Basic Research Needs for Microelectronics Workshop October 23-25, 2018: *Preliminary findings*

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Robinson Pino (ASCR)
Eric Colby (HEP)

on behalf of DOE Office of Science

Basic Energy Sciences, Advanced Scientific Computing, High Energy Physics

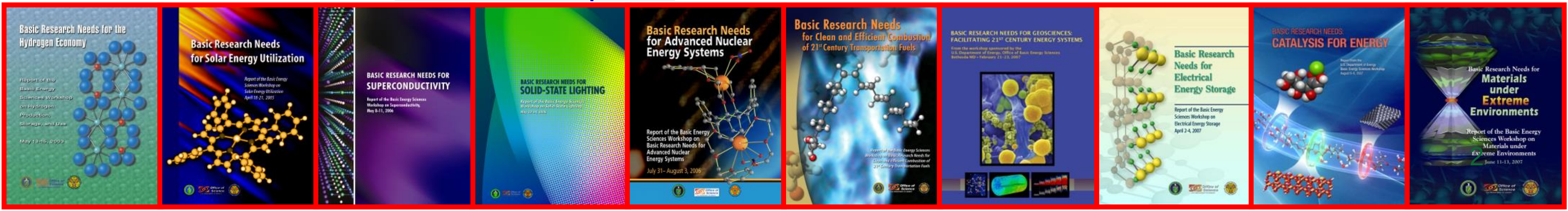
Basic Research Needs … Workshops

21 reports; 14 years; >2,000 participants from academia, industry, and DOE labs

- **BRN to Assure a Secure Energy Future BESAC (2002)**
- **BRN for Hydrogen Economy (2003)**
- **BRN for Solar Energy Utilization (2005)**
- **BRN for Superconductivity (2006)**
- **BRN for Solid State Lighting (2006)**
- **BRN for Advanced Nuclear Energy Systems (2006)**
- **BRN for Geosciences (2007)**
- **BRN for Clean and Efficient Combustion (2007)**
- **BRN for Electrical Energy Storage (2007)**
- **BRN for Catalysis for Energy Applications (2007)**
- **BRN for Materials under Extreme Environments (2007)**
- **New Science for Sustainable Energy Future (2008)**
- **BRN for Carbon Capture (2010)**
- **Computational Materials Science and Chemistry (2010)**
- **Science for Energy Technology (2010)**
- **Controlling Subsurface Fractures and Fluid Flow (2015), Next Gen Tools(2016)**
- **BRN for Environmental Management, Energy-Water-Nexus (2016)**
- **BRN for Quantum Materials (2016)**
- **BRN for Synthesis Science (2016)**
- **BRN for Next Generation Electrical Energy Storage (2017)**
- **BRN for Future Nuclear Energy (2017)**
- **BRN for Catalysis Science to Transform Energy Technologies (2017)**

- **BRN for Microelectronics (2018)**

http://science.energy.gov/bes/community-resources/reports/



Basic Research Needs – Use Inspired Basic Research

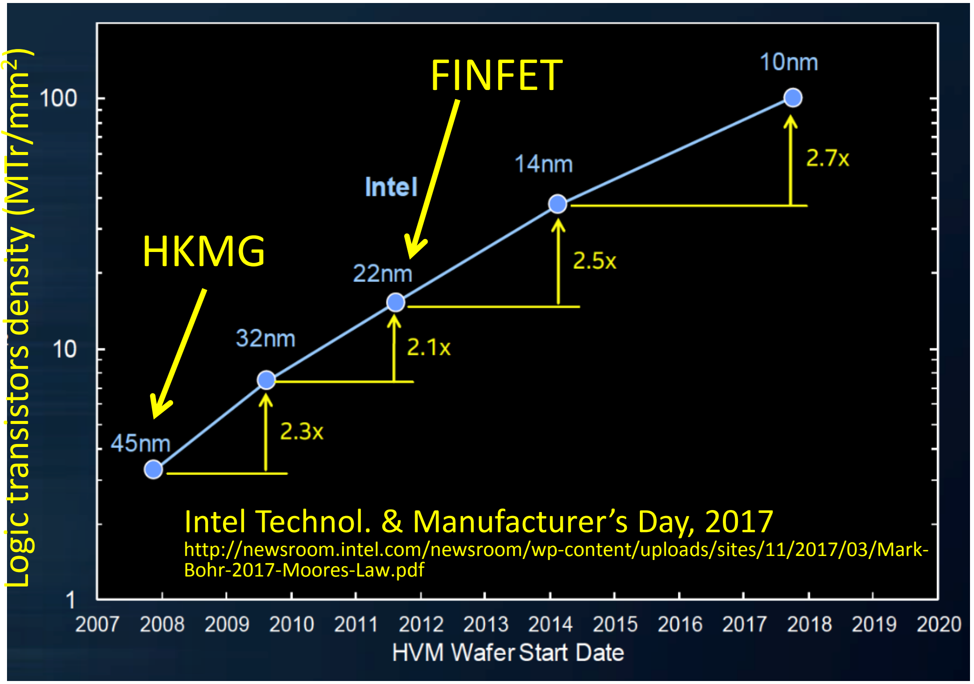
- Transformative, not incremental research directions
- Fundamental science challenges to move the technology forward
- New techniques and methods
- 10-30 years out

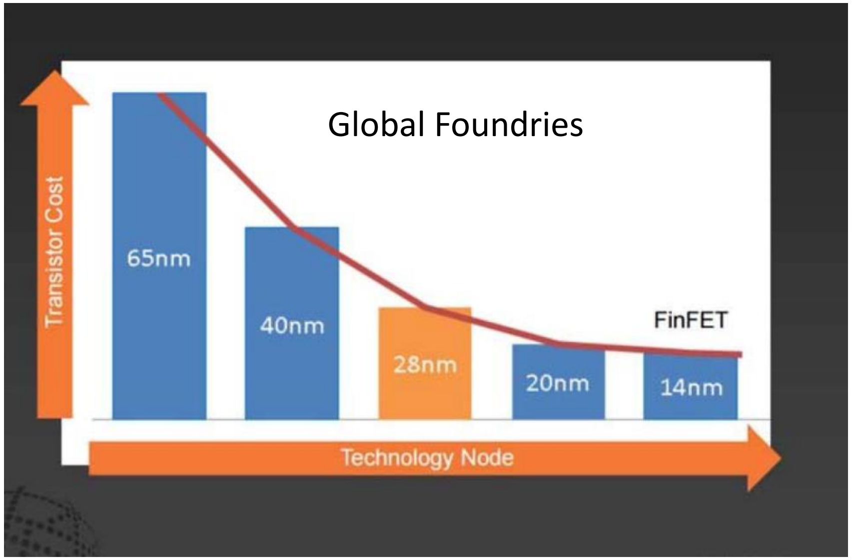
BRN for Microelectronics Workshop – Motivation

- Semiconductor-based microelectronics are critical to the U.S. economy, scientific advancement, and national security
  - Semiconductor products are currently the third largest class of U.S. exports (behind aircraft and automobiles)
  - U.S. companies account for more than 50% of the world market by revenue
  - Semiconductor industry directly employs ~250,000 people; ~1 million associated jobs
- The decades long success of Moore's Law was driven by innovation
  - Materials and chemical sciences
  - Computer science
  - Electrical engineering
  - Fabrication technologies
- Additional innovation needed to keep up with dramatic market growth

Sources: SIA "Made in America: The Facts about Semiconductor Manufacturing," Aug. 2015
SIA "2014 Factbook", 2014

Motivation: CMOS scaling slowdown

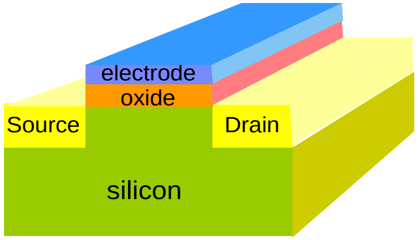




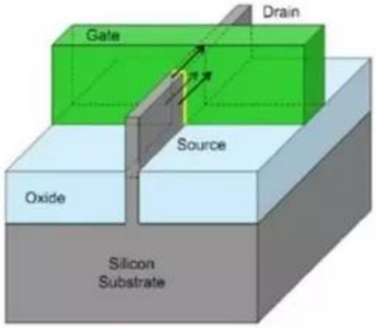
http://www.swtest.org/swtw_library/2015proc/PDF/SWTW2015_Keyr McCann_GlobalFoundries.pdf

Uncertainty at 7 nm node complexity and cost

Physics gets in way



bulk

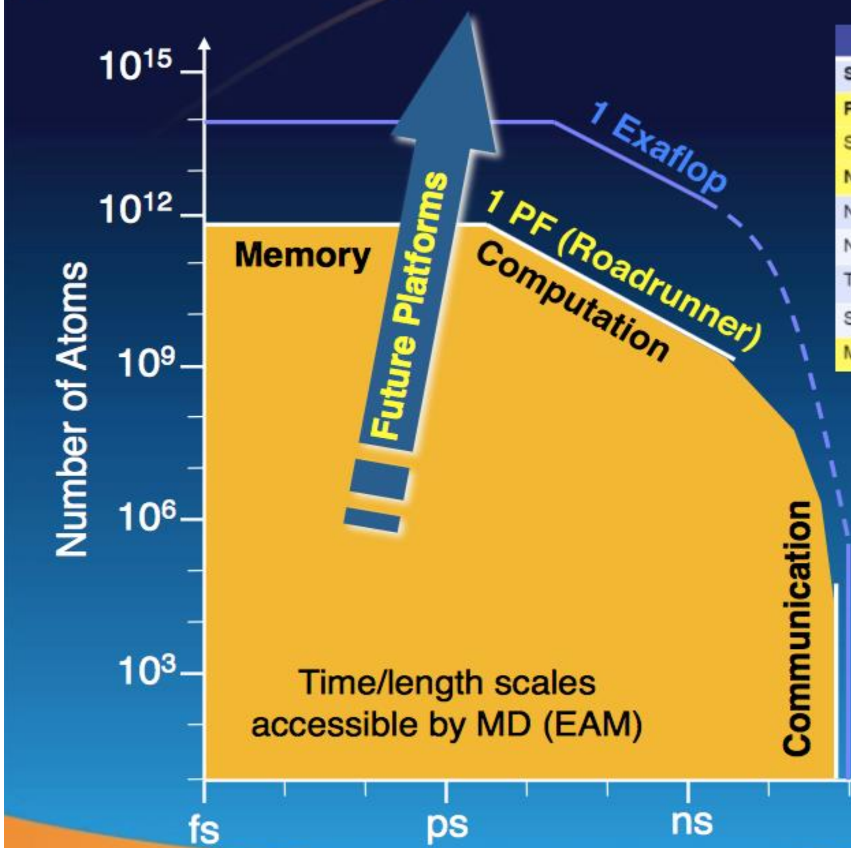


https://www.quora.com/What-is-a-FinFET-transistor

Impact to computational materials science--example

Current trends will increase the *length* scales accessible by large-scale molecular dynamics simulations

Los Alamos NATIONAL LABORATORY EST. 1943



System attributes	2010	"2015"	"2018"
System peak	2 Peta	200 Peta	1 Exa
Power	6 MW	~15 MW	~20 MW
System memory	0.3 PB	5 PB	32-64 PB
Node performance	125 GF	0.5 TF or 7 TF	1 TF or 10x
Node memory BW	25 GB/s	0.1 TB/s or 10x	0.4 TB/s or 10x
Node concurrency	12	O(100)	O(1k) or 10x
Total Node Interconnect BW	1.5 GB/s	20 GB/s or 10x	200 GB/s or 10x
System size (nodes)	18,700	50,000 or 1/10x	O(100,000) or 1/10 x
MTTI	days	O(1day)	O(1 day)

Source: DOE Exascale Initiative Technical Roadmap

Clock speeds and bandwidths will not increase substantially, so the *timescale* challenge is going to become increasingly critical.

NNSA

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

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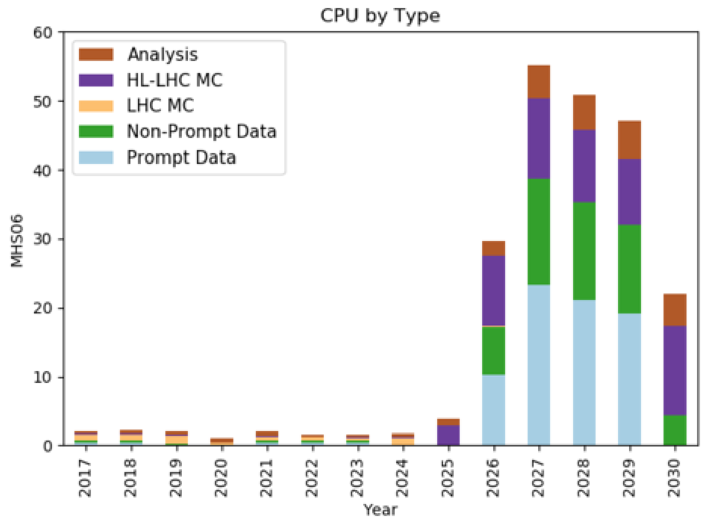
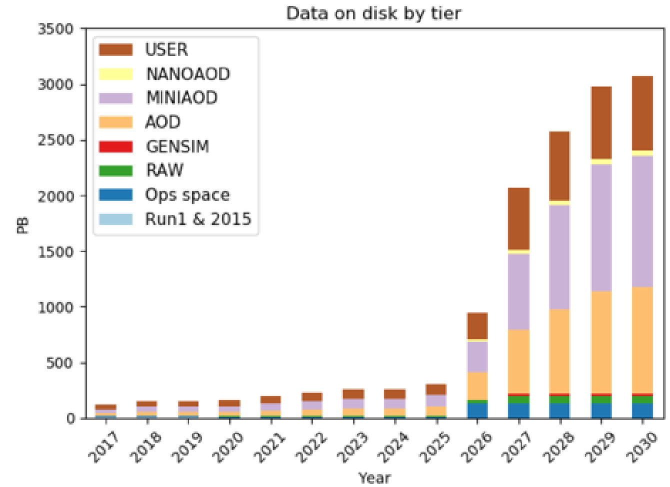
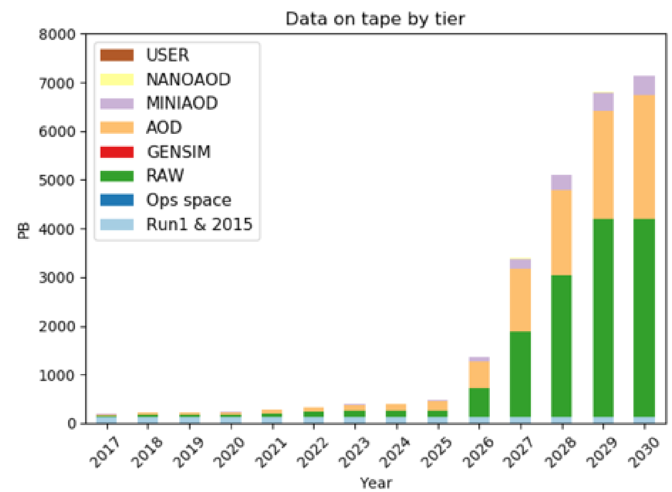
Rise of data intensive & edge computing: future Compact Muon Solenoid (CMS) computing needs at Large Hadron Collider (LHC)





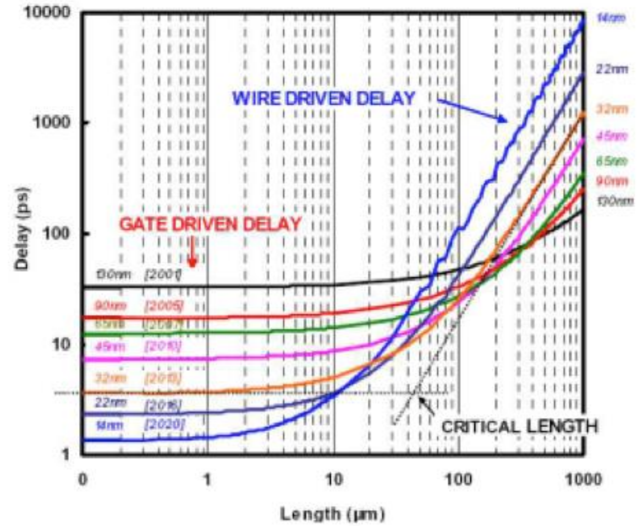
A data storage and movement problem

- Exa-byte scale disk and tape storage, 50x w.r.t. now
- CPU needs 5M cores, 20x w.r.t. now
- transfer of exa-byte-sized data samples across the Atlantic at 250-500 Gbps, (today: 40Gbps allocated by ES Net)



(From talk by L Bauerdick, Fermilabs, conveyed by S. Habib, ANL)

Rise of data intensive & edge computing

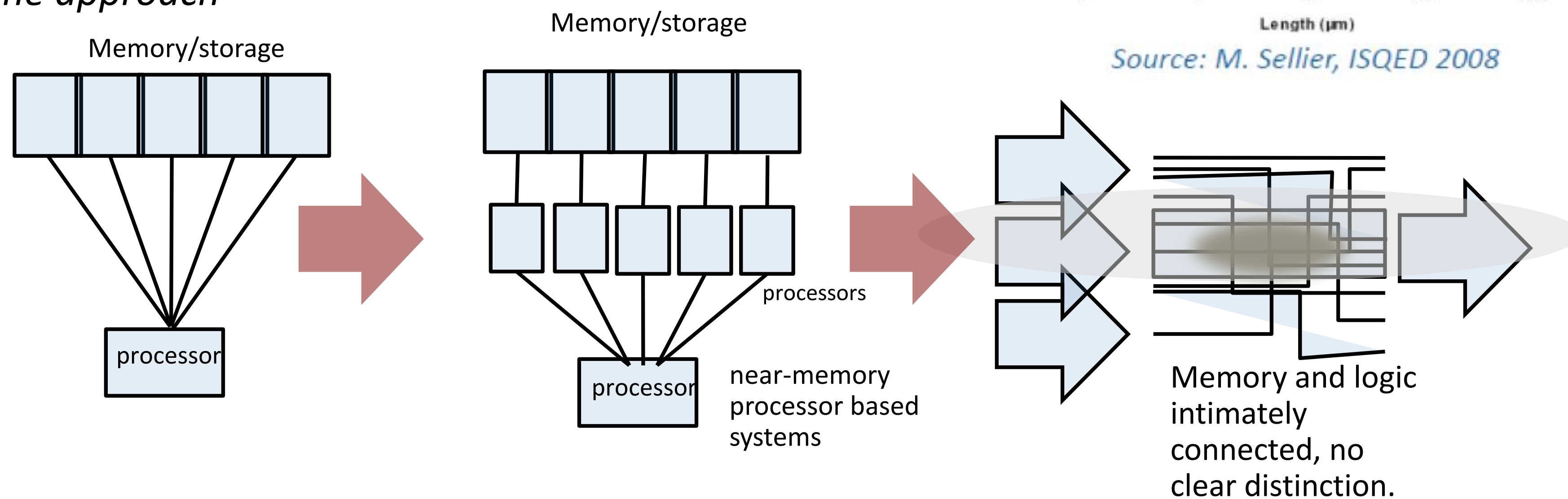


Source: M. Sellier, ISQED 2008

Need for new computing paradigms

Memory bottlenecks
Data transport
Low power computing

One approach



Future Computing Technologies are Important to DOE

as well as many other Federal Agencies

- High-performance computing & simulation underpin DOE missions in energy, environment, and national security
  - Historical role of computing in DOE
  - DOE/vendor synergies in deploying computing technologies

- Future computing technologies (e.g., quantum, neuromorphic, probabilistic, etc.) hold promise for next-generation DOE mission applications
  - DOE research and facilities (e.g. HEP experiments, ASCR HPC, BES light sources) will depend on advanced computing and sensing technologies
  - Likely will augment, not replace, conventional supercomputing
  - Could open new avenues for use of computing in science (data analytics, machine learning, artificial intelligence, …)

- New directions for applied mathematics and computer science are likely to emerge that could enable new science across DOE-SC

Call To Action

- Significant challenges as CMOS extends below 5nm
- The end to Moore's Law will impact U.S. industry and competitiveness
- The importance of this issue and its technical complication will require *innovative approaches* to keep the U.S. in a leadership position
- Solving a problem of this scale will require *"whole of government"* approach and a robust *public/private partnership* to apply the best research from *industry, academia and government research facilities* to allow the U.S. to successfully make this technology transition
- DOE, and particularly the Office of Science, will play a significant role in this effort
- DOE-SC was charged with organizing a *Basic Research Needs Workshop* to define the highest priority research directions

Basic Research Needs for Microelectronics – Charge

- A thorough assessment of the scientific issues associated with advanced microelectronics technologies for applications relevant to the DOE mission.
- Identify critical scientific challenges, fundamental research opportunities, and priority research directions that require further study as a foundation for advances in microelectronics over the next decade and beyond.
- Particular emphasis on energy-relevant applications, and areas that are aligned with the missions and needs of ASCR, BES, HEP including data management and processing, power electronics, and high performance computing.
- Examine extension of CMOS and beyond CMOS technologies, **beyond exascale technologies. however Quantum Information Science is outside the scope of this workshop**.
- focus on a co-design innovation ecosystem in which materials, chemistries, devices, systems, architectures, and algorithms are researched and developed in a closely integrated fashion.

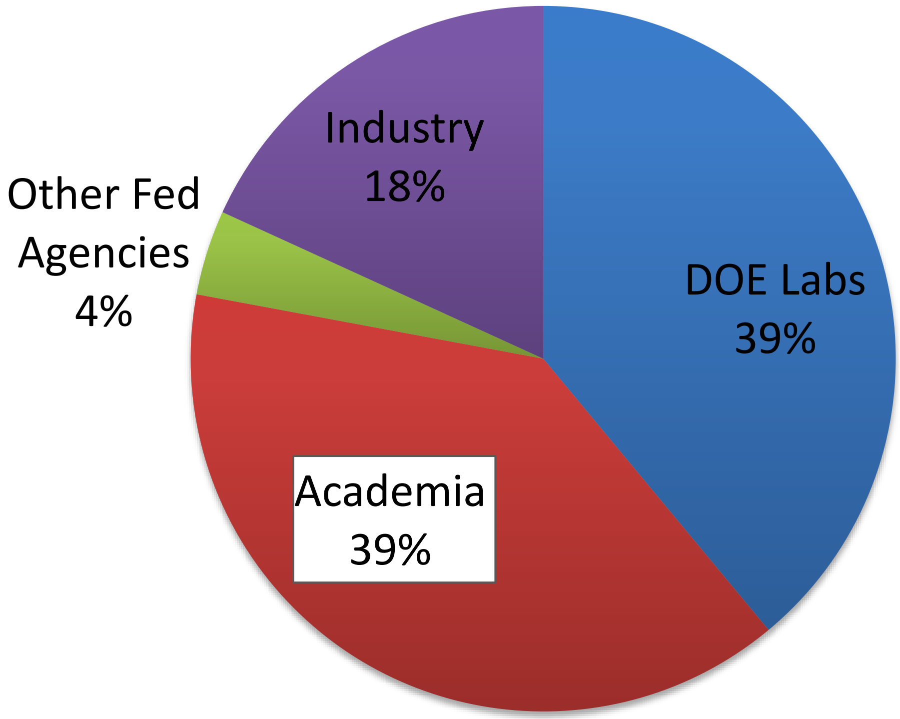
Innovation Opportunity Space

- Materials Research
- Device Physics
- Design and Fabrication
- Computer Engineering: architectures and micro-architectures
- Computer Science & Applied Math

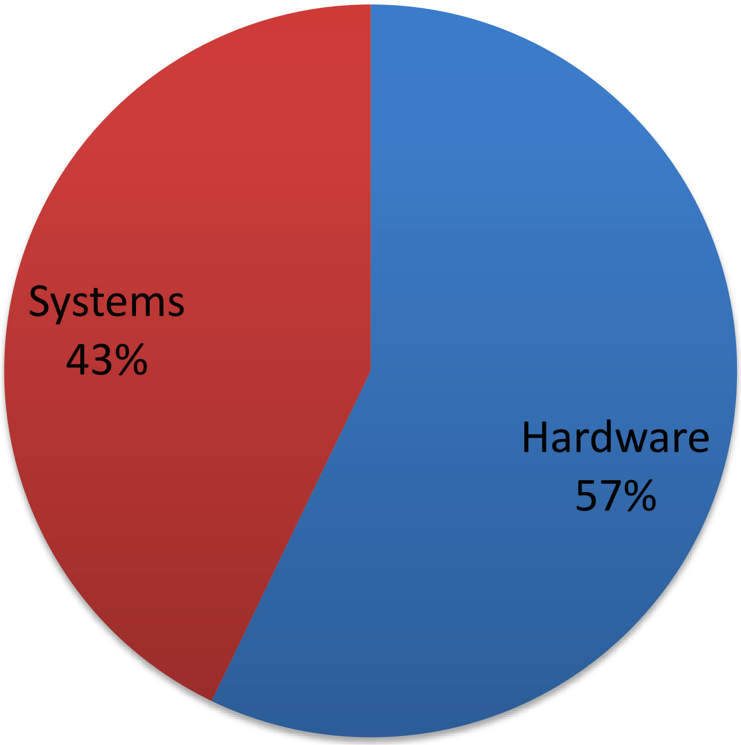
- Other Considerations
  - *Outside the box*: Alternative materials, devices, fabrication techniques and architectures are likely to result
  - *Use-inspired science*: Function and application need to be considered at early stages

Basic Research Needs for Microelectronics Workshop participation

77 panelists, ~70 observers



By affiliation



By expertise

<u>Systems</u>: circuits, micro-architecture, architecture, algorithms, software
<u>Hardware</u>: devices, materials, physics, chemistry

PLENARY TALKS TO SET THE SCENE AND PRESENT CHALLENGES

- **Justin Rattner (Intel, ret)**
- **Mike Witherell (LBNL)**
- **Bill Chappell (DARPA)**
- **Tsu-Jae King Liu (UC Berkeley)**
- **Dushan Boroyevich (VA Tech)**

Panels

Panelists were invited for their expertise – and are assigned to a particular panel that will determine priority research directions in the breakout sessions

1) Big data collection, analytics, processing for SC facilities

Leads: Kirsten Kleese van Dam (BNL) and Sayeef Salahuddin (UC Berkeley)

2) Co-design for high performance computing beyond exascale

Leads: James Ang (PNNL) and Thomas Conte (Georgia Tech)

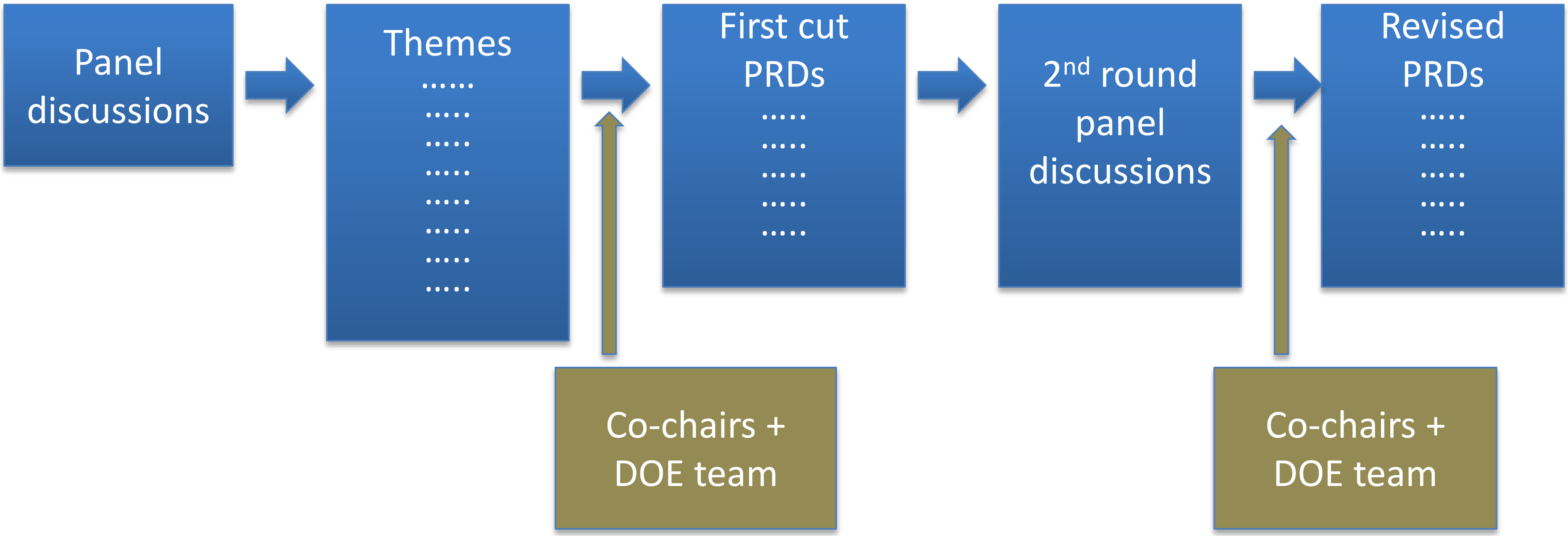
3) Power control, conversion and detection

Leads: Debdeep Jena (Cornell U) and Robert Kaplar (SNL)

4) Crosscutting themes – *may roam and join other panels*

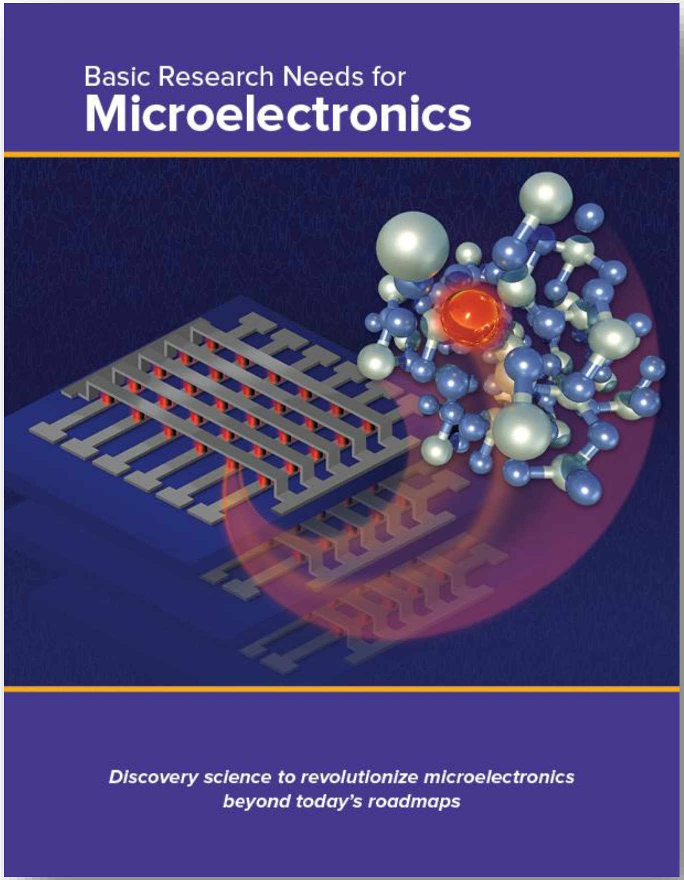
Leads: Harry Atwater (Caltech) and Rick Stevens (ANL)

Oct 22-25



Target dates:
Brochure published on DOE website: Dec 7, 2018
BRN report ready for publication: Feb 2019

Summary Brochure Published on 7 December 2018



Five Priority Research Directions (PRDs) Identified

Priority Research Directions

- **Flip the current paradigm: Define innovative material, device, and architecture requirements driven by applications, algorithms, and software**

  Key Questions: *How can we optimize and integrate across physical, logical, and communication and control hierarchies? How will system-level optimization enable directed materials/device discovery and innovation?*

  Materials properties, microelectronic devices, architectures, and algorithms must be understood and designed from the atomistic to the systems level to address the critical technical challenges facing DOE in its missions of science, energy, and national security. The outcome of an "end-to-end co-design framework" will reshape high performance computing, data analytics, the electricity grid, and other computing intensive and high power applications.

- **Revolutionize memory and data storage**

  Key Questions: *How do we link physics, materials, architectures, and algorithms to overcome current physical limits on access and retention times for memory and storage? What innovations will minimize data movement and reduce energy consumption by orders of magnitude?*

  Memory technologies are critically important in all aspects of data acquisition, analysis, and storage, and have the potential to perform efficient computations within, or proximally close to, the memory element. We face fundamental tradeoffs between fast memory access, capacity, and data retention time, as well as key challenges in energy usage and heat dissipation. Meeting these challenges will require coordinated breakthroughs in materials, device design, computer architecture, and algorithms.

- **Reimagine information flow unconstrained by interconnects**

  Key Questions: *How can we minimize data movement while maximizing information transfer? What novel electronic/optical states of matter can be discovered and manipulated to design non-traditional interconnects at the atomic, micro, and macro scales?*

  A co-design approach to developing novel interconnect architectures will enable seamless integration of large-scale, real-time computation with communications and sensing to dramatically improve data transfer rates, connectivity, and reconfigurability.

- **Redefine computing by leveraging unexploited physical phenomena**

  Key Questions: *What unexplored materials, phenomena, or alternative computing models could perform computation far more efficiently than today's technology? How will these new systems be modeled and programmed?*

  The capabilities of the prevailing model of computation, the von Neumann model, are increasingly constrained by the energy inefficiency of established hardware and architecture. Understanding and using new computing models based on unexploited phenomena require a co-design approach spanning architectures and algorithms to physics, materials science, and new devices.

- **Reinvent the electricity grid through new materials, devices, and architectures**

  Key Question: *Using a co-design approach, how do we create novel devices based on new materials to enable revolutionary breakthroughs in the performance, reliability, and security of power conversion systems?*

  Revolutionary advances in power electronics for the electricity grid will require the design, synthesis, understanding, processing, and integration of advanced semiconductors and magnetic and dielectric materials. Novel device, circuit, and thermal transport concepts will be developed to exploit the unique physical properties of these materials. Such energy-efficient power conversion systems are necessary to replace the century-old electricity grid with one appropriate for the 21st century. They could also be applicable to electric transportation and use in extreme environments such as accelerators and power generation facilities.

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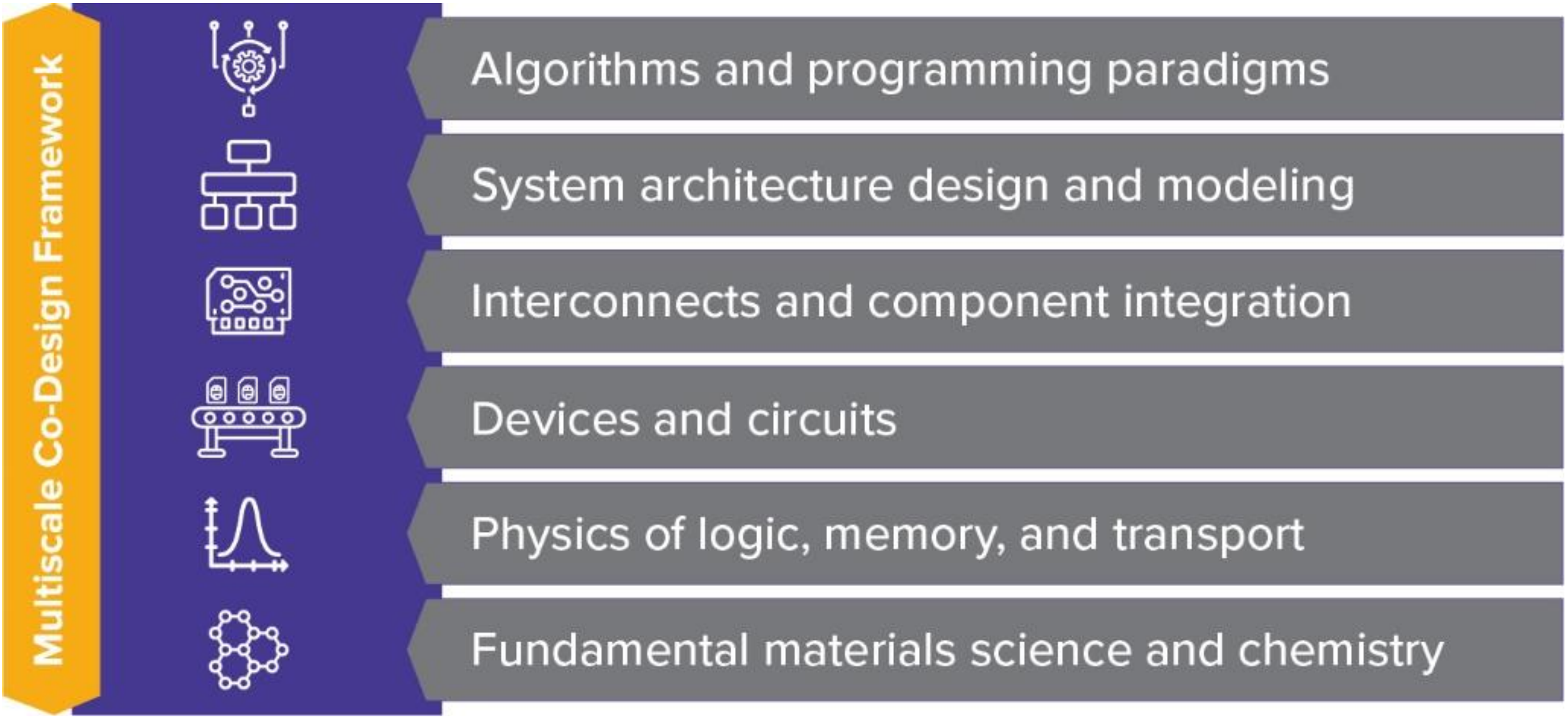
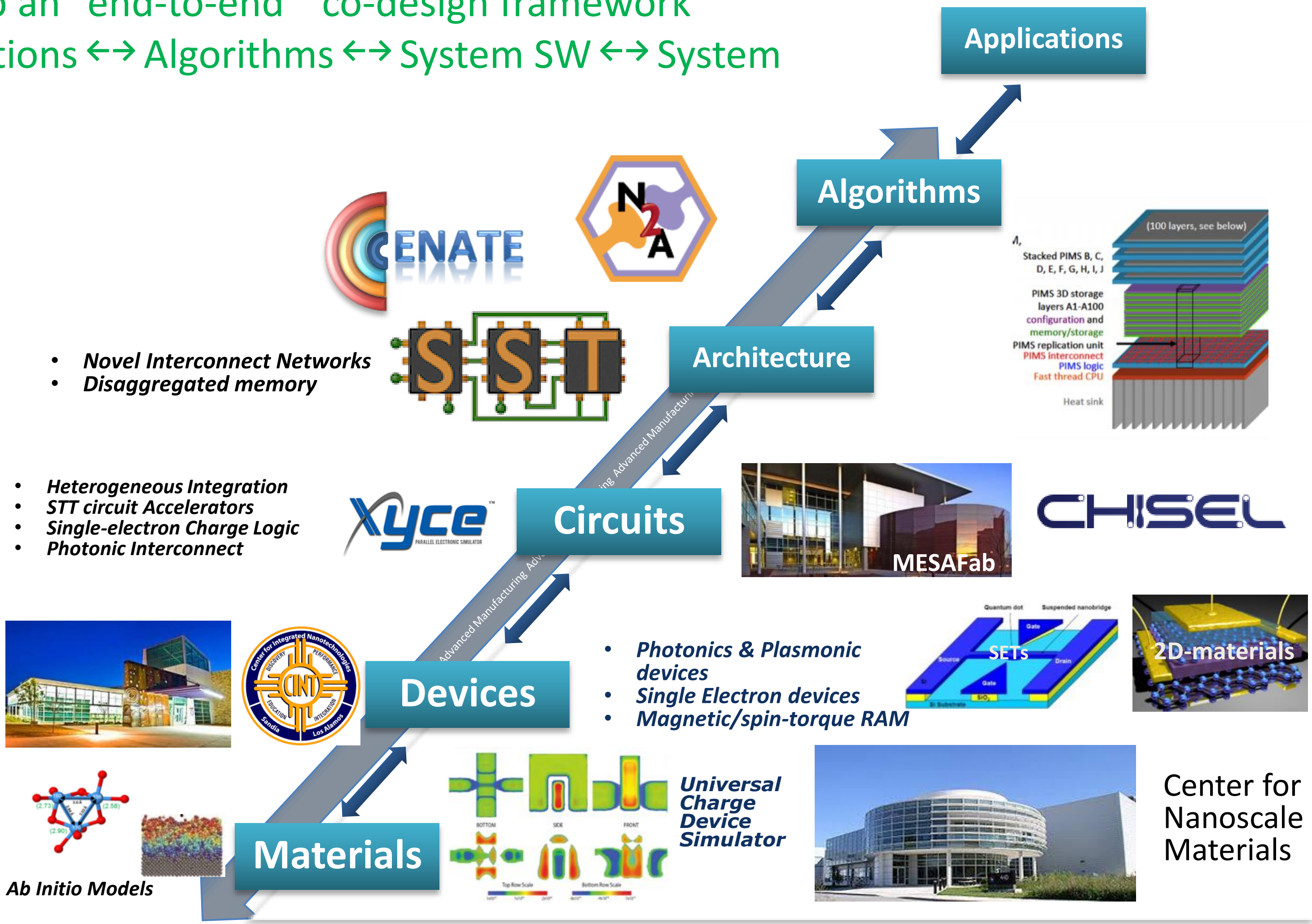
https://science.energy.gov/ascr/community-resources/program-documents/
https://science.energy.gov/bes/community-resources/reports/
https://science.energy.gov/hep/community-resources/reports/

Principles of co-design underpin all five priority research directions (PRDs)



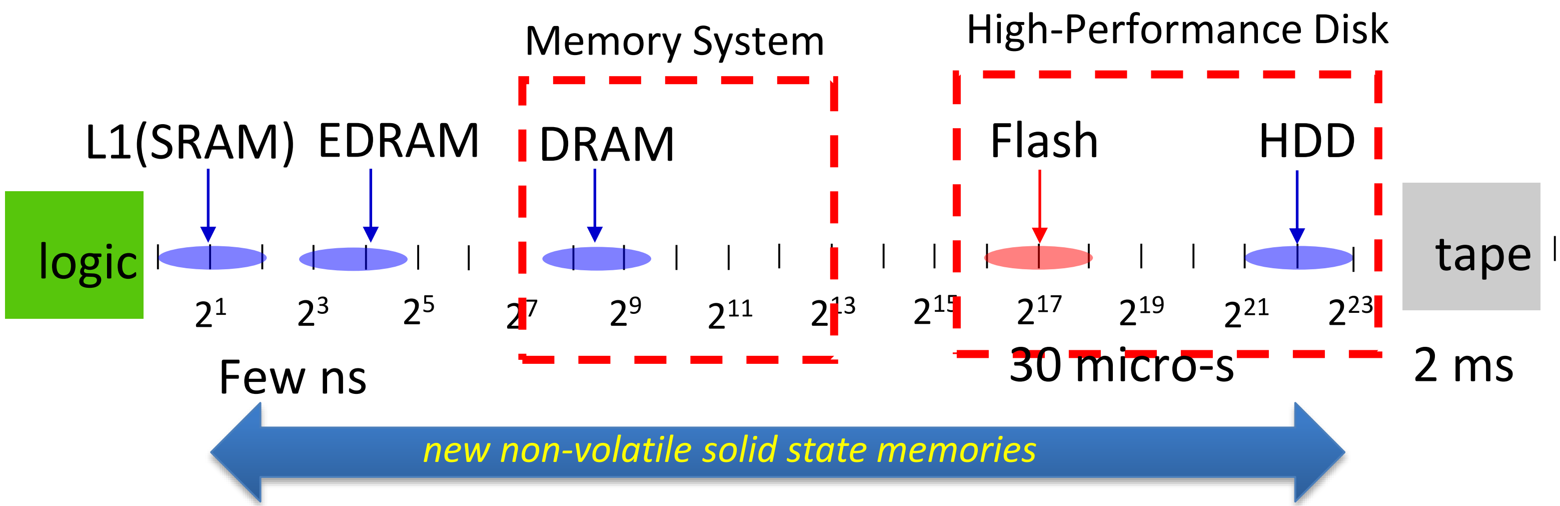
PRD 1: Flip the current paradigm: Define innovative materials, device, and architecture requirements driven by applications, algorithms, and software

- Develop an "end-to-end" co-design framework
- Applications ↔ Algorithms ↔ System SW ↔ System HW

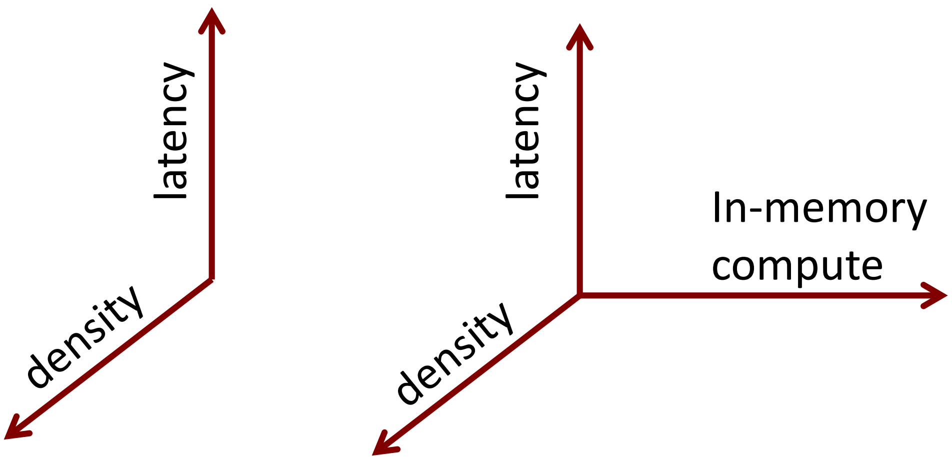


PRD 2: Revolutionize memory and data storage

Typical access latency in processor cycles (@ 4 GHz)



Density
Latency
Bandwidth
In-memory computing

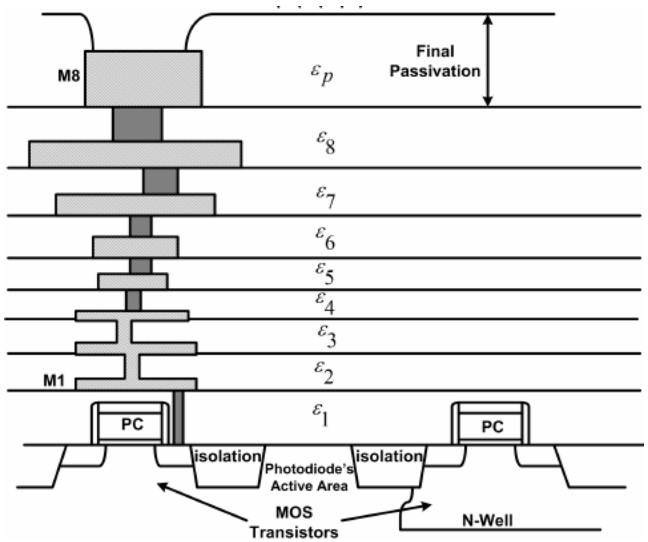


PRD 3: Reimagine information flow unconstrained by interconnects

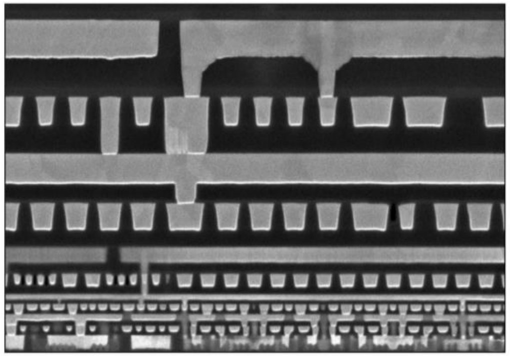
Data movement is growing exponentially

pJ/bit not ramping down significantly

Worthy Goal: Tbyte/sec-mm channel capacity for <100 fJ/bit



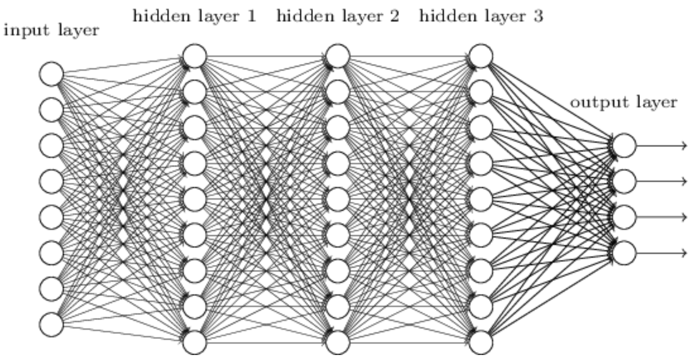
https://www.researchgate.net/figure/General-structure-of-130-nm-technology-with-Back-end-of-line-metallization-and-dielectric_fig11_224918168

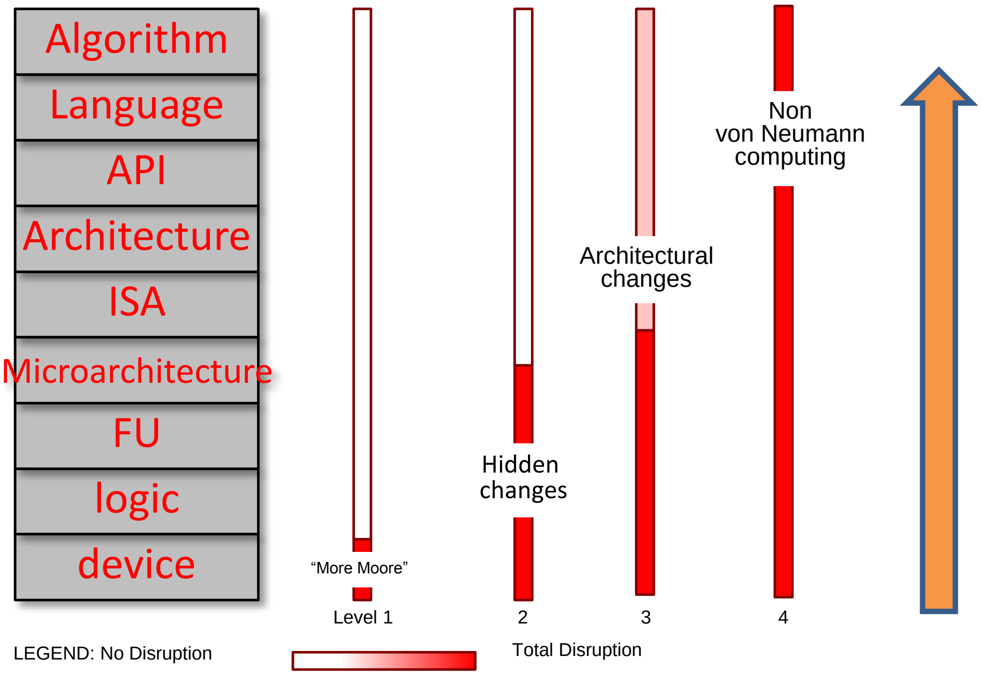


https://images.anandtech.com/doci/8367/14nmInterconnect.jpg

PRD 4: Redefine computing by leveraging unexploited physical phenomena

Finding and understanding physical phenomena that can express computation
New ways of reasoning about computation
Leveraging physical processes to compute ("analogous computing")
NvN Optimizers, both continuous and integer
Artificial Neural Networks

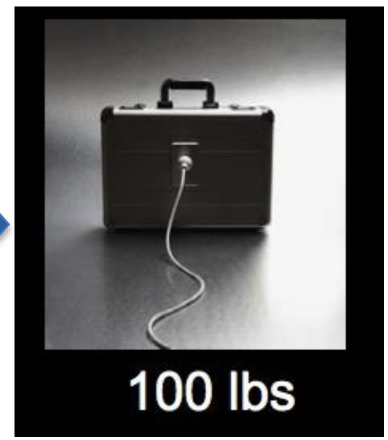




PRD 5: Reinvent the electricity grid through new materials, devices, and architectures

Substation in a Suitcase

8000 lbs, 60 Hz Distribution Transformer



Silicon Carbide IGBT;
15 kV, 100 A;
50 kHz from Cree Inc.