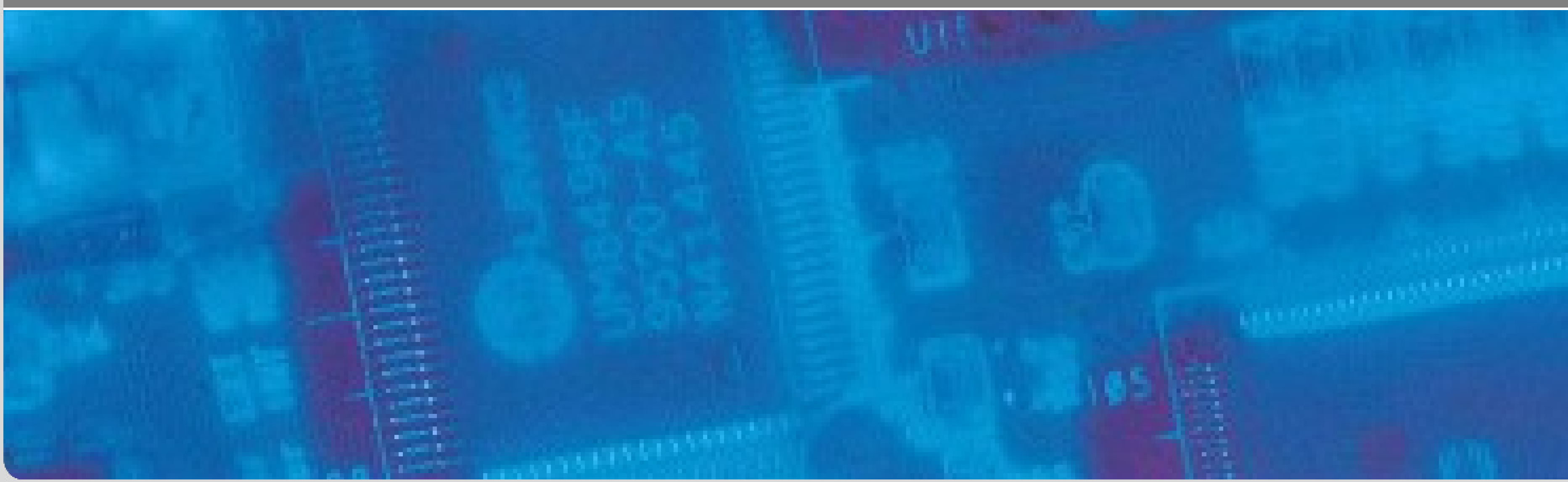
Low Power Design

Volker Wenzel on behalf of Prof. Dr. Jörg Henkel
Summer Term 2016

Karlsruhe Institute of Technology
CES – Chair for Embedded Systems



Lecture Slides Download

Organizational Issues

- Slides available online
  - **http://cesweb.itec.kit.edu/teaching/LPD/s16/slides/**
  - Username: student
  - Password: CES-Student
- Jabber/XMPP Conference Channel
  - ces-lowpower@conference.kit.edu
- Homework
  - practice reading of scientific papers
  - marked on the last slide
- Oral exam
  - make appointment with our secretary 6-8 weeks in advance
  - can be held in German/English
  - more information: **http://ces.itec.kit.edu/972.php**

Overview Low Power Design Lecture

- Introduction and Energy/Power Sources (1)
- Energy/Power Sources(2): Solar Energy Harvesting
- Battery Modeling
- Hardware power optimization and estimation – Part 1
- Hardware power optimization and estimation – Part 2
- Hardware power optimization and estimation – Part 3
- Low Power Software and Compiler
- Thermal Management – Part 1
- Thermal Management – Part 2
- Aging Mechanisms in integrated circuits
- Lab Meeting

Overview for today

- Motivations for low power design
- Examples of Power/Energy-aware applications
- Theoretical Limits of Low Power Design
- Battery issues (re-chargeable batteries)

Why design for low power/energy?

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(src: A. Raghunathan, NEC)

LOW POWER DESIGN

Portable Systems

- Smart Phones,Tablets,Wearables,Notebooks,etc.
- Battery-driven – long battery life crucial
- System cost
- Batteries limited by system weight (black board)
- Slow growth in battery technology
- Must reduce energy drain from batteries

Thermal Considerations

- 10°C increase in operating temperature → component failure rate doubles
  - Packaging: ceramic vs. plastic
  - Cooling requirements
- Increasing levels of integration worsen problem

Environmental Concerns

- EPA estimate: 80% of office equipment electricity used in computers
  - "Energy Star" program to recognize power efficient PCs
  - Power management standard for desktops and laptops
- Drive towards "Green IT"

Reliability Issues

- Electromigration
  - I·R drops on supply lines
  - Inductive effects
  - many more
- Tied to peak/average power consumption

Side Note: Jevons Paradox

- William Stanley Jevons (1865)
- efficiency of resource usage increases

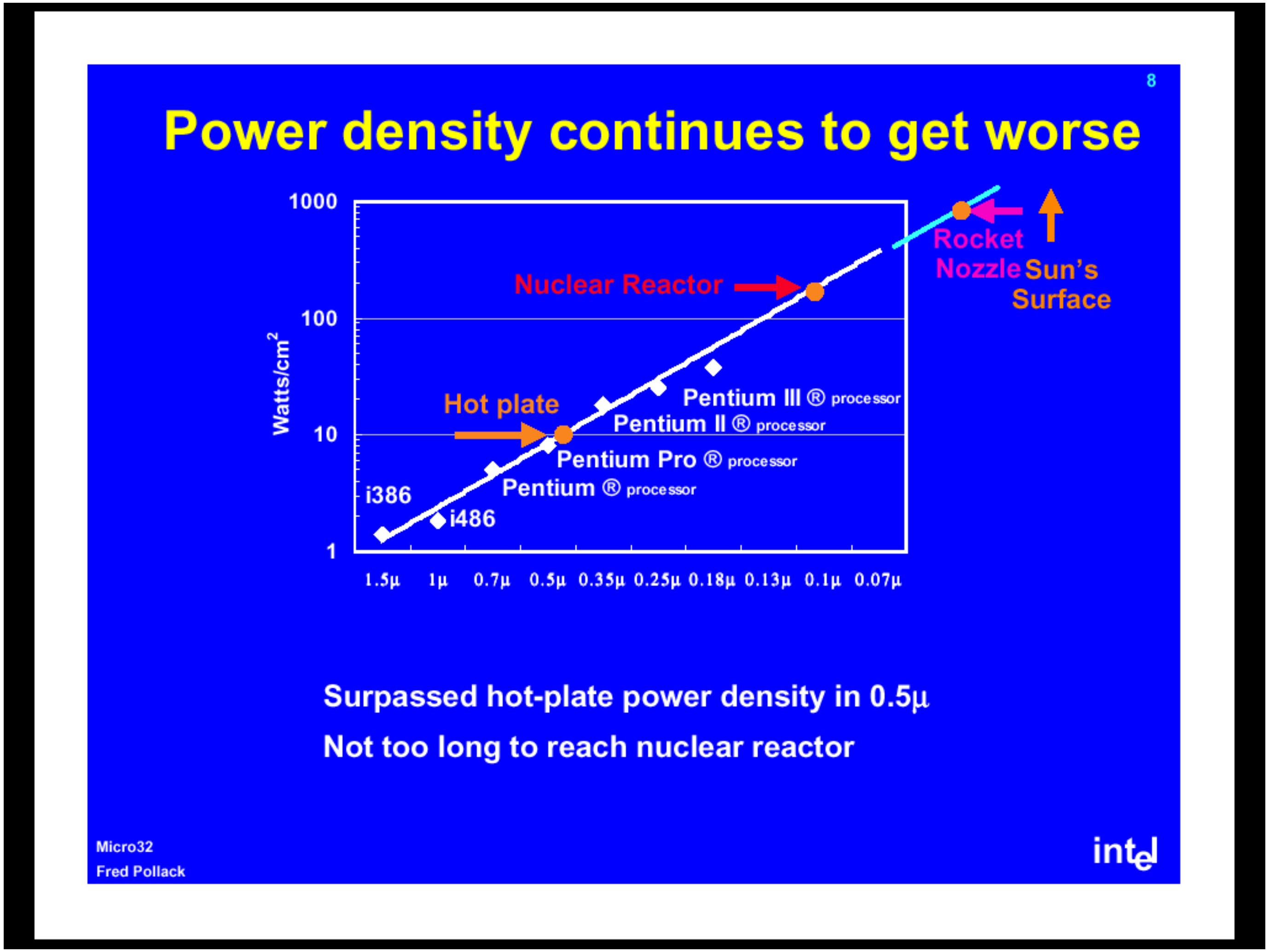
  ~~→ usage decreases~~

  → usage increases

- cf. with previous slide

src: en.wikipedia.org

Power densities I/II

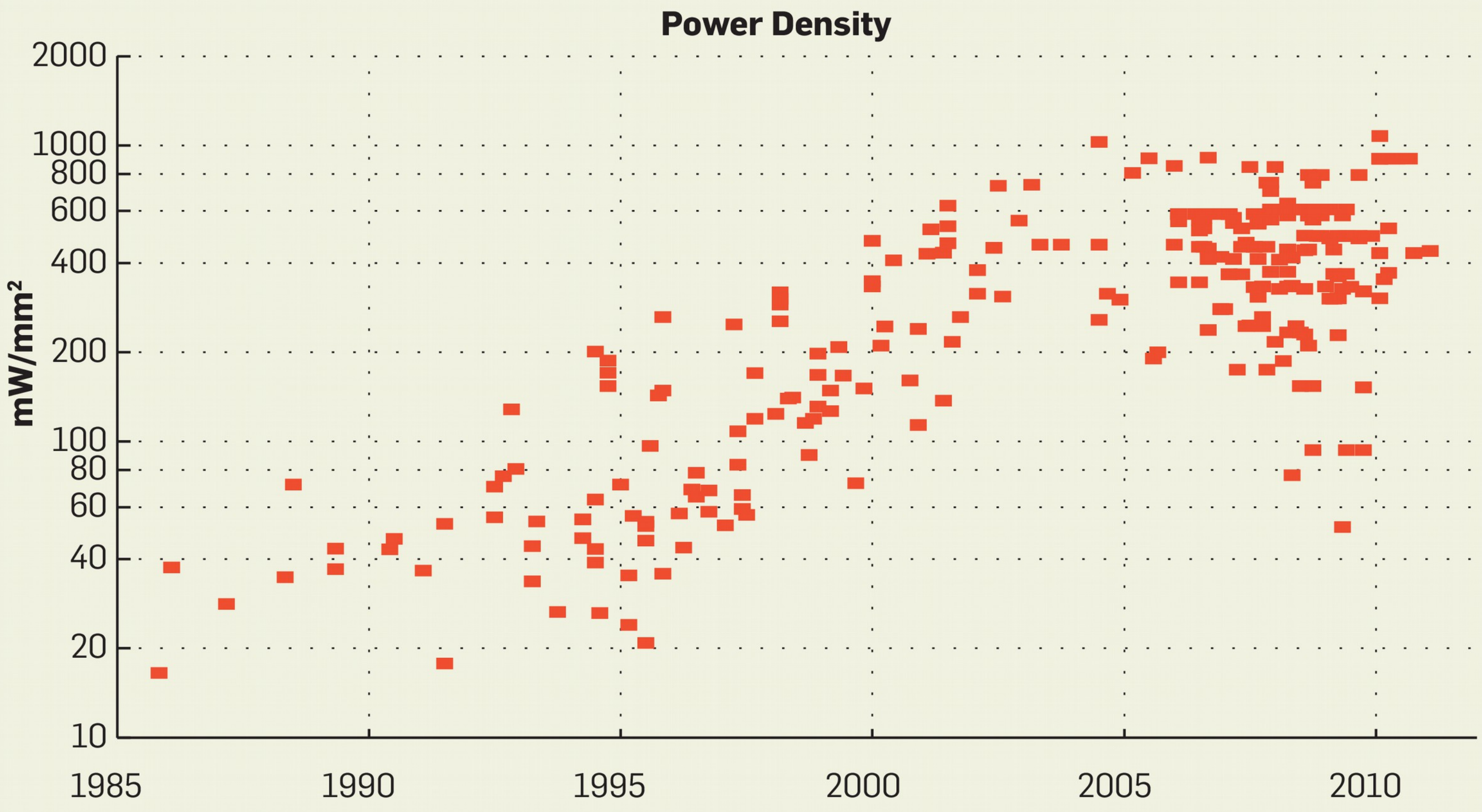


year 1999

(src: F. Pollack, Intel)

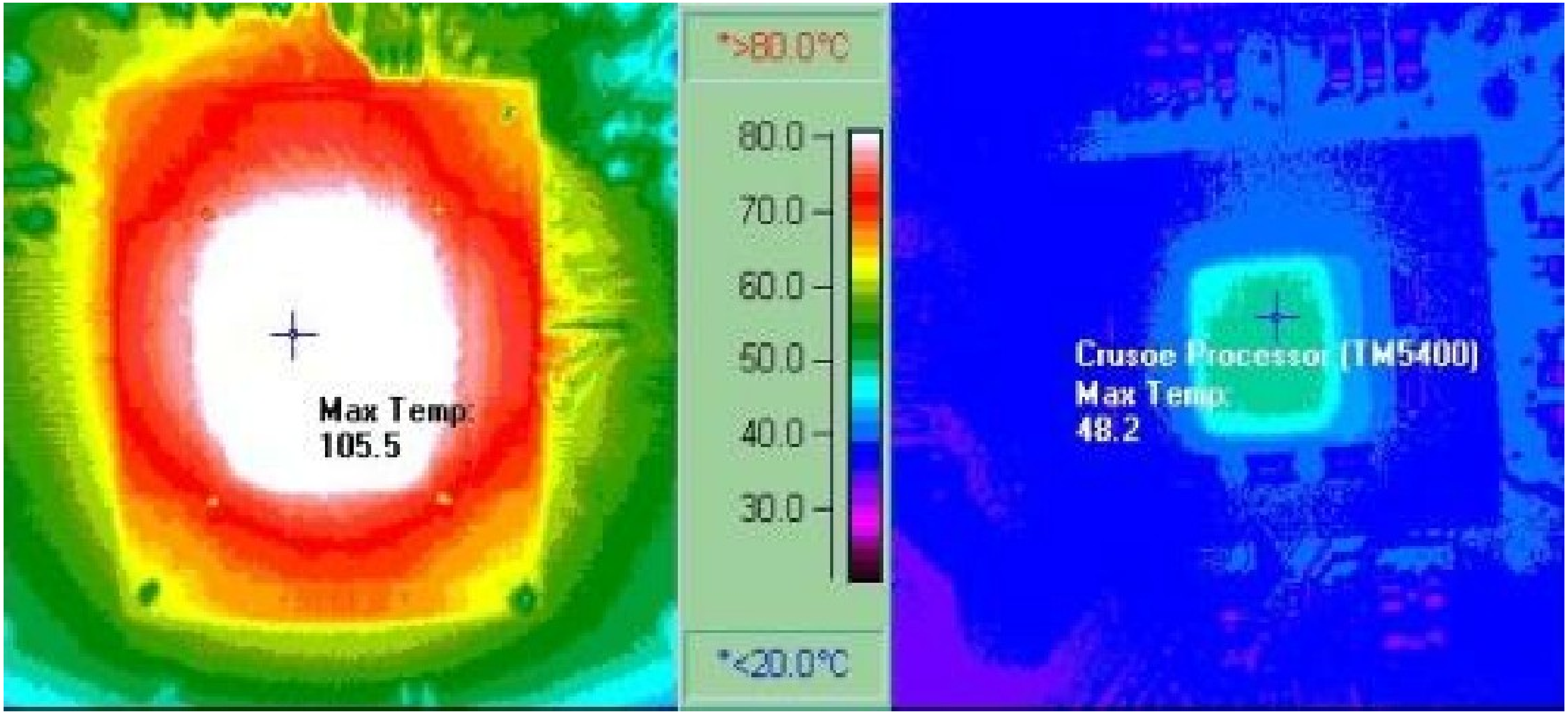
Power densities II/II

Figure 8. Power density over time. From 1985 through 2005, power density grew by roughly a factor of 32. Since 2005, power density has largely started to decrease.



(src.: [Danowitz])

Power consumption: motivation



Pentium 4

Crusoe Processor

(src: www.transmeta.com)

Power consumption: motivation

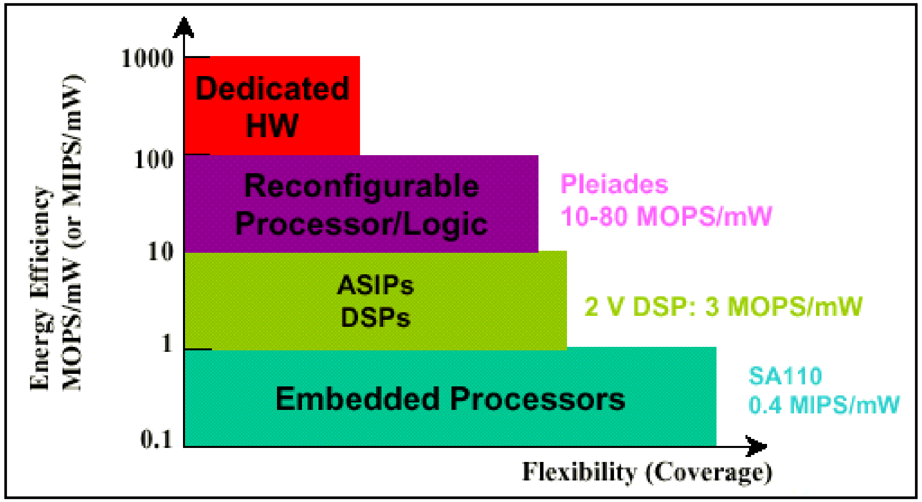
- Facebook Data Center in Luleå, Sweden
- 2°C avg. temperature allow for simpler cooling
- cheap electricity

(src.:www.cnet.com)

~June 2013
(src.:www.cnet.com)

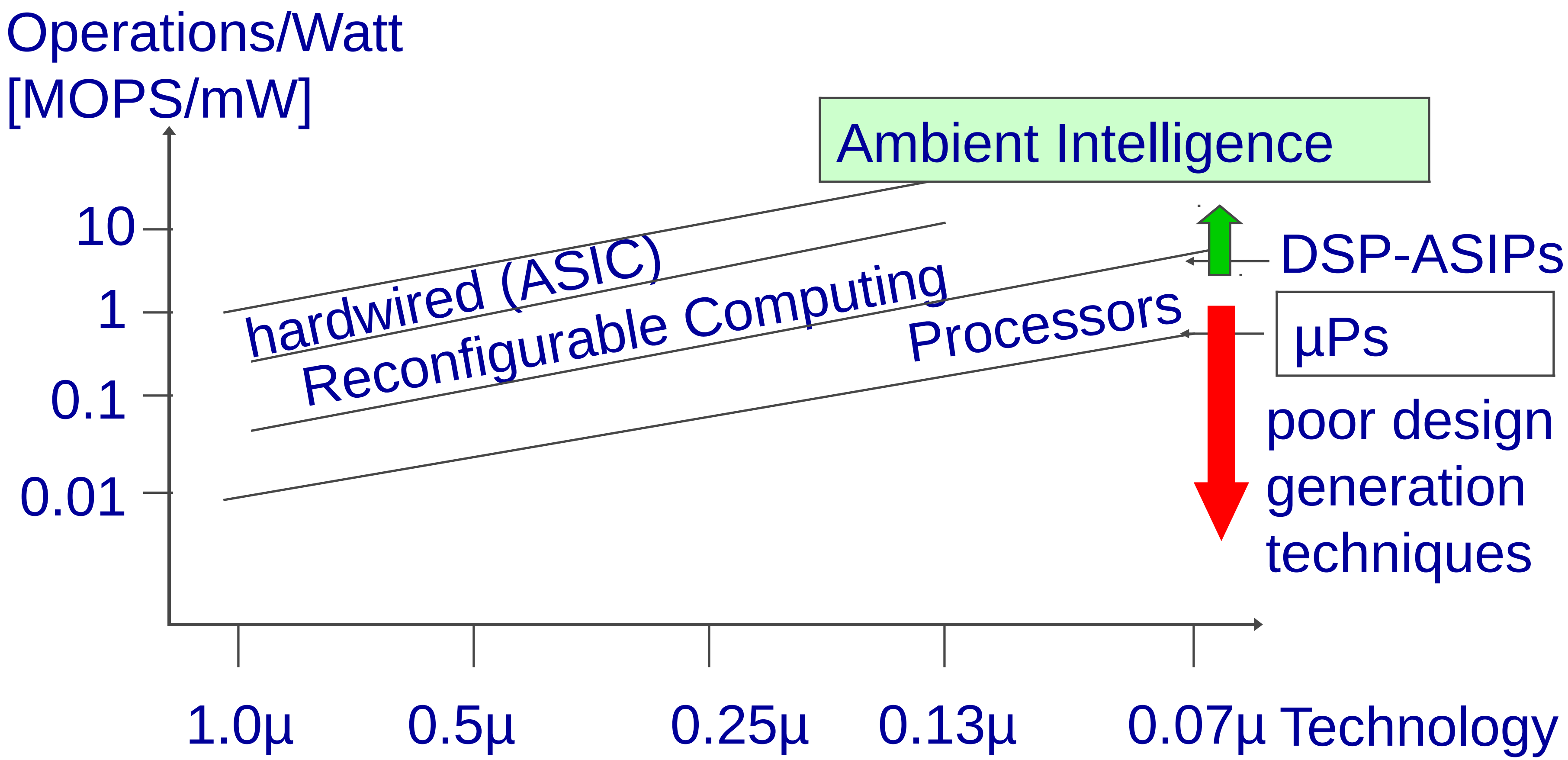
Energy vs. Programmability

- large gap (100x-1000x) in energy efficiency between
  - fully programmable and
  - fully custom implementations
- ample scope for tradeoffs



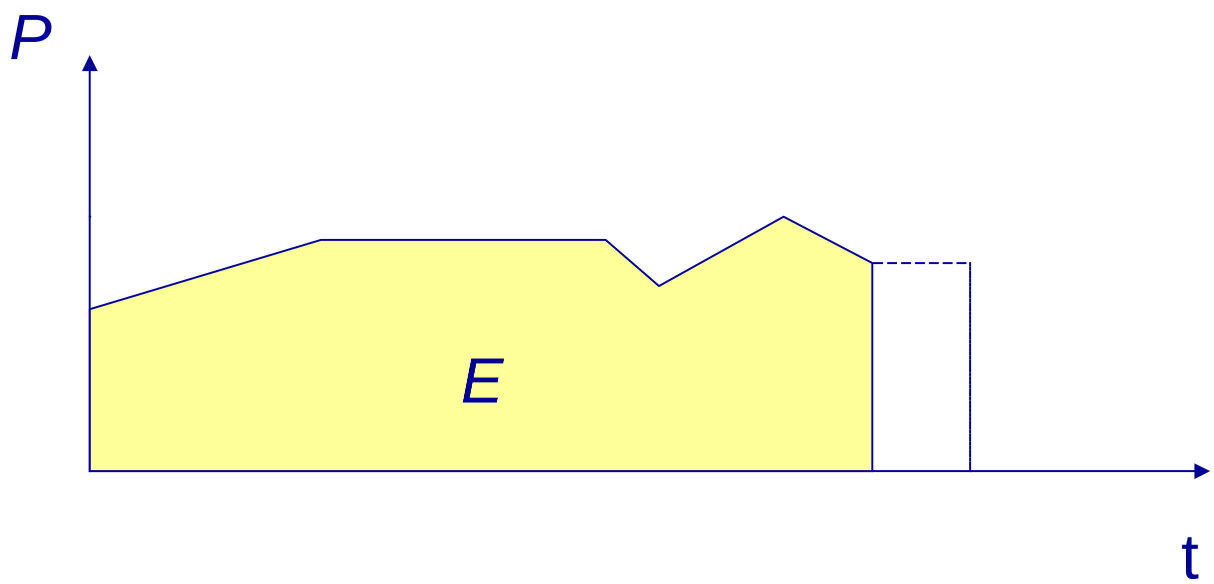
Source: Rabaey *et. al.*, IEEE Computer, July 2000

Power consumption by processing type



(src:[Marw03])

Relationship between power and energy



$$E = \int P \, dt$$

Energy: 1 Ws = 1 VAs = 1 Joule = 1 Nm

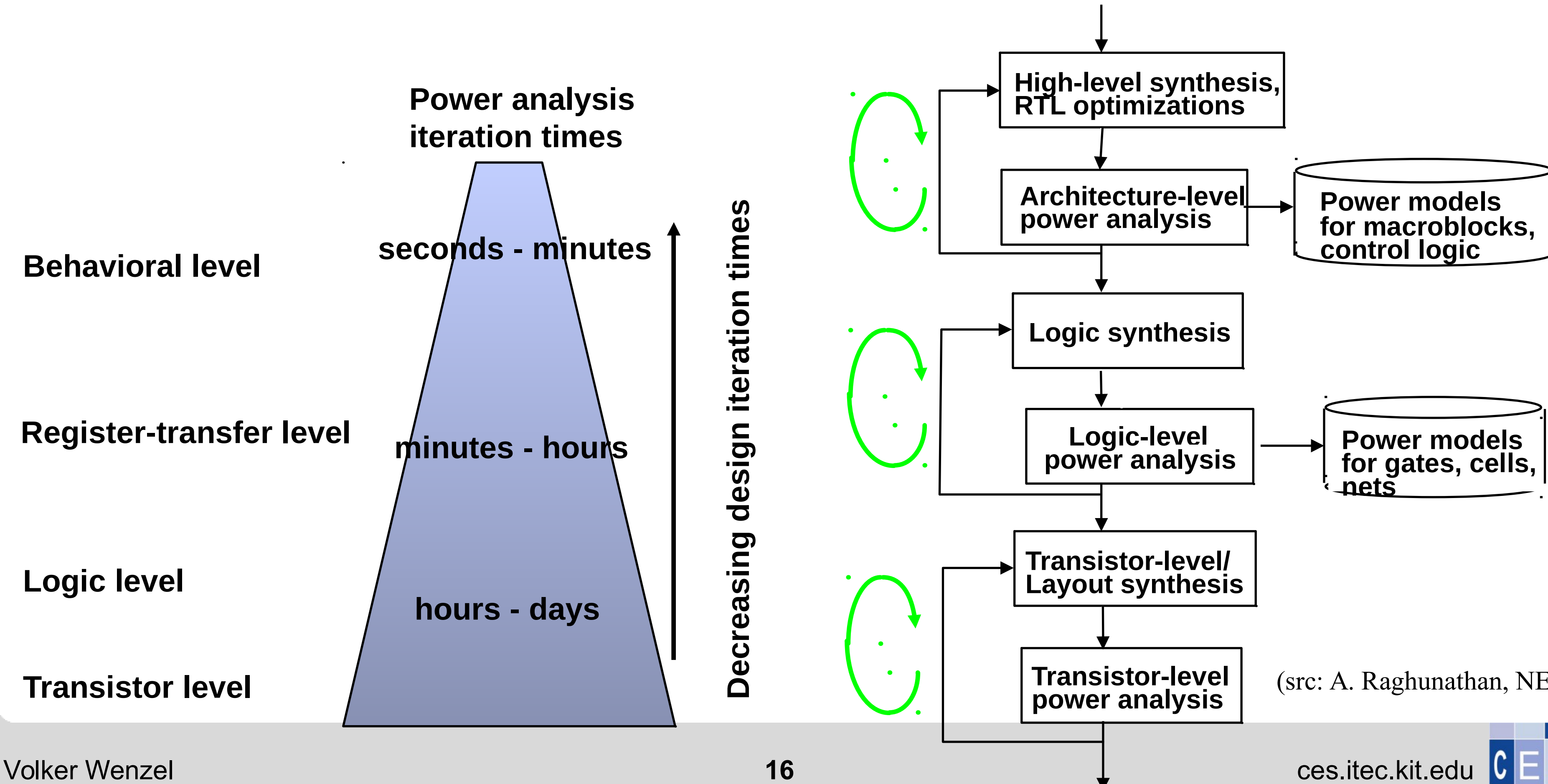
Power vs. Energy Minimization

- Minimizing power consumption important for:
  - design of power supply
  - design of voltage regulators
  - dimensioning of the interconnect
  - short term cooling
- Minimizing energy consumption important for:
  - limited availability of energy (eg. mobile systems)
  - to maximize amount of computation accomplishable with given amount of energy
    - limited battery capacities (only slowly improving)
    - very high costs of energy (solar panels, in space)
  - cooling
    - high costs
    - limited space
  - dependability
    - long lifetimes
    - low temperatures

(src: [Marw03])

Hardware Power Consumption

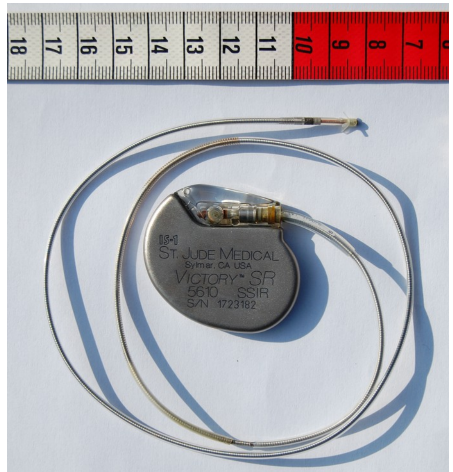
$$\text{Power} = \text{Cap\_Switching\_Power}\left(\tfrac{1}{2}\, C_L \cdot V_{dd}^2 \cdot A \cdot f\right)$$
$$+ \text{ Leakage/Static Power} + \ldots$$

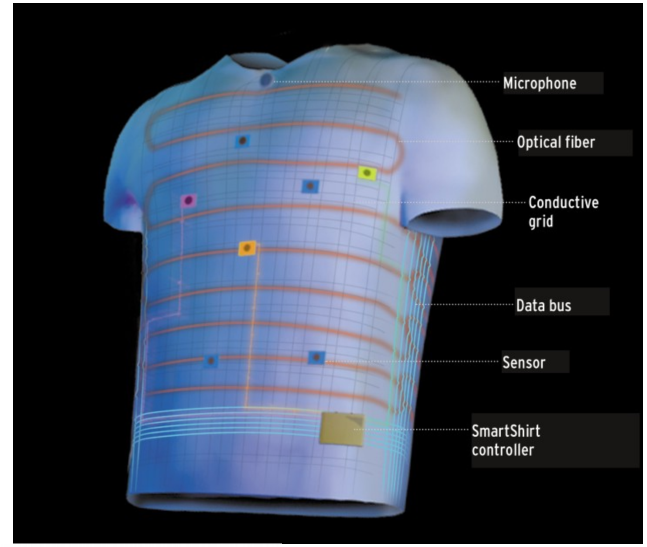


(src: A. Raghunathan, NEC)

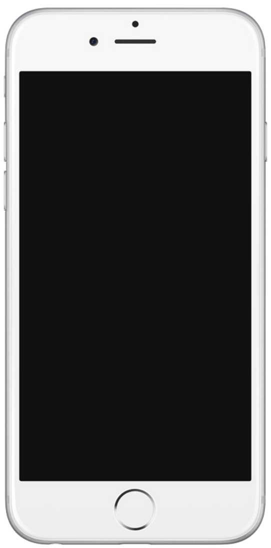
Examples of Power/Energy-aware applications

(src: [42])



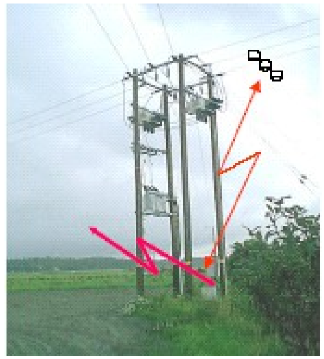


(src: [Marc03])



src: commons.wikimedia.org

Example Sensor Networks

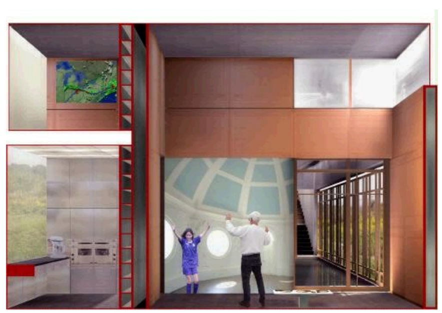
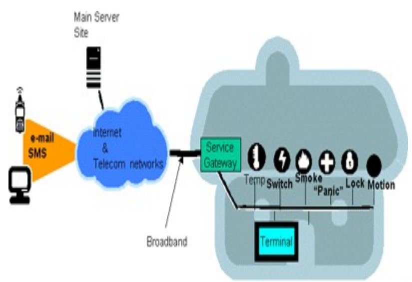



Manufacturing plants & Power distribution
- Improve reliability, operating efficiency

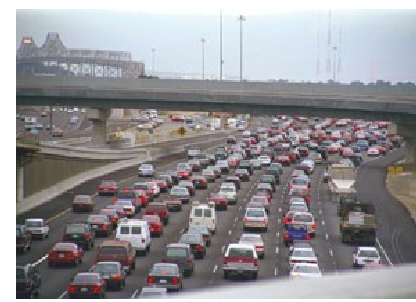
Energy-efficient buildings
- $55 B / year opportunity in the US

Disaster Prevention & Emergency Response

Health care
- Unwired operating rooms
- Early detection of cardiac attacks

“Smart” environments
- Homes, Offices, Schools, …
- Convenience, Productivity, Security



Traffic control
- Reduce commute time by 15 min => $15B/year in California alone

(source: A. Raghunathan, NEC)

More examples

- Banking & Money transfer smart cards, …
- Consumer cell phone, MP3 player, PDA, …
- Clothing electronic textiles
- Environment sensor networks
- Healthcare hearings aids, pace maker, …
- Telecom Systems satellite, …
- …

Examples of Power/Energy-aware applications

MSP430F1x MCUs

Key Features

Clock
- Up to 8 MHz CPU speed

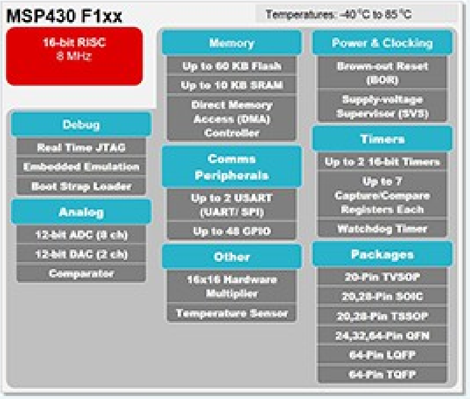
Analog
- Wide range of high-performance analog and intelligent digital peripherals

Memory
- Up to 60 KB Flash
- Up to 10 KB SRAM

Low power
- 200 µA / MHz active mode
- 0.7 µA real-time clock mode
- 0.1 µA RAM retention
- Ultra-fast wake-up from standby mode in <6 µs

Voltage
- 1.8 – 3.6V operation

Block Diagram



Enlarge

Applications

- Industrial
- Medical
- Security and safety
- Consumer & portable electronics

(src.:www.ti.com)

Theoretical Limits of Low Power Design

Theoretical Limits of Low Power Design

What is **Entropy**?

- state function of a thermodynamic system
- „measure of disorder“
- extensive property (like mass)
- unit [J/K]
- ΔS = 0 is a reversible process
- ΔS > 0 is an irreversible process
- S = 0 @ T = 0°K

$$\Delta S = \int \frac{\delta Q_{\mathrm{rev}}}{T}$$

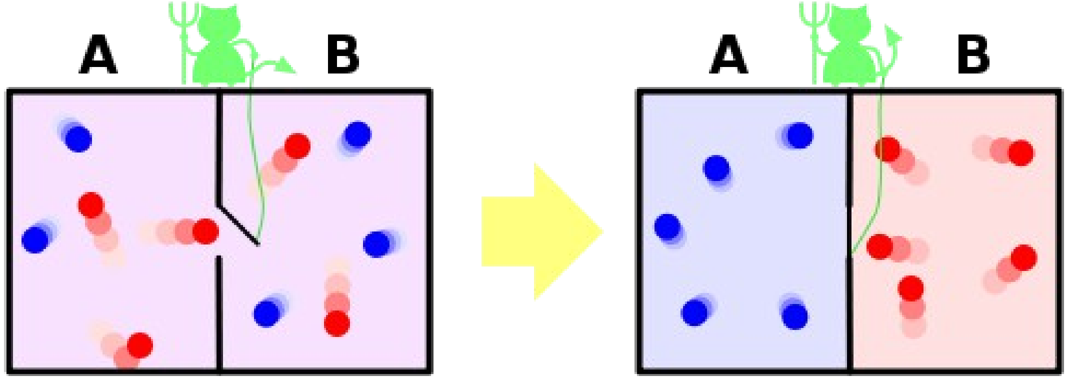
Theoretical Limits of Low Power Design (cont'd)

What is the **Second Law of Thermodynamics**?

- "The second law of thermodynamics states that for a thermodynamically defined process to actually occur, the sum of the entropies of the participating bodies must increase. In an idealized limiting case, that of a reversible process, this sum remains unchanged."
- $\Delta S \geq 0$

Theoretical Limits of Low Power Design (cont'd)

What ist the **Maxwell Demon**?



(src.:en.wikipedia.org)

Theoretical Limits of Low Power Design (cont'd)

What is the **Landauer principle**?

- lower theoretical limit of energy consumption of computation
- An elementary operation (e.g. deleting one bit) must be accompanied by an energy dissipation of

  $$\mathbf{W = kT \ln 2}$$

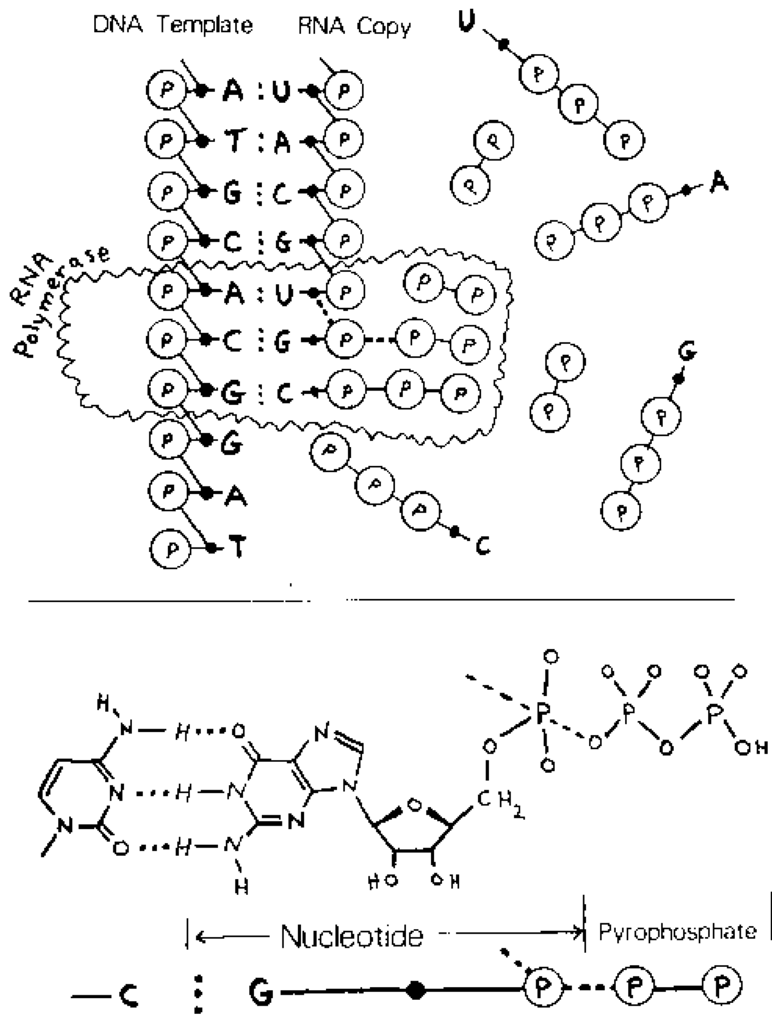
  $$S = k \ln 2$$

- Example
  - W = 0.0172eV at room temperature 20°C

Theoretical Limits of Low Power Design (cont'd)

- Example of (really) low power computation:
  - Neurons dissipate ~10^{11}kT per discharge
  - DNA replication, transcription and translation dissipates 20-100kT per step

    ("Brownian computer")



(src.: [Bennett])

Dark Silicon

- failure of Dennard scaling
- power densities cannot be increase further
- → foreseen: not all parts of the chip can be powered at the same time
- Dark Silicon: % of Silicon that cannot be powered on
- possibly the end of multicore scaling?
- heterogeneous compute elements

Ref. [43] (www.zeit.de → Dark Silicon)

Power/Energy Sources

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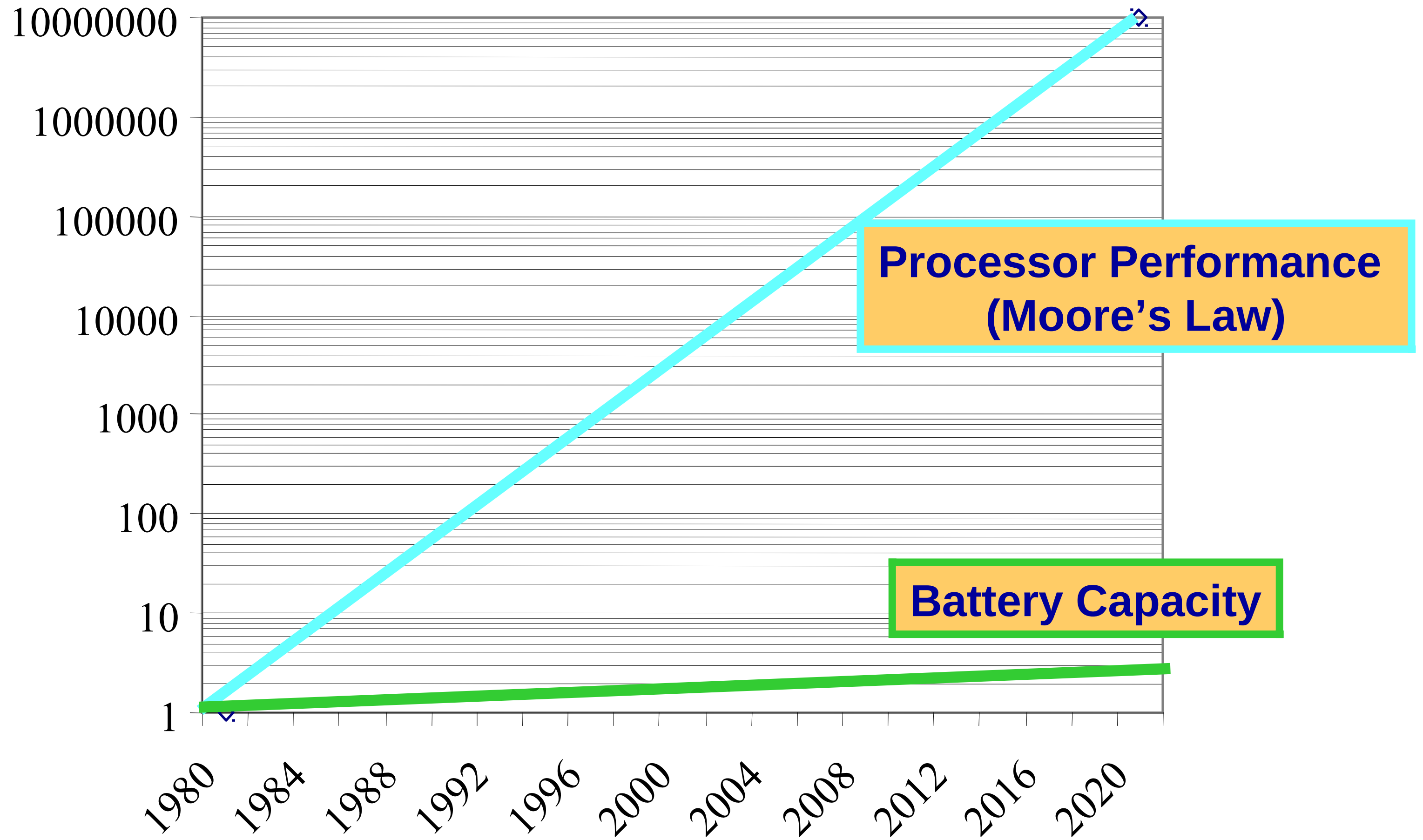
Problem of battery capacity in comparison



(src: A. Cuomo, ST Micro, Stockholm, Sept.8, 2004)

Primary/Secondary Batteries

- Primary batteries

  + availability

  + no re-charging required

  + often higher density compared to secondary batteries (later)

  - cannot be re-charged (replacement of cartridge etc. instead)

  - user needs to carry replacement batteries

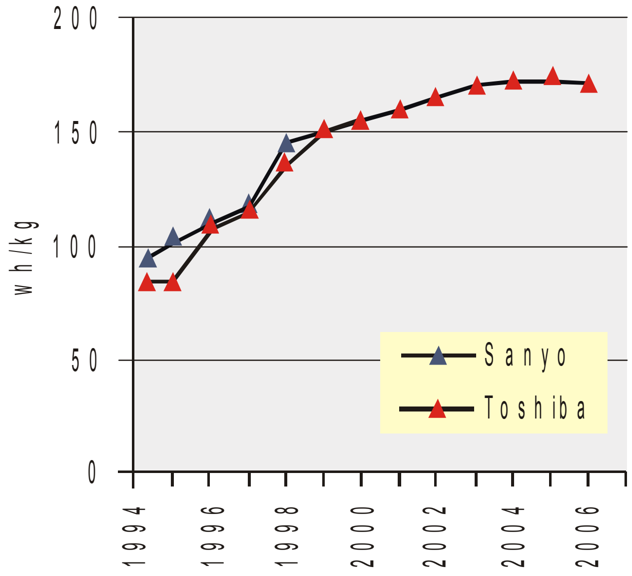
  - form-factor often unfavorable (not flat as desired)

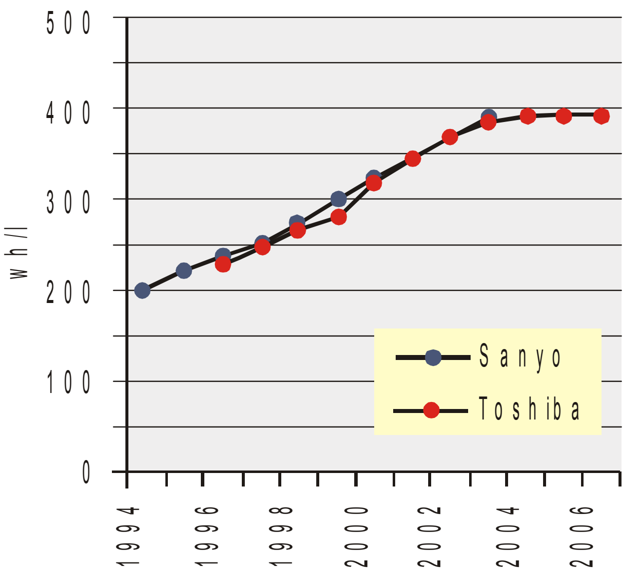
- Secondary batteries
  - Ni-Cd (nickel-cadmium)
  - NiMH (nickel-metal-hydride)
  - Lithium-Ion, Lithium-polymer

  + can be re-charged

  - smaller energy density compared to primary

- **Gravimetric**: Wh/kg → Watt * hours / kg
- **Volumetric**: Wh/l → Watt * hours / liter



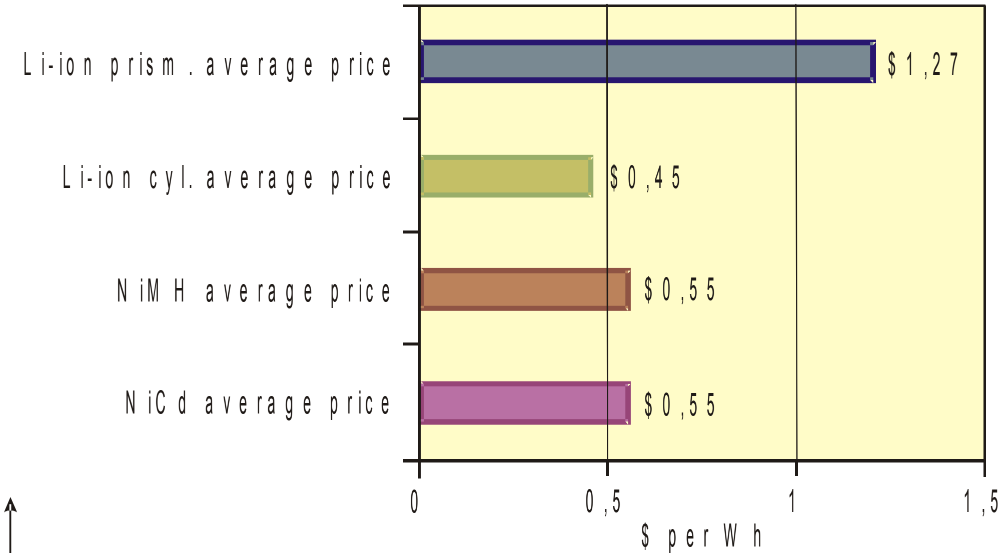


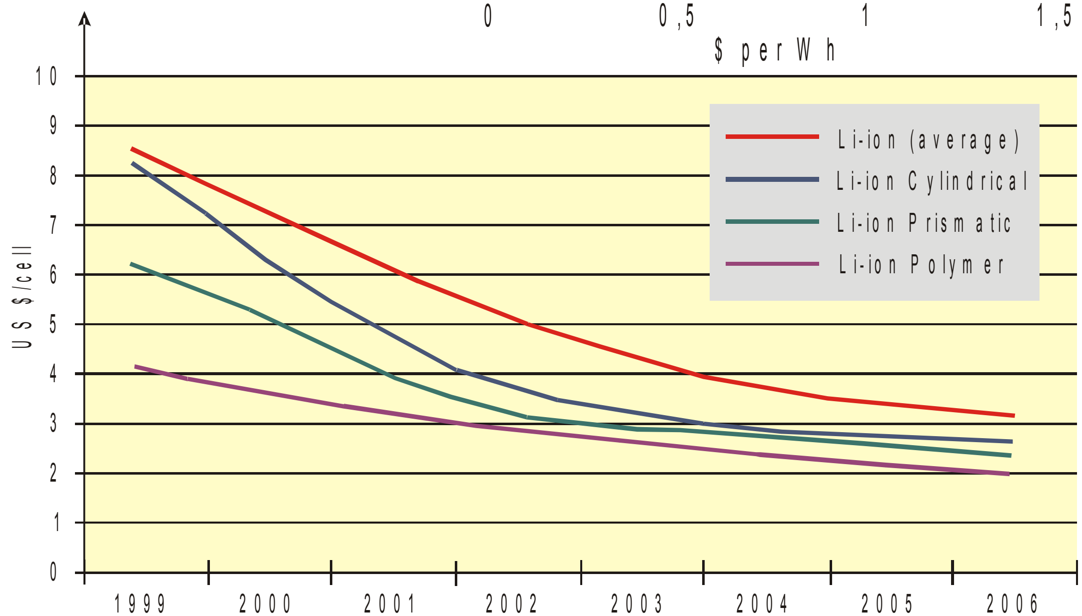
shown: Lithium-Ion technology

(src: [Blo04])

Metrics: cost –secondary batteries–

- average cost of Lithium-Ion technology ~9.5US$/Wh (2005)
- will decrease further but curve is predicted to flatten





Tesla Gigafactory 1

- huge factory for lithium-ion batteries
- currently under construction (Apr, 2016)
- expected to reduce cost of 1kWh by 30%
- planned annual battery production capacity of 35GWh

(src.:www.teslamotors.com)

- example: metal-air system
- obtain oxidant from environment to reduce weight and volume
- anode is metal (eg. Al, Li, Zn, ...)
- positive electrode is ambient air.

- **Negative electrode:**
  - $Zn + 4\,OH^- \rightarrow Zn(OH^-)_4^{2-} + 2\,e^-$ $E_0 = -1.266V$
- **Positive electrode:**
  - $\frac{1}{2}\,O_2 + H_2O + 2\,e^- \rightarrow 2\,OH^-$ $E_0 = 0.401V$
- **Allover reaction:**
  - $Zn + H_2O + \frac{1}{2}\,O_2 \rightarrow ZnO$ $E_0 = 1.667V$

Metal-air system (cont'd)

- Oxidation reaction of zinc with oxygen produces very high energy density: 1350 W·h/kg (theoretical)
- Reaction begins by presence of air and continues until zinc has been used up

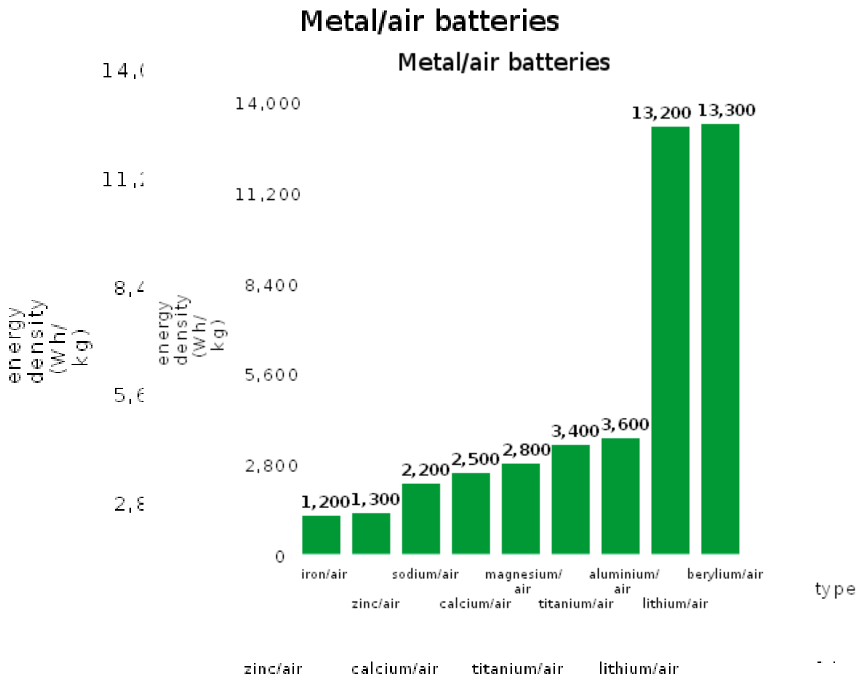
  - For continuous use only

  - No re-charging (then energy density would drop)

  + low cost

  + simple to use

  + environmentally OK (no heavy or noble metals nor hazardous compounds involved)



src.:en.wikipedia.org

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