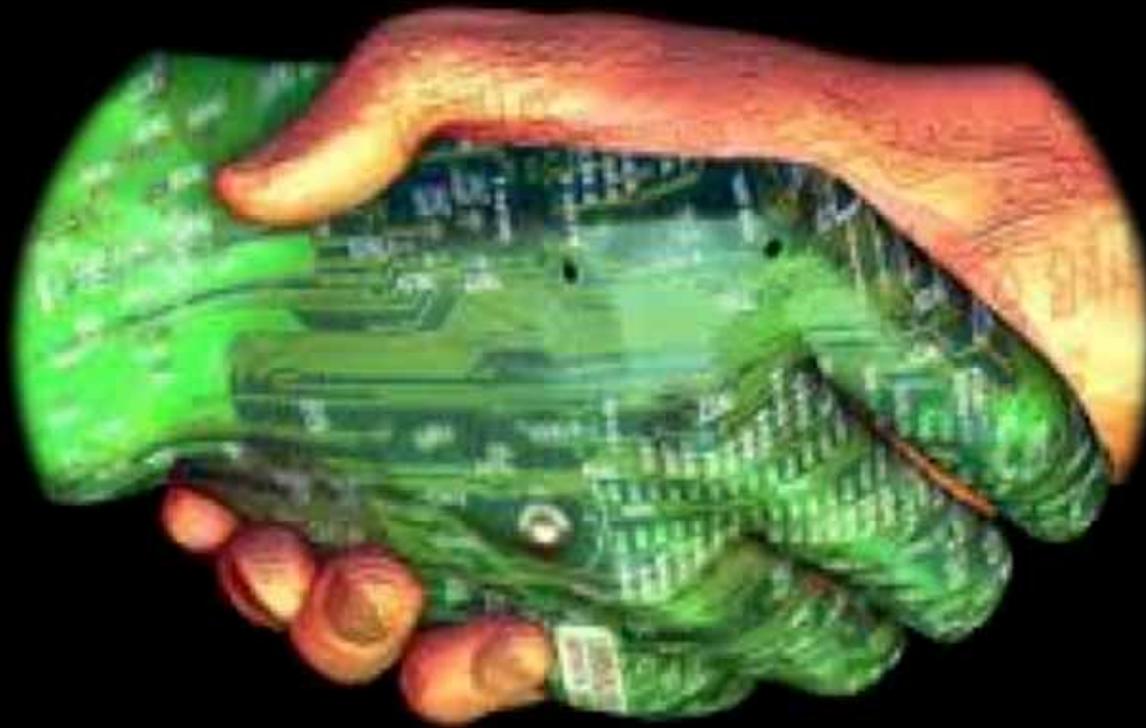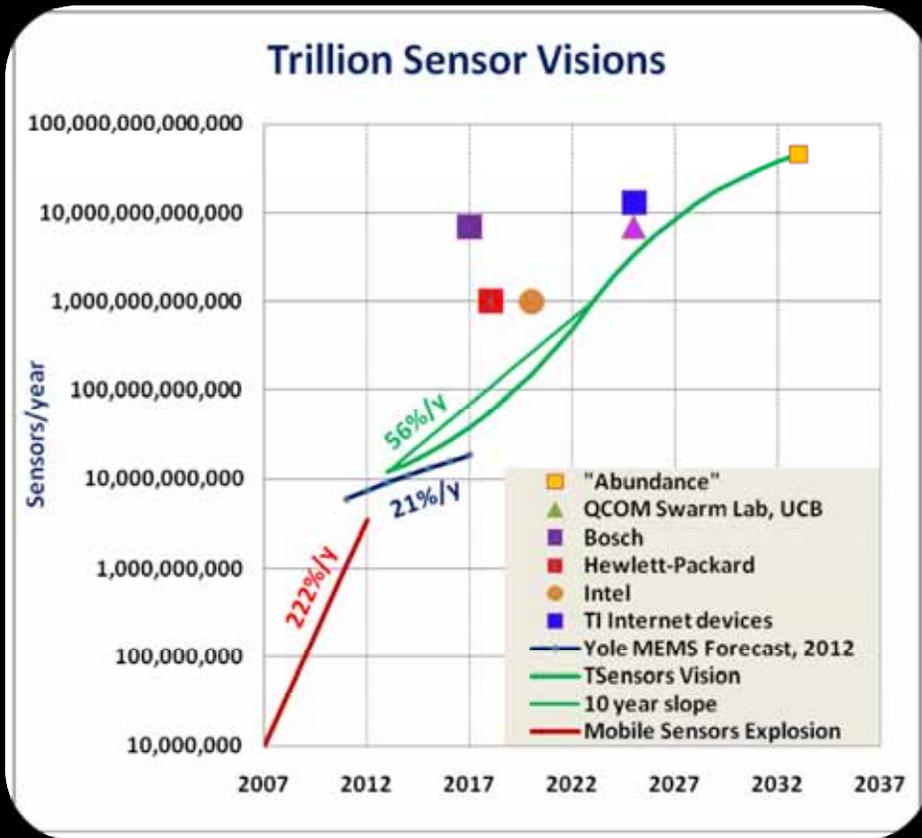# Brain-Machine Interfaces -
The Core of the Human Intranet

IEEE Brain Initiative
NY, December 14 2015

Jan M. Rabaey
University of California at Berkeley

Living in a Smart World

Trillion Sensor Visions

It is happening!

Smart things, smart buildings, smart city, smart everything …

How will us, humans, cope with all of this?

Living in a Smart Dynamic World

How will us, humans, cope with all of this?

[MIT Cheetah, Google car, Lexus quadrotor ad]

One viable option ... extend ourselves!

Mobiles
A limited bandwidth proposition

Extend ourselves - An old idea

Augmenting Human Intellect

A Conceptual Framework

Doug Engelbart, 1962

"Meaning: More-rapid comprehension, better comprehension ..., speedier solutions, better solutions, and the possibility of finding solutions to problems that before seemed insolvable."

"Mother of all demos"
NLS – December 1968, SF

A viable option ... extend ourselves!

[Wired Magazine, January 2014]

[Time Magazine, September 2014]

The Promise of Wearables

Wearable ...

Any object or tool
that moves in concert with human,
and enhances functionality and/or knowledge

Includes: mobiles, watches, bangles, rings, patches,
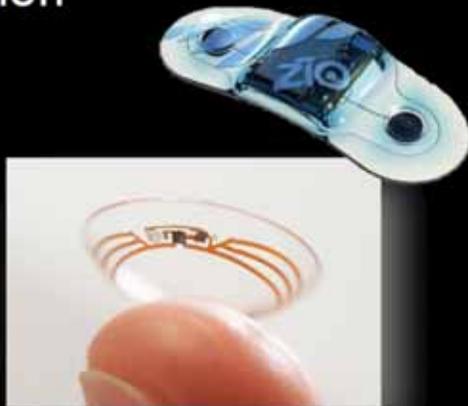tools, bicycles, cars, exoskeletons, implants, ...

The multiple roles of wearables

Extrospection

Extension / Enhancement

Introspection

Brain-Machine Interfaces - A Prime Target

NG NeuroGaming Conference and Expo 2015
Hackathon

'We Did It!' Brain-Controlled 'Iron Man' Suit Kicks Off World Cup

The Matrix

Breaking New Grounds

SUBNETS

UNLEARNING
Systems Dysfunction in
Neuropsychiatric Disorders

Edward Chang (UCSF) PI

Basic tenet: Depression, anxiety, PTSD, chronic pain, addiction **are acquired and can be unlearned**

Distortions across many domains of behavior - requires system level solution

Closed-loop modulation at network level a possible answer

The OMNI Device

Lawrence Livermore National Laboratory
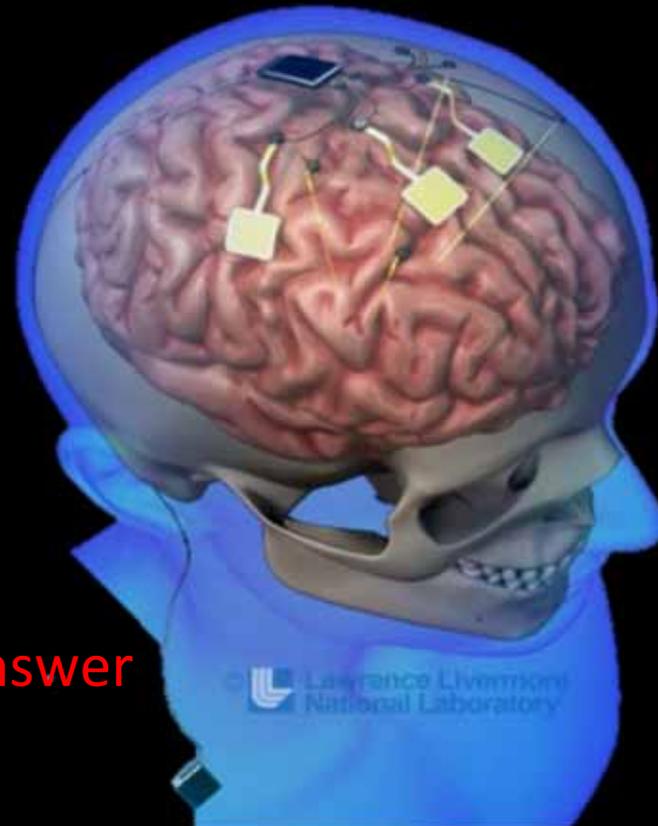
How to correctly assess mood?

Moodify:
Quantifiable symptoms from self-report measures
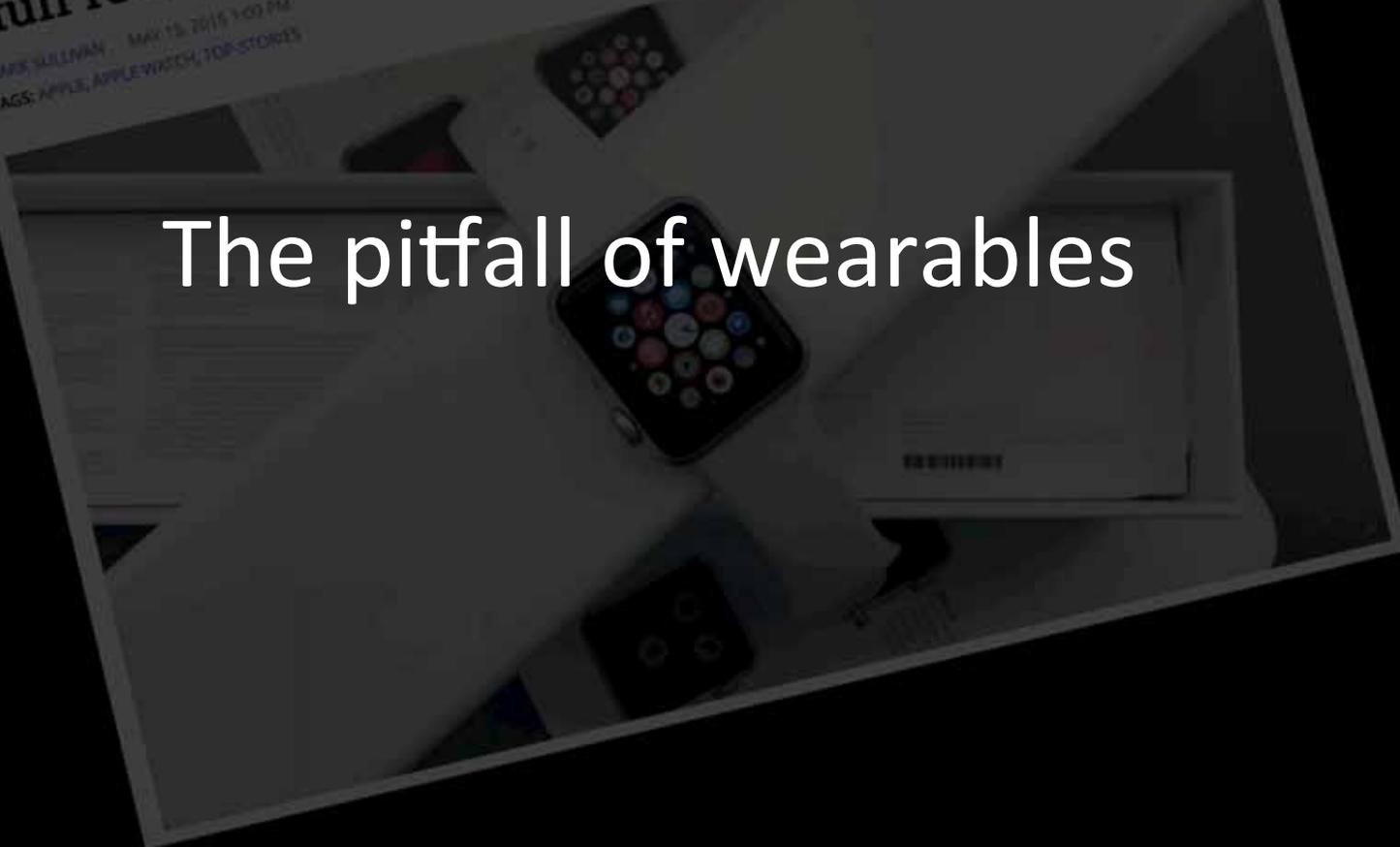
[Courtesy: E. Chang and Subnets team]

PHQ-9, GAD-7

Over the last 2 weeks, how often have you been bothered by the following problem?
Feeling nervous, anxious, or on edge

Not at all sure   Several days   Over half the days   Nearly every day

Depression. anxiety

Immediate Mood Scaler

Using the buttons, rate how you feel now.

Depressed   Happy

Tension – Stress – ... Emotion

Skin conductance   Full day trace (8 AM to 11 PM)

3D accelerometer

Activity

[Jo De Boeck, IMEC, ISSCC 2011]

Combination of various wearable sensors

The pitfall of wearables

Opportunity hampered by "gadgetry"

- Single or restricted function

- Limited attention lifetime

- Only compatible with devices of same company

- Limited engagement with environment
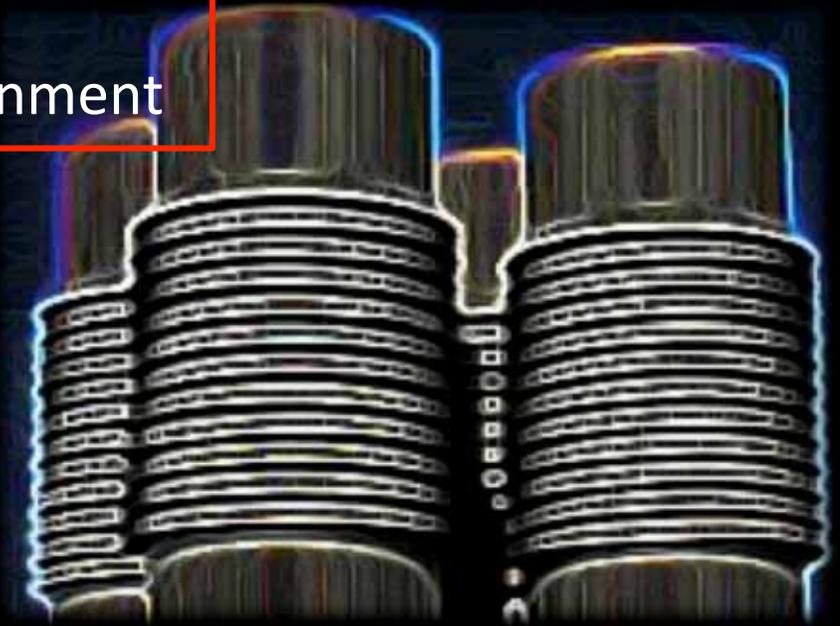
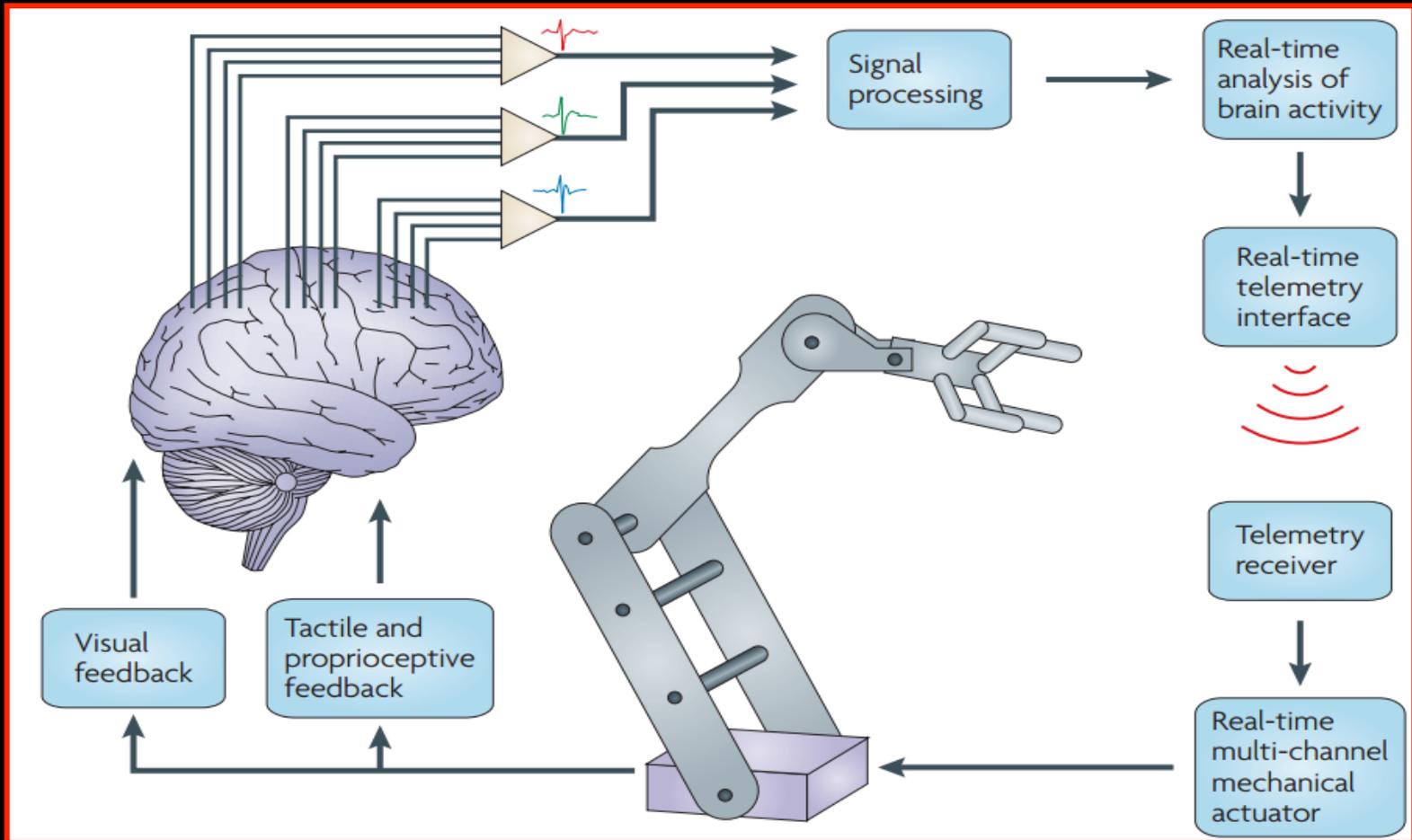Stovepipes …

Envision a Human Intranet

An open platform of sensors, processors, actuators, storage and network links around, on or inside the human body – formfitting, long-term, robust, safe
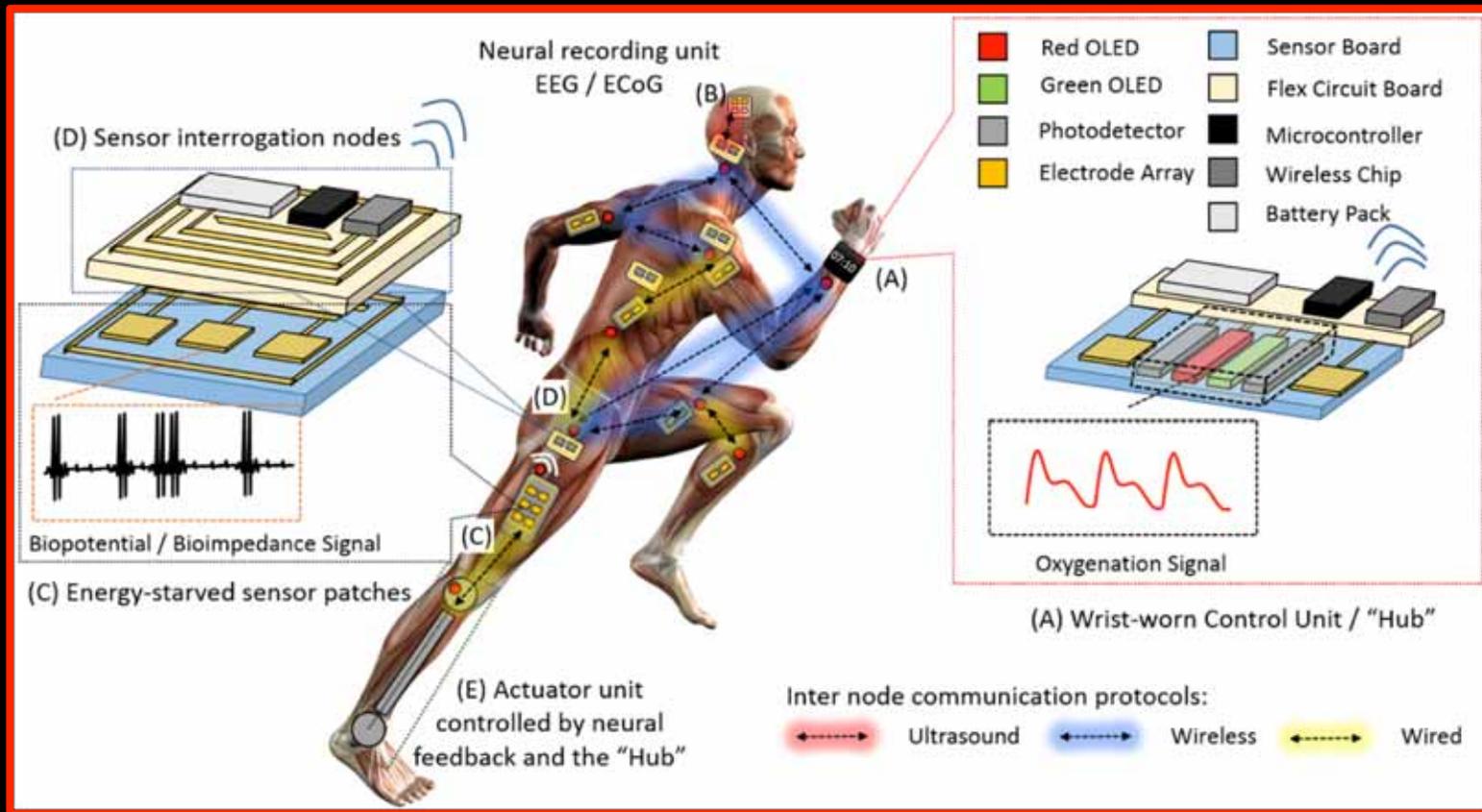
[Image courtesy of Yasser Khan, UCB]

Empowered Humans in an Augmented World

BMI as a Most Compelling Driver

Typical BMI System

BMI as a Most Compelling Driver

Subnets OMNI Device: Modular, distributed, intelligent, efficient

- **Neuromodulator (NM)**
  - High-density cortical and sub-cortical electrode arrays
  - Ultra-low power electronics for stimulation and recording on up to 512 channels

- **Aggregator Module (AM)**
  - System modularity
  - Miniaturized, chronically implantable
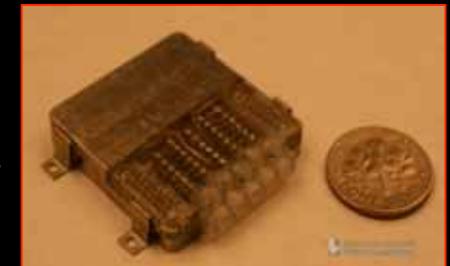
- **Control Module (CM) (or Hub)**
  - Closed-loop control
  - Power management and delivery
  - Telemetry

DARPA SubNets Program

Propulsed by amazing new technologies

Pushing boundaries of miniaturization,
conformity, wearability and efficiency

Enabler: Miniaturization
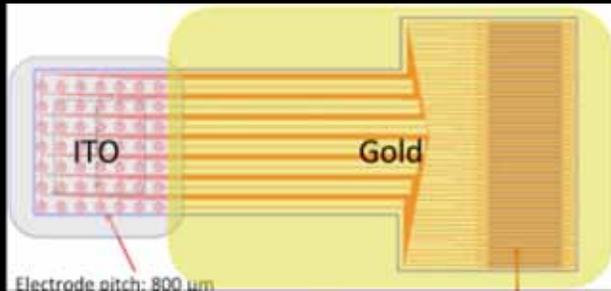
transparent ITO μECoG
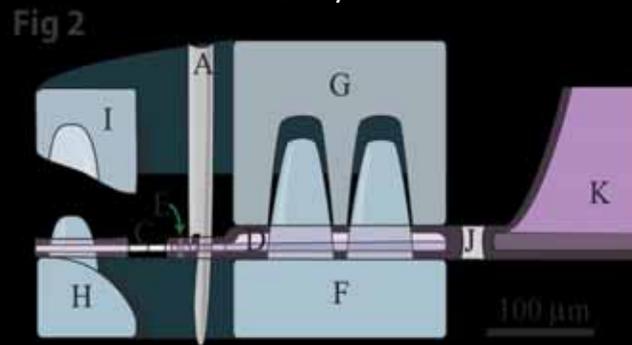Brian Pepin / Nathalie Gaudreault
Blanche / Maharbiz
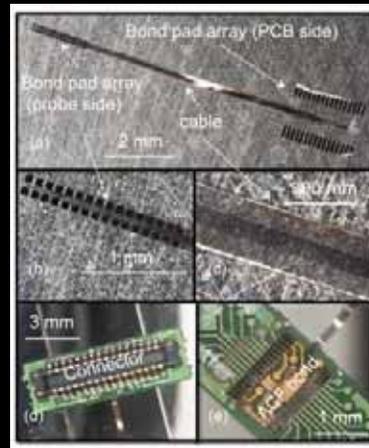
Scalable Flexible
Ultracompliant Nanocables
Peter Ledochowitsch / Raphael Tiefenauer
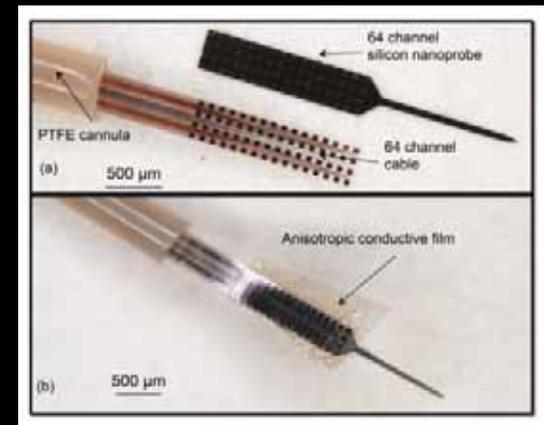Blanche / Maharbiz
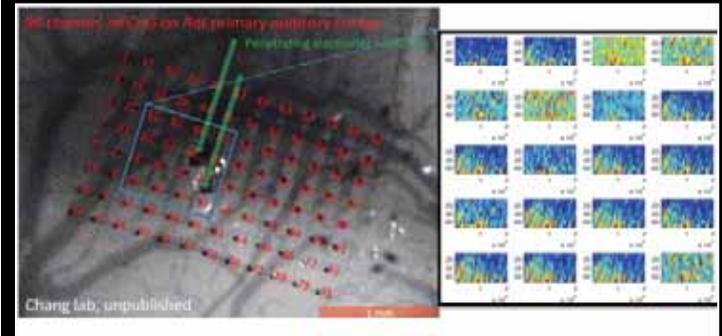
μECoG for auditory cortex
Peter Ledochowitsch /
Chang / Maharbiz
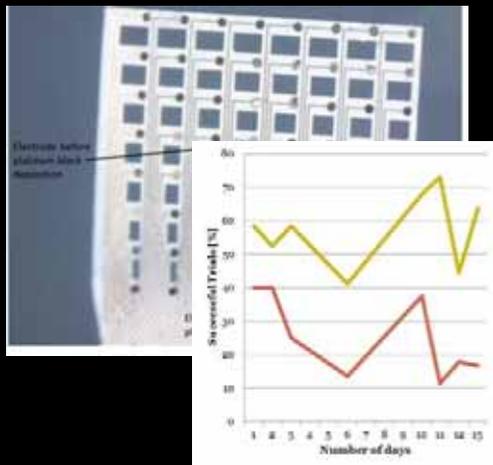
*μ*ECoG+BMI
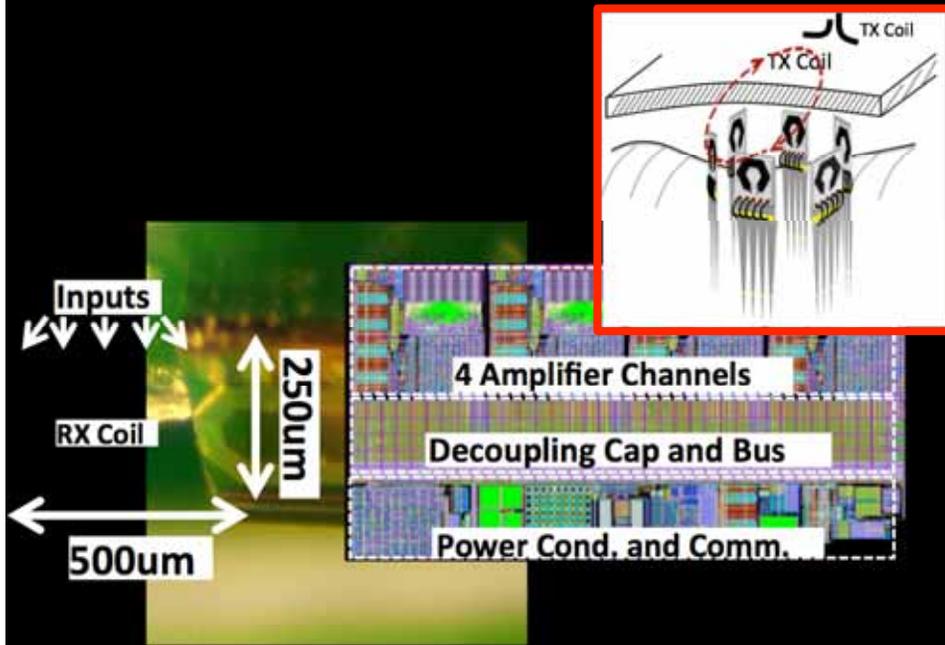Peter Ledochowitsch / Aaron Koralek
Carmena / Maharbiz

Insertion robotics for ultra-compliant
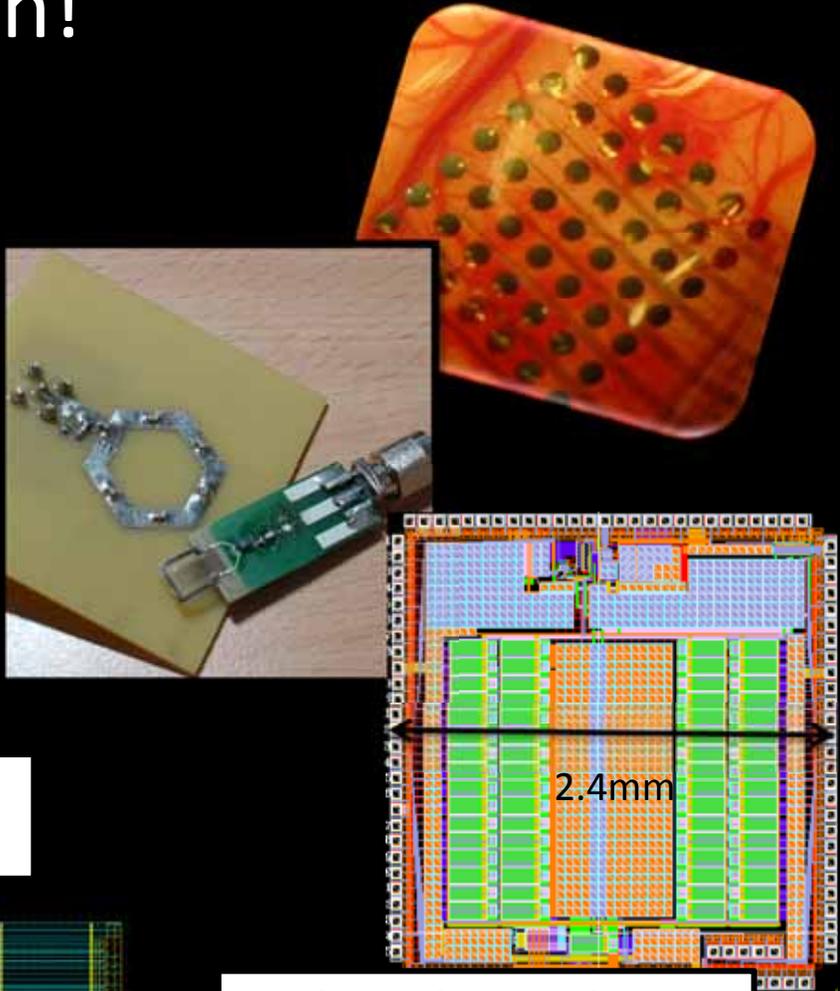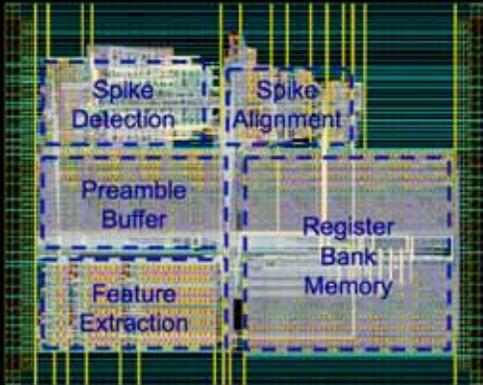electrodes
Tim Hanson
Sabes / Maharbiz

High Density Flexible Nanotrodes:
Electrical + Optical
Maysam Chamanzar
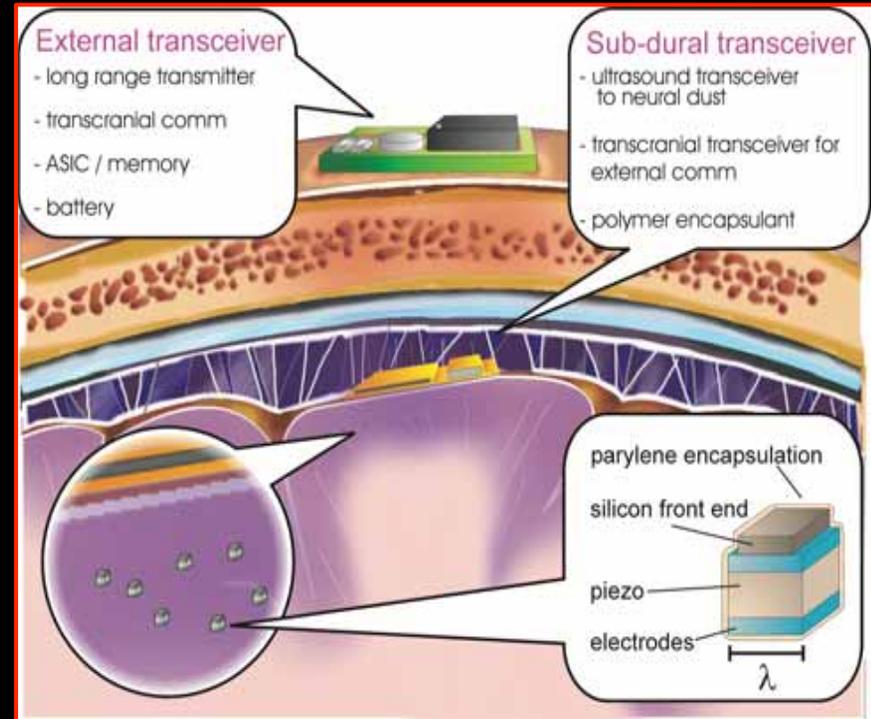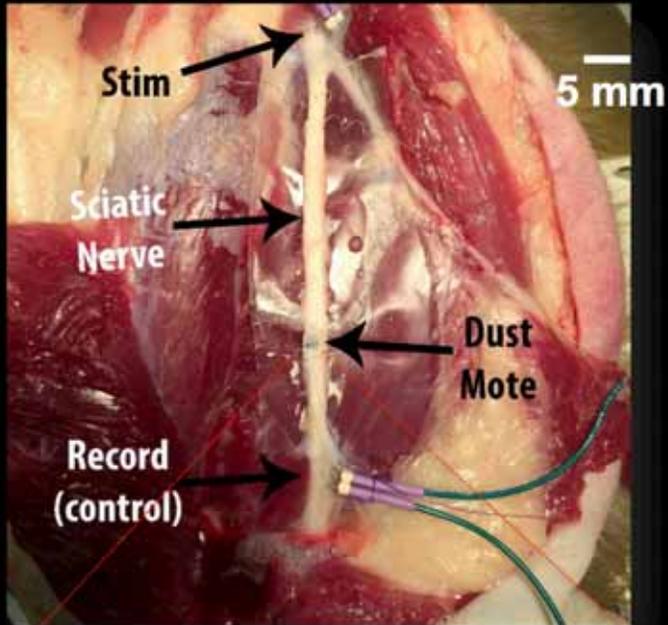Blanche / Maharbiz

Enabler: Miniaturization!

Free-floating wireless AP acquisition electrodes
[Biederman, Yeager, VLSI12]
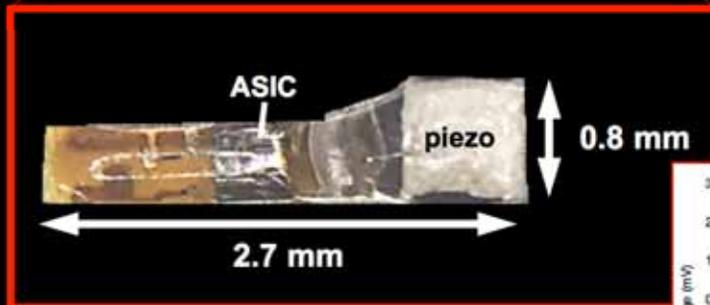
Asynchronous 250 nW/
channel spike-sorting
[Liu, VLSI12]

64 channel remotely
powered wireless uECoG
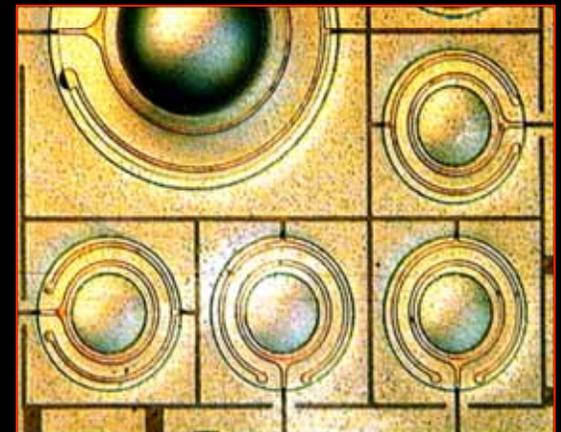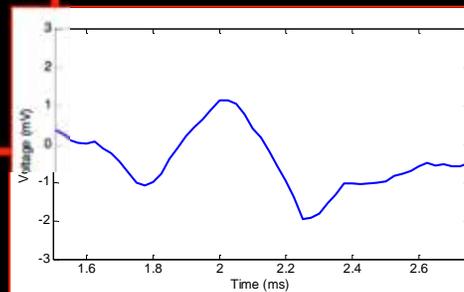[Muller, Le, Ledoschowicz,
Li]

Miniaturization

[DJ Seo et al, SfN Oct 15]

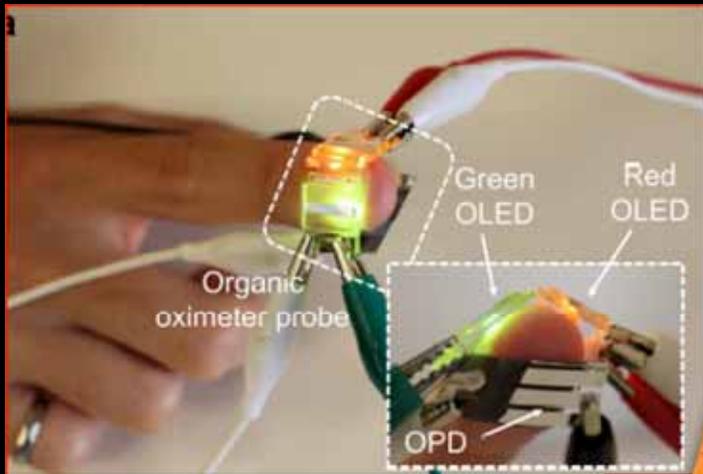**Neural dust**: microscopic nodes free floating in tissue to record neural activity

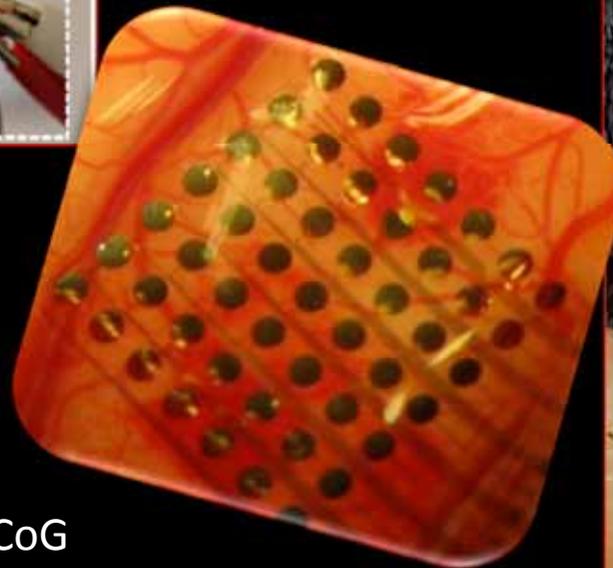Piezo beamforming array
[B. Boser, UCB]

Enabler: Flexible Electronics

For sensing

Blood oxonometry, EEG, EMG, ECG, heart rate, thermistors, humidity, stress, …

Printed oxonometry system
[Courtesy: A. Arias, UCB]

Thin Film µECoG
[Courtesy: M. Maharbiz, UCB]
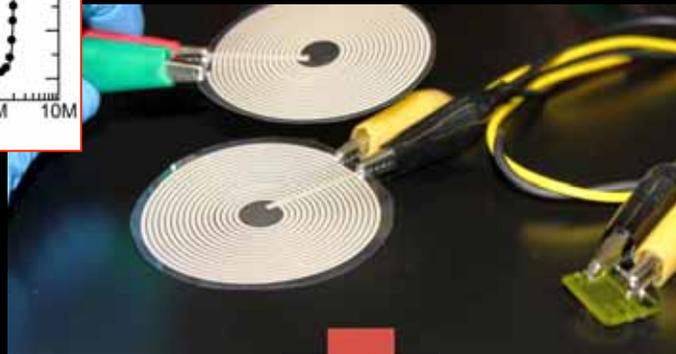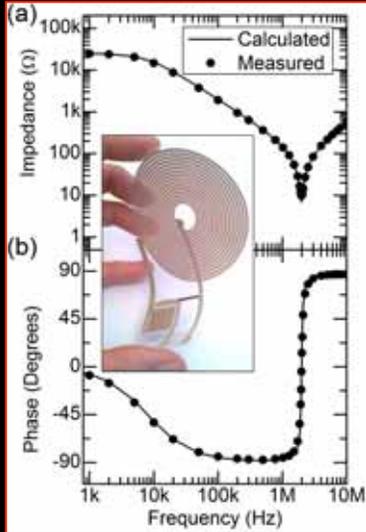

Thin Film EEG
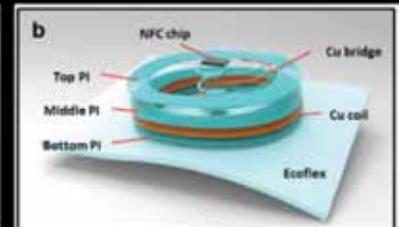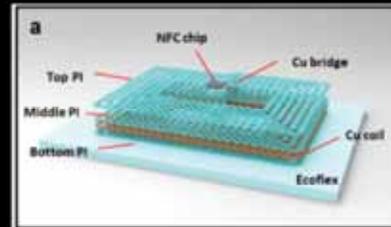[Courtesy: J. Rogers, UIUC]

Cheap, compliant, flexible, …

Enabler: Flexible Electronics
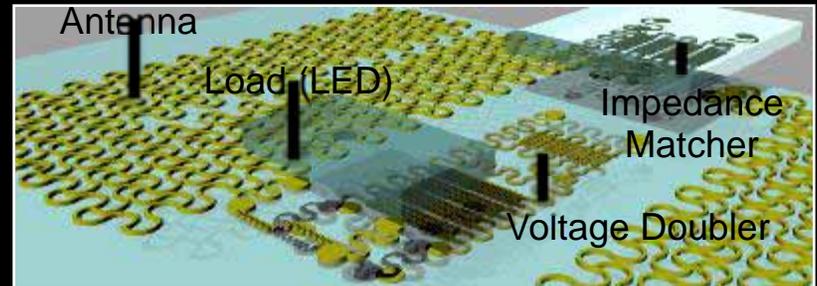
For energy delivery and communications

Inductive interrogator [A. Arias, UCB]

RFID-like energy harvester [J. Rogers, UIUC]

1 cm

Antenna
Load (LED)
Impedance Matcher
Voltage Doubler

The ultimate wearable technology

Skintillates
Conformal, flexible, wearable electronics

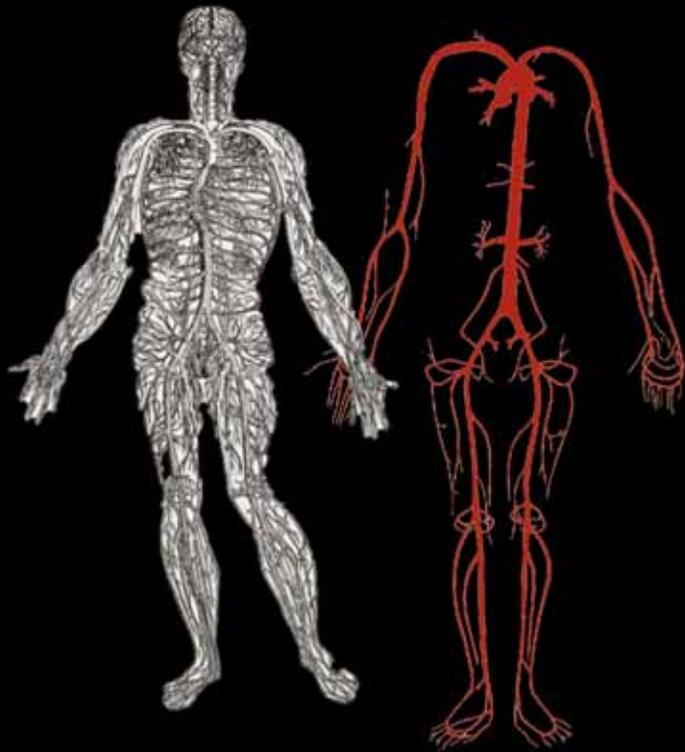[See also: OCTattoos, Peter Hamilton, Pandora's Star]

[Courtesy JoAnne Loh and Eric Paulos, UCB]

The Human Intranet

Plenty of Challenges

Energy, connectivity, safety, security, adaptivity

Challenge: Energy sparsity

## Intertwining of energy and information distribution

- Organically formed mesh network routes energy and data from sources to sinks

- Dynamically configured based on needs and availability

- Heterogeneous physical links (wired/wireless, electromagnetic, inductive, resistive, acoustic, …)

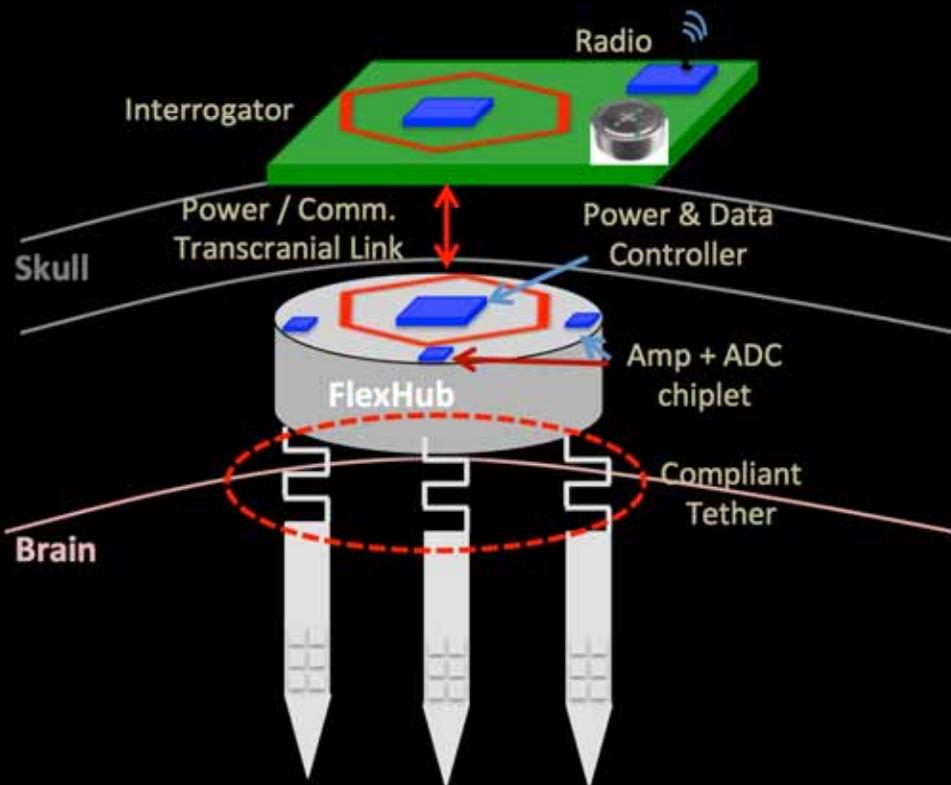Symbiotic to natural nervous and capillary system

Moving Forward: Focus on the Network

**Body-Area network
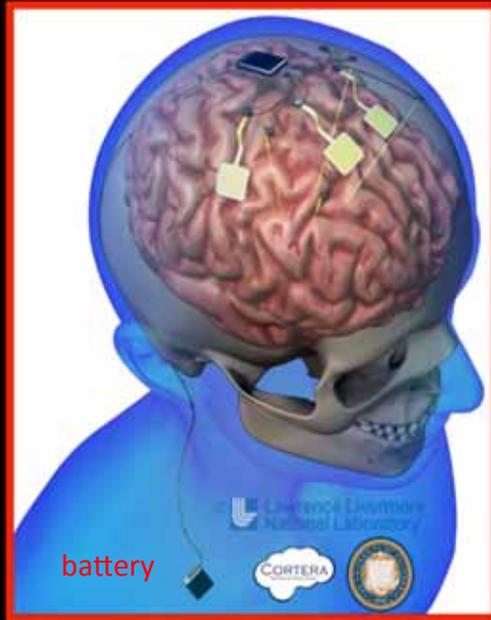skeleton/skin
formed by mesh of hub nodes**

- Seamless local addition of sensorymotor nodes by linking to hubs
  - *pick your favored physical layer*
- Power and data skeletons partially merged
  - Energy-aware protocols
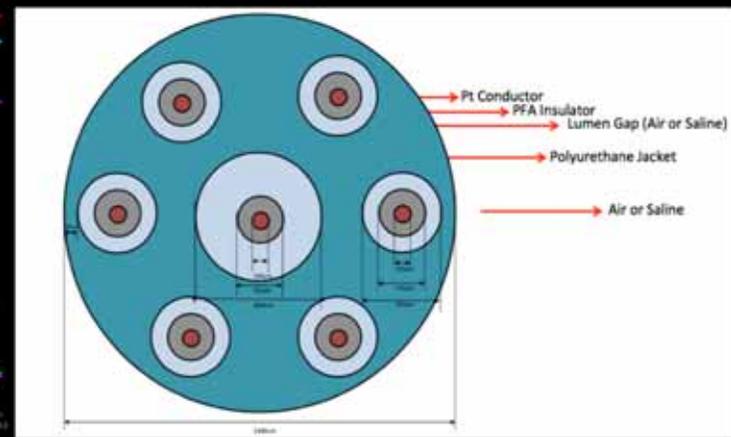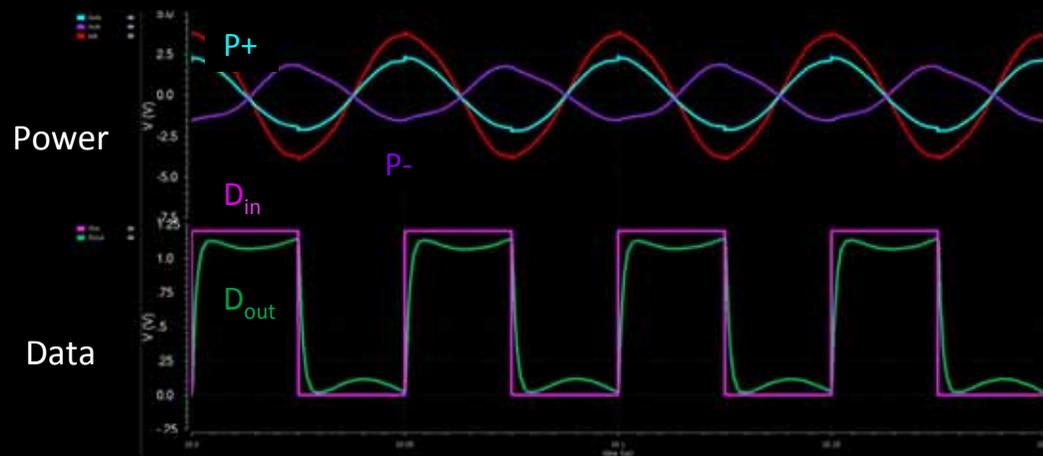- Hubs could be off-body as well
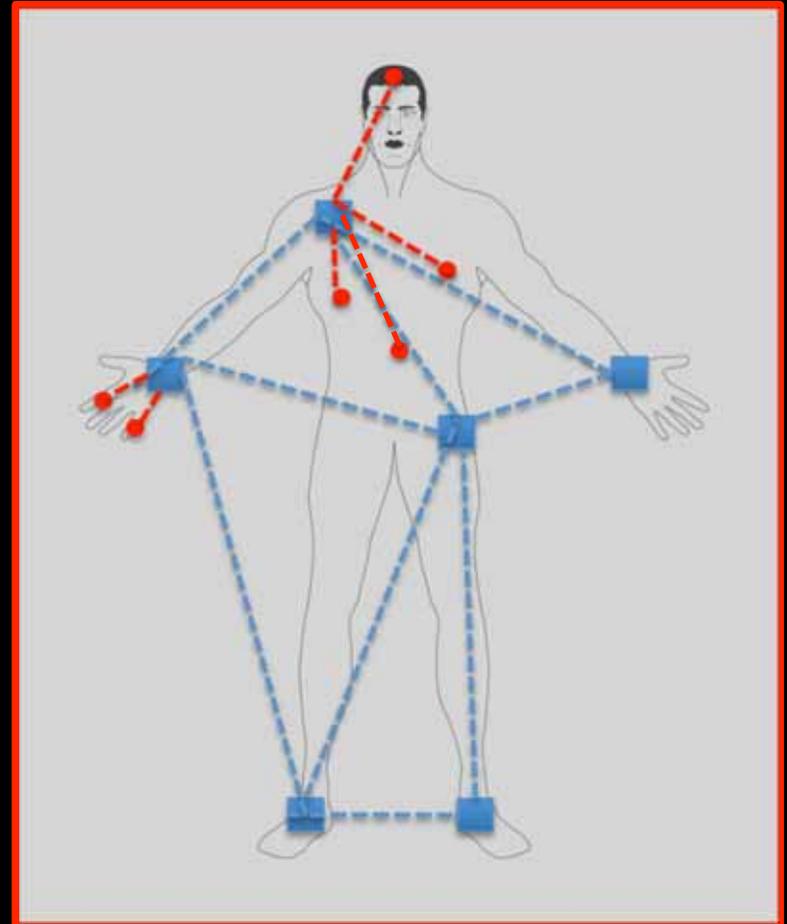
Examples in BMI
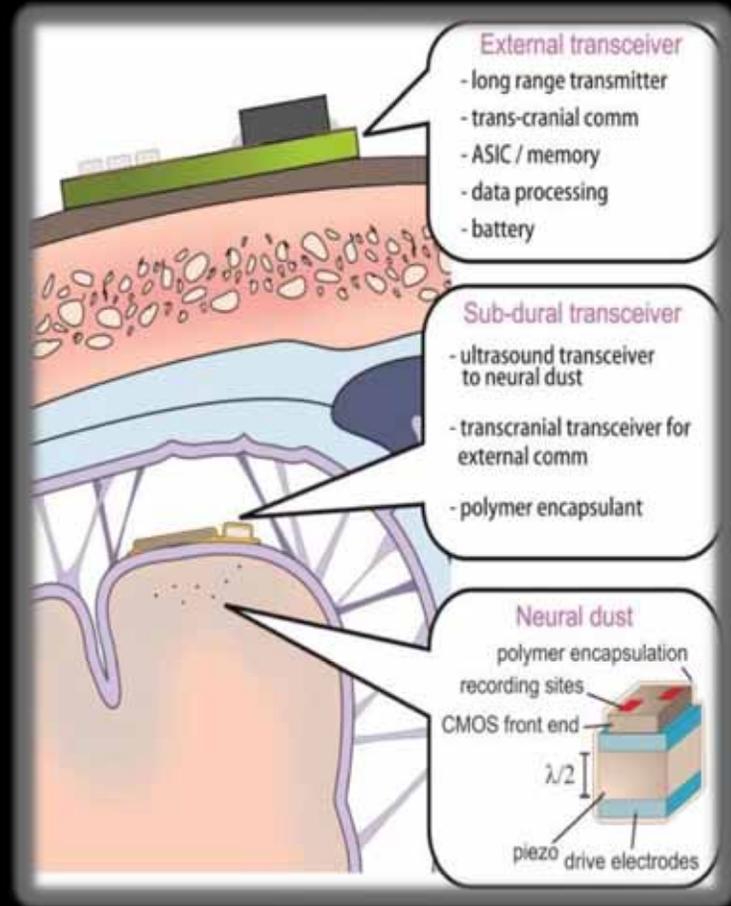
OMNI: The Network Challenge

battery

- Cable bundle combines power and data
- Digital protocol allows for scalability and modilarity
- Zero dc-contents for biocompatibility

Power

P+

P-

D$_{in}$

D$_{out}$

Data

Pt Conductor
PFA Insulator
Lumen Gap (Air or Saline)
Polyurethane Jacket
Air or Saline

Unpublished material – do not replicate

Challenge: Retain basic or partial functionality under **all** circumstances

Inherently fail-safe and robust
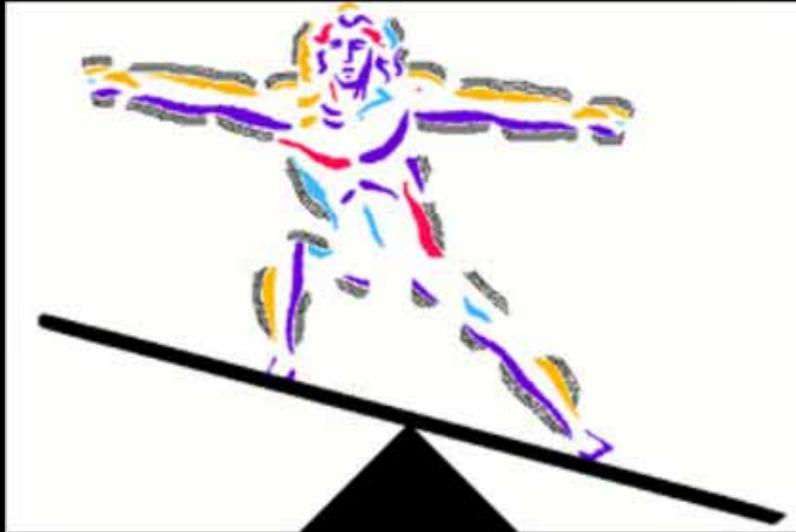
- Implicit baselining and fall-back modes
- Redundancy in network and compute resources
- Adaptivity and reconfiguration

Robustness in numbers and diversity
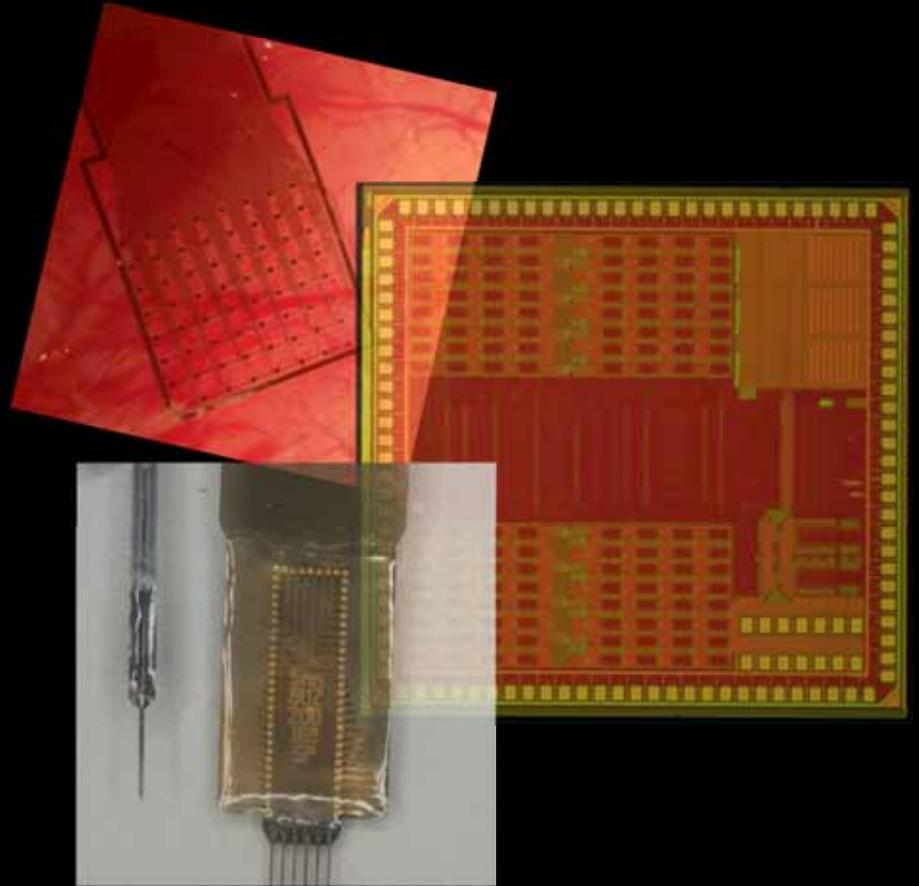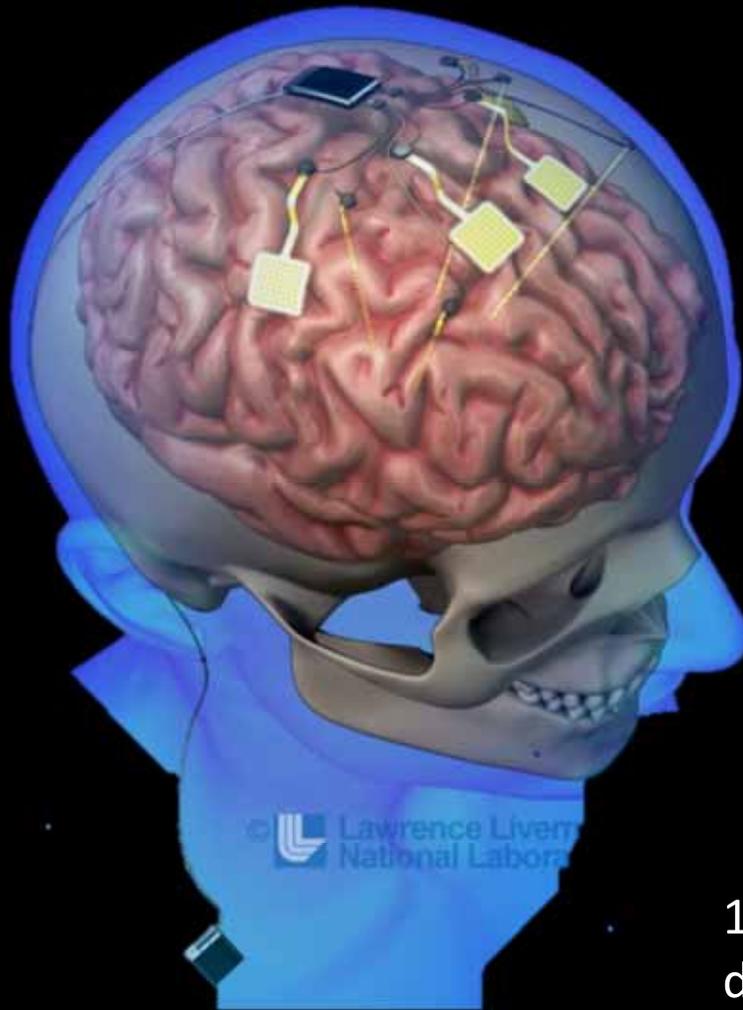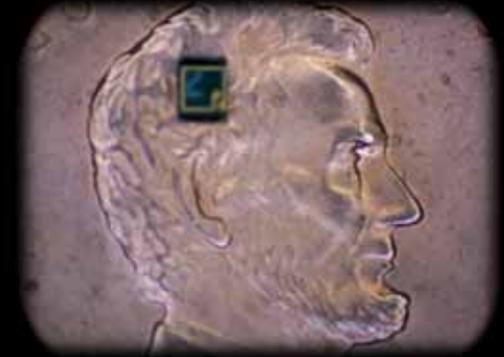
100s of channels from diverse sensors and diverse locations

Challenge: Secure and private

Human firewall

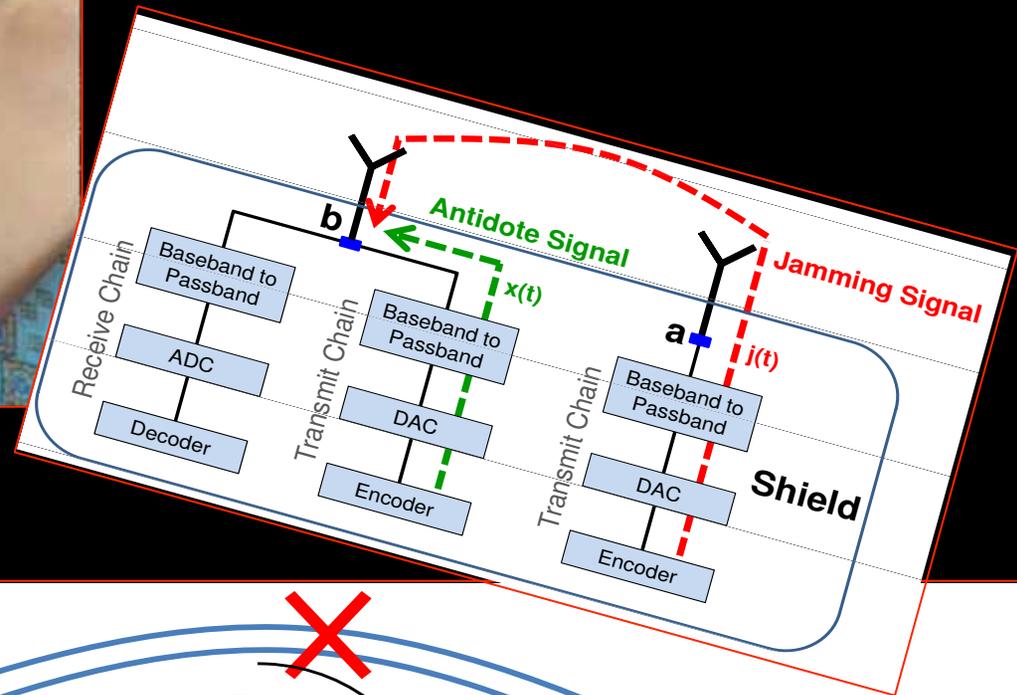*"Can I hack your brain?"*

- Every link to be encrypted
- Keys generated from local observations (channel properties, biomarkers)
- Creation of virtual cloak using deliberate self-interference
- Adaptivity to avoid spamming

[Harry Potter invisibility Cloak]

Real and Virtual Cloaks

Skintillates can be used as private or public wearable device

[Courtesy JoAnne Loh]

Receive Chain
- Baseband to Passband
- ADC
- Decoder

Transmit Chain
- Baseband to Passband
- DAC
- Encoder

Transmit Chain
- Baseband to Passband
- DAC
- Encoder

b

a $j(t)$

Antidote Signal $x(t)$

Jamming Signal

Shield

Jam hostile communcations and prevent overhearing
[Gollakota 2011]

IMD   **Shield**   Encrypted Communication   **Programmer**
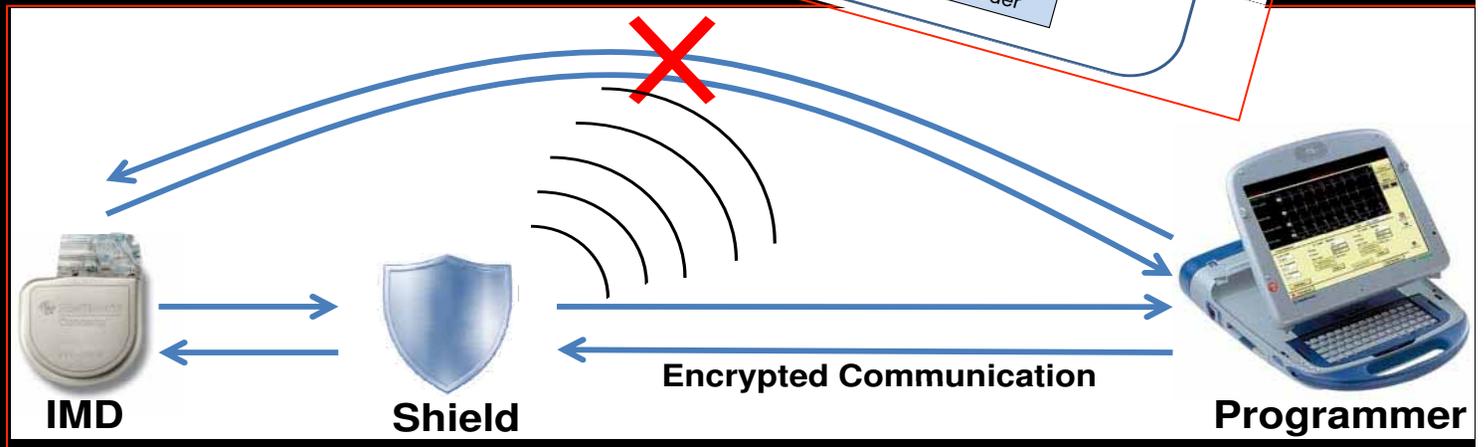
Challenge: Dynamically changing conditions

A: Hubs
B: Sensor clusters

Adaptive and evolutionary systems
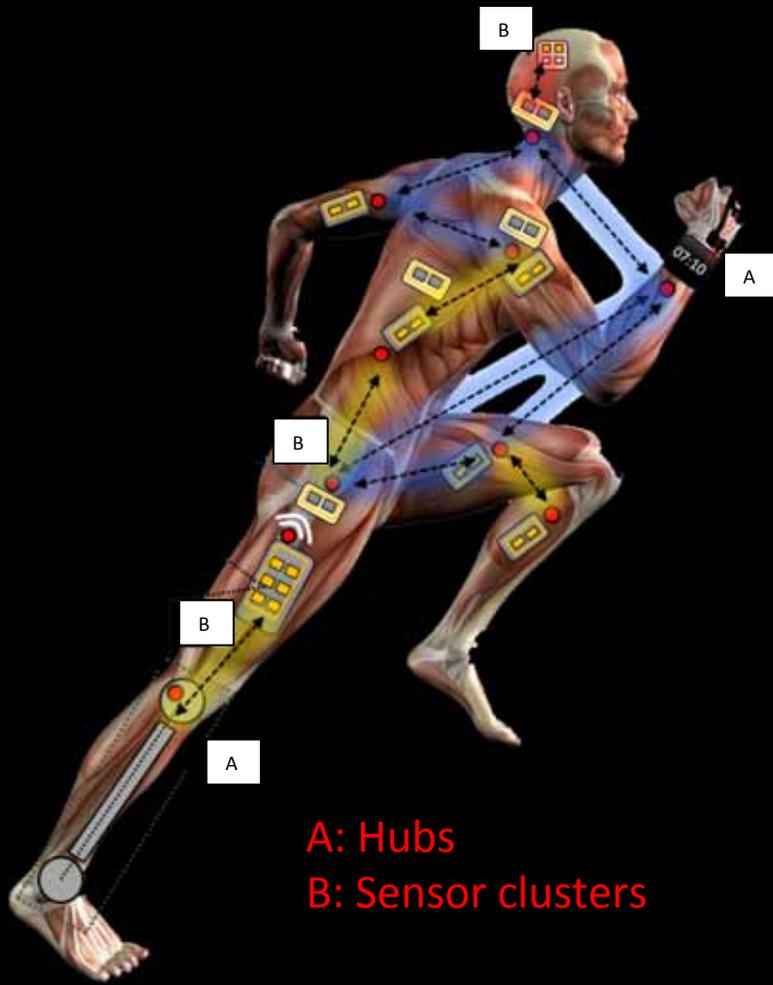
- Combining local information extraction and decision making with centralized global learning and optimization
- Supporting long-range and global functions such as feature extraction, sensor fusion, adaptation and learning

Closing the loop

Huge appetite for on-line computation

- Signal conditioning and feature extraction
  - Spectral analysis, filtering
  - Artifact removal
- Model creation and execution
  - Classification
  - Various forms of adaptive control; e.g. Model-Predictive Control
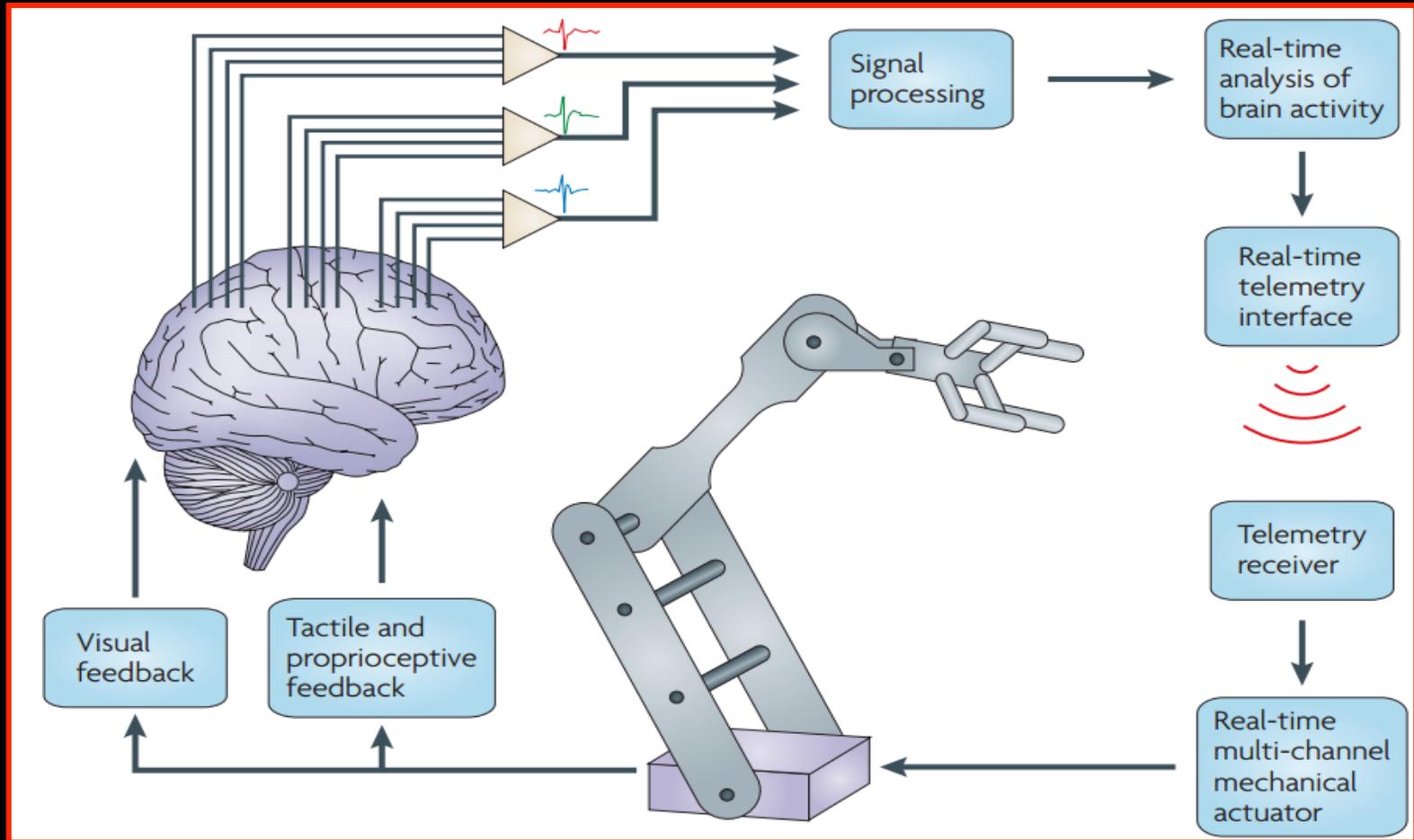 - Machine learning

Energy efficiencies > 2 orders of magnitude better than state-of-the-art embedded processors
~ mW at 10 MGFlop-10 GOP/sec
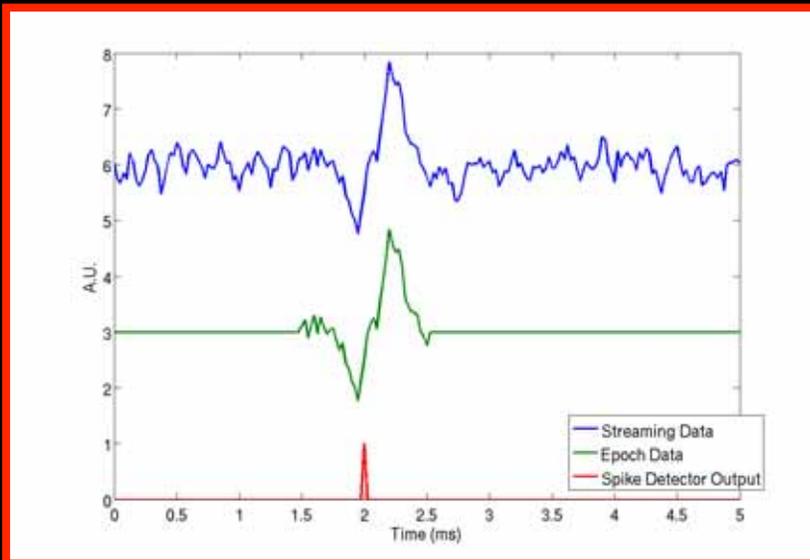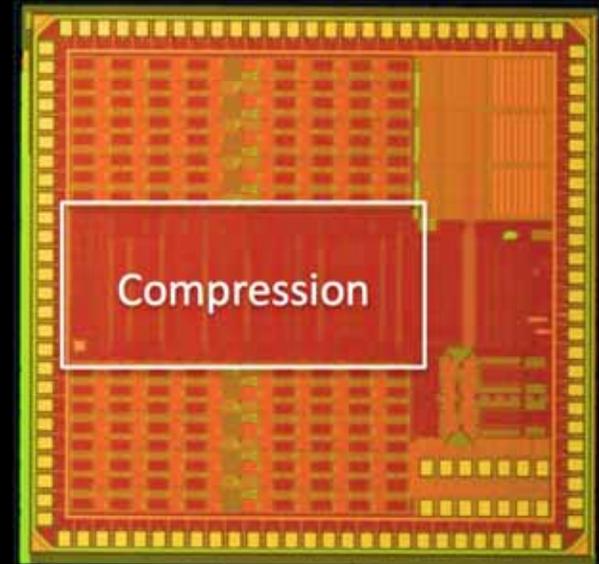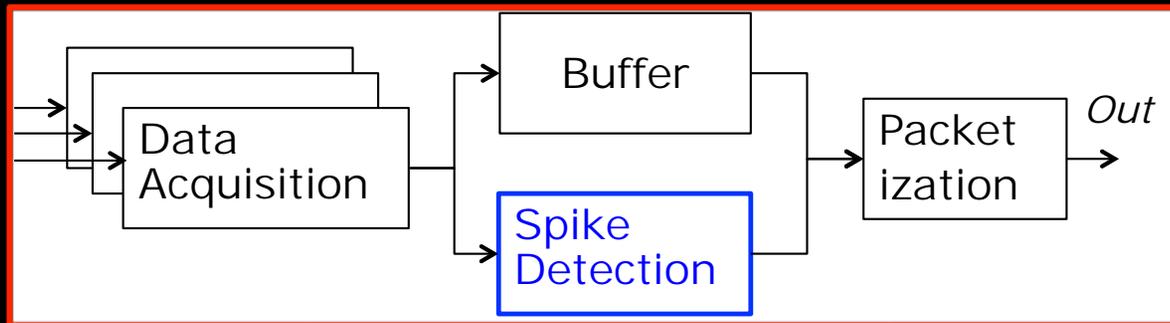
?

Closing The Loop

Low latency, adaptive, multi-variate, hybrid

Typical BMI System
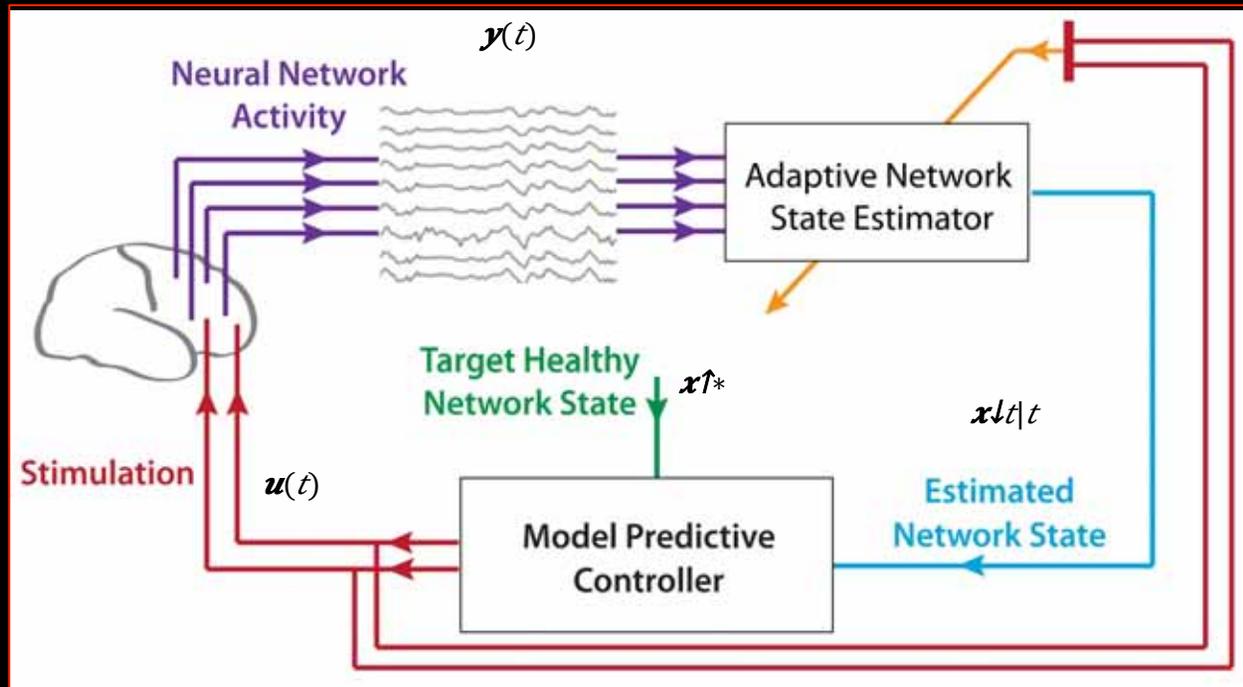
Reducing the Data Deluge

Number of recordable channels limited by throughput of wireless channel and energy/channel
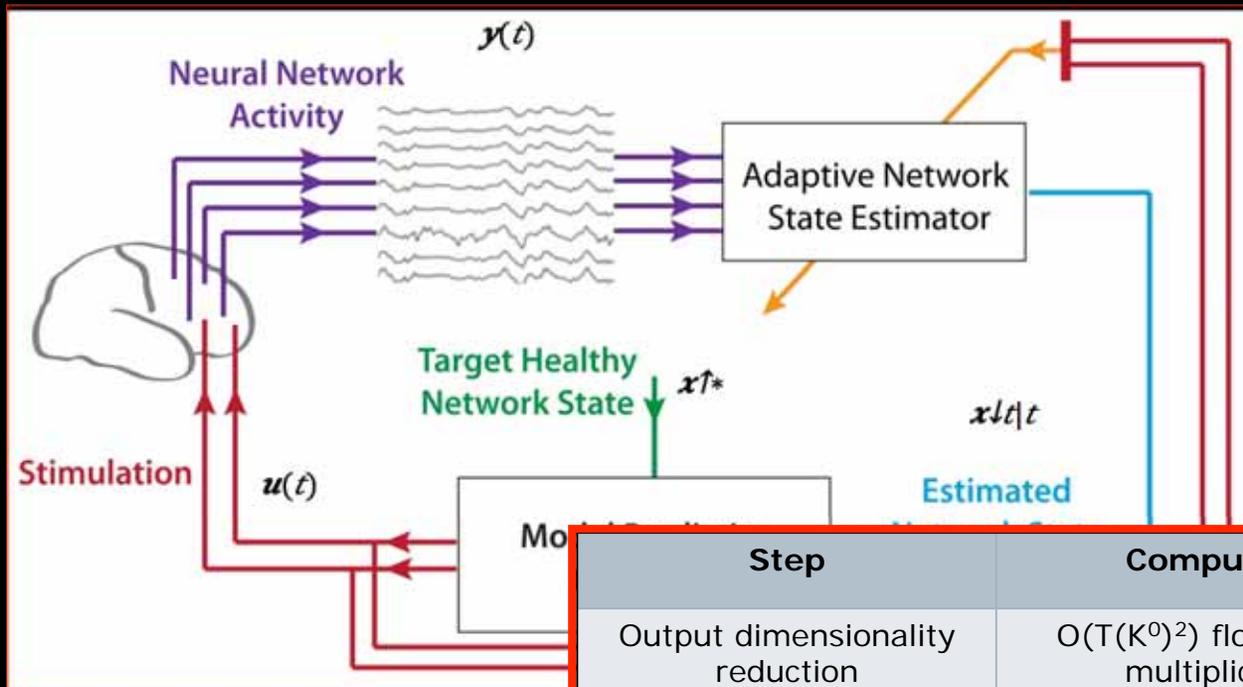

Solution: Compression at the source
- Raw: 210 Kbps/channel
- Epochs: < 32 Kbps/channel
- Firing Rates: 150 bps/channel

[D. Yeager et al, VLSI 14]

Advanced closed-loop systems

Advanced closed-loop systems

[Courtesy: M. Shanechi, USC]

Step	Computation	Complexity
Output dimensionality reduction	$O(T(K^0)^2)$ floating point multiplications	$O(10^9)$
System identification ("offline")	$O(4N(K + N)(K + M)M^2(K + N)^2)$ floating point multiplications	$O(10^{12})$
State estimator	$O(KM)$ multiplications	$O(10^3)$
Feedback controller (MPC)	$O(hM^3N^2)$ multiplications	$O(10^9)$

Dedicated accelerators supplementing embedded microcontrollers necessary

Computation - An Alternative Approach

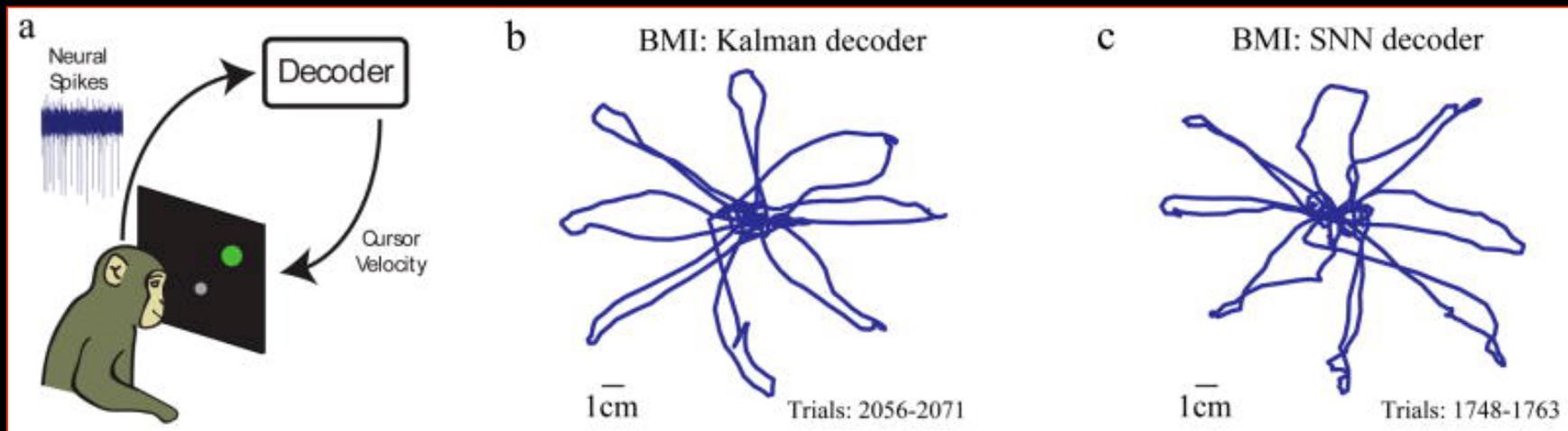Efficient distributed machine-learning engines

[Courtesy: M. Causo, ST]
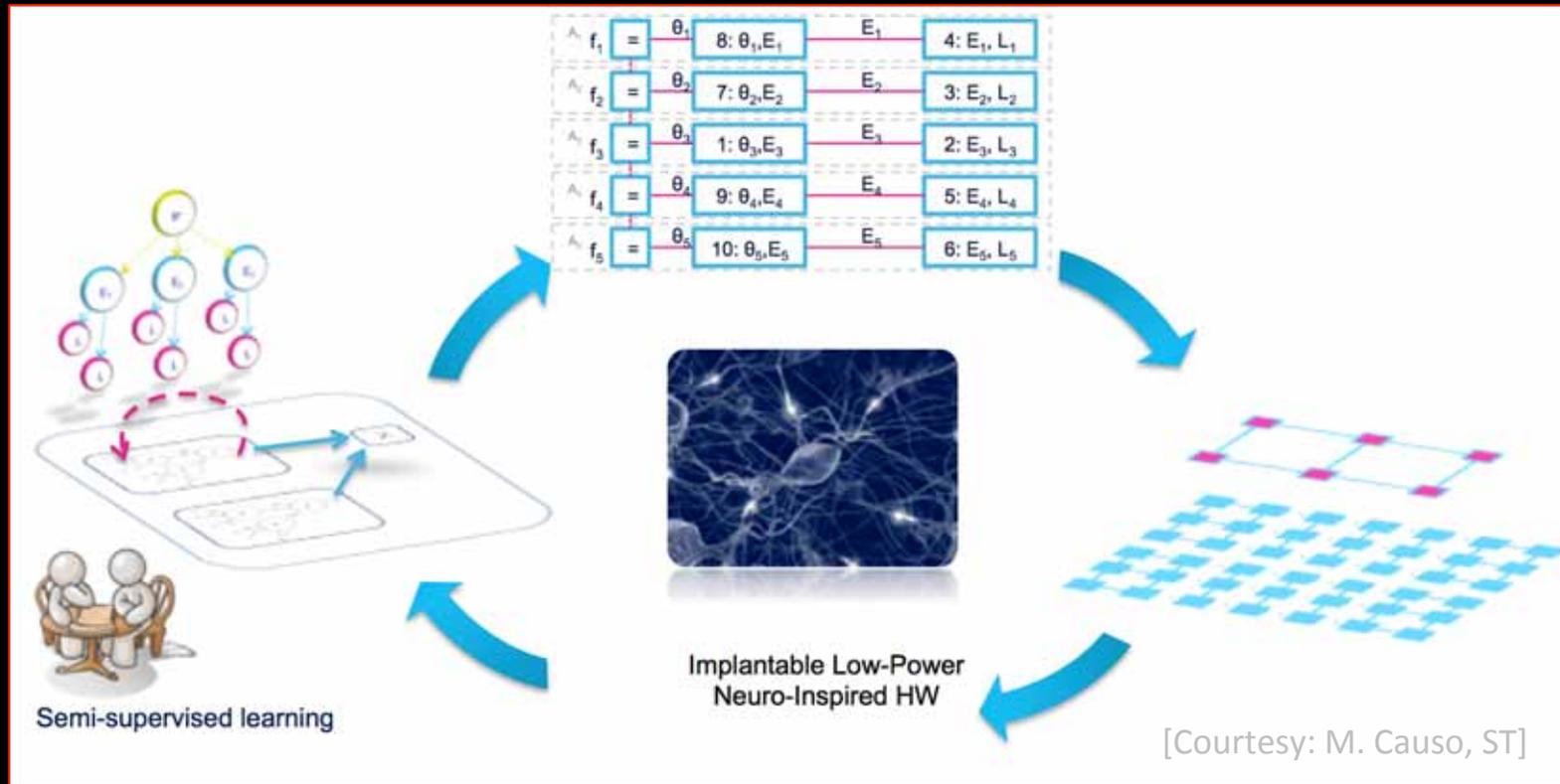
Window of opportunity for neuro-inspired architectures

- Deep learning successes in machine automation
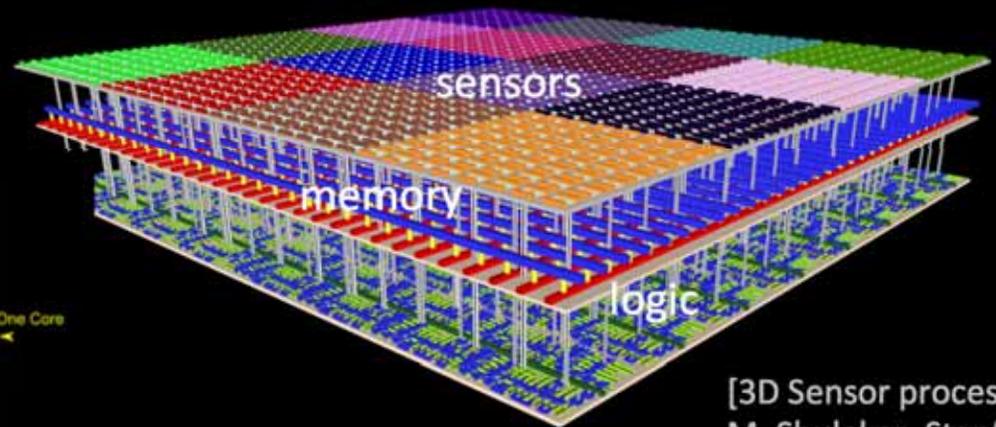
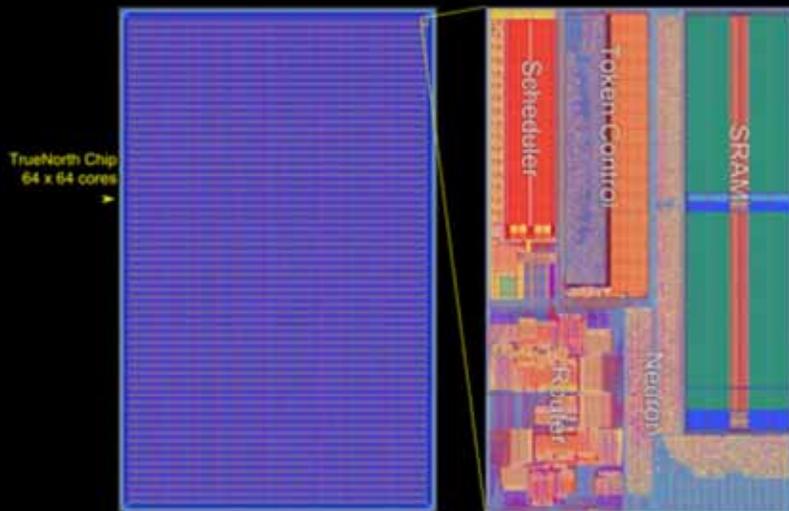# Computation – An Alternative Approach

A very first indicator: BMI Control using Spiking Neural Networks

[Dethier et al, Adv Neural Inf Processing Systems, 2011]

Computation – An Alternative Approach

Major Opportunities

TrueNorth Chip
64 x 64 cores

Scheduler
Token Control
SRAM
Router
Neuron

One Core

[TrueNorth Processor,
S. Modha, IBM]

sensors

memory

logic

[3D Sensor processor,
M. Shulaker, Stanford]

Fundamental Challenges

- Computation at low SNR
- Massively parallel and redundant operation
- Programming models that scale horizontally and vertically

High-order bits

- The new age of information processing: ubiquitous, distributed and VERY personal

- Redefining information technology - Stretching bounds in energy scaling, miniaturization, and wireless distributed system design.

- BMI center and fore. Yet, just scratching the surface. Many more opportunities to emerge!

- Will challenge society and humanity in many unforeseeable ways – the conversation starts NOW!

Acknowledgements