18-349: Introduction to Embedded Real-Time Systems
Lecture 1: Overview

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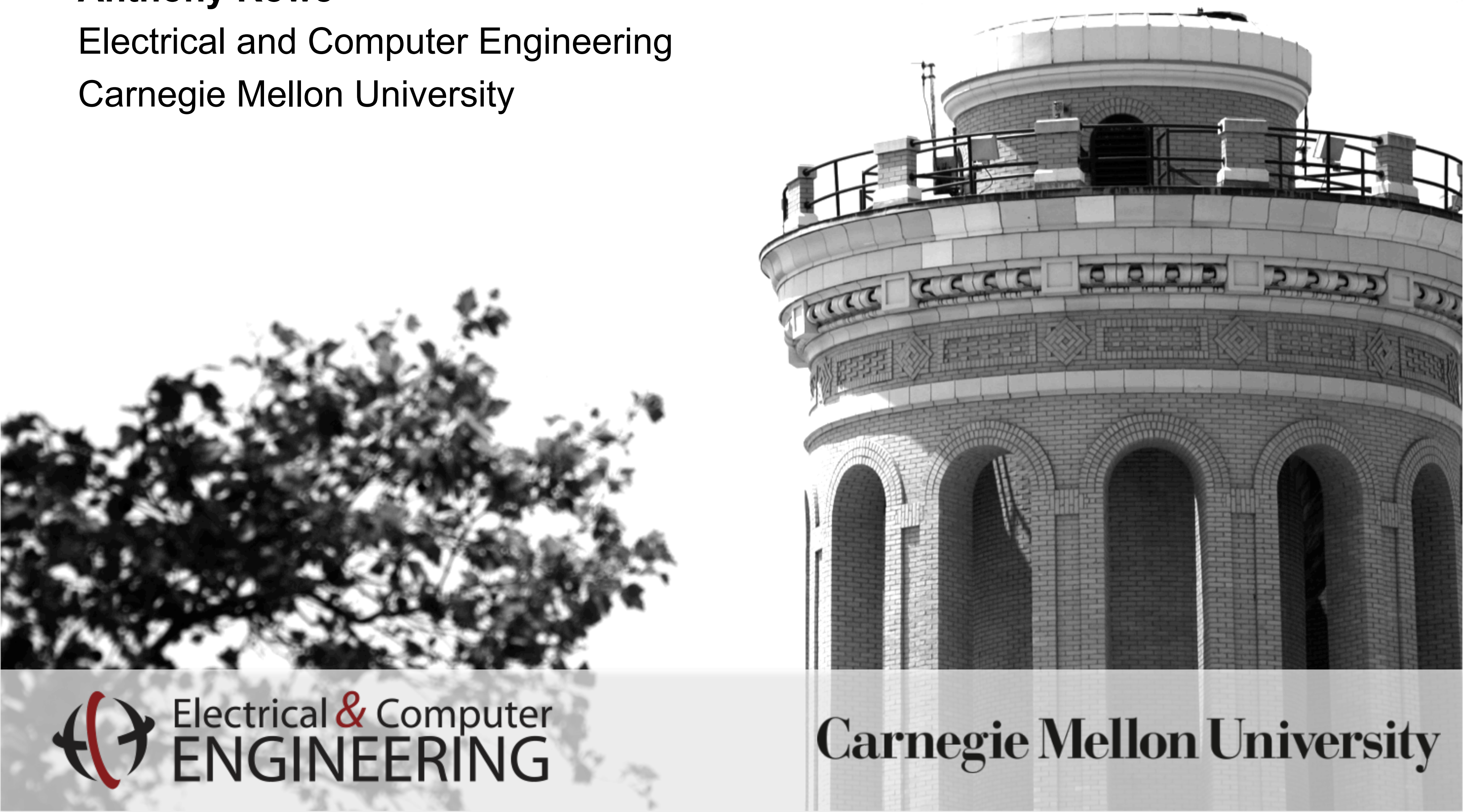


Electrical & Computer ENGINEERING

Carnegie Mellon University

What is an embedded system?

An introduction

- Computer system hidden (embedded) in other systems
  - Often interacts with the physical environment
- Purpose built
- End users see “smart” device rather then computer
- Special-purpose vs. general-purpose computing

Embedded, Everywhere

Embedded, Everywhere - Internet of Things

People Connecting
Through Machines

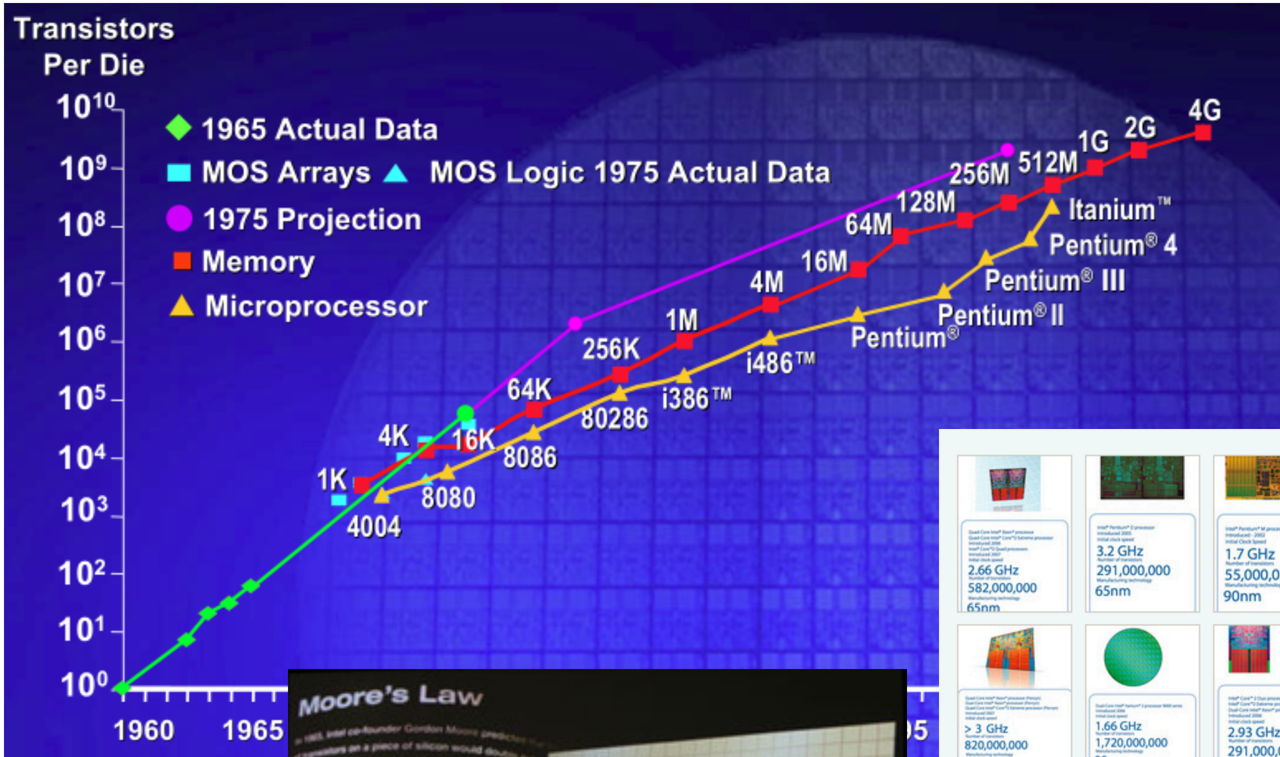
Machines Connecting to Machines
and the Physical Environment

Embedded in Your Daily Life

- How many micro-controllers are around you?
  - Bathroom scale with digital read out
  - Iron that turns itself off automatically
  - Electronic toothbrush (with ~3000 lines of code)
  - Cooking range
  - Laundry machine and dryer
  - Toaster
  - Microwave
  - Home-security
  - TV, cable-box, AV system
  - Game console
  - Thermostat
  - Cars, Toys, Medical Devices…

What is driving the embedded explosion?

Moore’s Law (a statement about economics): IC transistor count doubles every 18-24 mo



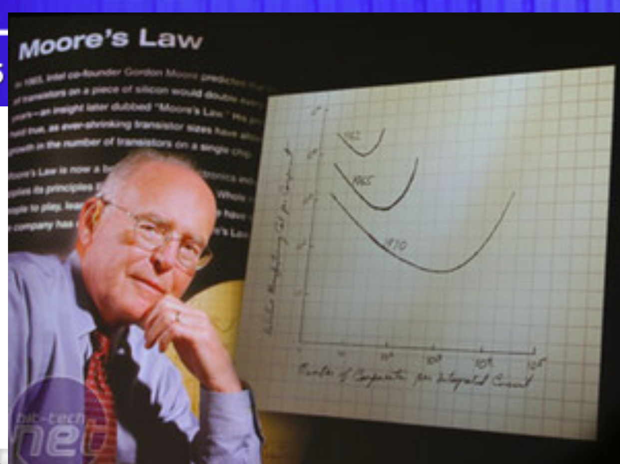
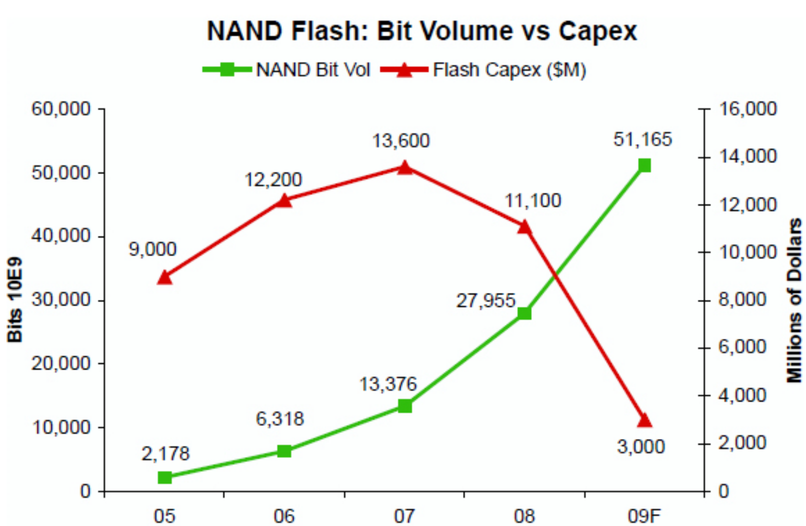
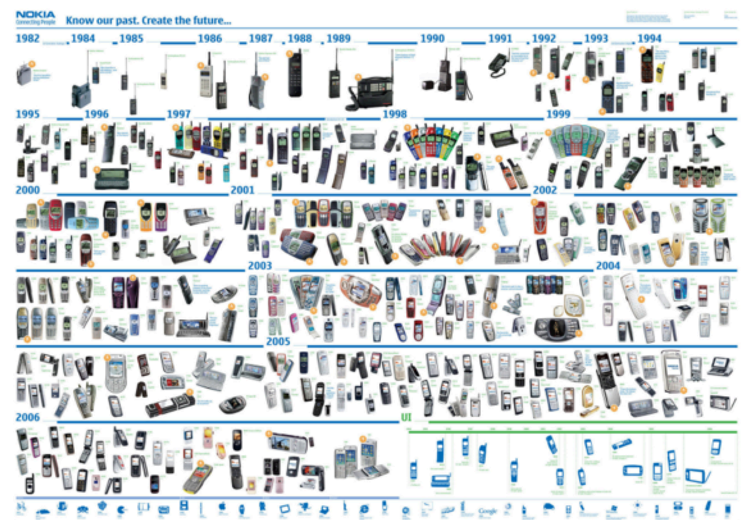


Photo Credit: Intel

Flash memory scaling:
Rise of density & volumes; Fall (and rise) of prices





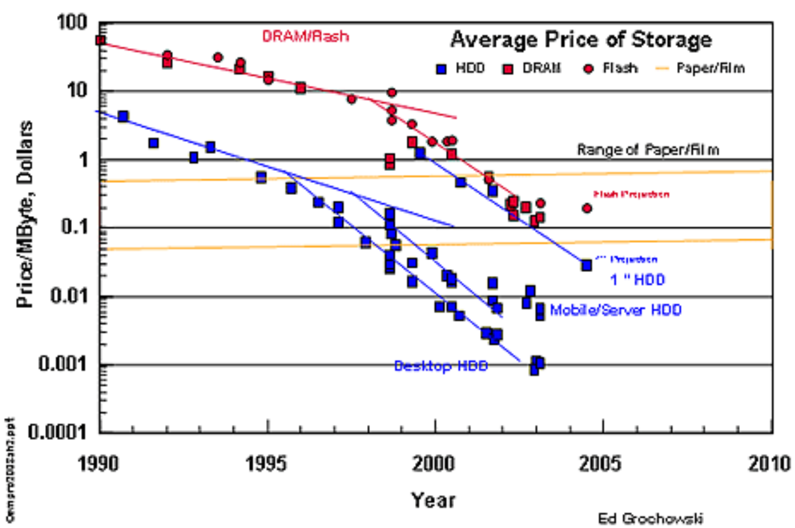
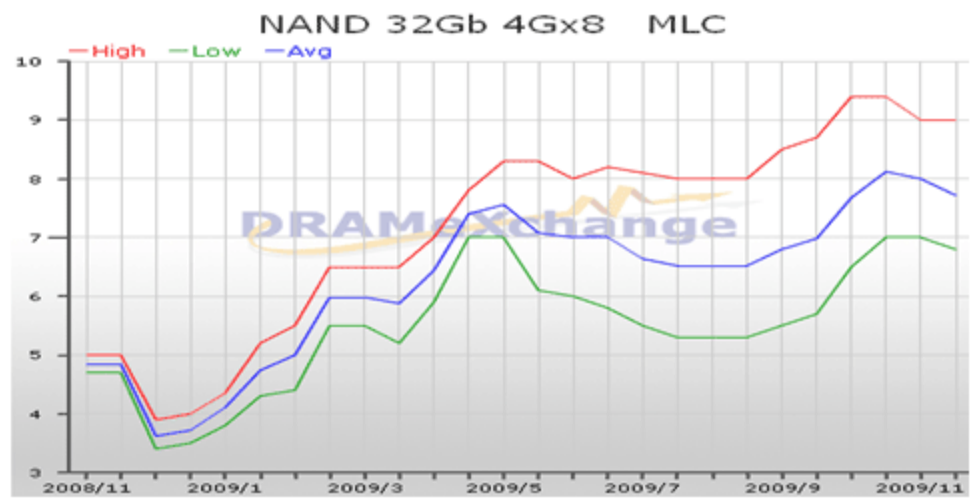
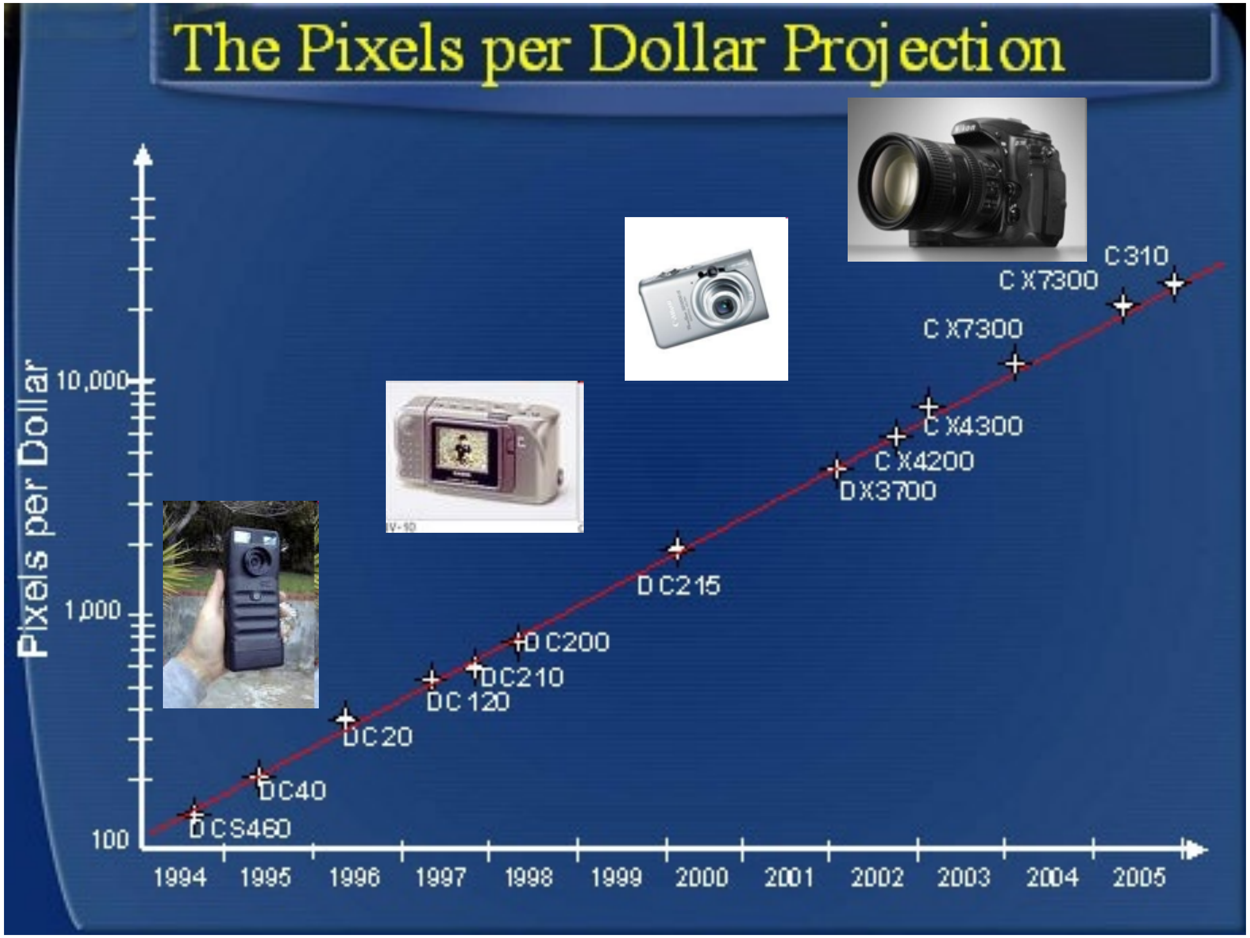


Figure-1 32Gb MLC NAND Flash contract price trend



Source: DRAMeXchange, Nov. 2009.

Hendy's "Law":
Pixels per dollar doubles annually



Credit: Barry Hendy/Wikipedia

Dennard Scaling made transistors fast and low-power: So everything got better!

Design of Ion-Implanted MOSFET's with Very Small Physical Dimensions

ROBERT H. DENNARD, MEMBER, IEEE, FRITZ H. GAENSSLEN, HWA-NIEN YU, MEMBER, IEEE, V. LEO RIDEOUT, MEMBER, IEEE, ERNEST BASSOUS, AND ANDRE R. LEBLANC, MEMBER, IEEE

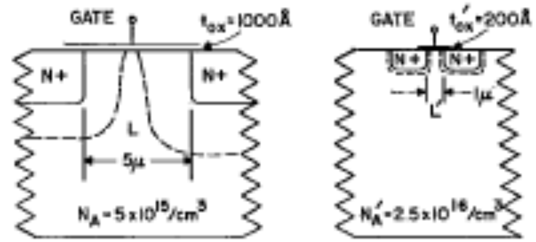
Classic Paper

This paper considers the design, fabrication, and characterization of very small MOSFET switching devices suitable for digital integrated circuits using dimensions of the order of 1 μ. Scaling relationships are presented which show how a conventional MOSFET can be reduced in size. An improved small device structure is presented that uses ion implantation to provide shallow source and drain regions and a nonuniform substrate doping profile. One-dimensional models are used to predict the substrate doping profile and the corresponding threshold voltage versus source voltage characteristic. A two-dimensional current transport model is used to predict the relative degree of short-channel effects for different device parameter combinations. Polysilicon-gate MOSFET's with channel lengths as short as 0.5 μ were fabricated, and the device characteristics measured and compared with predicted values. The performance improvement expected from using these very small devices in highly miniaturized integrated circuits is projected.

I. List of Symbols

α	Inverse semilogarithmic slope of subthreshold characteristic.
D	Width of idealized step function profile for channel implant.
ΔW_f	Work function difference between gate and substrate.
$\epsilon_{Si}, \epsilon_{ox}$	Dielectric constants for silicon and silicon dioxide.
I_d	Drain current.
k	Boltzmann's constant.
κ	Unitless scaling constant.
L	MOSFET channel length.
μ_{eff}	Effective surface mobility.
n_i	Intrinsic carrier concentration.
N_a	Substrate acceptor concentration.
Ψ_s	Band bending in silicon at the onset of strong inversion for zero substrate voltage.
Ψ_b	Built-in junction potential.
q	Charge on the electron.
Q_{eff}	Effective oxide charge.
t_{ox}	Gate oxide thickness.
T	Absolute temperature.
V_d, V_s, V_g, V_{sub}	Drain, source, gate and substrate voltages.
V_{ds}	Drain voltage relative to source.
V_{s-sub}	Source voltage relative to sustrate.
V_t	Gate threshold voltage.
w_s, w_d	Source and drain depletion layer widths.
W	MOSFET channel width.

This paper is reprinted from IEEE Journal of Solid-State Circuits, vol. SC-9, no. 5, pp. 256–268, October 1974.
Publisher Item Identifier S 0018-9219(99)02196-9.



(a) (b)

Fig. 1. Illustration of device scaling principles with $\kappa = 5$. (a) Conventional commercially available device structure. (b) Scaled-down device structure.

portion of the region in the silicon substrate under the gate electrode. For switching applications, the most undesirable "short-channel" effect is a reduction in the gate threshold voltage at which the device turns on, which is aggravated

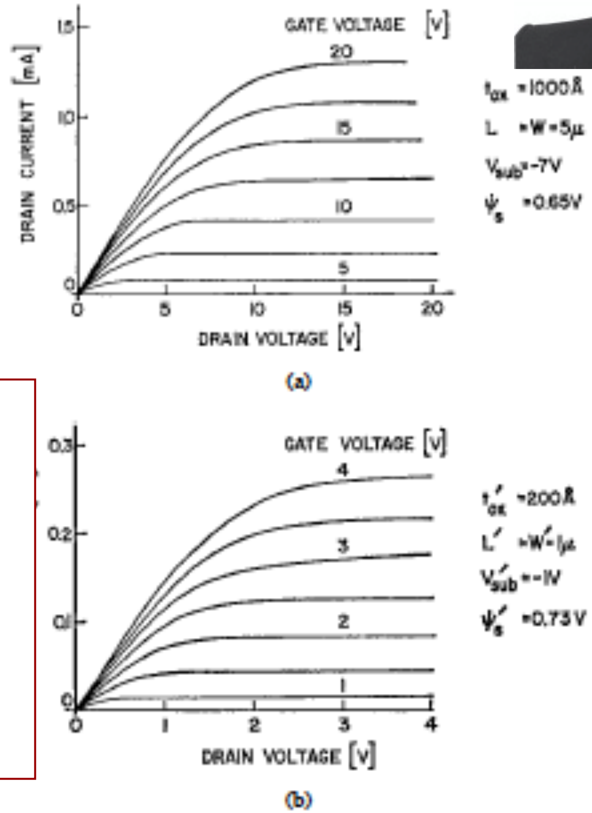
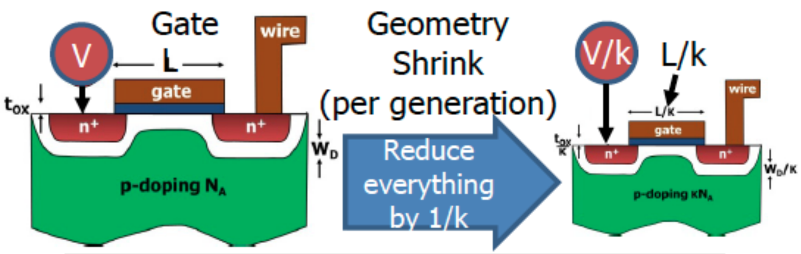


Fig. 2. Experimental drain voltage characteristics for (a) conventional, and (b) scaled-down structures shown in Fig. 1 normalized to $W/L = 1$.

Industry's ride is over

The past: Dennard's Scaling



$P_{density} = N_g C_{load} V^2 f$
= power per unit area

N_g = CMOS gates/unit area
C_{load} = capacitive load/CMOS gate
V = supply voltage
f = clock frequency

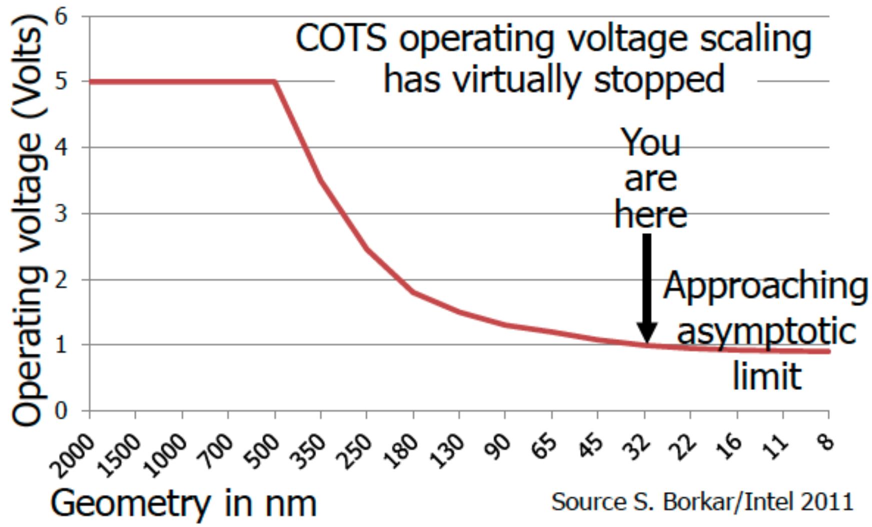
k = scaling factor
k = typically 1.4 per geometry shrink
1/k = device feature scaling factor
(typically 0.7 per geometry shrink)

For each generation/geometry shrink:

$$P_{density\ (scaling)} = (k^2)(1/k)(1/k^2)(k) = 1$$

Double the transistors (functionality) and increase the clock speed 40% per generation with the same power

Today: Dennard's Scaling is dead



Source S. Borkar/Intel 2011

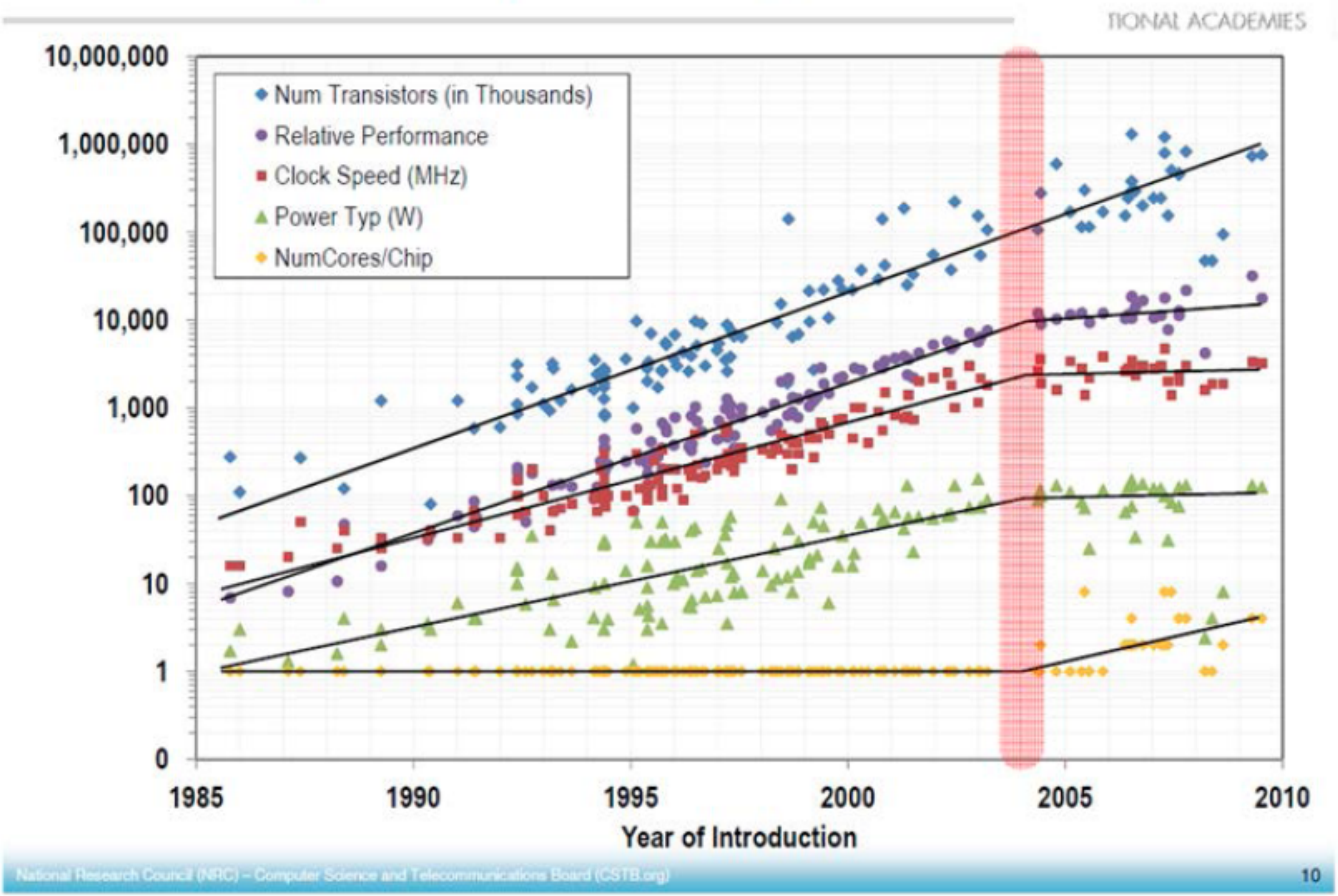
$$P_{density\ (scaling)} = (k^2)(1/k)(1\mathbf{X}k^2)(k) = k^2 \cong 2$$

But, power density cannot increase!

This physics is limiting COTS power efficiency to well below what we need for embedded sensor processing applications

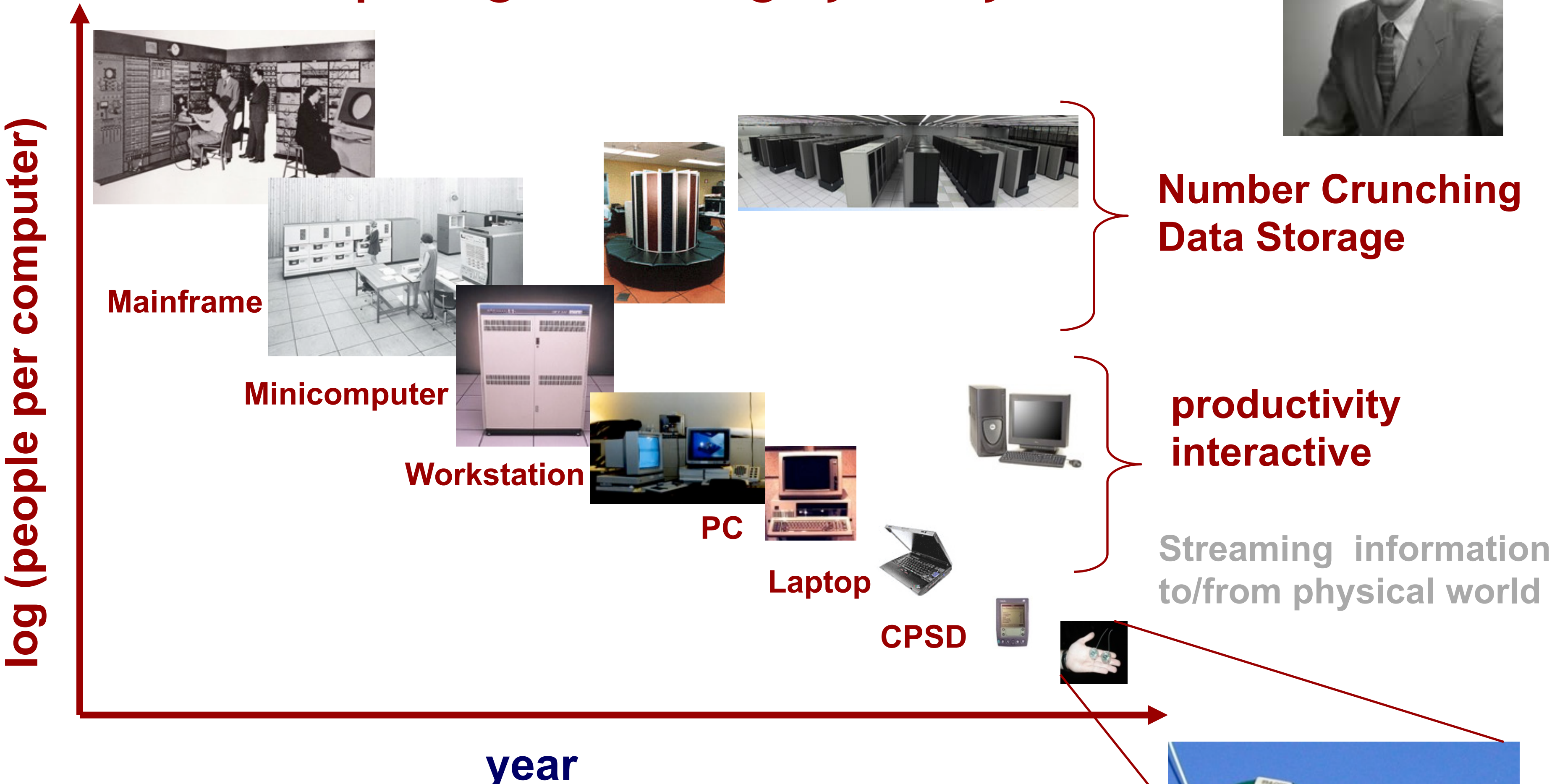
Source: Joe Cross, DARPA MTO

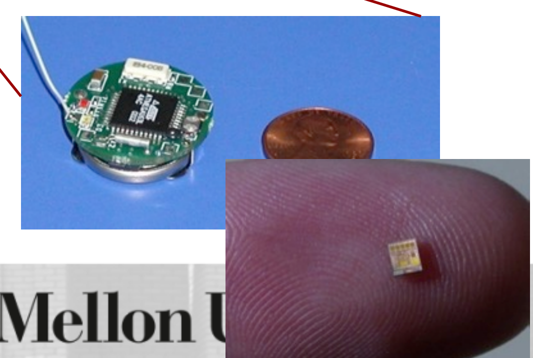
Decades of exponential performance growth stalled in 2004



Source: NRC, <u>The Future of Computing Performance, Game Over or Next Level?</u>

Not so fast! Bell's Law of Computer Classes: A new computing class roughly every decade





"Roughly every decade a new, lower priced computer class forms based on a new programming platform, network, and interface resulting in new usage and the establishment of a new industry."

Technology Trends

- Multi-core embedded with SoC
- Better, cheaper, lower power sensors
- Better communication
  - Bluetooth Low-Energy
  - 802.15.4
  - 802.11 AC
- Energy Harvesting

Why is embedded different?

Typical Embedded System Challenges (1-2)

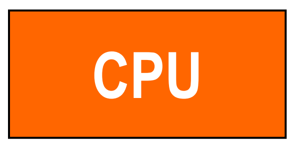
- Small Size, Low Weight
  - Handheld electronics
  - Transportation applications weight costs money
- Low Power
  - Battery power for 8+ hours (laptops often last only 2 hours)
  - Limited cooling may limit power even if AC power available

Typical Embedded System Challenges (2-2)

- Harsh environment
  - Heat, vibration, shock
  - Power fluctuations, RF interference, lightning
  - Water, corrosion, physical abuse
- Safety-critical operation
  - Must function correctly
  - Must not function incorrectly
- Extreme cost sensitivity
  - $.05 adds up over 1,000,000 units

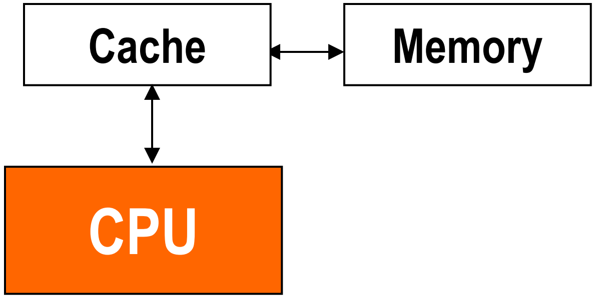
CPU: An All Too Common View of Computing

- **Measured by: Performance**



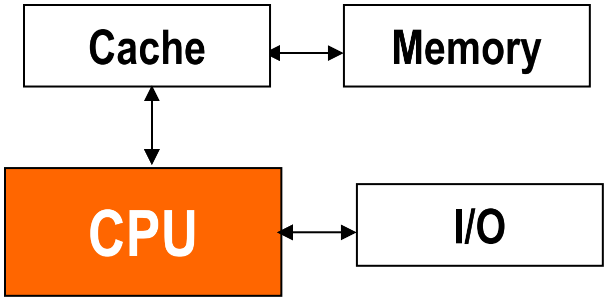
An Advanced Computer Engineer's View

- **Measured by: Performance**
  - Compilers matter too...



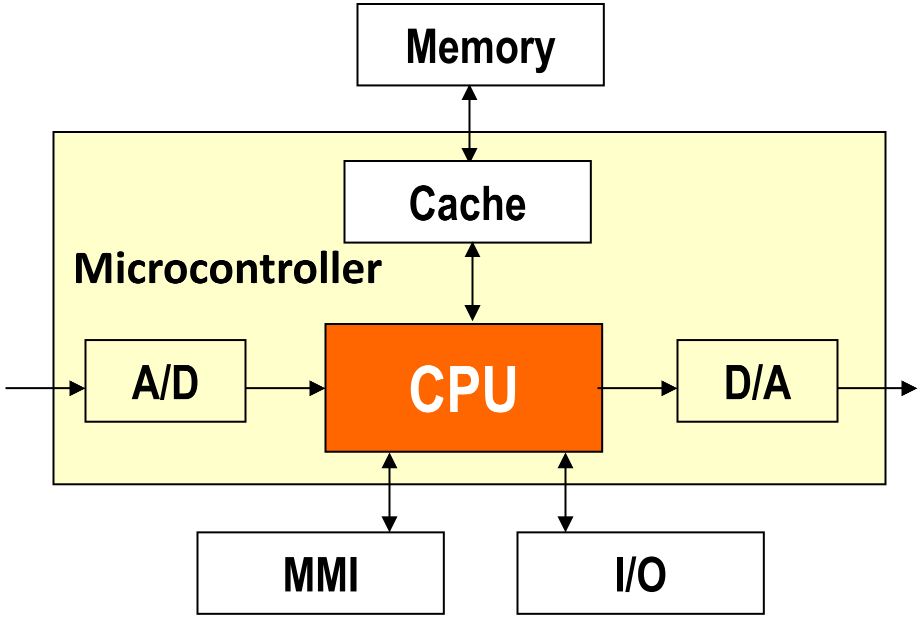
An Enlightened Computer Engineer's View

- **Measured by: Performance, Cost**
  - Compilers & OS matter



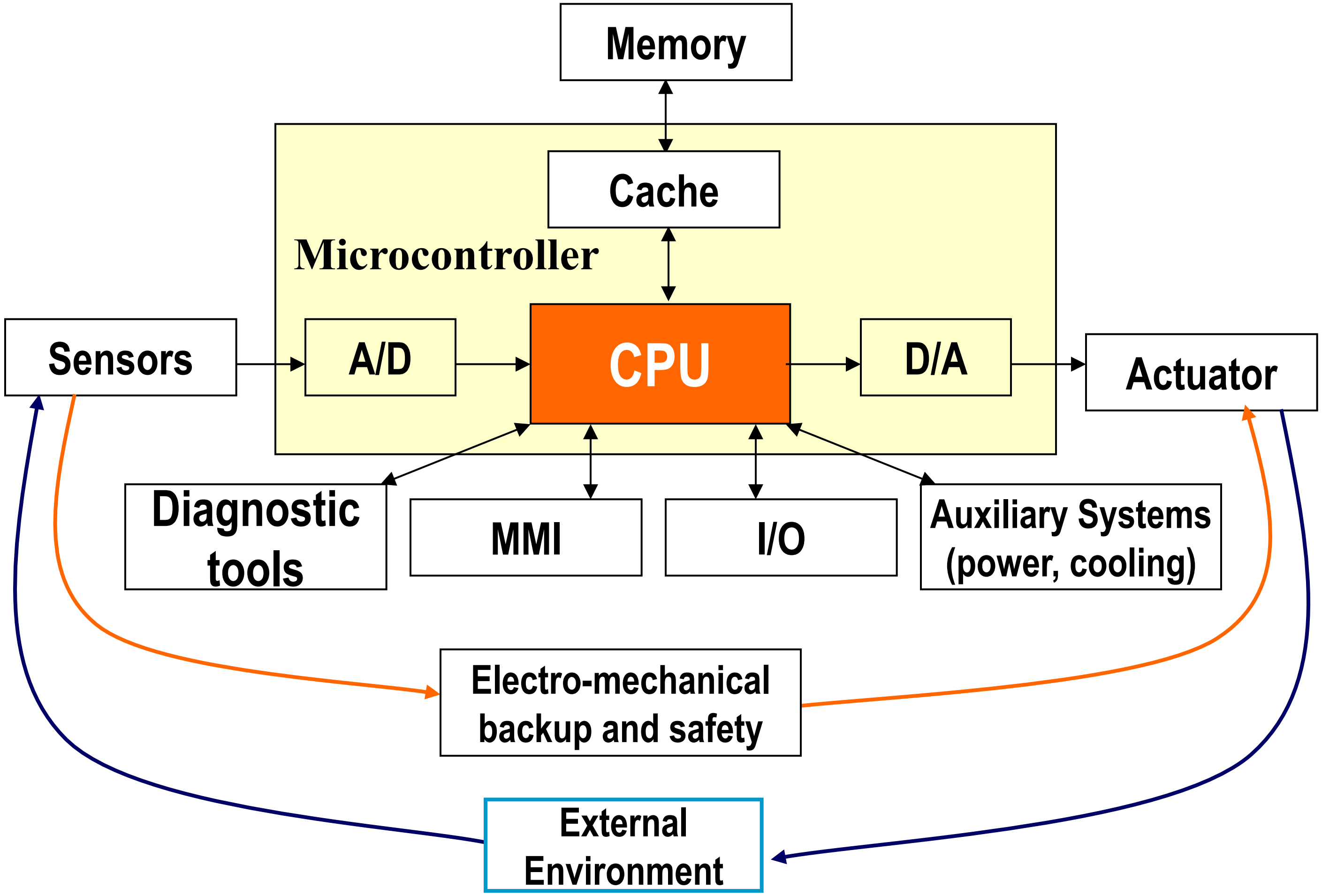
An Embedded Computer Designer's View

- Measured by: Cost, I/O connections, Memory Size, Performance



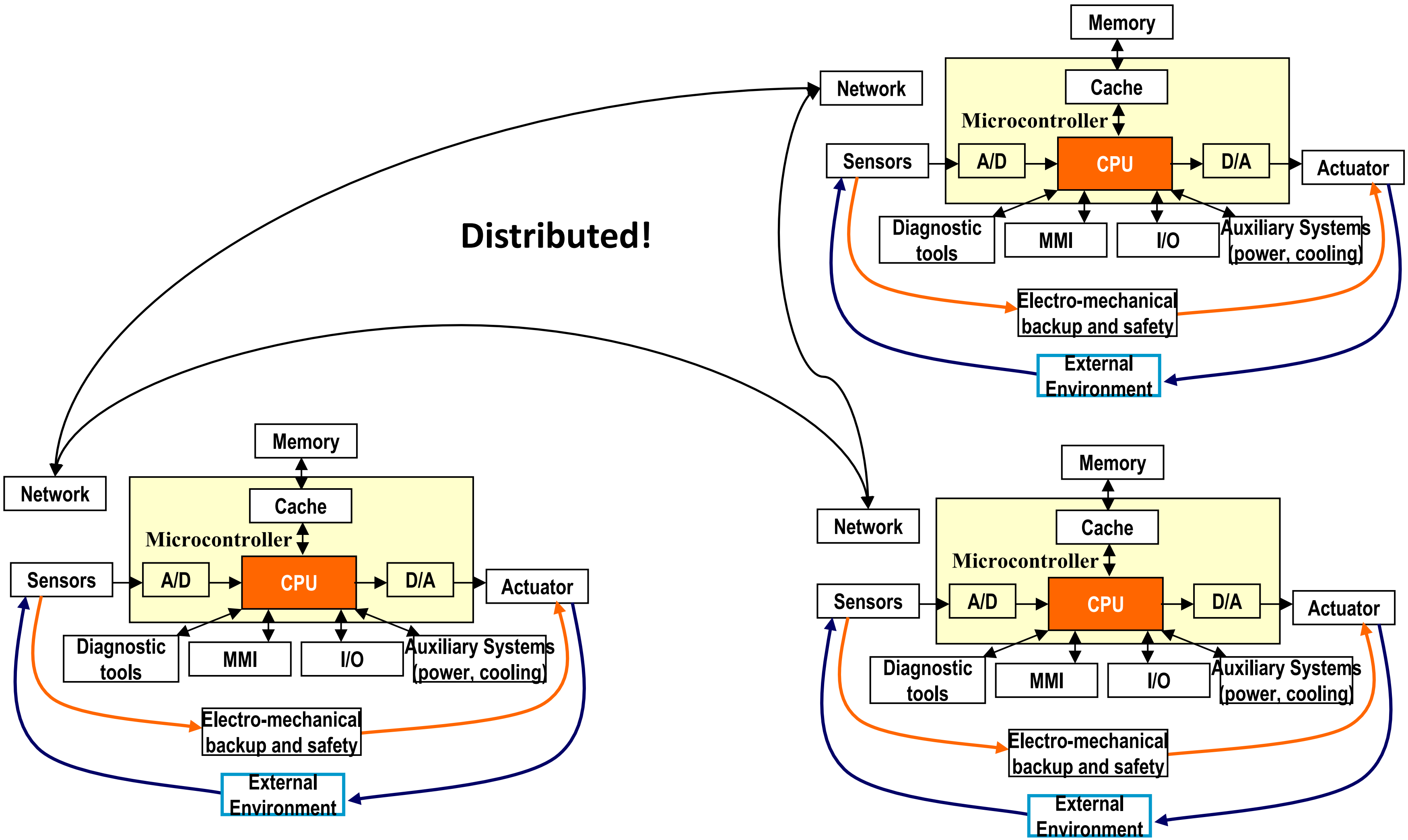
An Embedded Application Designer's View

- Measured by: Cost, Timetomarket, Cost, Functionality, Cost & Cost.



Modern Embedded Systems View

- Measured by: Does it actually work? (and all of the other stuff)



Embedded Computers *Rule* the Marketplace

- ~80 Million PCs vs. ~3 Billion Embedded CPUs annually
  - Embedded market growing; PC market *mostly* saturated

- Domain Experts Needed…
  - **General Computing**
    - Set-top boxes, video game consoles, ATM, …
  - **Control Systems**
    - Airplane, Heating and Cooling System
  - **Signal Processing**
    - Radar, Sonar, Video Compression, Human-Brain interface
  - **Communication**
    - Internet, Wireless Communication, VoIP…

Embedded Systems Careers

nest

TESLA
TESLA MOTORS

cisco

meraki

SPACEX

MICROCHIP

Boston Dynamics

BOSCH

GM

ATMEL

iRobot

Ford

ARM

BOEING

Green Hills SOFTWARE

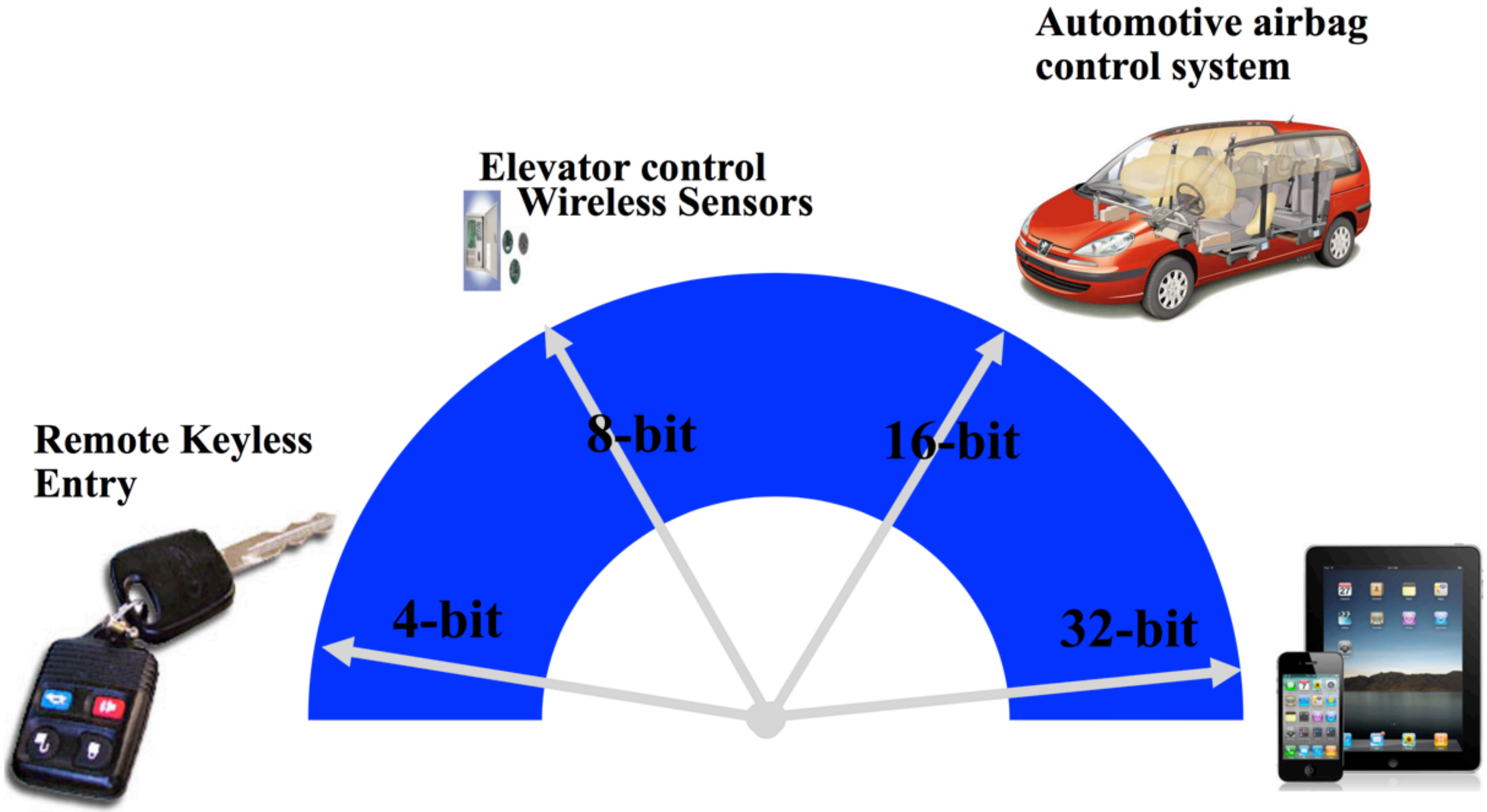
intel

SAMSUNG

Microsoft

Misconceptions (1)

- Embedded systems = low end microcontrollers



Misconceptions (2)

- Embedded system programing = programming in assembly to optimize the code for space, time etc.
- Compilers are typically better then humans at generating the best code
- Code portability issues -> some device-driver dependent code written in assembly, but most app code is written in higher-level languages

Misconceptions (3)

- Embedded systems = old topic
- Always new and exciting developments that track technology
  - New sensors / actuators
  - More powerful chips
  - New communication mechanisms
- Embedded systems + Internet = Internet of Things
  - Massively hot topic right now!