# 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

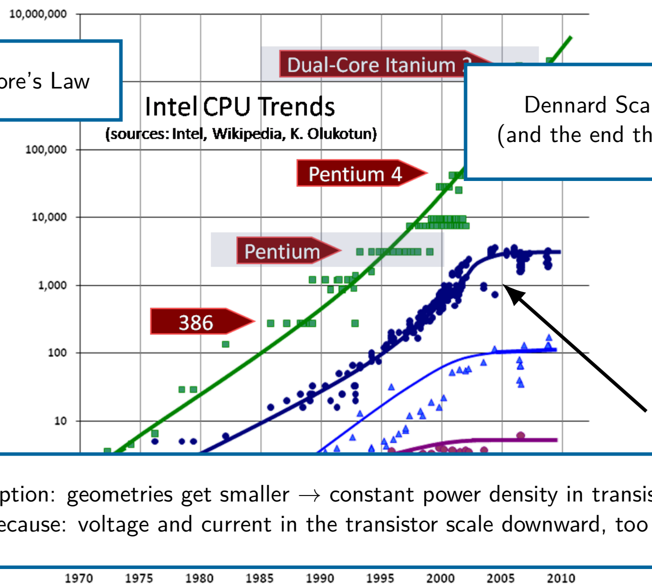
Interlude: Dark Silicon

System Characterization
- Basic Metrics
- Extended and Composite Metrics

Summary



## Preface: The Free Lunch is Over




Moore's Law

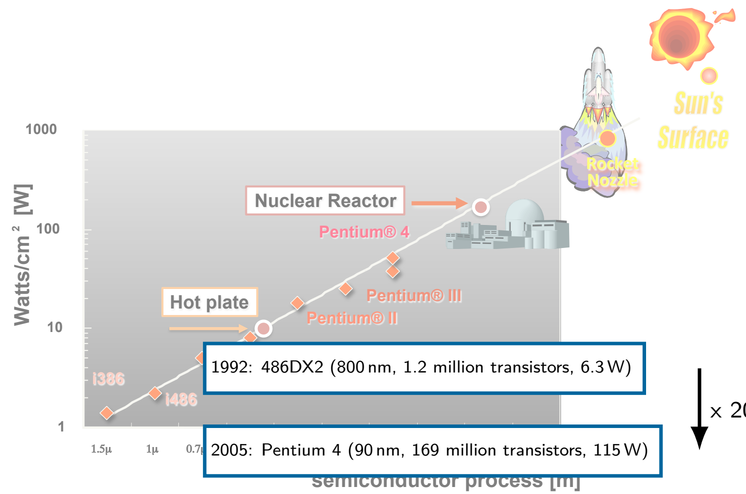
Dennard Scaling (and the end thereof)

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




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

× 20

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

× 1.2

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

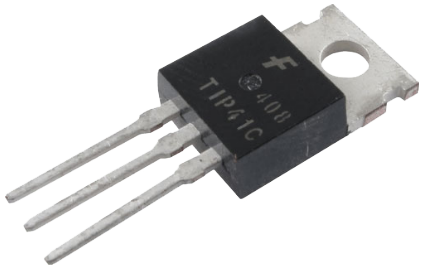
- leading questions → system constraints
  - what is the average or maximum power demand? → supply requirements
  - which limits (e.g., thermal) must be adhered to? → demand limit
  - is there a maximum energy demand? → extend system service duration
- metrics
  - what are the correct **metrics** to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

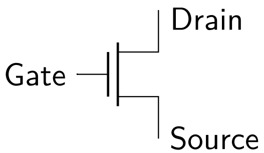
dt. Schaltkreise

- 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)

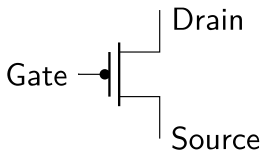


## Basic System Components: Transistors

- NMOS




- PMOS



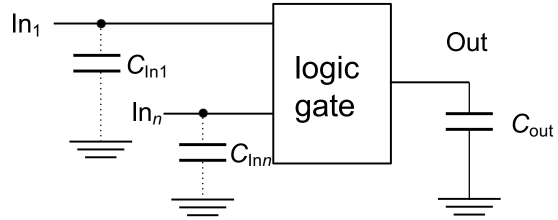


logic 1 $V_{gate} > V_{threshold\_high}$ logic 0 $V_{gate} < V_{threshold\_low}$



## Logic Gates

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

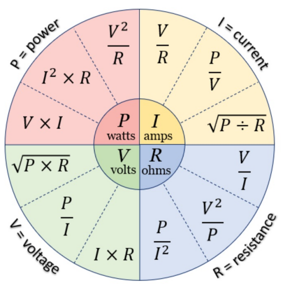



- charges move into and out of capacitors
  - input capacitances (e.g., gate capacitances)
  - output capacitances (e.g., wire length, fanout → # driven gates)



## 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 ⇒ power: rate of doing work
  - Watt, unit: W → V · A ...or: J / s
- Energy $E$
  - energy that is transmitted by electricity or stored in electrical fields ⇒ energy: ability to do work
  - Joule, unit: J → 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.

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

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

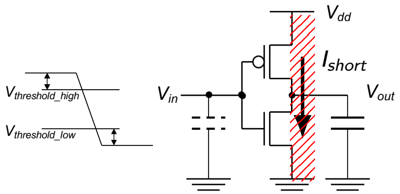
$$P_{dynamic} = C_{load} \cdot f_p \cdot A \cdot {V_{dd}}^2$$

- Capacitance
  ↪ circuit design
- Clock Frequency
  ↪ limits determined by circuit
  ↪ has performance impact
- Activity Factor
  ↪ depends on circuit and usage
- Supply Voltage
  ↪ limits determined by circuit
  ↪ has impact on circuit switching



# Short Circuit and Static Power Demand

- Short-Circuit Power Demand
  - finite rise and fall times of voltages
  - NMOS/PMOS transistors conduct simultaneously ⇒ $P_{short} = I_{short} \cdot V_{dd}$




- Static Power Demand (Leakage)
  - gate leakage
  - sub-threshold current
  - drain junction leakage
- Trends
  - capacitances decrease → less power is required to drive the capacitance
  - lower supply voltages → lower leakage current
  - but: lower threshold voltages → 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 ⇒ ↑ density of transistors ⇒ ↑ 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...

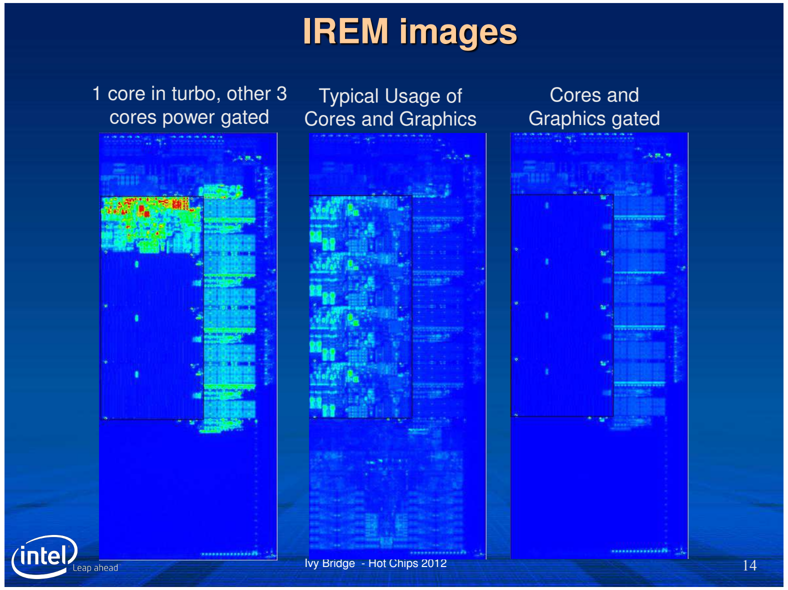
Although cores fit onto die as to shrinking semiconductor scaling, they can't be powered simultaneously due to power constraints[a]

[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






Jahagirdar '12 [4]

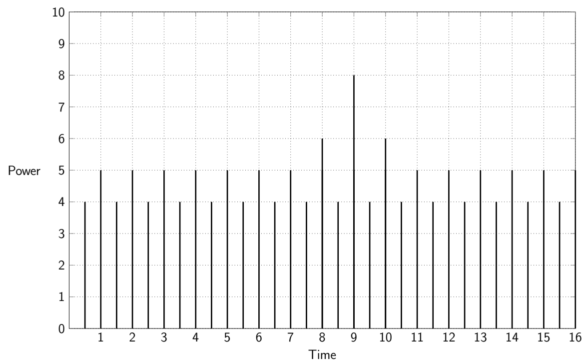
# Dennard Scaling Revisited: Dark Silicon

- 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

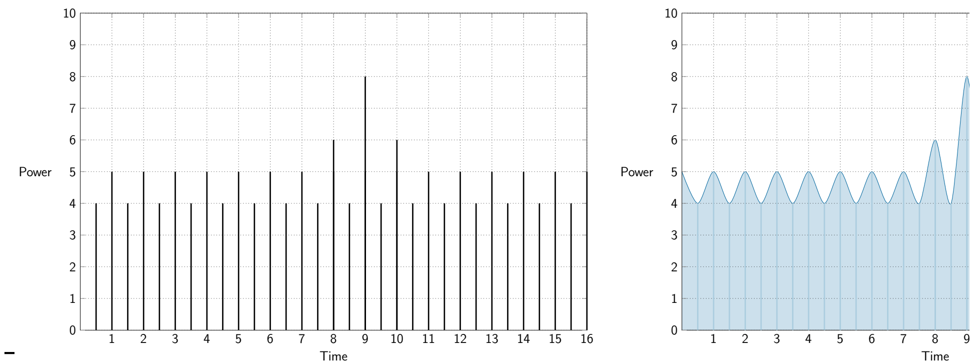
- Power $P$ (Watt, unit: W or J / s)
  - rate at which electrical energy is transferred by an electric circuit
    ⇒ power: rate of doing work
- Power is a suitable metric for...
  - power supply constraints, cooling facilities → peak power
  - prediction of heat dissipation → average and peak power






# 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...

*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 → $ED^2P$
- energy-delay-squared product ($ED^2P$)
  - metric good for fixed micro architecture with dynamic voltage scaling
  - Brooks et al. [1]
- energy-delay-cubed product ($ED^3P$)
  - 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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Conservation Cores: Reducing the energy of mature computations.
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