Pervasive Systems

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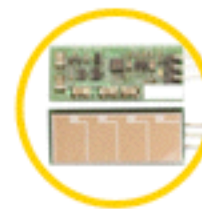
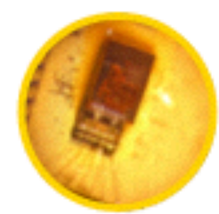
100 cm^3
[IPSN'12]

50 cm^3
[Sensys'12]



1 cm^3
[IPSN'12]



1 mm^3
[ISSCC'12]

NSF/CCC Extensible Distributed Systems Workshop

Waterview Conference Center in Arlington, VA

January 21-22, 2015

1981: Byte Magazine saw it coming

1991: Mark Weiser's Vision of Ubiquitous Computing

- Who is Mark Weiser?
  - Michigan alumnus: MA('77), PhD ('79)
  - Professor, UMD, College Park
  - Chief Technologist, Xerox PARC
  - Father of ubiquitous computing
  - Work is incredibly influential

- What are the principles of ubiquitous computing?
  - The purpose of a computer is to help you do something else
  - The best computer is a quiet, invisible servant
  - The more you can do by intuition the smarter you are; the computer should extend your *unconscious*
  - Technology should create calm
  - Calm technology: "that which informs but doesn't demand our focus on attention"

Are We There Yet?

Hundreds of Tabs? Tens of Pads? One or two Boards?



ParcTab	MPad	Liveboard
Dimensions: 10.2- × 7.8- × 2.4cm Weight: 7.2 oz Screen: 6.2- × 4.2cm, 128- × 64 monochrome Touch input: passive pressure sensing Sound: Piezo speaker Wireless interfaces: IR at 850nm, DEC/Olivetti active badge compatible, 19.2k baud PWM baseband modulation, CSMA Processor: Intel 8051-type, 8k (v1) 128k (v2) nvram Ports: I^2C external bus, recharge port Battery: 12 hours continuous or est. 2 weeks normal use, rechargeable	Dimensions: 22.2- × 28- × 3.8cm Weight: 5llbs 4oz Screen: 640- × 480 LCD Display (3 levels of grey) Pen: tethered electromagnetic sensing Sound: Built-in microphone, Speaker, Piezo Beeper Wireless Interfaces: 250Kbps Radio, 19.2Kbps IR Processor: Motorola 68302, 4MB of DRAM, 1/2MB of VRAM, 1/4MB of EPR External Ports: Stylus/microphone, PCMCIA, 1MB Serial, RS232, I^2C bus, Keyboard Internal Ports: Second audio channel, ISDN, Expansion Port Battery: rechargeable, 3 hours	Dimensions: 83in, 52in and 30in Weight: 560lb (250kg) Screen: very bright 45- × 65in, 1024- × 768 monochrome pixels, 640- × 480 pixels color, also NTSC video Pen: IR wireless Stereo sound Networking, processor, and ports determined by choice of embedded workstation, either PC or Sun 12 amps at 115 volts

But the work did have impact

- Due, in part, to emphasis on <u>computing</u> issues:

  "The fruitfulness of ubiquitous computing for new computer science problems justified our belief in the…framework"

- Issues like
  - Hardware components
    - Low power (P=C*V^2*f gives lots of degrees of freedom)
    - Wireless - custom radios (SS/FSK/EM-NF→ bits/sec/meter^3 metric)
    - Pens (how do you write on walls?)
  - Network Protocols
    - Wireless media access (MACA: RTS/CTS)
    - Gigabit networks (lots of little devices create a lot of traffic)
    - Real-time protocols (IP telephony)
    - Mobile communications

But the vision remains unrealized…
our technology is anything but calming

- “The most profound technologies are those that disappear.”
  - Mark Weiser

- We’re burdened with a growing constellation of things
  - Broken
  - Insecure
  - Depleted
  - Mal-adapted

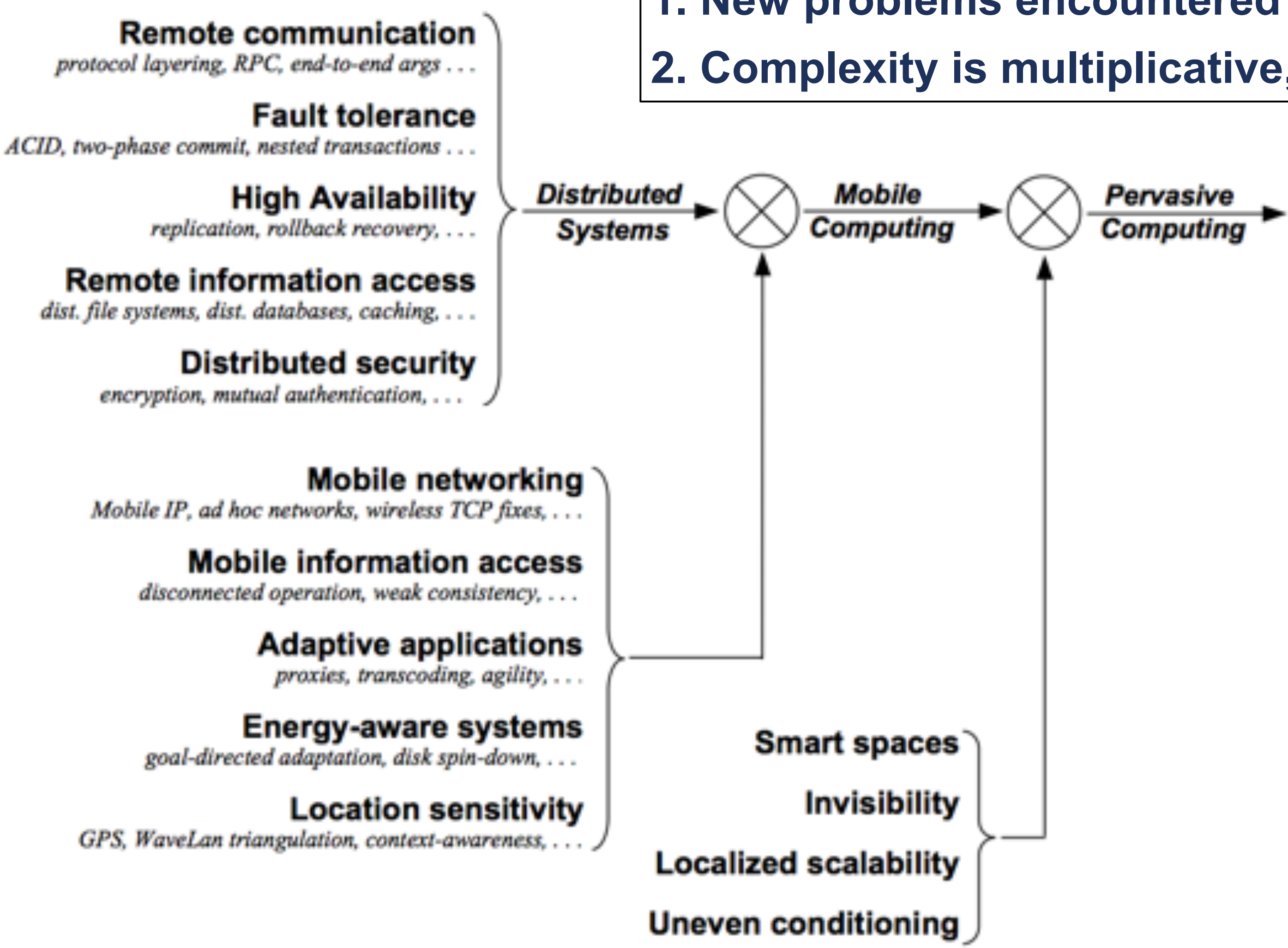
- Steep learning curve + impatience = user frustration
  - Configuration
  - Connectivity
  - Reliability
  - Maintenance
  - Integration

2001: Pervasive Computing: Visions and Challenges
M. Satyanarayanan, *IEEE Pervasive Communications*

How are *Distributed*, *Mobile*, and *Pervasive* Computing are related:

1. New problems encountered moving L→R!

2. Complexity is multiplicative, not additive!

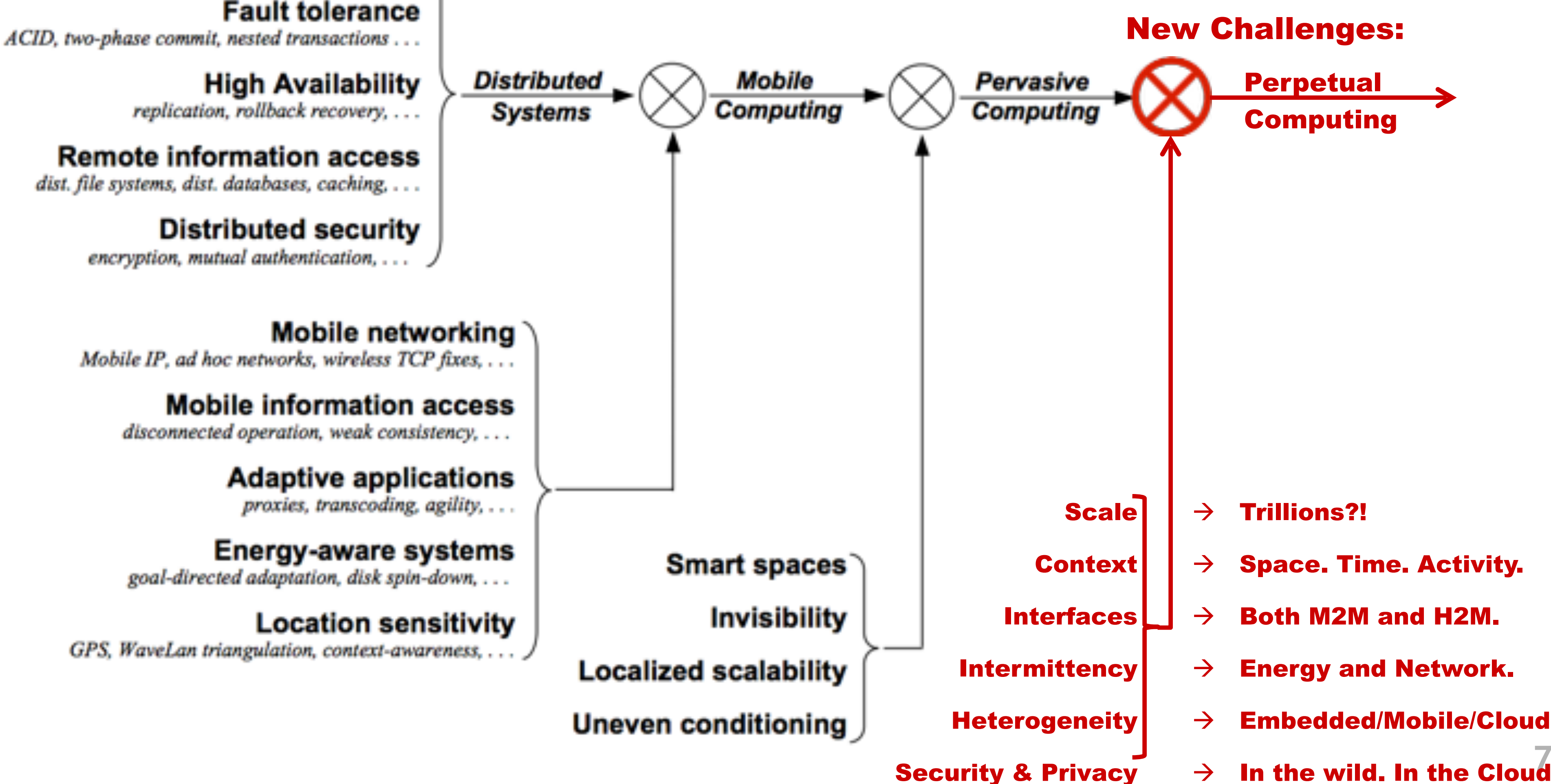


Things are going to get worse before they get better

How are *Distributed*, *Mobile*, *Pervasive*, and *Perpetual* Computing are related:

1. New problems encountered moving L→R!

2. Complexity is multiplicative, not additive!



Outline

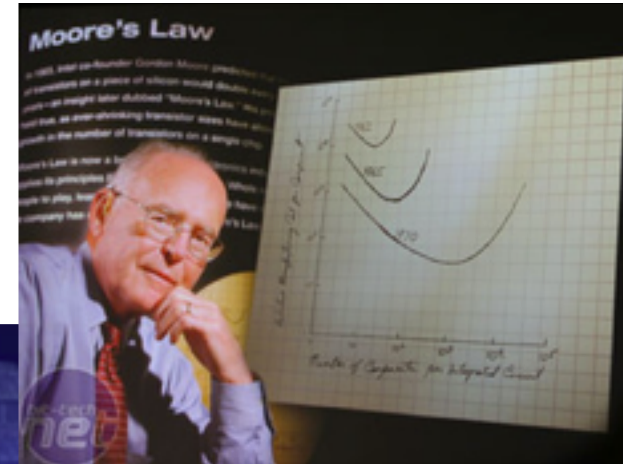
Historical Roots

Technology Trends

Application Explosion

Open Problems

Moore's Law doubled transistors counts every 18-24 months



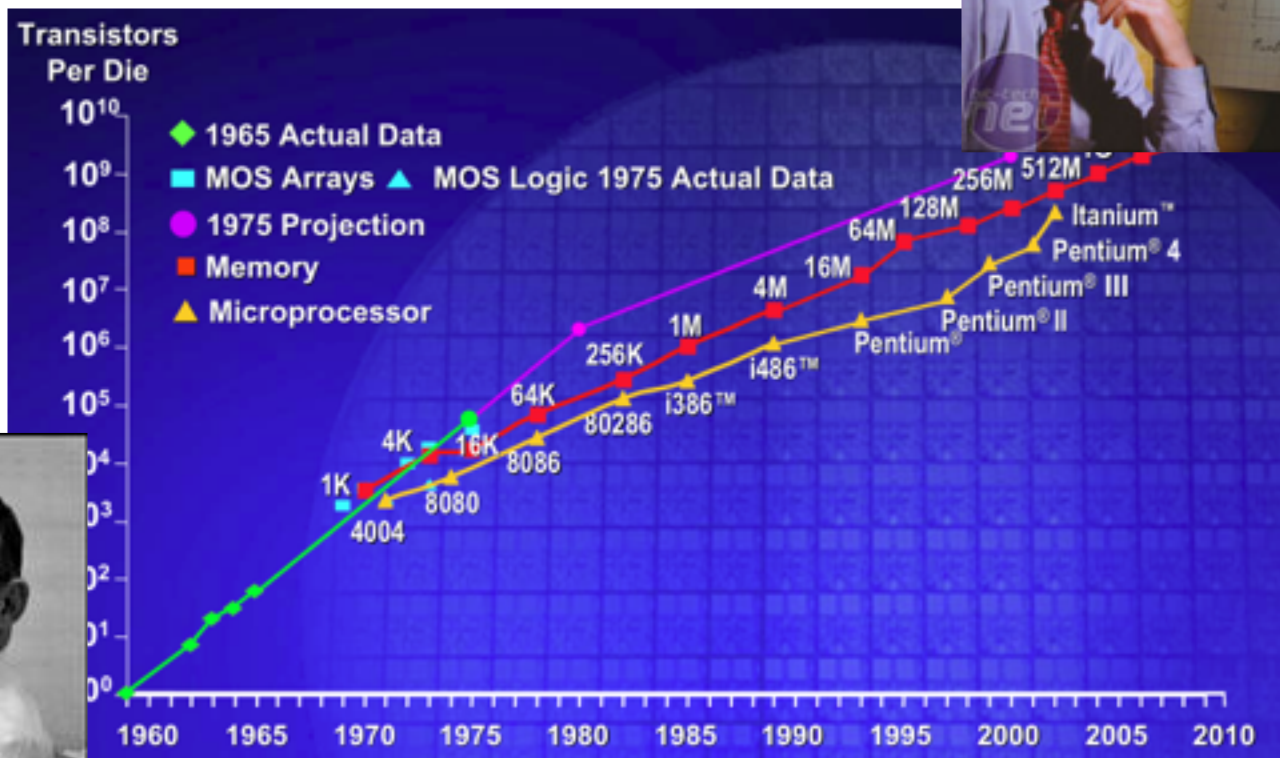
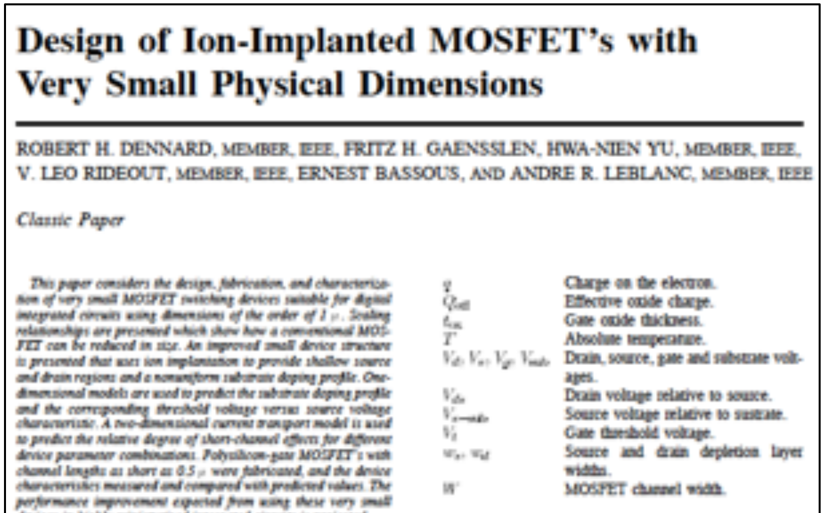


Photo Credit: Intel

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 substrate.
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)00294-9.

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

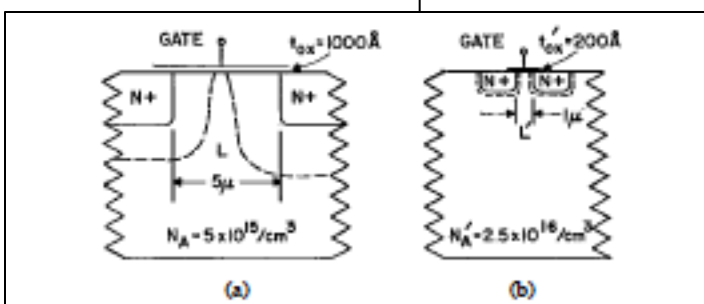


Fig. 1. Illustration of device scaling principles with $\kappa = 5$. (a) Conventional commercially available device structure. (b) Scaled-down device structure.

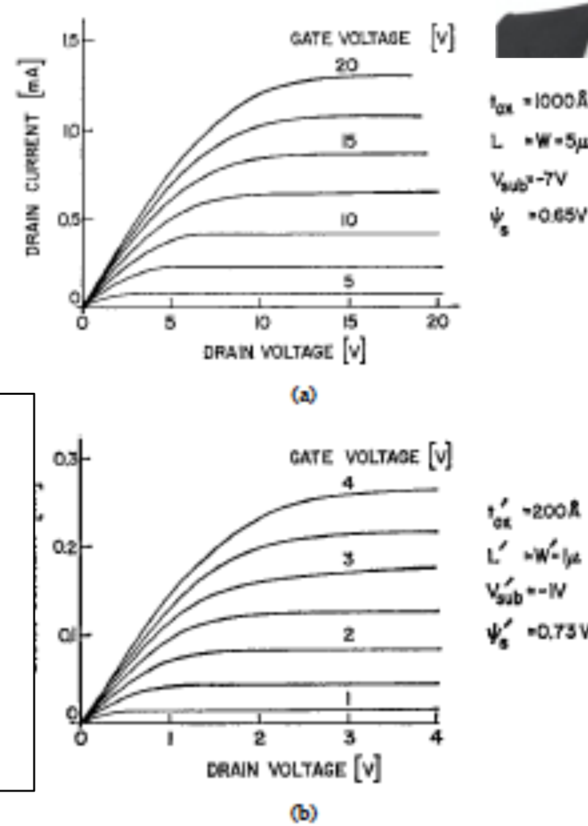


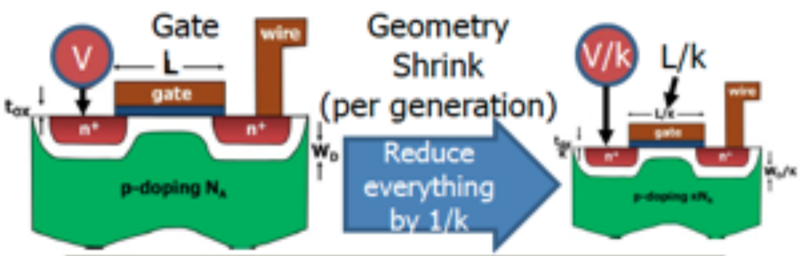
Fig. 2. Experimental drain voltage characteristics for (a) conventional, and (b) scaled-down structures shown in Fig. 1 normalized to $W/L = 1$.

But, Dennard Scaling is now dead

Industry's ride is over

Source: Joe Cross, DARPA MTO

The past: Dennard's Scaling



$P_{density} = N_g C_{load} V^2 f$

= power per unit area

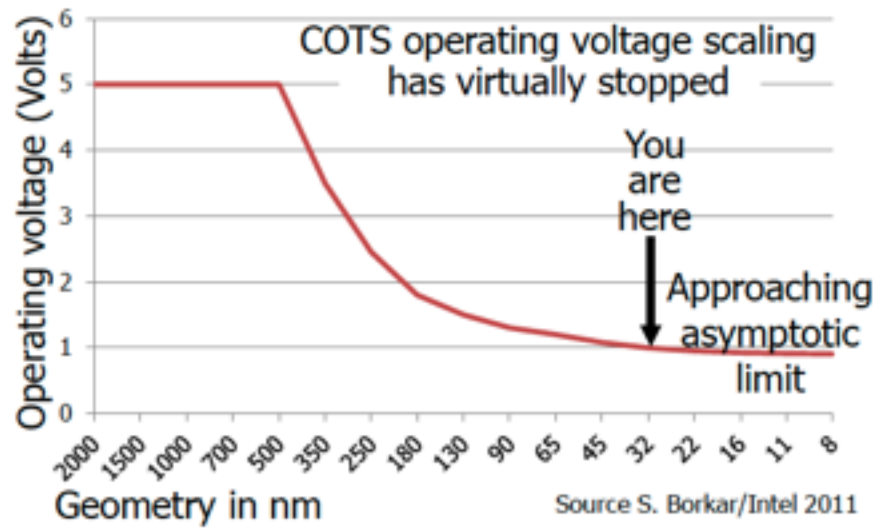
- N_g = CMOS gates/unit area
- C_{load} = capacitive load/CMOS gate
- V = supply voltage
- f = clock frequency
- k = scaling factor
- k = typically 1.4 per geometry shrink
- 1/k = device feature scaling factor (typically 0.7 per geometry shrink)

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

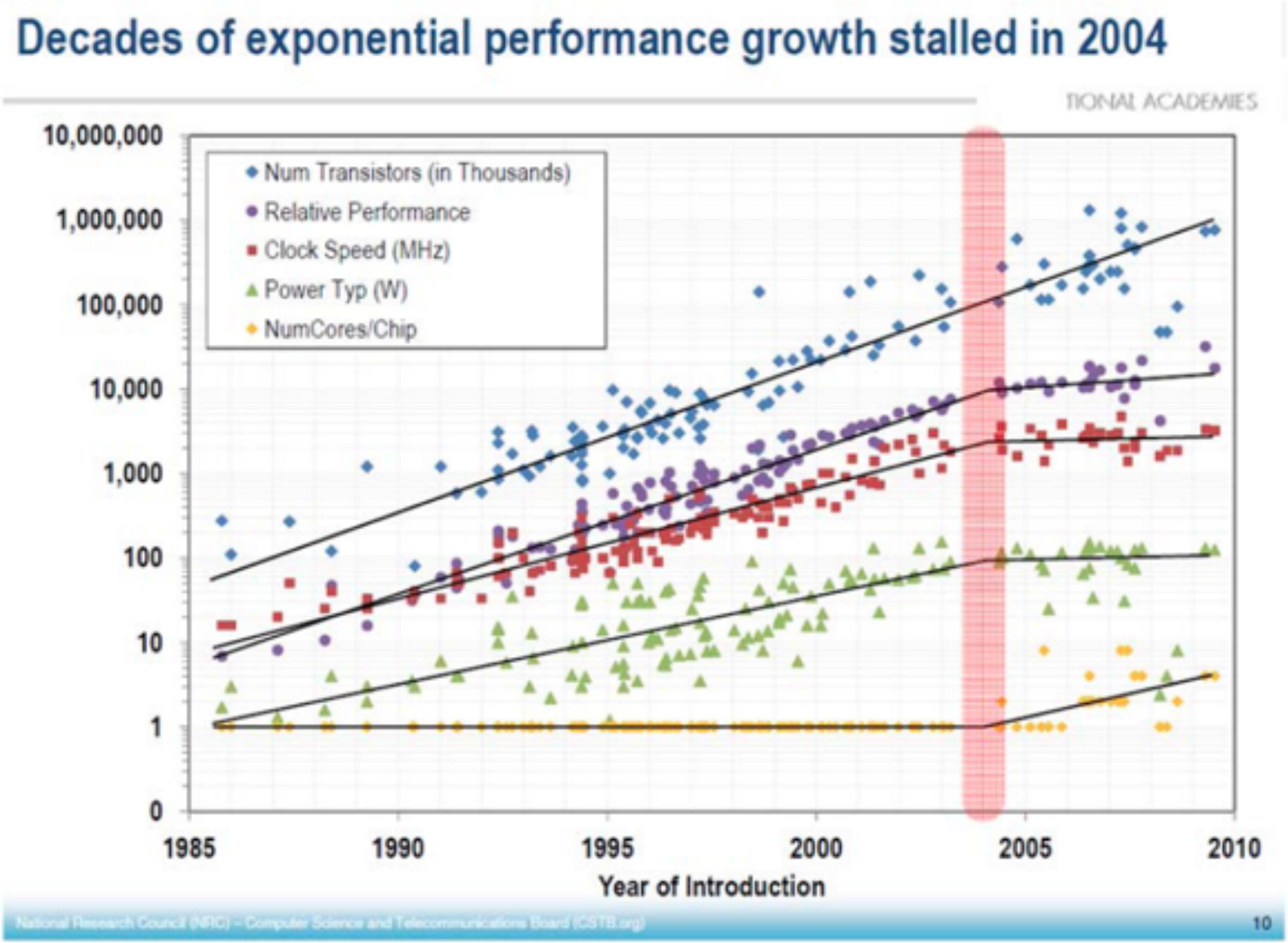


$$P_{density\ (scaling)} = (k^2)(1/k)(\cancel{1/}k^2)(k) = k^2 \cong 2$$

But, power density cannot increase!

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

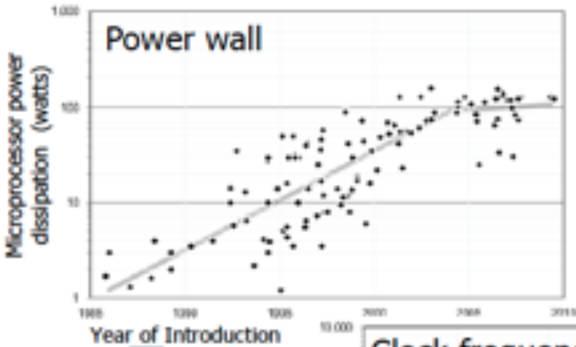
And the party's over…

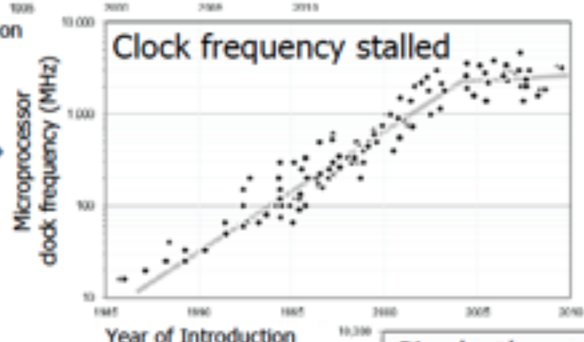


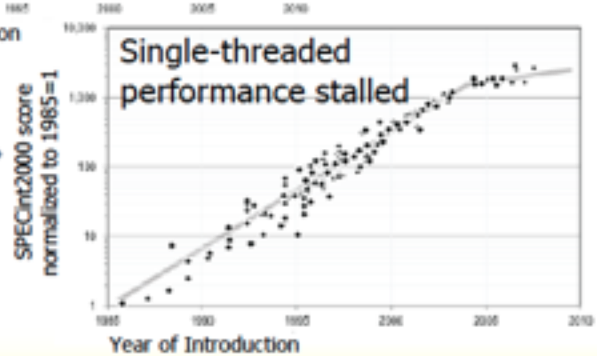
Source: NRC, The Future of Computing Performance, Game Over or Next Level?

Or is it? Concurrency is the way forward.

Technology landscape: move past power limitations, effectively utilize concurrency

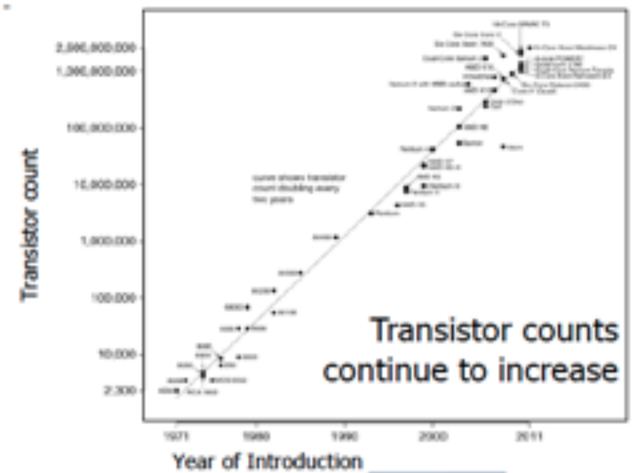






2011 NRC/CSTB Study: "The Future of Computing Performance"

Meanwhile:

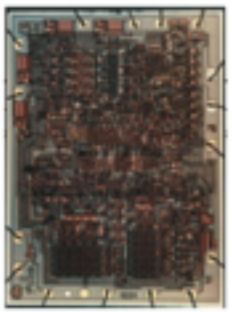


CONCURRENCY

- More but slower workers
- Potentially more performance
- Potentially more power efficiency

Concurrency only path left – National Academy of Science report

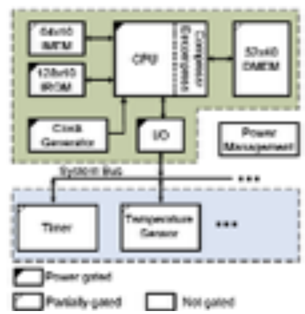
Corollary to Moore's Law

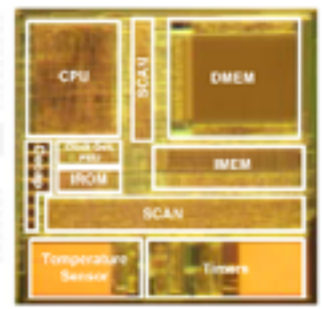


Intel® 4004 processor
Introduced 1971
Initial clock speed
108 KHz
Number of transistors
2,300
Manufacturing technology
10µ

Quad-Core Intel® Xeon® processor
Quad-Core Intel® Core™2 Extreme processor
Introduced 2006
Intel® Core™2 Quad processors
Introduced 2007
Initial clock speed
2.66 GHz
Number of transistors
582,000,000
Manufacturing technology
65nm

15x size decrease
40x transistors
55x smaller λ



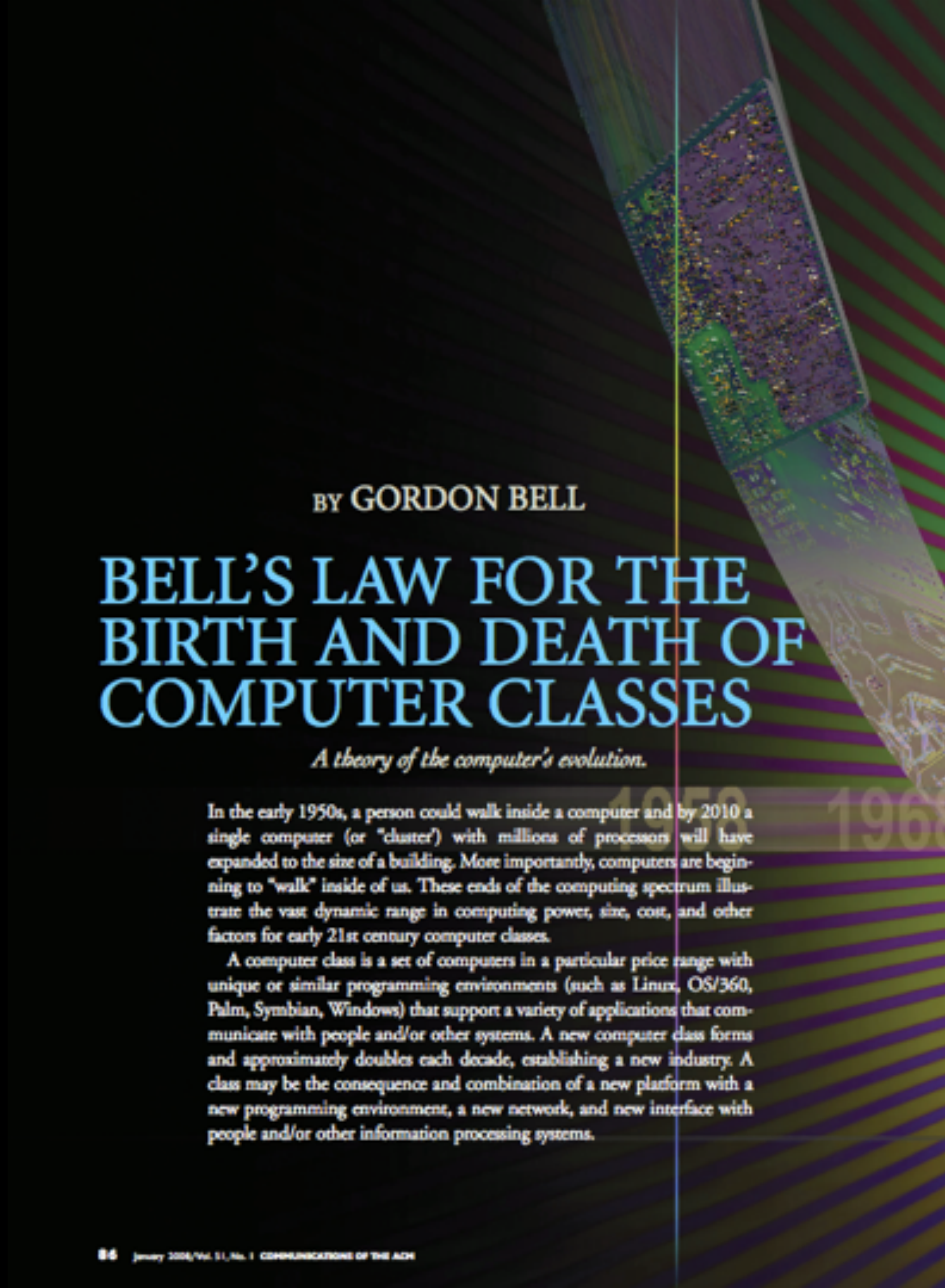


UMich Phoenix Processor
Introduced 2008
Initial clock speed
106 kHz @ 0.5V Vdd
Number of transistors
92,499
Manufacturing technology
0.18 µ

Photo credits: Intel, U. Michigan

“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.”

\- Gordon Bell [1972,2008]



BY GORDON BELL

BELL’S LAW FOR THE BIRTH AND DEATH OF COMPUTER CLASSES

A theory of the computer’s evolution.

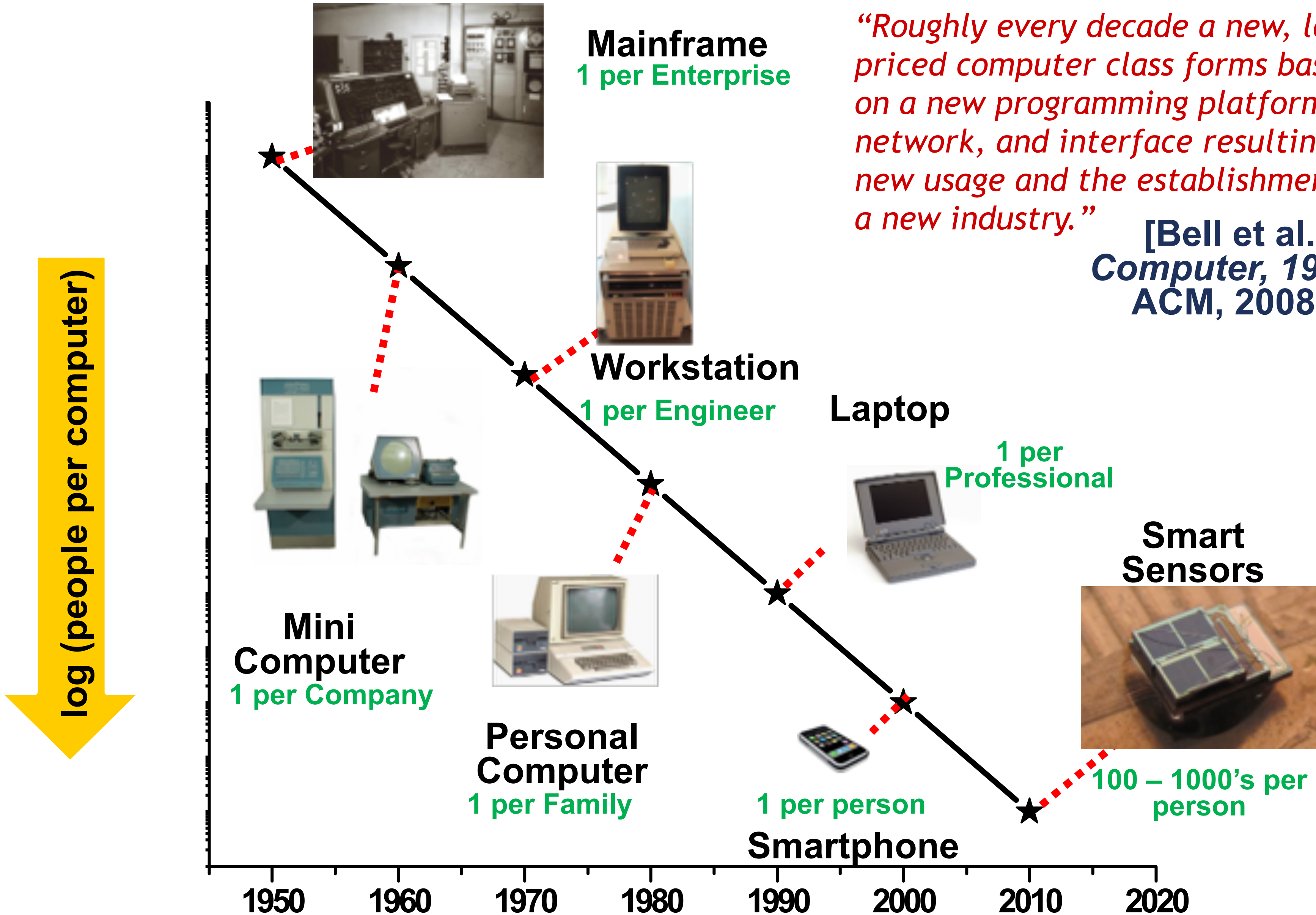
In the early 1950s, a person could walk inside a computer and by 2010 a single computer (or “cluster”) with millions of processors will have expanded to the size of a building. More importantly, computers are beginning to “walk” inside of us. These ends of the computing spectrum illustrate the vast dynamic range in computing power, size, cost, and other factors for early 21st century computer classes.

A computer class is a set of computers in a particular price range with unique or similar programming environments (such as Linux, OS/360, Palm, Symbian, Windows) that support a variety of applications that communicate with people and/or other systems. A new computer class forms and approximately doubles each decade, establishing a new industry. A class may be the consequence and combination of a new platform with a new programming environment, a new network, and new interface with people and/or other information processing systems.

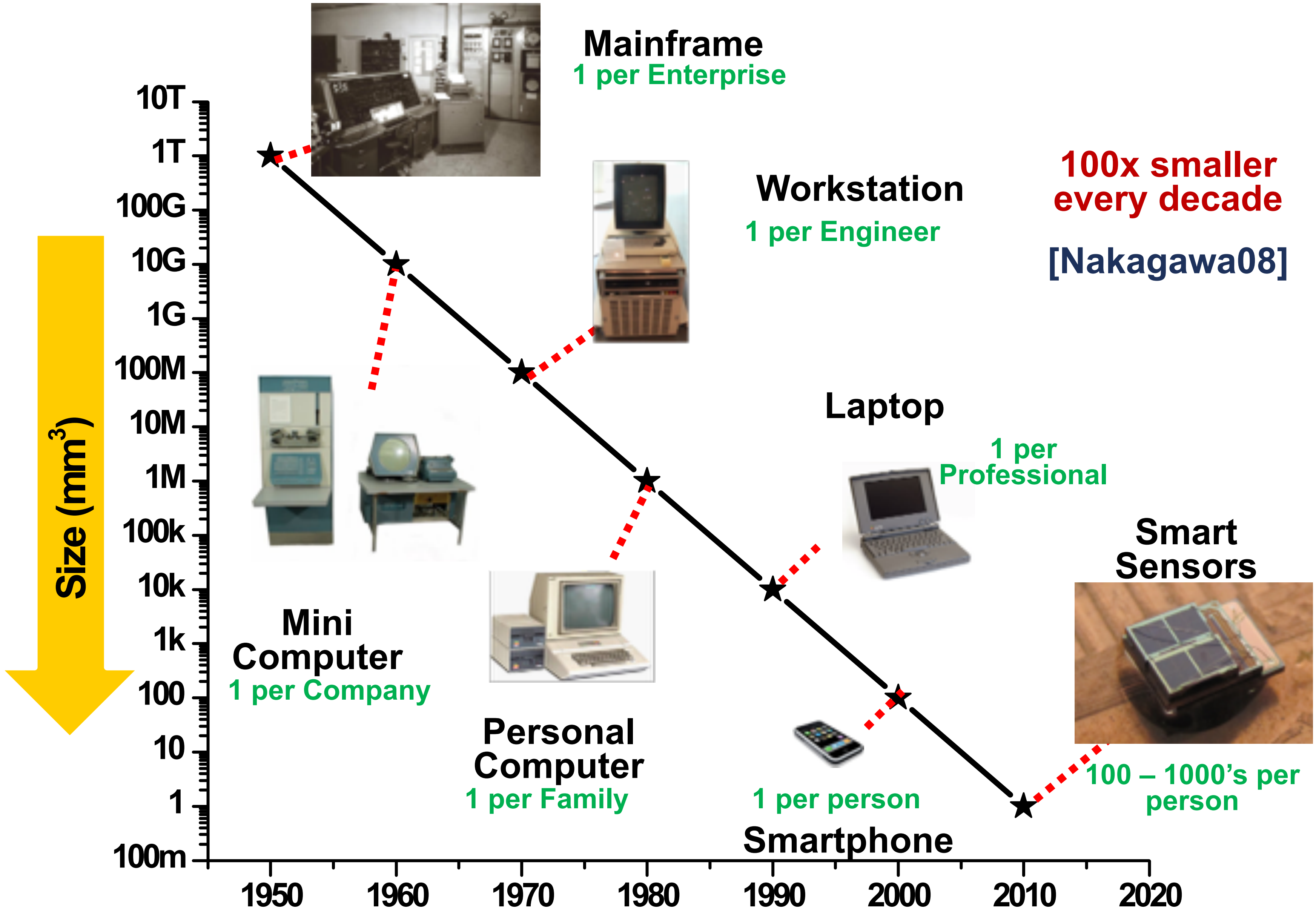
Bell's Law of Computer Classes:
A new computer class emerges roughly every decade

"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."

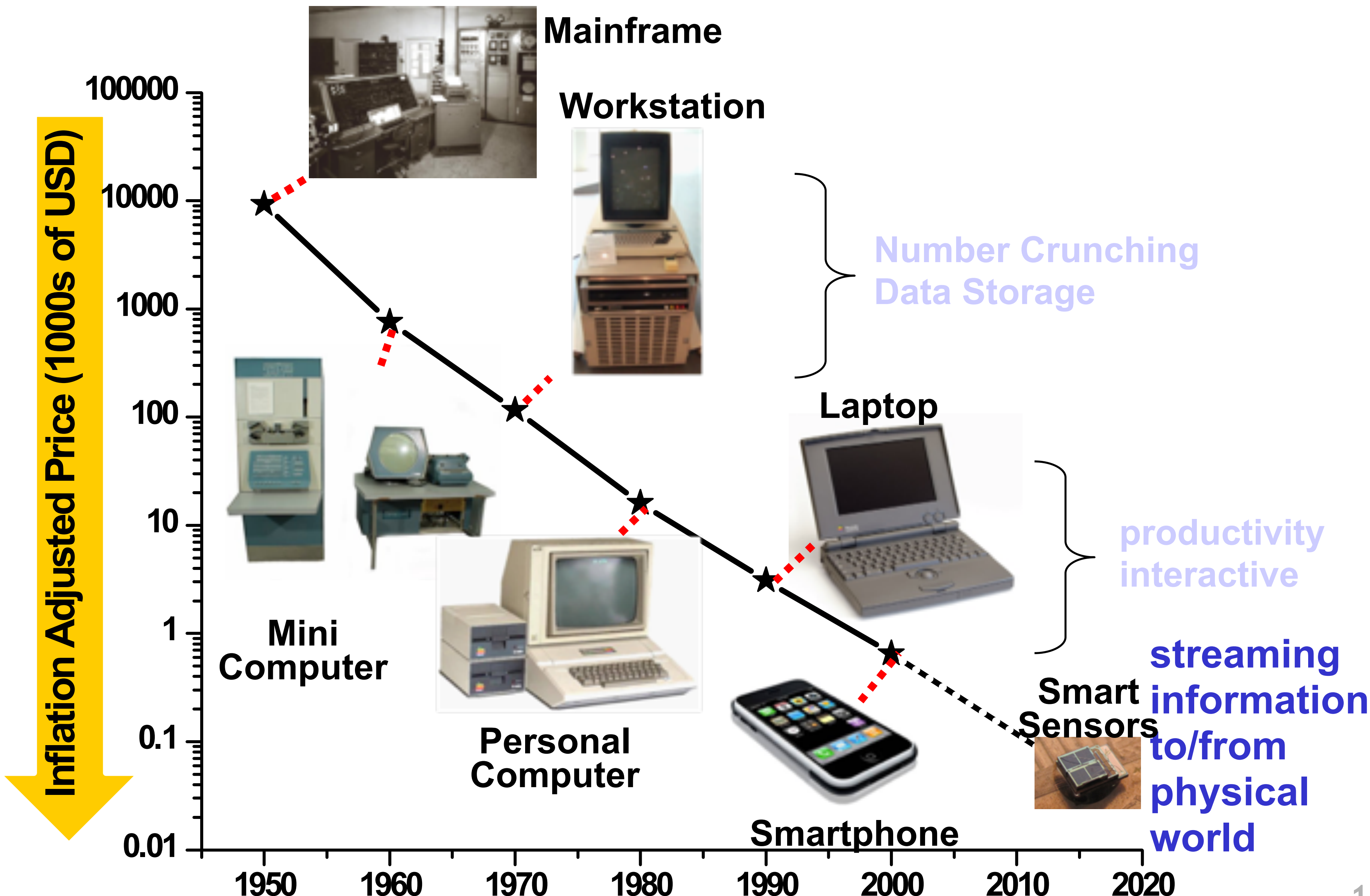
[Bell et al. *Computer, 1972*, ACM, 2008]



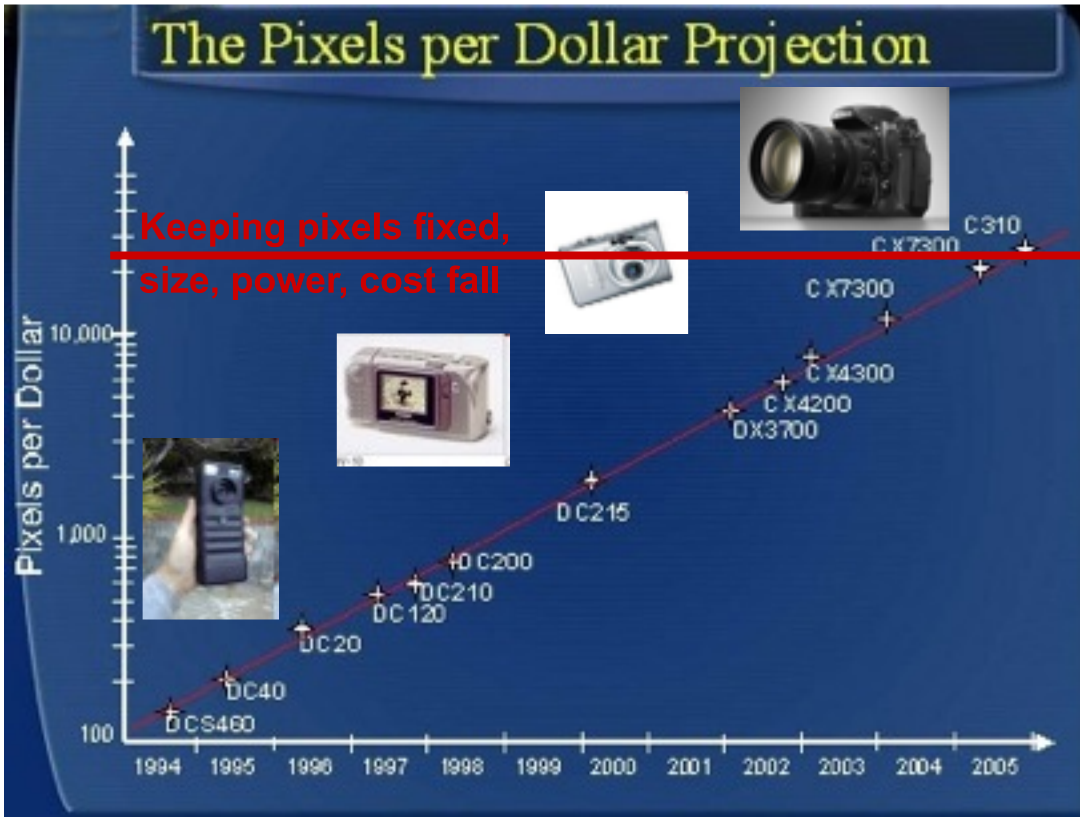
Bell's Law of Computer Classes (Corollary 1): Volume shrinks by 100x every decade



Bell's Law of Computer Classes (Corollary 2): Price falls dramatically, enables new applications

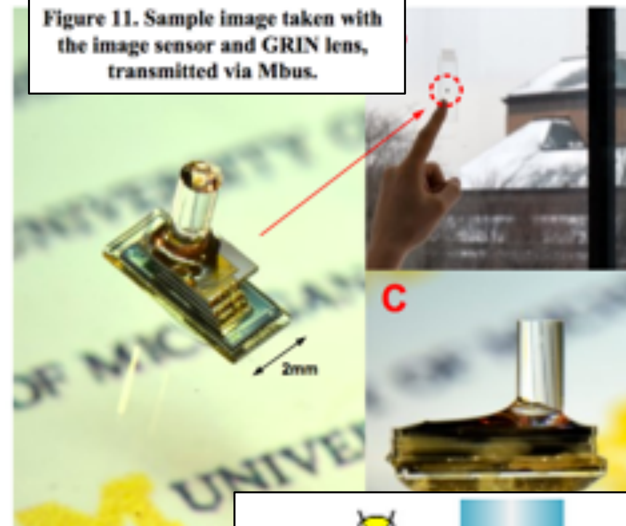


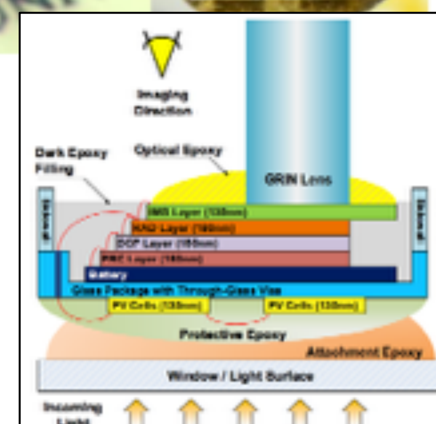
Hendy's "Law": Pixels per dollar doubles annually



Credit: Barry Hendy/Wikipedia

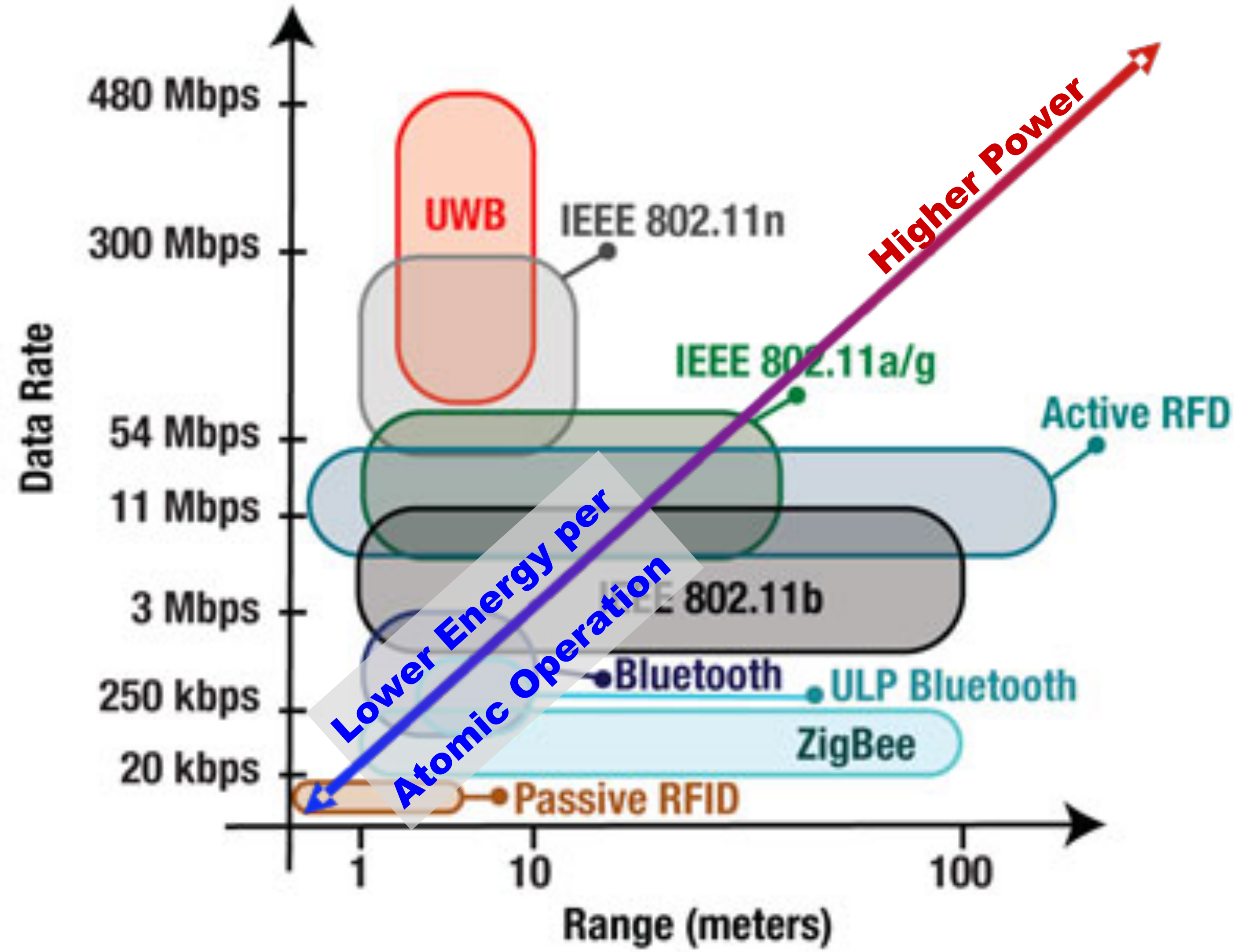
Figure 11. Sample image taken with the image sensor and GRIN lens, transmitted via Mbus.





G. Kim, Z. Foo, Y, Lee, P. Pannuto, Y-S. Kuo, B. Kempke, M. Ghaed, S. Bang, I. Lee, Y. Kim, S. Jeong, P. Dutta, D. Sylvester, D. Blaauw, "A Millimeter-Scale Wireless Imaging System with Continuous Motion Detection and Energy Harvesting,
In Symposium of VLSI Technology (VLSI'14), Jun. 2014.

Radio technologies enabling pervasive computing



Source: Steve Dean, Texas Instruments
http://eecatalog.com/medical/2009/09/23/current-and-future-trends-in-medical-electronics/

Established Interfaces: 802.15.4, BLE, NFC

- IEEE 802.15.4 (a.k.a. "ZigBee" stack)
  - Workhorse radio technology for sensornets
  - Widely adopted for low-power mesh protocols
  - Middle (6LoWPAN, RPL) and upper (CoAP) layers

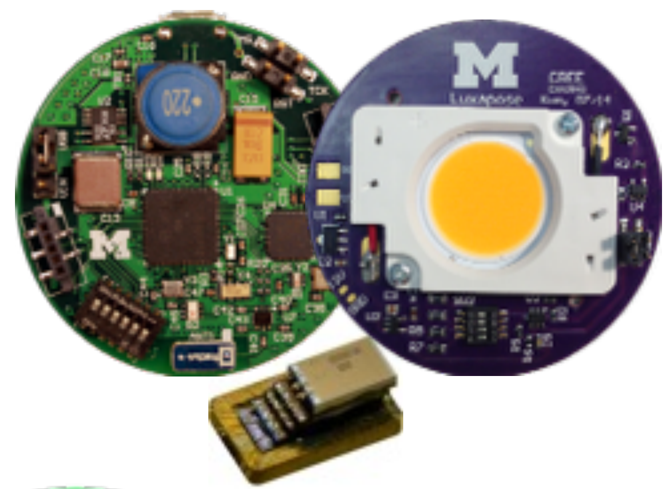
- Bluetooth Low-Energy (BLE)
  - Short-range RF technology
  - On phones and peripherals
  - Can beacon for years on coin cells

- Near-Field Communications (NFC)
  - Asymmetric backscatter technology
  - Small (mobile) readers in smartphones
  - Large (stationary) readers in infrastructure
  - New: ambient backscatter communications

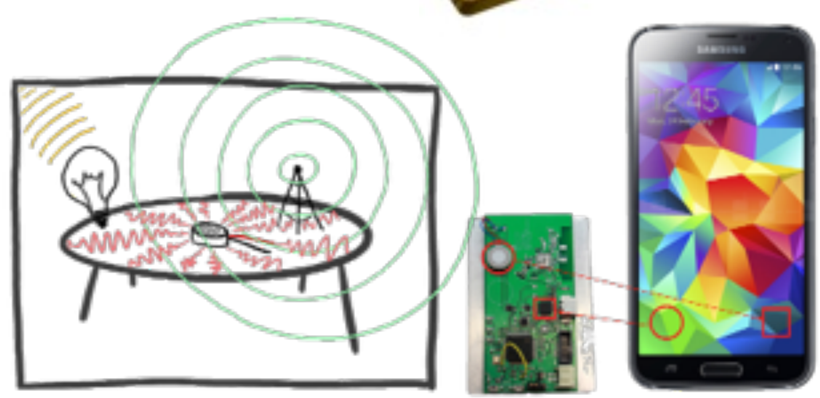
Emerging Interfaces: Ultrasonic, Visible Light, Vibration

- Ultrasonic
  - Small, low-power, short-range
  - Supports very low-power wakeup
  - Can support pairwise ranging of nodes

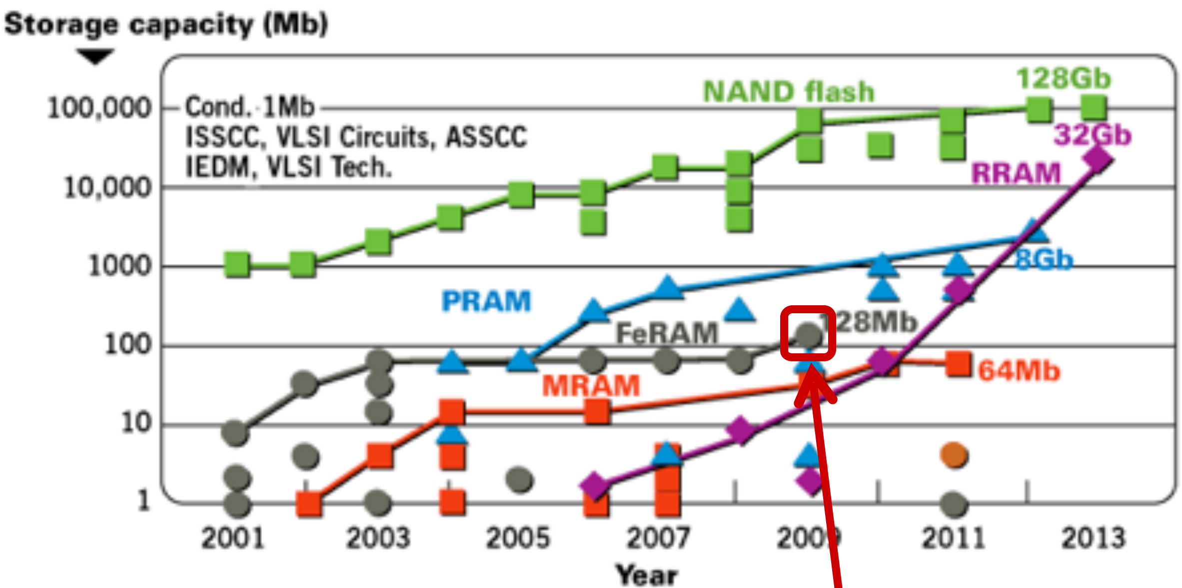
- Visible Light
  - Enabled by pervasive LEDs and cameras
  - Supports indoor localization and comms
  - Easy to modify existing LED lighting

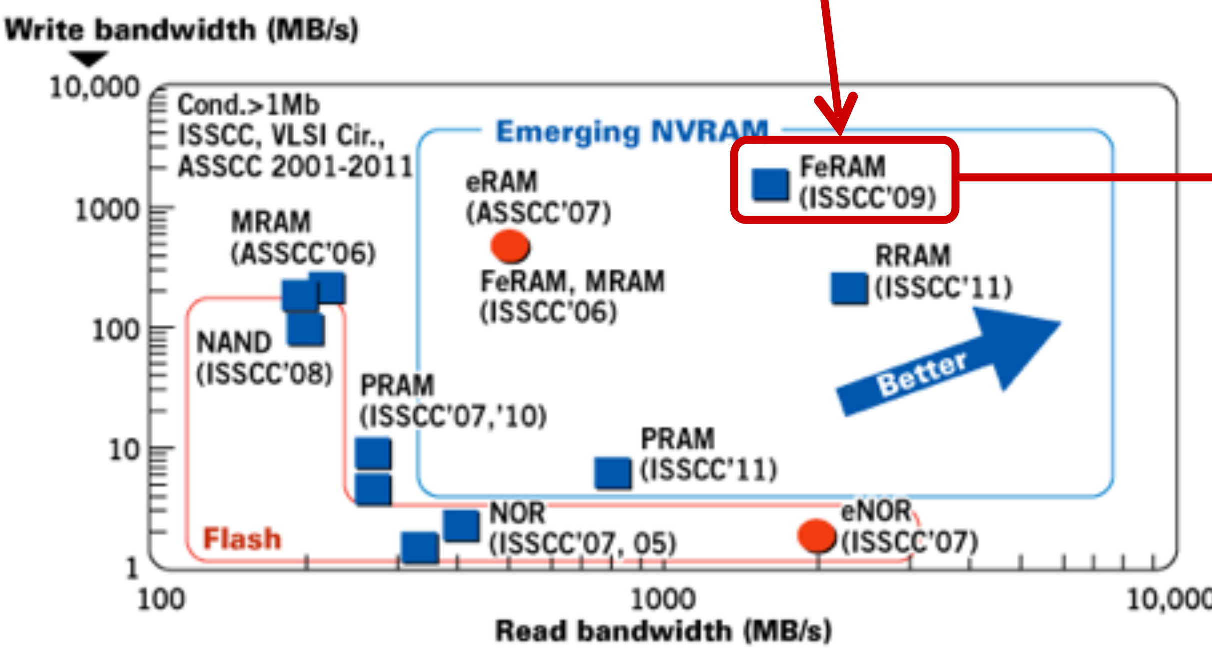


- Vibration
  - Pervasive accelerometers
  - Pervasive Vibration motors
  - Bootstrap desktop area context



Non-volatile memory capacity & read/write bandwidth

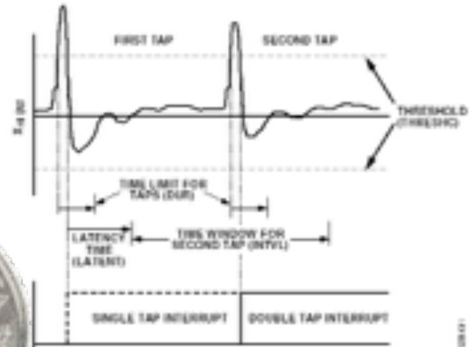




Lower capacity but
Higher R/W speeds
and
Lower energy per
atomic operation
and
High write
endurance

MEMS Sensors:
Rapidly falling price and power of accelerometers

O(mA)



[Analog Devices, 2009]
ADXL345

25 μA @ 25 Hz

Price

Power

10 μA @ 10 Hz @ 6 bits

[ST Microelectronics, annc. 2009]

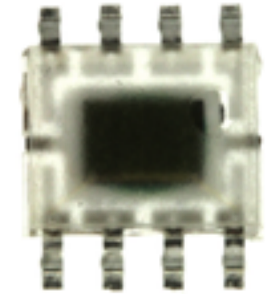
ADXL362

1.8 μA @ 100 Hz @ 2V
300 nA wakeup mode

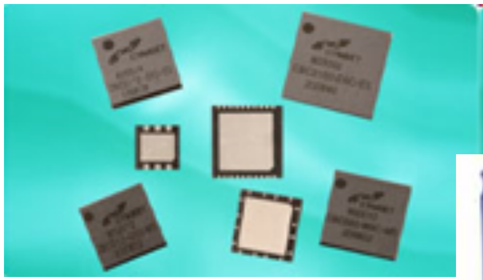
[Analog Devices, 2012]

Energy harvesting and storage: Small doesn't mean powerless…

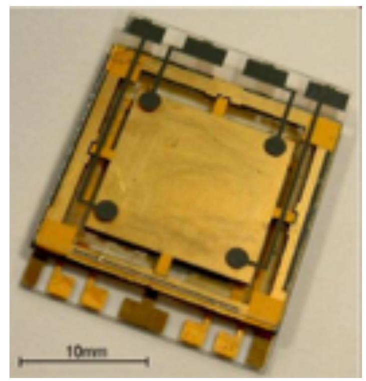
RF [Intel]



Clare Solar Cell

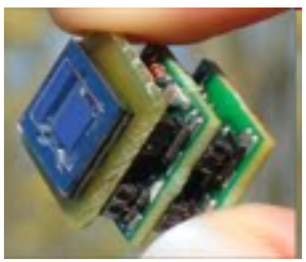


Thin-film batteries

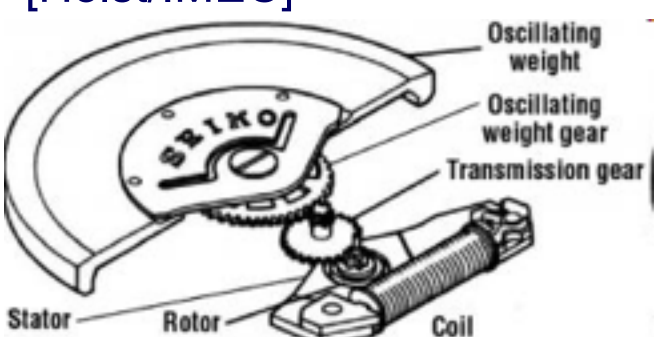


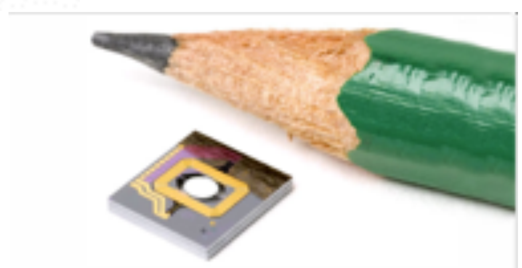
Electrostatic Energy Harvester [ICL]

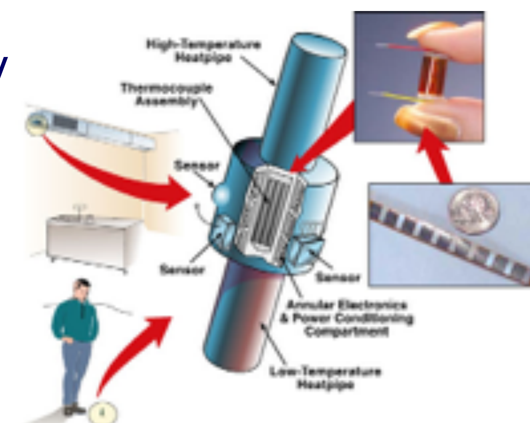
Shock Energy Harvesting CEDRAT Technologies



Piezoelectric [Holst/IMEC]

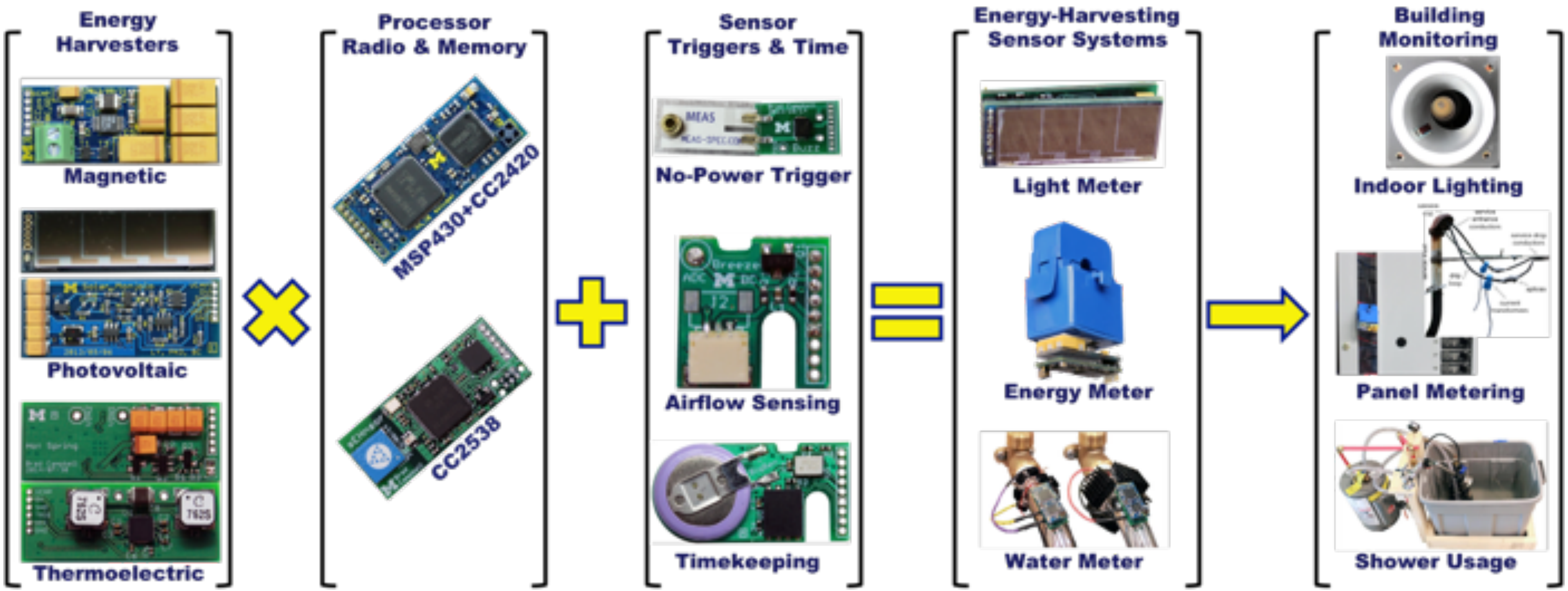






Thermoelectric Ambient Energy Harvester [PNNL]

Enough harvested energy to do interesting things

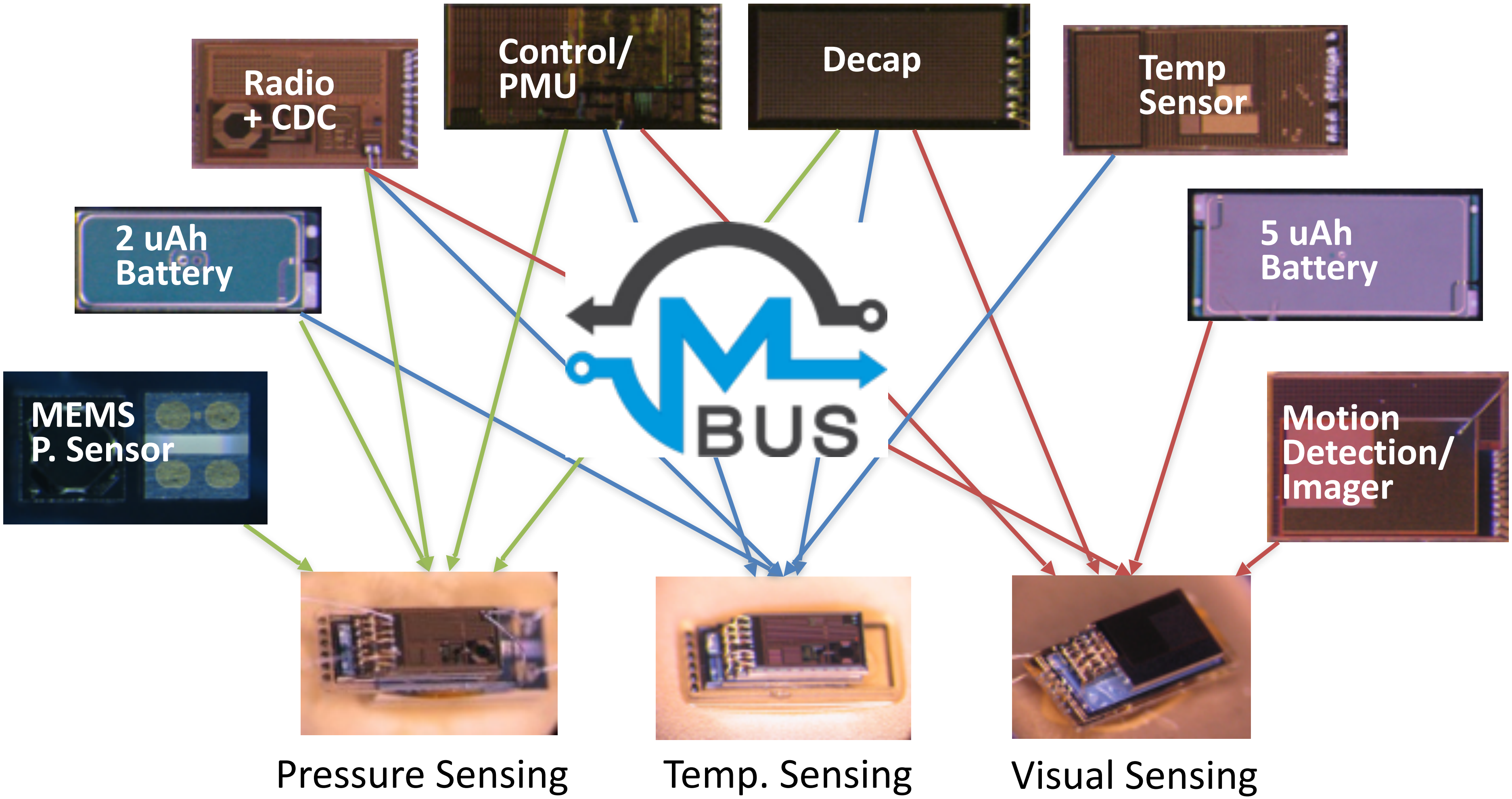


Bradford Campbell and Prabal Dutta,
"Gemini: A Non-Invasive, Energy-Harvesting True Power Meter,"
In Proceedings of the 35th IEEE RTSS, Dec. 2-5, 2014.

Bradford Campbell, Branden Ghena, and Prabal Dutta,
"Energy-Harvesting Thermoelectric Sensing for Unobtrusive Water and Appliance Metering,"
In Proceedings of the 2nd ENSsys, Nov. 6, 2014.

Bradford Campbell and Prabal Dutta,
"An Energy-Harvesting Sensor Architecture and Toolkit for Building Monitoring,"
In Proceedings of the 1st ACM BuildSys, Nov. 5-6, 2014.

Michigan Micro Mote (M^3) modular, nano-power platform w/ David Blaauw, Dennis Sylvester, and Dave Wentzloff



Y-S. Kuo, P. Pannuto, G. Kim, Z. Foo, I. Lee, B. Kempke, P. Dutta, D. Blaauw, and Y. Lee,
"MBus: A 17.5 pJ/bit/chip Portable Interconnect Bus for Millimeter-Scale Sensor Systems with 8 nW Standby Power,"
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Y. Lee, S. Bang, I. Lee, Y. Kim, G. Kim, M. H. Ghaed, P. Pannuto, P. Dutta, D. Sylvester, and D. Blaauw,
"A Modular 1mm^3 Die-Stacked Sensing Platform with Low Power I2C Inter-die Communication and Multi-Modal Energy Harvesting,"
In IEEE Journal of Solid-State Circuits (JSSC'14), Vol. 48, No. 1, Jan. 2013.

Outline

Historical Roots

Technology Trends

Application Explosion

Open Problems

"Applications are of course the whole point…"

- Mark Weiser, 23-Mar, 1993

"In the future, an increasing proportion of computer science research will be application-driven"

- Eric Brewer and Mike Franklin, CS262A

Pervasive Computing starts with Embedded, Everywhere

Re-imagine the thermostat:
Digital, wireless, multi-sensor, networked, and learning

Source:

Re-imagine industrial automation: High reliability

DUST NETWORKS

EMERSON
Process Management

- ✓ Battery
- ✓ 4-20 mA loop
- ✓ Solar

GE Energy

- ✓ Battery
- ✓ Vibration

SIEMENS

- ✓ Battery
- ✓ 4-20 mA loop
- ✓ Thermal

Thousands of networks, 100+ countries, six continents

buildings, breweries, refineries, mines, city streets, chemical plants, deserts, trains, steel mills, data centers, pharmaceutical plants, offshore oil rigs…

Source: Kris Pister, Dust Networks (now part of Linear Technology)

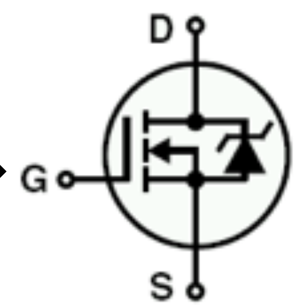
Re-imagine lighting: from milli-Hz to mega-Hz switching

≠

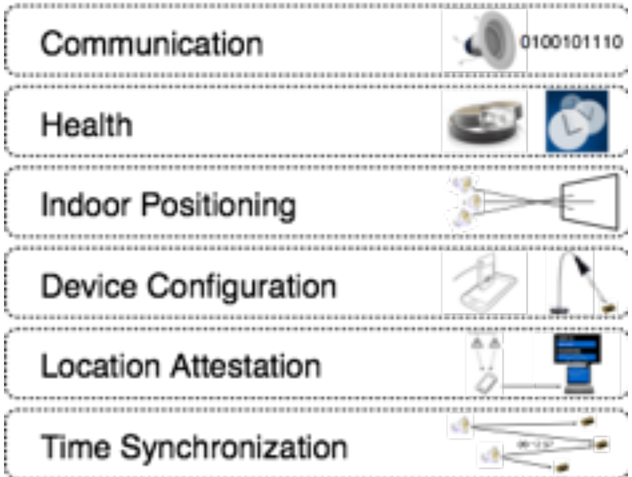
~10^0 Hz

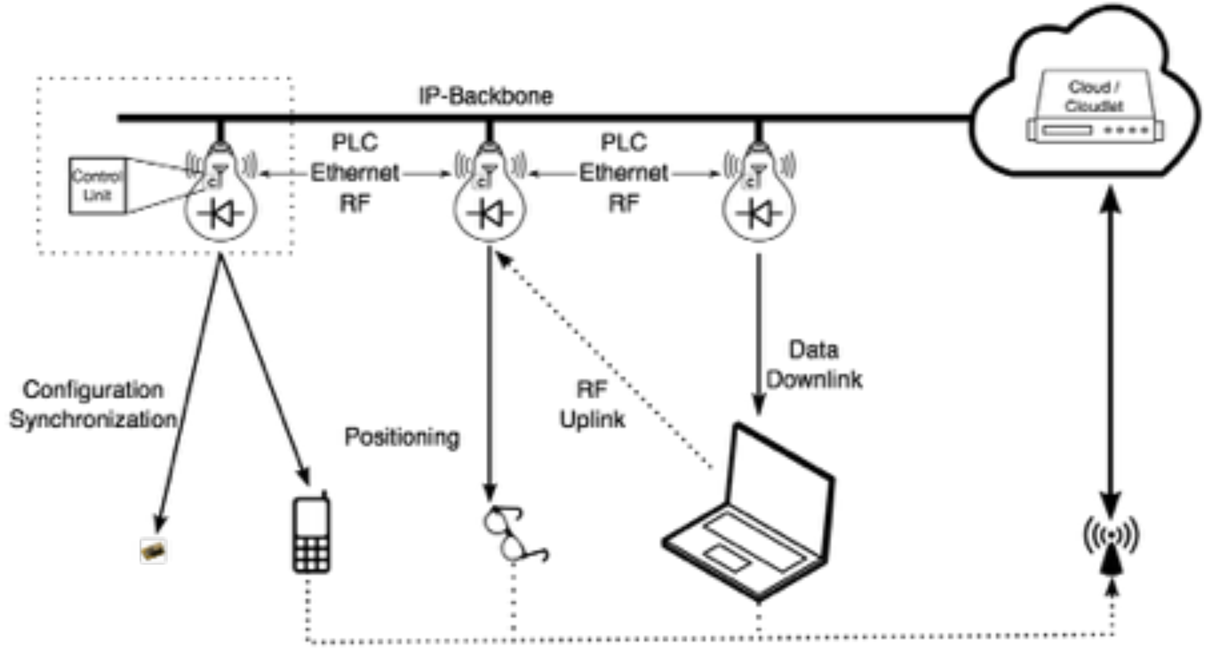
~10^7 Hz

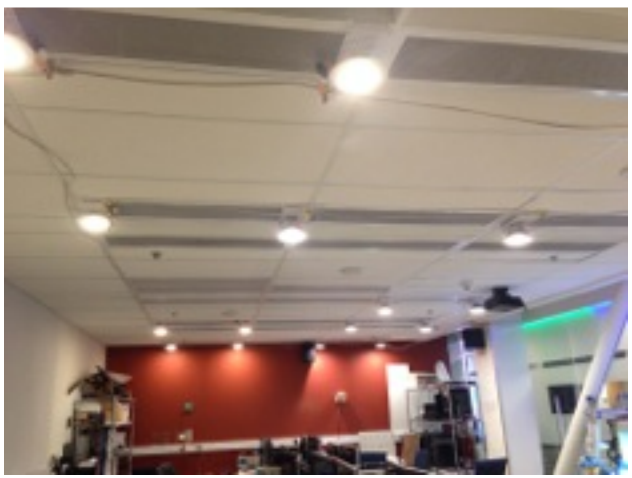
00010100 →



Software-defined lighting: multiprogramming the lights



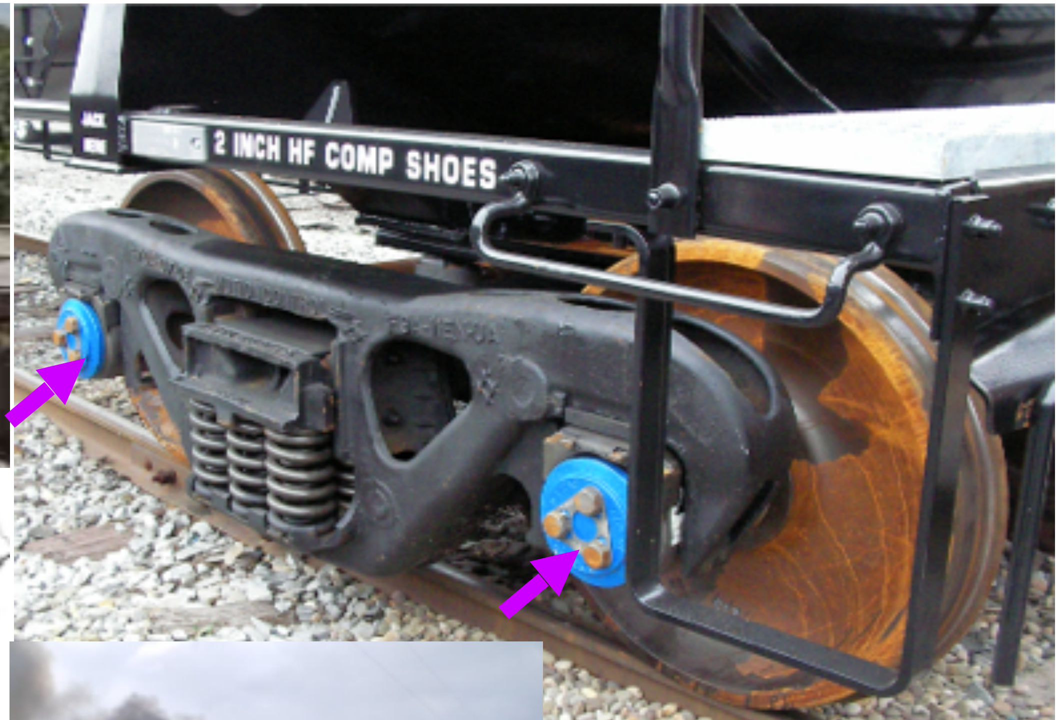




Ye-Sheng Kuo, Pat Pannuto, Ko-Jen Hsiao, and Prabal Dutta,
Luxapose: Indoor Positioning with Mobile Phones and Visible Light,
In Proc. of MobiCom ’14: The 20th ACM MobiCom, Sep. 7-9, 2014.

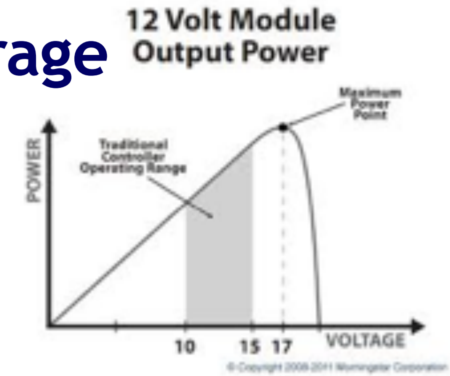
Ye-Sheng Kuo, Pat Pannuto, and Prabal Dutta
System Architecture Directions for a Software-Defined Lighting Infrastructure
In VLCS ’14: The 1st ACM Workshop on Visible Light Communication Systems, Sep. 7, 2014.

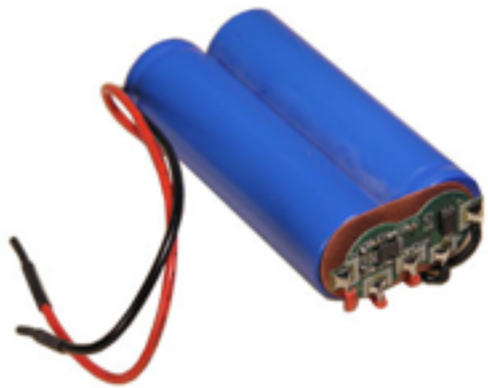
Re-imagine the railroad:
From the railway network to the railcar network

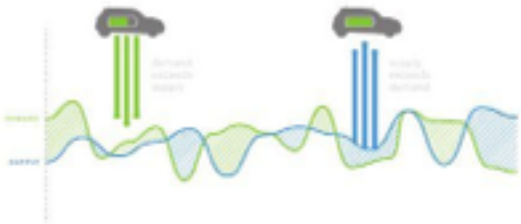


Sources:
http://www.dailywireless.org/2012/04/03/railroad-sensors-predict-derailments-wirelessly/
http://www.intel.com/references/pdfs/Intel_ESS_Union_Pacific_Case_Study_HR.pdf
http://robotics.eecs.berkeley.edu/~pister/presentations/LBL110316.ppt

Re-imagine the battery:
From black box to PCM to MPPT to grid storage

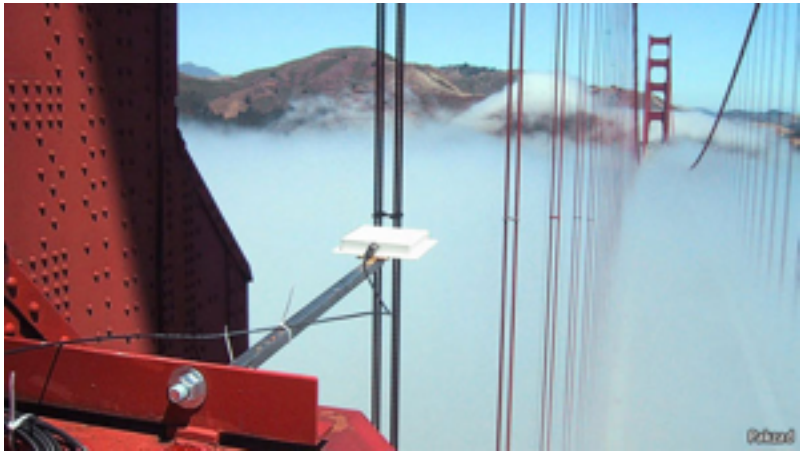




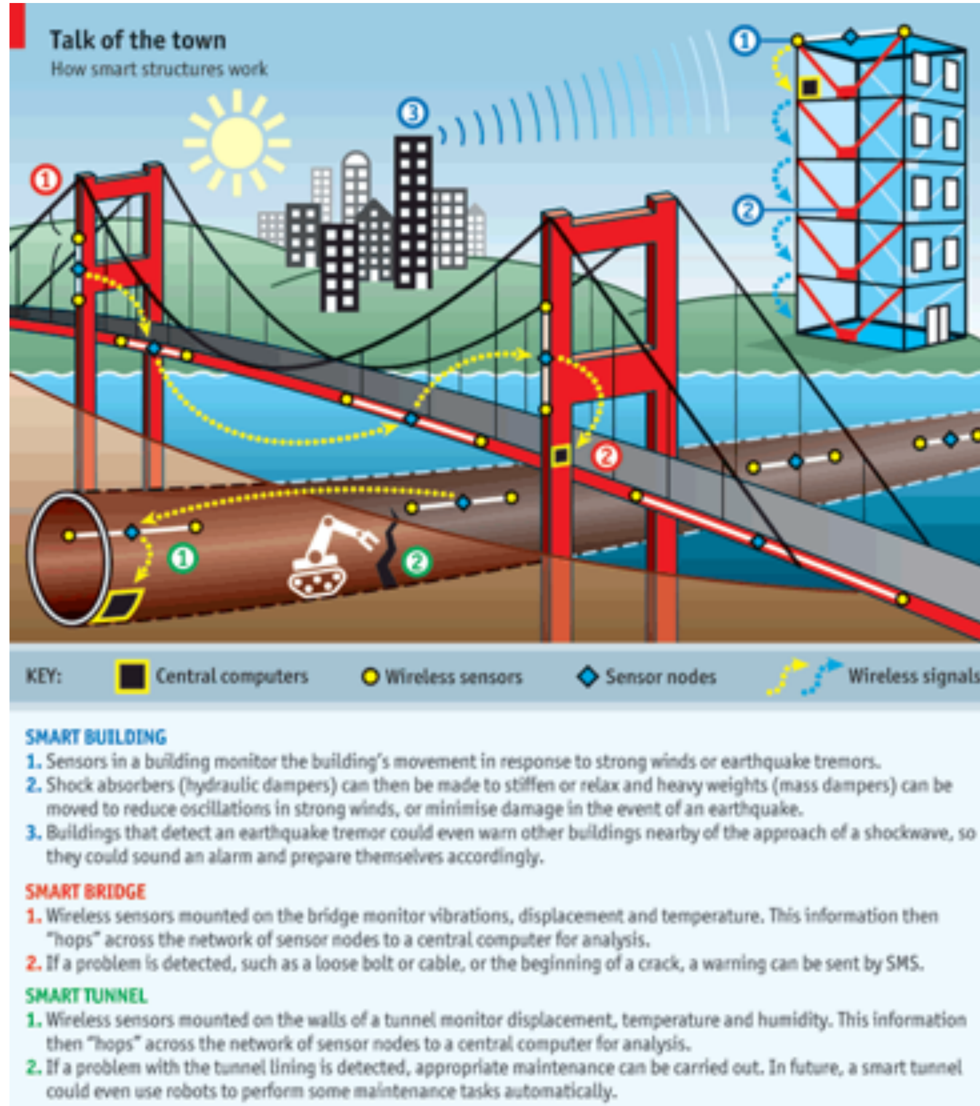


Sources:
http://gas2.org/2011/10/24/revenge-of-the-electric-car-movie-review/
http://blogs.scientificamerican.com/guest-blog/2011/10/27/vehicle-to-grid-technology-electric-cars-become-power-grid-batteries/

Re-imagine the bridge (and building and tunnel): Infrastructures becomes intelligent and self-diagnostic

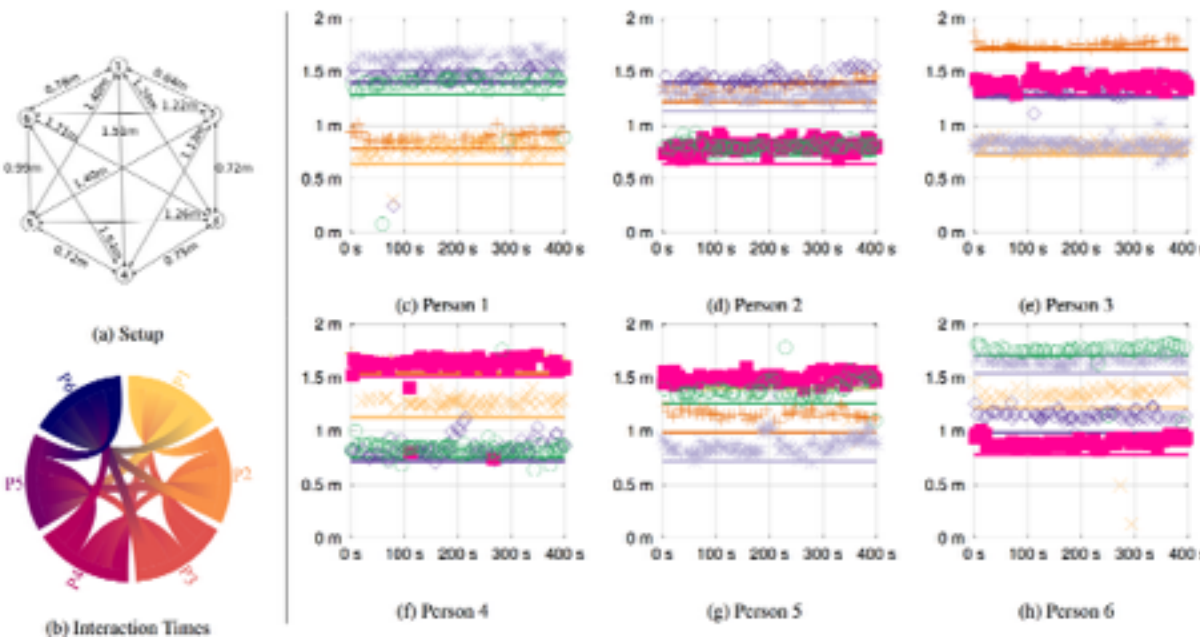


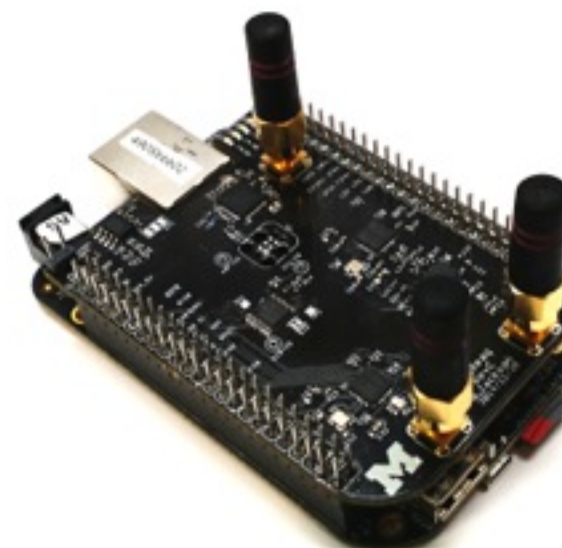
…
"Getting these sensor networks to work reliably proved unexpectedly difficult."
…
"There were physical problems to be overcome, too: within a day of being installed on the Underground, several sensors fell off the concrete walls of the tunnel and had to be reattached with different glue. Within a few weeks, all the equipment was found to be covered in thick layers of brake dust and needed to be put into protective casing. After six months and numerous battery changes, some of the incline sensors mysteriously failed and had to be replaced."
…



Source: http://www.economist.com/node/17647603

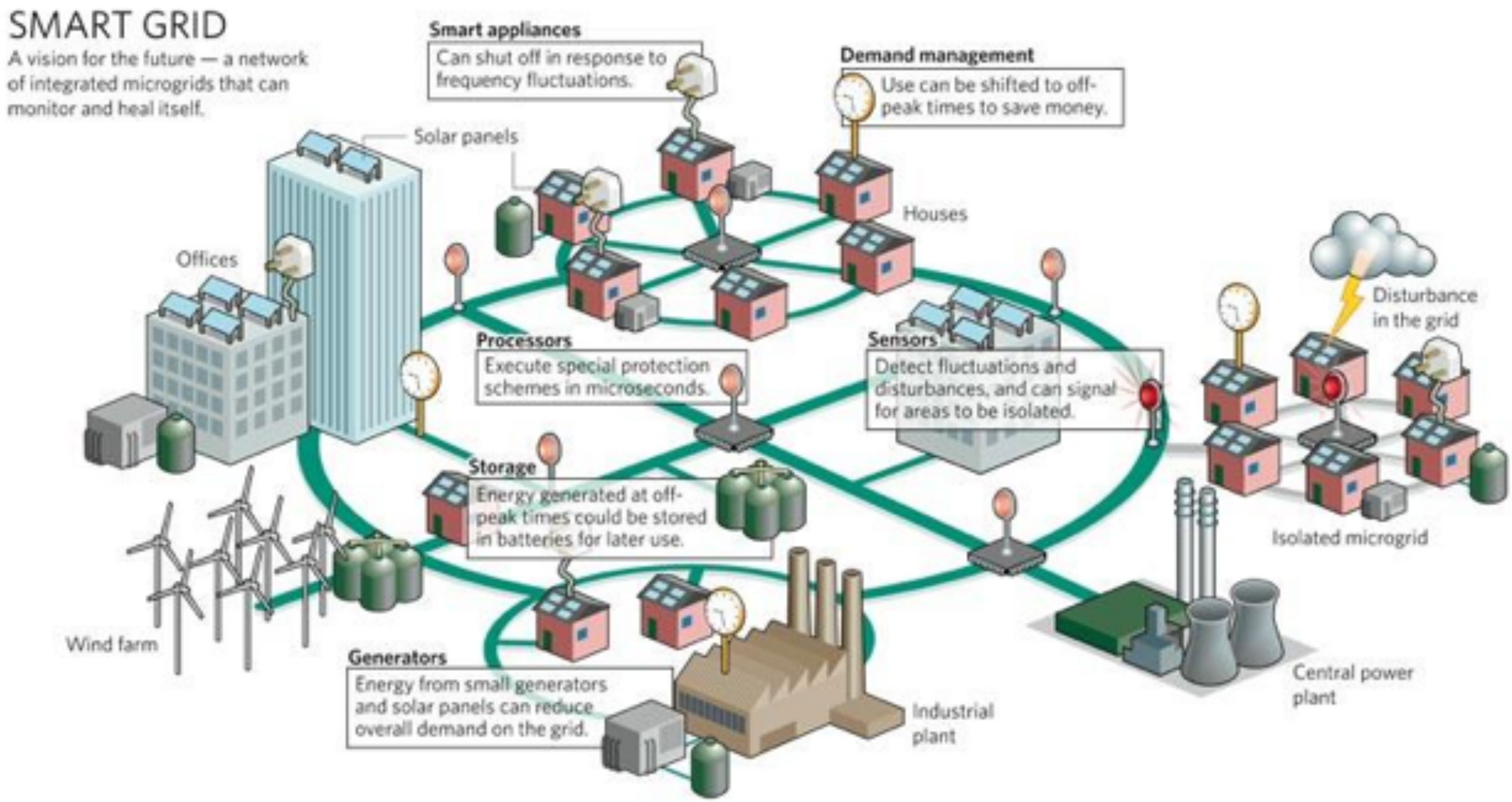
Re-imagine social networking:
From facebook to real-time, human inter-contact data





William Huang, Ye-Sheng Kuo, Pat Pannuto, and Prabal Dutta,
"Opo: A Wearable Sensor for Capturing High-Fidelity Face-to-Face Interactions,"
In Proceedings of the 12th ACM Sensys'14, Nov. 3-6, 2014.

Re-imagine the power grid:
Smart, responsive, decentralized, and adaptive



http://www.horizonenergy.blogspot.com/

Re-imagine health care:
Continuous, mobile, wireless, digital, and networked

Source: http://www.ercim.eu/publication/Ercim_News/enw60/husemann.html

Re-imagine all the things: They're now phone attachments

Geiger Counter

EKG Monitor

Thermometer

CC Terminal

CO Sensor

Soil Moisture

Re-imagine all the things: some favorites

Kinsa Thermometer

Ryobi™ Phone Works™

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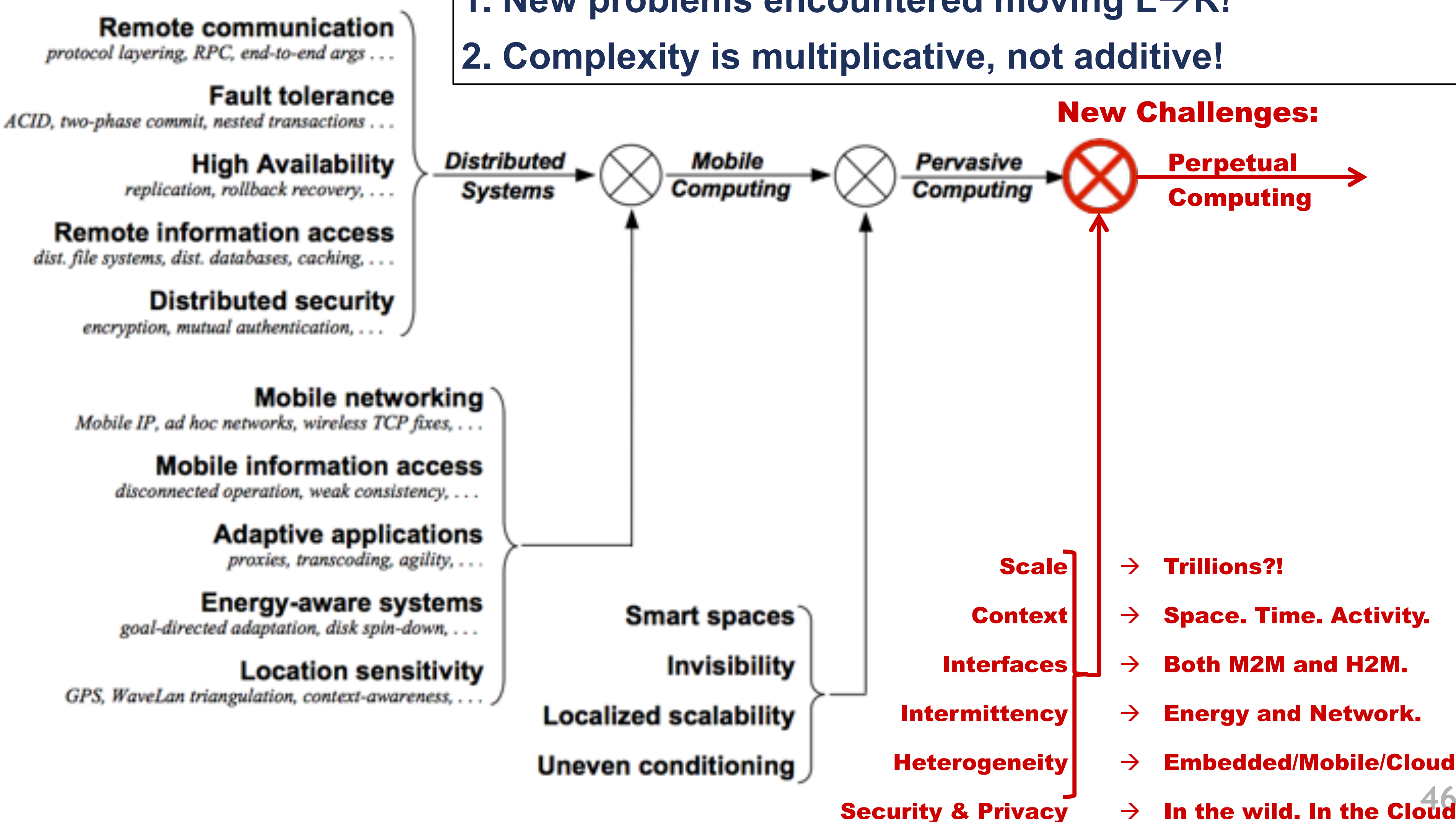
Open problems, new challenges

How are *Distributed*, *Mobile*, *Pervasive*, and *Perpetual* Computing are related:

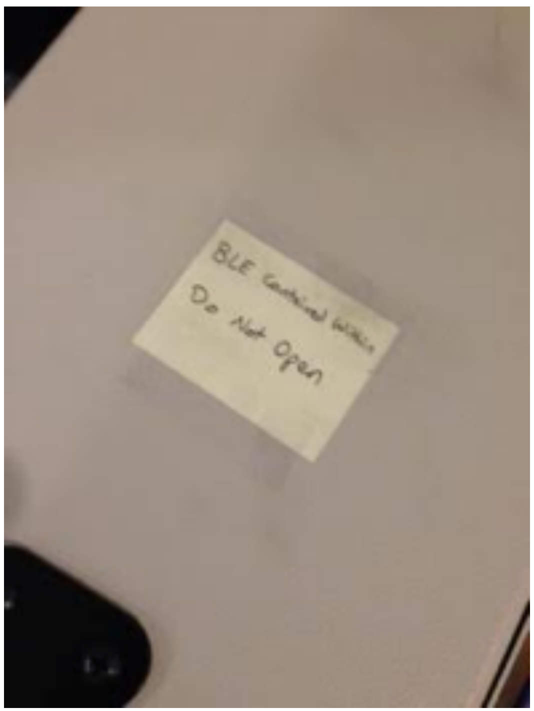
1. New problems encountered moving L→R!

2. Complexity is multiplicative, not additive!



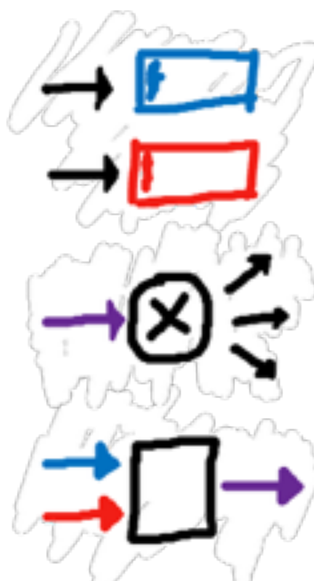
Scale & Context

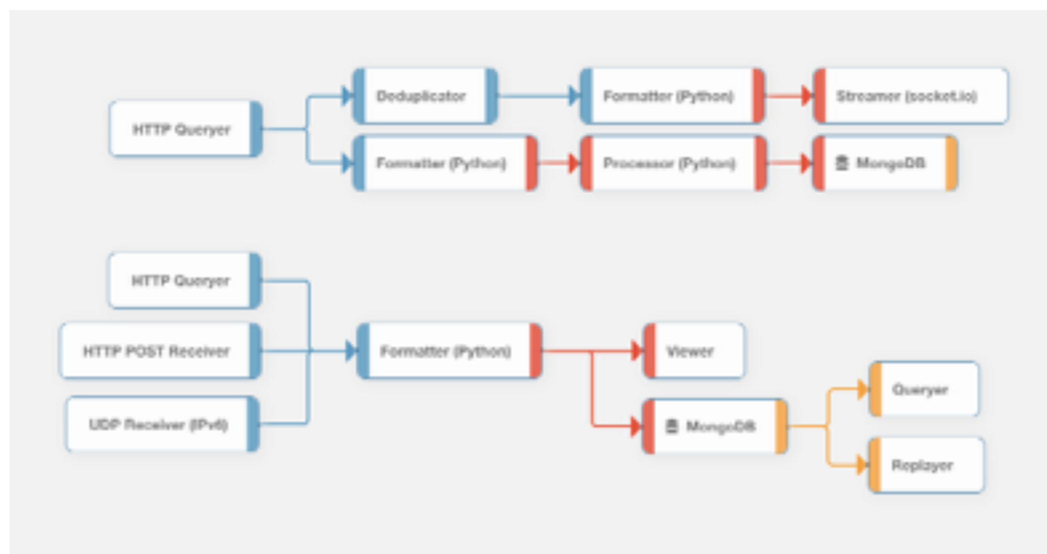
- Immense scale will be a challenge
- Proximity helps…but only so much
- Need better ways to establish context



Interfaces to man and machine

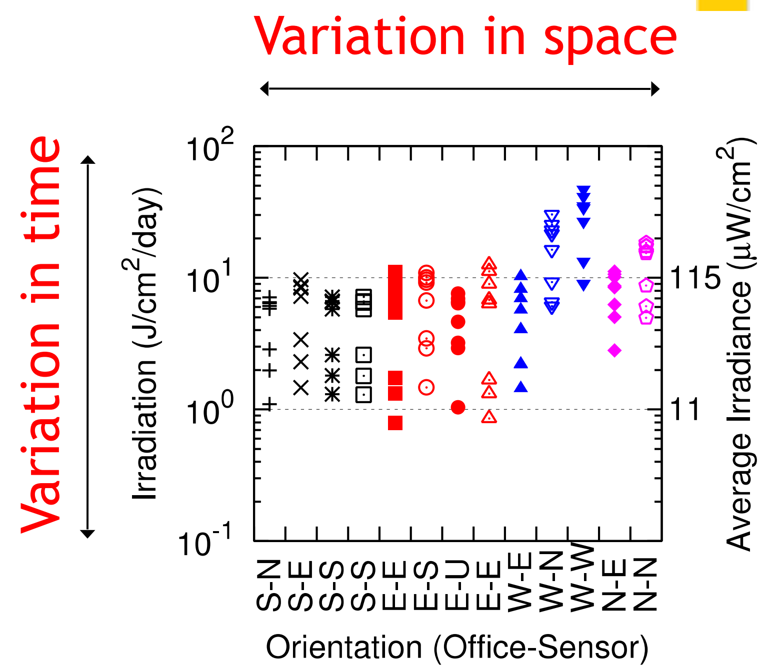
- Many devices will have no user interface
- But could have multiple communications interfaces
- How to associate, configure, and interact with them?
- How to collect, process, and distribute sensor data?
- How to find and bind to new resources in new places?

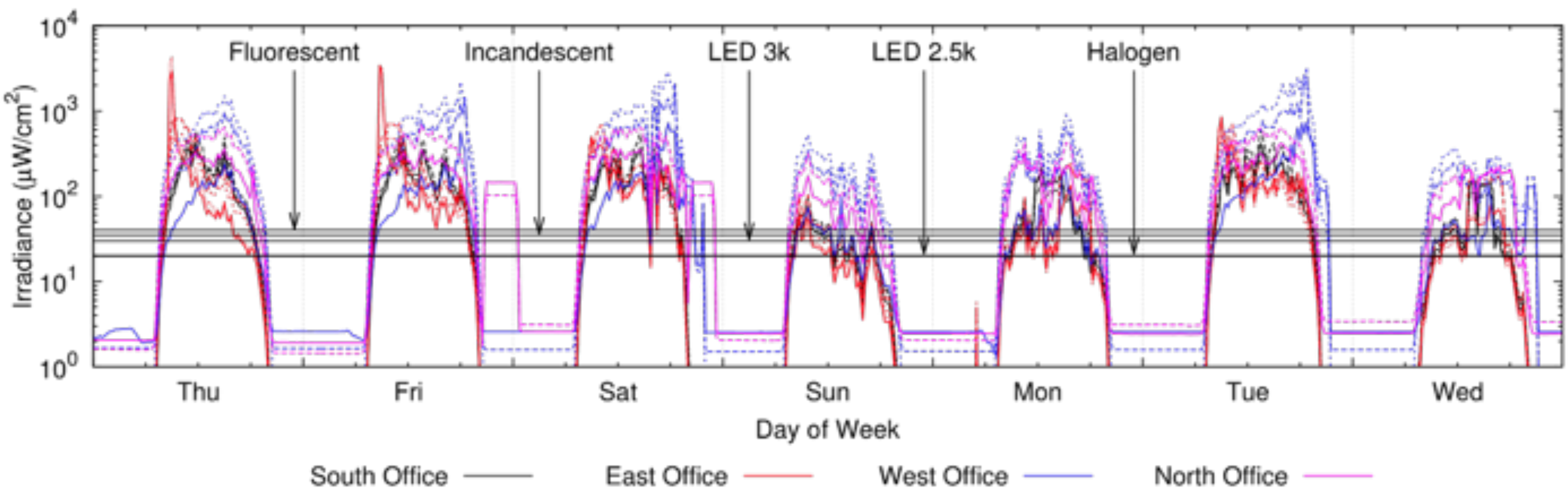




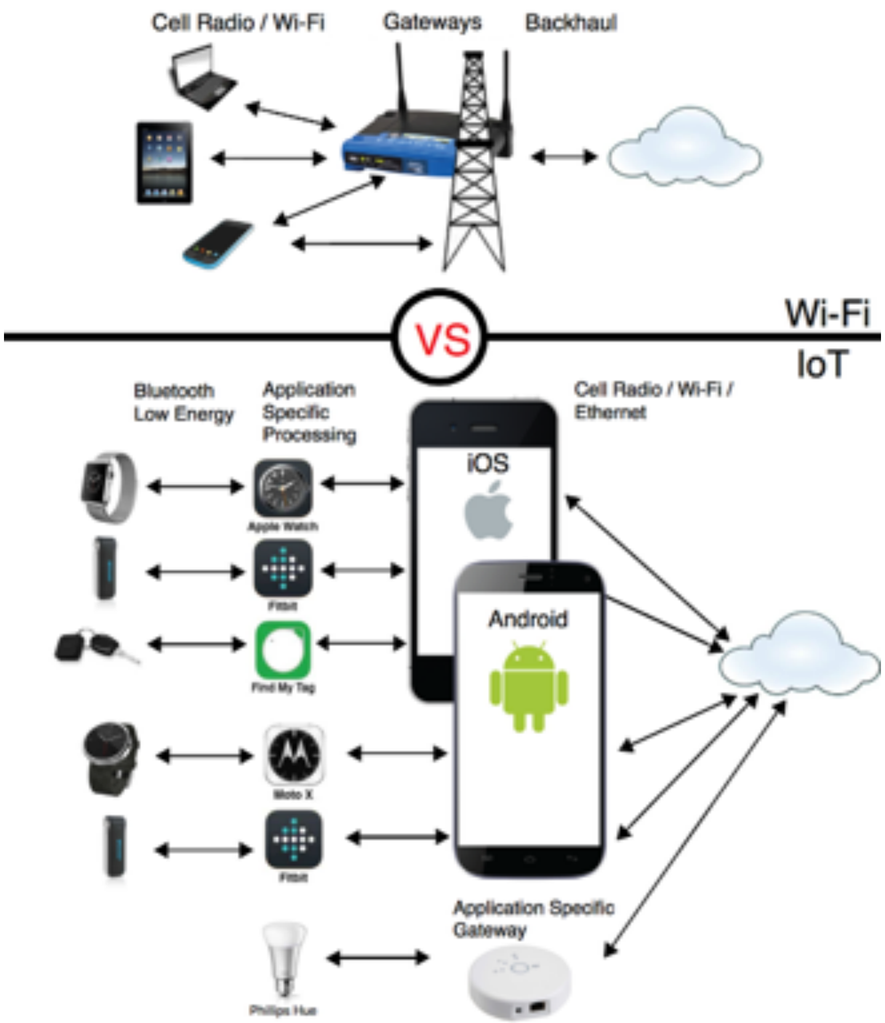
Energy and communications intermittency

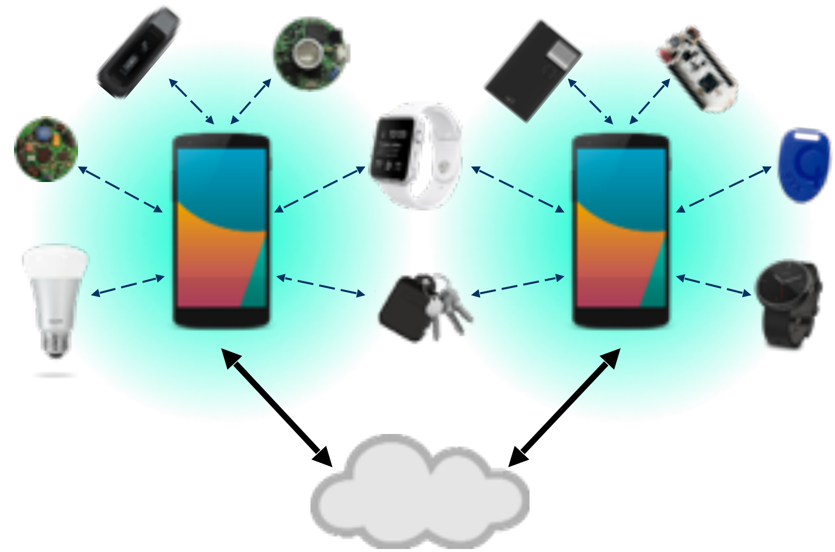
- Harvested energy is variable
  - Space
  - Time
  - Energy / area / time
  - 1-10's J/cm^2/day
- Implication: widely differing node duty cycles





The Internet of Things has a Gateway Problem



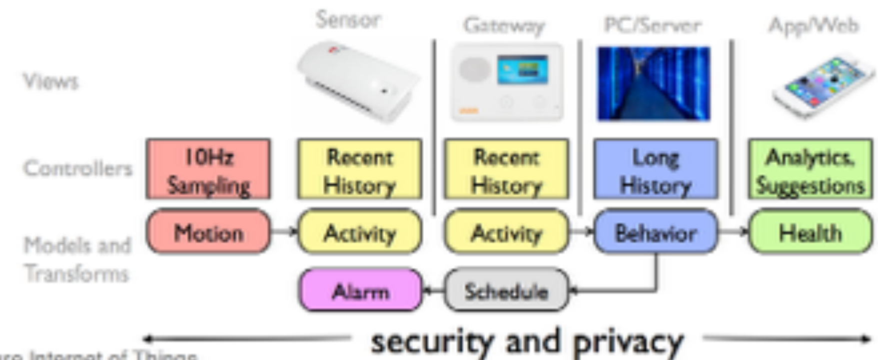


Thomas Zachariah, Noah Klugman, Bradford Campbell, Josh Adkins, Neal Jackson, and Prabal Dutta,
"The Internet of Things has a Gateway Problem,"
In The 16th International Workshop on Mobile Computing Systems and Applications (HotMobile'15), Feb. 12-13, 2015

Building applications across heterogeneous systems

Building an Application

- Write a data processing pipeline
  - Consists of a set of *Models*, describing data as it is stored
  - *Transforms* move data between Models
  - Instances of Models are bound to devices
  - *Views* can display Models
  - *Controllers* determine how data moves to Transforms



Secure Internet of Things

24

Accessors

Interact with the world.

The world is a complicated place.

Accessors provide a standardized interface for controlling, reading, and interacting with the devices around you.

Code comes standard, too.

An interface is great, but code is what makes it work. Accessors include the code needed to use the interface.

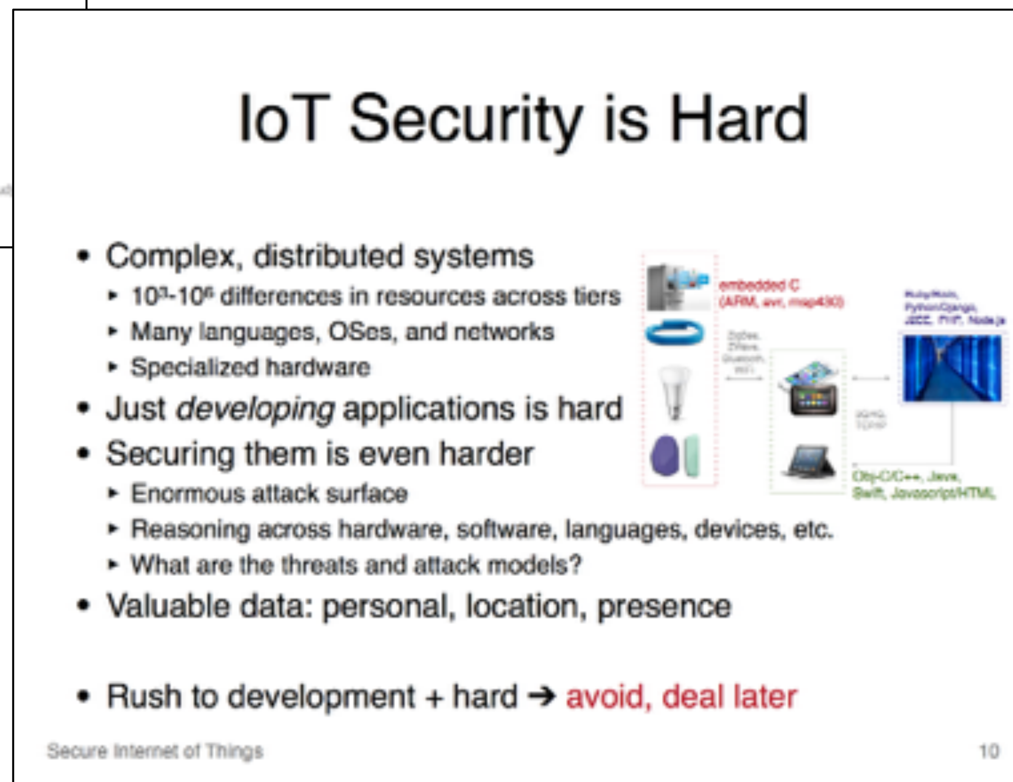
Accessors are versatile.

Accessors can run any where Javascript does. Plus the configuration is easily parsable JSON.

Brad Campbell, Pat Pannuto, Univ. of Michigan
http://accessors.io:5000/

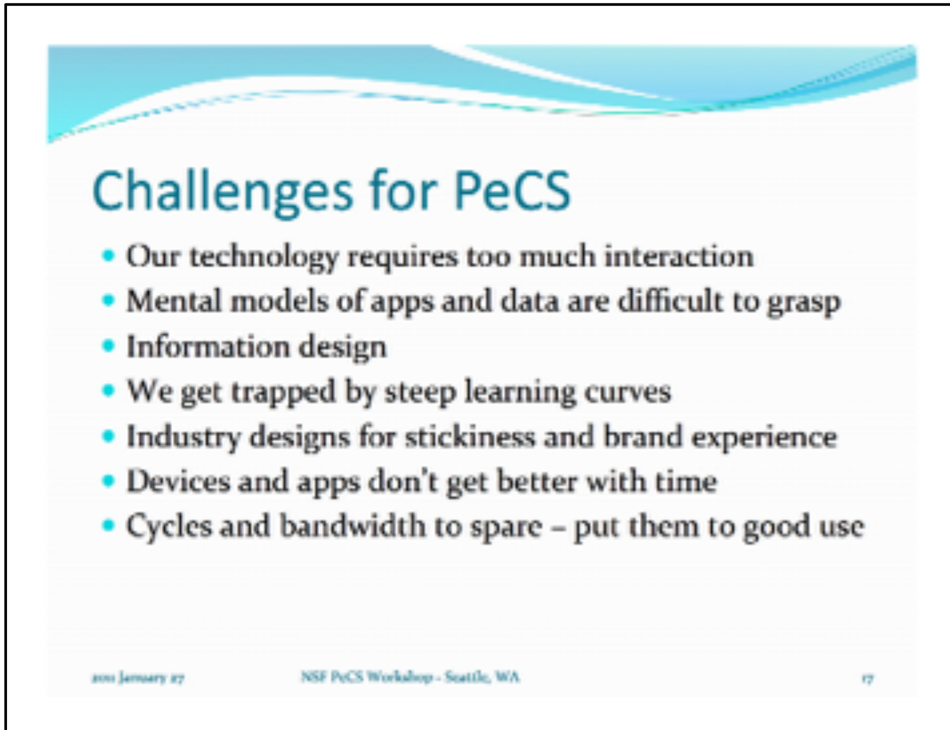
Philip Levis, Stanford University, SITP 2014 Industrial Workshop
http://iot.stanford.edu/workshop14/SITP-8-11-14-Levis.pdf

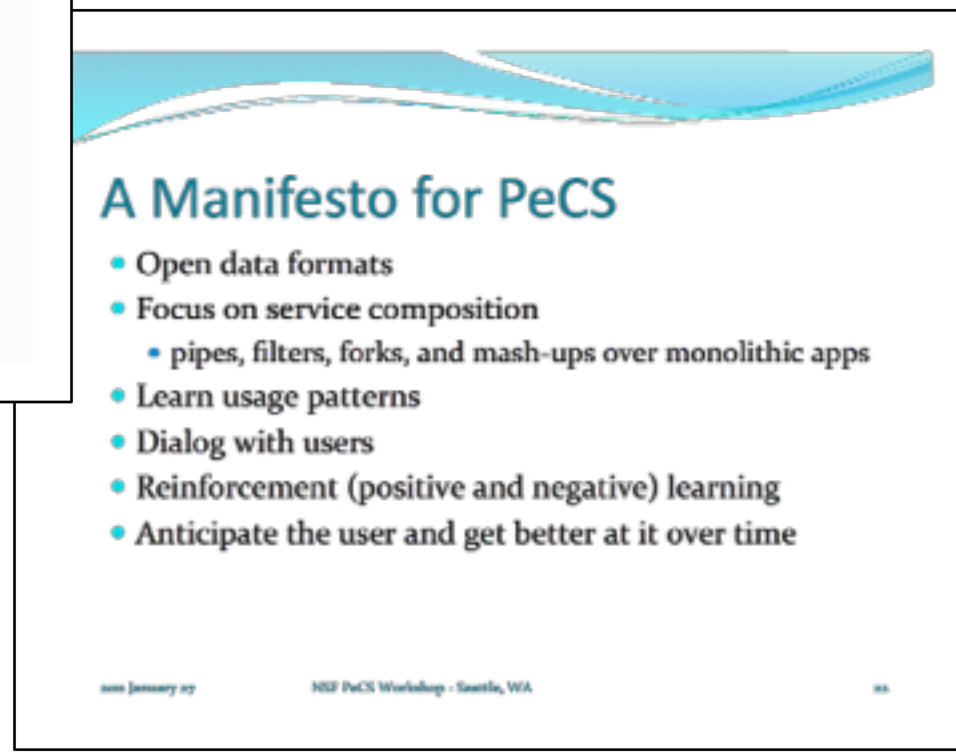
The Internet of (Infected and Compromised) Things



Philip Levis, Stanford University, SITP 2014 Industrial Workshop
http://iot.stanford.edu/workshop14/SITP-8-11-14-Levis.pdf

2011: In Gaetano Borriello's words





Gaetano Borriello (University of Washington),
"Looking Forward to Ubiquitous Computing that Looks Ahead,"
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January 27-28, 2011

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WHERE DISCOVERIES BEGIN

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TerraSwarm

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Questions?

Comments?

Discussion?