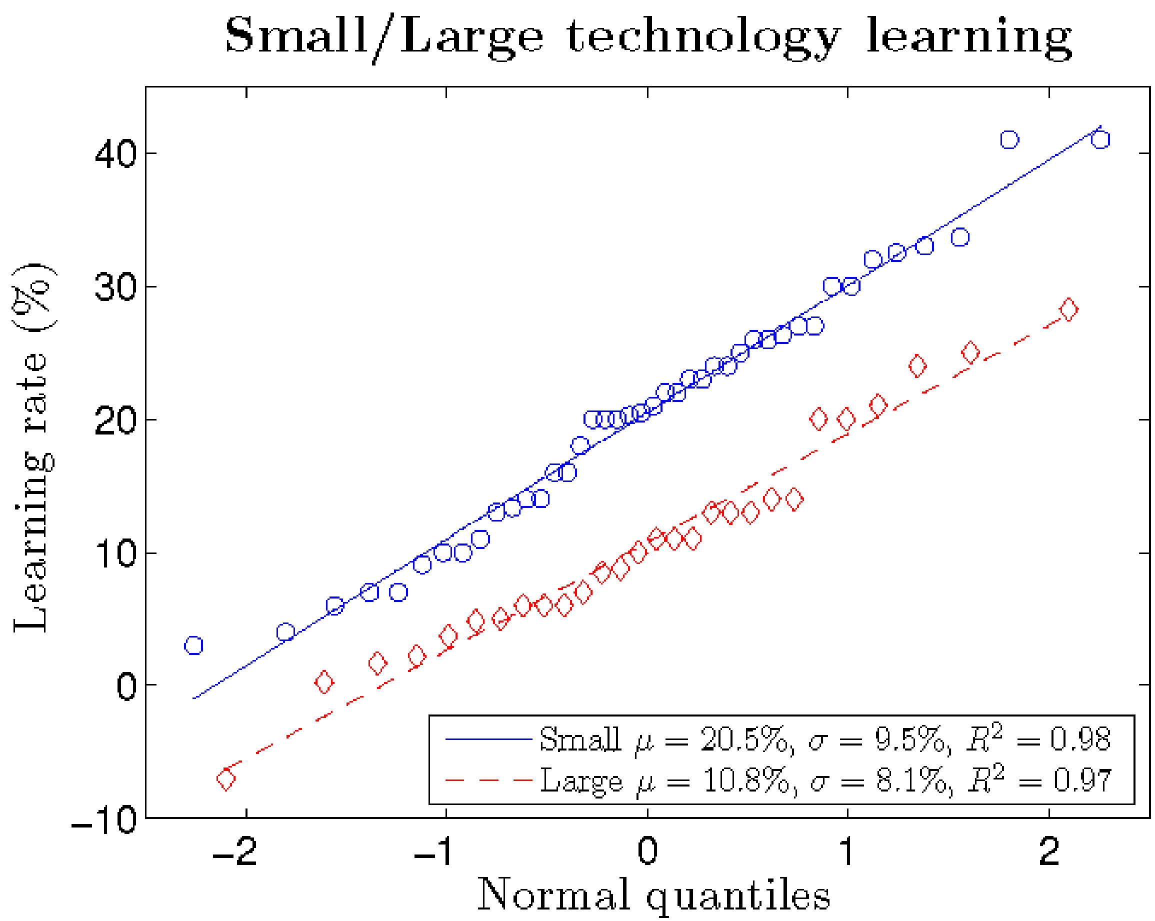
Empirically: $\alpha \cong 1 + \log_2 \varepsilon$

Labor cost favors large units

▪ Images from Wikipedia

Learning is faster for small units

- Range of learning coefficients changes with size



Eric Dahlgren, Ph. D. Thesis 2013

Fixed cost favors large plants

- **Fixed costs affect each plant, centralization reduces unit output cost**
  - Central administration, sales etc.
  - Central maintenance
  - Centralized delivery of goods
  - Operation of distribution hub
- **However, large plants could be modular**
  - Massively parallel units vs. large monoliths

Efficiency scaling is complex

large units are better

- **Heat retention**
  - Insulation gets cheaper
- **Wall losses (evap, etc.)**
  - Turbines need to be large
  - Wall corrosion
  - Contamination from walls
- **Wall friction**
  - Pistons etc.
- **Control systems**
  - Less coordination required

small units are better

- **Heat transfer**
  - Diffusion is helped
- **Transport and diffusion**
  - Take advantage of fast reactions
- **Mixing**
  - Faster and more uniform
- **Accurate control**
  - Temperature, pressure, etc.
- **Redundancy**
  - Parallel systems

Case by case analysis required
Each process has its intrinsic scale

Wall area to volume ratio?

- **The law of the walls does not work**
  - Structural considerations indicate
    - That bigger walls are thicker
    - Thickness grows linearly or faster
  - Mass of the walls grows faster than volume

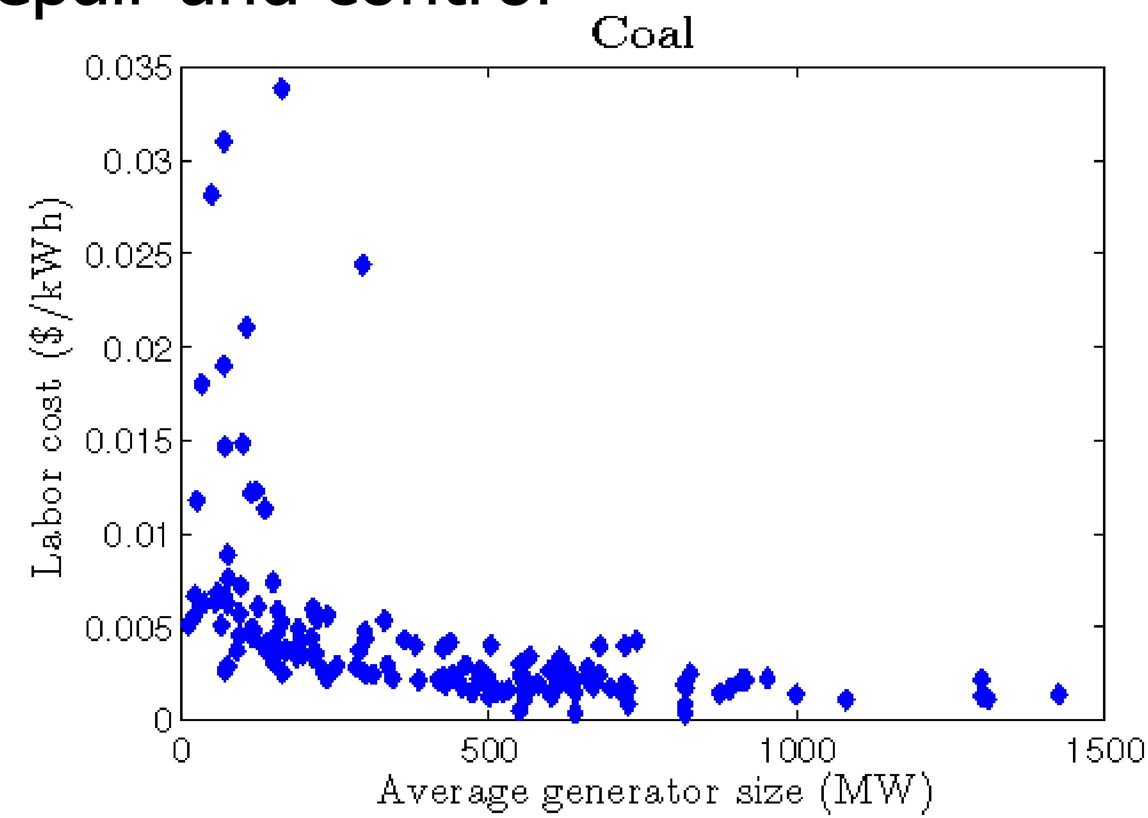
$$\partial_i \sigma_{ij} + F_j = \rho \partial_t^2 u_j$$
$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl}$$
$$\varepsilon_{kl} = \frac{1}{2}(\partial_k u_l + \partial_l u_k)$$

Scaling: Surface to volume ratio

- Surface to volume ratios can help or hurt
- Structurally it hurts

Personnel costs drive scale

- Fixed and variable cost – pilots and attendants
- Large fraction of cost scales with number of units
- Maintenance, repair and control



Automation breaks the link

http://wot.motortrend.com/google-autonomous-car-testing-fleet-adds-lexus-rx-450h-logs-300000-miles-245621.html

Why scale up?

- **Large demand allows large plants**
  - Monolithic has been cheaper than modular (economies of scale)
  - Cars cannot scale up, so they stayed small (learning curve)
- **Modular systems need control**
  - Managing many parallel units
- **Personnel cost**
  - Scales with number of units

Cost of information processing and simple decision making is dropping precipitously

Automation and robotic control systems can break the link between labor and unit size

The advantages of being small

- **Reliability constraints are relaxed**
  - Replaced by ultra-high redundancy
  - Automatic fault detection and replacement
- **Shorter deployment times**
  - Faster response time
  - Risk reduction
- **Flexibility in deployment**
- **Operational life times can be shortened**
  - More learning, mistakes are less costly
  - Reduce risk
- **Some efficiency gains**

Inertia of large systems

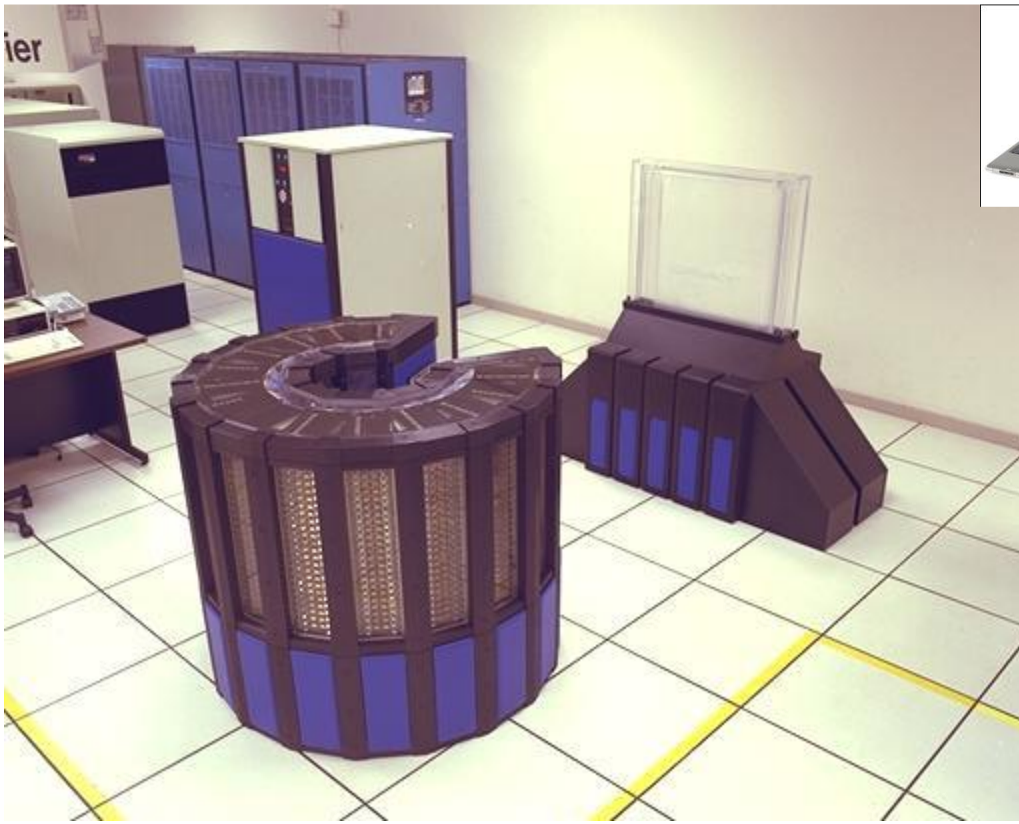
- **Investments are large**
  - High risk aversion
  - Tried and true technologies
  - Little innovation
  - Large hurdle to start
- **Life times are long**
  - Long lead times
  - Great uncertainty in future markets
  - Little learning

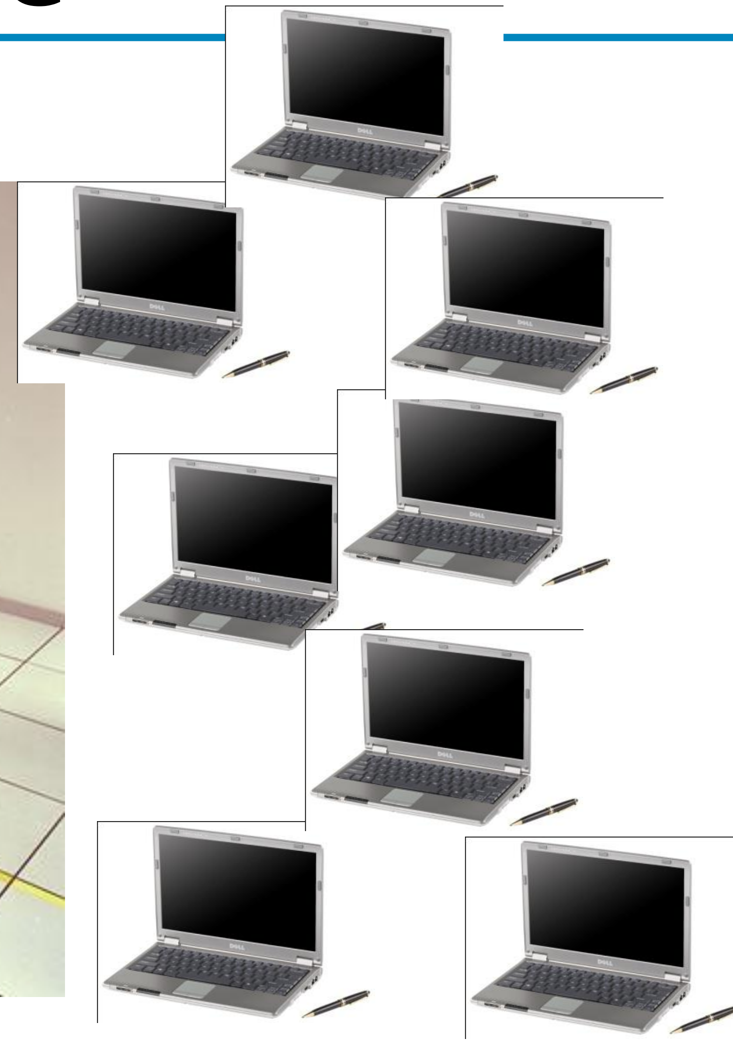
Moving to a Mass Production Paradigm

- **Shorter Lifetime**
  - Encourages learning
  - More generations of learning
- **Lower unit cost**
  - Encourages experimentation
  - Gives new ideas a chance

2 generations from Thomas Alva Edison
20 generations from Henry Ford
100 generations from Turing

Rescaling is disruptive





Cray supercomputer (from NASA)

One ton per day unit

100 million units would eliminate all emissions

world production of cars:
80 million per year