Assessing trends in the electrical efficiency of computation over time

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Presented at LLNL, Livermore, CA

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Alternate title: Why we can expect ever more amazing mobile computing devices in coming decades

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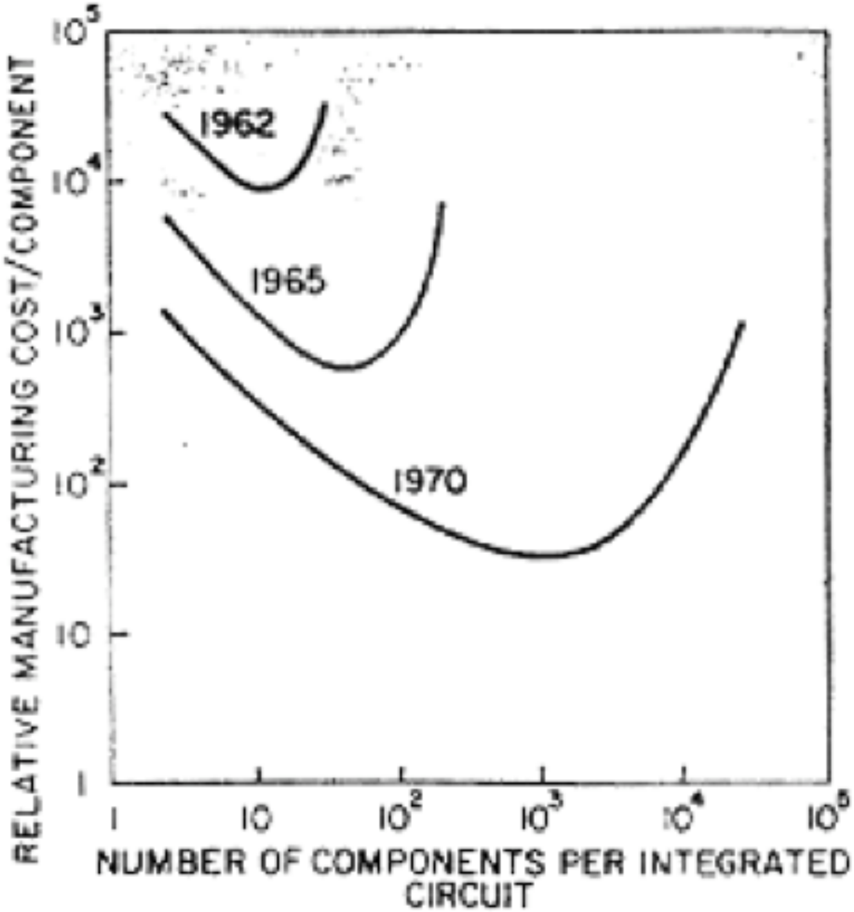
The key result: computations per kWh have doubled every 1.6 years since the 1940s

Koomey, Jonathan G., Stephen Berard, Marla Sanchez, and Henry Wong. 2009b. *Assessing trends in the electrical efficiency of computation over time.* Oakland, CA: Analytics Press. August 17. <http://www.intel.com/pressroom/kits/ecotech>. In Press at the IEEE Annals of the History of Computing as of May 2010.

Moore’s law

- Not a “law” but an empirical observation about components/chip
  - 1965: doubling every year
  - 1975: doubling every 2 years
- Characterizes economics of chip production, not physical limits
- Often imprecisely cited, interpretations changed over time (Mollick 2006)

Moore's original graph



Transistors/chip (000s)

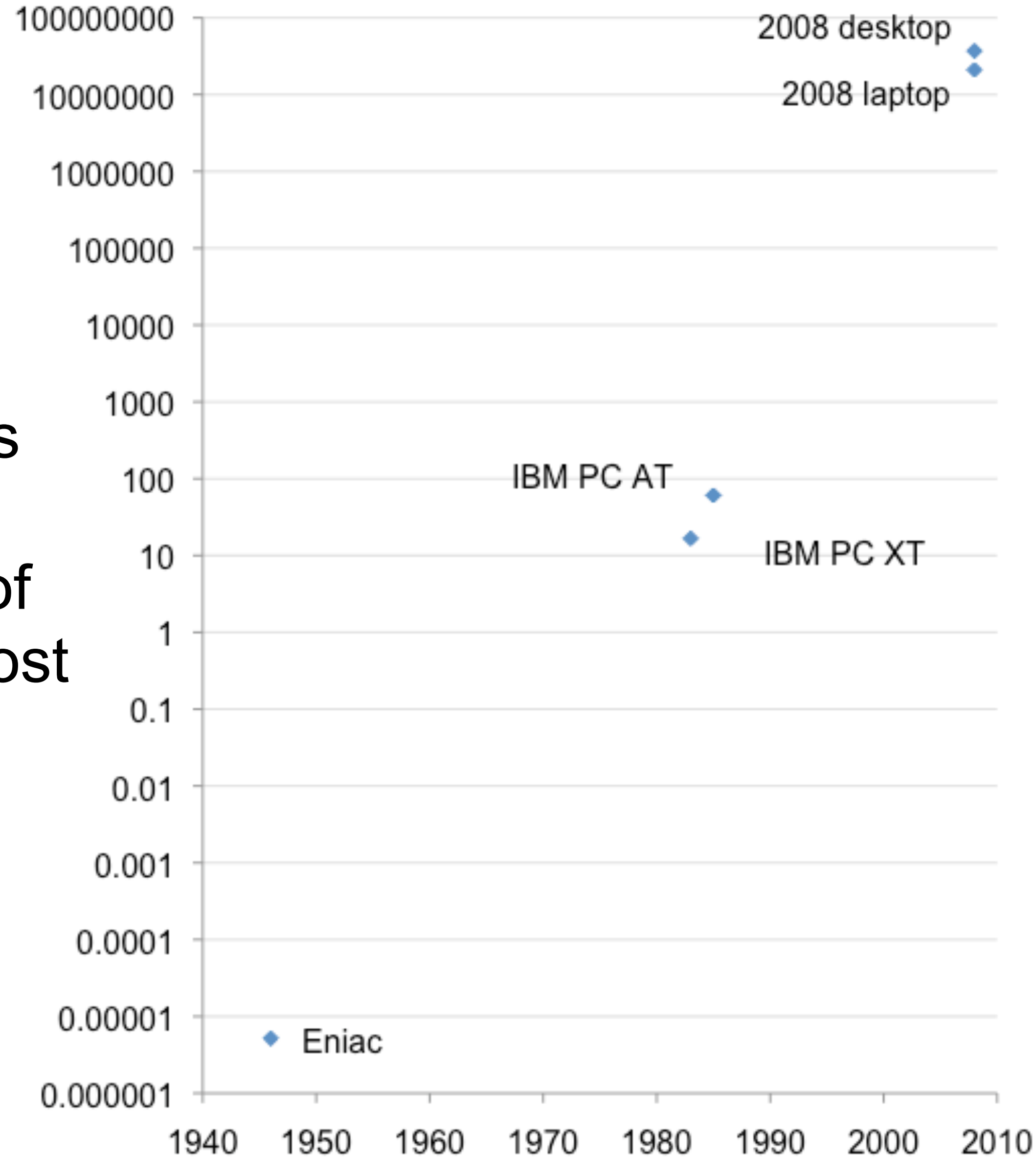
The doubling time from 1971 to 2006 is about 1.8 years. Data source: James Larus, Microsoft Corporation.

Origins of this work

- I initially thought to replicate my recent work on costs, energy, and performance trends in servers (Koomey et al. 2009a), for computing more generally
- Discovering Nordhaus (2007) led me to reorient my research
  - He analyzed costs and performance
  - I focused on energy and performance

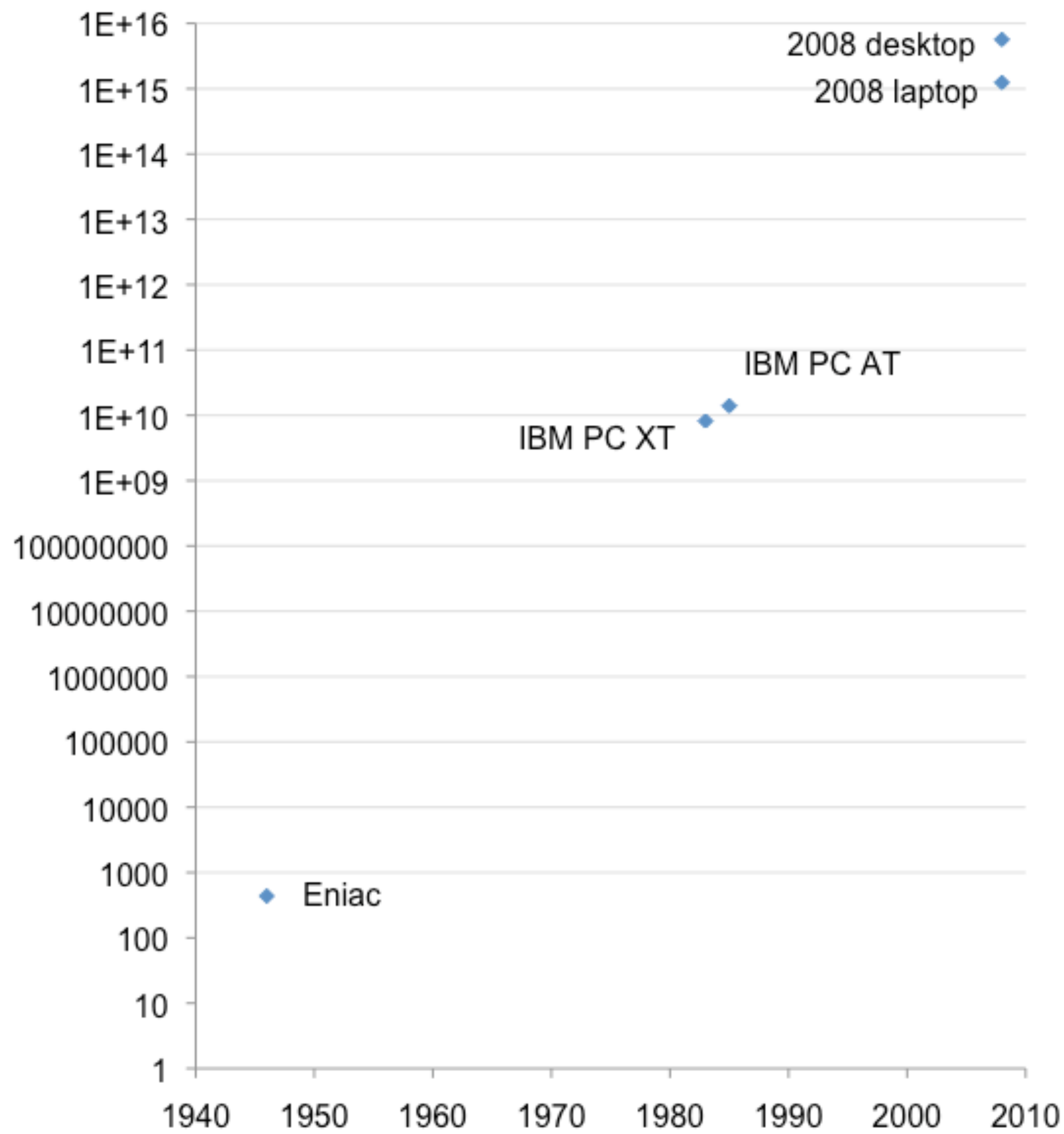
First I made this graph

Calculations per second per 2009$ of purchase cost



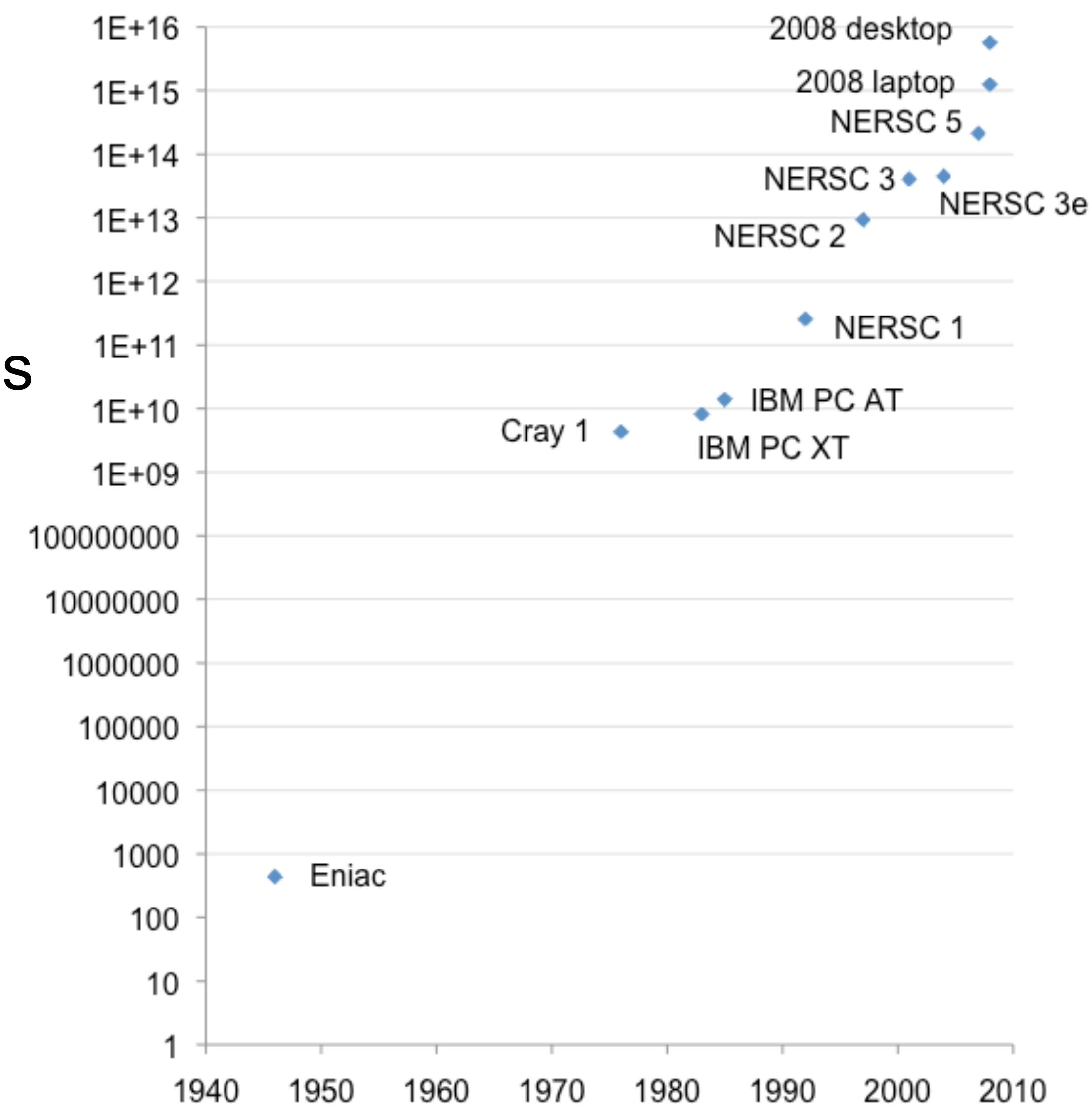
Then I made this one

Computations per kWh



But this one really got me to investigate

Computations per kWh



Method

- Computations per kWh =

$$\frac{\text{Number of computations per hour at full load}}{\text{Measured electricity consumption per hour at full load (kWh)}}$$

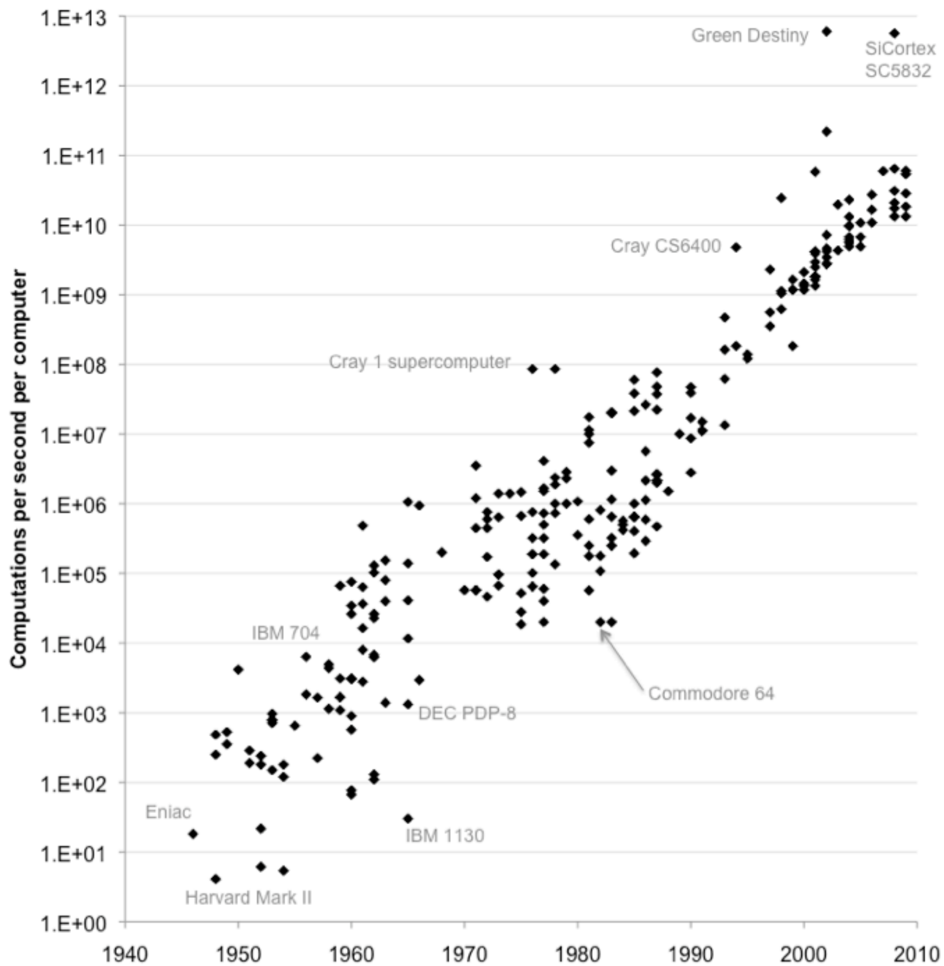
Data

- Performance from Nordhaus (2007) or normalized to that source using benchmarks for more recent computers
- Used measured power data, either published (e.g. Weik 1955, 1961, 1964) or from archival or recent computers
  - with computer fully utilized
  - with screen power subtracted for portables

Performance trends

- Performance trends with real software ≠ performance trends from benchmarks ≠ transistor trends!
- Doubling time for performance per computer = 1.5 years in the PC era

Performance trends (2): Computations/s/computer



Source: Nordhaus (2007) with additional data added by Koomey (2009b)

Because that’s where the computers are…

- Power measurements conducted at
  - Microsoft computer archives
  - Lawrence Berkeley National Laboratory
  - My in-laws’ basement
  - Erik Klein’s computer archives
- Computer History Museum’s web sites and discussion forums

An oldie but a goodie

And another

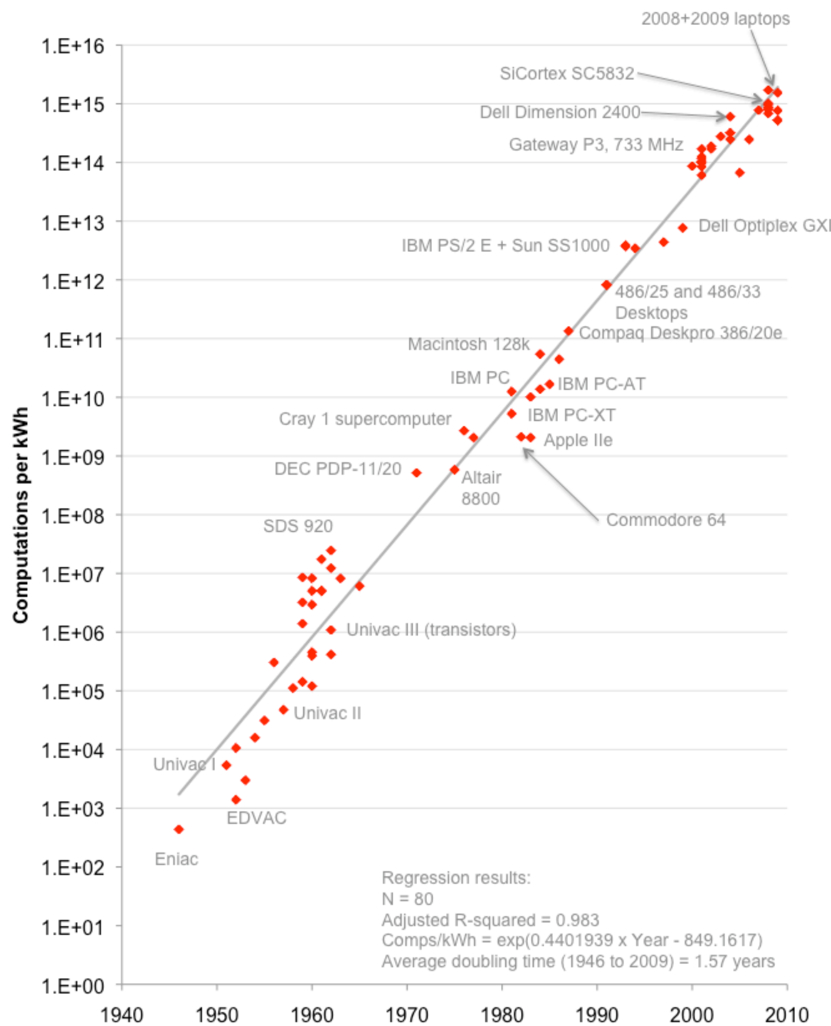
Still another

Erik Klein,
computer history buff

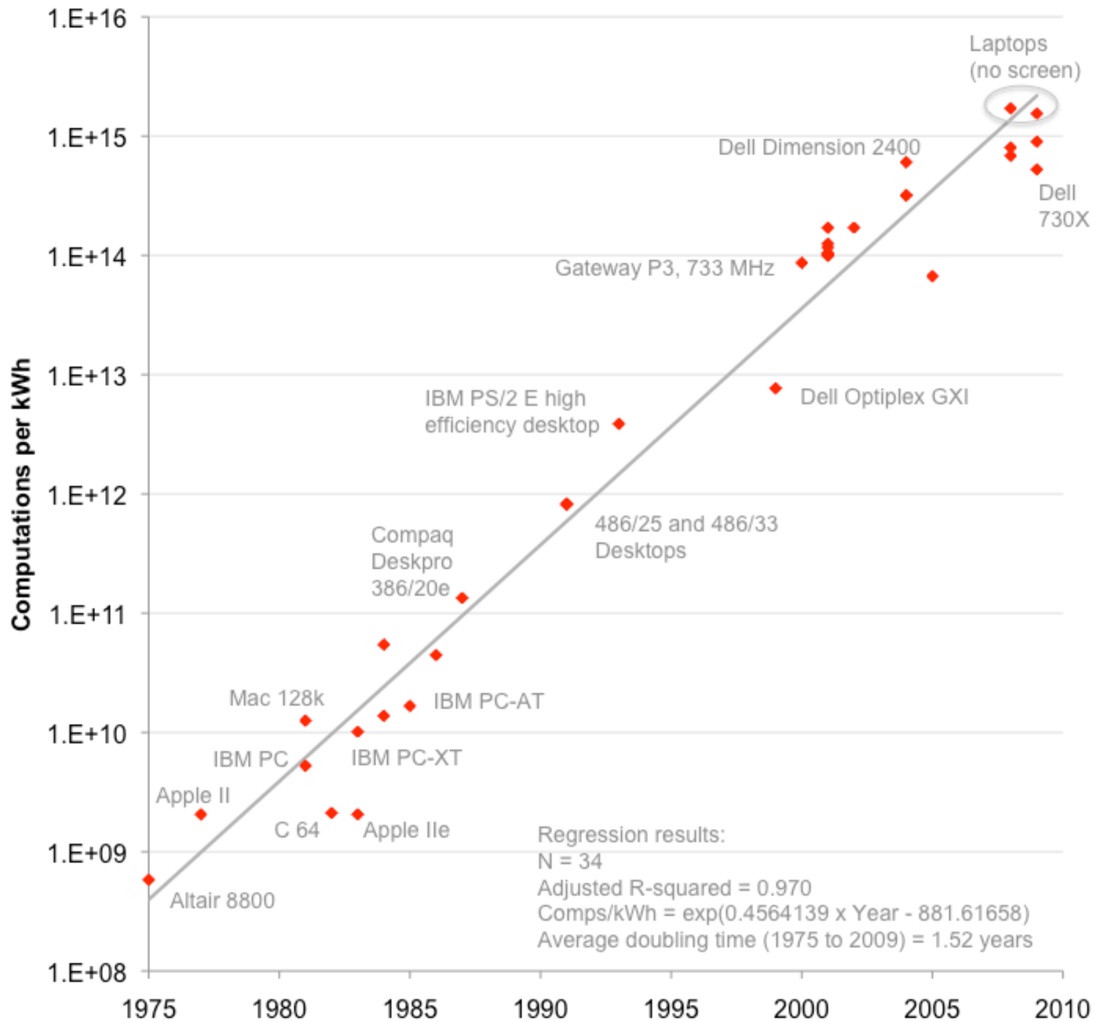
Good correlation, clear results

- R^2 for computations/kWh
  – 0.983 for all computers, 1946-2009
  – 0.970 for PCs, 1975-2009
- Doubling time for computations/kWh
  – All computers: 1.6 years
  – PCs: 1.5 years
  – Vacuum tubes: 1.35 years
- Big jump from tubes to transistors

Computing efficiency trends



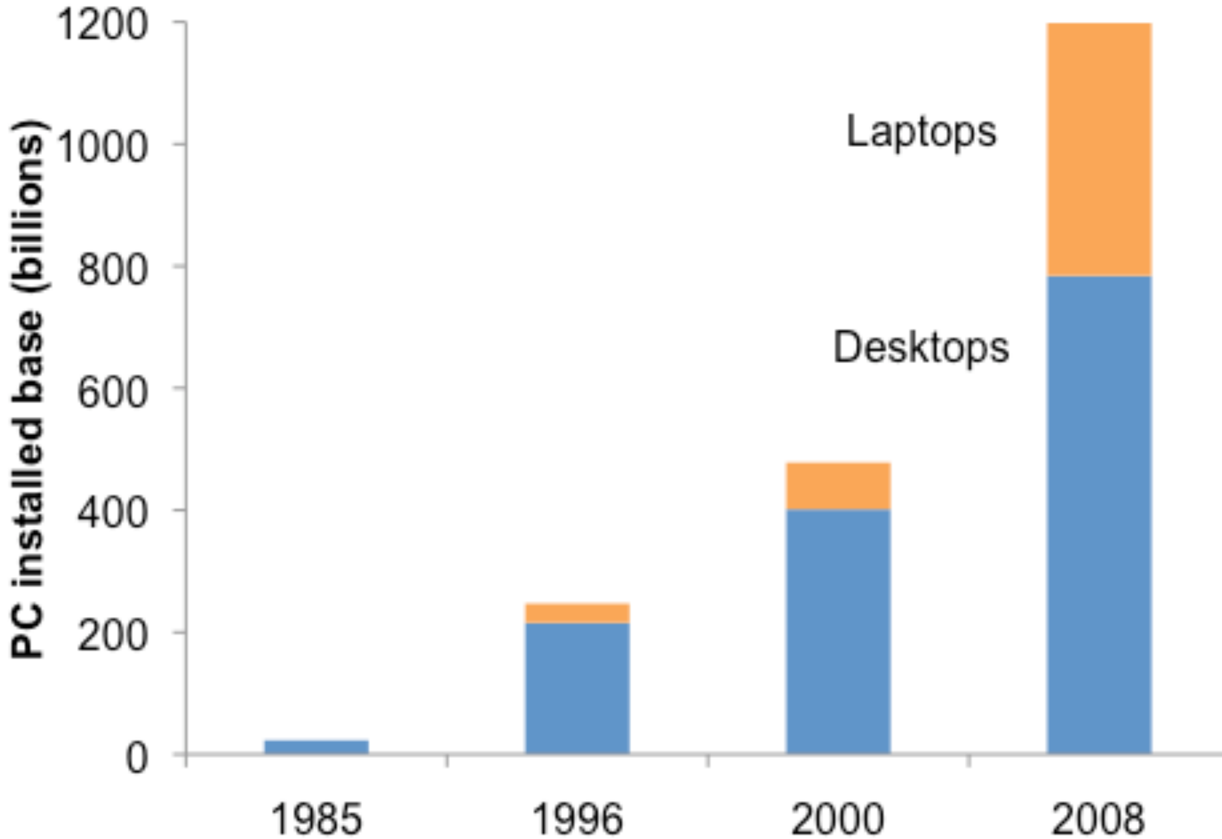
Efficiency trends: PCs only



Implications

- Actions taken to improve performance also improve computations per kWh
  - Transistors: Smaller, shorter distance source to drain, fewer electrons
  - Tubes: Smaller, lower capacitance
- Trends make mobile and distributed computing ever more feasible (battery life doubles every 1.5 years at constant computing power)

Laptops growing fast (world installed base, billions)



Sources—1985: Arstechnica + Koomey calcs 1996-2008: IDC

An example of mobile computing enabled by efficiency

- Compacts trash 5 x
- Sends text message when full
- PC panel uses ambient light
- An economic and environmental home run

http://www.bigbellysolar.com

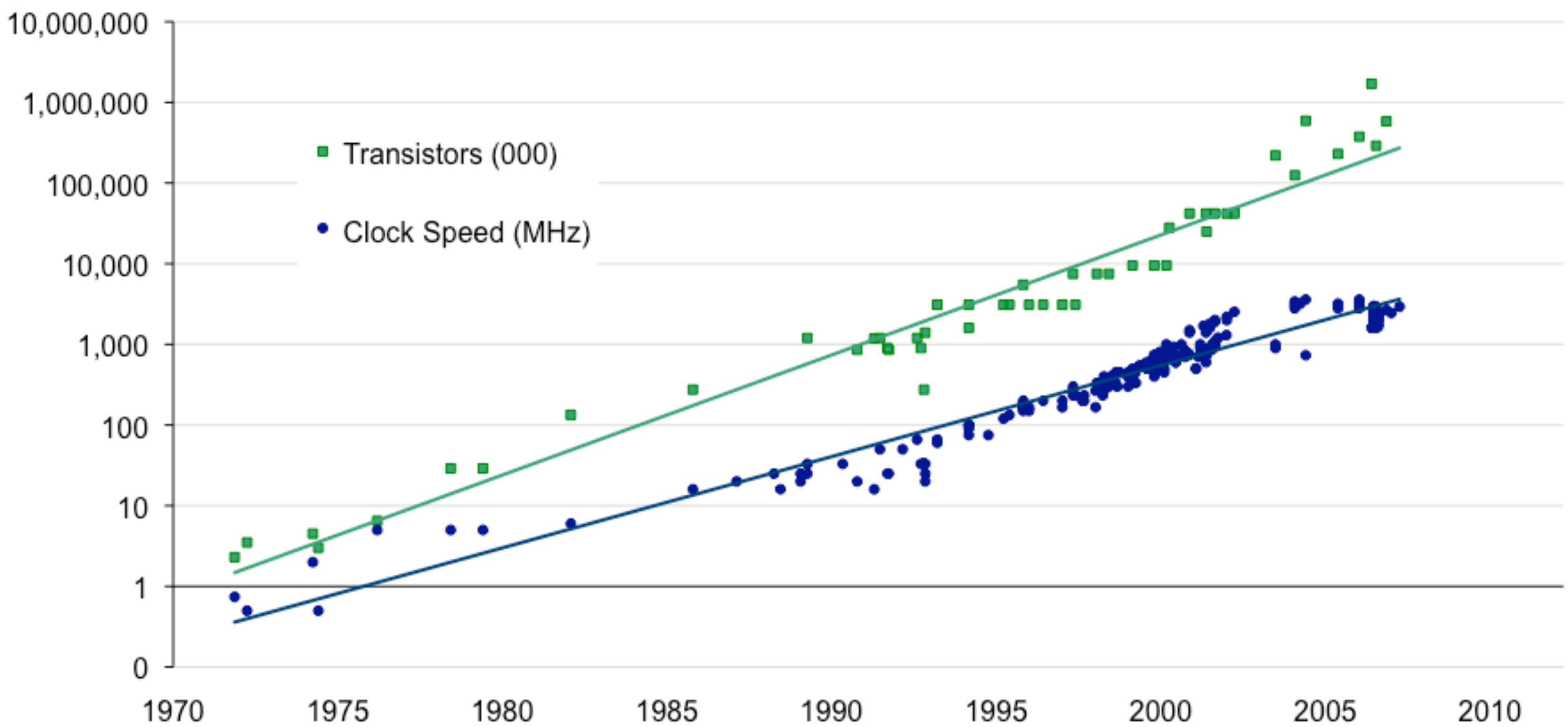
Implications (2)

- We're far from Feynman's theoretical limit for computations/kWh
  - 1985: Factor of 10^{11} potential
  - 1985 to 2009: Improvement of $< 10^5$
- Assuming trends in chips continue for next 5-10 years, significant efficiency improvements still to come

Future work

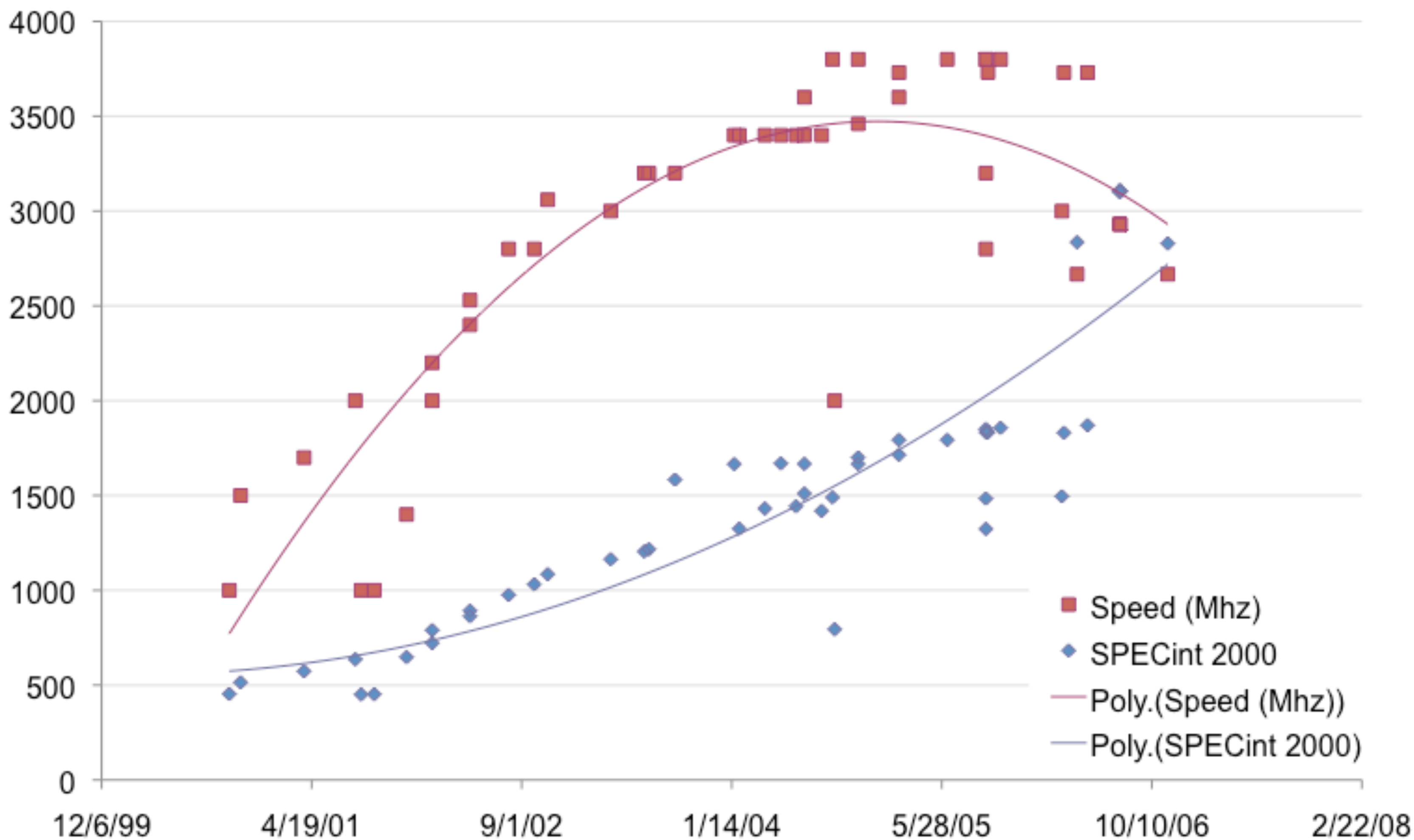
- Add more laptops to the data set (also PDAs, perhaps game consoles)
- Investigate how trends might differ between mainframes, PCs, PDAs, laptops, and servers
- Are power and performance trends for low-end chips different than for the most sophisticated CPUs?
- Real world performance vs. benchmarks

Clock speed and Moore's law



Data source: James Larus, Microsoft Corporation.

A complexity: multiple cores



Data source: James Larus, Microsoft Corporation.

Big unanswered questions

- Are there technological innovations (software or hardware) that could allow us to substantially exceed the historical trend in the electrical efficiency of computation?
- What roadblocks might prevent these trends from continuing after the current innovation pipeline is exhausted?

Conclusions

- Quantitative results
  - In the PC era (1976-2009) performance per computer and computations per kWh doubled every 1.5 years
  - From ENIAC to the present, computations per kWh doubled every 1.6 years
- Performance and efficiency improvements inextricably linked.
- Still far from theoretical limits
- Big implications for mobile technologies

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