Panel Session
Design Tools for 'Beyond CMOS' Technologies

Statement

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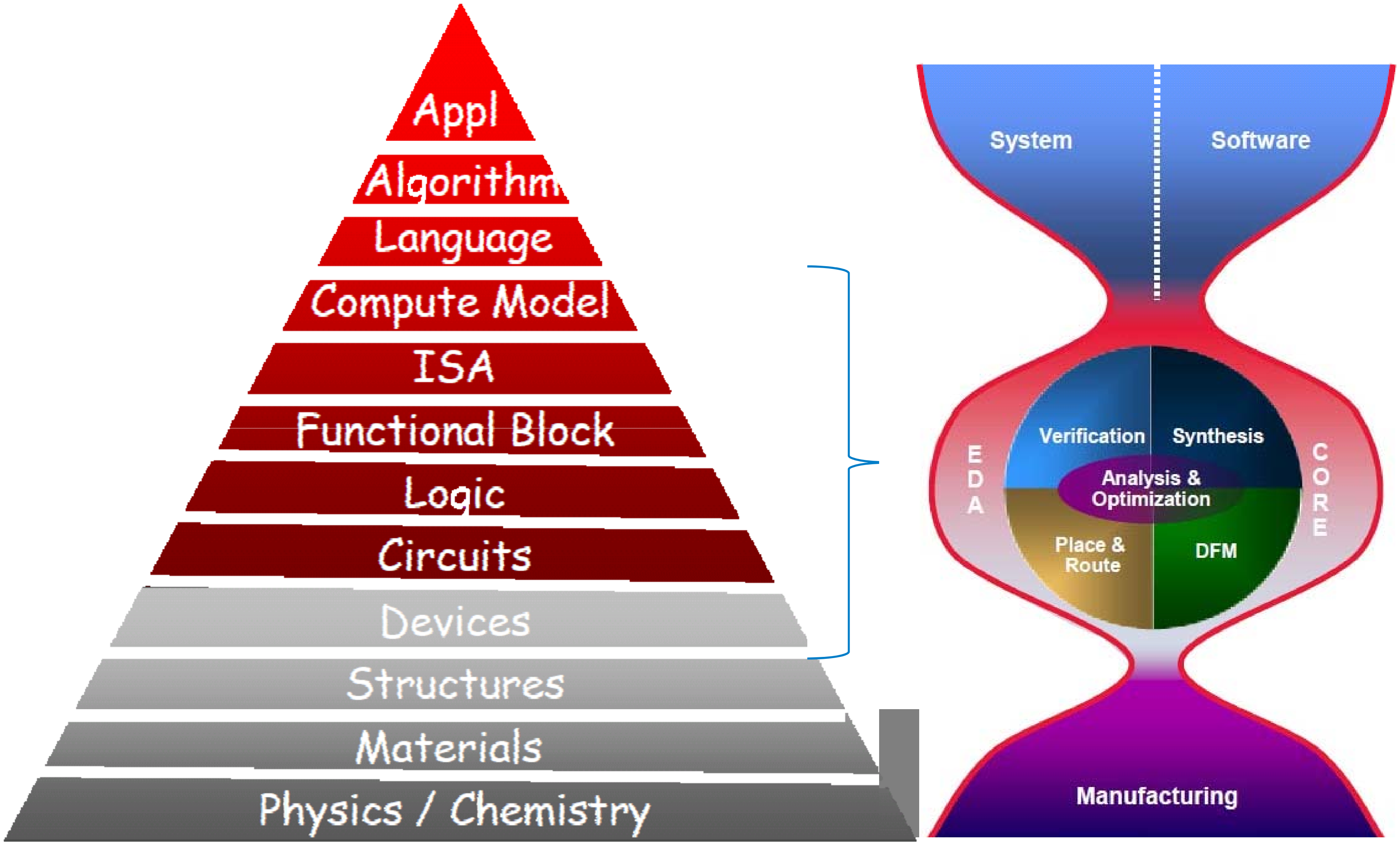
Design Tools Exist Mainly for CMOS



Source: R. Rutenbar, 2010

Today‘s design facilities in ‚Beyond CMOS‘

At present:

(i) A variety of nanodevices can be reliably fabricated using various materials, technologies and processes.

(ii) Several open questions still exist concerning the mode of operation of such devices.

(iii) Modeling and simulation is necessary for better understanding of these devices.

(iv) A multi-scale approach is needed in order to describe real systems.

(v) Novel circuits, architectures and design methodologies are needed for a full exploitation of nanodevices.

(vi) Education is far away from teaching a new generation of designers who know about nanodevices and related technology.

To design for future applications using new 'Beyond CMOS' technologies we need …

(i) **models and abstractions** at all levels of the design process as a key issue

(ii) **compatibility and integratability** to existing industry design standards if the technology should be connected with CMOS.

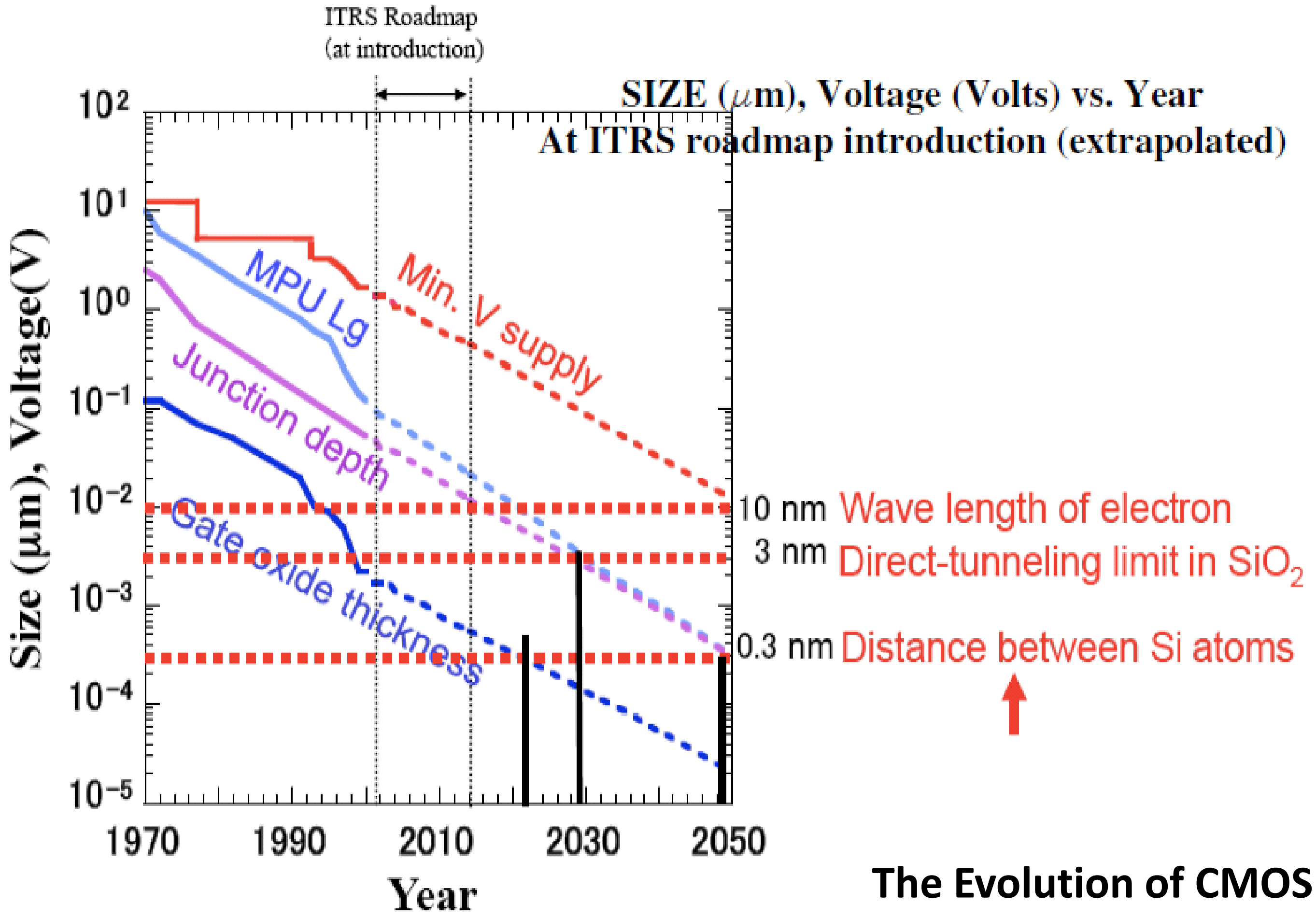
(iii) **new system-level design methodologies** taking into account Beyond CMOS technologies to increase the productivity of designers, otherwise efficient use cannot be made of advanced devices and materials.

(iv) **robust optimization methodologies** in the middle of the design process, to provide guaranteed performance of integrated systems composed of devices with high **variability** and uncertain **reliability**.

(v) **design for manufacturing** to support the design of high-yield systems that obtain maximum utilization of a technology and to assure that products can be produced using new technologies.

(vi) **design tools for the 'Beyond CMOS' devices** with multi-physics and multi-scale characteristics. Without proper tools the true exploitation of the emerging devices in ICT will become extremely difficult or even impossible.

The "Brick Walls" imposed to Silicon Scaling



The Evolution of CMOS Technology

The minimum supply voltage, oxide thickness and junction depth.
Comparison to basic physical limits – electron wavelength in conduction-band and distance between silicon atoms [Hiroshi, I.].

Publications on Design Tools for Beyond CMOS (I)

[01.] Extending the road beyond CMOS, JA Hutchby, GI Bourianoff, VV Zhirnov - Circuits and Devices, 2002

[02.] High-performance CMOS variability in the 65-nm regime and beyond, K. Bernstein, D. J. Frank, et al., 2006

[03.] Specifications, methodologies, and results of evaluation of optical critical dimension scatterometer tools at the 90nm CMOS technology node and beyond, Benjamin D. Bunday ; Amy Peterson ; John A. Allgair, 2005

[04.] Design and CAD challenges in 45nm CMOS and beyond, DJ Frank, R Puri, D Toma - Computer-Aided Design, 2006

[05.] Beyond CMOS: quantum devices, J Gautier - Microelectronic engineering, 1997

[06.] Beyond CMOS-benchmarking for future technologies, S Torres, J Ahopelto, MWM Graef - Automation & Test, 2012

[07.] Metrology and Characterization Challenges for Emerging Research Materials and Devices, CM Garner, D Herr, Y Obeng - AIP Conference Proceedings, 2011

[08.] Challenges and Emerging Technologies for System Integration beyond the End of the Roadmap of Nano-CMOS, S Bampi, R Reis - VLSI-SoC: Technologies for Systems Integration, 2011

[09.] Design perspectives on 22nm CMOS and beyond, S Borkar - Design Automation Conference, 2009. DAC'09. 2009

[10.] TAMTAMS: A flexible and open tool for UDSM process-to-system design space exploration, M Vacca, M Graziano, D Demarchi… - Ultimate Integration on …, 2012

[11.] A physical design tool for carbon nanotube field-effect transistor circuits, J Huang, M Zhu, S Yang, P Gupta, W Zhang… - ACM Journal on

[12.] Design tools for the 3D roadmap, L McIlrath, W Ahmed, A Yip - 3D System Integration, 2009

[13.] Design for manufacturability: Then and now, AB Kahng - IEEE Design and Test of Computers, 2011

[14.] Great challenges in nanoelectronics and impact on academic research: more than Moore or beyond CMOS?, R De Keersmaeker, M Roukes, D Antoinadis, DATE '10 Proc. Conf. on Design, Automation & Test in Europe, Pages 1677-1677

[15.] Challenges and Emerging Technologies for System Integration beyond the End of the Roadmap of Nano-CMOS, Sergio Bampi und Ricardo Reis

[16.] Design and simulation of 2-D 2-dot quantum-dot cellular automata logic, LR Hook, SC Lee - Nanotechnology, IEEE Transactions on, 2011

Publications on Design Tools for Beyond CMOS (II)

[17.] Design Technology for Heterogeneous Embedded Systems von Gabriela Nicolescu, Ian O'Connor und Christian Piguet von Springer Netherlands (16. November 2011), ISBN: 978-9400711242

[18.] Nanoelectronic dynamically reconfigurable FPGA design and design automation, W Zhang - 2010 - BUCH

[19.] Challenges for nanoscale MOSFETs and emerging nanoelectronics, YB Kim - Trans. Electr. Electron. Mater, 2010

[20.] More-than-Moore white paper, W Arden, M Brillouët, P Cogez, M Graef, B Huizing... - Version, 2010

[21.] Device and architecture outlook for beyond cmos switches, K. Bernstein, R. Cavin, W. Porod, A. Seabaugh, and J. Welser

[22.] EuroTraining-Supporting University Programmes in Nanoelectronics, IR Nielsen, E Bruun - European Workshop on ..., 2010

[23.] Survey of new trends in Industry for Programmable hardware: FPGAs, MPPAs, MPSoCs, Structured ASICs, eFPGAs and new wave of innovation in FPGAs, SZ Ahmed, G Sassatelli, L Torres - Logic and Applications, 2010

[24.] TCAD: present state and future challenges, T Ma, V Moroz, R Borges, L Smith - Electron Devices Meeting, 2010

[25.] When More Moore meets More than Moore and Beyond CMOS, Enrico Sangiorgi, Presentation

[26.] Graphene for Beyond CMOS Devices, Luigi Colombo and Rodney S. Ruoff, white paper, The University of Texas at Austin, Austin, TX 78712-0292

[27.] Variable temperature Raman microscopy as a nanometrology tool for graphene layers and graphene-based devices, I. Calizo, F. Miao, W. Bao, and C. N. Lau, A. A. Balandina, APPLIED PHYSICS LETTERS 91, 071913 (2007)

[28.] Research directions in beyond CMOS computing, George I. Bourianoff, Paolo A. Gargini, Dmitri E. Nikonov, Elsevier, Solid-State Electronics 51 (2007) 1426-1431

[29.] Molecular Electronics: Devices, Systems and Tools for Gigagate, Gigabit Chips, Michael Butts, Andre DeHon, Seth C. Goldstein, International Conference on Computer-Aided Design, November 2002 (ICCAD'02)

[30.] The future of nano-computing, George Bourianoff, Presentation to International Engineering Consortium and Electrical and Computer Engineering Department Heads, Jan. 27, 2003

[31.] The Physical Implementation of Quantum Computation, David P. DiVincenzo, Journal on Quantum Physics, arXiv:quant-ph/0002077v3 13 Apr 2000

[32.] Beyond the silicon roadmap, Neil Mathur, NATURE|VOL 419 | 10 OCTOBER 2002

Electronic Design Automation Tools for Beyond CMOS

Not many tools for Beyond CMOS…

- ASTRAN (by Instituto de Informatica, Porto Allege, Brazil, 2007)
  - Tool to generate full layouts of stacked transistors from its transistor level netlist in SPICE format
- TAMTAMS (by Politecnico di Torino, Italy, 2012)
  - Tool to predict system level features starting from technology variables
- 2-D 2-DOT SIMULATION DESIGN TOOL (by Hook, Lee,2010)
  - Approach to QCA (Quantum-dot Cellular Automata) circuit design improves the design and simulation reliability by reducing the total number of electrons and quantum dots in circuitry starting from technology
- TCAD Tools (by Synopsys, 2010)
  - Tool is used for modeling a wide variety of devices (MEMS, NEMS) (Analog, power, image sensors, solar, and through-silicon vias)
- Nanometrology tool (by University of California at Irvine, 2007)
  - Variable temperature Raman microscopy as a nanometrology tool for graphene layers and graphene-based devices
- NANOFUNCTION network, launched in sep. 2010
  - Beyond CMOS Nanodevices for Adding Functionalities to CMOS
- IPWGN, launched in sep. 2006
  - International Planning Working Group on Nanoelectronics

Conclusions and Recommendations

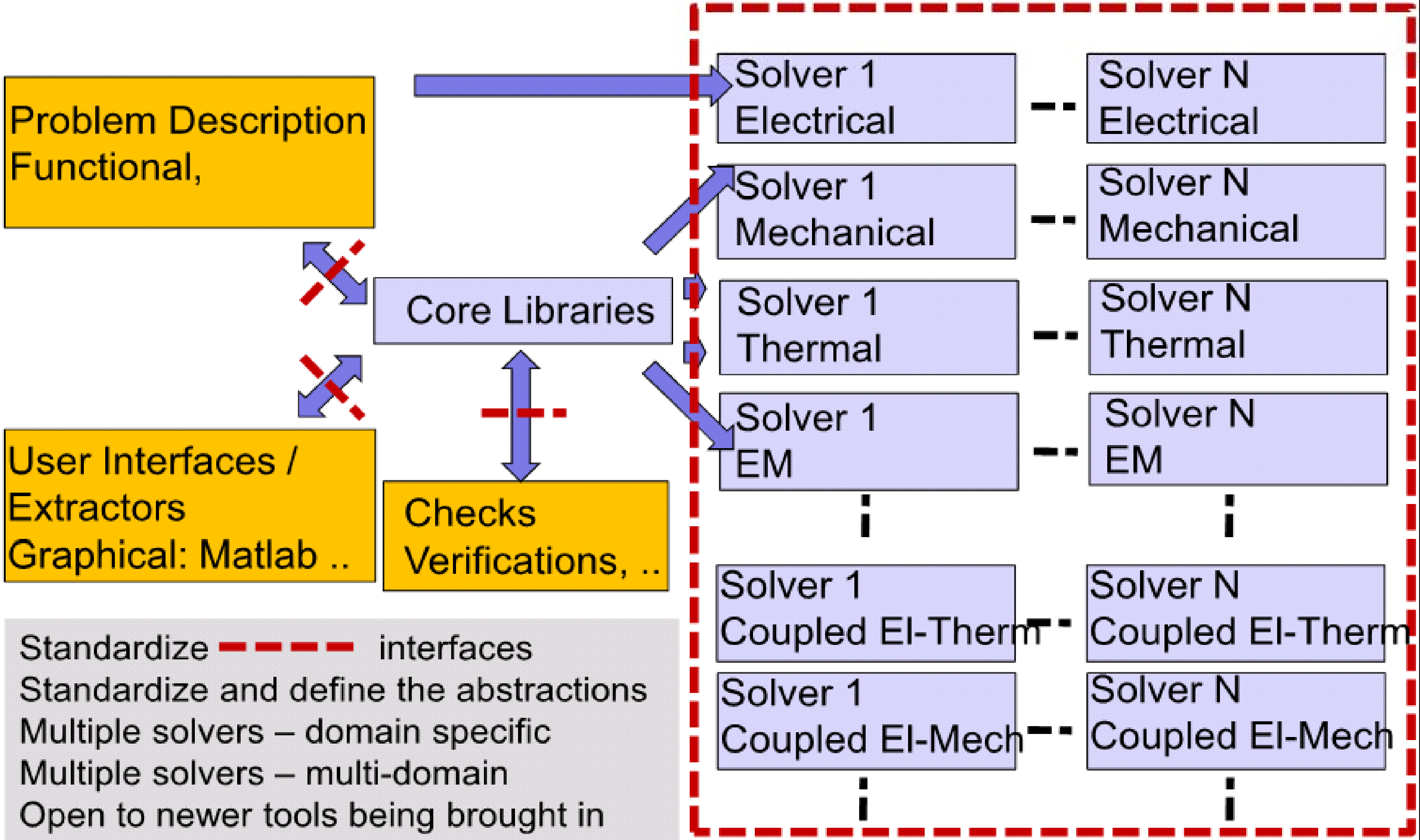
There is …

1) … a need to rethink design processes for 'Beyond CMOS'
2) … a need of a new open infrastructure for the development of 'Beyond CMOS' design

A POSSIBLE TECHNOLOGY & DESIGN INFRASTRUCTURE

Build A New Open Infrastructure

S Tiwari



Source: S. Tiwari, 2nd NANO-TEC-Workshop, Oct. 2011, Athens

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Tasks:

- Motivation and support to facilitate communication and cooperation between design and technology actors from academia and industry

Ultimate Measures of Success . . .

For the ***technologist***:

I/V curve in *Nature*

For the ***circuit designer***:

Best Paper Award at ISSCC

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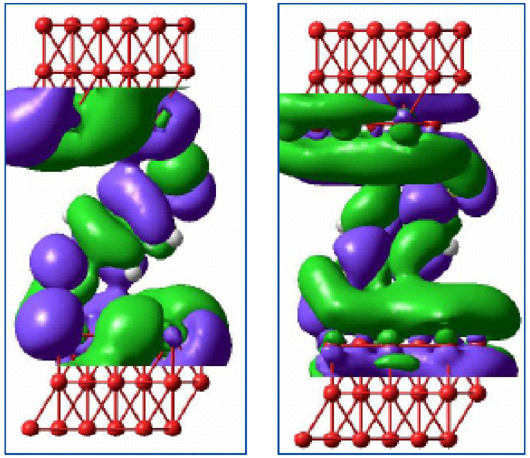
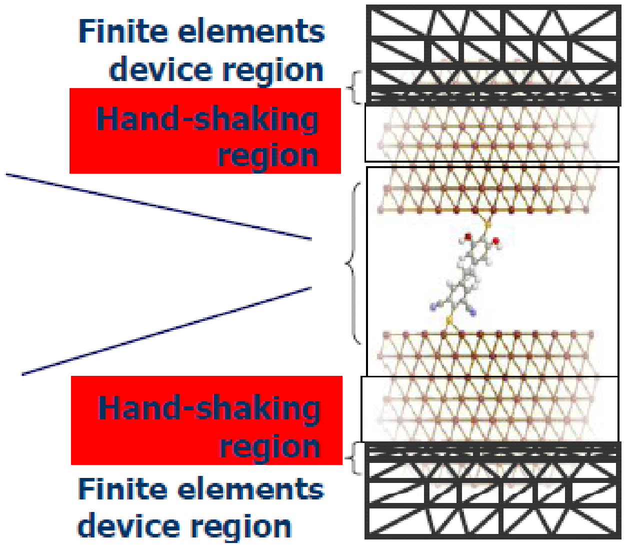
- Multi-scale modeling and simulation of 'Beyond CMOS' devices and circuits have to be developed to gain sustainable knowledge.

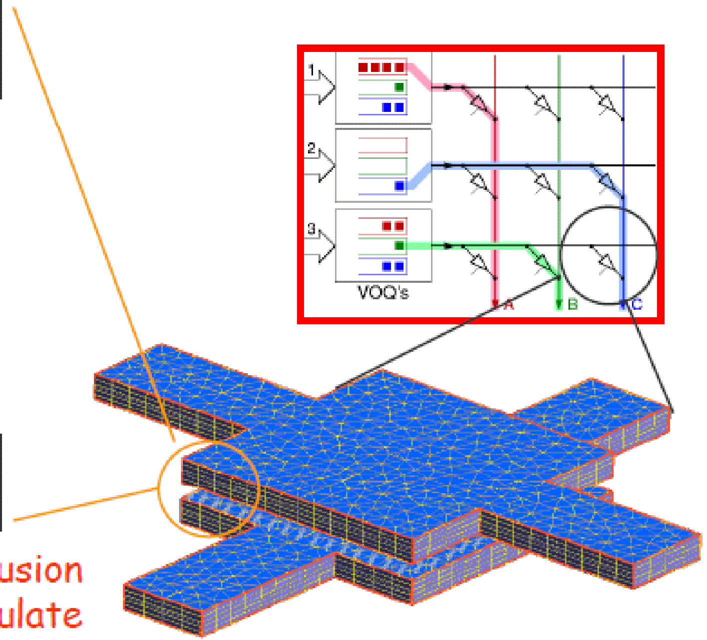
Multiscale modeling



DFTB + quantum-transport approaches using Non-equlibrium Green Functions.



Well-established drift diffusion simulator codes are used to simulate contacts and devices surrounding the molecules.



Circuit level

nanometer region | submicron to micron region | Micron to millimeter regions

Ab initio models | **Quantum-classical interfaces** | **Continuum-based and circuit models**

Physics ⟷ Engineering

Source: P. Lugli, 1st NANO-TEC-Workshop, Jan. 2011, Granada

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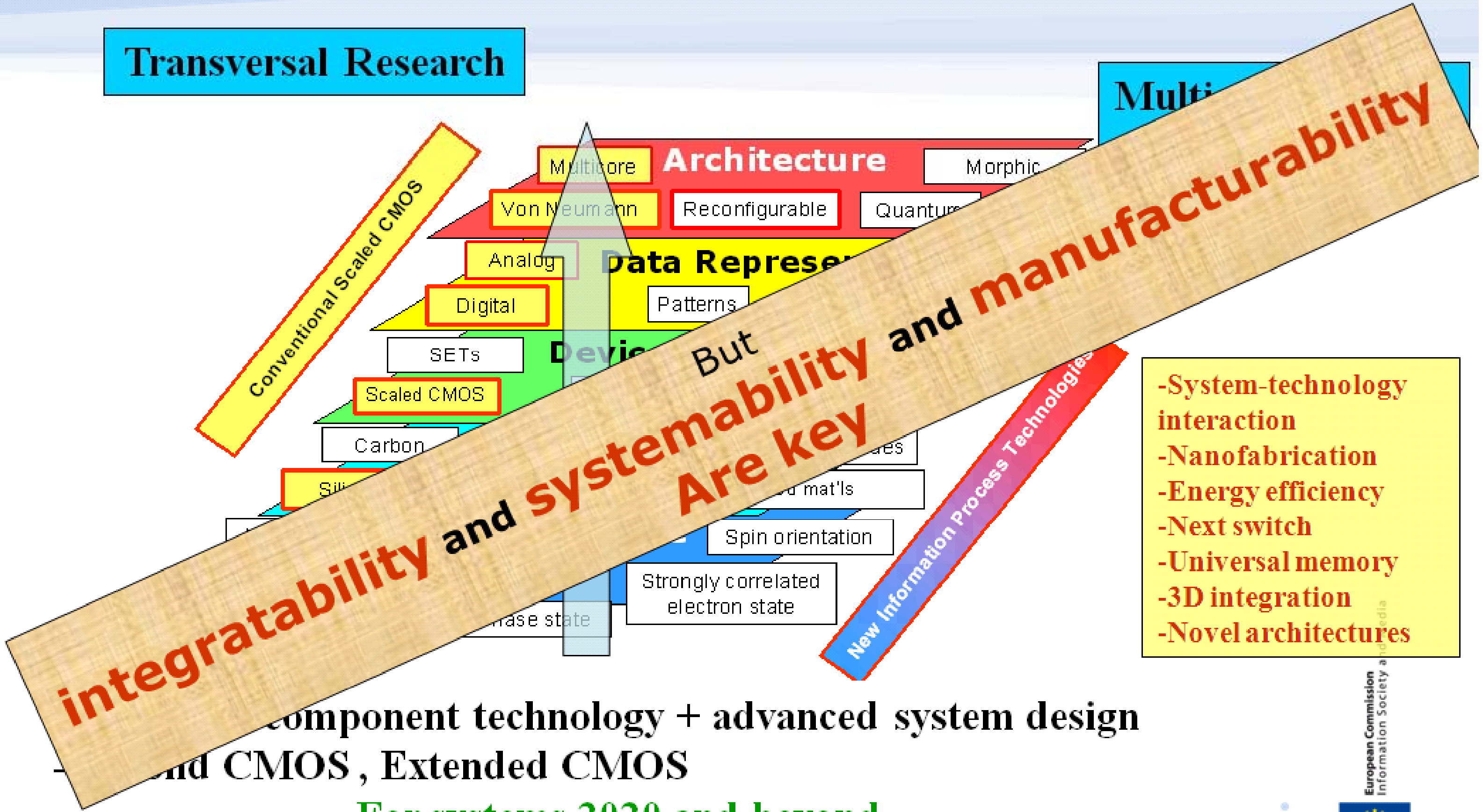
Tasks:

- Motivation and support to facilitate communication and cooperation between design and technology actors from academia and industry
- Modeling and simulation of 'Beyond CMOS' devices and circuits have to be developed to gain sustainable knowledge.
- From the resulting exchange of knowledge, the "systemability" of 'Beyond CMOS' devices has to be proven.
- In addition "integratability" (with CMOS), manufacturability of novel technology and reliability are key factors.

Design Challenges for Beyond CMOS

General system enabling concepts

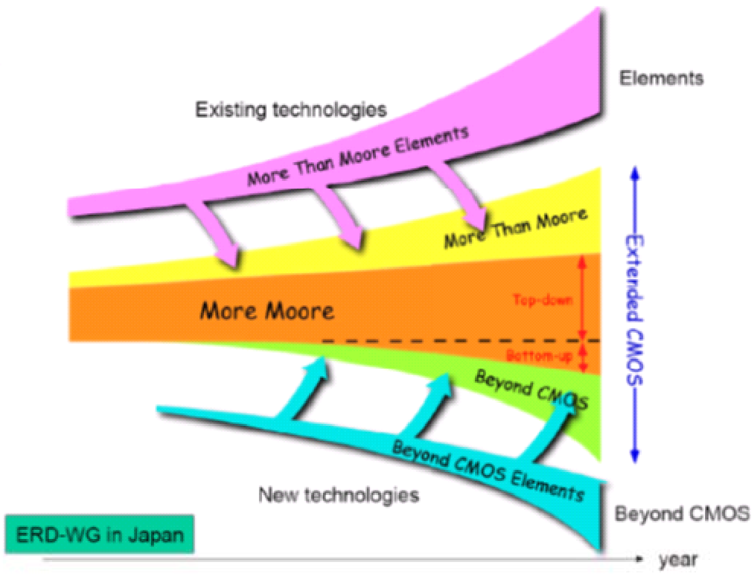


For systems 2020 and beyond

Source: D. Beernaert, 4th NANO-TEC-Workshop, Nov. 2012, Barcelona

Design Challenges for Beyond CMOS

Third: (Very) Advanced *Nano-electronics as system enablers and solution providers*
(energy, functionality, system-technology interaction, ...)



ITRS-ERD vision of the role of Beyond CMOS and More than Moore elements to form future extended CMOS platforms.

- **Beyond CMOS and advanced More than Moore as an extended-CMOS vision.**
- **Hybridizing silicon** with molecular switches, ferromagnetic logic, spin devices and sensors in order to ***enable heterogeneous and morphic system architectures.***
- **Integrate-ability, system-ability** and **manufacturability** of novel technology and **reliability** are key factors.

Source: D. Beernaert, 4th NANO-TEC-Workshop, Nov. 2012, Barcelona

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- From the resulting exchange of knowledge, the "systemability" of 'Beyond CMOS' devices has to be proven.
- In addition "integratability" (with CMOS), manufacturability of novel technology and reliability are key factors.
- **→ to bridge the design – technology gap we have to concentrate and focus on the most promising Beyond CMOS technologies and work on the complete value chain**