Electrical Engineering at a Crossroad:

Challenges and Opportunities

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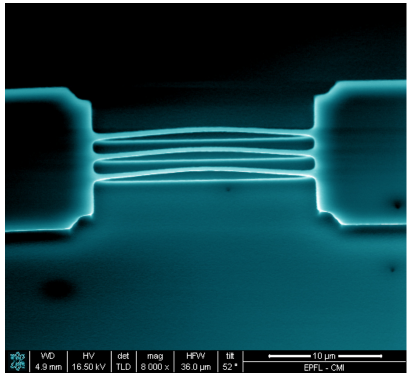
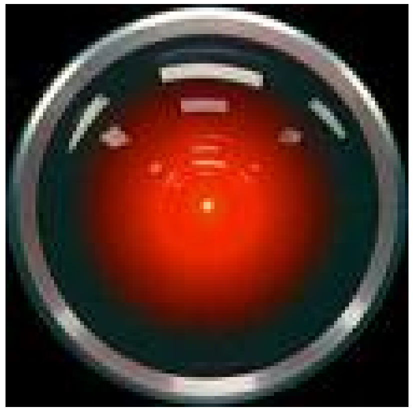
DEVICES
NANO-BIO
SYSTEMS

A minimalist view

- Electrical Engineers deal with:
- Devices:
  - The switch
  - The wire
  - The source
  - The storage
- Systems:
  - The power grid
  - Computers and Internet
  - Ubiquitous communication
  - Cyber-physical systems



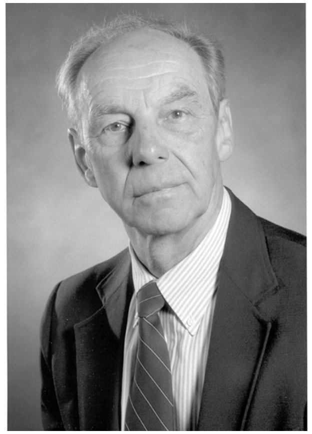


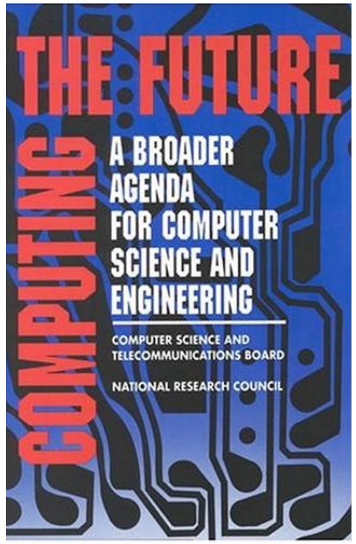
A first set of questions

- Is EE science or technology?
  - Is there space for fundamental research?
- Are system applications driven by the economy?
  - Is the research agenda driven by the economy?
- Are these the right questions to ask?

The case of Computer Science and Engineering

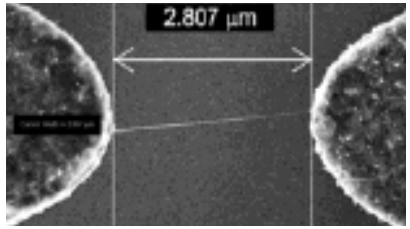
- The Hartmanis committee was asked to examine the fundamental nature of CS&E
- The Hartmanis committee reported:
  - *CS&E is coming of age*
  - *Intellectually challenging problems arise outside CS&E per se*
  - *The traditional separation of basic research, applied research and development is dubious*
  - *The ubiquity of computing places a premium on the widest diffusion – to be achieved via undergraduate education*
- The debate between *fundamental discipline* and *service discipline* inflamed researchers

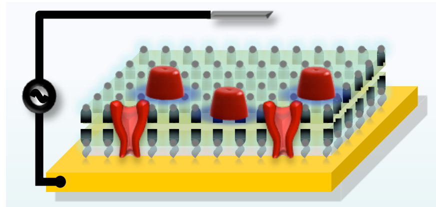




Looking for scientific novelty

- 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

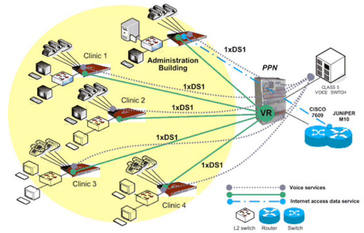
Looking for impact

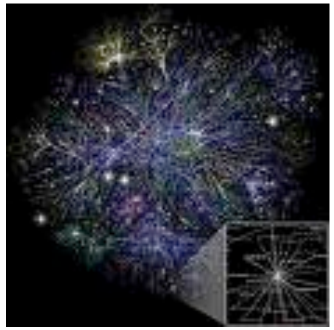
- The **economic and societal pull**:
  - World Economic Forum (Davos 10)
  - Improve the *State of the World*: Rethink, Redesign, Rebuild

- 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



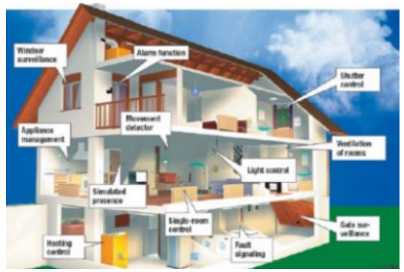


A first answer

- Electrical engineering must strike the balance between innovation and impact
  - New electrical phenomena
    - From photonics to electro-chemistry
  - Means to achieve societal/economic impact
    - From wireless to Internet
- Connectivity is the *paradigm*
  - Smart grid to deliver energy
  - Connecting humans to enhance wellness
  - Monitoring the planet
  - Providing security and mitigating risks

The drivers

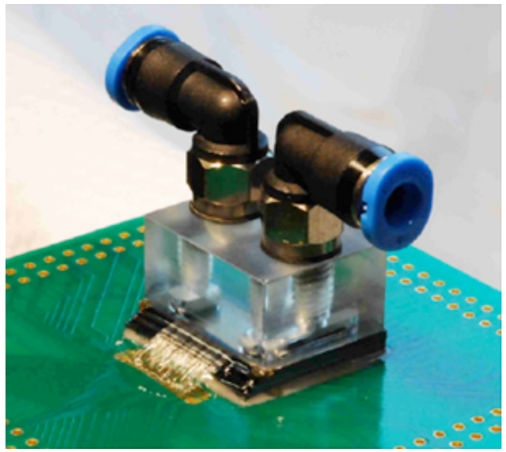
Smart energy


- 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*

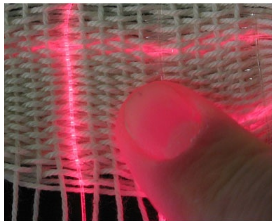
Example: data centers

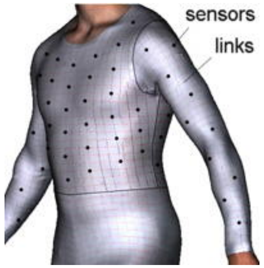
- Data centers are key to services like Google, Yahoo!, Microsoft…
  - Information is economic power
- Data centers consume 2-4% of world energy
  - Computation, storage and cooling
  - Localization of data centers
- Green data centers:
  - Dynamic power management
    - Hardware control and cooling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

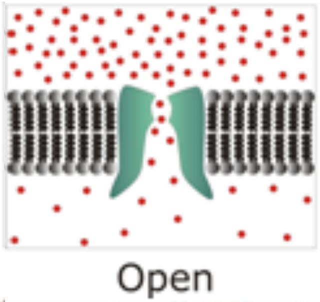


Electronic health

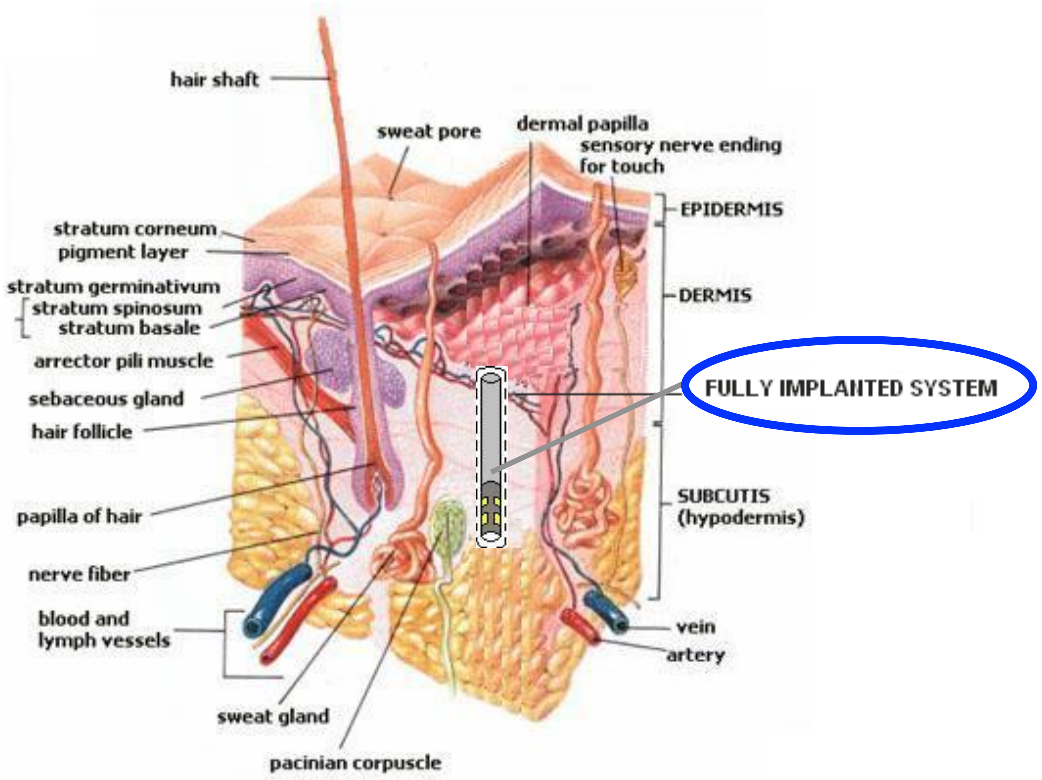
- Body monitoring
  - Biosensors
  - Body area networks
  - Smart textiles
- Clinical support
  - Remote diagnosis
  - Drug delivery
- Prevention
  - Monitoring nutrition
- *Challenges:*
  - *Non-invasiveness*
  - *Safety and security*
  - *Autonomy and adaptation*

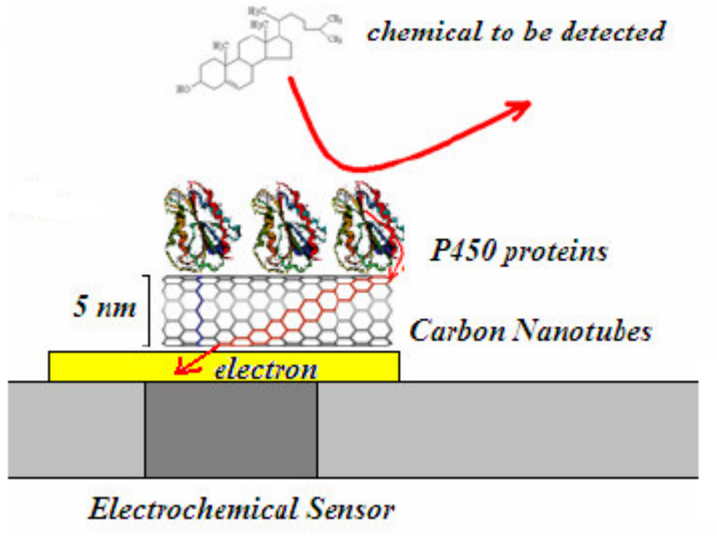


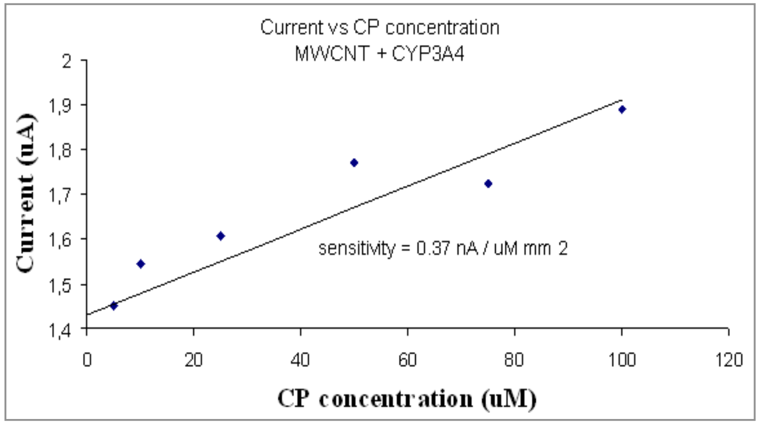




Example: smart implants

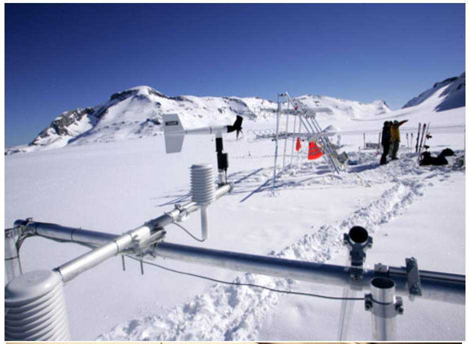




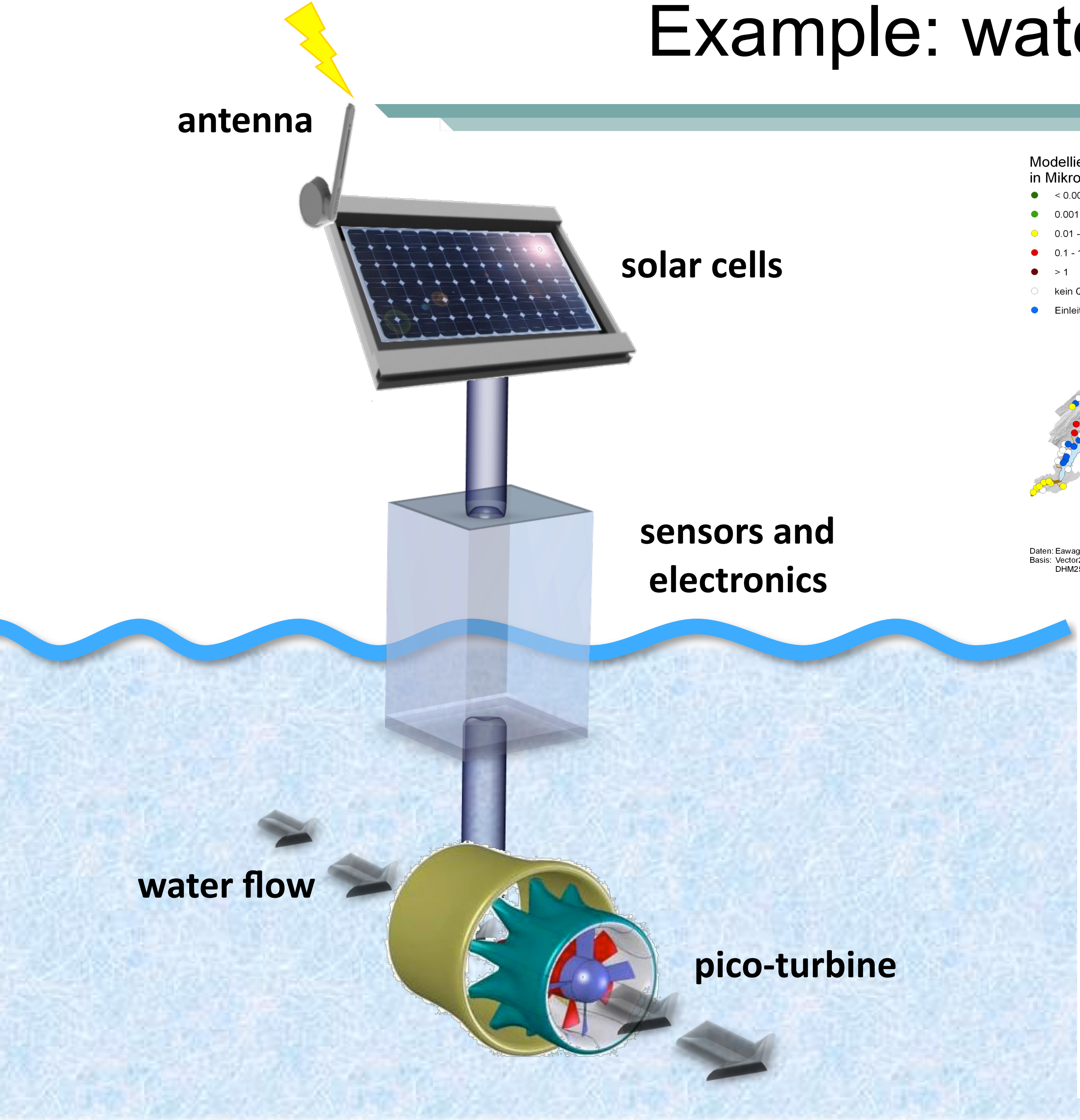


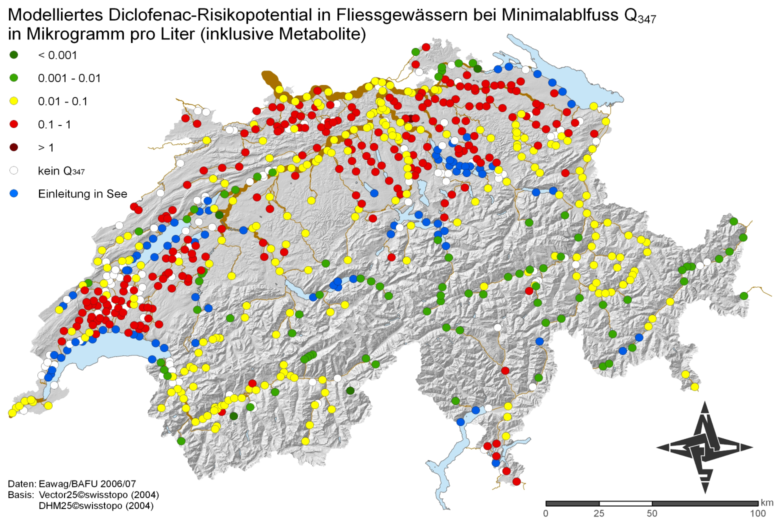
Environment

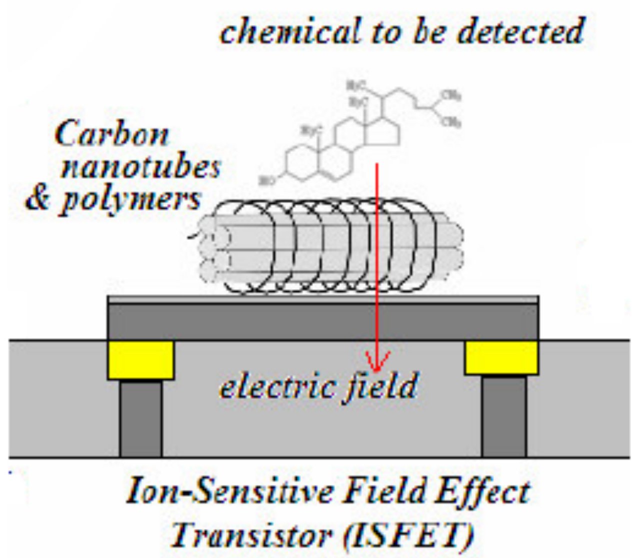
- Monitoring heat, wind, vibration
  - Earthquake, flood prediction
  - Movement of glaciers
- Controlling pollution
  - Water, air purity
  - Bio-contamination
- Emergency relief control
  - Real time support for reaction
- *Challenges:*
  - *Seamless presence*
  - *Biodegradability*
  - *Autonomous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



Example: water purity



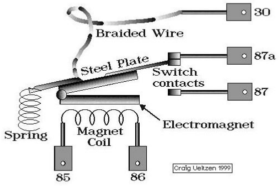


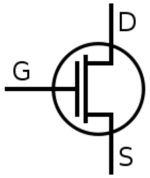


The technology

The technology support

- The switch
  - The link between information science and electronics
  - Relay
  - Triode
  - Transistor
  - CNT nano-mechanical switches

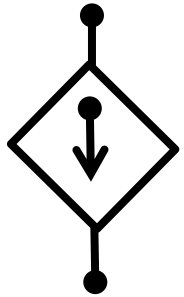


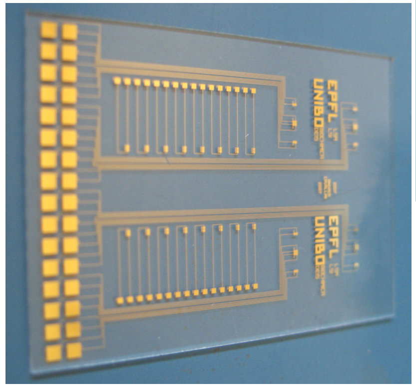


- *Challenges:*
  - *Cutoff frequency:* f_{cut}
  - *Leakage:* I_{on}/I_{off}
  - *The coupling gain:* g_m

Transconductance and transductors

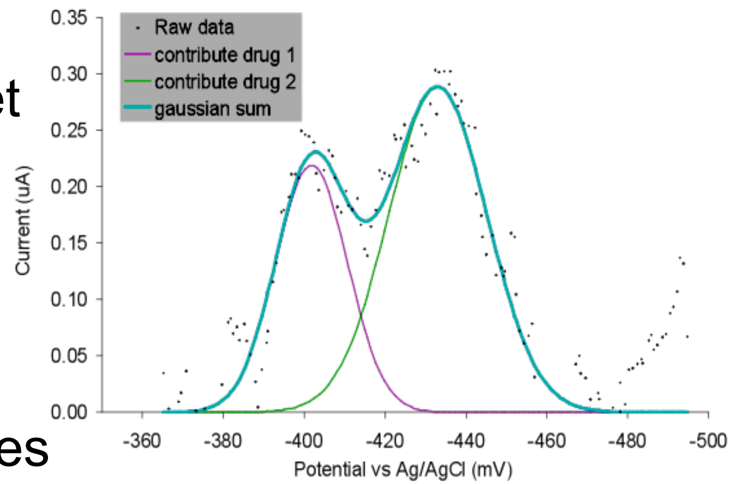
- Transconductance sensors
  - Map target concentration into current
- Example:
  - DNA, protein, pH, gas, etc
  - Semiconductor devices can be extended to sense a wide set of targets
- *Challenges:*
  - *Sensitivity*
  - *Specitivity*
  - *Reliability, energy cost, parallelism*





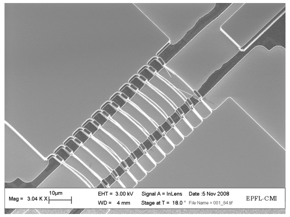
Smarter, better sensors

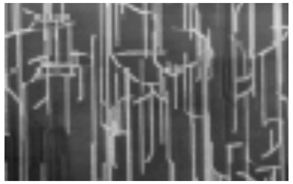
- Evolution in sensor field:
  - From single target to multi-target
  - From static to portable
    - Low-power sensing
    - Couple bio-chemistry to data acquisition
  - Use parallel sensing architectures
- Integrate *in situ* data processing
- Co-design of sensors within *wireless sensor networks*

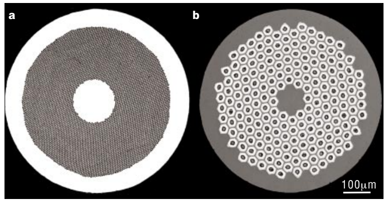


The wire

- From nanowires to terawires
- Nanowires:
  - Silicon, CNT and other materials
  - Top down and bottom-up fabrication
- Terawires
  - Materials for electric power lines:
    - High T_c superconductors
- *Challenges:*
  - *Interfaces to the very small and very large*
  - *Matching voltage, current, impedence*
  - *Integrate transport with switching*

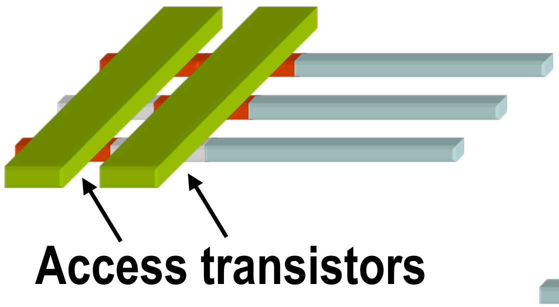


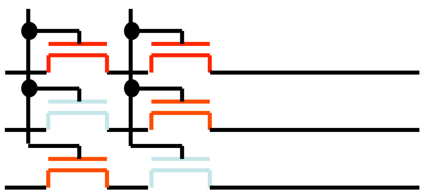


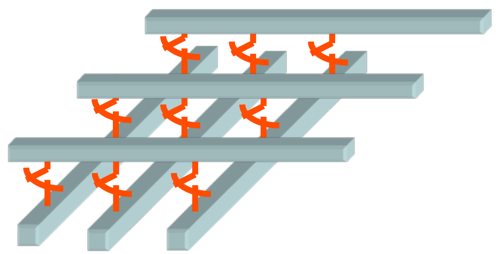


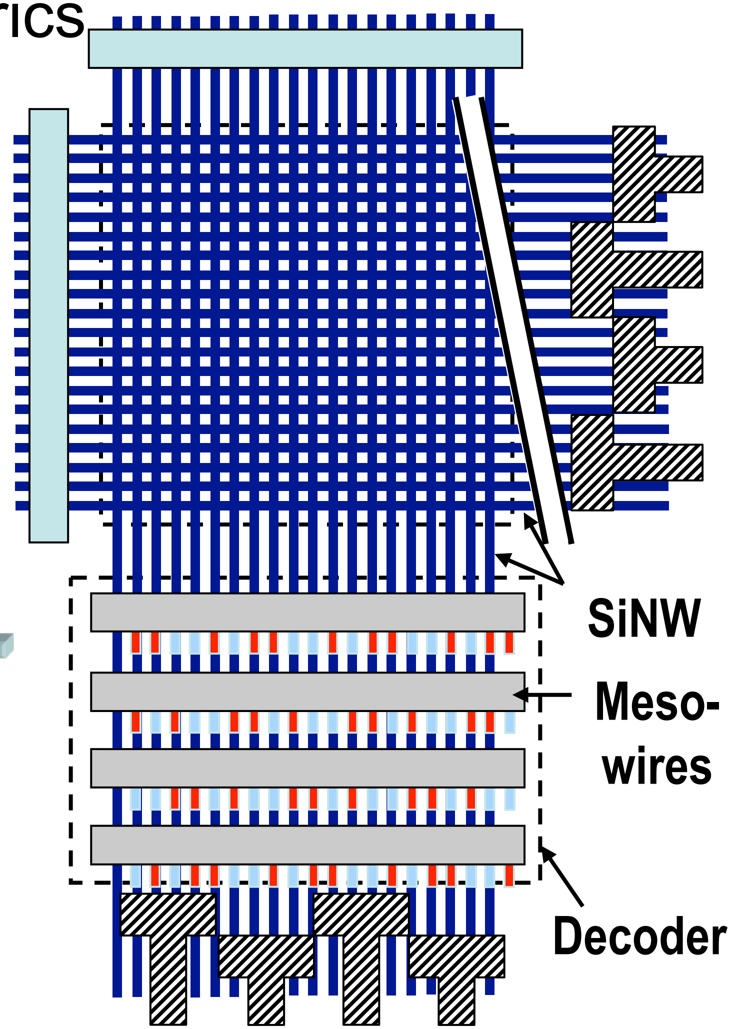
Example: integrate wires and switches

- Regular computational fabrics
  - Predictable timing
  - Fast design closure

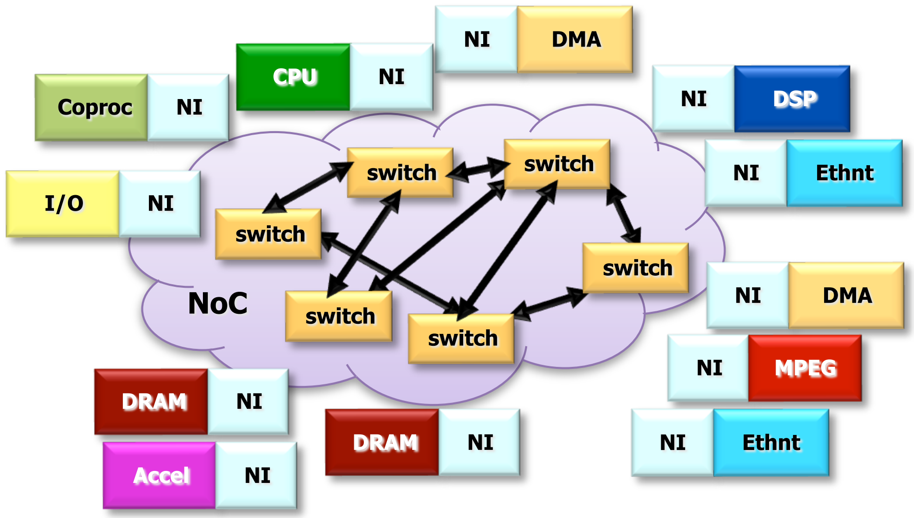






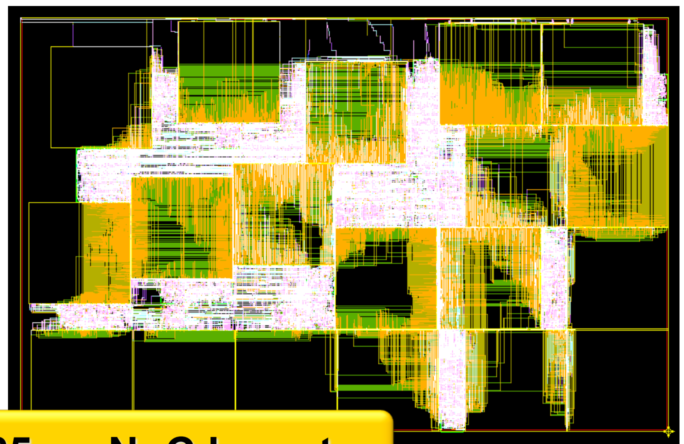


Modular on-chip communication fabric



Advantages:

- Easier physical desing
- Guaranteed timing closure
- Higher bandwidth
- Lower power consumption



65nm NoC layout

Challenges:

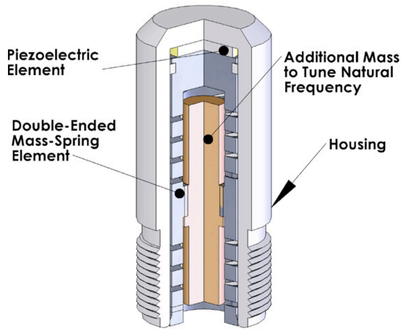
- DVFS / multiple domains
- 3D stacked NoCs
- Topology design
- Quality of Service

The source

- Electric power is always in demand
  - 15TW total power consumption
  - Environmental and distribution issues are the limit
- Fixed systems:
  - Energy cost, heat, environmental issues
- Mobile systems:
  - Longevity, battery limitations, weight
- *As demand for information and services increases, we need to raise the efficiency of electrical production, transport and consumption*

Non-conventional sources

- Energy harvesting
  - Mechanical
  - Heat difference
  - Solar



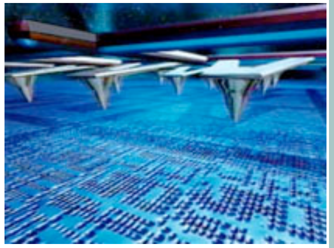
- Power transmission
  - Use magnetic or electromagnetic coupling
  - Transmit data and power
- *Challenges:*
  - *Harvesters generate 10-100X less energy than needed*
  - *Increasing amount of EM radiation*
  - *Fluctuation of available energy*

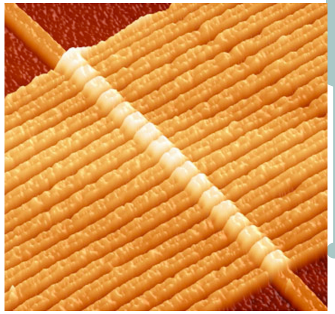
Energy storage

- Large-capacity energy storage
  - Good solutions for hydroelectric energy
  - Other approaches include thermal and compressed air
- Portable energy storage
  - New battery technologies, e.g., semiconductor
  - Hydrogen cycle
  - Supercapacitors provide effective solutions at low voltages
- *Challenges:*
  - *A spectrum of solutions for storing various capacities*
  - *Storage capacity improvement lags energy demands*
  - *Dynamic power management*

Data storage

- Information technology requires massive data storage
  - DRAM, Flash, hard disks, optical storage
- Novel materials
  - Phase change and ferroelectric memories
  - Millipede technology
- Novel devices
  - Memristor (Polymers, TiO_2)
- *Challenges:*
  - *High density, low power, low cost*
  - *Pushing the limits of semiconductors*
  - *Interfacing with data processing*





Back to the key question

- Is EE a *service* or a *fundamental discipline*?

A better answer

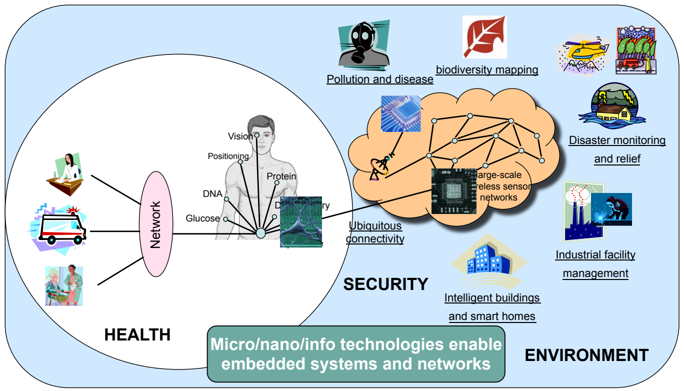
- EE involves a rich set of technological issues
  - New devices exploit new physical phenomena
  - Much space is still left for scientific discovery
- Application areas address societal needs
  - Impact of EE technologies is increasingly stronger
  - We need a systems view of electronic devices
- Discipline crossbreeding favors new discoveries
  - New scientific areas at the intersection of disciplines
  - **No distinction between service and fundamental discipline**
- What else ?

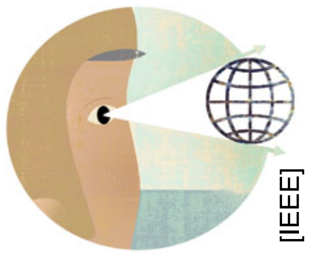
Education

- Form electrical engineers who master both:
  - The standard electrical technologies
  - Holistic view of systems engineering
- Attract, retain and retrain engineers
  - A hard challenge for western cultures
  - Gender gap
- Redesign curricula driven by applications
  - Share educational load across campuses

Cooperative engineering

- Bringing together engineers/scientists/doctors with different skills
  - Communication and vocabulary
  - Abstraction and modularity
- Collaborative programs and centers





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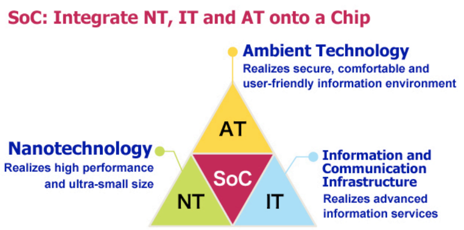

Conclusions

- Are we really at a crossroad?
  - EE provides the *enabling technology* for developing *systems applications*
  - There are many growth paths which are intellectually and financially rewarding
- We need to foster technology crossbreeding of EE
  - Computational, communication and natural sciences
- Research and education must evolve
  - Form graduates with both deep and broad knowledge
  - Collaborative research and educational structures must bridge the gap among traditional disciplines

Thank you