THE WIRELESS REVOLUTION CONTINUES -
FROM MOBILES TO SWARMS

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University of California at Berkeley

HONORARY DOCTORATE
LUND, MAY 24 2012

Information Processing in the 1980s
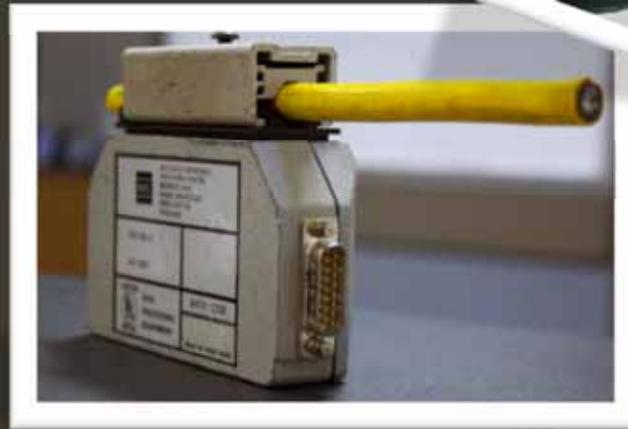
Minicomputers ➡ Workstations ➡ Desktops ➡ Laptops

A Defining Moment ...


On a sunny day in Berkeley in the mid 1980's,

"One decade from now, mobile phones will be digital, and will fit in your shirt pocket,"

Sven-Olof Öhrvik, Ericsson Radio Systems and faculty at Lund University

Just imagine the opportunities …

1990 Question:

"What would computers look like if wireless connectivity becomes ubiquitous?"

InfoPad in the Office

Picocells

Shared I/O Devices

Multiple wireless portable terminals

InfoPad

- Goal is to provide information access of multimedia data in a device that is as simple, low cost and small size as possible
  - Network support, high bandwidth connectivity and ease of use - like a network computer
  - Wireless connectivity and portability - like a phone
  - User interface and form factor - like a PDA

[R. Brodersen, ISSCC keynote 1997]

The UCB Infopad Project (1992-1996)

The Birth of the Tablet

Towards Human-Centric Devices

➡ Desktops ➡ Laptops ➡ **Handhelds**

2010 – The tablet as the gateway to the cloud
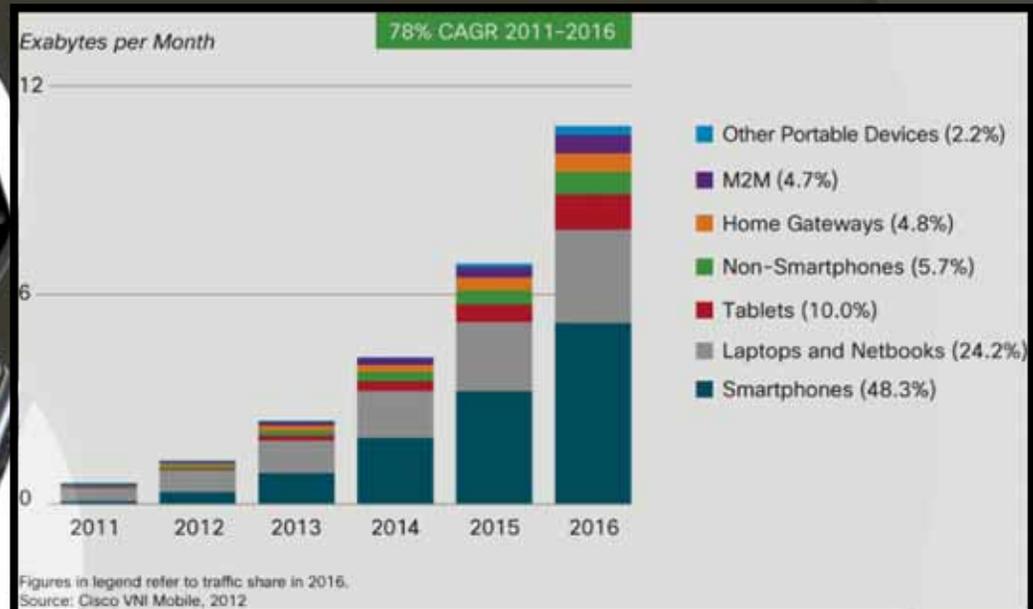
- By end of 2012, mobile connected-components will exceed earth population
- Tablets to exceed 10% of global mobile data traffic in 2016

Key Infopad Concept:
Move Computation to the "Backbone"

The "Proto-Cloud"
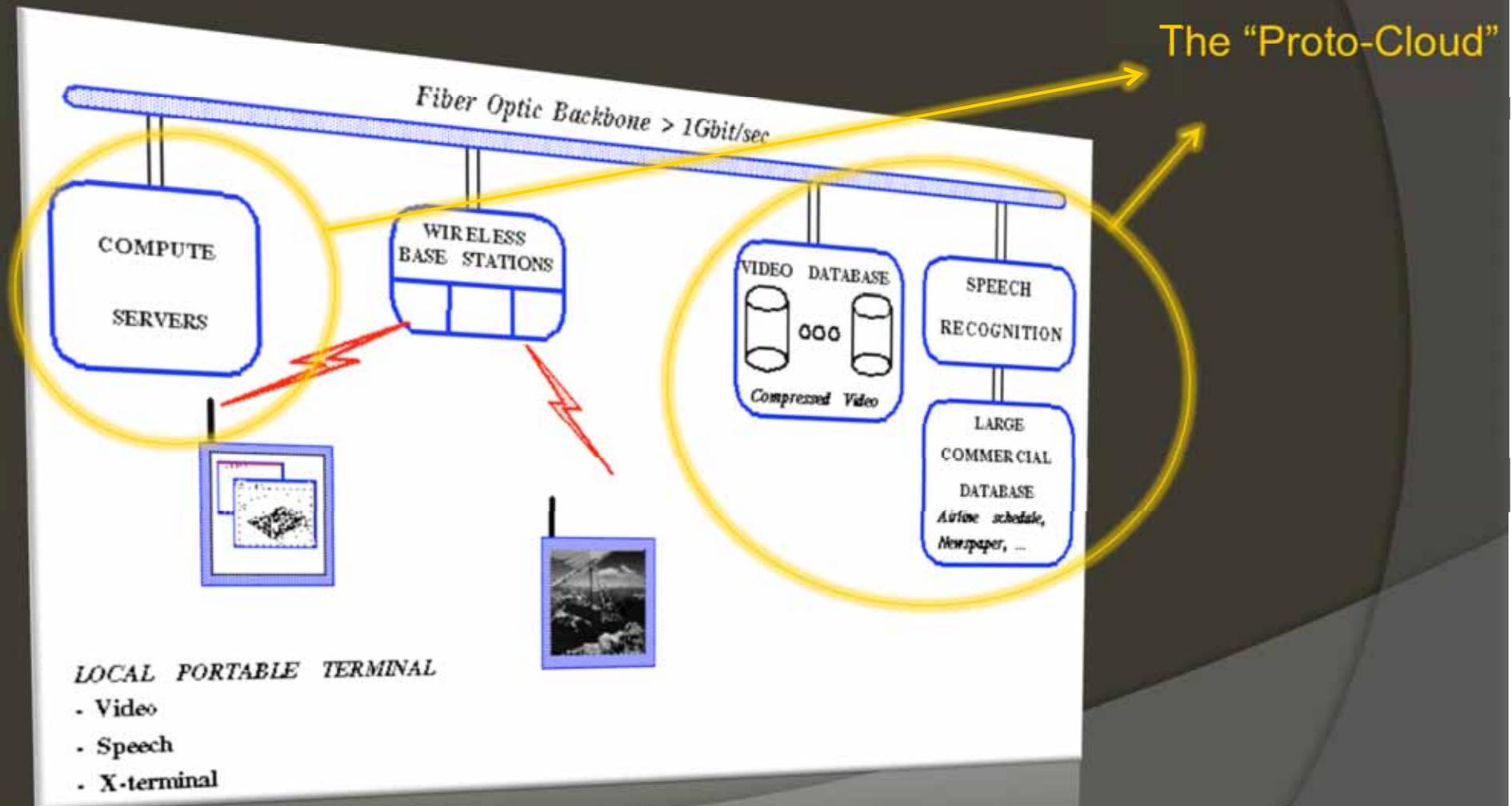
[Infopad, 1992]

Moving Computation to the Cloud

Mobile Access

[J. Rabaey, ASPDAC'08]

The Cloud

[Source: Cisco VNI Mobile, 2012]

353 MB

- Netflix (109 MB)
- Pandora (55 MB)
- Facebook (40 MB)
- Web (89 MB)
- E-mail (60 MB)

149 MB

Email+Web   +Facebook   +Pandora   +Netflix

Source: Cisco analysis of Arbitron Mobile data, 2012
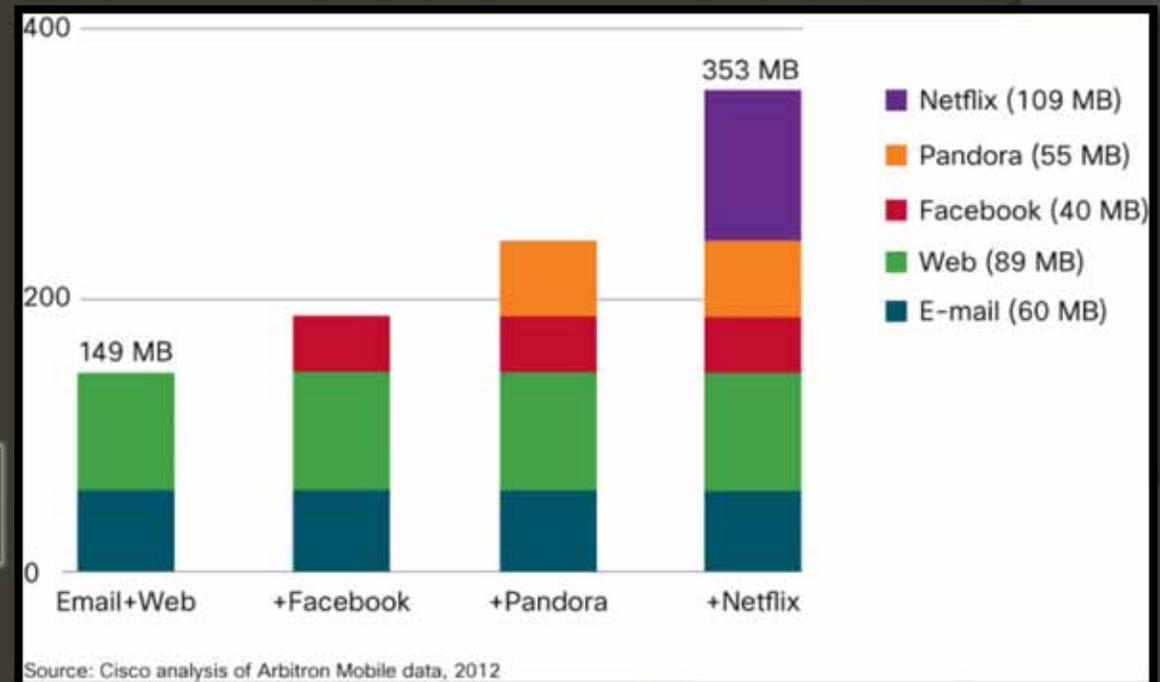
"A user with an 8 GB smartphone who streams cloud video and music will consume more content over the course of 2 years than can be stored on the device itself"

Key Infopad Concept:
Energy Efficiency through Concurrency

Parallel units allow energy reduction with constant throughput
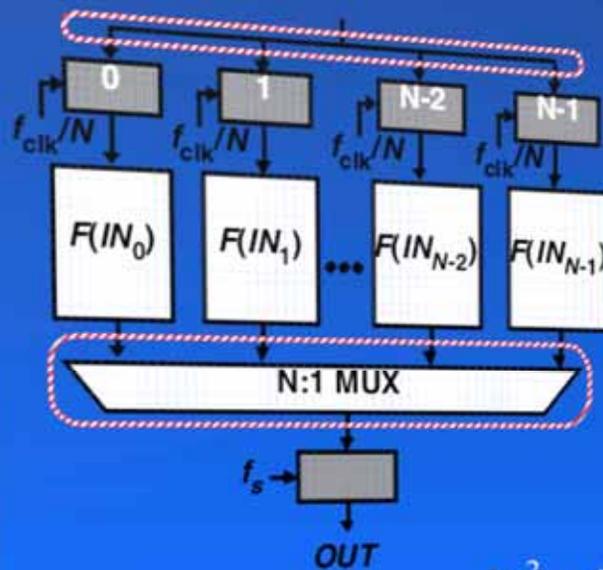
- N parallel units allow an N-fold clock rate reduction
- Supply voltage can be reduced to V_{final}
- Final energy is

$$V_{final}^2 (NC)\left(\frac{f_{clk}}{N}\right)T_{samp} = E_{init}\left(\frac{V_{final}}{V_{init}}\right)^2$$

[R. Brodersen, ISSCC keynote 1997]

[Chandrakasan et al, JSSC 92, ICCAD 92]

It takes a road wreck ....

Performance and Power Efficiency Increase with Parallel Architecture
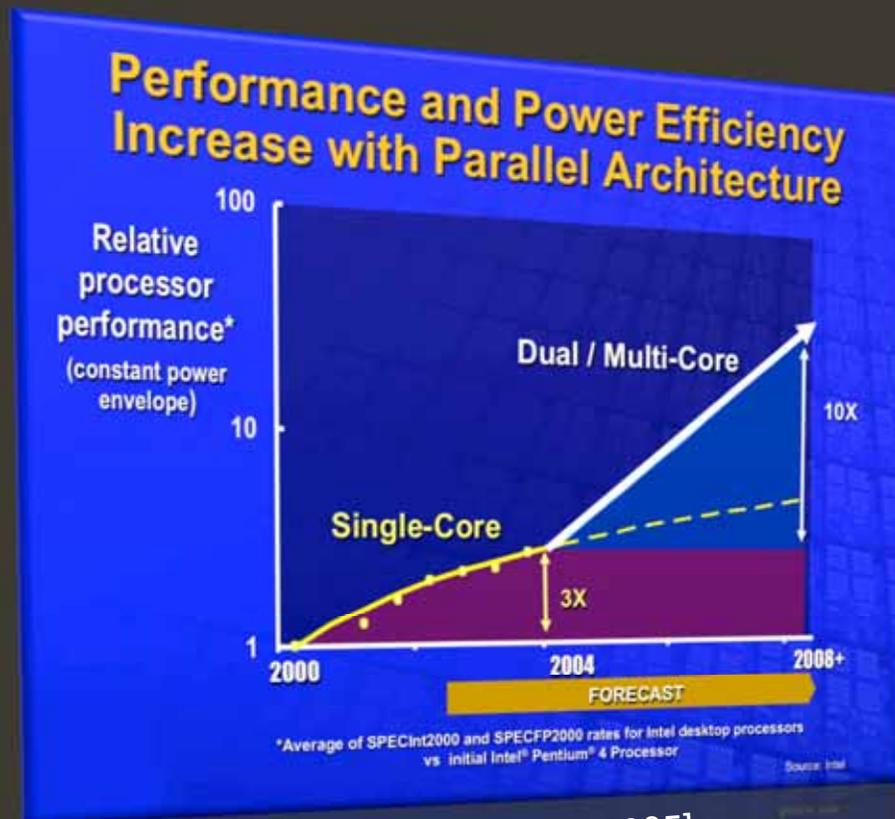
[S. Chou, Intel, Keynote ISSCC 2005]

AMD DualCore

Intel Montecito

IBM Cell
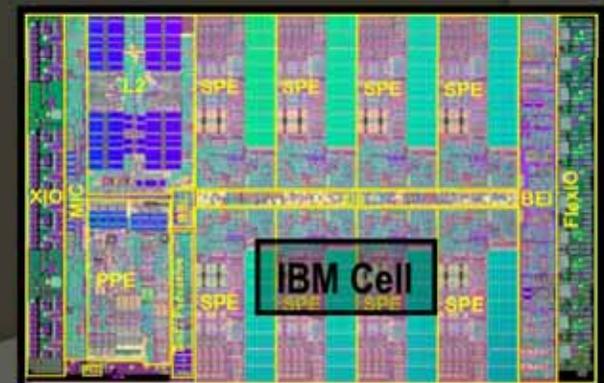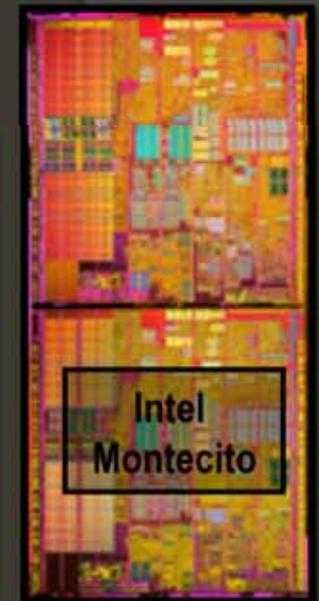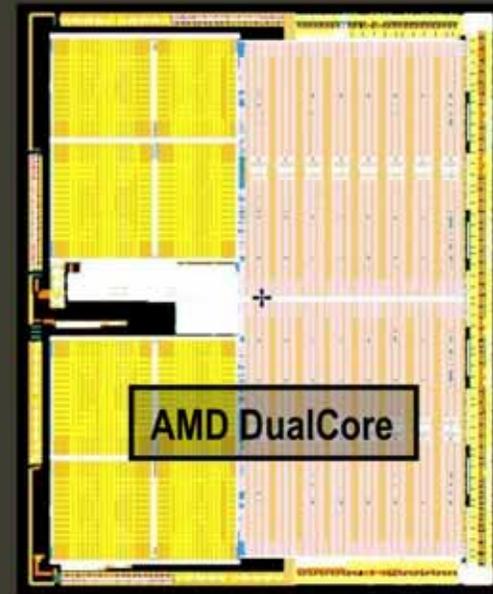
Concept fully embraced by industry in the early 2000's

The Power of Multi-Disciplinary Collaboration

ATM and Fast Ethernet Backbone

BASE STATION and WIRED to WIRELESS BRIDGE

PC/Ethernet Scalable Hardware Basestation

Scheduling for Quality of Service and Capacity Optimization

MAC Layer Protocols for Up and Down Links

CDMA PowerControl Algorithms

Optimization of Modulation and SS Techniques for Interference Limited, Picocellular Channels

User Interface based on Pen and Speech Input

Indoor Picocellular Channel Measurements

Network and InfoPad Aware Design Tools

Support for Distributed Processing for the Mobile Network (the InfoNet)

Low PowerMonolithic CMOS Radio Implementations - Wideband Spread Spectrum & DECT Radio (TDMA)

System Level Power Analysis Tools

Migration of processing between Pad and Network

Low Power Signal Processing Accelerators

Energy Optimized ARM Processor Core

Text/Graphics Decompression for Color Display

Concurrent Electrical/Mechanical Casing Design

SPEECH AND HANDWRITING RECOGNITION

DESIGN TOOL APPLICATIONS

InfoNet AUDIO, PEN AND VIDEO TYPE SERVERS

InfoNet NAMESERVER, CELL and PAD SERVERS

1997: What's Next? (after Infopad)

"Since you will be discussing how we might work together, I thought I would give you a quick update on what we have begun to evolve.

We have been thinking of trying to improve the coordination of Berkeley and research and industrial activities in wireless work that incorporates some of the things we have talked about. The idea is to have a site in Berkeley **(probably off campus for space reasons)** that would be a center which would be staffed and be a place **where industrial and student researchers could work.**
This would be open to any company who was willing to help support the effort. Below is a short writeup which describes what we are thinking about.

...
Some of the companies that we are thinking might be able to work together and with whom we already have strong relationships are companies like TI, Cadence (who already have a research lab in Berkeley), Thompson CSF, HP and cellular providers such as Pac Bell or Sprint. We haven't begun to approach these companies yet with a concrete plan, but a number of them have indicated they would be interested in working in some sort of relationship like this.
"
...

email from Bob Brodersen to Per ("Pekka") Tjernlund (Ericsson) - July 1997

Berkeley Wireless
Research Center

Opened January 1999

Berkeley Wireless Research Center (BWRC)

A partnership between UC researchers, industry (~20 companies) & government exploring the generation-after-next wireless devices and systems
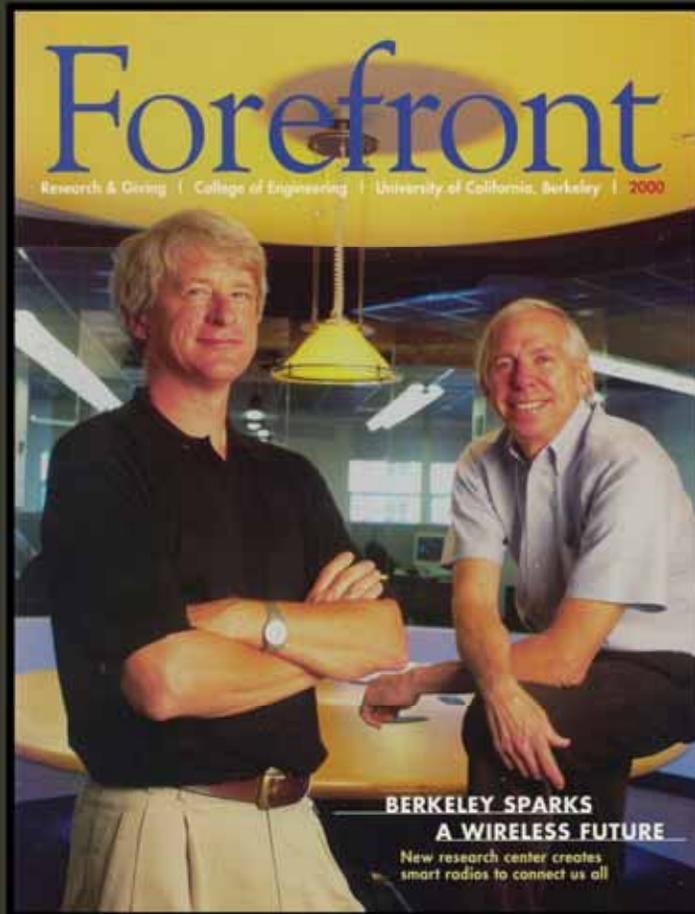
Center Drivers (1999)

- "Fourth-Generation" Universal Radio
  » Supports multiple formats and protocols, adapts to environment and data in intelligent way
  » Initial target: UMTS
- Ultra Low-Power Picoradio
  » Dedicated radio for point-to-point link. Energy dissipation and footprint are of uttermost importance importance
  » Goal: $P < 100\ \mu W$
- Very High-Bandwidth Millimeter Radio
  » Uses the most-advanced CMOS processes (< 0.05 μm) to provide Gbits/sec bandwidth in the 60 GHz band

Berkeley Wireless Research Center

Another 90's Question:

"What happens if sensors become tiny, wireless, and self-contained?"

Smart Dust Components
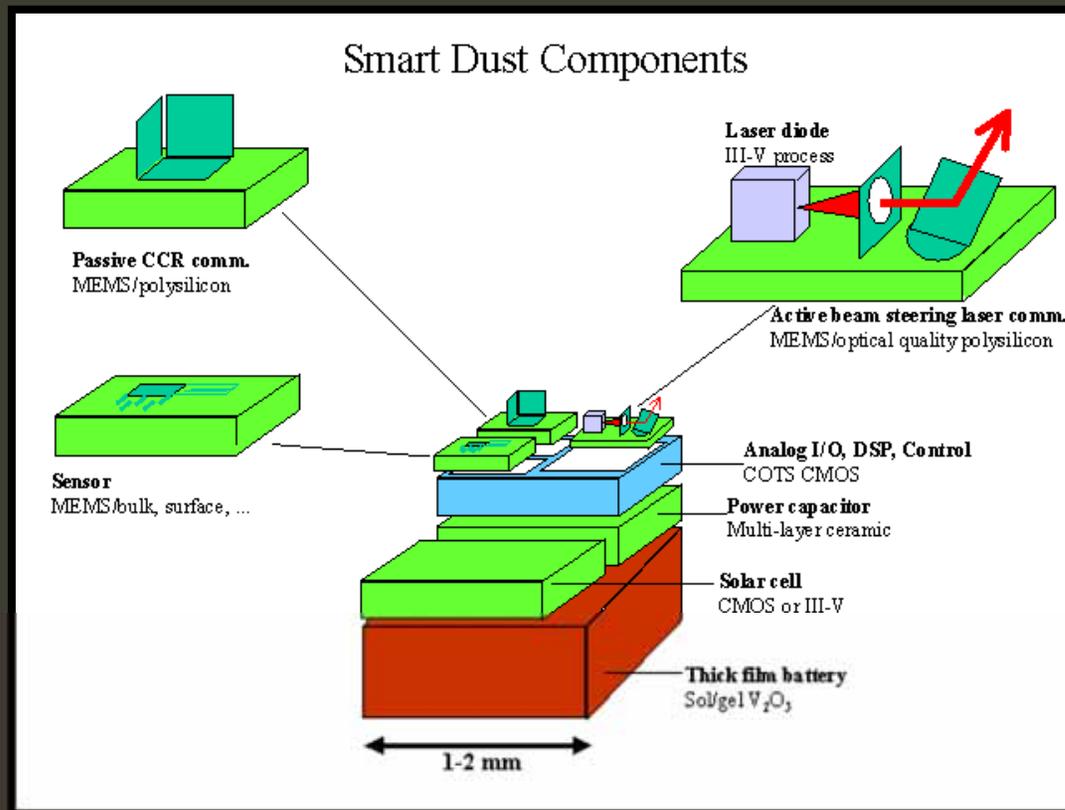
[Courtesy: K. Pister, UC Berkeley]

… **Wireless Sensor Networks**

Linking the Cyber and Physical/Biological Worlds

CyberPhysical Systems [Gil08]

CyberBiological Systems [Rab11]

Center for Information Technology in Support in the Interest of Society (CITRIS)

- Founded 2001 - California grant
- Main mission: Shift information technology from productivity increase to societal enhancement
- Grounded in sensor-network platform

[R. Newton, R. Katz, J. Demmel, P. Wright, J. Rabaey, 2000]

The PicoRadio Project (99-06)

Meso-scale low-cost wireless transceivers for ubiquitous wireless data acquisition that

- are fully integrated
    - Size smaller than 1 cm^3
- are dirt cheap ("the Dutch treat")
    - At or below 1$

- minimize power/energy dissipation
    - Limiting power dissipation to 100 μW enables energy scavenging
- and form self-configuring, robust, ad-hoc networks containing 100's to 1000's of nodes

[J. Rabaey, 2000]
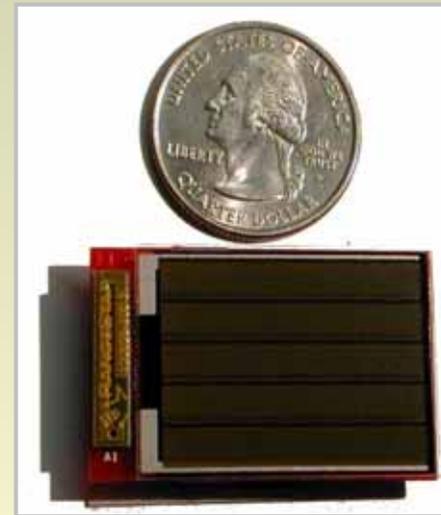
The First Generation (2000)
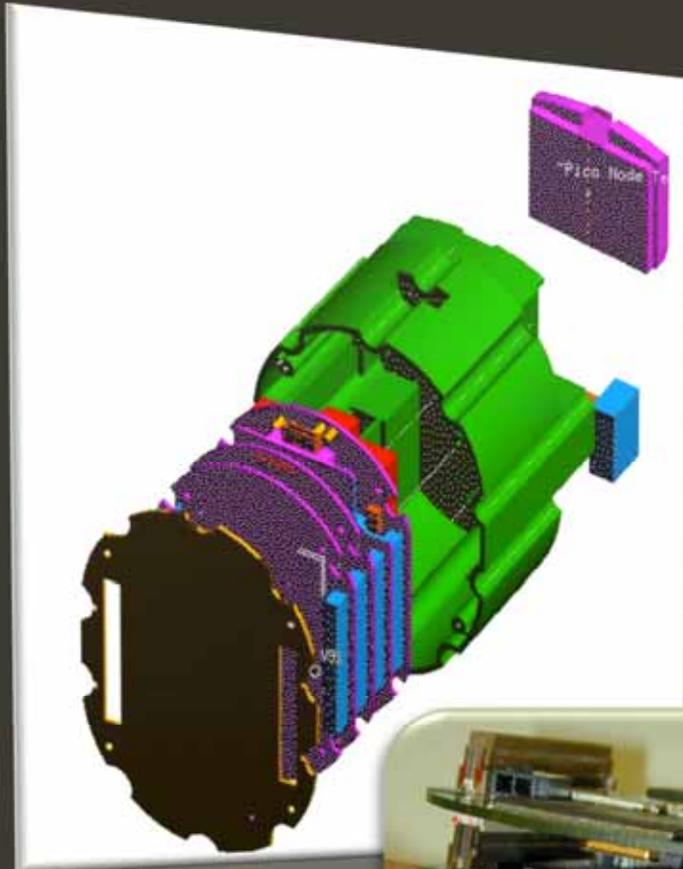
A flexible platform for experimentation with protocol and networking strategies
(400 cm^3– power dissipation < 1 W)

Crucial challenge:
Short-distance low-power radios!

Prototype 1st generation Bluetooth
(Courtesy Sven Mattison, Ericsson)
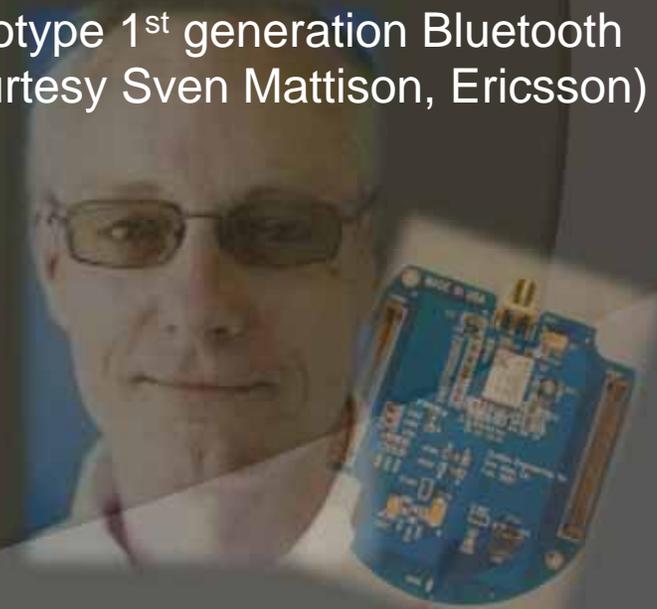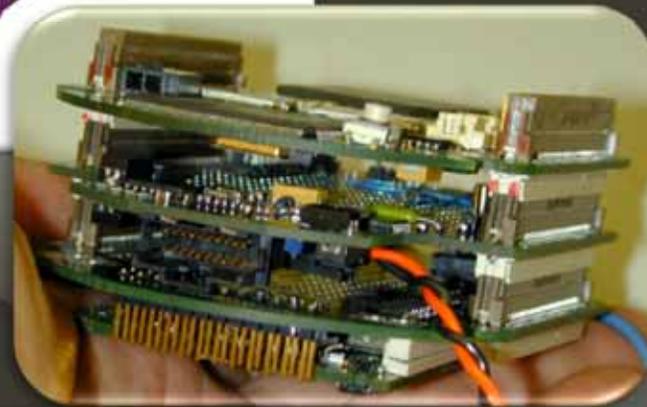
Fast Forward to 2006

UC Berkeley PicoCube
Volume: 1cm^3
Pave: 6 μW
Energy self-contained
2-3 orders of magnitude!
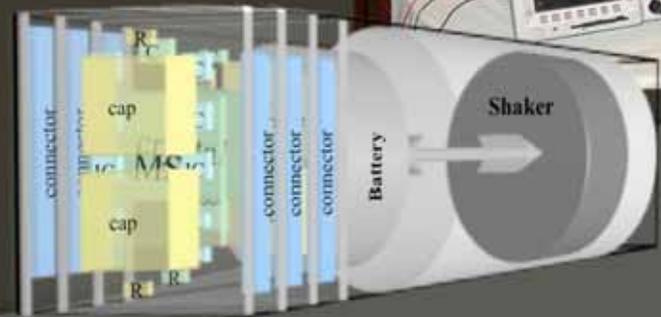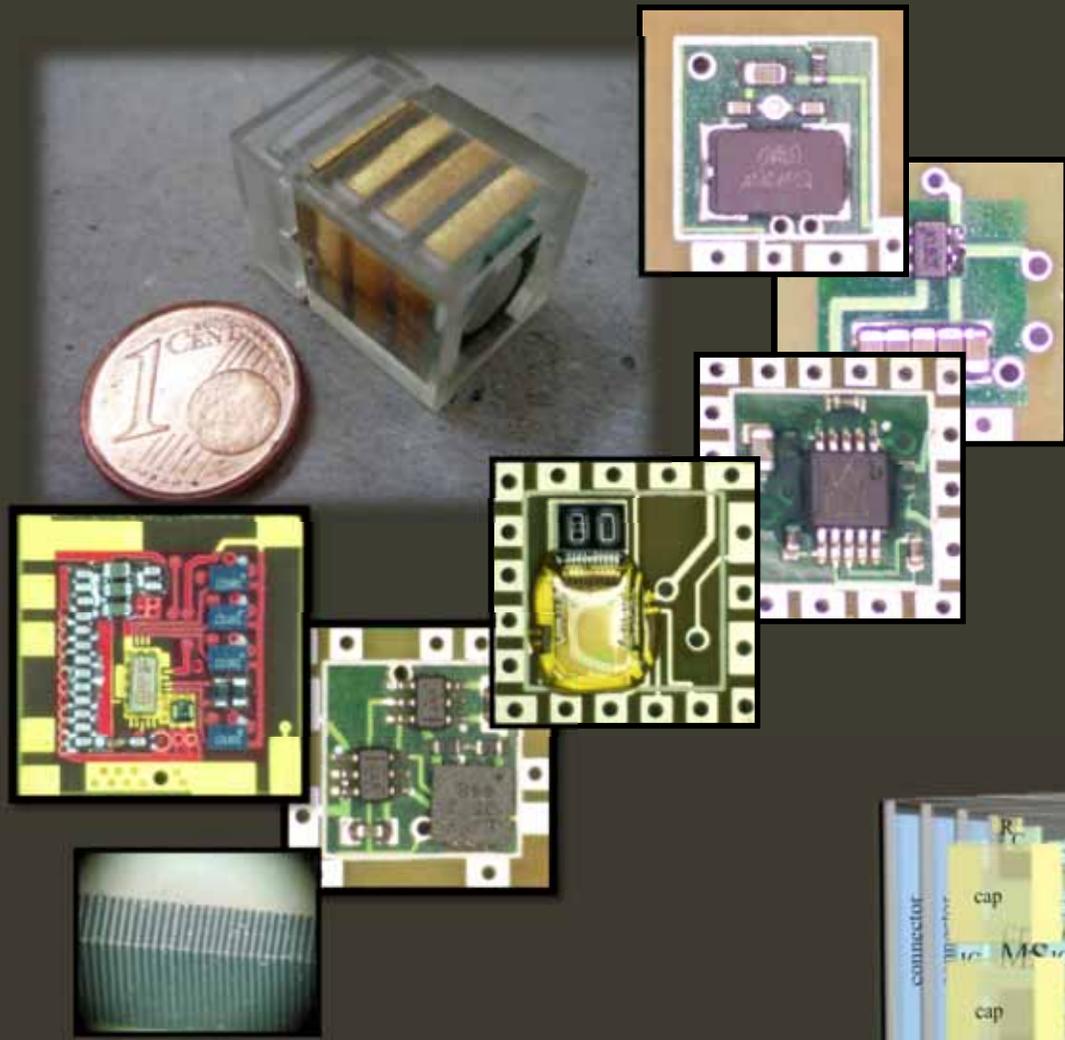
[Burghardt et al, 2007]

The Power of Multi-Disciplinary Collaboration

Applications

Energy harvesting

Packaging

ULP Radios

Antennas

Technology

Architecture

Localization

Services

Network

PHY & Link
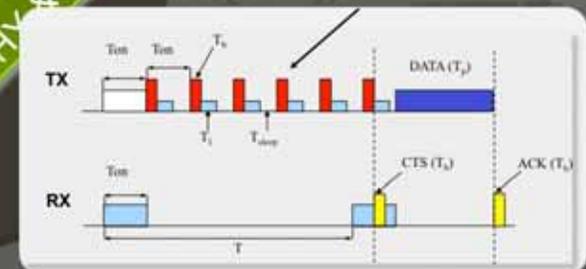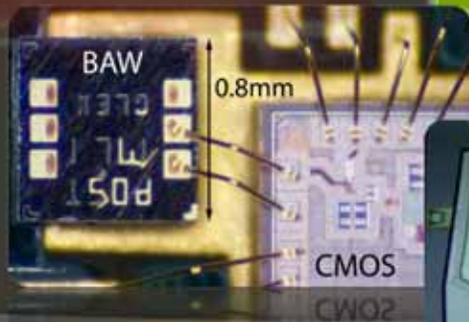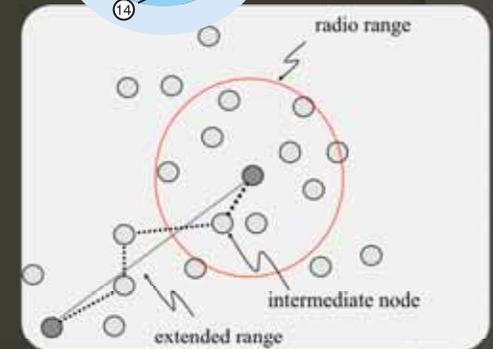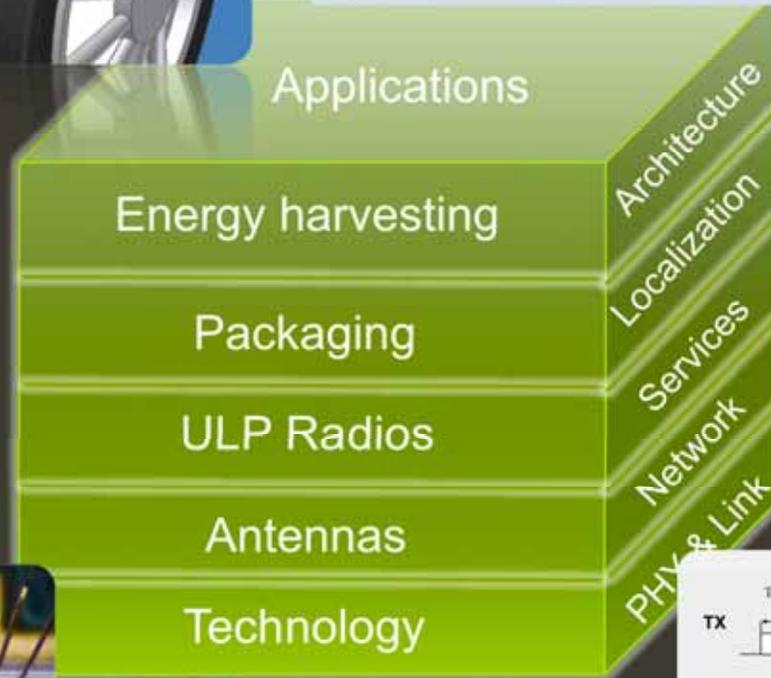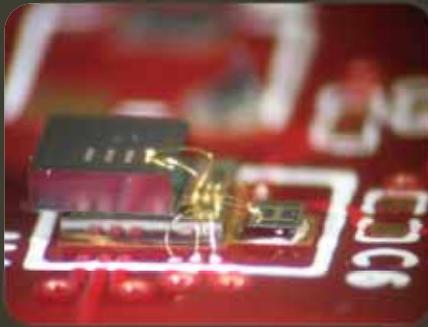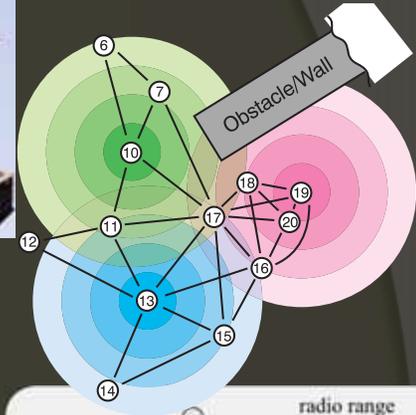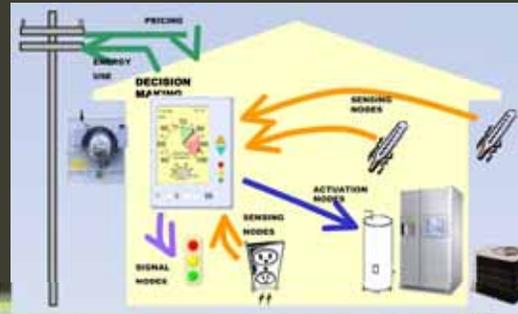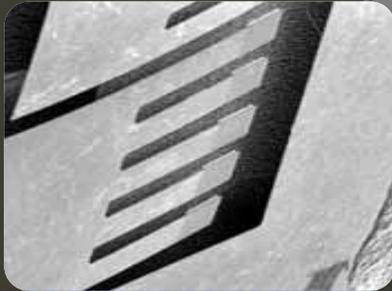
"The Art of Creativity" [H. De Man – ISSCC 2005]

A Promise Unfulfilled (So Far)....
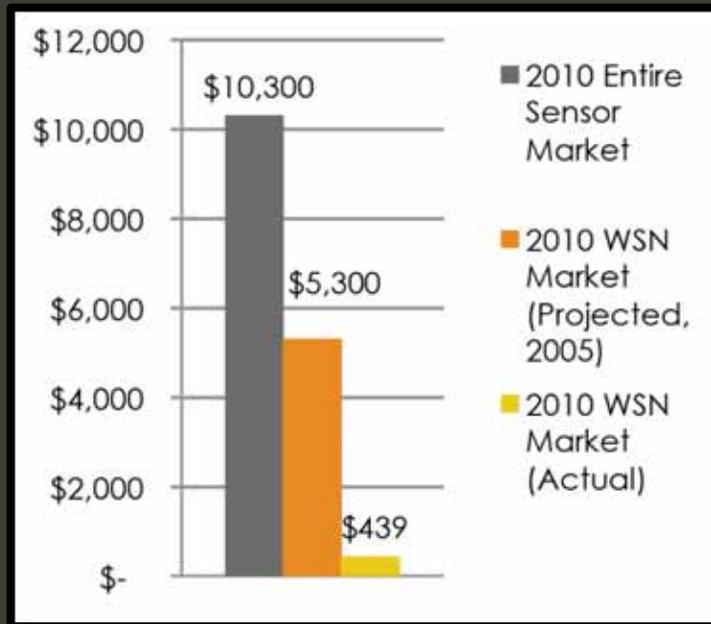
(Source: On World)
- Cost savings not yet disruptive
- Reliability
- Energy (battery life)
- Ease of use

NO OF ECONOMY OF SCALE
Stovepipes, Fragmentation, Non-interoperability,
Lack of Virtualization

More later …

Meanwhile... From CCCD to SoS

Fast Forward Again - Vision 2025

- Integrated components will be approaching molecular limits and/or may cover complete walls

- Every object will have a wireless connection, hence leading to trillions of connected devices,

- Opportunistically collaborating to present unique experiences or to fulfill common goals

What will it Enable?
The Birth of the Swarm

The Swarm at The Edge of the Cloud

Mobile
Access & Relay

The Swarm

The Cloud

[J. Rabaey, ASPDAC'08]

A Phase Transition in the Making

The Cloud

Mobile Access

Sensory Swarm
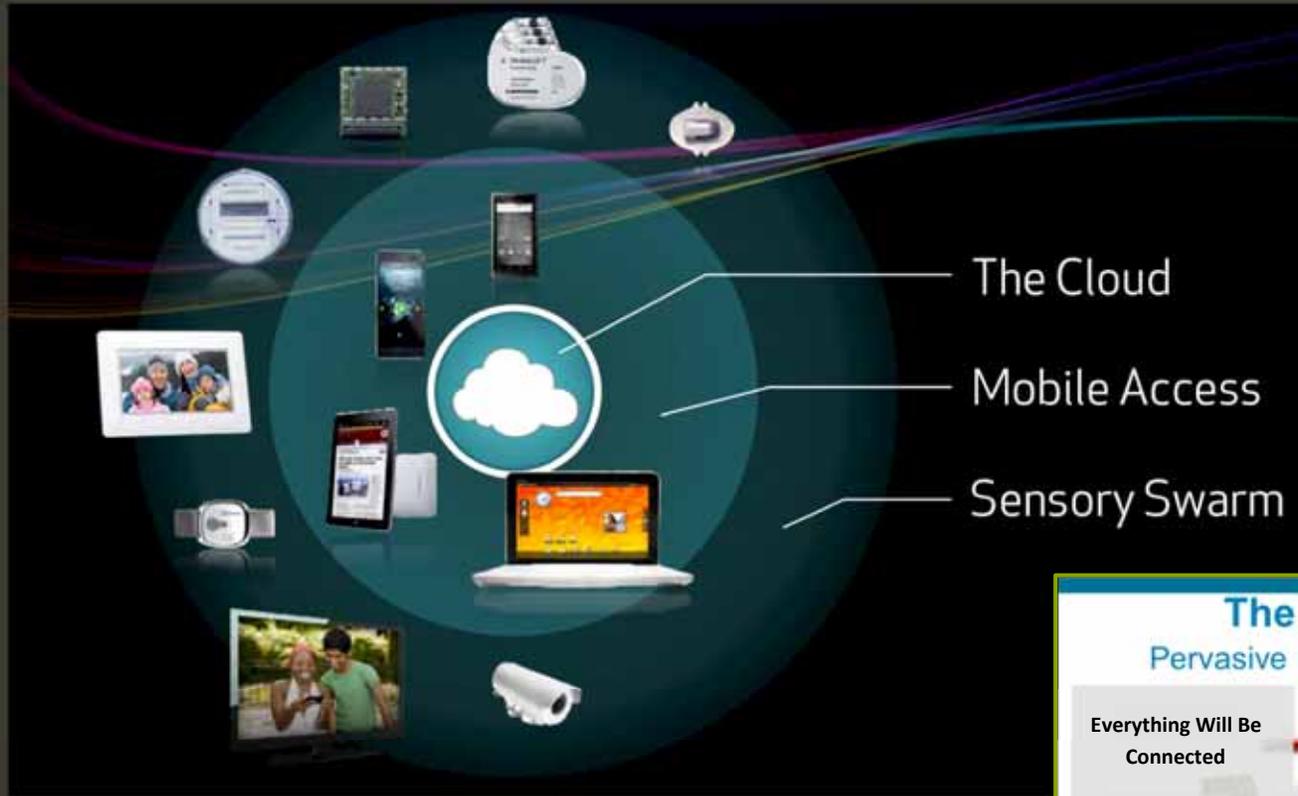
Courtesy: F. Bonomi, Cisco

Courtesy: P. Jacobs, Qualcomm

And many other versions …
(also known as the Internet of Things, Societal IT)

The Emerging IT Platform
Pervasive Computing + Storage + Networking

Everything Will Be Connected

Total 1 Trillion

140 Devices per Person on Earth

2013

Infrastructural core

Sensory swarm
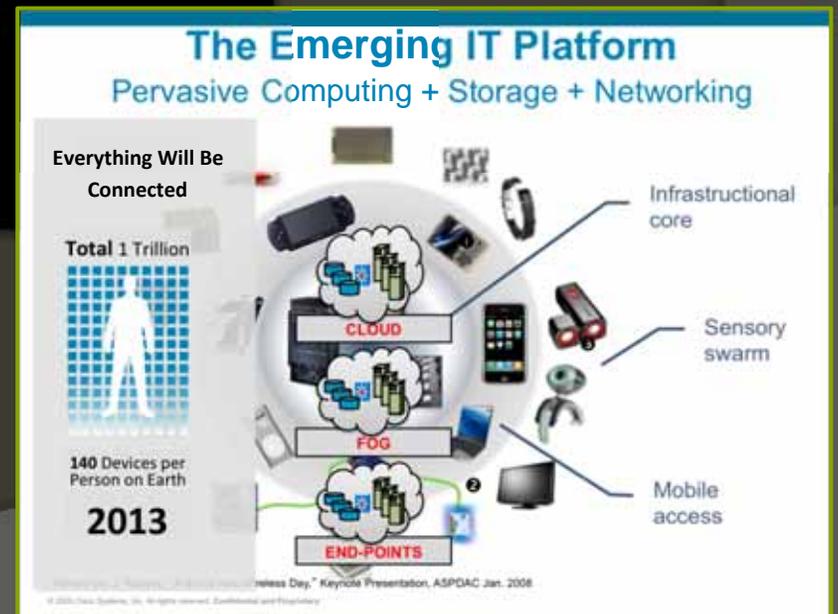
Mobile access

The Missing Link

An open platform accessible to everyone!

Apps

Home security/ emergency

Energy-efficient home

Health monitoring

Unpad

SWARM-OS

Resources

Sensors/ Input devs

Actuators/ Output devs

Networks

Storage

Computing
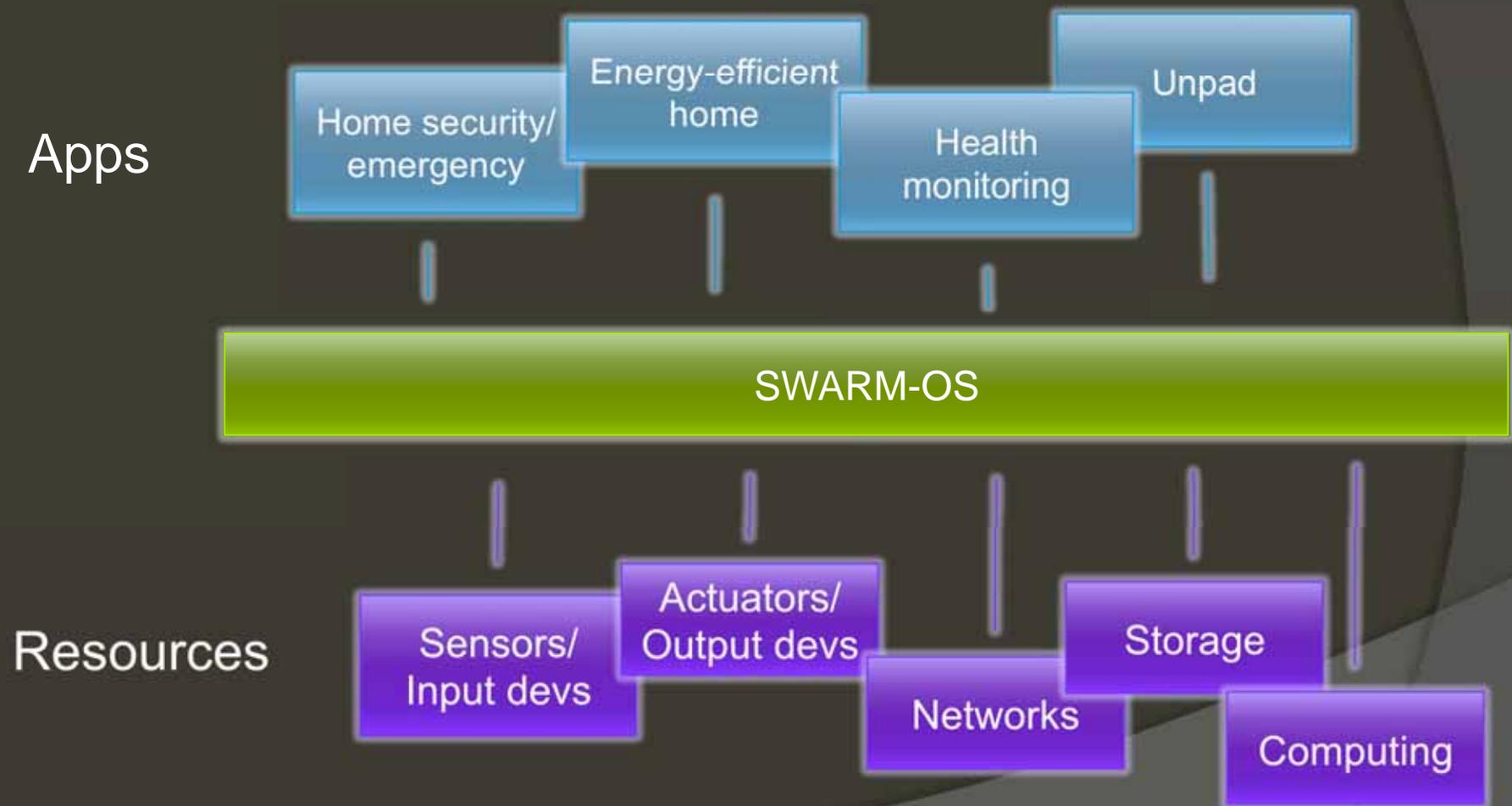
A mediation layer – similar to Unix and Android

2010 Question:

"How to interact with information in a world where enriched senses and interfaces are omnipresent?"

Mobiles to disappear or unravel! **The unPad***

Towards (Human-)Aware Devices

Desktops ➡ Laptops ➡ Handhelds ➡ unPads

- "Pad" goes away, but functionality (plus more) stays: enriched and unpackaged I/O, communication, computation, storage.
- People seamlessly interact with content, environment and one another through of collection of interconnected sensors and actuators.
  - Sensors and actuators opportunistically cluster as needed for a particular functionality.

unPads coming aLive

- Example: Google Glasses

[http://www.youtube.com/watch?v=9c6W4CCU9M4]

unPads ... What it Takes!

- Providing ubiquitous wireless connectivity at last
- Managing the swarm and its resources
- Maximizing experience, reliability, safety and security

A Hard and Complex Problem!
Distributed, heterogeneous, dynamic …

Adopt a "Swarm Perspective"
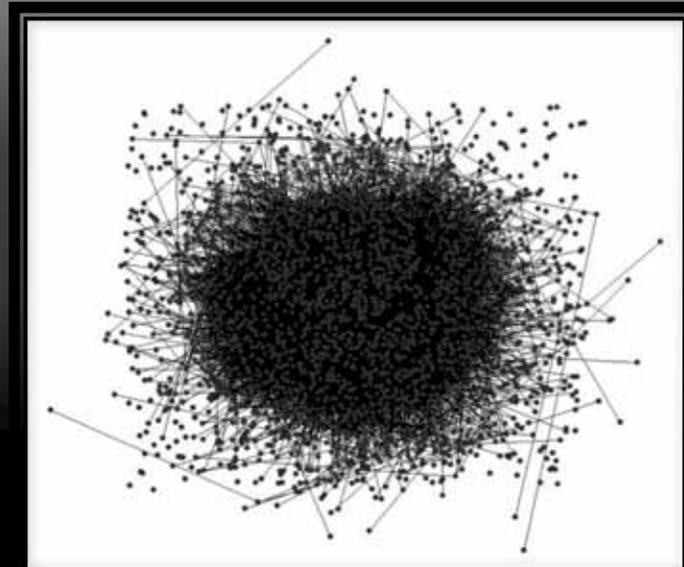
The function is in the swarm, not in the individual components
Use components opportunistically based on availability
Exploit the "power of numbers"

A Swarm Perspective:
"Dennard Scaling" Applied to Wireless Connectivity

Wireless connectivity strategies that scale (capacity, energy, reliability) with increasing numbers!

"mesh"

Directly contradicts todays model!
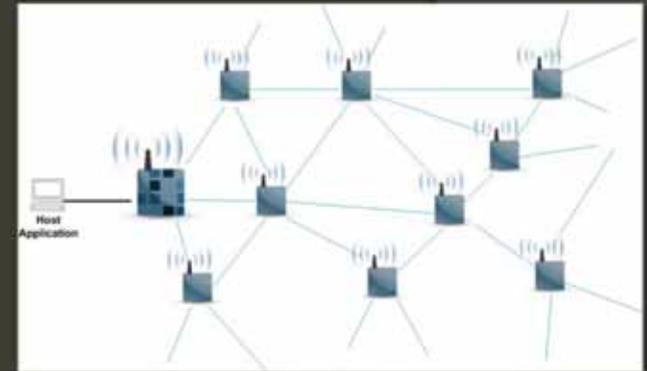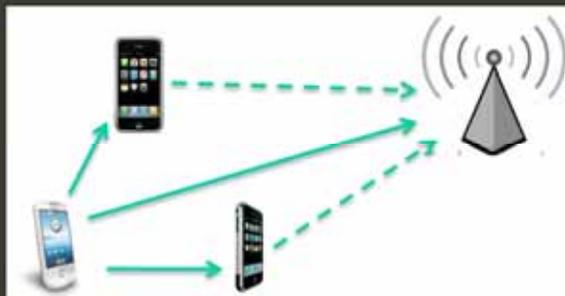
"relay"

Make cells smaller!
- Exploit locality/proximity
- Exploit density
- Collaborate!

"peer-to-peer"

A Swarm Perspective:
Learning from Multicore Systems

Reengineering the OS: Tesselation

- Basics Concepts:
  - Resources are primary citizens
  - It is all about data streams, computation is an afterthought
  - Distributed in nature
  - Security from the ground up.
- The "Cell" as the Basic Unit of Resource and Security
  - Resource guarantees negotiated hierarchically
  - Continuous discovery and optimization
  - Cells communicate over secure channels
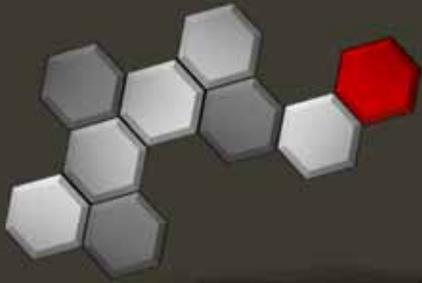
Making Swarms Happen:
The Ubiquitous SwarmLab at Berkeley

"Create an open and universal platform to foster the creation and distribution of a broad range of innovative swarm applications"

Inaugurated December 2011 –
Seeded by Qualcomm donation

An **incubator for Swarm applications**, building on Berkeley's combined strengths in technology, circuits, architectures, software and systems

The Power of Multi-Disciplinary Collaboration

- Jan Rabaey – Swarm Visions
- Shankar Sastry – Swarm Security
- John Wawrzynek – unPad
- Ruzena Bajczy – Observing people
- Björn Hartmann – Swarm user interfaces
- Paul Wright – Swarms and manufacturing
- Jay Han – Swarms and rehabilitation
- Michel Maharbiz – Neural swarms
- Claire Tomlin –Mobile swarms
- Pieter Abbeel – Robot learning
- John Kubiatowicz – Swarm OS
- Bernhard Boser – Swarm sensor platforms
- Ana Arias – Large scale platforms
- Kris Pister – Swarm networks

Swarm Visions

[C. Tomlin, UCB]

[V. Kumar, U.Penn]

Trajectory Planning

[M. Maharbiz, UCB]

Swarm Visions:
Neural Swarms and Brain-Machine Interfaces

Bridging the gap between the human brain and the cyberworld

Mind Out of Body: Controlling Machines with Thought

In an exclusive excerpt from his new book, a pioneering neuroscientist argues that brain-wave control of machines will allow the paralyzed to walk, and portends a future of mind melds and thought downloads

[Scientific American, February 2011]
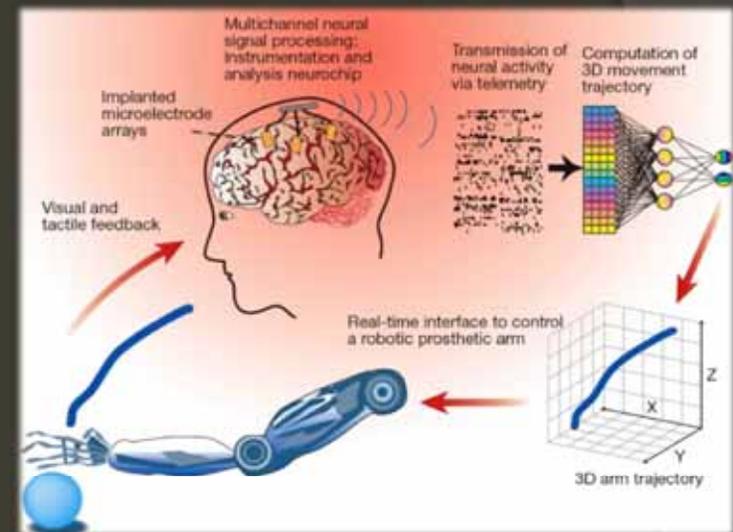
[Nicolelis, Nature, 18 January 2001]
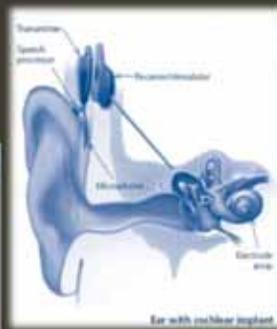
Benefits to humanity hard to overestimate
- Addressing neural impairments: auditory and vision impairments, spinal cord injury, stroke, parkinson, epilepsy…
- Human enhancement

Science Fiction or Imminent Reality?

Listening to the voices inside your head

"Neuroscientists may one day be able to hear the imagined speech of a patient unable to speak due to stroke or paralysis, according to University of California, Berkeley researchers."
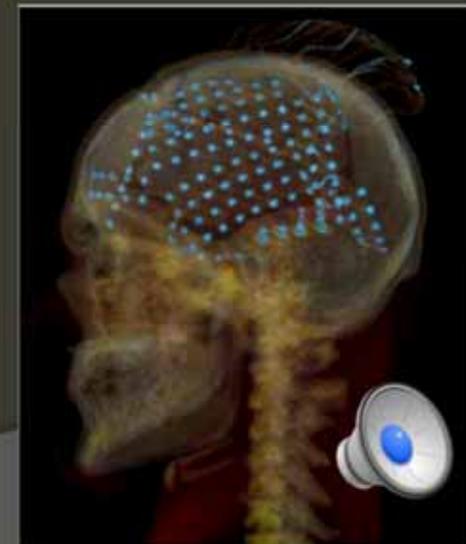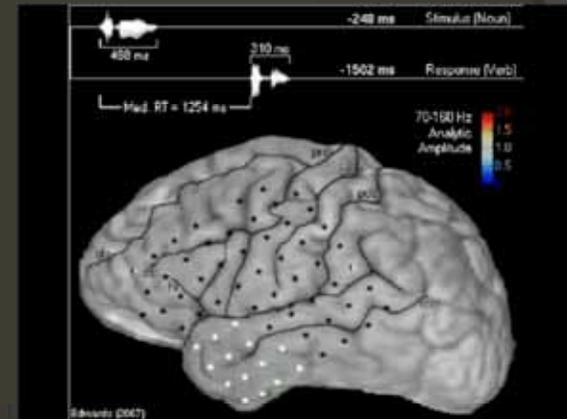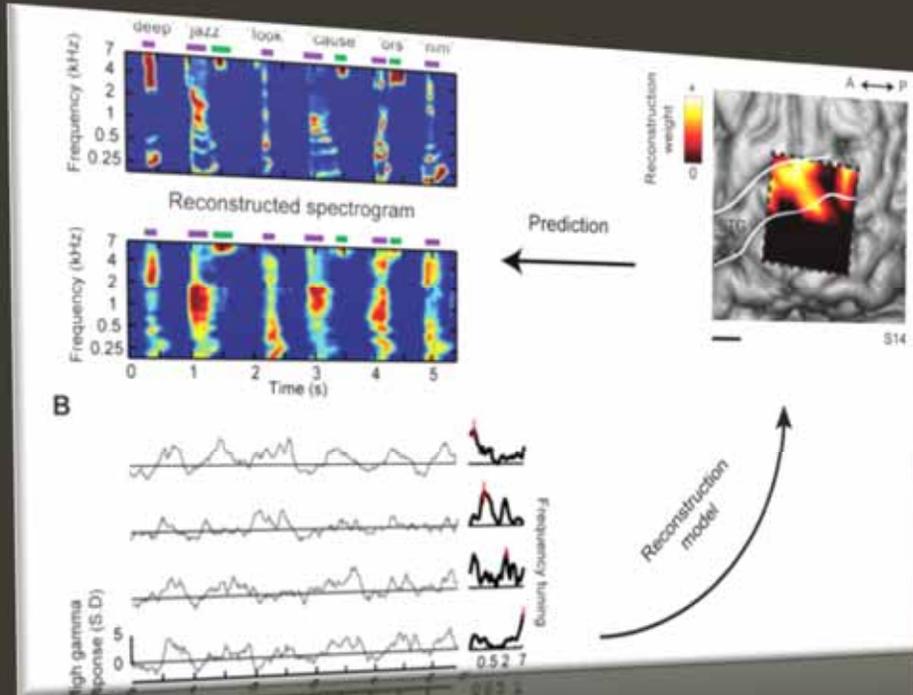
[Pasley at al, PLOS, 2012]

Wireless µECoG

- May provide up to 1000 channels with pitch as low as 200 µm.
- Providing unprecedented resolution.
- Powered wirelessly
- Antenna printed on electrode polymer substrate

5 mm

Power Supply

Rx Tx Neural Amplifiers

DSP ADC

3 mm

A1
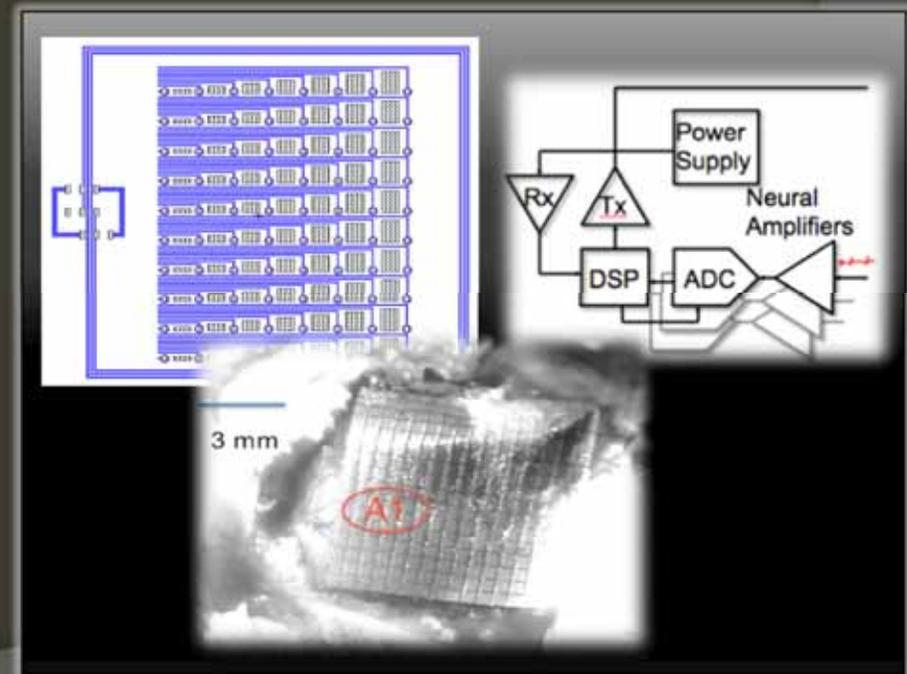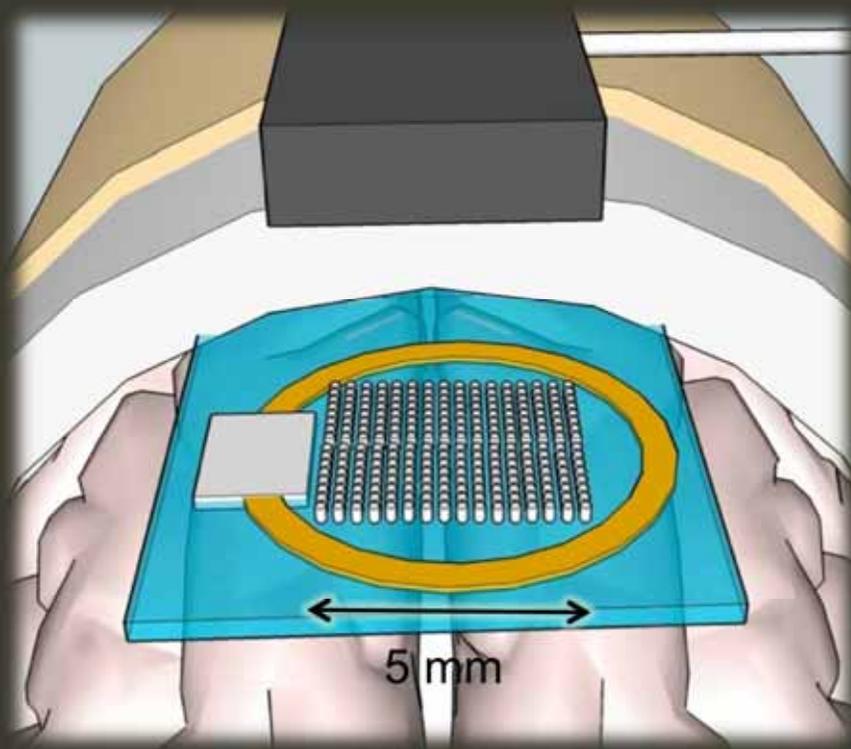
[Courtesy: P. Ledochowich, R. Muller, M. Maharbiz, J. Rabaey, 2012]

Neural Dust as the (Long-Term) Vision
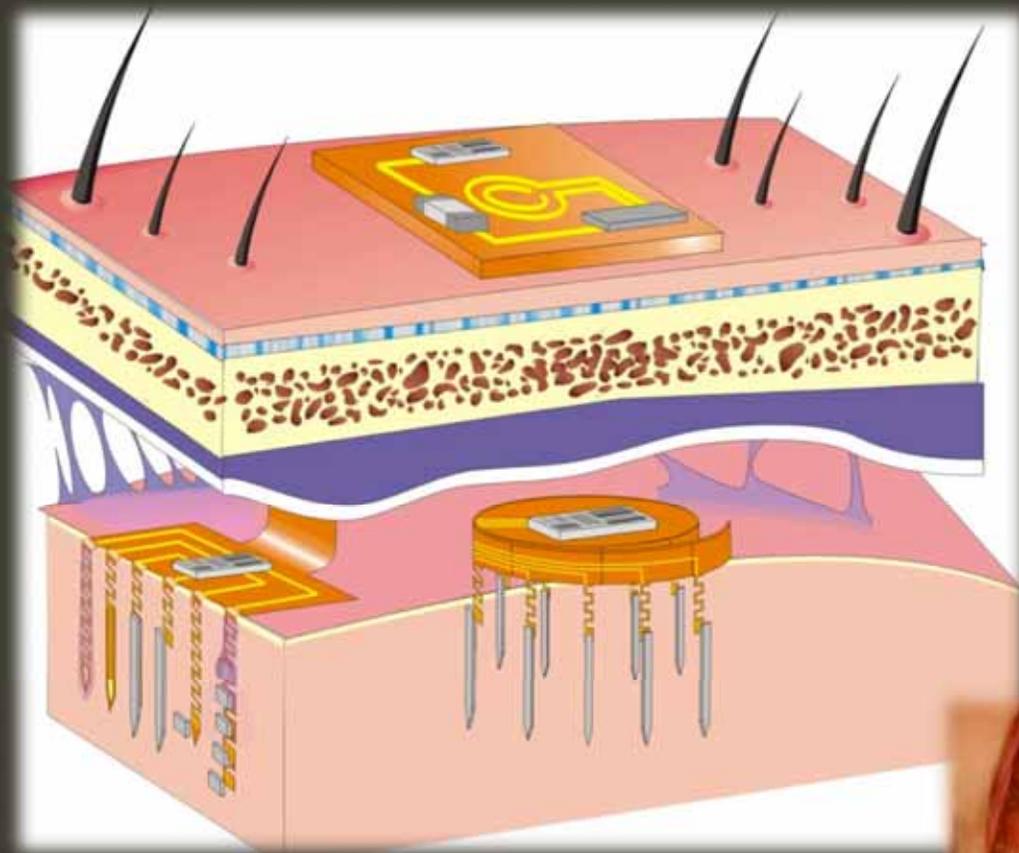
"An implanted neural interface that can provide imaging and acquisition of neural activity at multiple scales of resolution using arrays of patterned and free-floating sensors"
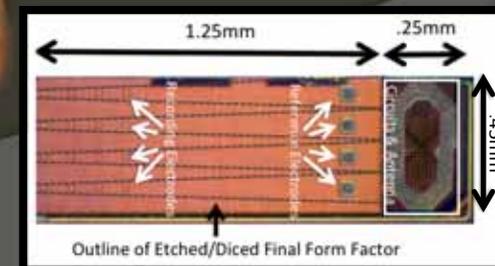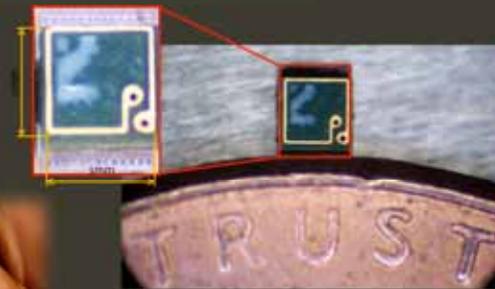
[Courtesy: M. Mark, D, Chen, W. Biederman, D. Yeager, R. Muller]

Outline of Etched/Diced Final Form Factor

Concluding Reflections
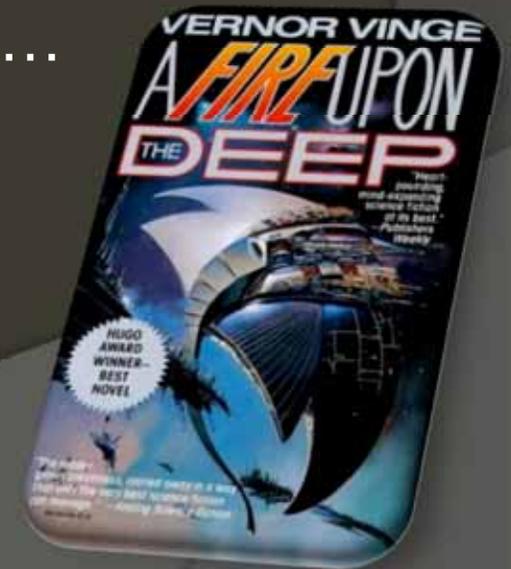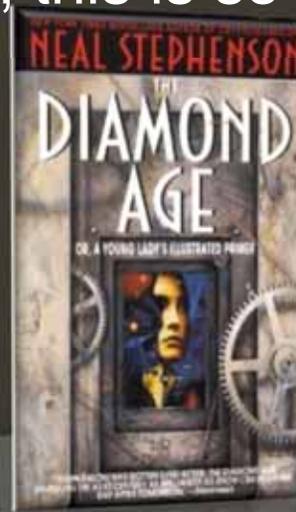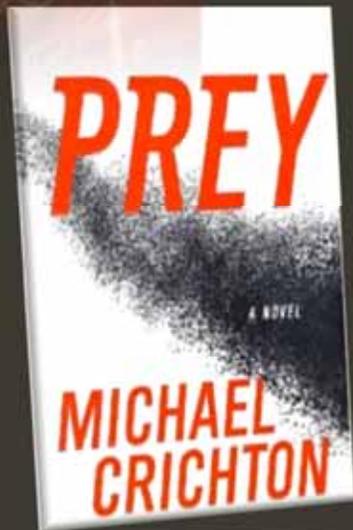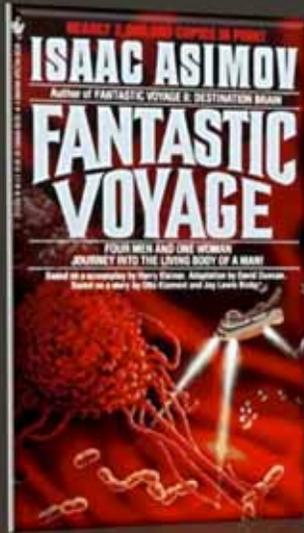
- Over the past two decades, wireless technology has fundamentally transformed the ways we work, communicate and live.
- The revolution is still on – the next few decades will be just as exciting and transforming.
- No single technology is solely responsible for any these transformations – integration of multiple ideas is key!
- Cross-disciplinary thinking is becoming ever more important – in lieu of renaissance man, collaboration is a must.

- Boy, this is so much fun …

My deepest gratitude to Lund University.

Tack så mycket,
for the many years of superb interactions and thought interchange!

- The early generation: Sven-Olof Öhrvik, Jan Uddenfeldt, Per (Pekka) Tjernlund
- Next gen: Sven Mattison, Mats Torkelson, Viktor Öwall, Jiren Yuan
- The current crew – Peter Nilsson, Henrik Sjöland, Pietro Adreani, Joachim Rodrigues, Lars-Erik Wernersson and, of course, Pia Bruhn

Lund – The end of the road? NOT!

Thank you!

Many thanks to V. Vinge, N. Stephenson, I. Asimov, and C. Stross for providing the true visions!