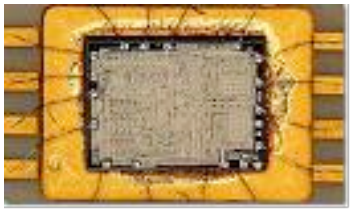
Nanosystems
for a healthier and safer tomorrow

Giovanni De Micheli

What direction for electronic research?

- We came a long way …
  - 50 years of electronics


[Bell labs]


[Intel]

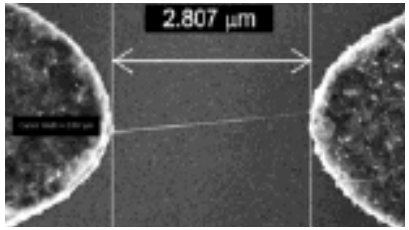

[IBM]

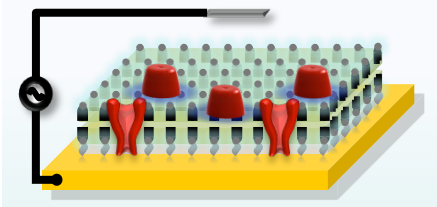
- … and where are we going?
  - The next 50 years


[Kubrick:2001]

Looking for scientific novelty

- The **technology push**:
  - New materials:
    - Carbon, organic electronics
  - Nano-devices:
    - Quantum confinement effects
  - Sensors:
    - Transduction mechanisms





- The boundary conditions:
  - Societal changes over 50 years of EE
    - From (transistor)-*radio days* to *facebook*
  - Computing and communication technologies bring a new universal perspective

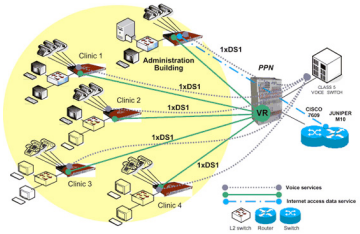
Looking for impact

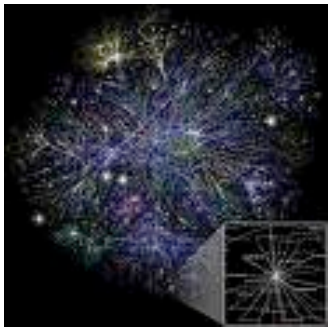
- The **economic and societal pull**:
  - World Economic Forum (Davos 10)
  - Improve the *State of the World*: Rethink, Redesign, Rebuild

- Summit on the global agenda (Dubai 09)
  - Most pressing technological/economic issues affecting the world growth
  - Directions for young generation
    - From students to leaders
- Strong overlap with broad EE issues
  - Information technology boosts the value of specific advances in devices to achieve a global perspective

The global agenda

- Ensuring sustainability
  - Smart energy production and distribution
  - Intelligent water management
- Strengthening welfare
  - Better, affordable health care and wellness
  - Dealing with ageing and young population
- Mitigating risks
  - Preventing catastrophes and pandemics
  - Monitoring the environment
- Enhancing security
  - Future of the internet
  - Preventing cyber and physical attacks

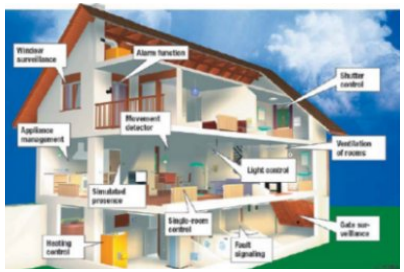




Smart energy

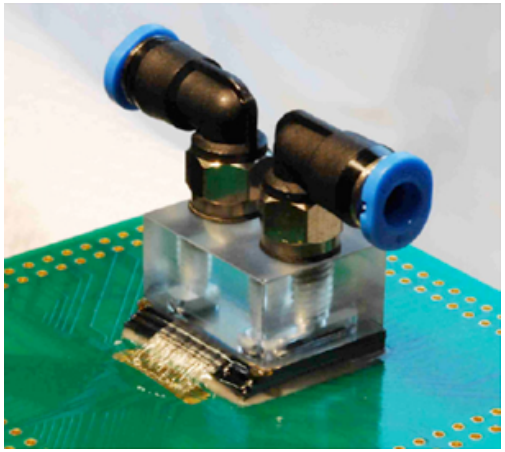
- Smart grid
  - Match supply and demand of energy in a diversified environment
- Smart home/workplace
  - Optimize energy consumption according to need
- Smart data centers
  - Provide information flow and distribution with limited energy cost
- *Challenges:*
  - *Real time response*
  - *Workload prediction*
  - *Optimum control*



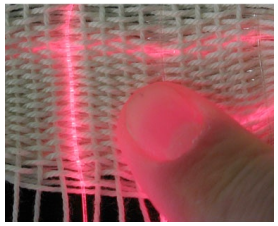

Example: data centers

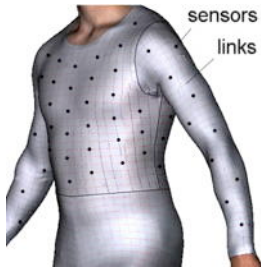
- Data centers are key to services like Google, Yahoo!, Microsoft…
  - Information is economic power
- Data centers consume 2-4% of world energy
  - Computation, storage and cooling
  - Localization of data centers
- Green data centers:
  - Dynamic power management
    - Hardware control and cooling
  - Hw/Sw co-design:
    - Virtualization to save energy
    - Online learning
- *Challenges:*
  - *Energy vs availability vs latency*

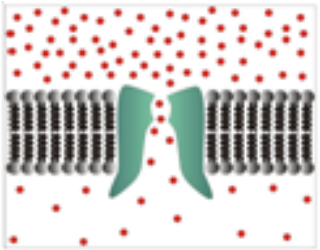


Electronic health

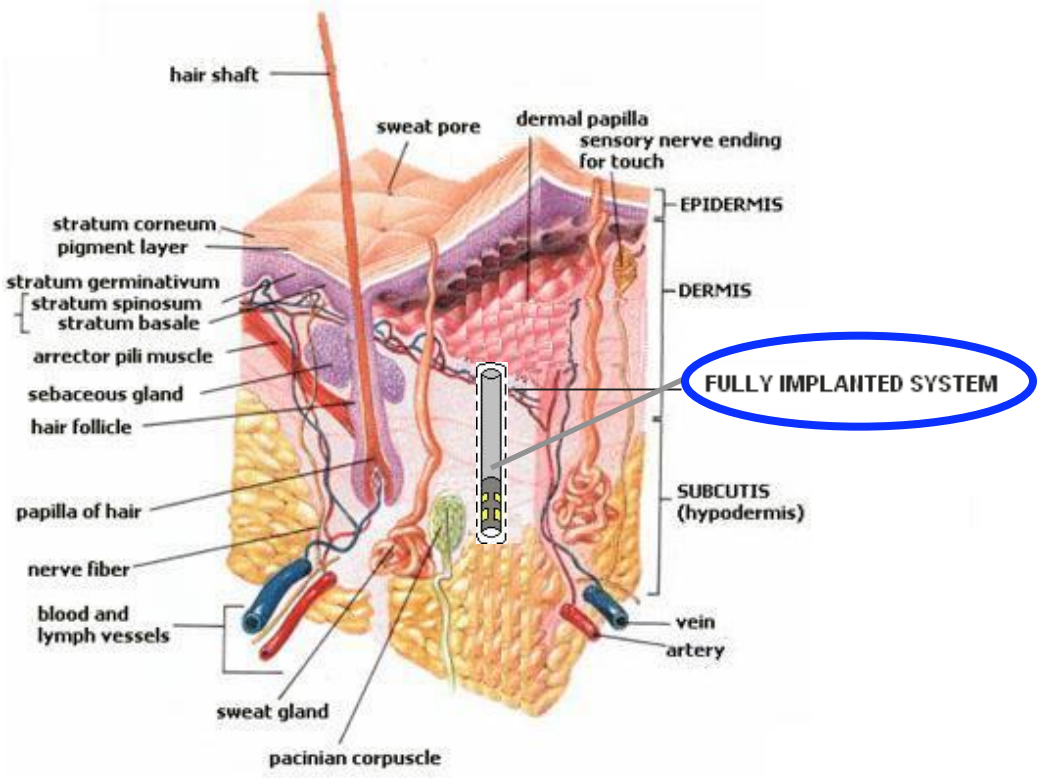
- Body monitoring
  - Biosensors
  - Body area networks
  - Smart textiles
- Clinical support
  - Remote diagnosis
  - Drug delivery
- Prevention
  - Monitoring nutrition
- *Challenges:*
  - *Non-invasiveness*
  - *Safety and security*
  - *Autonomy and adaptation*

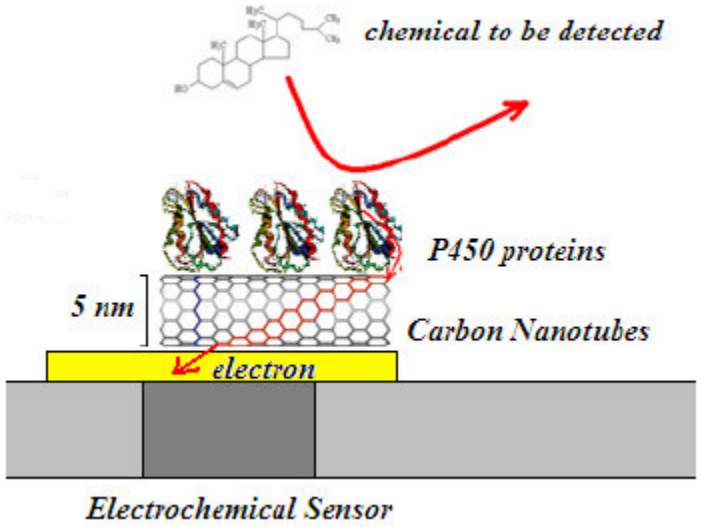


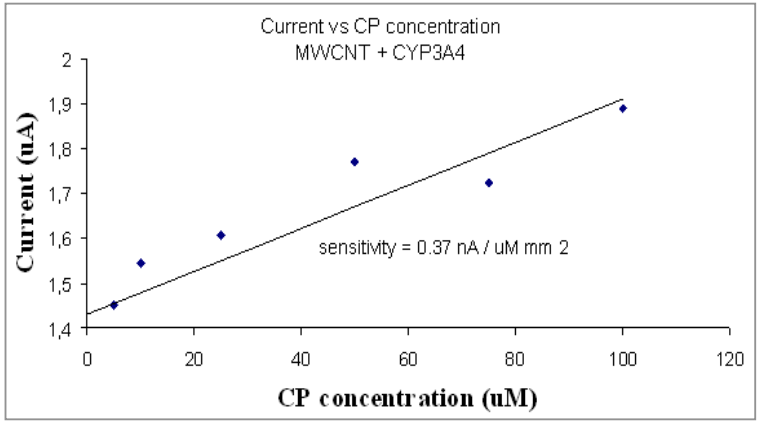




Example: smart implants



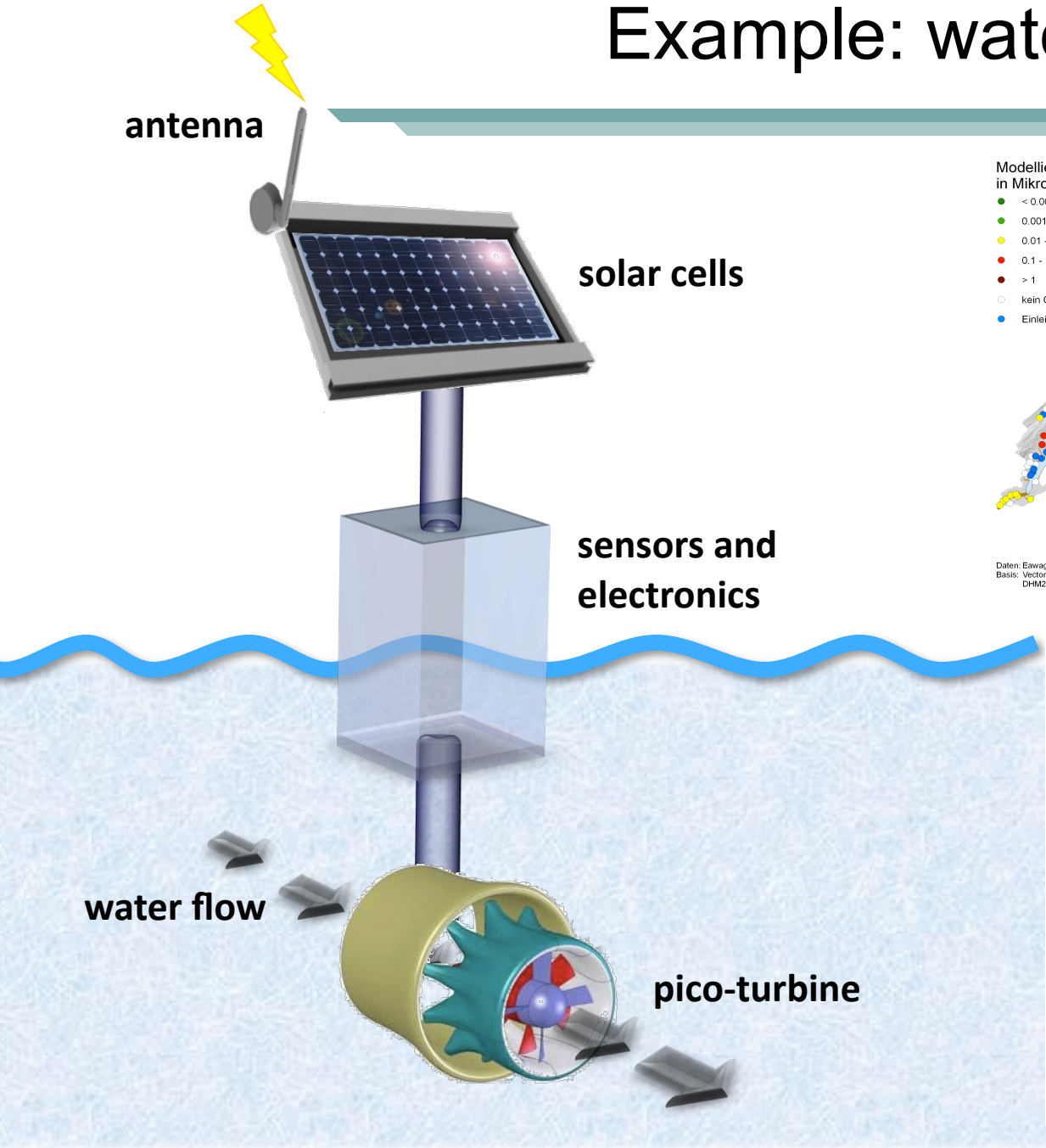


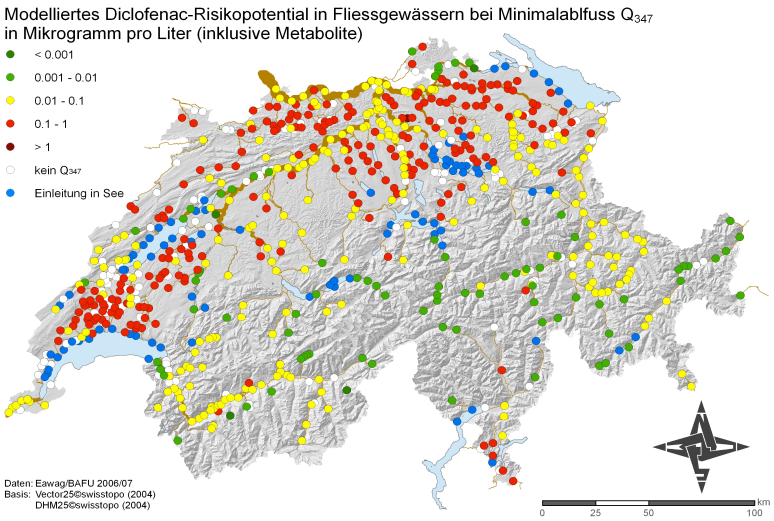


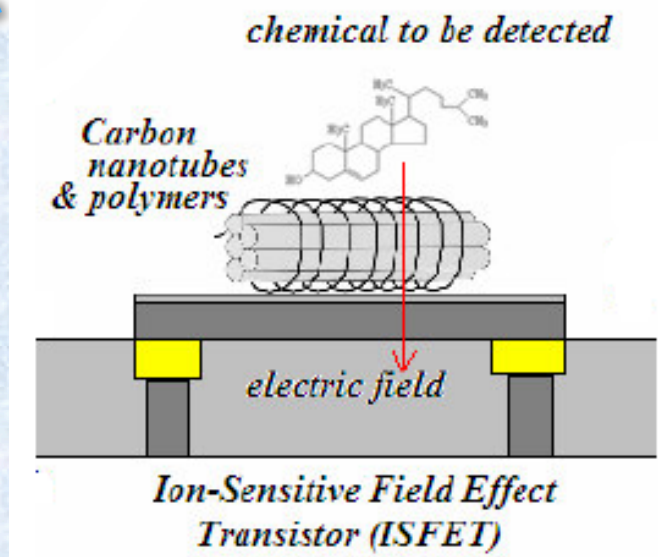
Environment

- Monitoring heat, wind, vibration
  - Earthquake, flood prediction
  - Movement of glaciers
- Controlling pollution
  - Water, air purity
  - Bio-contamination
- Emergency relief control
  - Real time support for reaction
- *Challenges:*
  - *Seamless presence*
  - *Biodegradability*
  - *Autonomous and adaptive operation*

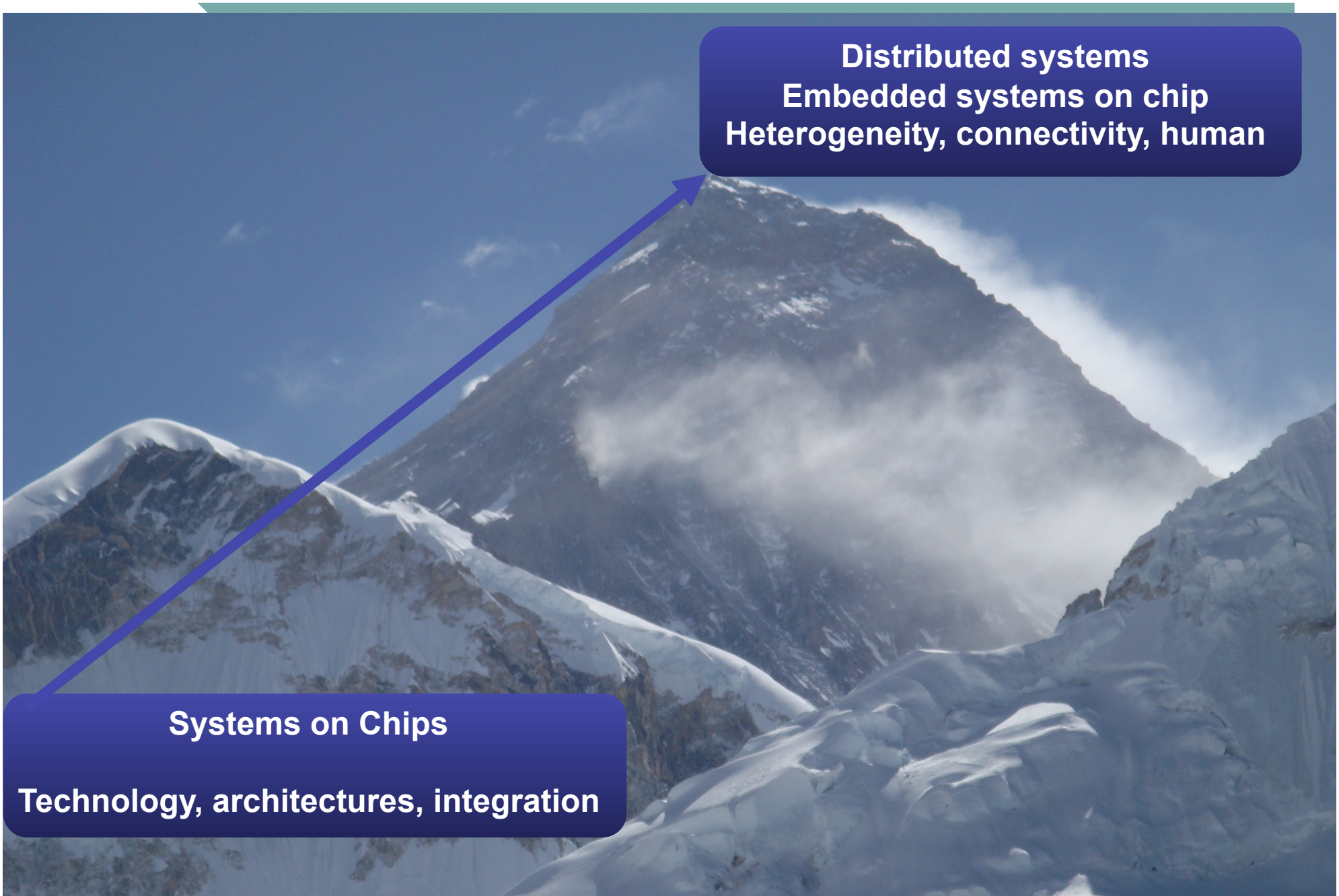
Example: water purity



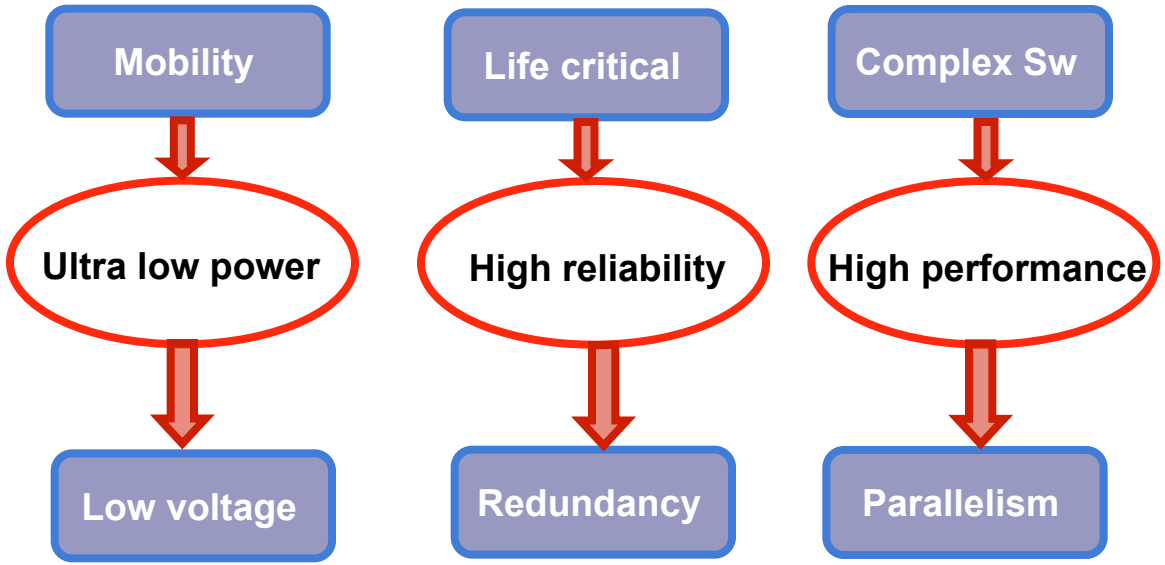




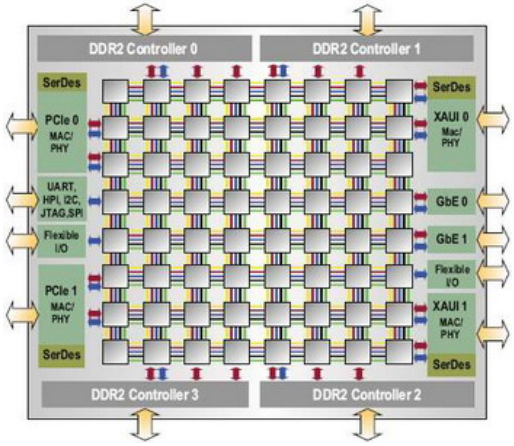
The way ahead



Requirements for electronic chip design



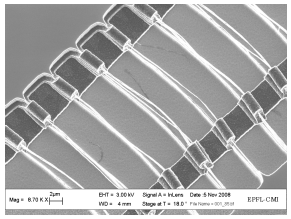
- From processors to multi-processors
  - Scalable computing and communication architectures
  - Systems and software redesign

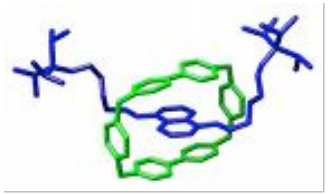


[Tilera]

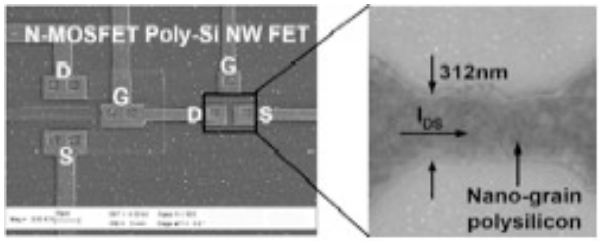
The fabrication technology support

- Beyond CMOS: a myriad of new ideas

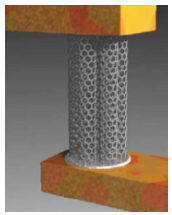




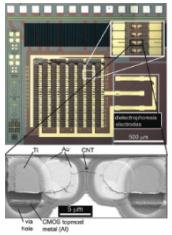
- Are these technologies apt/ready for system design?
- Can they mix and match with CMOS?



[Leblebici, EPFL]



[Infineon]

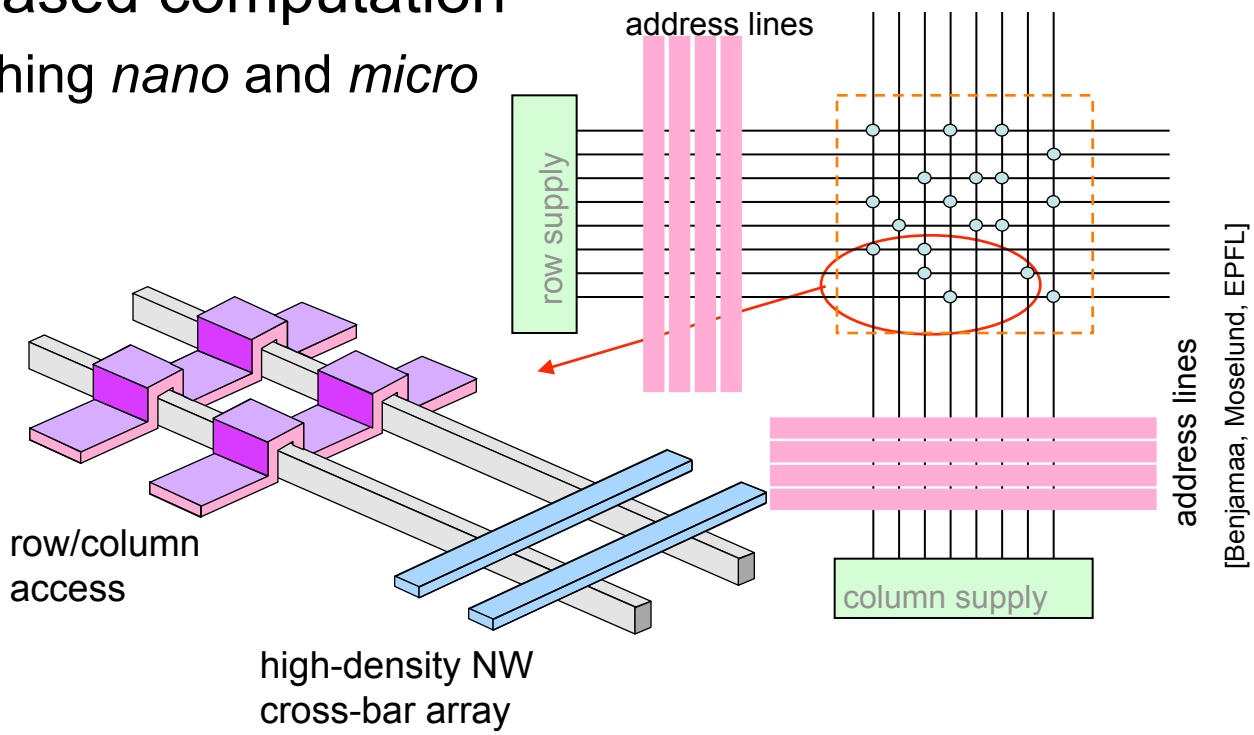


[Close, Stanford]

- How do we design with these technologies?
  - Higher defect densities and failure rates

New computational structures

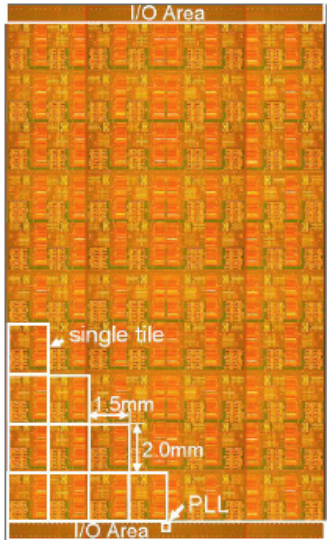
- Computation requirements
  - Predictable design
  - Fast design closure
- Array based computation
  - Matching *nano* and *micro*



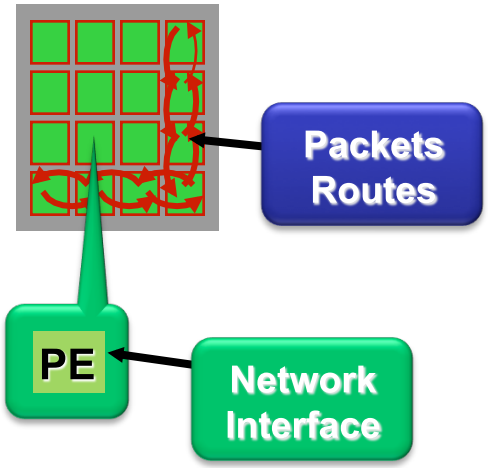
[Benjamaa, Moselund, EPFL]

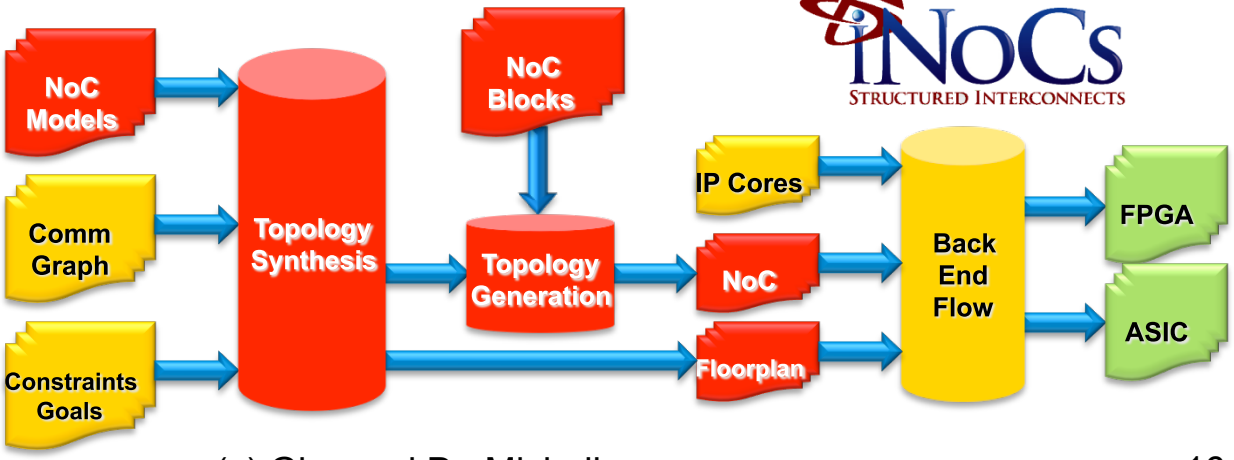
New communication structures

- Design requirements:
  - Predictable design
  - Fast design closure
- Network on Chip communication
  - Modular and flexible interconnect
  - Reliable on-chip communication
  - Structured design with synthesis and optimization support



[Vangal, Intel07]

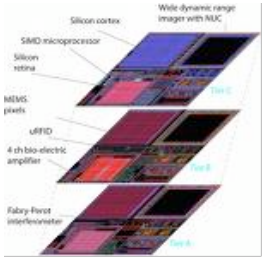


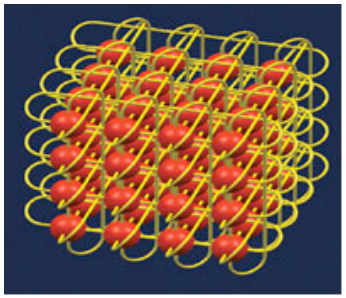


New packaging technologies

- From planar to 3D integration
  - Chips have limited wiring resources
  - Electrical and manufacturing constraints limit heterogeneous planar integration
- *Through silicon vias* allow designer to stack:
  - Computing arrays
  - Memory arrays
  - Analog and RF circuitry
- 3D NoCs provide effective and reconfigurable means of realizing communication

[Fraunhofer]

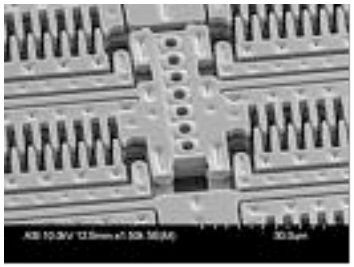




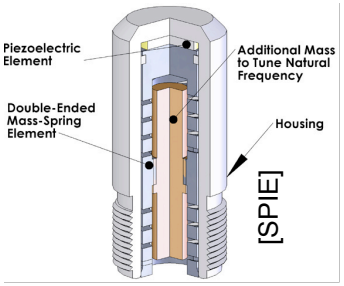
[IBM]

Heterogeneous integration

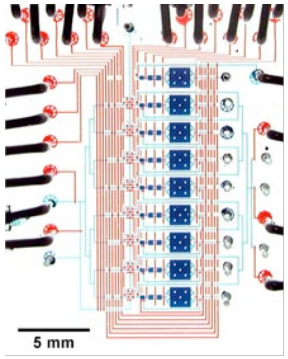
- Electrical and mechanical parts
  - Microactuators, scavengers, microfluidics



[Sandia]

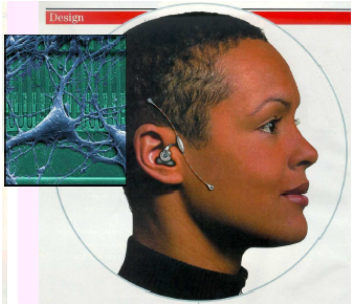


[SPIE]



[Quake, Stanford]

- Electronics meets the living world

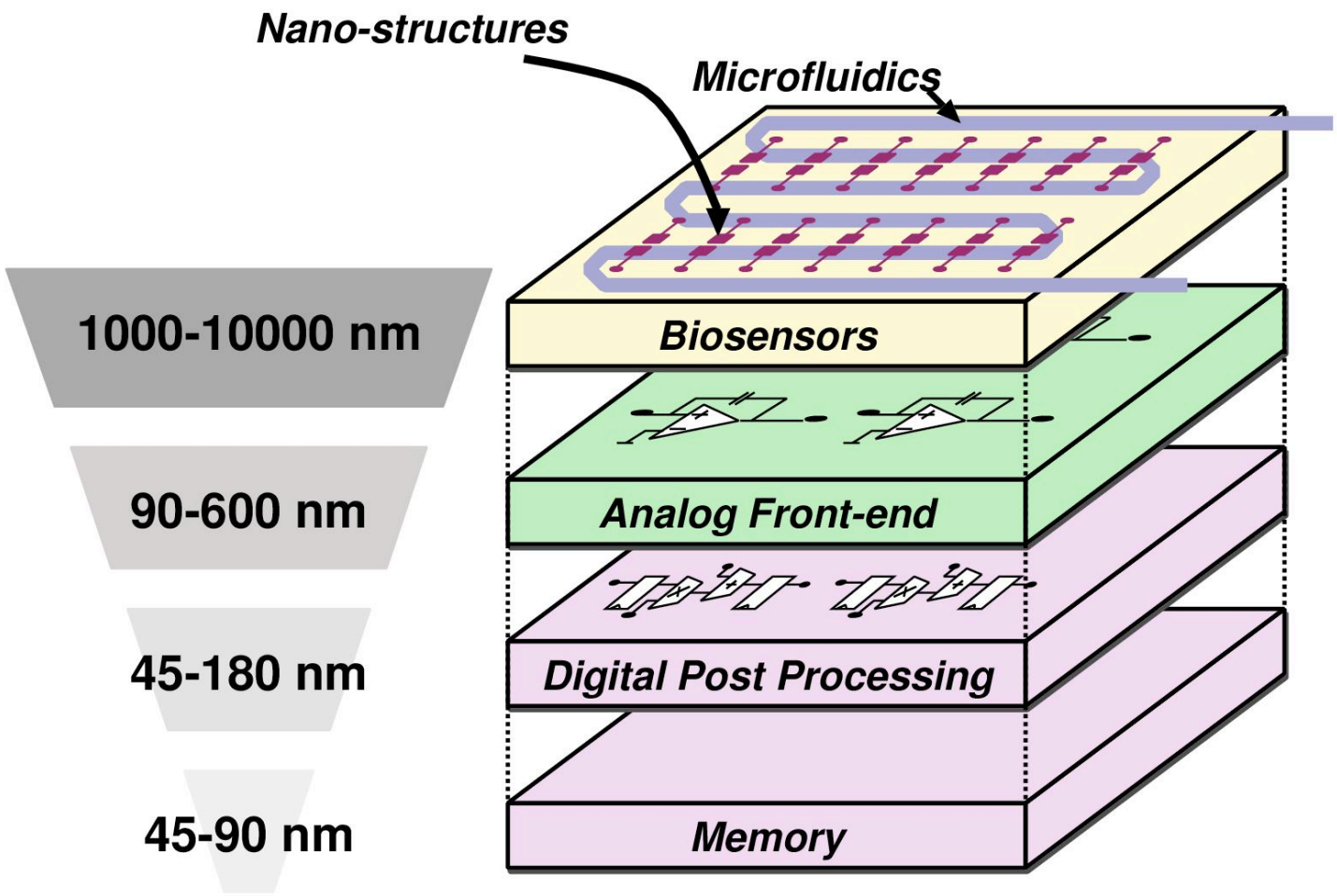


[Un. Missouri]

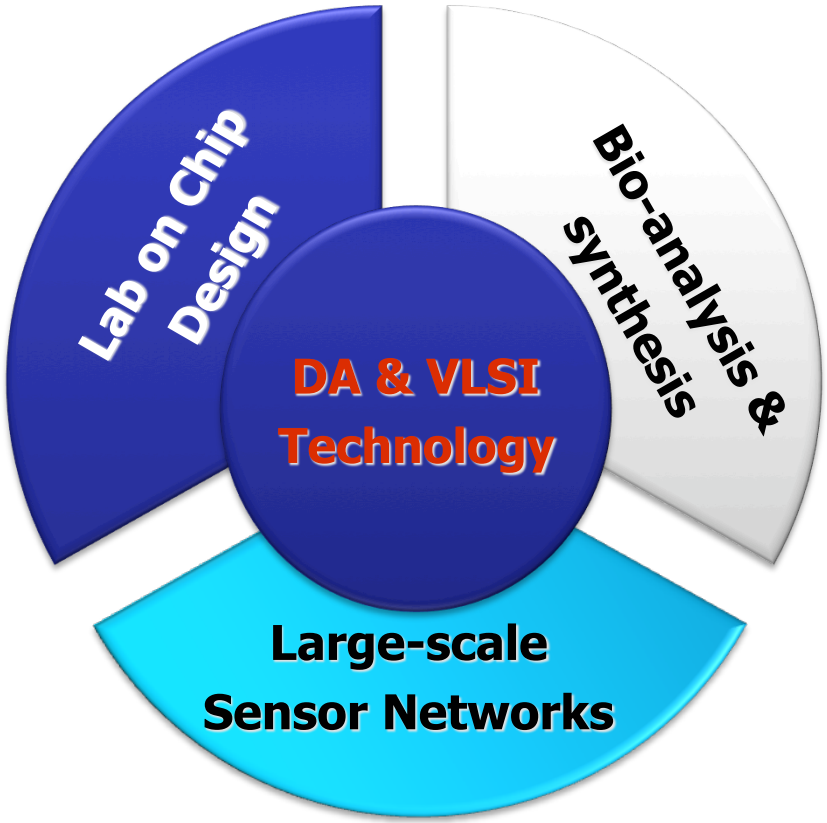
[RSC]

- Universal co-design

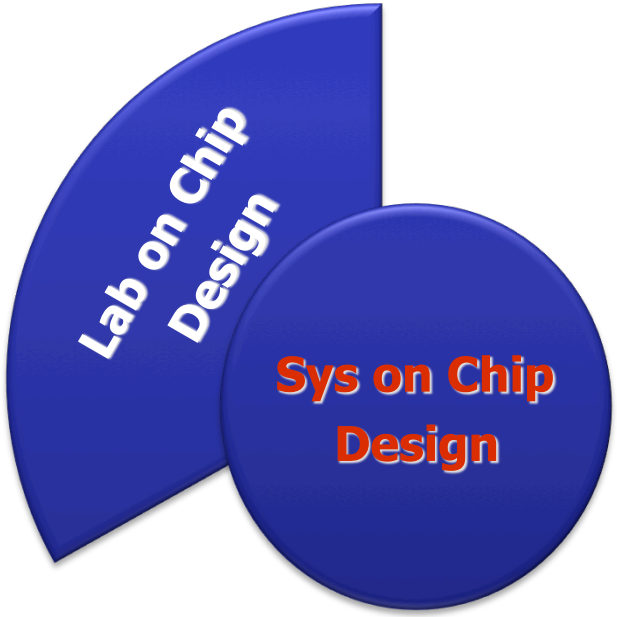
3D Biosystems integration



Electronic system evolution through three illustrative examples



Lab on Chip design

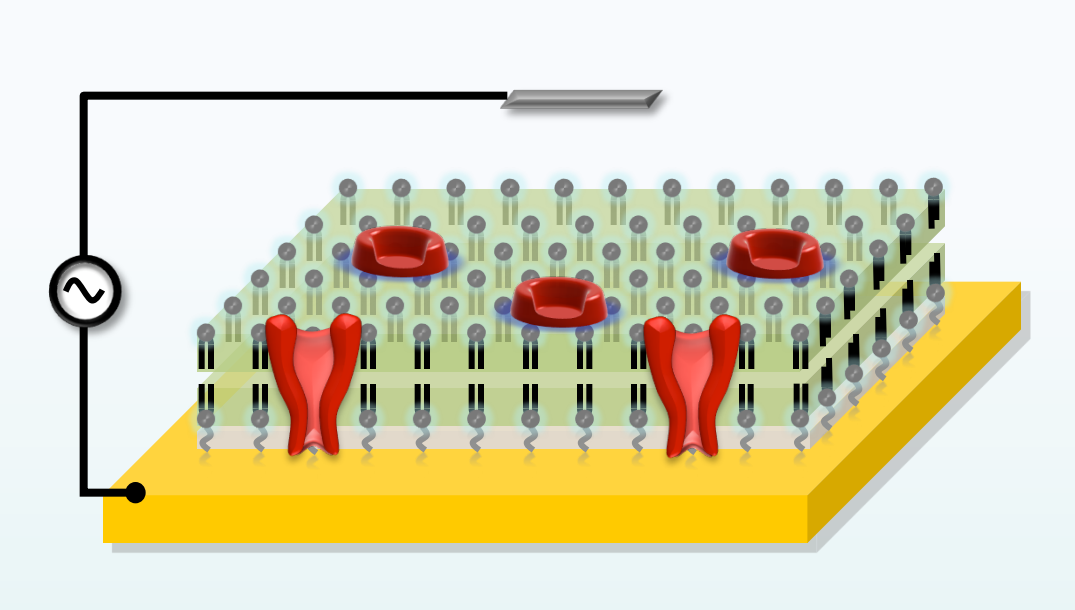


Computer-aided diagnosis (CAD?)

- *Lab on chip* at point of care
  - Perform biochemical test on the field
  - Faster, cheaper, more effective…
- How
  - The ultimate hybridization of technologies:
    - Microfluidics: sample transport
    - Sensors: binding proteins, DNA to probes
    - Low-noise electronics
    - Powerful data processing algorithms and software
- A promise of lab on chip is to revolutionize medical care and offer personalized medicine
- Lab on chips are instrumental in environmental monitoring

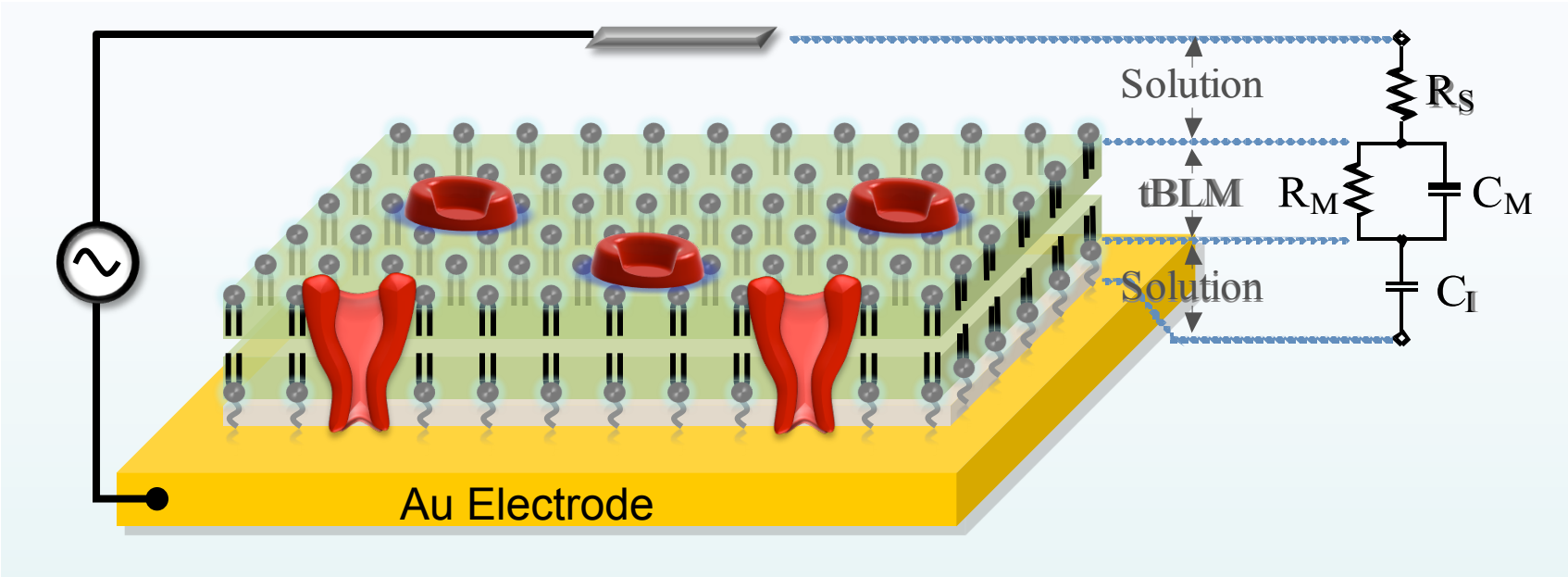
[STMicroelectronics]

Advanced integrated sensors



- Sense proteins, antibiotics
- Tethered bilayer:
  - Gold bottom electrode
  - Lipid bilayer
  - Ion channels
- Counter electrode in solution

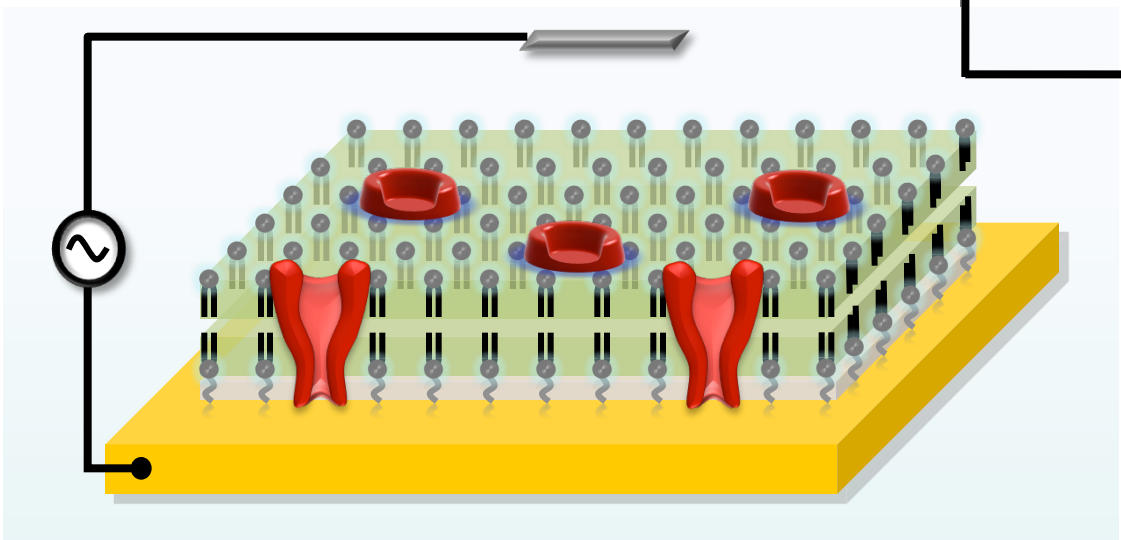
Equivalent electrical model

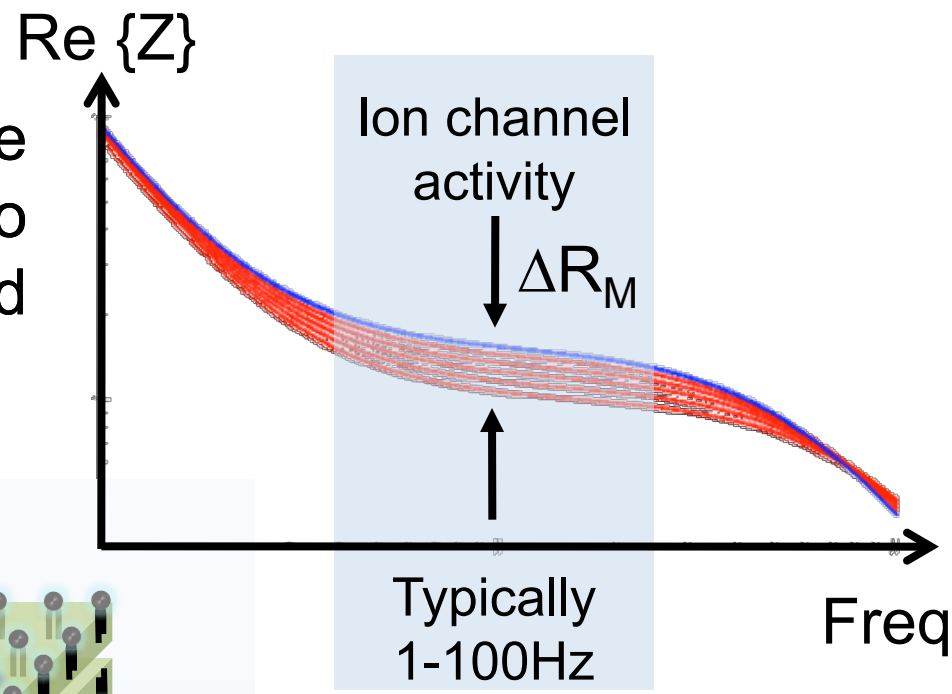


- $\mathbf{R_M}$ Bilayer resistance
- $\mathbf{C_M}$ Bilayer capacitance
- $\mathbf{C_I}$ Interface capacitance
- $\mathbf{R_S}$ Solution resistance

Modulation of membrane resistance

Modulation of the membrane resistance (R_M) is used to detect or quantify the ligand binding to an ion channel.

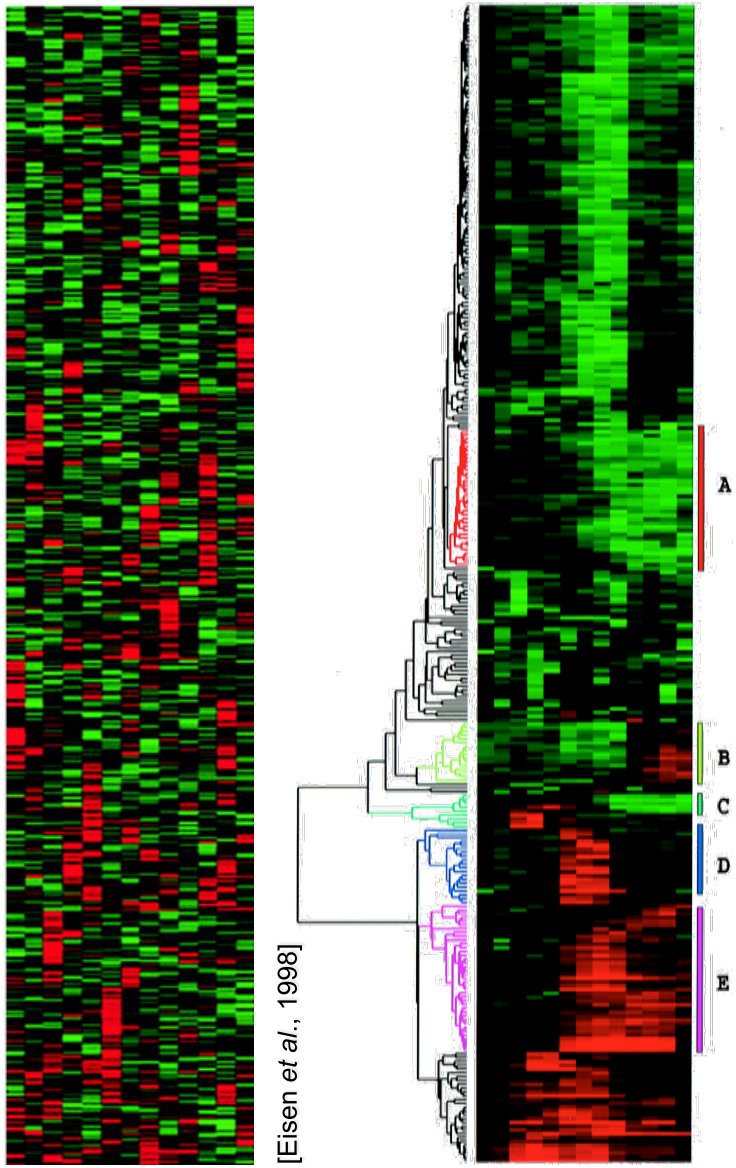




Increase in the Re{Z} as a function of concentration is seen at mid-frequencies

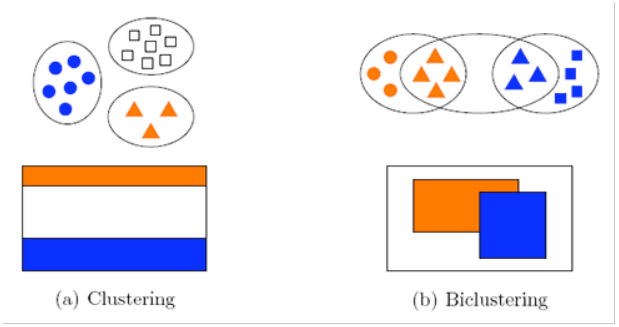
Data mining and interpretation

Data interpretation and clustering



[Eisen *et al.*, 1998]

- Grouping similar objects together
  - Detecting gene variations consistent with the sample choice
  - Inference of specific conditions
- Bi-clustering on large data sets
  - Simultaneous cluster of subsets of rows and columns
    - Gene and samples

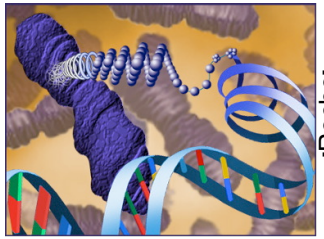


- Problem solved with ZDD technology
  - Fast and complete data interpretation

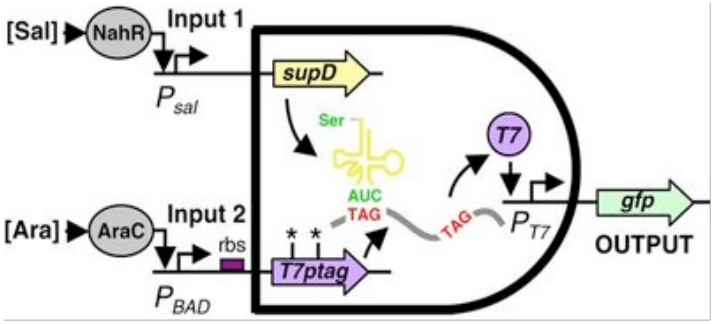
Bio analysis and synthesis

Analysis and synthesis

- Analysis - understand biological mechanisms
  - Comprehend in full the value of the *omics*
    - Genomics, proteomics, trascriptomics
- Synthesis - modify/create new realities
  - Synthesize drugs that alter genetic/metabolic pathways
    - Pharmacogenomics
  - Synthesize biological compounds that support computation
    - Synthetic biology



[Roche]

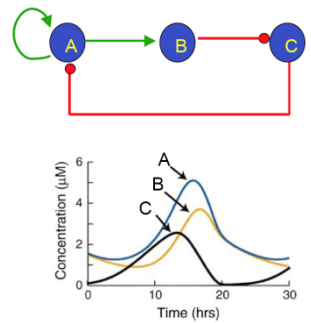


[UCSF,UCB]

- Multiple abstractions are needed for analysis and synthesis

Abstractions

- Bio-chemical abstraction
  - Event timing
  - Differential equation models

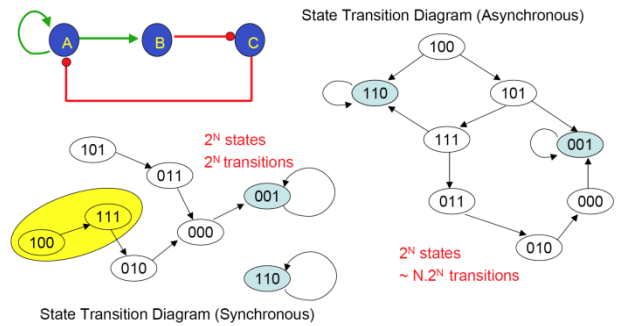


$$\frac{dx_a}{dt} = r_{aa}x_a + r_{ac}x_c - \gamma_a x_a$$

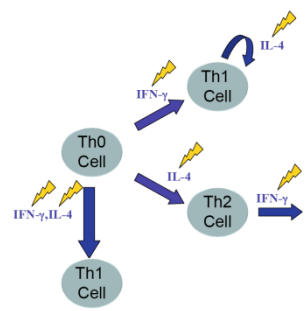
$$\frac{dx_b}{dt} = r_{ba}x_a - \gamma_b x_b$$

$$\frac{dx_c}{dt} = r_{cb}x_b - \gamma_c x_c$$

- Logic level abstraction
  - Zero-delay model
  - Finite-state system
    - Synchronous, asynchronous

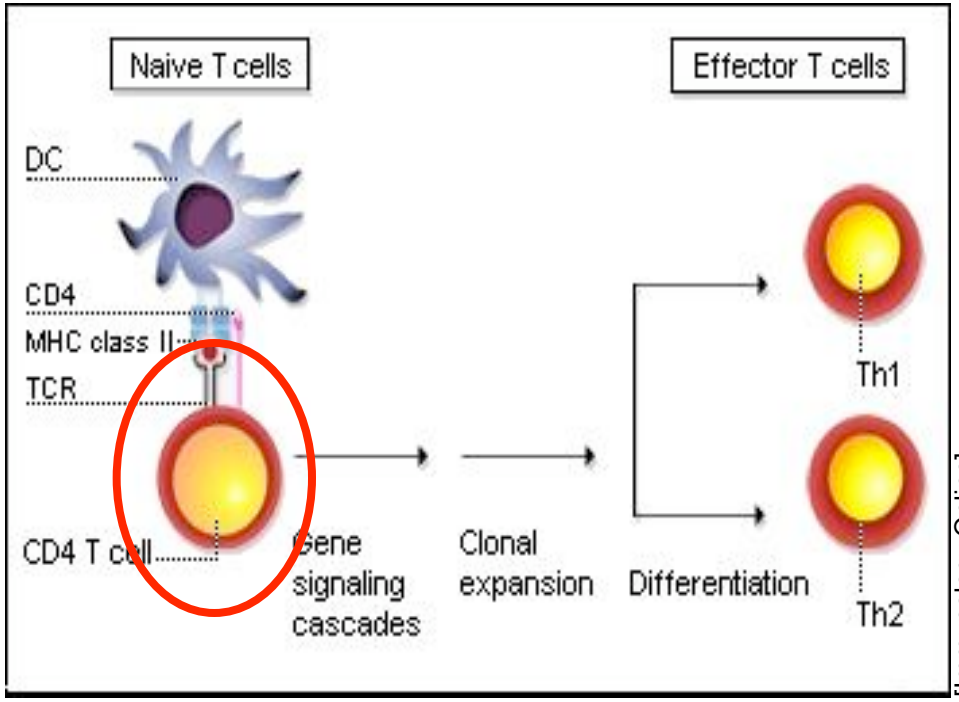


- Functional abstraction
  - Biological function
  - Input-output analysis



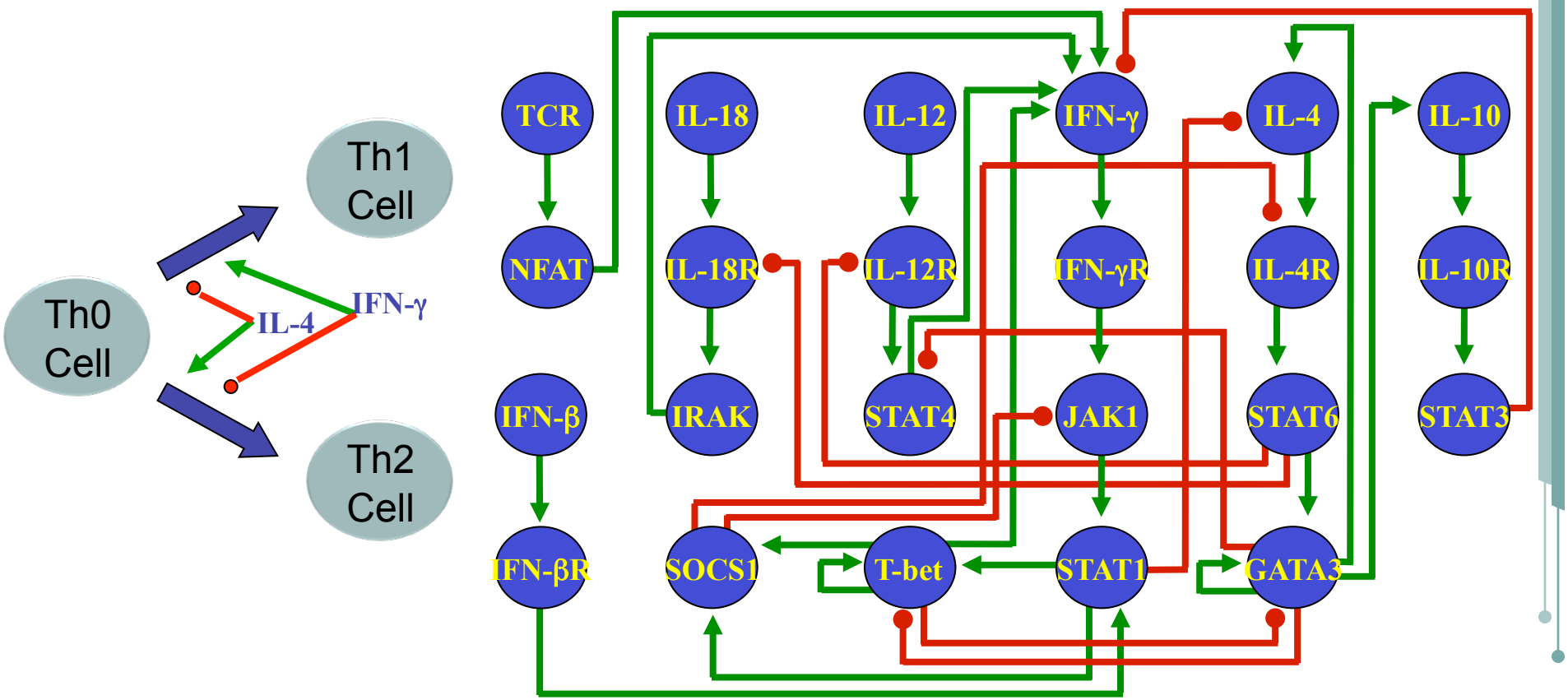
T-helper cells

- Observed behavior:
  - Precursor Th0 cells yield:
    - Effector Th1 cells
    - Effector Th2 cells
- Evolutions depends on specific gene expressions
- Evolution can be captured by a *gene regulatory network*



[Immunology Online]

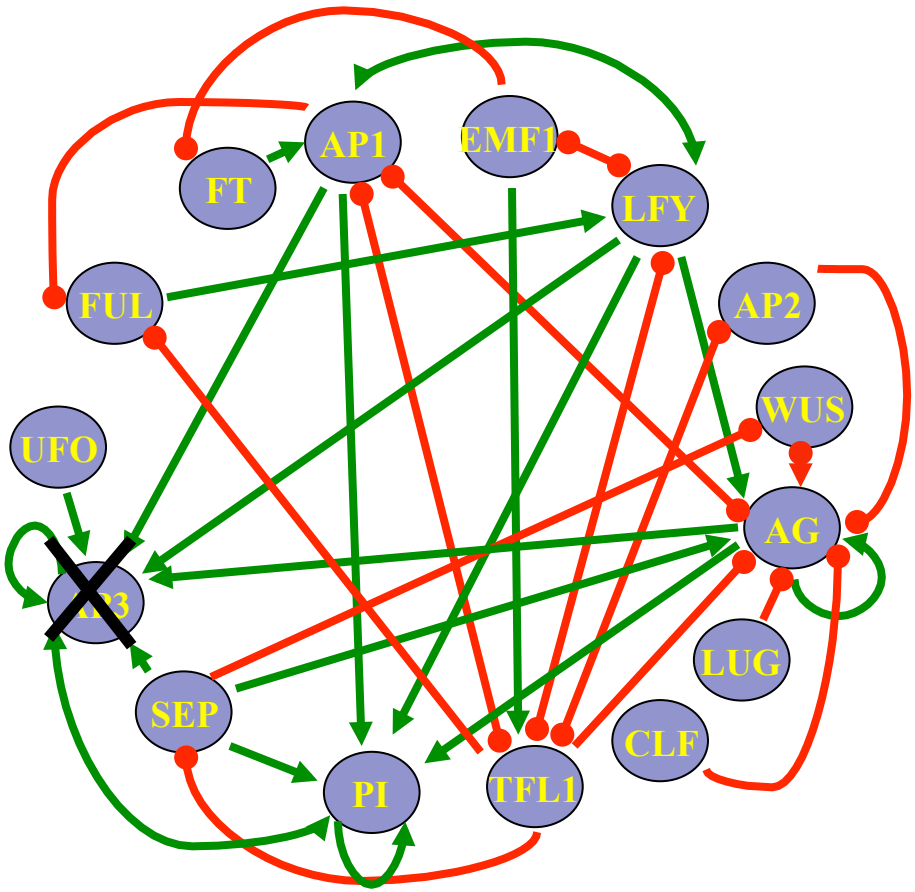
Functional and logic-level model of T-helper cell



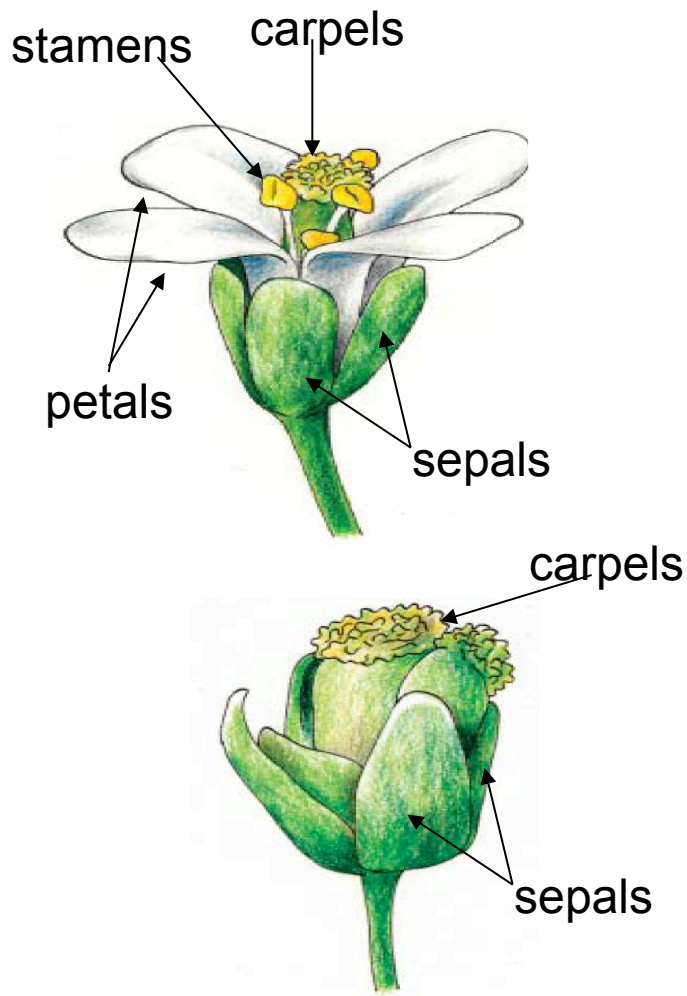
Issues

- Orthogonalization of concerns
  - Focus on terminal behavior independent from timing
- Simulation versus traversal
  - Steady state is often the objective
  - Implicit methods can handle large amount of data
- Modify system by perturbation
  - Knock-out experiment *in silico*
    - Silence a gene
  - Stuck-at 0 (déjà vu?)

Knock-out example: *Arabidopsis Thaliana*

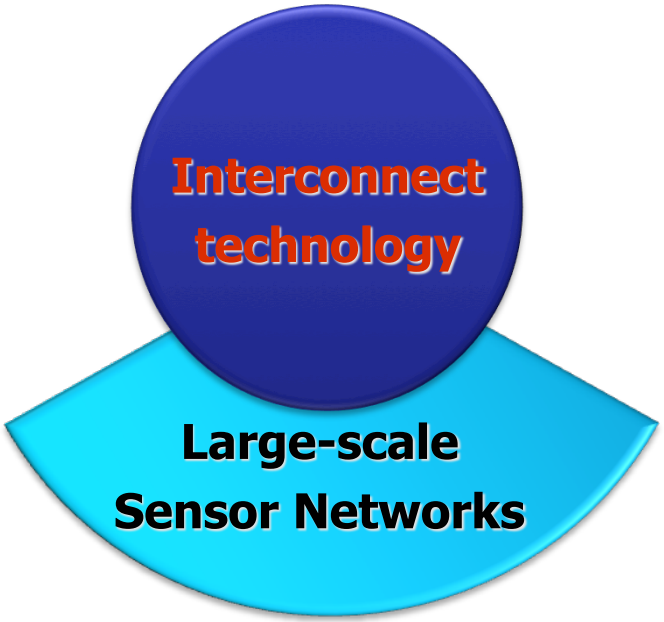


[Soto et.al. *Plant Cell*, (16):2004]



AP3 knockout

Environmental monitoring and control



The environment

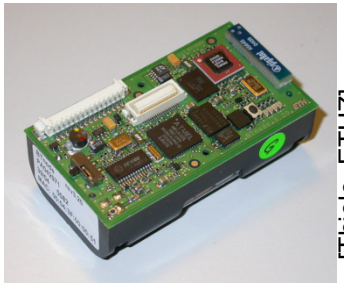
- We are embedded in the environment
  - Many inconvenient truths




- What are the challenges of wireless sensor networks to monitor/control the environment ?
  - Massive amount of data to process
  - Distributing and powering the nodes
  - Providing redundancy to tolerate local failures

Engineering environmental systems

- Integrated sensing, computation, communication and embedded software
  - Local vs. global data processing and communication
- The power of data abstraction
  - Data reduction and integration
- The distributed intelligence approach
  - Reason and act locally with (some) global information
  - New computational paradigms, as compared to classical supercomputer approaches



[Thiele, ETHZ]

The quest for energy efficiency

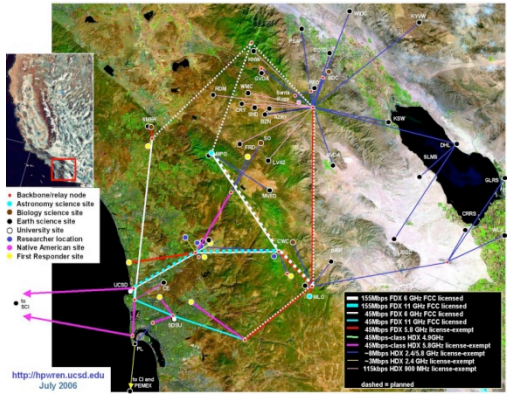
- Distributed wireless systems must (eventually) be autonomous
  - Energy harvesting from the environment
    - Mobile and fixed applications
  - Convert unused (degraded) energy into information
- Energy distribution systems must be efficient
  - Use information on the system to optimize energy distribution
    - Smart home, building, factory, …
    - Electric grid management
  - Convert information into energy savings
- Mutual interaction: energy ↔ information
  - Policies for run-time energy/information management will play a key role in system design

[Perpentum]


[Sandia]

Dependability, redundancy and connectivity

- Bio-circuits are distributed in the environment
  - Local sensing, processing and communicating



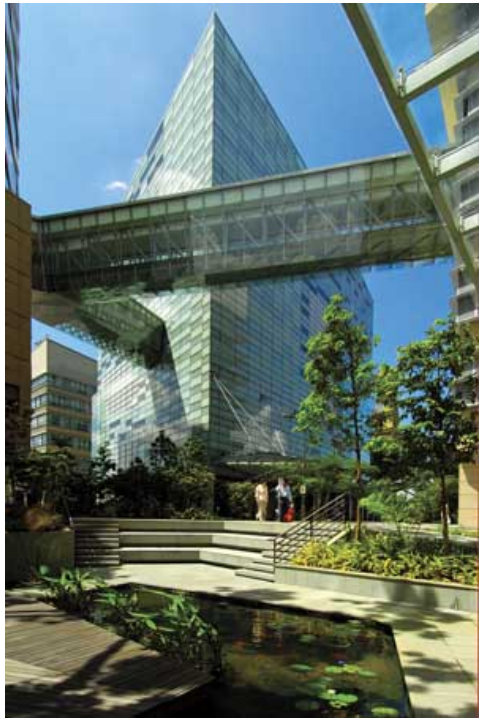
[HPWREN, UCSD]

- Dependability requires redundant components and links
  - Fault-tolerant HW, SW and communication
- Avoid system-level failure
  - Safety-critical applications

Cooperative engineering

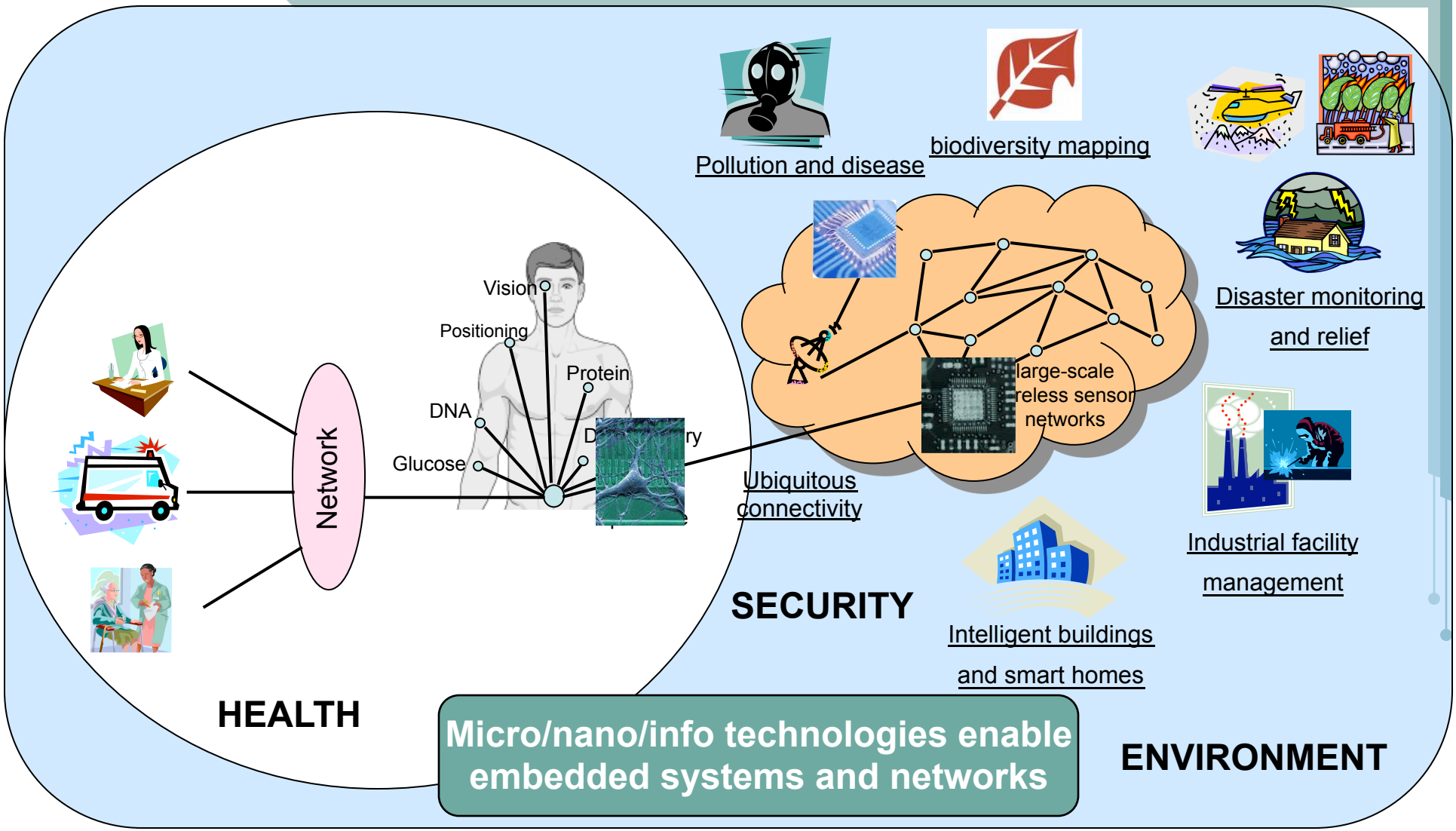
- Bringing together engineer/scientists/doctors with different skills
  - Communication and vocabulary
  - Abstraction and modularity
- Collaborative workspaces

[Stanford Clark Center]



[Singapore Biopolis]

The nano-tera.ch program



Summary

- The road ahead has challenges and rewards:
  - Expanding our horizon is key to scientific viability and commercial profitability
- We need heterogeneous hardware design and the corresponding software infrastructure
  - Product/system design is an extremely complex task, because of the variety of facets and technologies involved
- System-level design technologies are crucial for system conception, design and management
  - Progress leads us beyond advanced silicon chip design
  - Scientific and financial benefits will stem from the system/ service perspective

Thank you