Energy-Aware Computing Systems

Energiebewusste Rechensysteme

II. Principles

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EA SY

Agenda

Preface

Terminology

System Entities and Properties
  Switching Circuits
  Power and Energy Demand

Interlude: Dark Silicon

System Characterization
  Basic Metrics
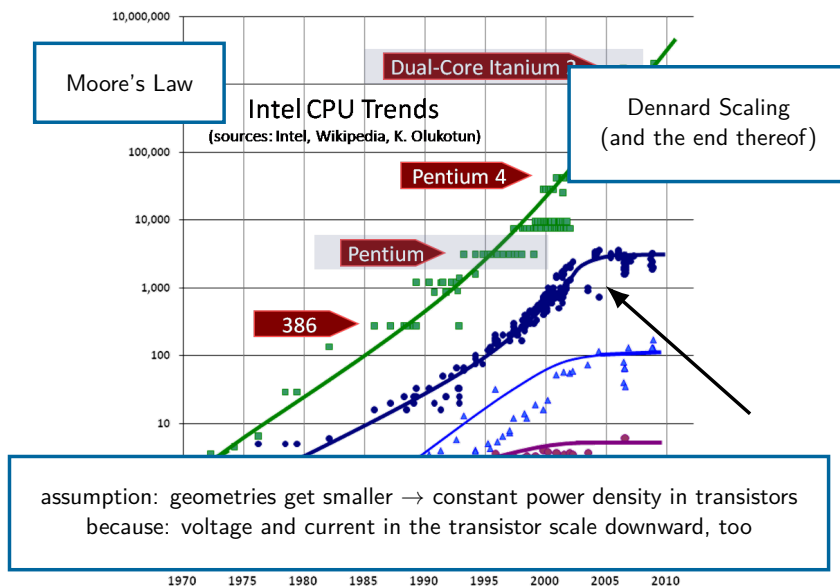 Extended and Composite Metrics

Summary

Preface: The Free Lunch is Over

Moore's Law

Intel CPU Trends
(sources: Intel, Wikipedia, K. Olukotun)

Dennard Scaling
(and the end thereof)

Dual-Core Itanium 2

Pentium 4

Pentium

386

assumption: geometries get smaller → constant power density in transistors
because: voltage and current in the transistor scale downward, too

Sutter '05 [7]

Preface: The Power Wall

Sun's Surface

Rocket Nozzle

Watts/cm^2 [W]

Nuclear Reactor

Pentium® 4

Hot plate

Pentium® III

Pentium® II

i386

i486

1992: 486DX2 (800 nm, 1.2 million transistors, 6.3 W)

× 20

2005: Pentium 4 (90 nm, 169 million transistors, 115 W)

× 1.2

semiconductor process [m]

2019: Core i9-7900X (14 nm, approx. 7 **billion** transistors, 140 W)
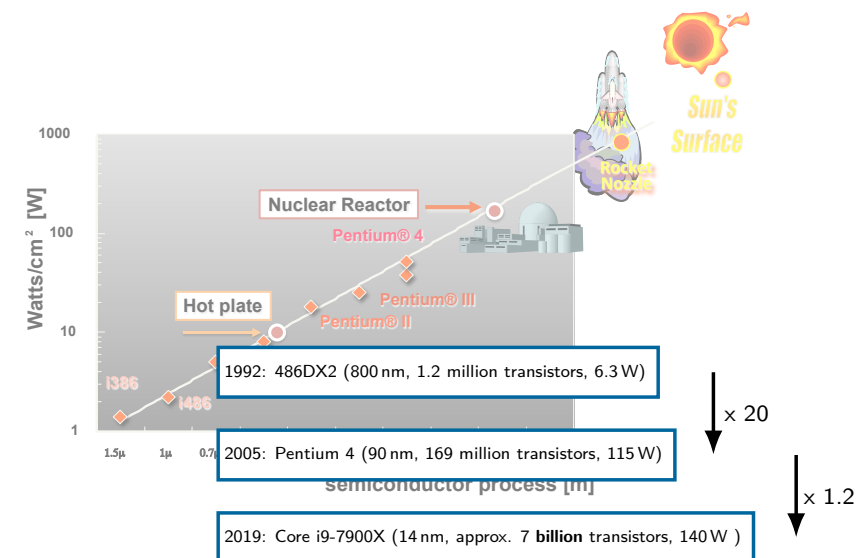
Disambiguation: Energy-Aware Computing Systems

recap: meaning of the lecture labelling in linguistic terms:

en·er·gy (gr.) *energeia*: word based upon *ergon*, meaning *work*
1. capacity for the exertion of power
2. a fundamental entity of nature that is transferred between parts of a system in the production of physical change within the system

aware (old en.) *gewær*
1. having or showing realization, perception, or knowledge
2. state of being conscious of something

com·put·ing (lat.) *computare*: *com* (together) + *putare* (to settle)
1. task of making a calculation
2. to use a computer

sys·tems plural of (gr.) *systēmas*: to place together
1. a regularly interacting or interdependent group of items forming a unified whole
2. a group of devices (...) or an organization forming a network especially for distributing something or serving a common purpose

Disambiguation: Energy-Aware Computing Systems

■ dissecting the terminology

energy	aware	computing	systems
energy	**efficient**	computing	systems
power	aware	computing	systems
power	**efficient**	computing	systems

■ energy vs. power
energy : capacity to do work
power : rate of doing work

■ to be aware as a prerequisite to be efficient
aware : perception and sensing → e.g., measure ground truth
efficient : retrospective, current, and predictive → e.g., ↑ results, ↓ efforts

■ also consider and reflect on: efficient vs. effective
efficient : useful work per quantity of energy invested
effective : degree of reaching a pursued goal
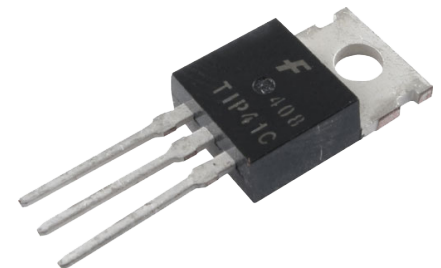
Energy-Aware Computing Systems

■ leading questions → system constraints
  ■ what is the average or maximum power demand? → supply requirements
  ■ which limits (e.g., thermal) must be adhered to? → demand limit
  ■ is there a maximum energy demand? → extend system service duration

■ metrics
  ■ what are the correct **metrics** to answer the leading questions?
  ■ what correlation towards other (non-functional) system properties must be respected?
  ■ what are the influencing factors and variables?

■ methods
  ■ what are the correct **methods** to answer the leading questions?
  ■ how to determine the relevant base data (e.g., power and energy demand)?
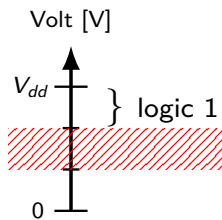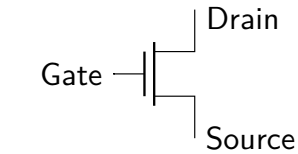 ■ what is the correct momentum of analysis? → a priori / at runtime / a posteriori

Switching Circuit   dt. Schaltkreise

■ switch: a device for making **and** breaking the connection in an *electric* circuit

■ basic components in CMOS technology
  ■ transistors (*imperfect* switches)
  ■ wires (interconnect)
■ transistor types
  ■ NMOS (n-type transistor)
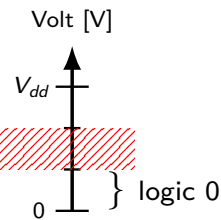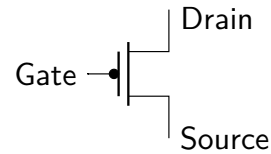 ■ PMOS (p-type transistor)

Basic System Components: Transistors

- NMOS

Drain

Gate

Source

- PMOS

Drain

Gate

Source

Volt [V]

V_{dd} $\}$ logic 1

0

Volt [V]

V_{dd}

0 $\}$ logic 0

logic 1 $V_{gate} > V_{threshold\_high}$ logic 0 $V_{gate} < V_{threshold\_low}$

Logic Gates

- NMOS and PMOS transistors
  - ...implement logic gates
  - ...switch capacitances

In_1

C_{In1}

In_n

C_{Inn}

logic gate

Out

C_{out}
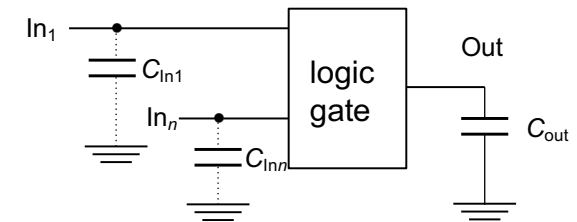
- charges move into and out of capacitors
  - input capacitances (e.g., gate capacitances)
  - output capacitances (e.g., wire length, fanout $\rightarrow$ # driven gates)

Recap: Base Units in Electric Circuits[1]

- Current I
  - flow of electric charge
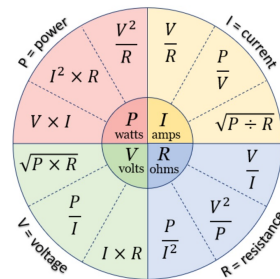 - Ampere, unit: A
- Voltage V
  - potential between two points
    (e.g., ground and V_{dd})
  - Volt, unit: V
- Power P
  - rate at which electrical energy is transferred by an electric circuit
    $\Rightarrow$ power: rate of doing work
  - Watt, unit: W $\rightarrow$ V · A   ...or: J / s
- Energy E
  - energy that is transmitted by electricity or stored in electrical fields
    $\Rightarrow$ energy: ability to do work
  - Joule, unit: J $\rightarrow$ V · A · s   ...or: W · s

[1]Digest

Power and Energy Demand of Systems

Definition (Energy Demand)

The energy demand E of a system is measured in joules (J) and is determined by the integral of power demand over time.

$$E_{\mathrm{op}} = \int_{t_0}^{t_1} p(t) \cdot \mathrm{d}\,t$$

Example

The energy demand E_{op} that is required to execute an operation is calculated by integrating the time function of the power demand $p(t)$ over the time $t_{op} = t_1 - t_0$ required to run the operation.

Power and Energy Demand of Systems

Definition (Power Demand)

The power demand P of a system is measured in joules per second (J/s). One joule per second equals one watt (W).

$$P_{total} = \underbrace{(C_{load} \cdot f_p \cdot A \cdot V_{dd}{}^2)}_{P_{dynamic}} + \underbrace{(I_{short} \cdot V_{dd})}_{P_{short-circuit}} + \underbrace{(I_{leak} \cdot V_{dd})}_{P_{static}}$$

Components of Power Demand

The instantaneous power demand of a circuit is split into three components: **dynamic**, **short-circuit**, and **static** power demand. Dynamic and static power demand commonly dominate.

Dynamic Power Demand

- Dynamic Power Demand
  - Capacitance $C_{load} \rightarrow$ {gate,diffusion,wire} capacitance
  - Operating Frequency $f_p \rightarrow$ clock frequency
  - Activity Factor $A \rightarrow$ fraction of clock frequency, $\{0...1\}$
  - Supply Voltage $V_{dd} \rightarrow$ (dynamic) voltage that is required for operation

$$P_{dynamic} = C_{load} \cdot f_p \cdot A \cdot V_{dd}{}^2$$

| Capacitance	Clock Frequency	Activity Factor	Supply Voltage
$\hookrightarrow$ circuit design	$\hookrightarrow$ limits determined by circuit	$\hookrightarrow$ depends on circuit and usage	$\hookrightarrow$ limits determined by circuit
	$\hookrightarrow$ has performance impact		$\hookrightarrow$ has impact on circuit switching

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Short Circuit and Static Power Demand

- Short-Circuit Power Demand
  - finite rise and fall times of voltages
  - NMOS/PMOS transistors conduct simultaneously $\Rightarrow P_{short} = I_{short} \cdot V_{dd}$
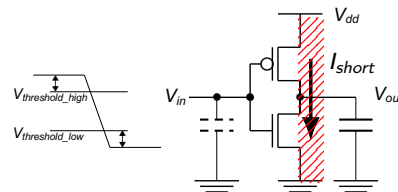
- Static Power Demand (Leakage)
  - gate leakage
  - sub-threshold current
  - drain junction leakage

- Trends
  - capacitances decrease $\rightarrow$ less power is required to drive the capacitance
  - lower supply voltages $\rightarrow$ lower leakage current
  - but: lower threshold voltages $\rightarrow$ higher leakage
  - gap between voltage scaling and transistor scaling results in higher power density and **dark silicon**...

Dennard Scaling Revisited: Dark Silicon   Interlude

- technology trend, state of the art
  - 2019: Core i9-7900X (14 nm, approx. 7 billion transistors, 140 W)
  - chip area unchanged $\Rightarrow \uparrow$ density of transistors $\Rightarrow \uparrow$ power density
  - result: violation of power constraints as to thermal limits
  - effect: hitting the utilization wall [8] leads to unpowered areas
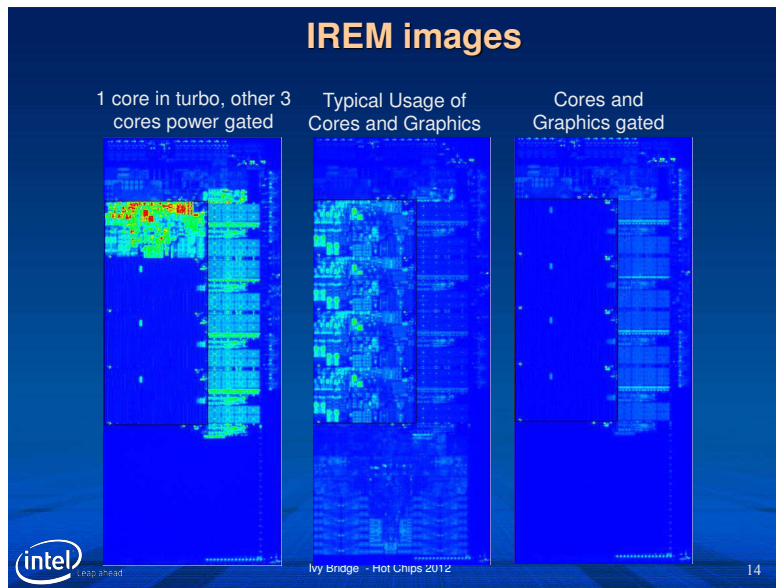
Dark Silicon [2] and its impact...

Although cores fit onto die as to shrinking semiconductor scaling, they can't be powered simultaneously due to power constraints[a]

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[a]at least not at with highest clock speed

- effective (and unbeloved) counter-measures
  - switch off cores
  - run cores with reduced clock speed
  - reschedule activities

Dennard Scaling Revisited: Dark Silicon

Dennard Scaling Revisited: Dark Silicon

- impact of dark silicon
  - future generation systems increasingly interweave design processes of hardware and software components
  - impose challenges for operating systems
  - strict focus on **energy-awareness**

- energy-aware system designs require...
  - comparison of systems with regards to different properties
    - power demand
    - energy demand
    - performance
    - latency
  - design criteria (static) → hardware *and* software
  - system planning (dynamic) → hardware *and* software

- **metrics** and methods for system characterization

Basic Metrics: Power

- Power P (Watt, unit: W or J / s)
  - rate at which electrical energy is transferred by an electric circuit
    ⇒ power: rate of doing work

- Power is a suitable metric for...
  - power supply constraints, cooling facilities → peak power
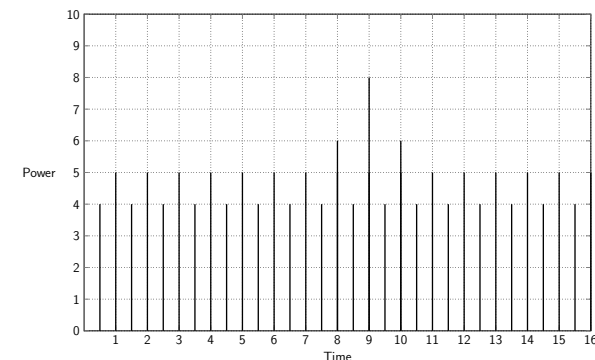 - prediction of heat dissipation → average and peak power
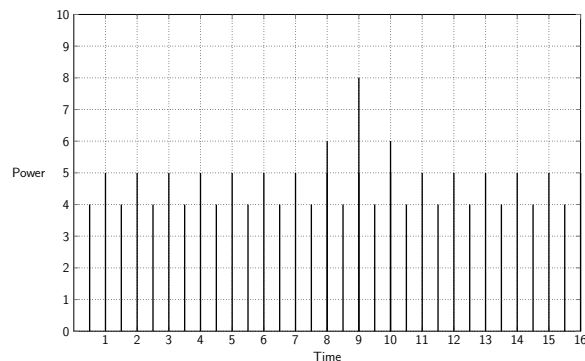
Basic Metrics: Energy

- Energy E (Joule, unit: J or W · s)
  - energy that is transmitted by electricity or stored in electrical fields
    ⇒ energy: ability to do work

- Energy is a suitable metric for...
  - dimensioning of electricity supplies → battery life
  - energy bill

Basic Metrics: Power vs. Energy Revisited

- power and energy demand are insufficient metrics
- system characteristics may differ strongly even though power or energy characteristics are the same
  - performance → execution time in systems
  - latency → response time in networked systems
- extended metrics combine basic metrics (e.g., power, energy demand) with additional system properties (e.g., execution time)

- **basic** metrics are used to build different **composite** metrics
  - **energy demand** itself can be interpreted as a composite metric
  - power-delay* product (PDP):
    power demand (in Watt) · delay (in seconds) → energy demand (in Joule)
- more complex metrics to be explored which consider and emphasize different system properties to varying degrees...

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*delay: time unit, i.e., measured in seconds

Extended and Composite Metrics

- power-delay product (PDP): $P_{avg} \cdot t$
  - average energy consumed per switching event
  - good for fixed voltage designs

- energy-delay product (EDP): $E \cdot t = P_{avg} \cdot t \cdot t$
  - equal weight for changes of **energy demand** and **performance**
  - Horowitz et al. [3]
    ↪ metric is misleading for systems with dynamic voltage scaling → ED²P

- energy-delay-squared product (ED²P)
  - metric good for fixed micro architecture with dynamic voltage scaling
  - Brooks et al. [1]

- energy-delay-cubed product (ED³P)
  - further emphasize on performance, used for high-performance scenarios
  - Srinivasan et al. [6]

Subject Matter

- **power** and **utilization walls** (dark silicon) forces drastic redesign of computing systems for energy awareness
- energy demand of computing systems must be seen in due **consideration** of other **non-functional properties** (e.g., performance)
- available **metrics** must be suitable for individual use

- reading list for Lecture 3:
  - ▶ Vivek Tiwari et al.
    Power Analysis of Embedded Software: A First Step Towards Software Power Minimization
    IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 1994.

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[3] HOROWITZ, M. ; INDERMAUR, T. ; GONZALEZ, R. :
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In: *Proceedings of 1994 IEEE Symposium on Low Power Electronics*, 1994, S. 8–11

[4] JAHAGIRDAR, S. ; GEORGE, V. ; SODHI, I. ; WELLS, R. :
Power management of the third generation Intel Core micro architecture formerly codenamed Ivy Bridge.
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technologies.
In: *Proceedings of the 32nd Annual ACM/IEEE International Symposium on
Microarchitecture*, 1999

[6] SRINIVASAN, V. ; BROOKS, D. ; GSCHWIND, M. ; BOSE, P. ; ZYUBAN, V. ; STRENSKI,
P. N. ; EMMA, P. G.:
Optimizing pipelines for power and performance.
In: *Proceedings of the 35th Annual IEEE/ACM International Symposium on
Microarchitecture*, 2002, S. 333–344

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[8] VENKATESH, G. ; SAMPSON, J. ; GOULDING, N. ; GARCIA, S. ; BRYKSIN, V. ;
LUGO-MARTINEZ, J. ; SWANSON, S. ; TAYLOR, M. B.:
Conservation Cores: Reducing the energy of mature computations.
In: *Proceedings of the 15th International Conference on Architectural Support for
Programming Languages and Operating Systems*, 2010, S. 205–218