Robotics and Embedded Systems

Technische Universität München

An introduction to Embedded Systems

Kai Huang

Outline

- What is an Embedded System?
  - Examples
- Characteristics of Embedded Systems
  - Embedded Systems vs. General Purpose Systems
  - Embedded Systems vs. Cyber Physical systems
- Trends in Embedded Systems
- Embedded Systems Design
- Future of Embedded Systems

What is an Embedded System?

- Many definitions exist:

> Embedded Systems = Information processing systems embedded into a larger product.
>
> -- Peter Marwedel, TU Dortmund

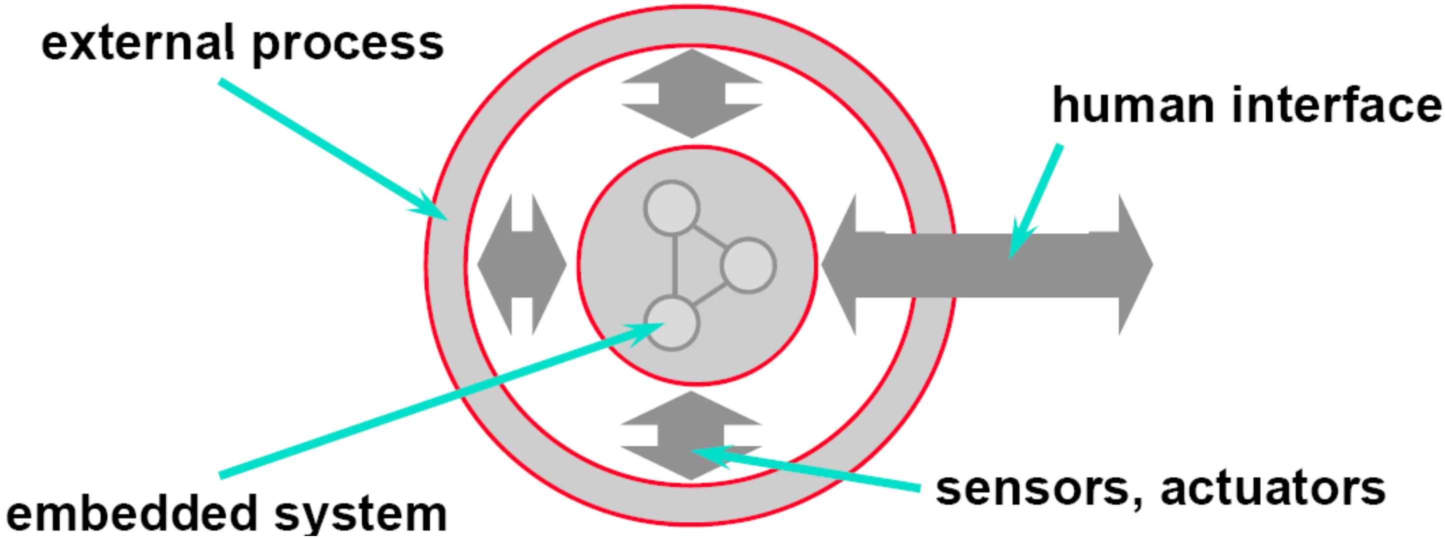
> Embedded Software = Software integrated with physical processes. The technical problem is managing time and concurrency in computational systems.
>
> -- Edward A. Lee, UC Berkeley

Yet Another Definition ...

> Embedded Systems = Information processing systems that are:
> - application domain specific (not general purpose)
> - tightly coupled to their environment

- Examples of application domains: automotive electronics, avionics, multimedia, consumer electronics, etc.
- Environment: type and properties of input/output information.
- Tightly coupled: the environment dictates what the system's response behavior must be. ("ES cannot synchronize with environment")

Embedded Systems

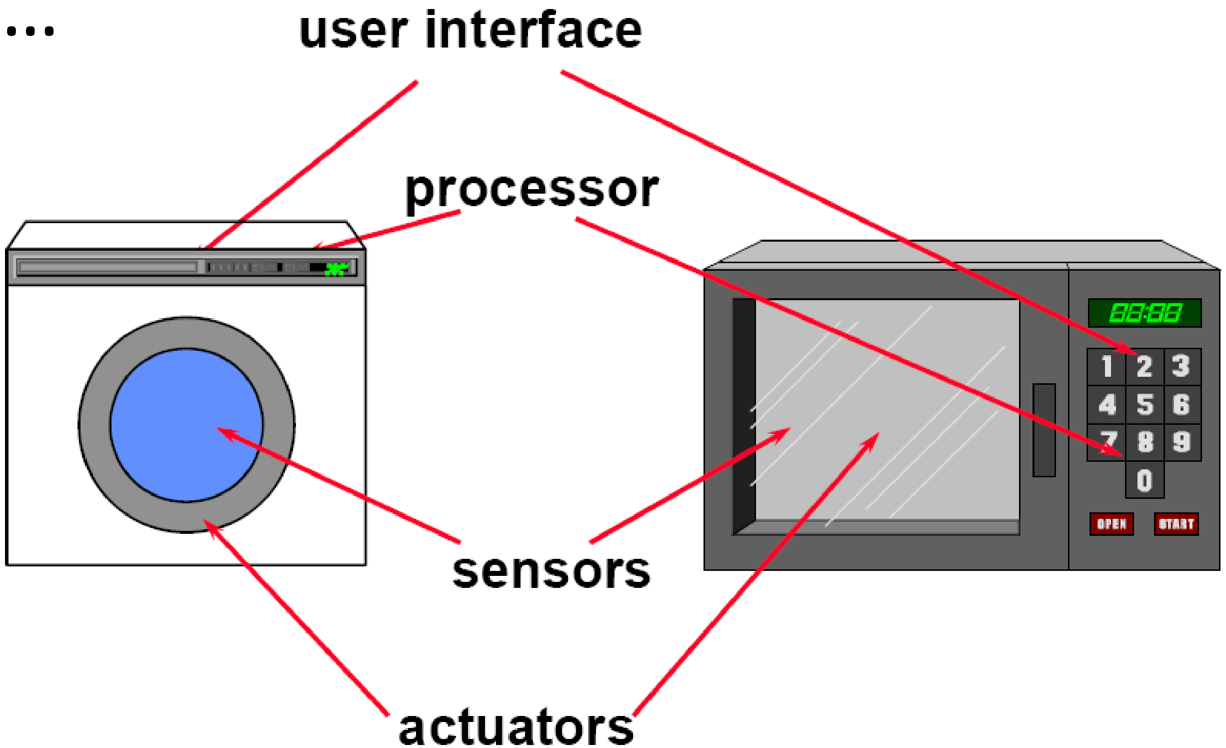


What they do:

- Sense environment(input signals)
- Process input information
- Respond in real-time (output signals)

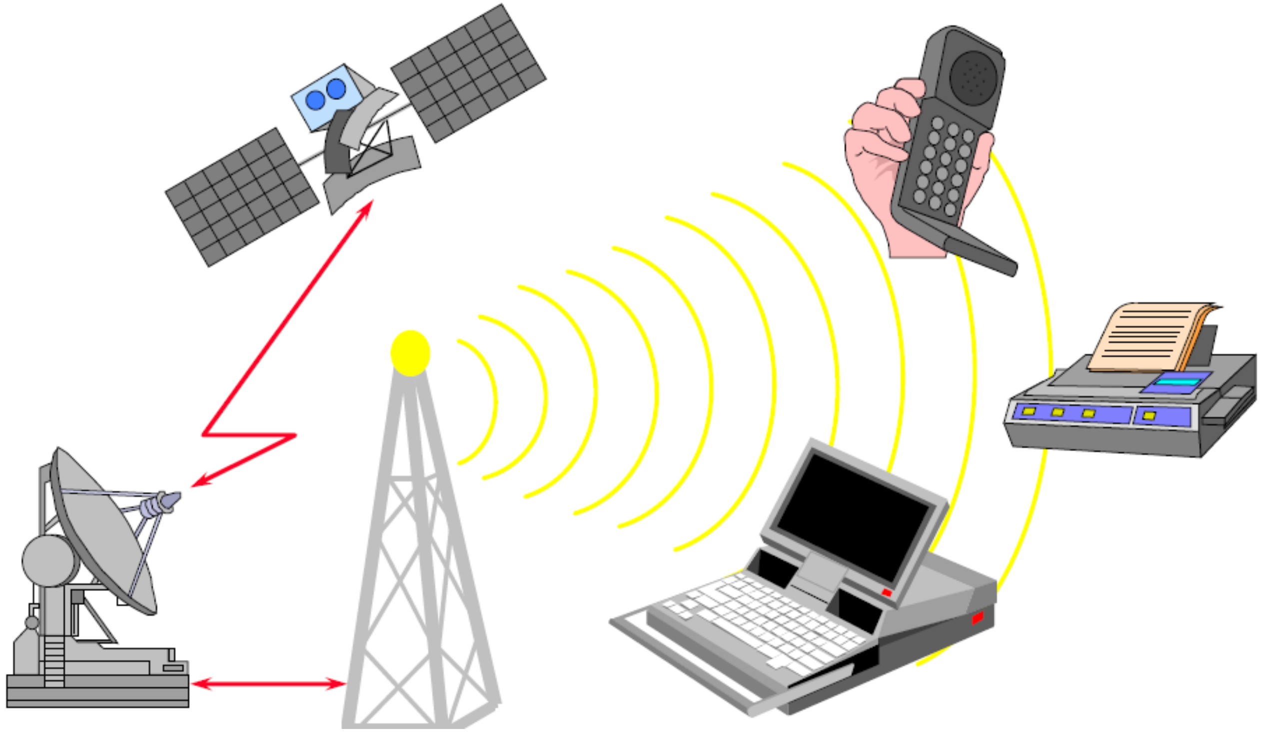
Examples: Consumer Electronics

- MP3 audio, digital camera, Home electronics (washing machine, microwave cooker/oven, …), …



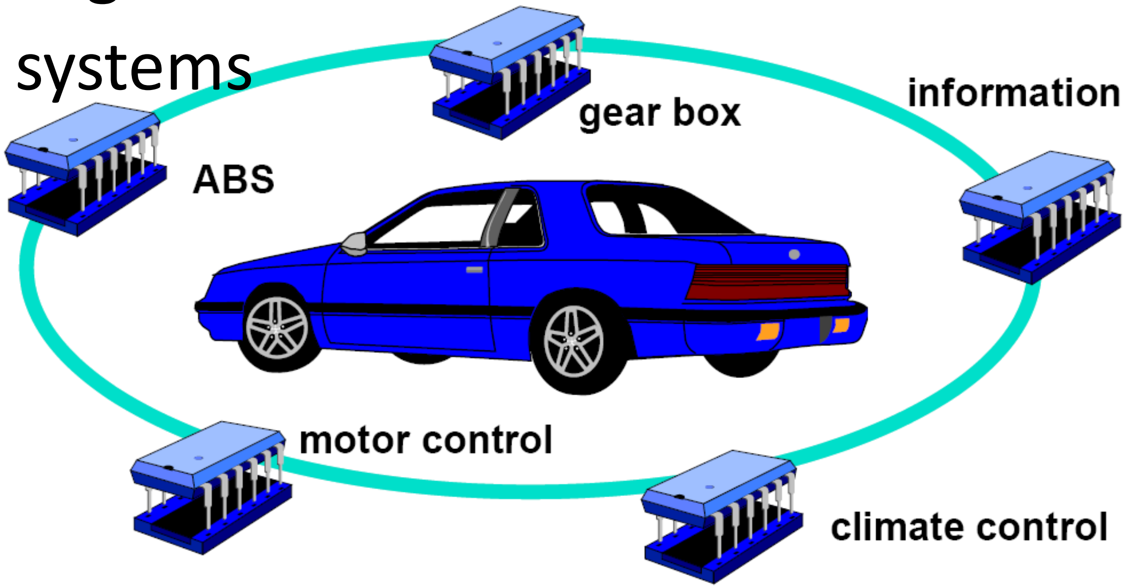
Examples: Telecommunication

- Wireless communication (GSM/3G base station, switch, router, access point, …), end-user equipment, mobile phone…



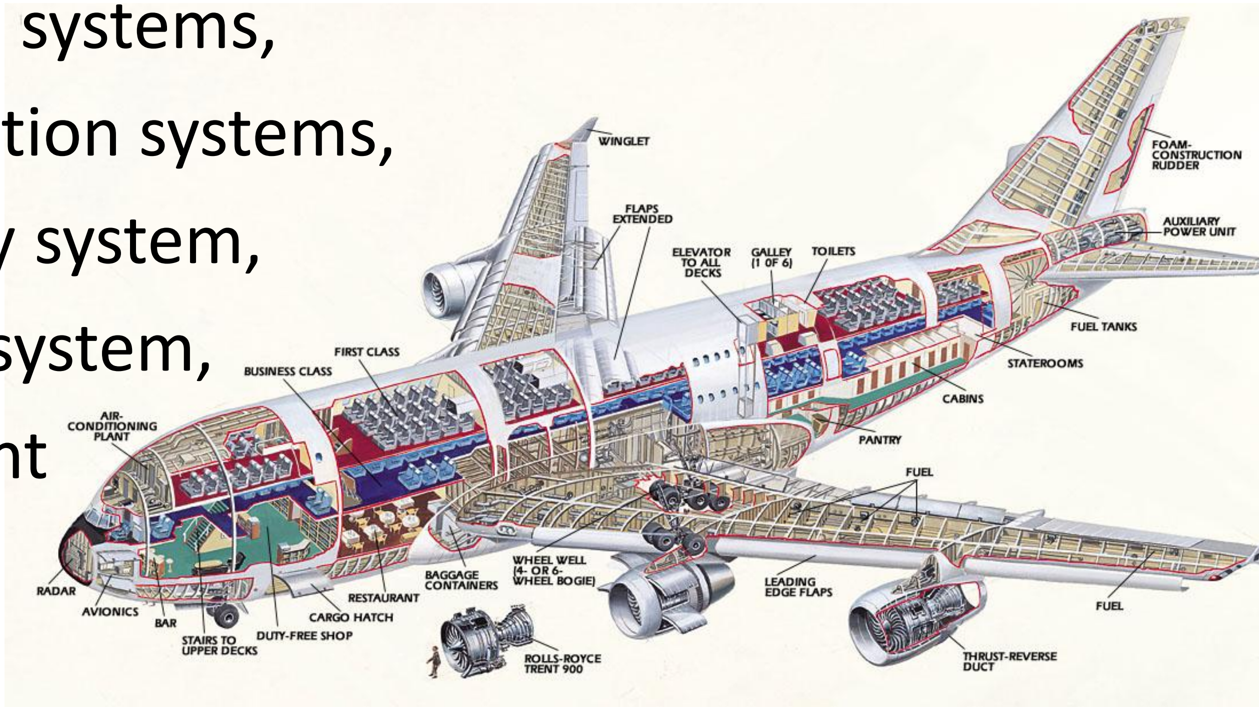
Examples: Automotive Electronics

- A car is an integrated control, communication, and information system.
  - Anti-lock braking systems (ABS)
  - Electronic stability control
  - Efficient automatic gearboxes
  - Blind-angle alert systems
  - Airbags
  - …



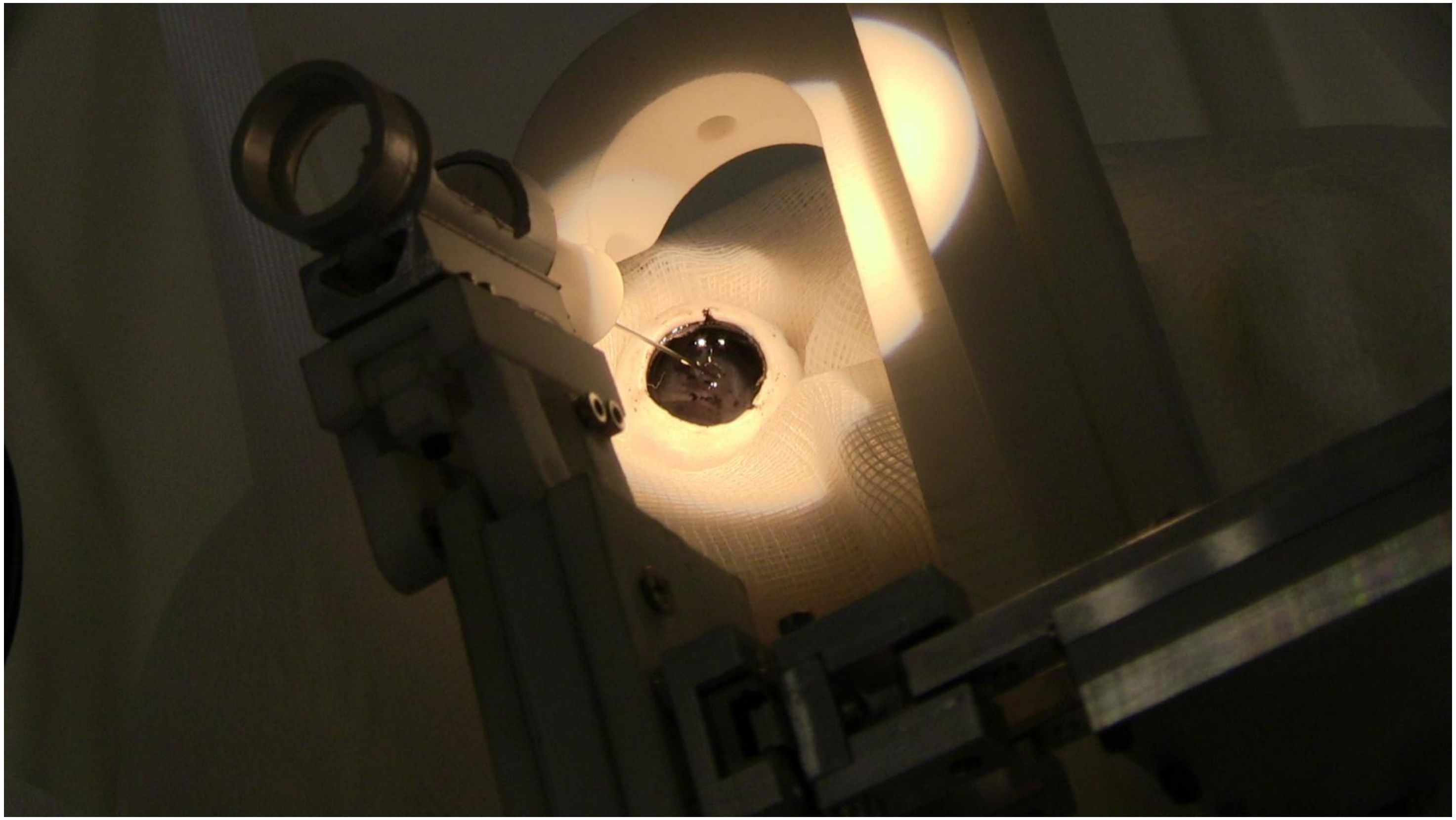
Examples: Avionics

- An plan is another integrated control, communication, and information system.
  - Flight control systems,
  - Anti-collision systems,
  - Pilot information systems,
  - Power supply system,
  - Flap control system,
  - Entertainment system
  - …



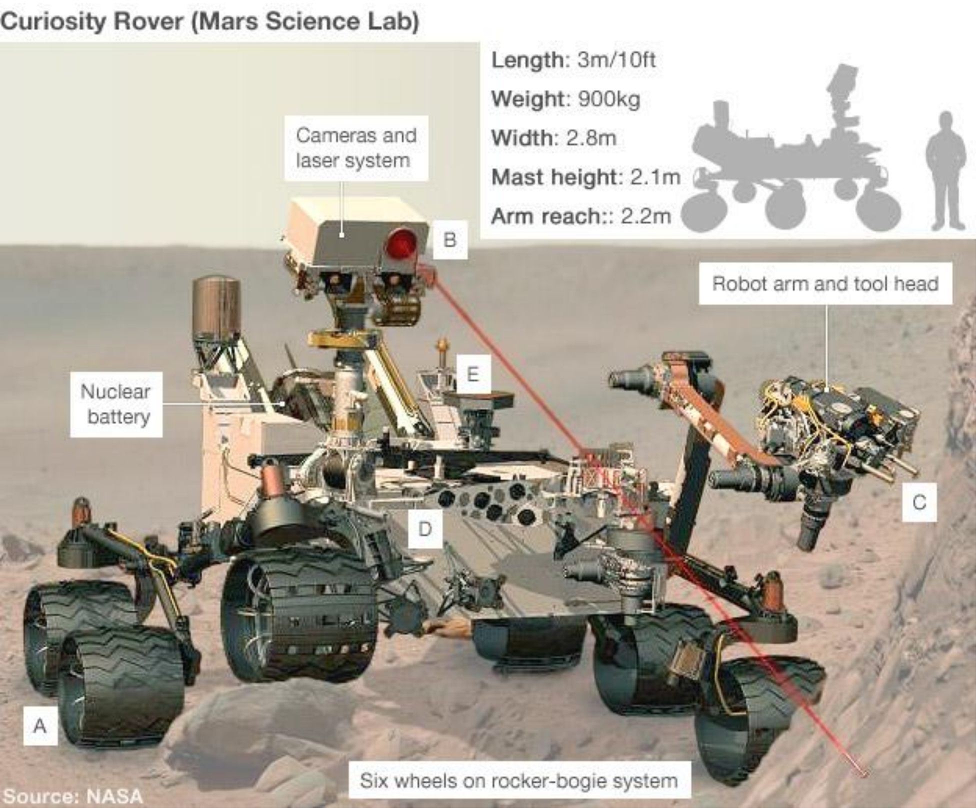
Examples: Medical Systems

- The future of surgery is not in blood and guts, but in bits and bytes.



Examples: Robotics

NASA Curiosity Rover



Sony Robotic Dog

Examples: Gaming

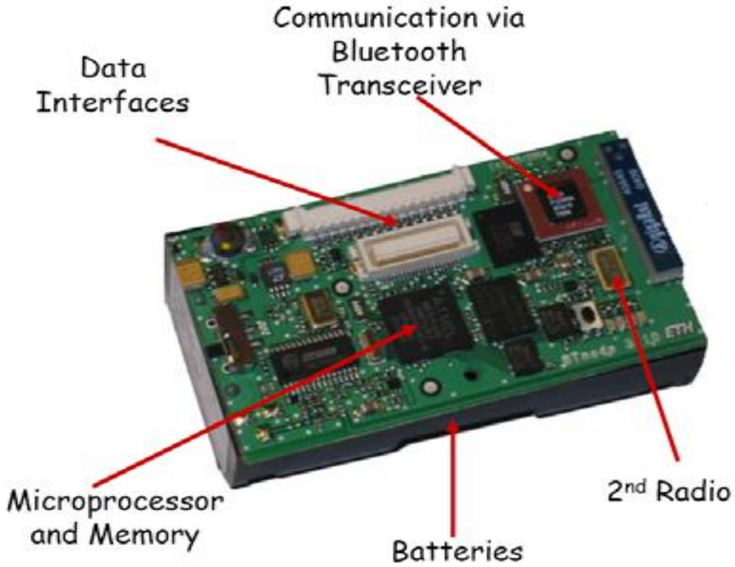
Wii

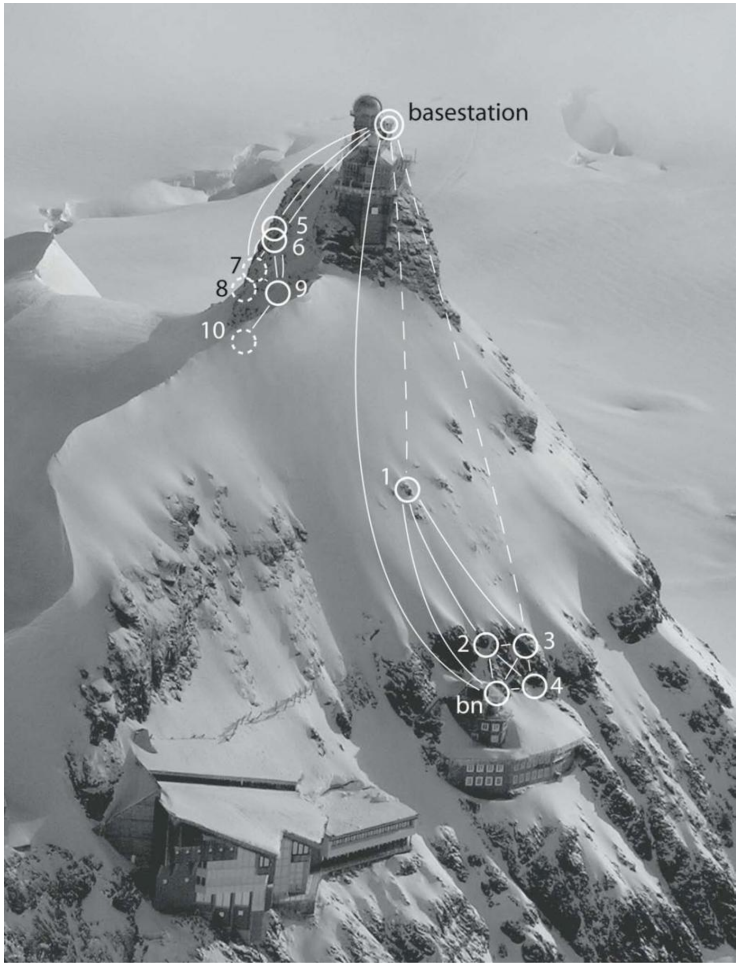
Play station 3

MS XBOX & Kinect

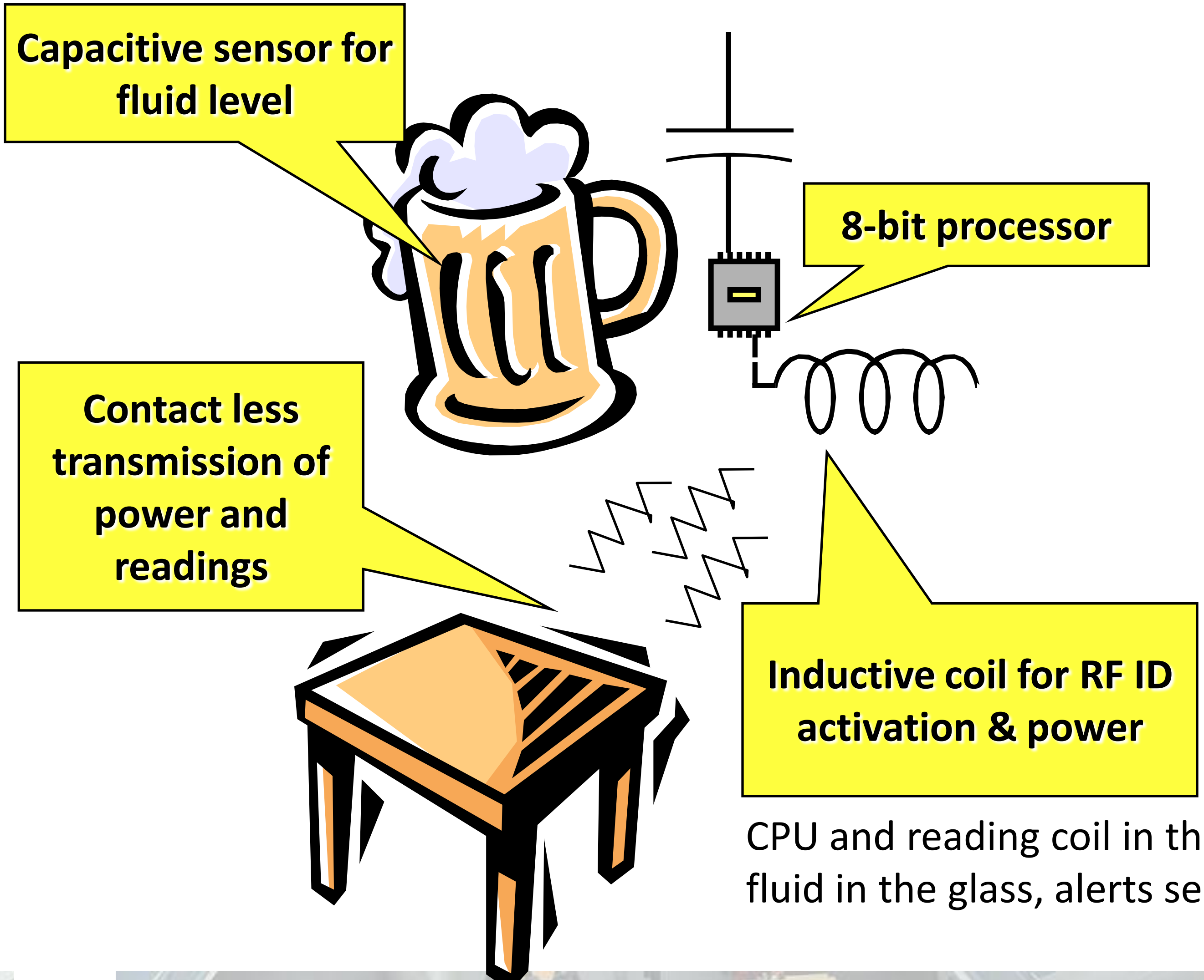
Examples: (Wireless) Sensor Network

- Sensor networks (civil engineering, buildings, environmental monitoring, traffic, emergency situations)
- Smart products, wearable/ubiquitous computing





Smart Beer Glass



- Integrates several technologies:
  - Radio transmissions
  - Sensor technology
  - Magnetic inductance for power
  - Computer used for calibration
- Impossible without the computer
- Meaningless without the electronics

CPU and reading coil in the table. Reports the level of fluid in the glass, alerts servers when close to empty

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Characteristics of Embedded Systems (1)

- Must be dependable
  - Reliability: R(t) = probability of a system working correctly at time t provided that it was working at t = 0
  - Maintainability: M(d) = probability of a system working correctly d time units after error occurred
  - Availability: A(t) = probability of system working at time t
  - Safety: no harm to be caused by failing system
  - Security: confidential and authentic communication

- Even perfectly designed systems can fail if the assumptions about the workload and possible errors turn out to be wrong.
- Making the system dependable must not be an after-thought, it must be considered from the very beginning.

Characteristics of Embedded Systems (2)

- Must be efficient
  - Energy efficient
    - Many ES are mobile systems powered by batteries
    - Customers expect long run-times from batteries but
    - Battery technology improves at a very slow rate
  - Code-size efficient (especially for systems on a chip)
    - Typically there are no hard discs or huge memories to store code
  - Run-time efficient
    - Meet time constraints with least amount of HW resources and energy – only necessary HW should be present working at as low as possible Vdd and fclk
  - Weight efficient (especially for portable ES)
  - Cost efficient (especially for high-volume ES)

Characteristics of Embedded Systems (3)

- Many ES must meet real-time constraints
  - A real-time system must react to stimuli from the controlled object (or the operator) within the time interval dictated by the environment.
  - For real-time systems, right answers arriving too late (or even too early) are wrong.

> “A real-time constraint is called hard, if not meeting that constraint could result in a catastrophe“ [Kopetz, 1997].

- All other time-constraints are called soft.
- A guaranteed system response has to be explained without statistical arguments.

Characteristics of Embedded Systems (4)

- ES are connected to physical environment through sensors and actuators.
- Hybrid Systems, i.e., composed of analog and digital parts
- Typically, ES are reactive systems

> "A reactive system is one which is in continual interaction with is environment and executes at a pace determined by that environment" [Bergé, 1995].

  - Behavior depends on input and current state.
    - automata model appropriate

Characteristics of Embedded Systems (5)

- All ES are dedicated systems
  - Dedicated towards a certain application:
    - Knowledge about the behavior at design time can be used to minimize resources and to maximize robustness
  - Dedicated user interface:
    - No mice, no large keyboards and monitors

Not every ES has all of the above characteristics, thus

> We can define the term “Embedded System” as follows: Information processing systems having most of the above characteristics are called embedded systems.

Comparison

Embedded Systems

- Execute few applications that are known at design-time
- Non programmable by the end user
- Fixed run-time requirements (additional computing power not useful)

- Important criteria
  - Cost
  - Power consumption
  - Predictability
  - ...

General Purpose Systems

- Execute broad class of applications
- Programmable by the end user
- Faster is better

- Important criteria
  - Cost
  - Average speed

Another Name？ Cyber-Physical Systems

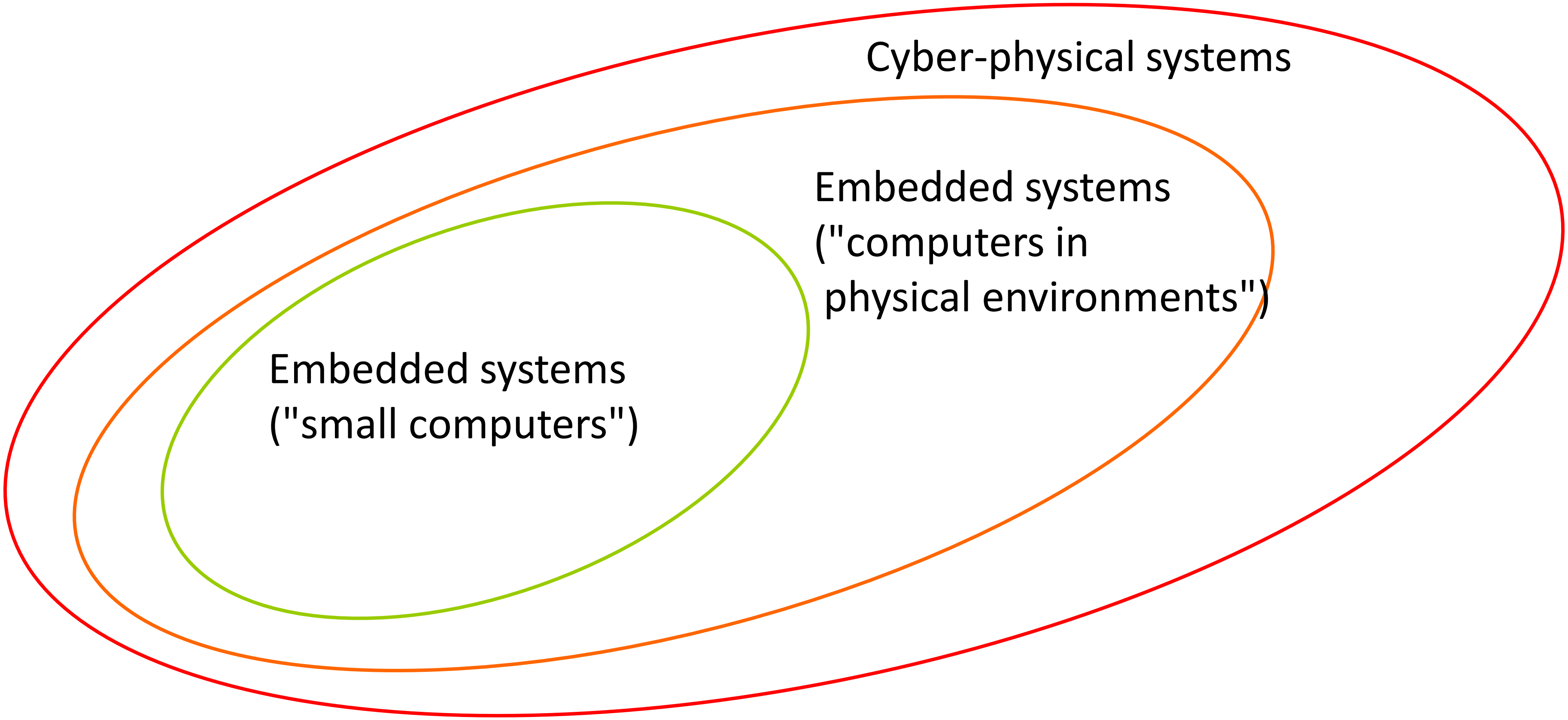
Definition of Cyber-Physical System

- Defined by those with Money
  - Smart electric grid
  - Smart transportation
- Wikipedia
  - A full-fledged CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices
- Cyber-Physical (cy-phy) Systems (CPS) are integrations of computation with physical processes [Edward Lee, 2006].

- *Cyber-physical system* (CPS) *=*
  Embedded System (ES) *+ physical environment*

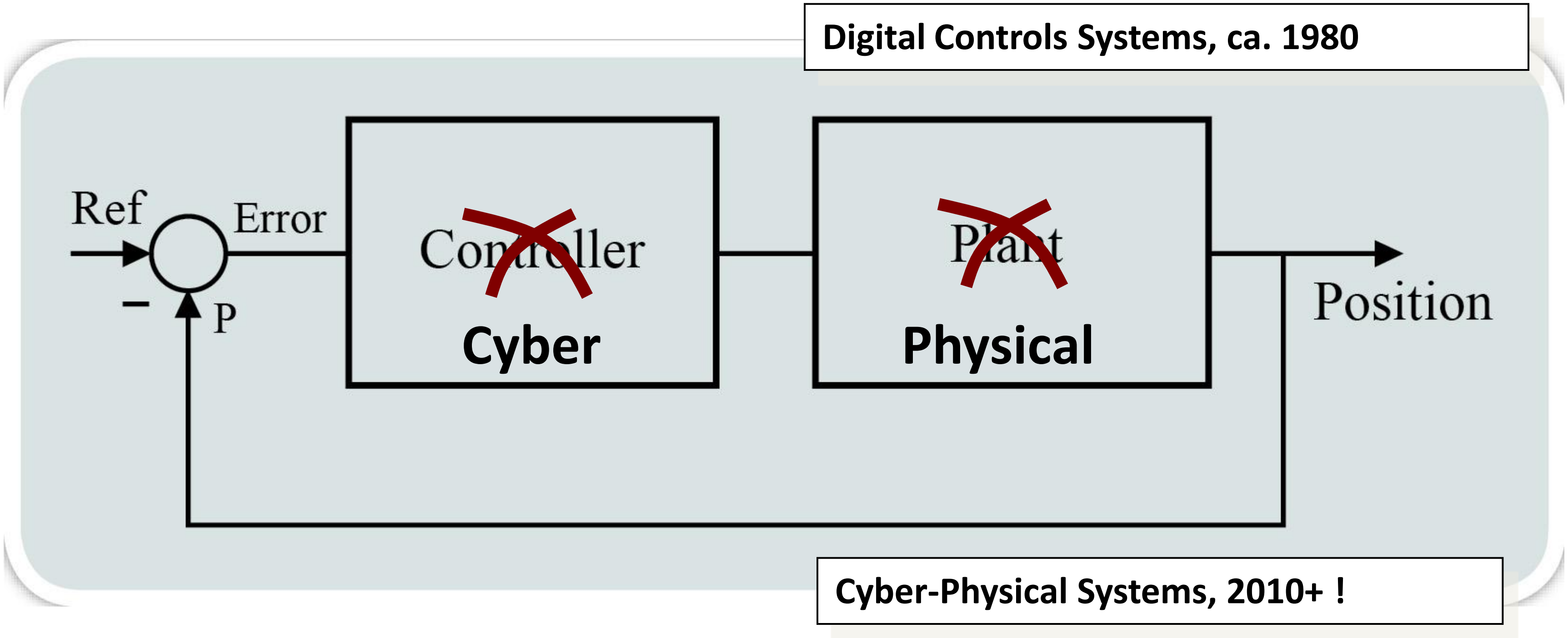
Cyber-Physical Systems and Embedded Systems

- *CPS = ES + physical environment*



What is a Cyber-Physical System?

- Extreme view:



Definition According to National Science Foundation (US)

- Cyber-physical systems (CPS) are engineered systems that are built from and depend upon the synergy of computational and physical components.
- Emerging CPS will be coordinated, distributed, and connected, and must be robust and responsive.
- The CPS of tomorrow will need to far exceed the systems of today in capability, adaptability, resiliency, safety, security, and usability.
- Examples of the many CPS application areas include the smart electric grid, smart transportation, smart buildings, smart medical technologies, next-generation air traffic management, and advanced manufacturing.
- http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503286

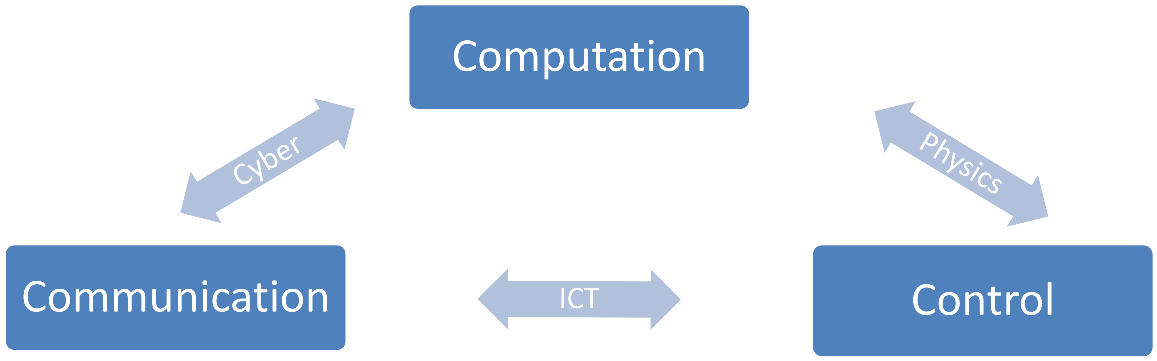
Definition According to Akatech

- The physical world and the virtual world – or cyber-space – are merging; cyber-physical systems are developing. Future cyber-physical systems will contribute to security, efficiency, comfort and health systems as never before, and as a result, they will contribute to solving key challenges of our society, such as the aging population, limited resources, mobility, or energy transition.

    - [Akatech: Cyber-Physical Systems. Driving force for innovation in mobility, health, energy and production, http://www.acatech.de/de/publikationen/stellungnahmen/kooperationen/detail/artikel/cyber-physical-systems-innovationsmotor-fuer-mobilitaet-gesundheit-energie-und-produktion.html]

Cyber-Physical Systems vs. Embedded Systems

- More safe
- CPS = systems of (embedded) systems
  - ES is sub-system of CSP
- The 3C concept
  - Computation, communication, and control



- New name for funding …

Content of an Embedded Systems Course

- ES focus
  - Hardware interfacing
  - Interrupts
  - Memory systems
  - C programming
  - Assembly language
  - FPGA design
  - RTOS design
  - …
- CPS focus
  - Modeling
  - Timing
  - Dynamics
  - Imperative logic
  - Concurrency
  - Verification
  - ...

-- Edward A. Lee, UC Berkeley

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Trends in Embedded Systems

- In the past Embedded Systems were called Embedded (micro-)Controllers
- They appeared typically in control dominated applications:
  - Traffic lights control
  - Elevators control
  - Washing machines and dishwashers
  - Electronic Control Unit (ECU)
  - ...
- They were implemented using a single µProcessor or dedicated HW (sequential circuit)

➢ All this is rapidly changing nowadays.
  - How And Why?

Trend 1: Towards Multi-Processor Systems

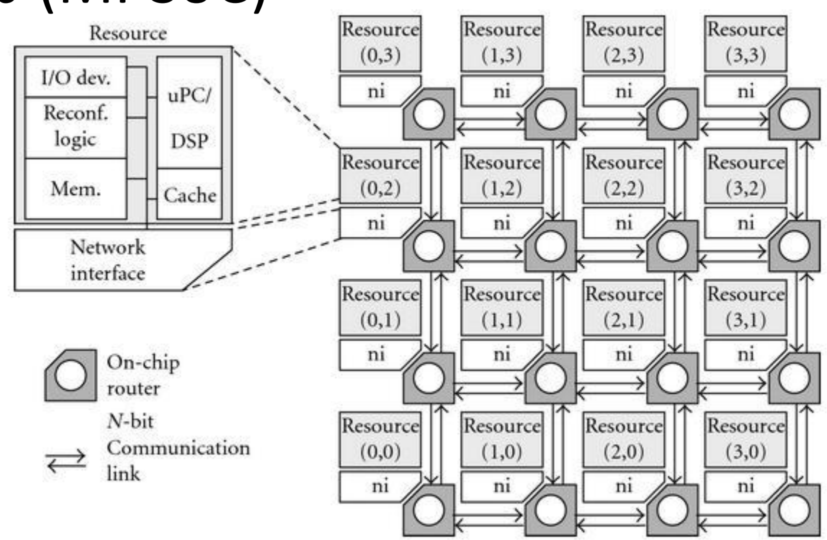
Complexity of ES is increasing, thus

- A single uProcessor is sufficient for some consumer products
  - Application performance demands relatively low
- For other systems – such as cars and aircrafts – a network of processors is needed
  - Due to performance requirements
  - Due to safety requirements (a single failed component should not cause total system failure)
- For some systems – such as mobile devices – a network of heterogeneous processors is needed
  - Due to run-time efficiency requirements
  - Due to power efficiency

Trend 2: Higher Degree of Integration

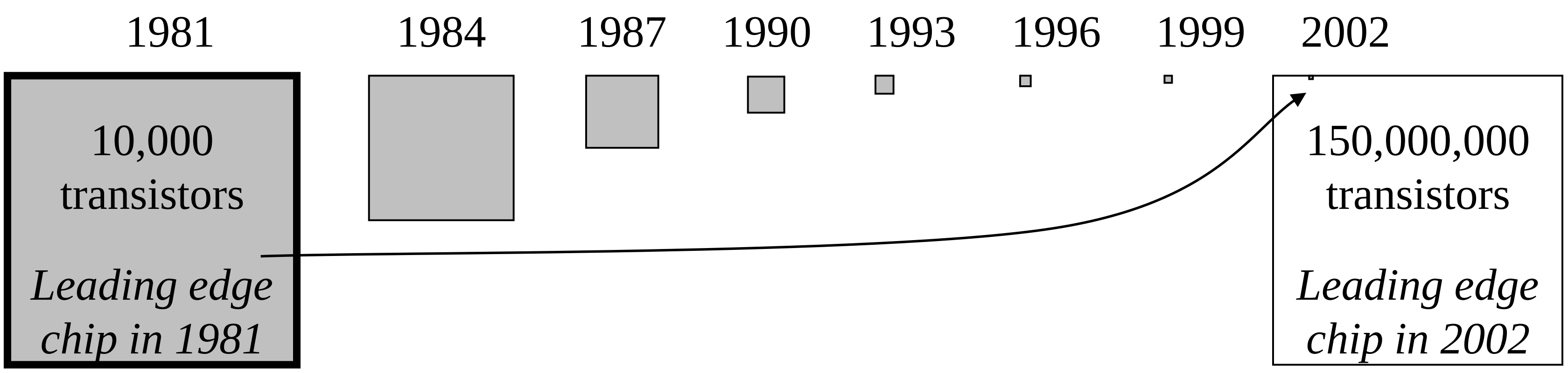
Moore's Law: the number of transistors that can be placed on a chip has doubled approximately every two years

- Microprocessor, microcontroller
- System-on-Chip (SoC)
  - Processor + memory + I/O-units + communication structure
- Multi-processor System on a Chip (MPSoC)
  - Processor – Co-processor
  - (Heterogeneous) Multi-processor
  - Network on Chip
    - Identical tiles
    - Scalable system



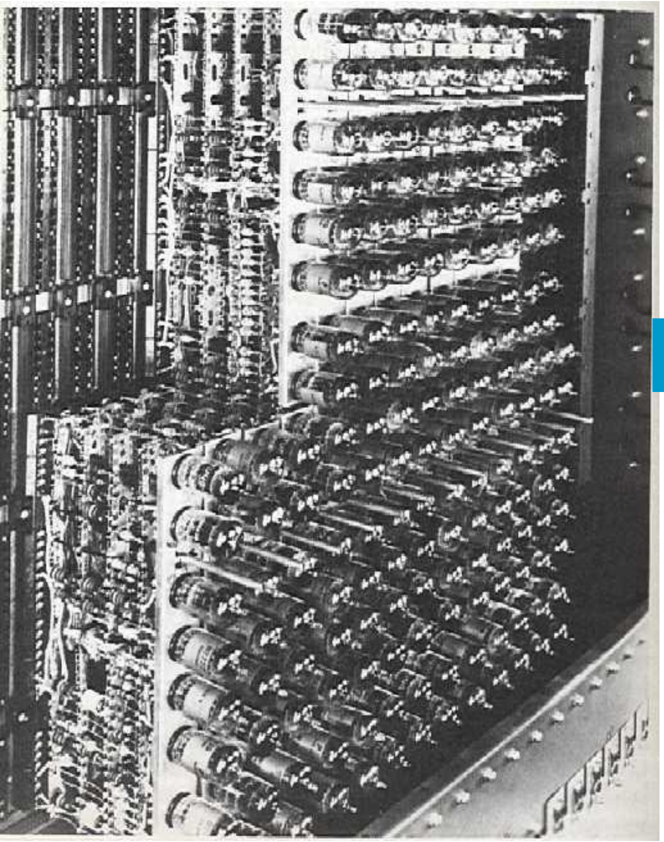
Graphical Illustration of Moore’s law

- **Moore's law** is the observation that, over the history of computing hardware, the number of transistors on integrated circuits doubles approximately every two years.

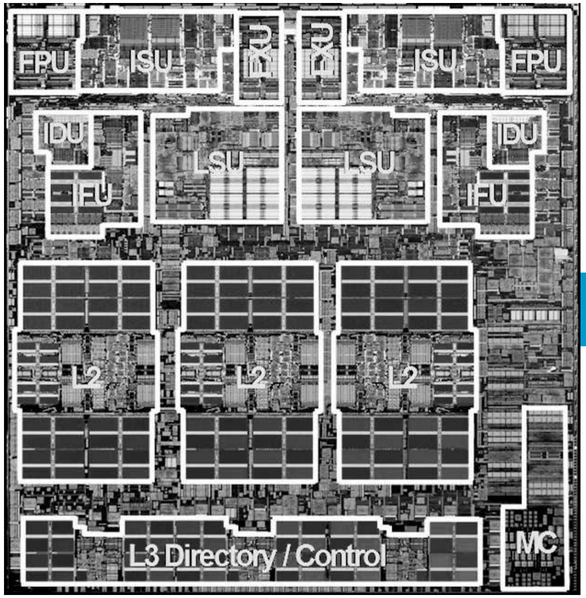


- Something that doubles frequently grows more quickly than most people realize!
  - A 2002 chip could hold about 15,000 1981 chips inside itself

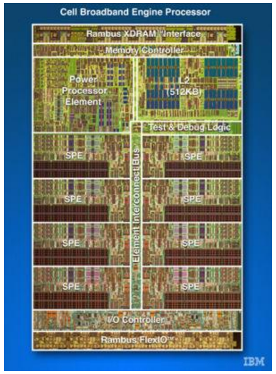
Graphical Illustration of Moore's law



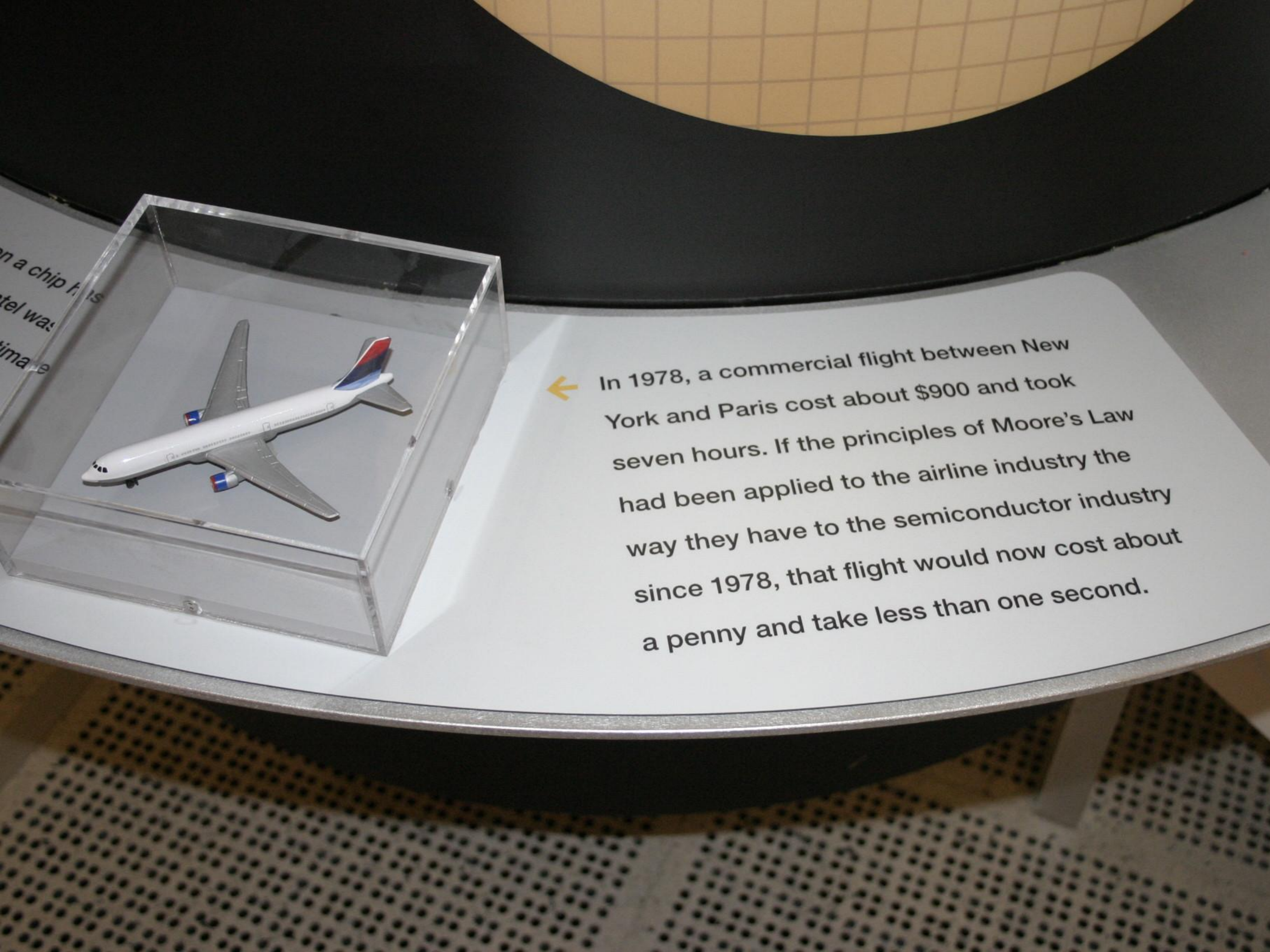
IBM 701 calculator (1952)



IBM Power 5 IC (2004)



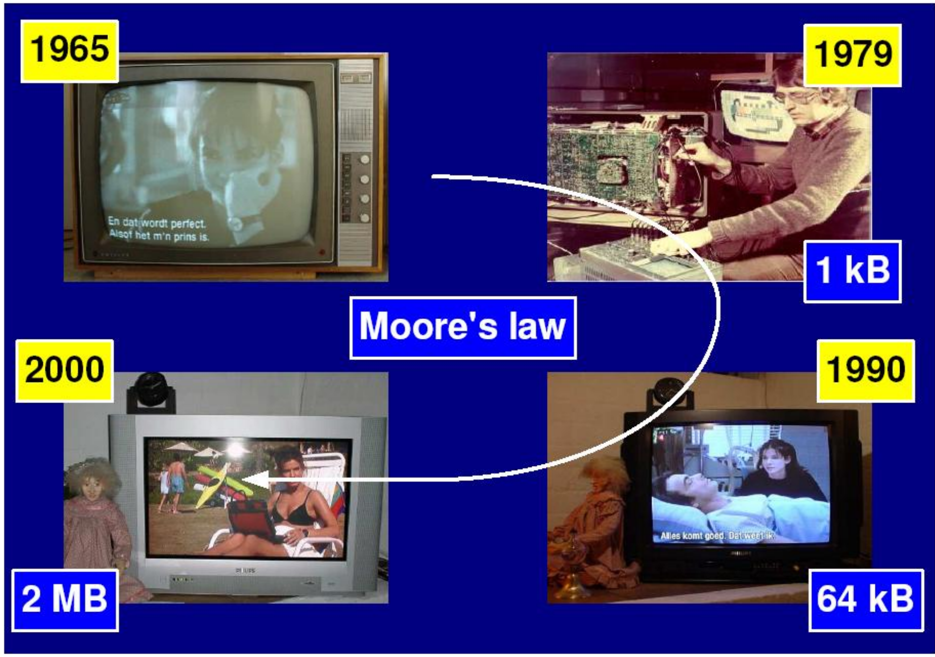
IBM PowerXCell 8i (2008)


In 1978, a commercial flight between New York and Paris cost about $900 and took seven hours. If the principles of Moore's Law had been applied to the airline industry the way they have to the semiconductor industry since 1978, that flight would now cost about a penny and take less than one second.

Trend 3: Software Increasing

Implementing ES in specialized HW brings lack of flexibility (changing standards) and very expensive masks, thus

- Most of the functionality will be implemented in software
  - On the average, a human "touches" about 50 to 100 micro-processors per day
  - State-of-art car has 70~100 micro-processors
- Exponential increase in software complexity



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Embedded Systems Design (1)

Embedded Systems Design is NOT just a special case of either hardware (Computer/Electrical Engineering) or software (SoftwareEngineering/Computer Science) design.

- An embedded system performs computation that is subject to physical constraints, i.e., interaction with a physical environment and execution on a physical (implementation) platform
  - Interaction constraints: deadlines, throughput, jitter
  - Execution constraints: available resources, power, failure rates
- It has functional requirements (expected services), and it has non-functional requirements (performance, power, cost, robustness, etc.)

Embedded Systems Design (2)

- Computer Science provides (software) functionality for Instruction Set Architectures (ISA) which are characterized by
  - Instruction set
  - Organization (program counter, register file, memory)
  - Both independent of any logical implementation and physical realization
- Computer/Electrical Engineering deals with
  - Logical implementation
  - Physical realization
- Embedded Systems design discipline needs to combine these two approaches, because non-functional behavior (such as timing, cost, power, robustness, etc.) is a crucial issue
  - when there are real-time constraints imposed by the environment
  - when to predict non-functional behavior using abstract models that cannot be well specified if the relation between functional behavior and non-functional behavior is obscure

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Future of Embedded Systems

- Embedded Systems are everywhere
- Embedded Systems market is much larger than the market of PC-like systems
  - Post-PC era in which information processing is more and more moving away from just PCs to embedded systems
- Embedded Systems provide the basic technology for Ubiquitous/Pervasive computing:
  - Model of human-computer interaction in which information processing has been thoroughly integrated into everyday objects and activities
  - Key goals is to make information available anytime, anywhere
  - Building Ambient Intelligence into our environment

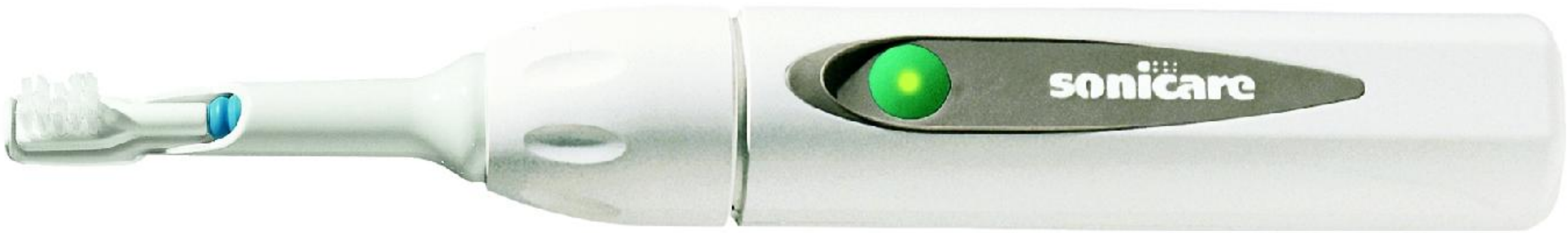
Embedded systems are everywhere

Our **daily lives** depend on embedded systems

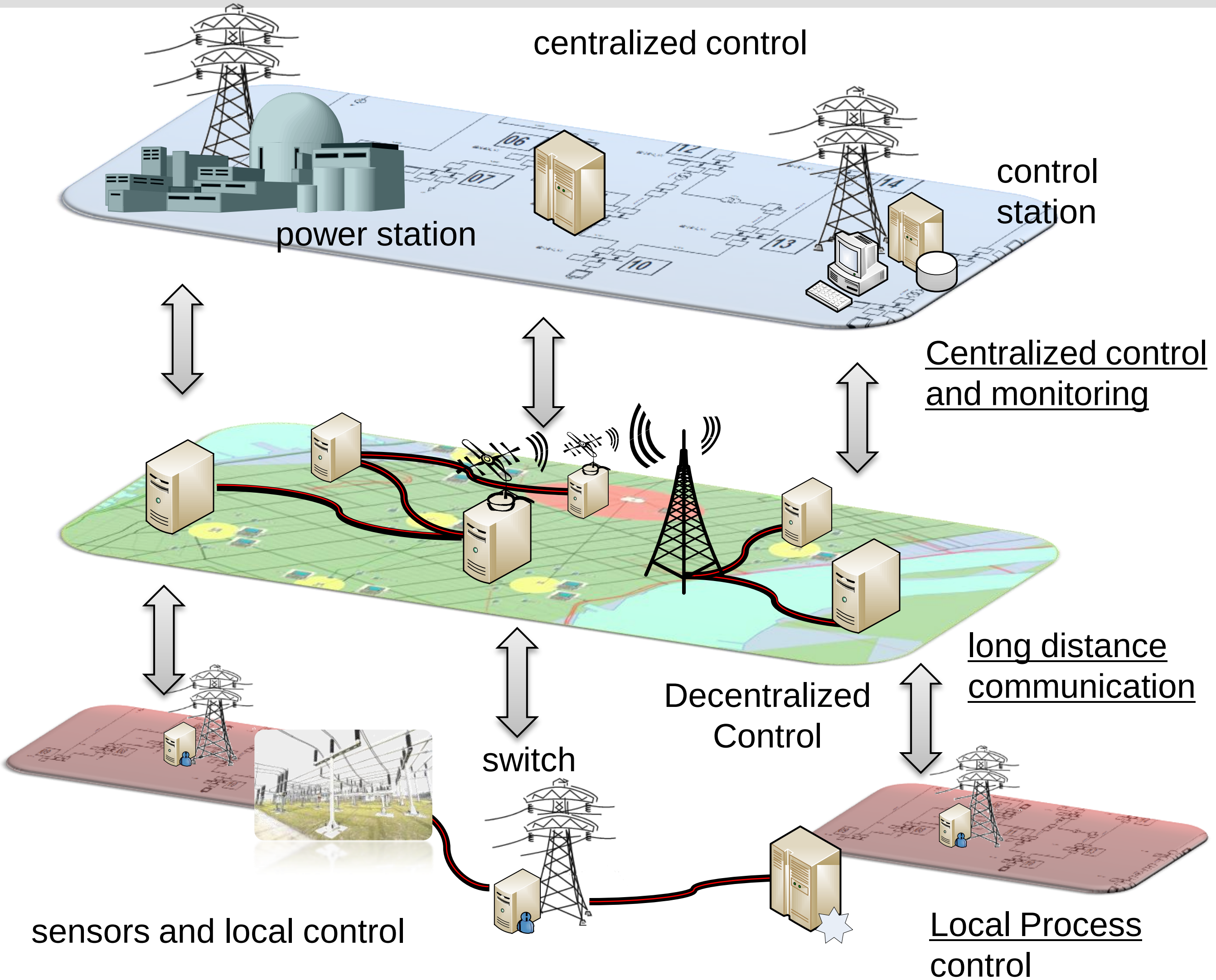
From Your Bathroom...

Product: Sonicare Plus toothbrush.

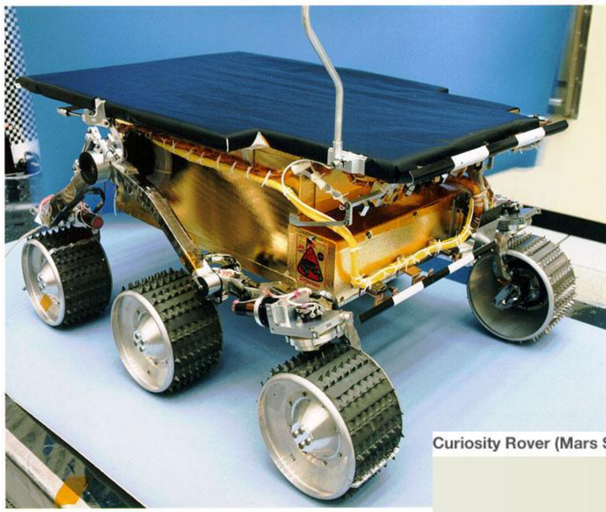
Microprocessor: 8-bit Zilog Z8.

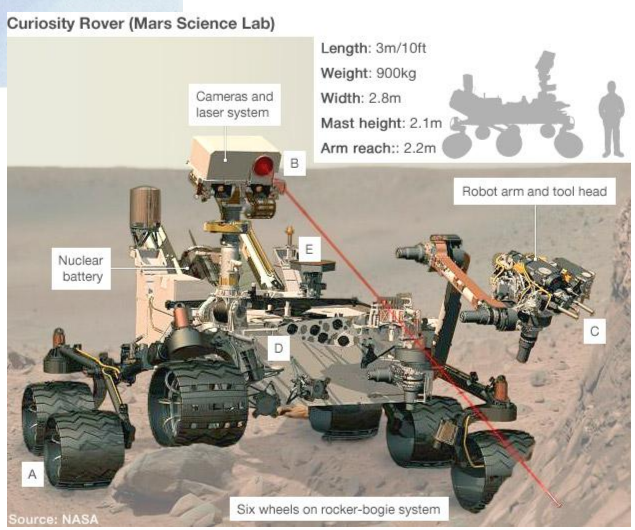


To Smart Grid



To Outer space

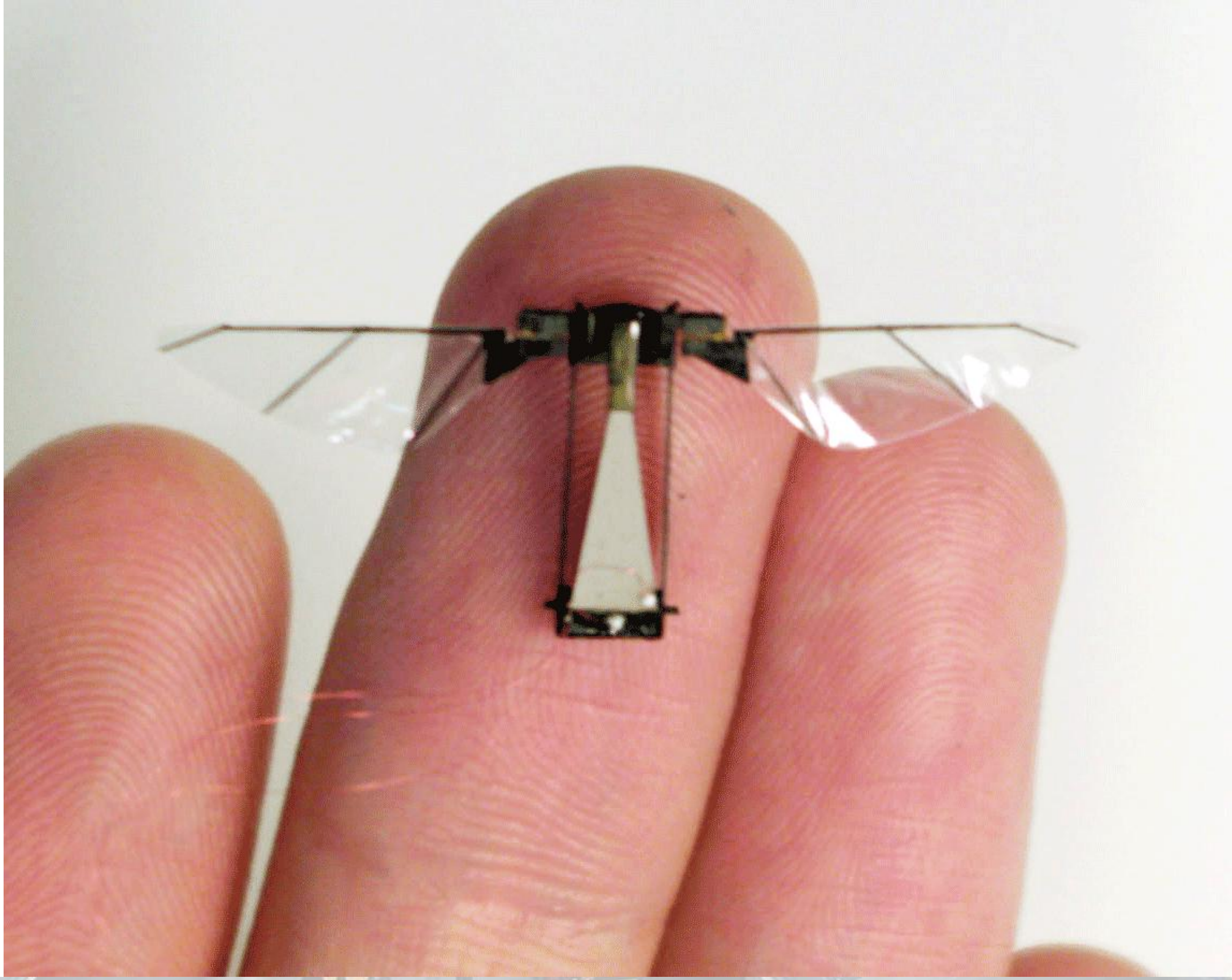




- 1996: NASA's Mars Sojourner Rover. Microprocessor: 8-bit Intel 80C85.
- 2012: NASA’s Curiosity Rover, with uC/OS-II RT OS

Big...

And Small...



Automotive Electronics

Embedded systems:
90% future innovations
40% price

Level of dependency

Electronic Injections
Check Control
Speed Control
Central Locking
...

Electronic Gear Control
Electronic Air Condition
ASC Anti Slip Control
ABS
Telephone
Seat Heating Control
Autom. Mirror Dimming
...

Navigation System
CD-Changer
ACC Adaptive Cruise Control
Airbags
DSC Dynamic Stability Control
Adaptive Gear Control
Xenon Light
BMW Assist
RDS/TMC
Speech Recognition
Emergency Call...

ACC Stop&Go
BFD
ALC
KSG
42 voltage
Internet Portal
GPRS, UMTS
Telematics
Online Services
BlueTooth
Car Office
Local Hazard Warning
Integrated Safety System
Steer/Brake-By-Wire
I-Drive
Lane Keeping Assist.
Personalization
Software Update
Force Feedback Pedal...

1970 | 1980 | 1990 | 2000 | 2020

source: BMW

Evolution of Handsets and Technology

Nokia Version

Evolution of Handsets and Technology

iPhone Version

Take-off Message

- Everything is embedded systems
- Everywhere is embedded systems
- The future is Embedded Systems