Nanosystems for a healthier and safer tomorrow

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What direction for electronic research?

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

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

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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

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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

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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

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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

- antenna
- solar cells
- sensors and electronics
- water flow
- pico-turbine

Modelliertes Diclofenac-Risikopotential in Fließgewässern bei Minimalabfluss Q_min in Mikrogramm pro Liter (inklusive Metabolite)
- < 0.001
- 0.001 - 0.01
- 0.01 - 0.1
- 0.1 - 1
- > 1

chemical to be detected

Carbon nanotubes & polymers

Ion-Sensitive Field Effect Transistor (ISFET)
The way ahead

Systems on Chips
Technology, architectures, integration

Distributed systems
Embedded systems on chip
Heterogeneity, connectivity, human
Requirements for electronic chip design

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

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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?

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

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New computational structures

- Computation requirements
  - Predictable design
  - Fast design closure

- Array based computation
  - Matching *nano* and *micro*

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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

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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
Heterogeneous integration

- Electrical and mechanical parts
  - Microactuators, scavengers, microfluidics

- Electronics meets the living world

- Universal co-design

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3D Biosystems integration

- Nano-structures
- Microfluidics
- Biosensors
- Analog Front-end
- Digital Post Processing
- Memory

1000-10000 nm
90-600 nm
45-180 nm
45-90 nm

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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
Advanced integrated sensors

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

- $R_M$ Bilayer resistance
- $C_M$ Bilayer capacitance
- $C_I$ Interface capacitance
- $R_S$ 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.

Ion channel activity

Typically 1-100Hz

Re {$Z$}

Freq
Data mining and interpretation
Data interpretation and clustering

- 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, transcriptomics

- Synthesis - modify/create new realities
  - Synthesize drugs that alter genetic/metabolic pathways
    - Pharmacogenomics
  - Synthesize biological compounds that support computation
    - Synthetic biology

- Multiple abstractions are needed for analysis and synthesis
Abstractions

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

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

- **Functional abstraction**
  - Biological function
  - Input-output analysis

\[
\begin{align*}
\frac{dx_a}{dt} &= r_a x_a + r_a x_c - \gamma_a x_d \\
\frac{dx_b}{dt} &= r_b x_a - \gamma_b x_d \\
\frac{dx_c}{dt} &= r_c x_b - \gamma_c x_c
\end{align*}
\]
T-helper cells

- Observed behavior:
  - Precursor Th0 cells yield:
    - Effector Th1 cells
    - Effector Th2 cells
  - Evolutions depend on specific gene expressions
  - Evolution can be captured by a gene regulatory network
Functional and logic-level model of T-helper cell

Th0 Cell

IFN-γ

IFN-β

IFN-βR

SOCS1

TCR

IL-18

IL-18R

NFAT

IFN-γ

IL-18R

NFAT

IL-12

IL-12R

JAK1

IFN-γR

IL-4R

IL-12

IL-18

IL-18R

IFN-γR

IFN-βR

STAT4

JAK1

STAT6

STAT3

TPR

IL-4

IL-4R

IL-10

IL-10R

STAT1

GATA3

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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*
Environmental monitoring and control

Interconnect technology

Large-scale Sensor Networks

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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
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
Dependability, redundancy and connectivity

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

- 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
The program

Micro/nano/info technologies enable embedded systems and networks

HEALTH

SECURITY

ENVIRONMENT

Pollution and disease
Biodiversity mapping
Ubiquitous connectivity
Large-scale wireless sensor networks
Disaster monitoring and relief
Industrial facility management

VISION
Blood pressure
Positioning
DNA
Glucose

PROTEIN

NETWORK

HEALTH

ENVIRONMENT
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