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DESIGN
AUTOMATION
CONFERENCE
JULY 10 - 14, 2022
MOSCONE WEST CENTER
SAN FRANCISCO, CA, USA

Strange loops in design and technology

Giovanni De Micheli

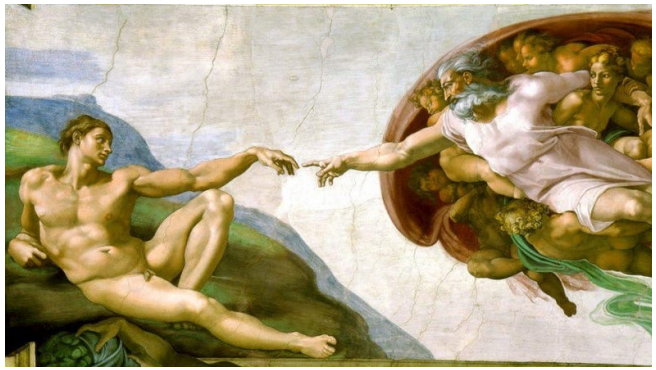
What are we talking about ?

- Inspiration:
  - Alberto Sangiovanni's *40th DAC keynote*: The Tides of EDA
  - Douglas Hofstadter's *Pulitzer prize* winning book: Gödel, Escher, Bach
- Strange loop:
  - Hierarchy of cycles, each linked to each other by some relation
  - Classic concept in cognitive science: emergence of consciousness
- Thesis of this talk:
  - *Cross breeding of technology and design leads to superior systems*

The tides of EDA

- Vico's historical cycles (corsi e ricorsi della storia):
  - History repeats itself with a regular *spiral-like pattern* [Scientia Nova 1650]
- The three ages of EDA:
  - Age of gods (Pioneers laid foundations)
  - Age of heroes (Enterpreneurs founded leading companies)
  - Age of man (Maturity and evolution)


PRINCIPJ
DI
SCIENZA NUOVA
DI
GIAMBATTISTA VICO
D'INTORNO ALLA COMUNE NATURA
DELLE NAZIONI
TOMO I.
IN NAPOLI MDCCXLIV.
NELLA STAMPERIA MUZIANA




NATO 86

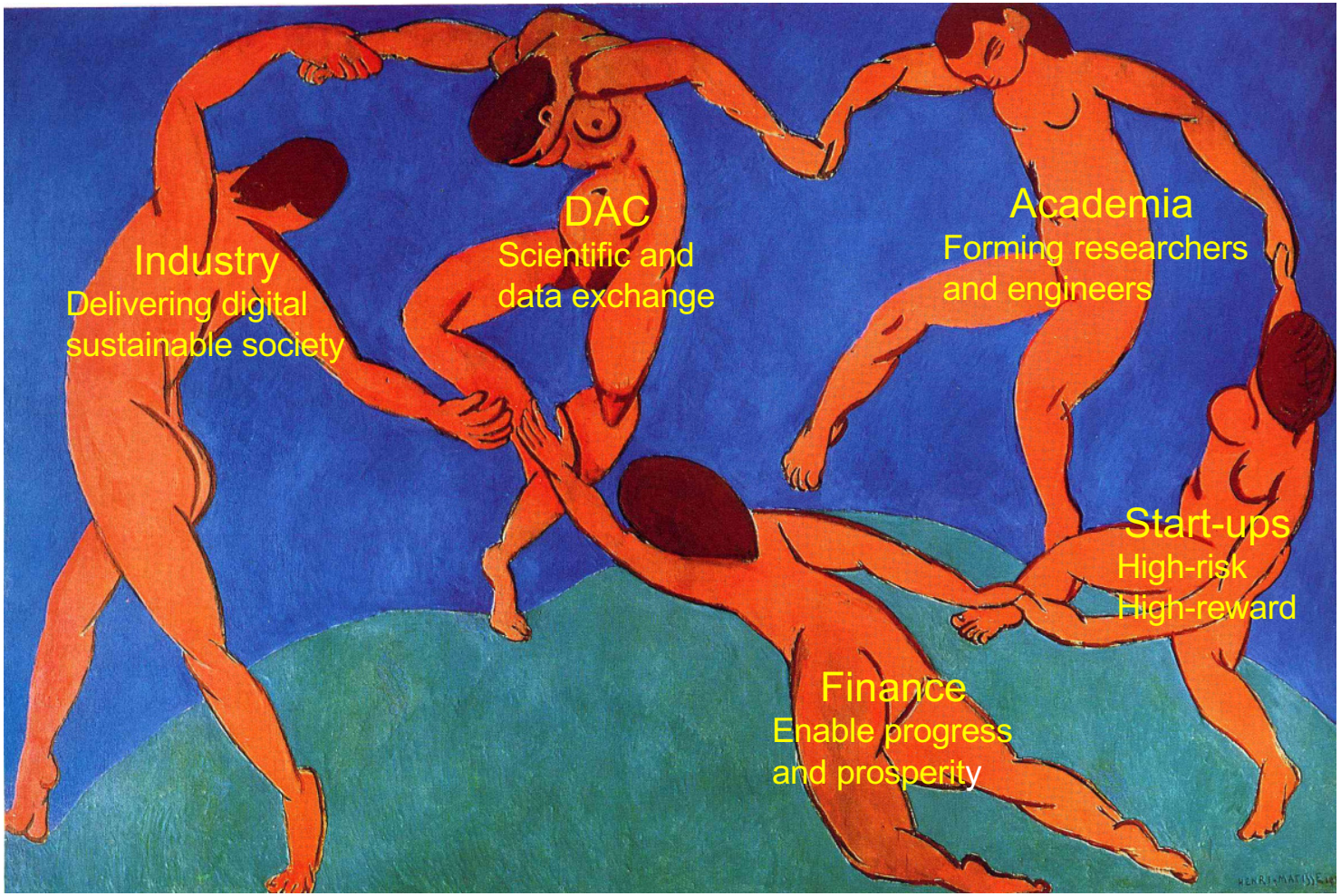
DAC 201X

What will the new tide bring to us?

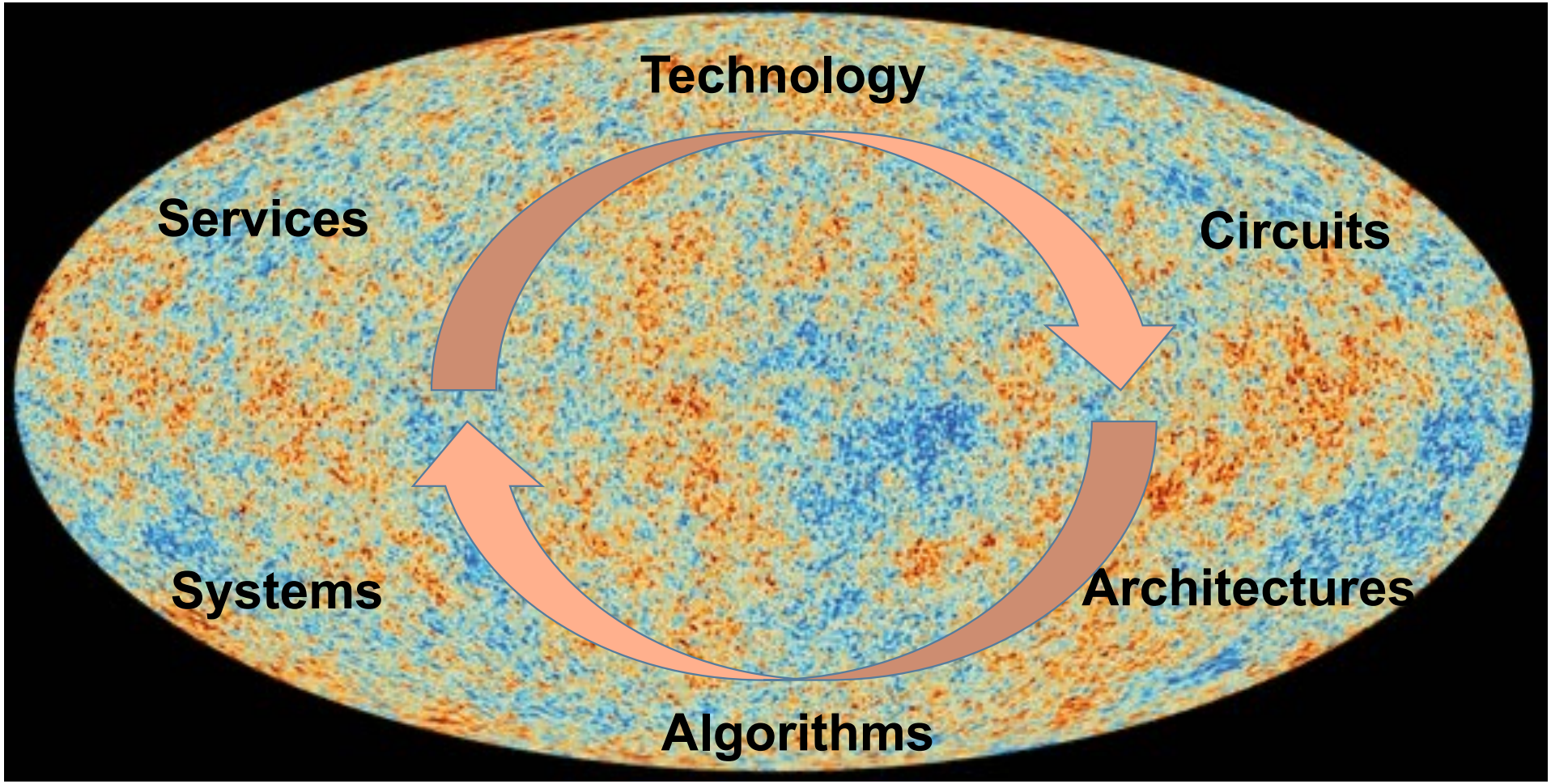
Hofstadter's message

- Loops are present in arts and science
  - Music: canon and fugue
    - Repeated music piece with variations
  - Painting:
    - 2-D pictures can convey a 3-D impression
  - Mathematics:
    - In any consistent system, there exist propositions that cannot be proven
- Loops show us features in a new dimension and we may discover further possibilities
  - *Stimulus for creation*

The actors in the EDA ecosystem



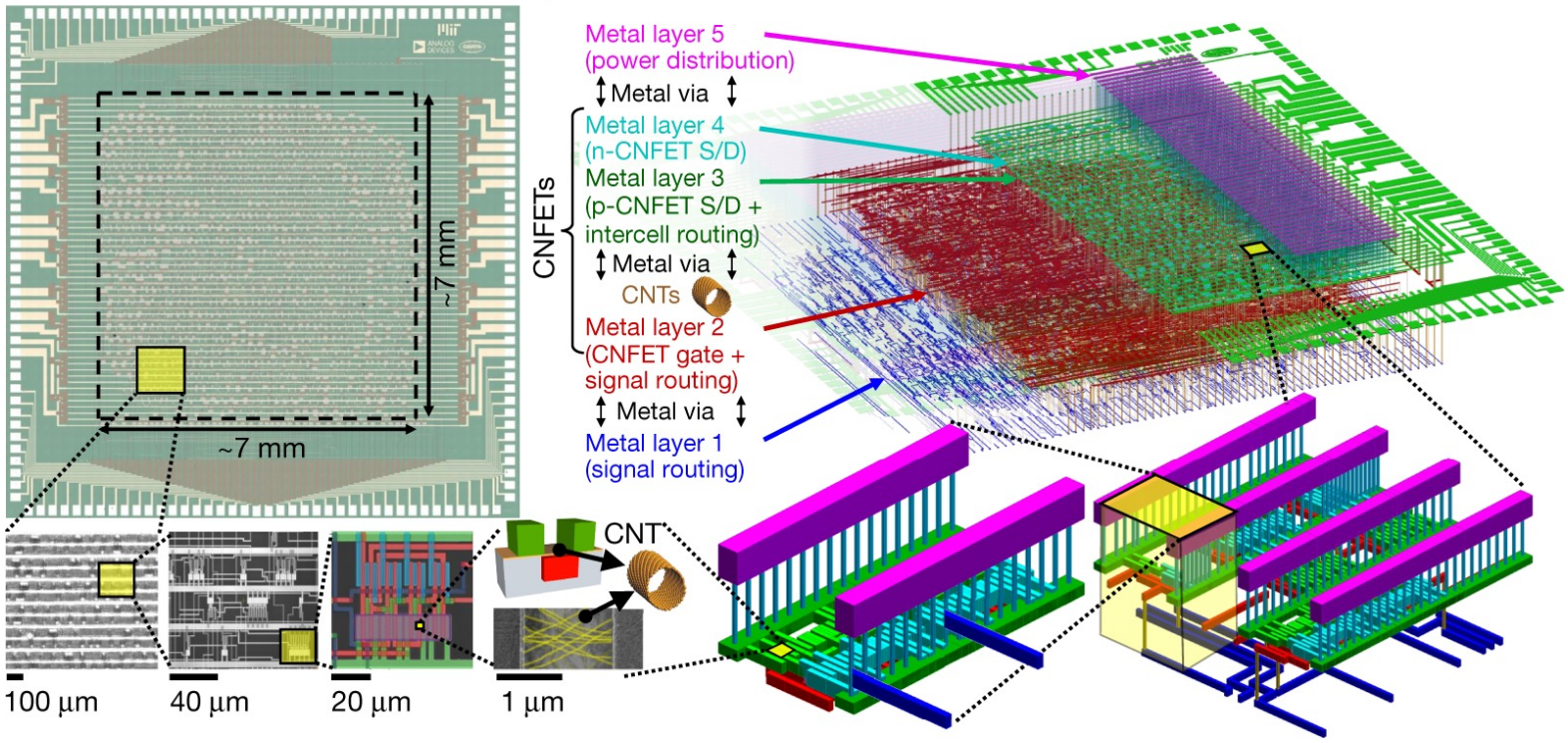
The engineering universe



Calling the questions

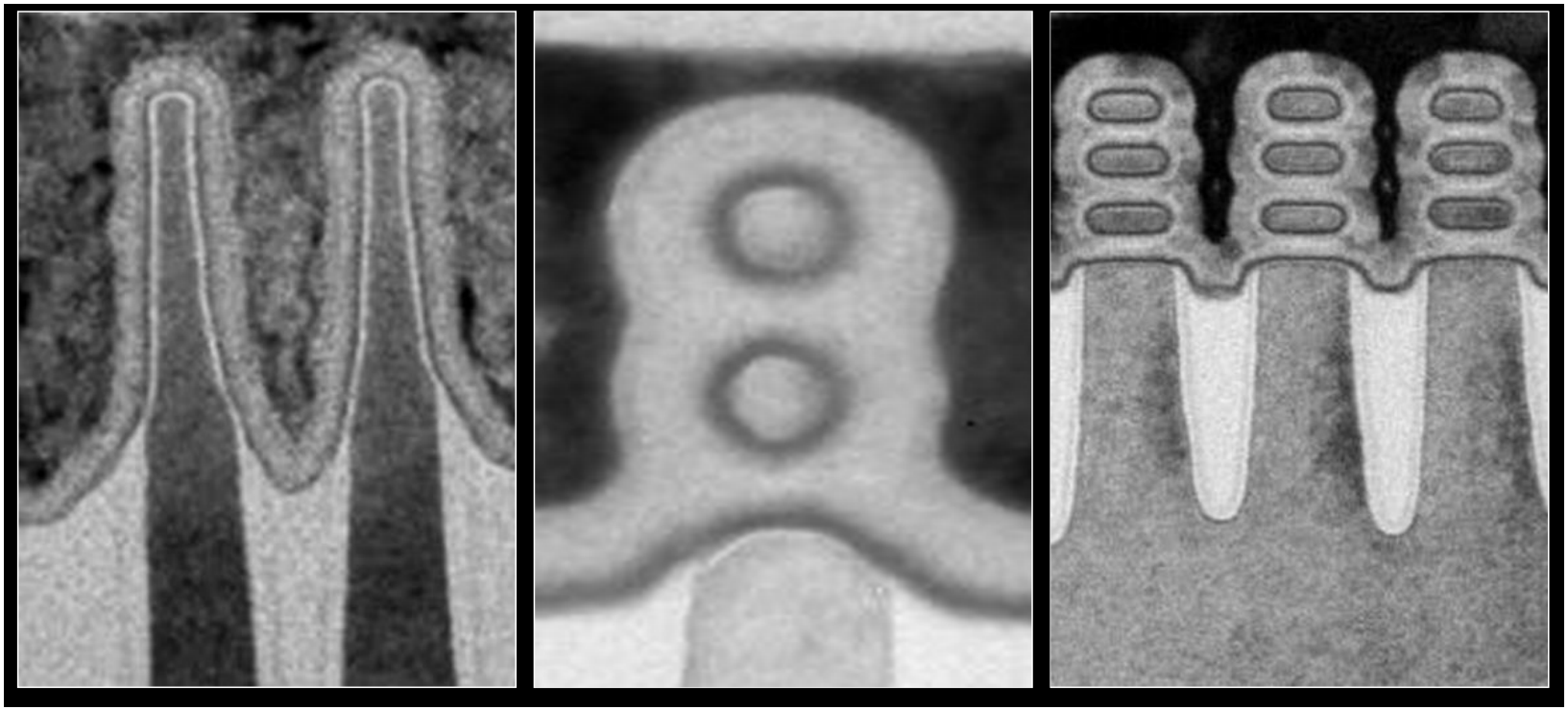
- **Will silicon and CMOS be our workhorse forever ?**
  - **How can new technologies emerge as competive solutions ?**
- Will classical computing be superseeded by new paradigms ?
  - Will we change our computational thinking ?
- Will living matter and computers merge ?
  - How will we enable an evolution of the human species ?

Will post-CMOS tecnologies be **always** the technologies of the future?



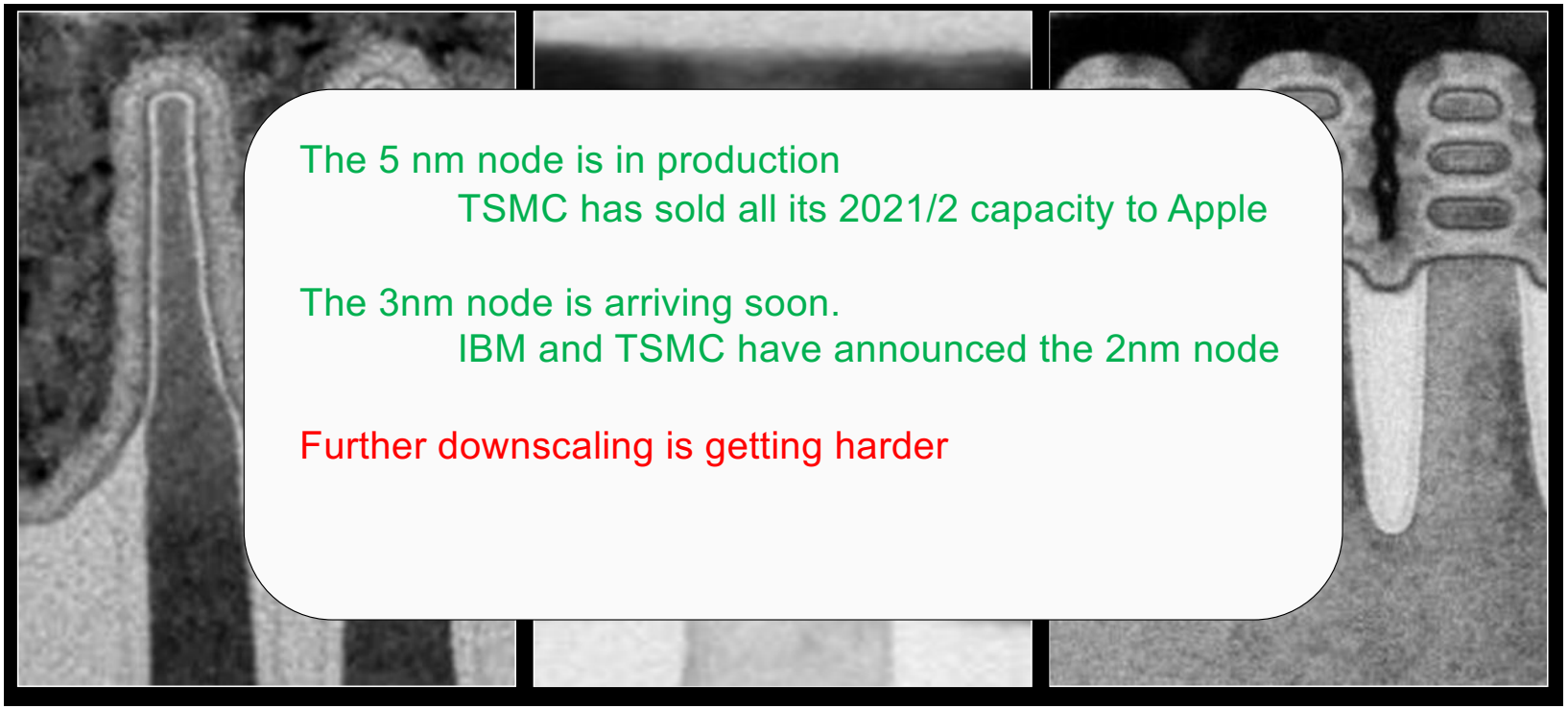
[Hills, Nature 19]

CMOS today: FINFETs, NanoWires and NanoSheets



[INTEL, 2017]

CMOS today: FINFETs, NanoWires and NanoSheets



The 5 nm node is in production

TSMC has sold all its 2021/2 capacity to Apple

The 3nm node is arriving soon.

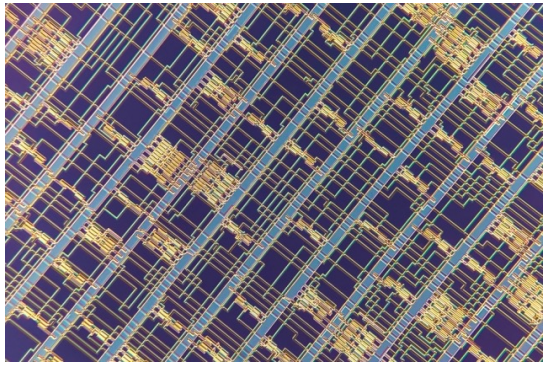
IBM and TSMC have announced the 2nm node

Further downscaling is getting harder

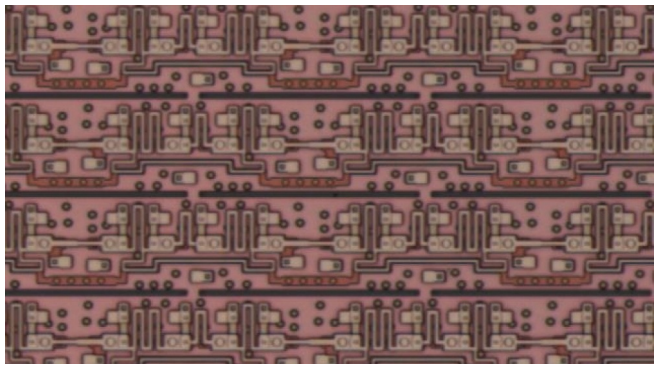
[INTEL, 2017]

Tomorrow?

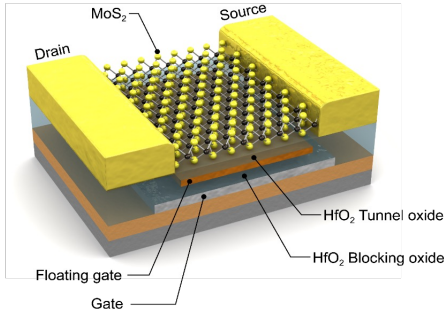
A plurality of technologies may be combined to achieve acceleration of computation and communication



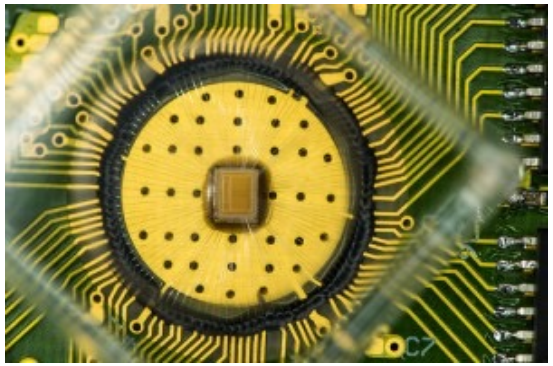
[Shulaker, MIT 2021]



[RFSQ, Lincoln Labs, 2020]

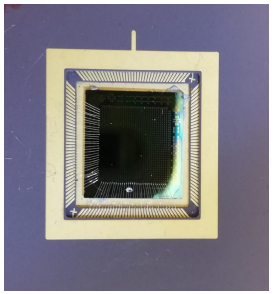


[Kis, Nature, 2011]



[Boybat, IBM 2020]

[Ramey, Hot Chips, 2020]

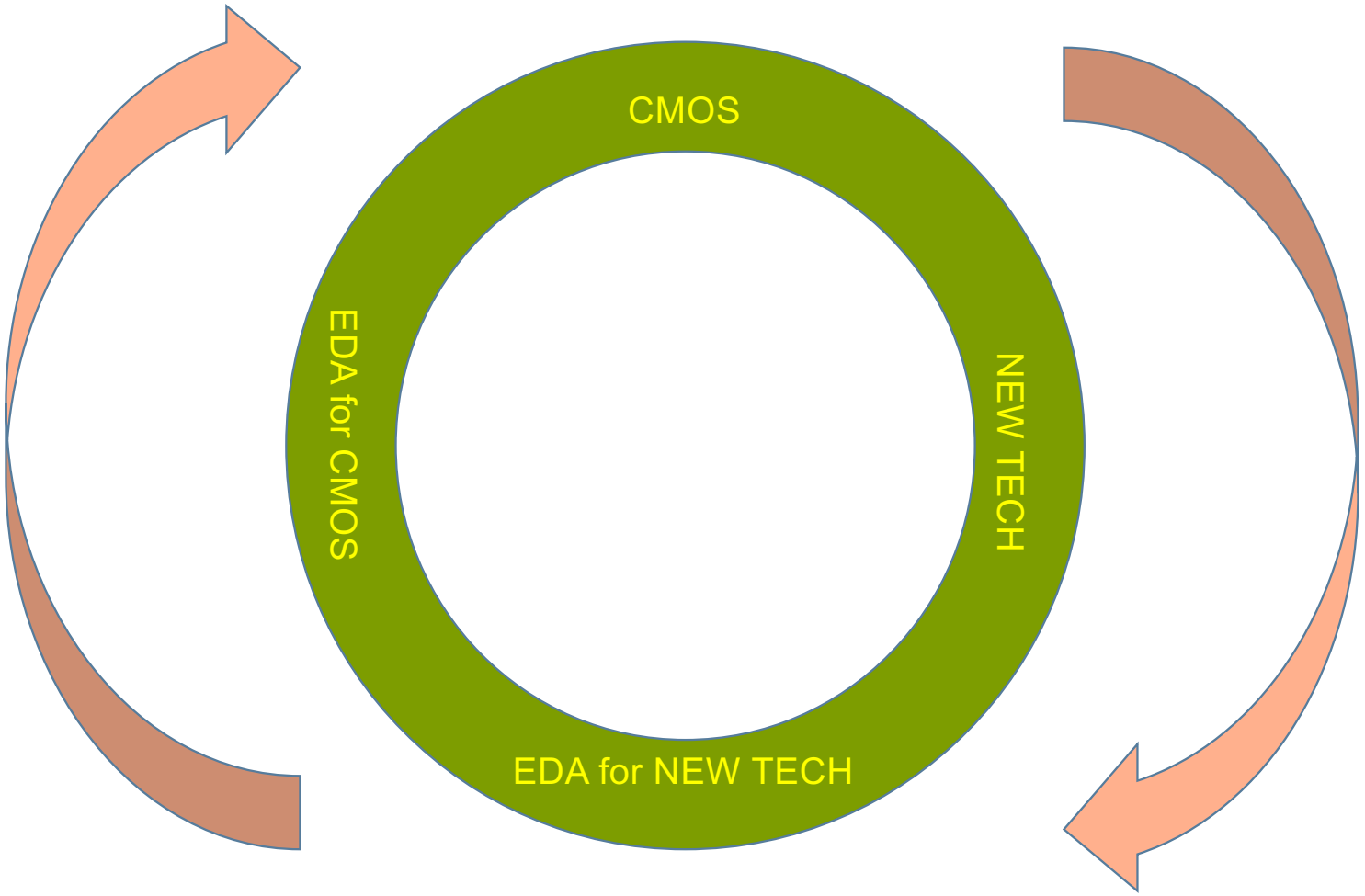


[Kis Nature, 2020]

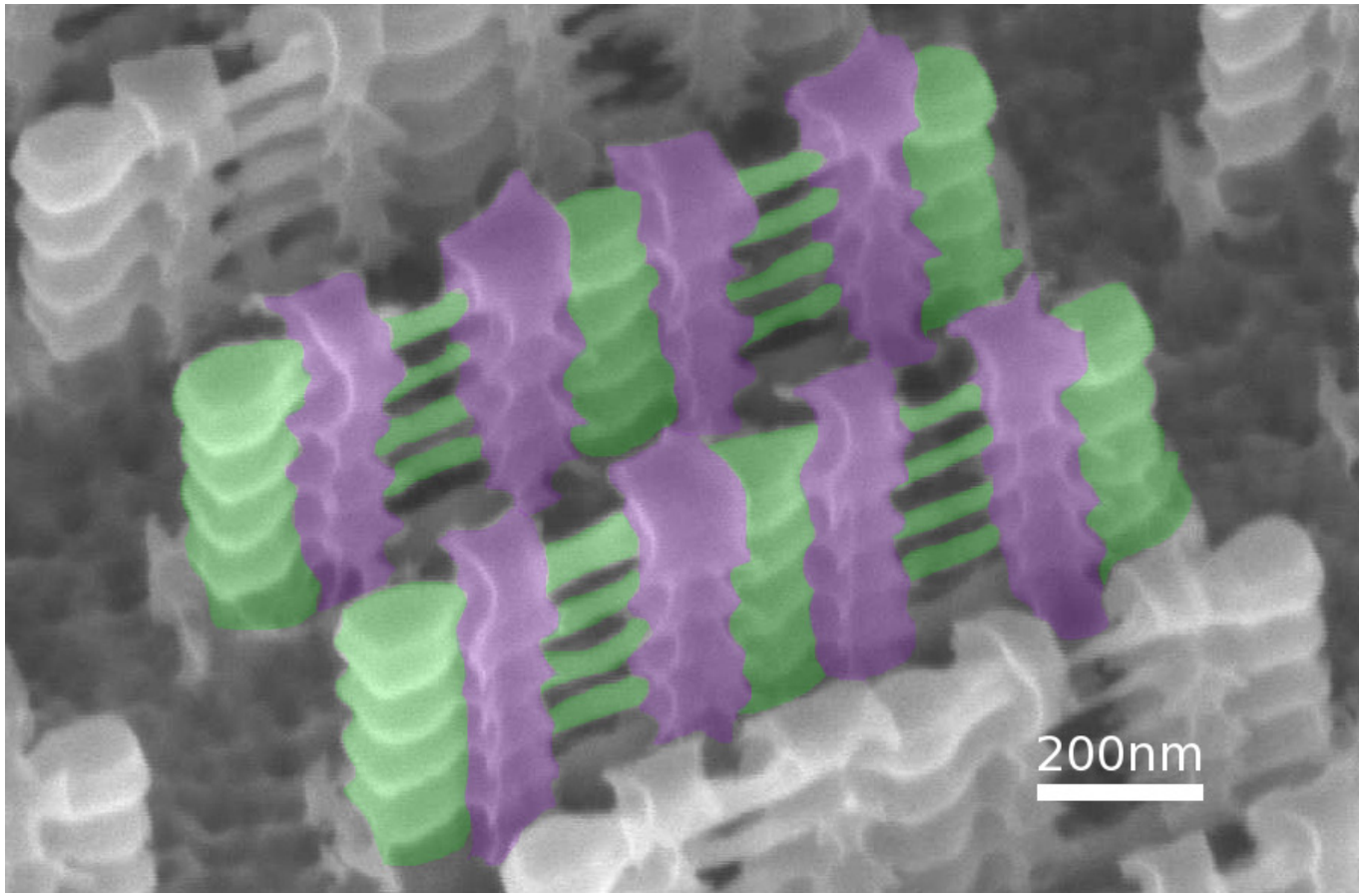
The challenge

- Where is the competitive advantage?
  - Application-specific accelerators
- What is the effort to design in a new technlogy?
  - New models
  - Adapting/creating EDA tools
- Is this a new design paradigm?
  - How disruptive/instructive is the new technology?

Loop



Controlled-polarity xtors on Si NanoWires



[De Marchi, IEDM, 2012]

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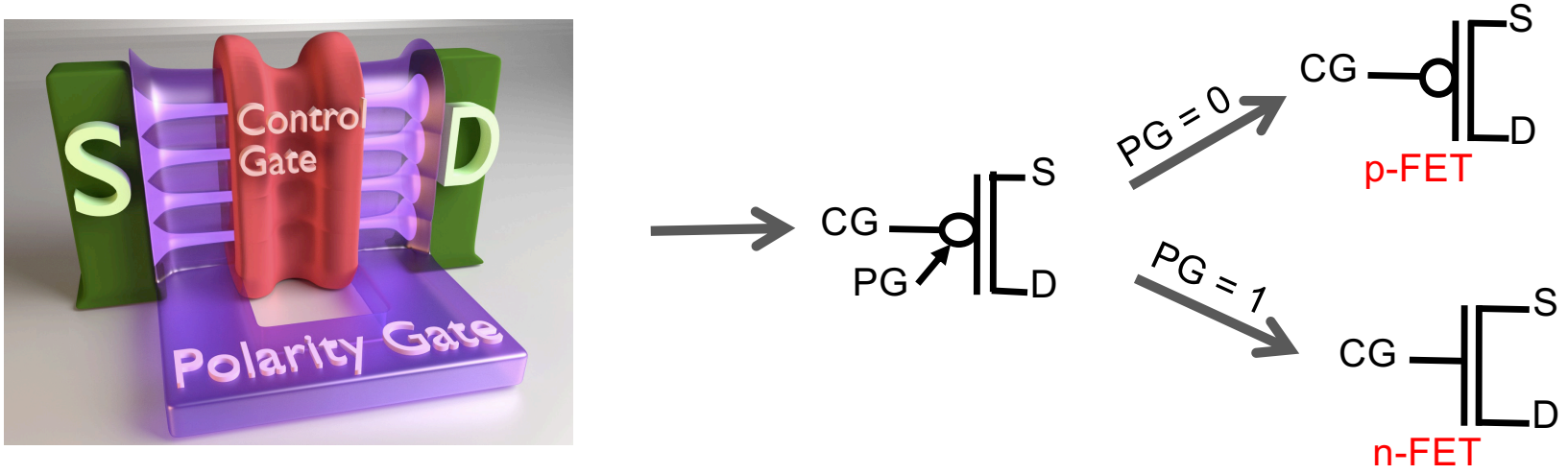
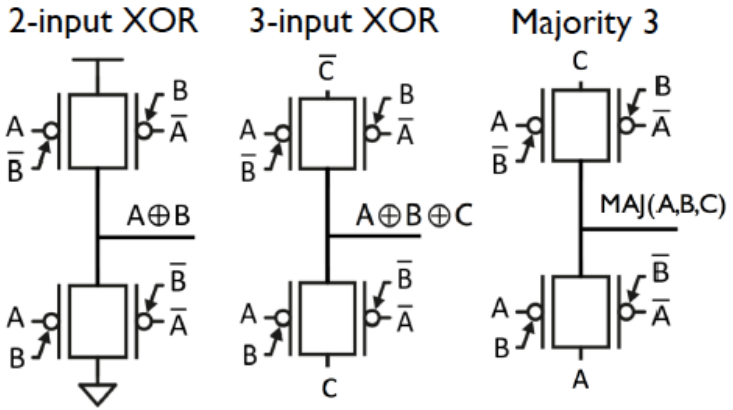


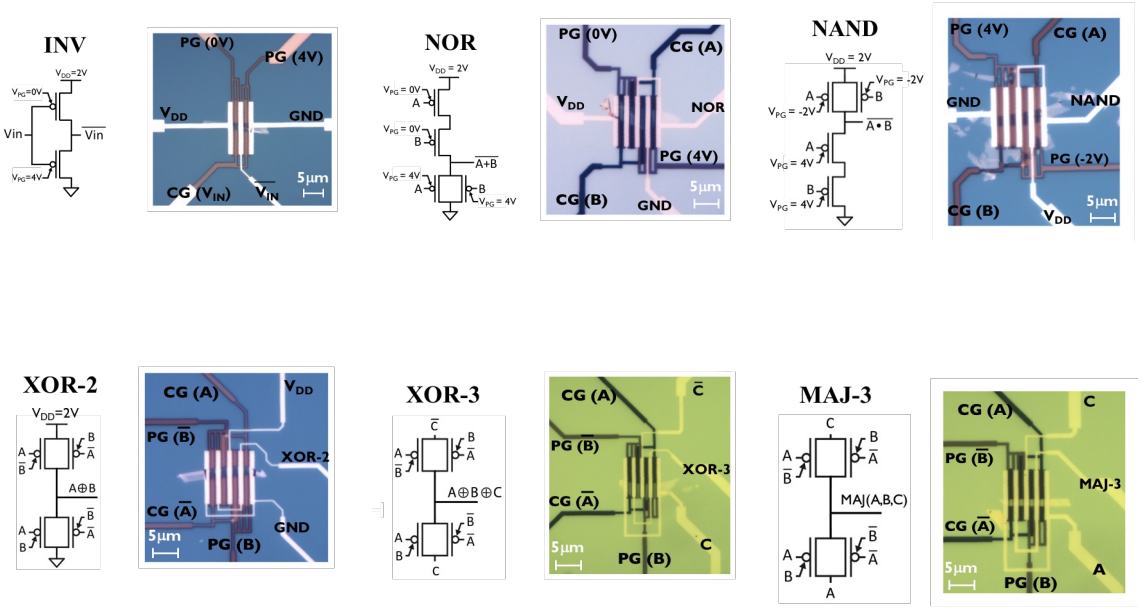
- *Electrostatic doping*
- Electrically program the transistor to either *n-type* or *p-type*
- Comparator-activated switch

Controlled-polarity xtors

- New gate topologies



- Cell library in WSe_2



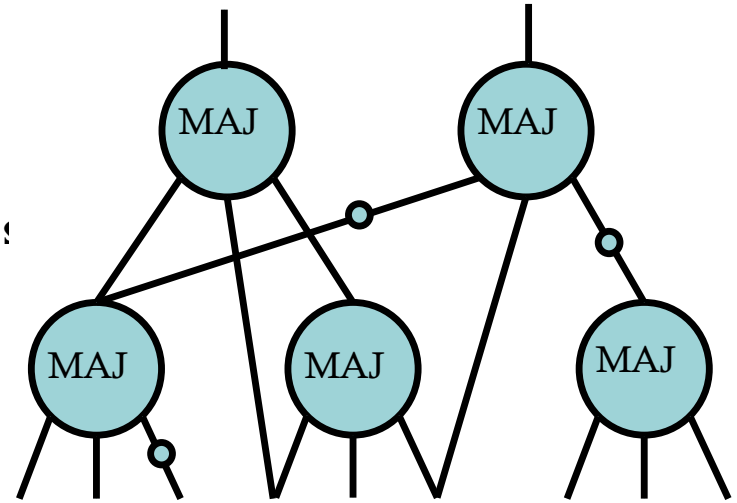
[Resta *et al. ACS Nano*, 2018]

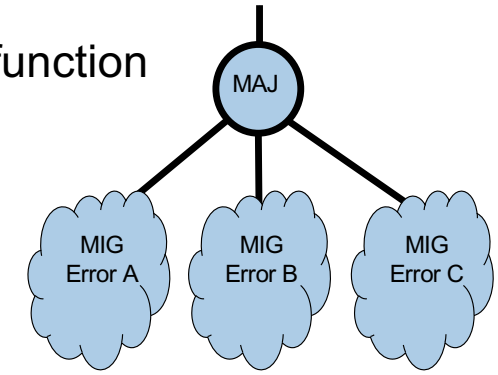
The logic abstraction

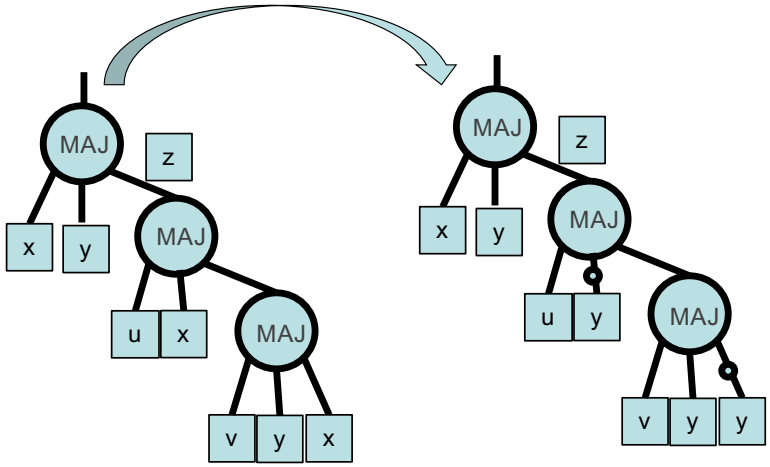
- We have designed for decades with NANDs/NORs in mind
- The majority operator is
  - Key to all arithmetic block design (e.g., carry function)
  - Native model for superconductors, non-volatile LiM, controlled-polarity transistors
- The majority Boolean algebra has strong properties
  - Majority-based EDA tools perform better in synthesis
  - In emerging and established technologies

EDA for emerging => established technologies

- Models
  - The majority algebra
  - Majority inverter graph
    - Reachability property
- Algorithms
  - Algebraic rewriting
    - Based on axioms and combination thereof
  - Boolean methods
    - Exploit redundancy of majority function
    - Boolean substitution







EDA for emerging => established technologies

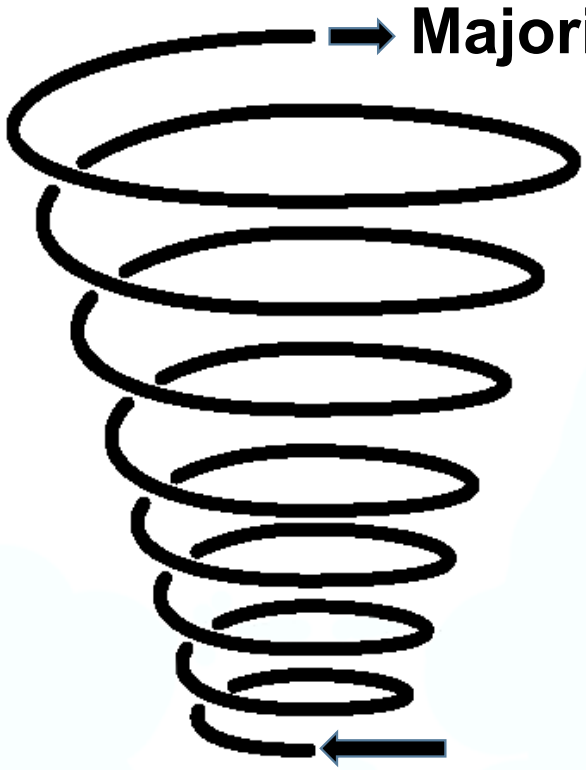
Majority-based algorithms:

improve commercial and academic logic synthesis for **CMOS**
15-20% delay reduction as compared to earlier methods

are very successful for many **emerging technologies**, like:

superconducting electronics
optical/wave based computing
logic in memory

Back to the future



Majority for superconducting electronics

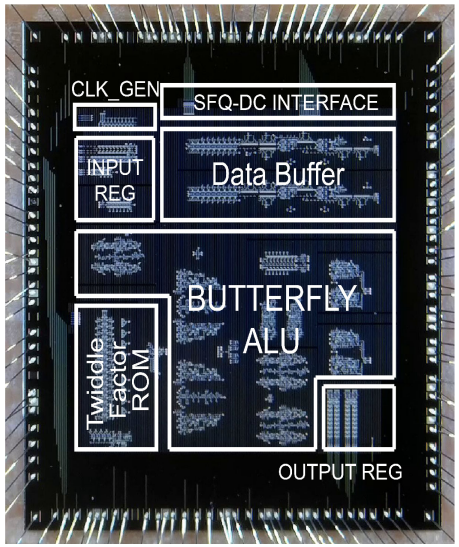
Majority for CMOS

Majority for CP devices

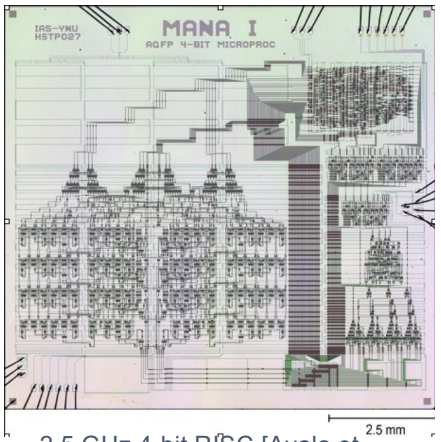
Controlled-polarity devices

Superconducting electronics

- Technology
  - No parasitic resistance at low temperature (4K)
  - Information by *quantized pulses* $\int V(t)dt = \varphi_0 = h/2e = 2.07$ mv ps
- Design features
  - *Classic computing paradigm* with *deep pipelined* logic
  - Ultrafast computation with small energy consumption
  - Many variants including adiabatic operation
- Majority logic is the native abstraction in some realizations

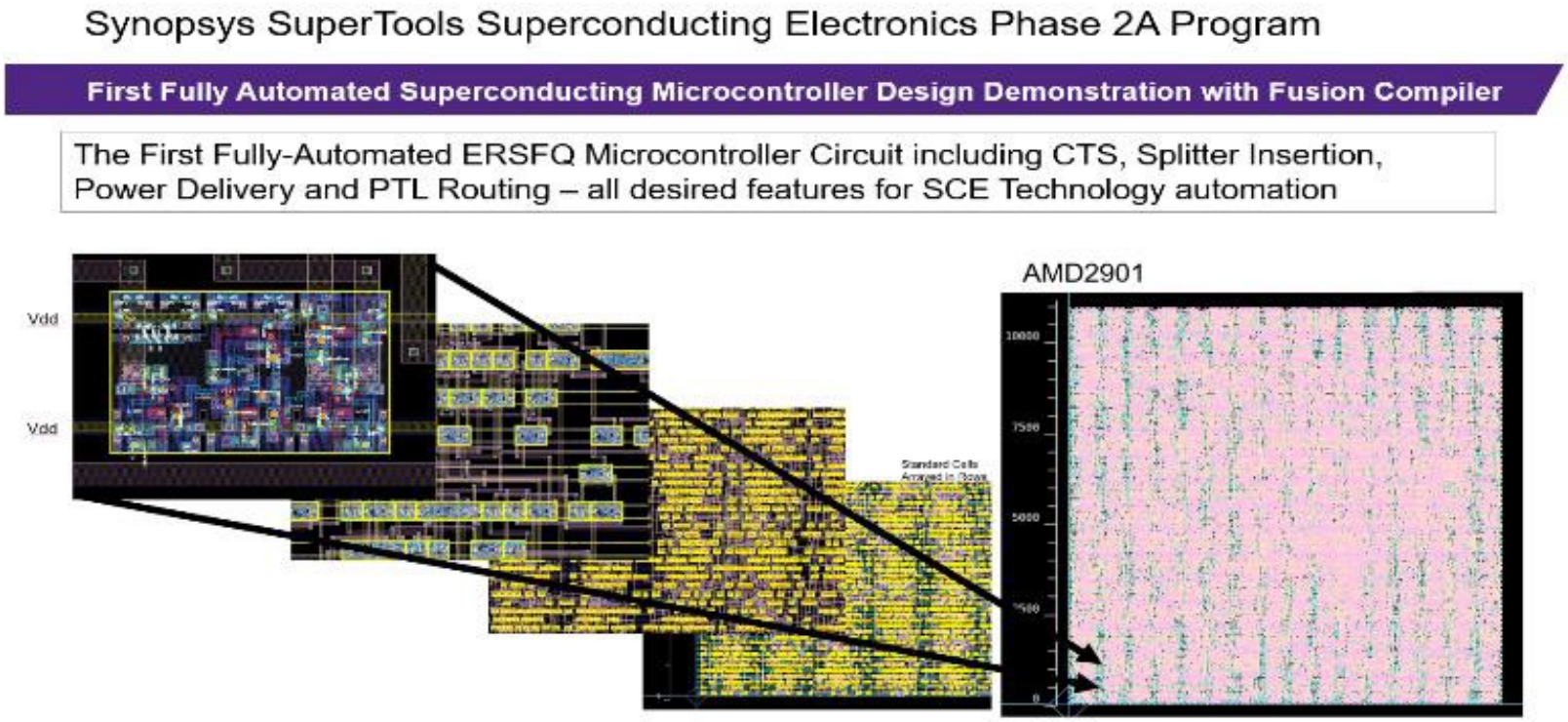


47 GHz SFQ FFT Processor [Ke et al.,2021]



2.5 GHz 4-bit RISC [Ayala et al.,2021]

Achievements



Fully synthesisized AMD 2901 [Amaru et al., 2021]

Superconducting electronics

Logic	Clock Freq. [GHz]	$E_{bit} / I_c\Phi_0$	Typical I_c [mA]	EDP [aJ·ps]
CMOS	4	-	-	~10^5
RSFQ [1]	50	19	150	120
eSFQ [2]	20	0.8	150	12
RQL [3]	10	0.33	150	10
LV-RSFQ [4]	20	3.5	150	54
AQFP [5]	5	0.0083	50	0.086
Quantum limit	-	-	-	5.3×10^{-5}

[1] X. Peng et al., IEICE Trans. Electron. **E97.C**, 188 (2014).
[2] M. H. Volkmann et al., Supercond. Sci. Technol. **26**, 015002 (2013).
[3] Q. P. Herr et al., J. Appl. Phys. **109**, 103903 (2011).
[4] M. Tanaka et al., IEEE Trans. Appl. Supercond. **23**, 1701104 (2013).
[5] N. Takeuchi et al., Supercond. Sci. Technol. 28, 015003 (2015).

Superconducting electronics

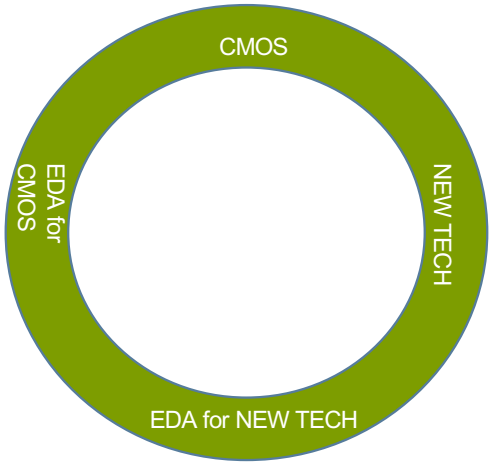
Superconducting electronics:

- gives a support for ultrafast accelerators
- low-power consumption
- bridge to quantum computing chips

Requires

- new EDA toolchain
- improvement in refrigeration technology

The broader impact



- EDA is a technology enabler
  - Early evaluation of emerging technologies
- Virtual laboratory for technology evolution
  - Physical models of emerging technologies
    Motivates new abstractions and computational methods
- New algorithms have beneficial effects on established technologies as well
  - Despite decades of progress in EDA, we are still far from optimality in many directions

The broader impact

The combination of:

- new application requirements
- new emerging technologies
- new design tools

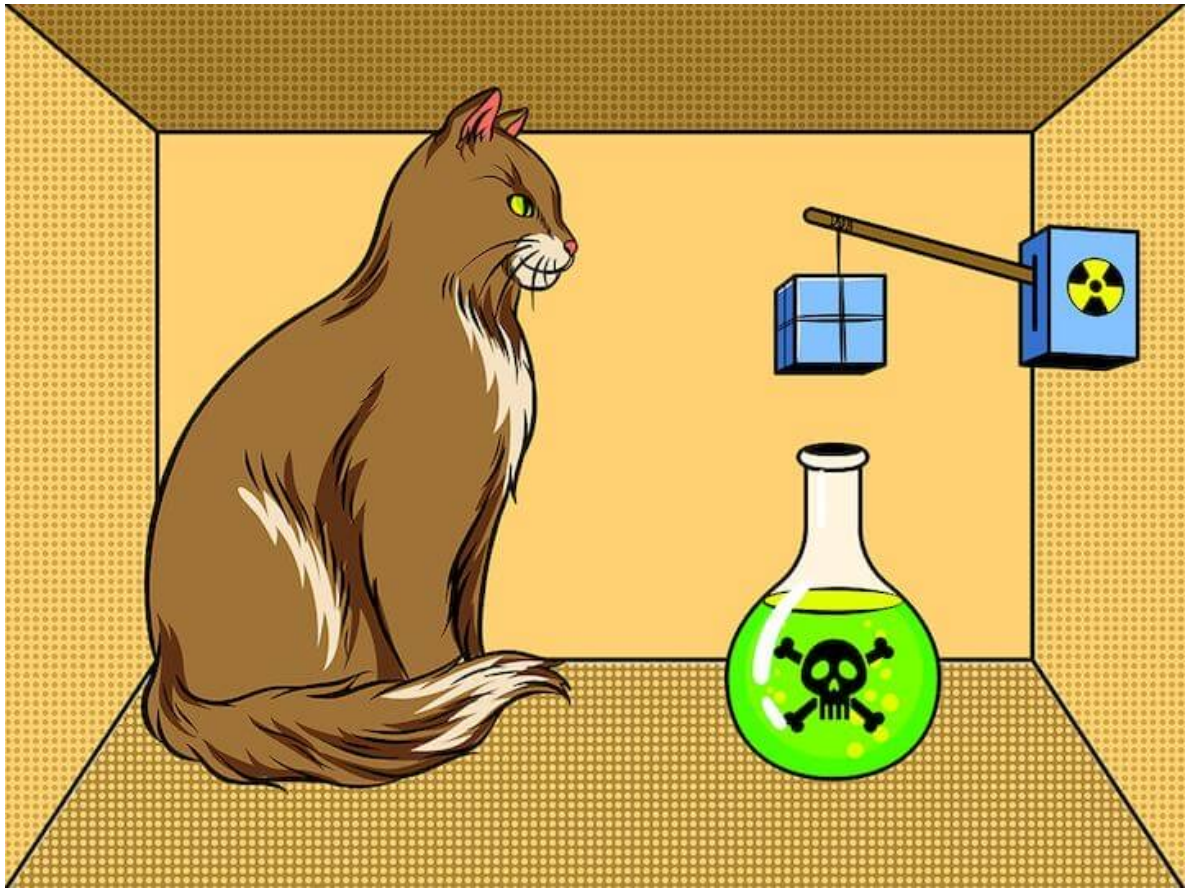
will enable us to design new families of computing systems

Progress will be on a spiral, and EDA is the compass

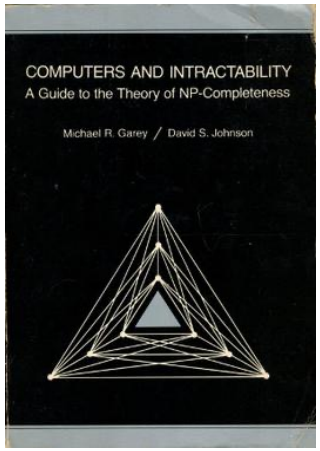
Calling the questions

- Will silicon and CMOS be our workhorse forever ?
  - How can new technologies emerge as solutions ?
- **Will classical computing be superseeded by new paradigms ?**
  - **Will we change our computational thinking ?**
- Will living matter and computers merge ?
  - How will we enable an evolution of the human species ?

Quantum or not quantum? This is the question!

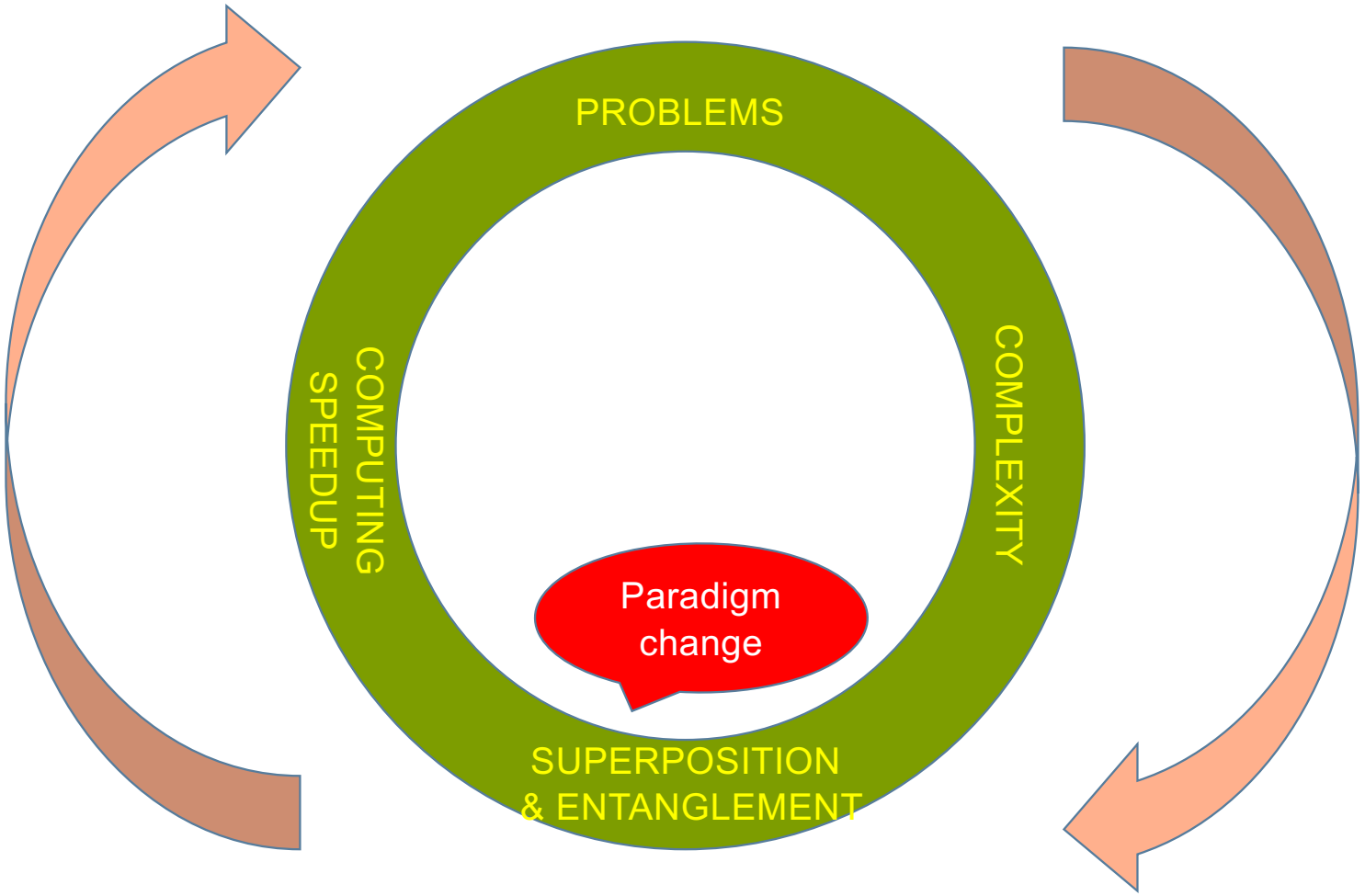


Quantum computing



- Why?
  - Our insatiable appetite for computing power
  - Most problems that are relevant are also computationally intractable
- QC provides an accelerator technology that is applicable to some problems
  - Factoring (post-quantum security)
  - Searching (universally used)
  - Quantum algorithm zoo (useful reference website)
- Today (2022) quantum computing is still a complex and fragile technology
  - Requires a specific environment (refrigeration or vacuum)
  - Limited by *coherence time* and *error rates*
- Several QC chips have proven to be successful and likely to scale-up

Loop

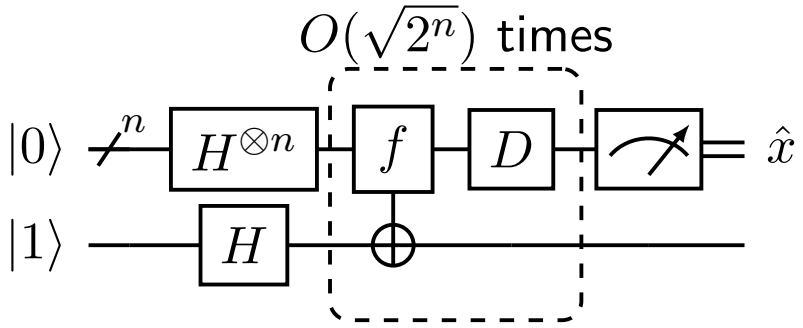

PROBLEMS
COMPLEXITY
SUPERPOSITION
& ENTANGLEMENT
COMPUTING
SPEEDUP
Paradigm
change

Relevant issues

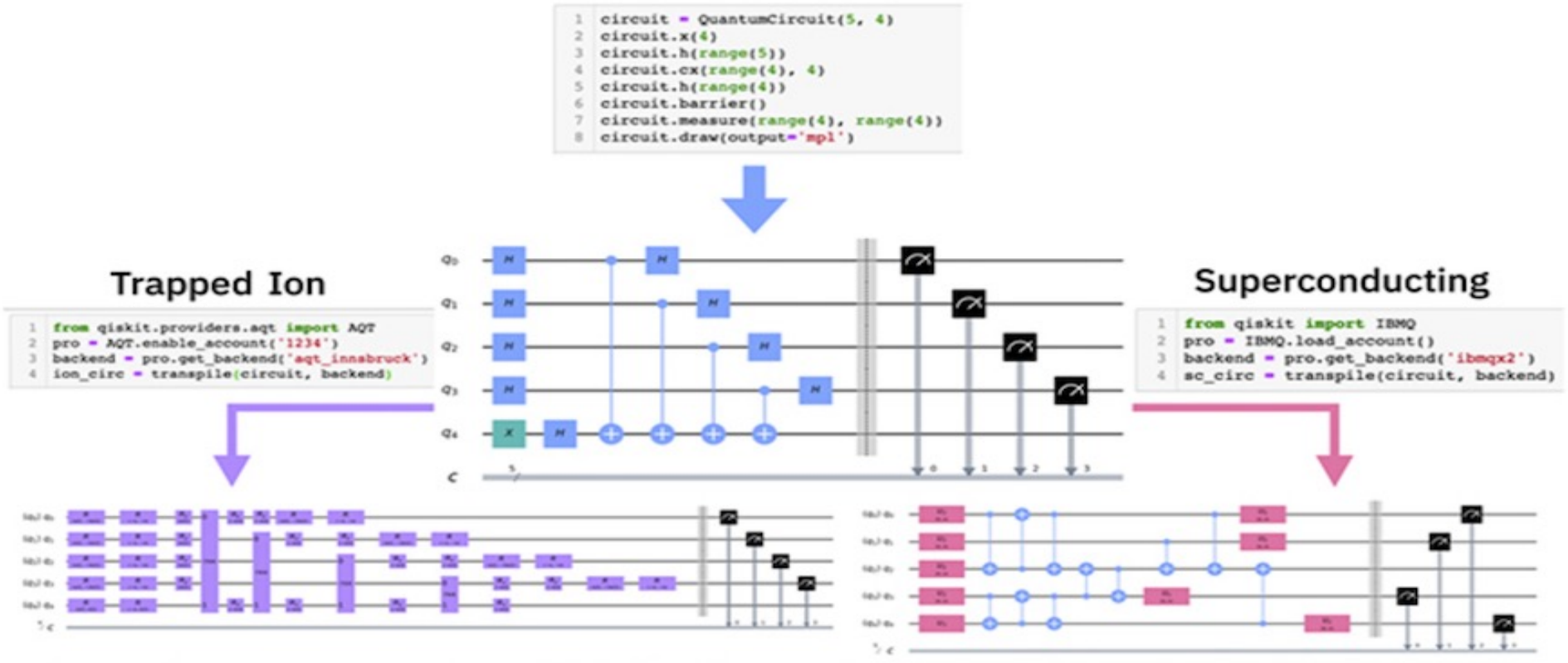
- How will we conceive algorithms for quantum computing?
- How will we create an environment for quantum coding and debugging
  - Languages, abstractions, cross-layer design
- Quantum compilation
  - Retargetable optimizing compilation
- Physical design of quantum chips and interfaces

Parallelism, superposition and entanglement

- How far can we think in a parallel way?
  - Can we envision a multiverse with exponentially-growing situations?
- How easily can we abstract parallel computation
  - Language and graphic models
    - High-level and low-level primitives
- How can we compile a model?
  - Technology-independent optimization
    - Reversible logic synthesis
  - Gate library and mapping
    - Clifford+T



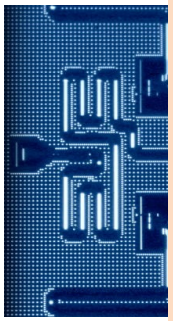
Quantum compilation

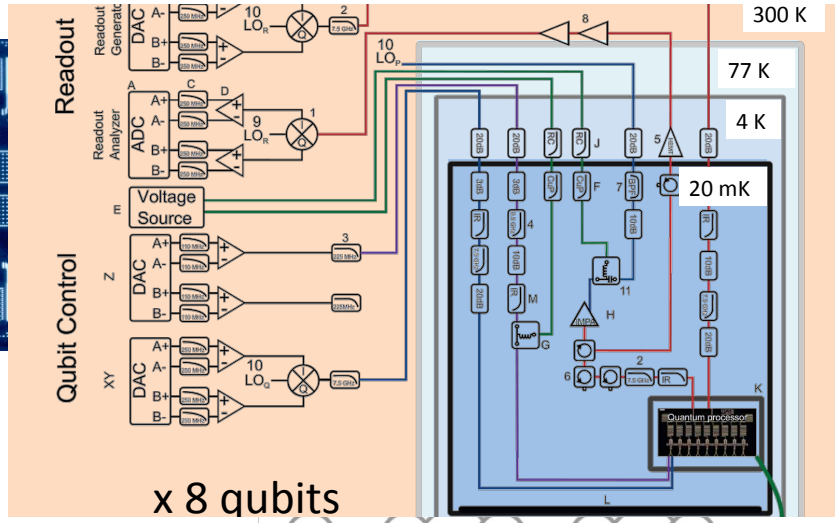


[Source: IBM]

Quantum physical design

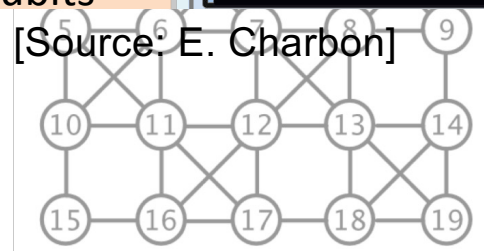
- Regular topology
  - Placement, routing
- Satisfying coupling constraints
  - Embedding *coupling graph* into mesh
- Interfacing
  - Analog, RF design and interfacing computation
- Determining *temperature transition boundaries*
  - Move control electronics to intermediate temperature
  - Move QC to higher temperature





x 8 qubits

[Source: E. Charbon]



[IBM Q20]

IBM’s Q

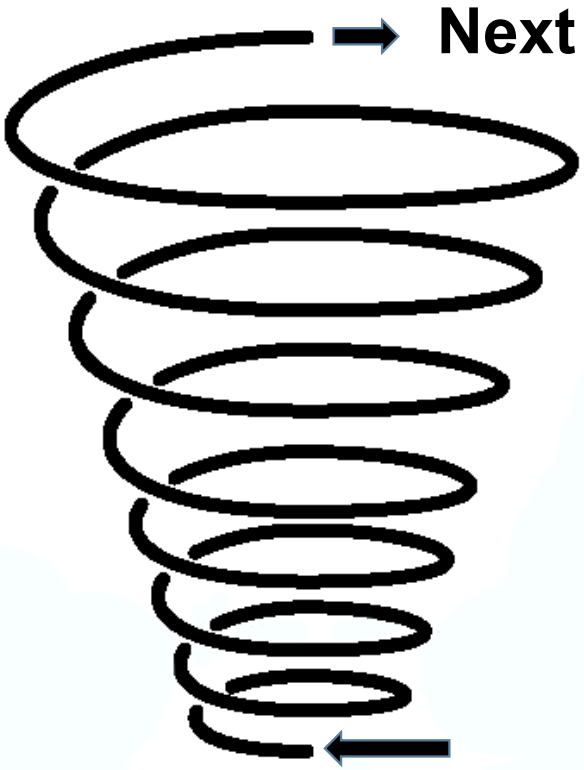
[Courtesy: IBM]

Quantum EDA

- Using QC for EDA:
  - Quantum optimizers for combinatorial optimization
    - Faster, not necessarily exponential advantage
  - Quantum semidefinite programming
    - Approximate solutions with exponential advantage
  - Searching
    - Grover's algorithm with square root advantage
- Most EDA problems do not need exact solutions
  - But need fast execution on large problem instances
- Enabler to build 'better' computers!

[Ragunathan and Stok 2020]

Back to the future



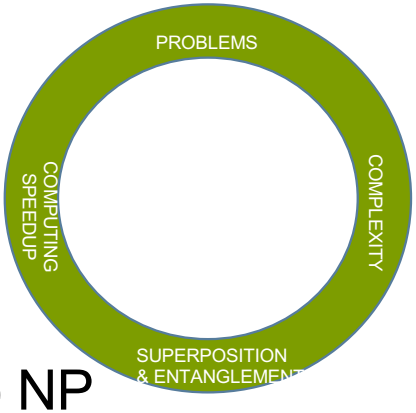
Next generation quantum computing

Quantum EDA

Quantum computing

2.5 GHz 4-bit RISC [Ayala et al.,2021]

The broader impact



- Advances in theory of computation
  - BQP - *bounded error quantum poly time* - includes P but not (?) NP
- Evolution in security
  - Post-quantum cryptography
- Solutions (approximate) to quantum chemistry and physics problems
  - NISQ – *noisy intermediate-scale quantum computing*
- Solutions (exact) to large instances of computatior oblems
  - Quantum error correction is needed
  - Practical demonstration of large-scale quantum chips yet

The broader impact

The combination of:

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- new computing paradigms
- new design tools

will enable us to design new families of computing systems

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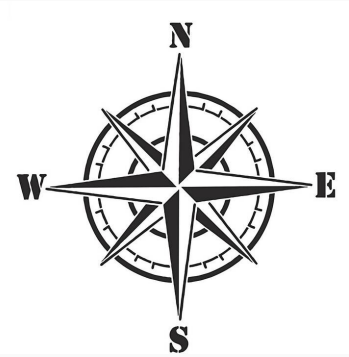

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- Will classical computing be superseeded by new models ?
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- **Will living matter and computers merge ?**
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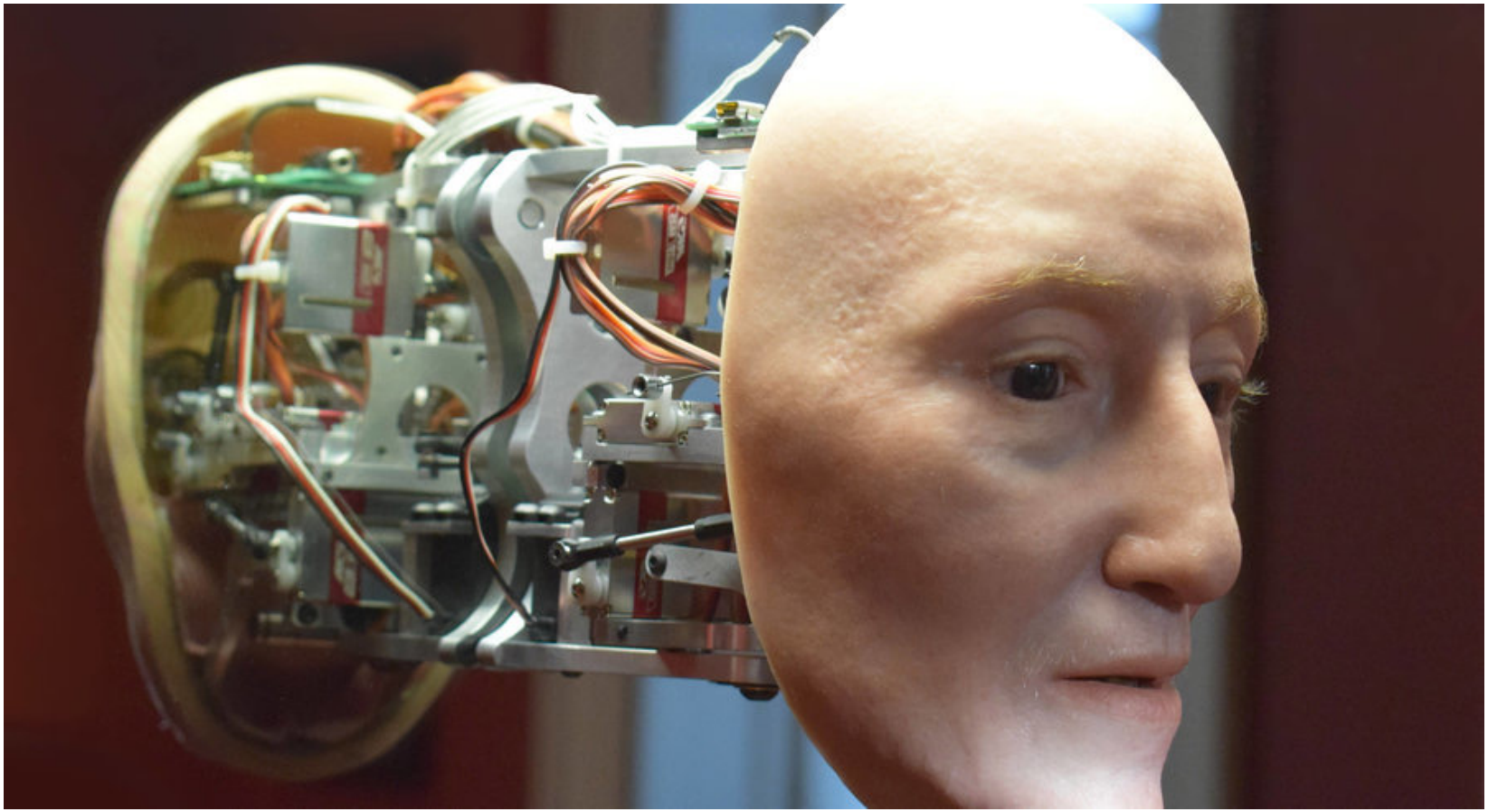
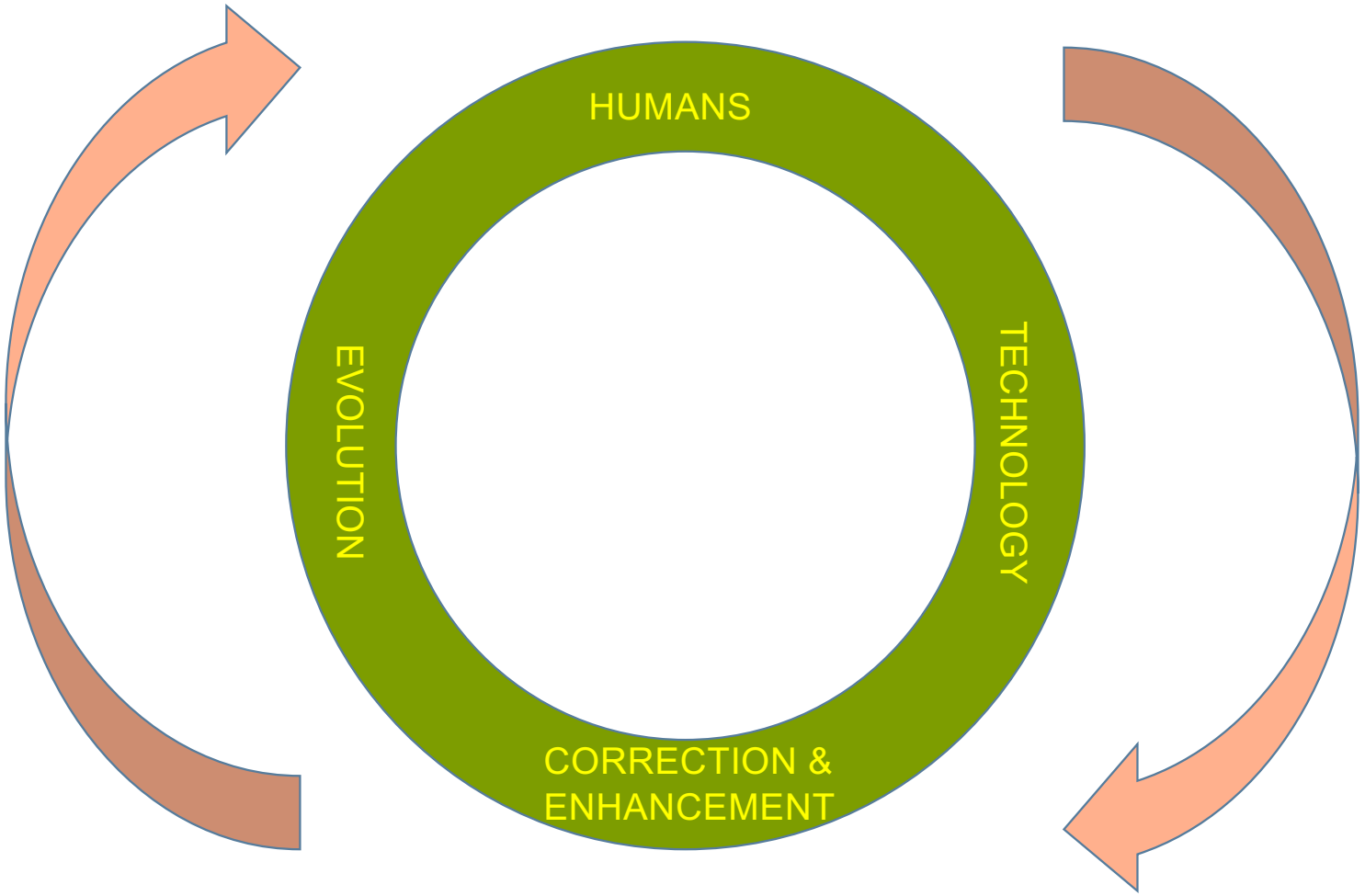
Science for life, life for science



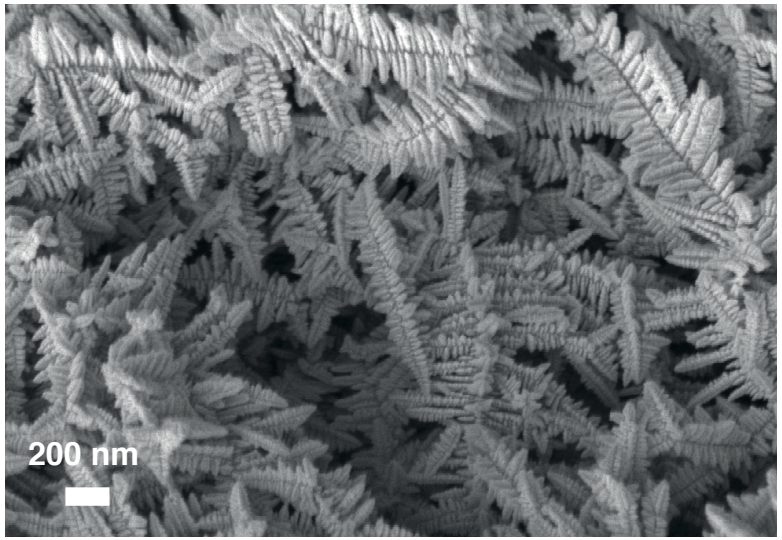
[The “Mask of youth” by Math Collischaw, 2018]

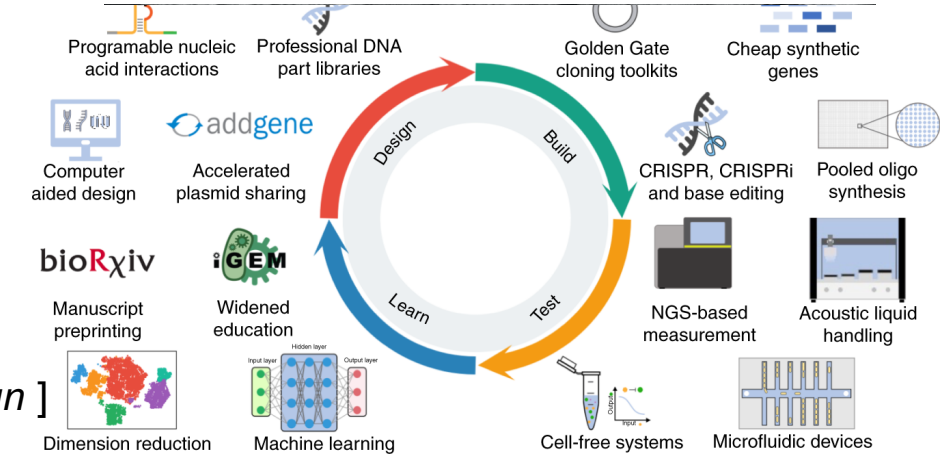
Loop



From biodiscovery to synthetic biology

- DNA microarrays and sequencing chips
  - Cluster analysis
- Bio-sensors for proteins and ions
  - Fusing electronics with sensor technology
- Design automation support for gene editing
  - CRISPR/CAS9 technology
- Synthetic biology
  - Creating artificial forms of life



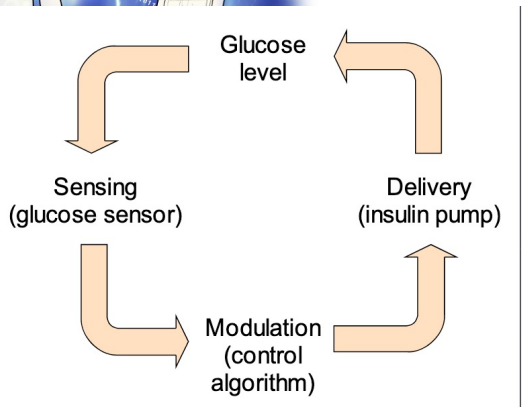


[Meng & Ellis,The second decade of synthetic biology. *Nat Commun*]

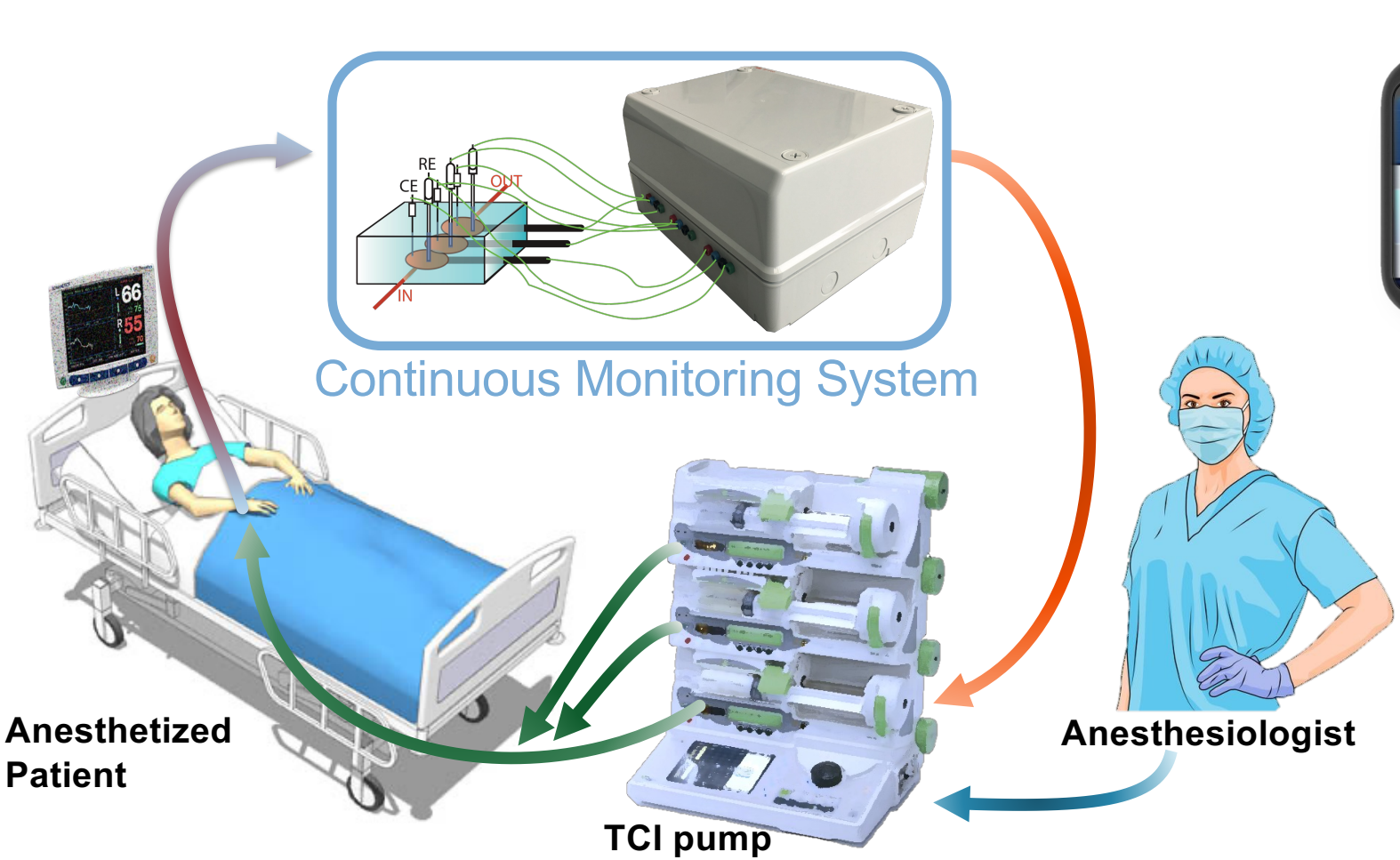
Tele-medicine: monitoring chronic patients

- Non-invasive monitors
  - Heart rate, SpO_2, blood pressure
- Implanted monitors:
  - Metabolites: glucose, lactate, cholesterol
  - Continuous measurements transmitted *off body*
- Wireless challenges
  - Secure transmission
  - Remote powering
- Closing the *feedback loop*?
  - Artificial organs (e.g., pancreas)

[Courtesy: Smartcardia]



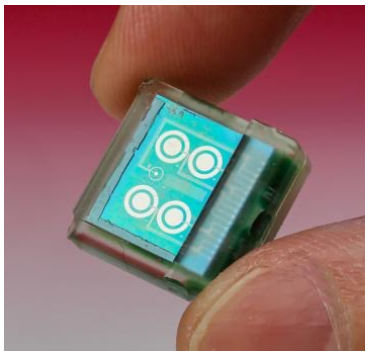
Precision medicine: anesthesia control



[F. Stradolini, E. Lavalle, et al., EAI Mobihealth 2016]

Where is EDA in bio-engineering ?

- Model, analyisis and design of new circuits and architectures
  - Linking living matter to computational systems
  - Low-power, low-noise circuits, flexible electronics
- Support the co-design of sensors and electronics
  - Integrated sensing units with regular design
- Semicustom design for integrated sensing units
  - Cell libraries of CMOS compatible sensors
  - Reduce *non-recurrent engineering costs* (NRE) of integrated sensors

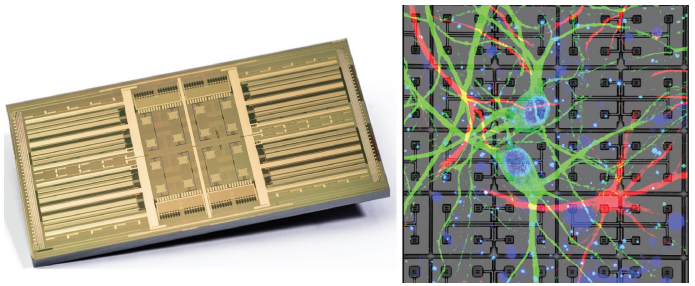


[Baj-Rossi et al, 2016]

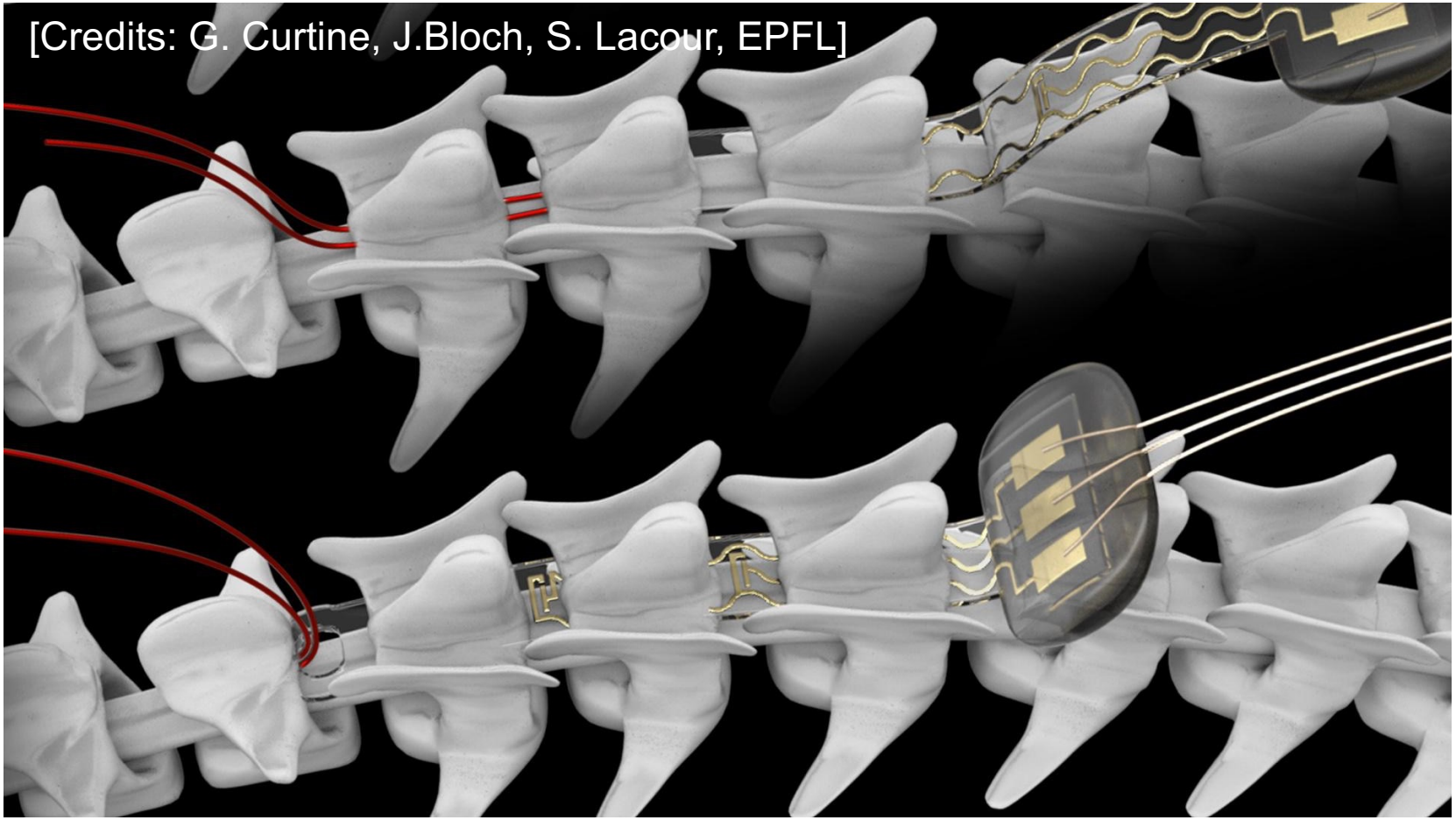
The ultimate challenge: the brain

- Understanding and mimicking the brain
  - Decoding and understanding the brain signals
  - Developing neuromorphic computing and learning models
- Brain-machine interfacing goals:
  - Controllability, observabity and connection
- Stimulating the human brain
  - Treatment of *Parkinson* and *amyotrophic lateral sclerosis* (ALS) diseases
- Brain on a chip:
  - Electronics communicating with neurons grown on chip

[Braeken, imec, 2020]



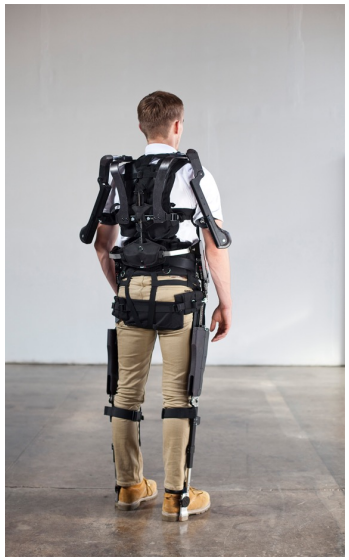
Restoring locomotion



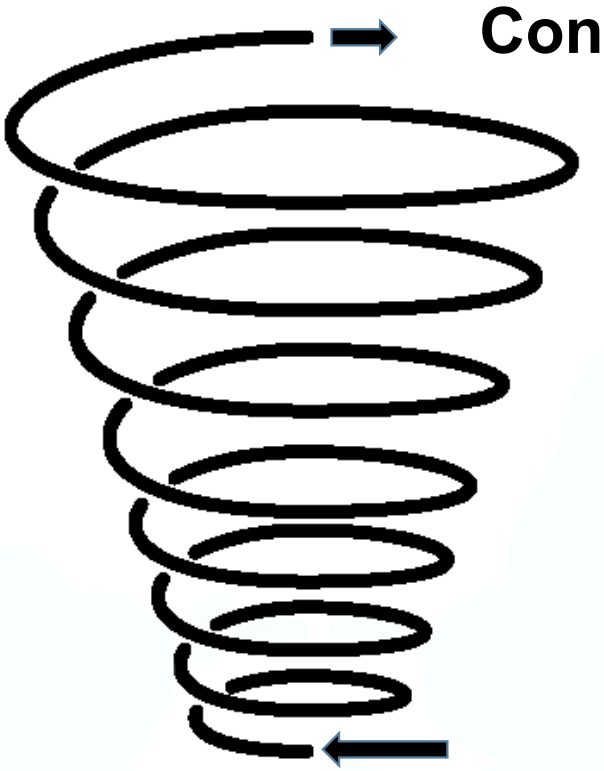
Restoring locomotion

Human enhancement

- Reproductive enhancement
  - *In vitro* technonologies
- Physical enhancement
  - Cosmetic/orthotic prostethics, artificial organs
- Mental enhancement
  - Nootropics, supplements to mental functions
  - Tablets, phones, watches
- Challenges
  - Extend our thinking depth and breath
  - Create seamless interconnection



Back to the future



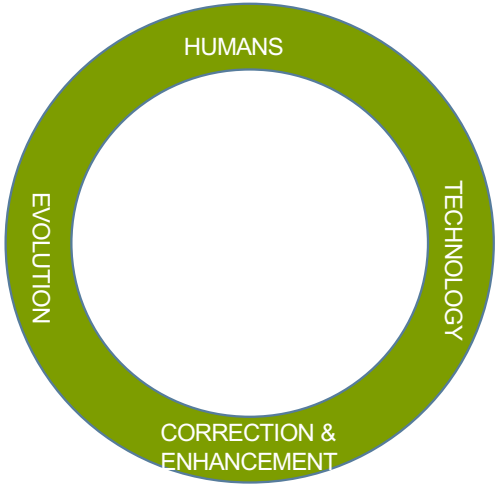
Connected humans

Interfacing neurons and edge devices

Internet of things

2.5 GHz 4-bit RISC [Ayala et al.,2021]

The broader impact



- Technology allows us to interface to living matter
  - Enormous progress in medicine and in biodiscovery
- EDA is a fundamental enabler
  - To design new architectures that interface and connect to living bodies
- The next level:
  - From brain to mind
  - Connecting artificial and natural intelligence

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The broader impact

The combination of:

advances in biology and medicine
new electronic and interfacing technologies

will enable us to design bio-medical systems to live better

It will enable us to connect the … dots

nano-tera.ch

Summary and conclusions

- *Natura non facit saltus* – nature does not make jumps
  - Engineering evolution is a spiral process involving various domains
- *Natura facit saltus* – nature makes jumps
  - Quantum mechanics brings us new way of understanding and computing
- Bridging quantum and classic domains is an unsolved problem in physics
  - Many phenomena are not yet understood – still we leverage them
- Connecting humans to computing systems is a broad timely challenge
  - To better human existence with smart medicine and to enable our evolution

Thank You