Nanoscale MOSFETs and beyond CMOS devices

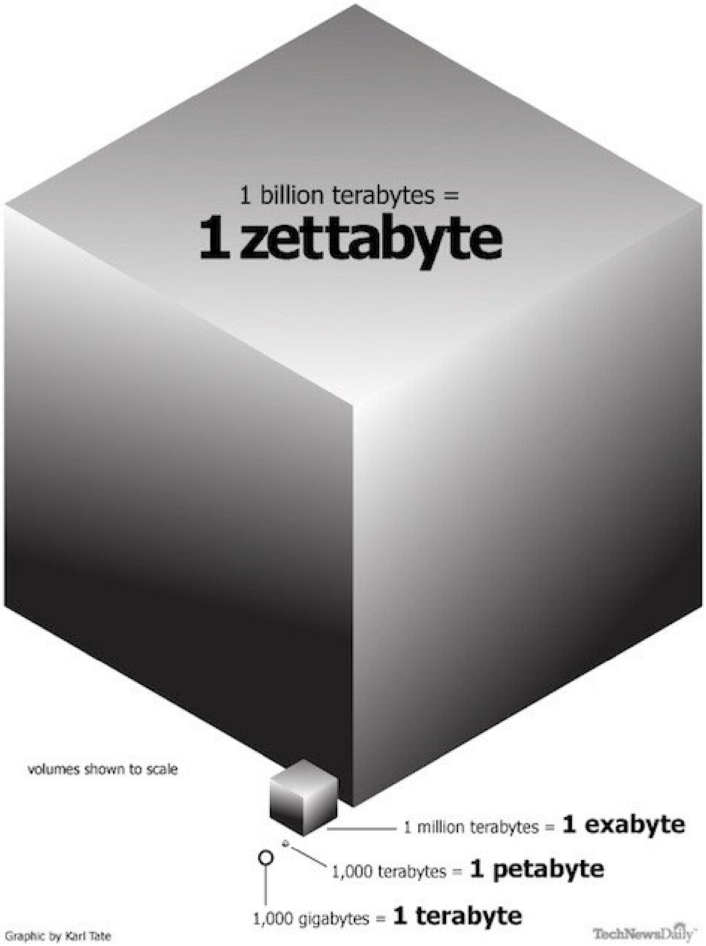
Adrian M. Ionescu, EPFL, Switzerland

Outline

- **Introduction to future electronic technologies in the Zettabyte era**
- The New Ecosystem of **Digital Transformation in Zettabyte Era**
- **Energy efficiency**: from devices to architectures
- **Cloud and Quantum Computing**
- **Edge Artifical Inteligence and Neuromorphic Computing**
- **Digital Twins**

INTRODUCTION

- **Introduction to future electronic technologies in the Zettabyte era**
- The New Ecosystem of **Digital Transformation in Zettabyte Era**
- **Energy efficiency**: from devices to architectures
- **Edge Artifical Inteligence and Neuromorphic Computing**
- **Cloud and Quantum Computing**
- **Digital Twins**

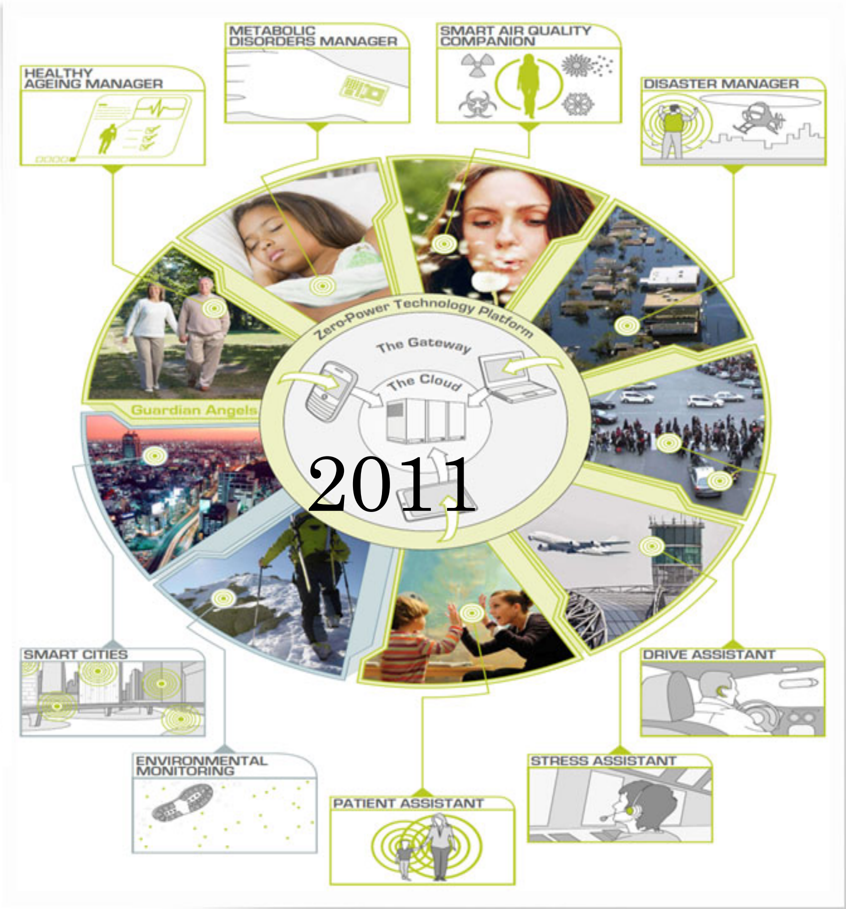


Iphone & Edge technologies….

- First wireless computer with sensors

2007

- Edge of the cloud technologies…



2011

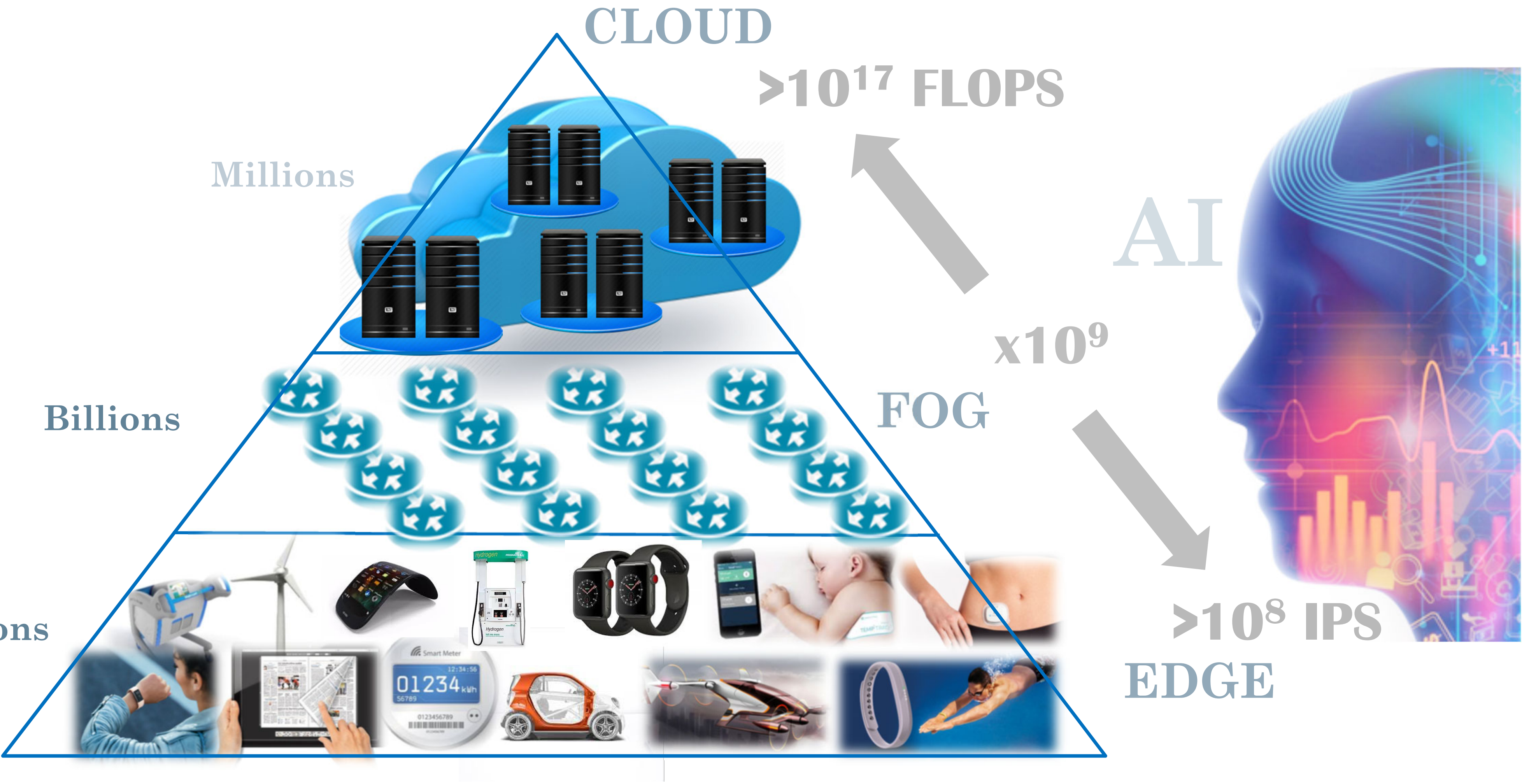
… for a smarter life: people want it…

- 2017: **500 million** edge IoT devices
- 2018: **more** edge IoT devices than Mobile phones
- 2022: **18 billion** edge IoT
- 2025: **50 Billion** Edge IoT devices

  11% of the world economy

  20% of energy use?!

Edge-to-Cloud Information Processing



CLOUD

$>10^{17}$ FLOPS

Millions

AI

x10^9

Billions

FOG

ons

$>10^8$ IPS

EDGE

What is required to compute AI?!

ImageNet 1-k benchmark:

90 epochs – with ResNet-50

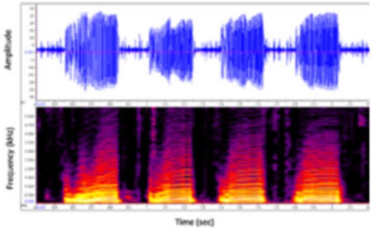
→ 10^{18} single precision ops

→ NVIDIA M40 GPU = 14 days!

The Cloud

Audio Analysis:

FFT(1024) ~ 10^5 operations ($5 \text{ N} \log_2(\text{N})$)
Audio Spectrogram /s: ~ 2×10^6 Ops.



Wearable Devices

Raw compute power is one thing,
Computational efficiency, i.e.
(Fl)ops per Watt is equally important!

?

~ x 10^9

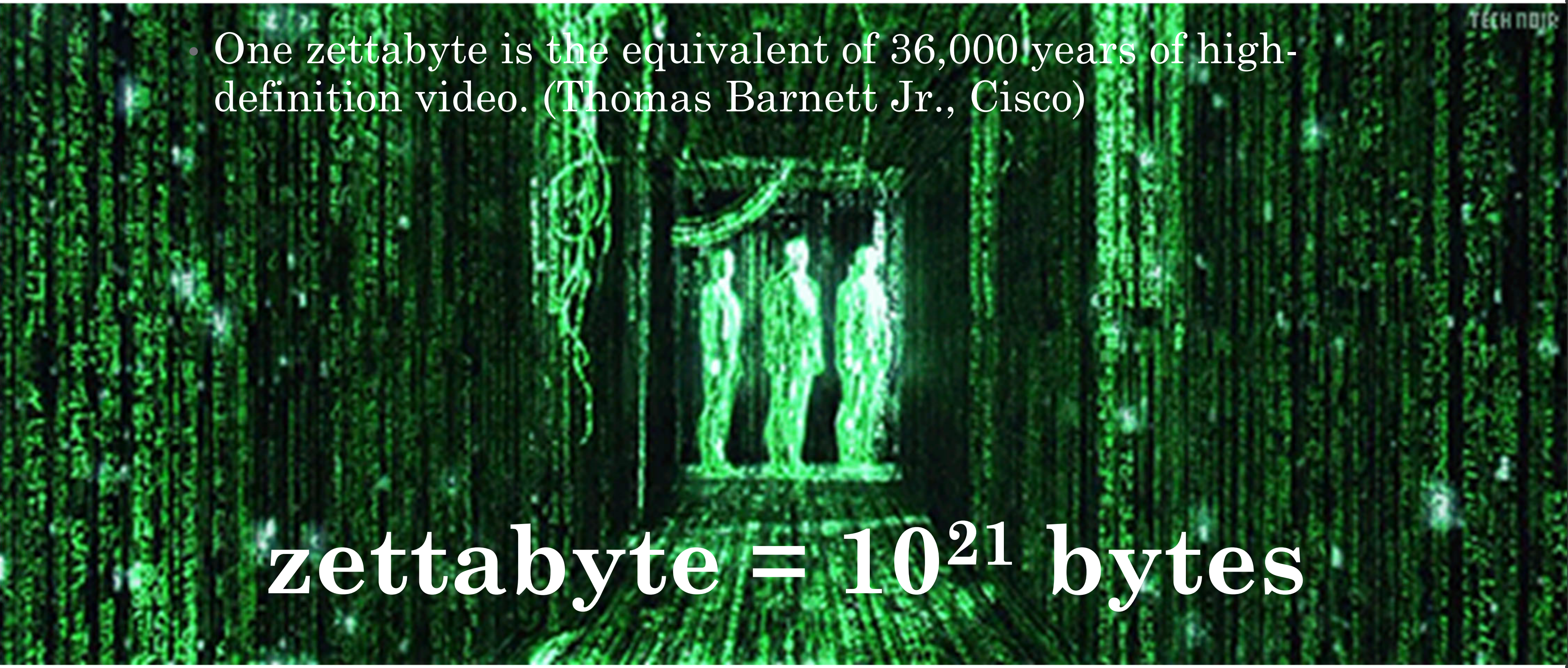
~ 10^{17} FLOPS

~ 10^8 IPS

Moving data is very expensive!

Source: J. Weiss, IBM.

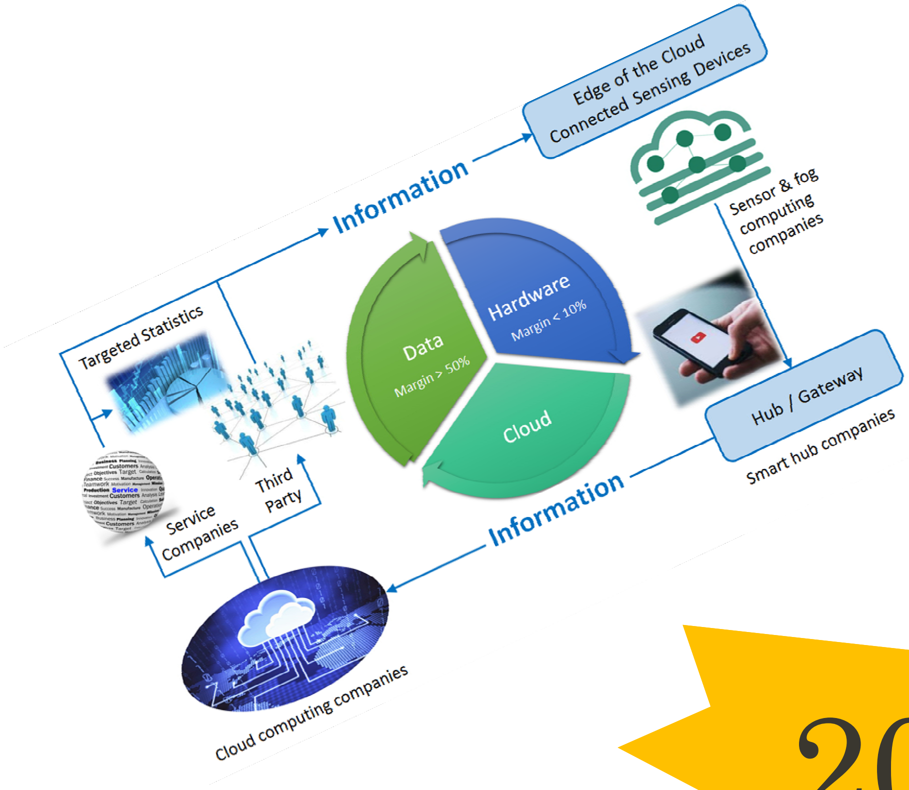
The Zettabyte Era… started in 2010!



- One zettabyte is the equivalent of 36,000 years of high-definition video. (Thomas Barnett Jr., Cisco)

zettabyte = 10^{21} bytes

The Zettabyte Era



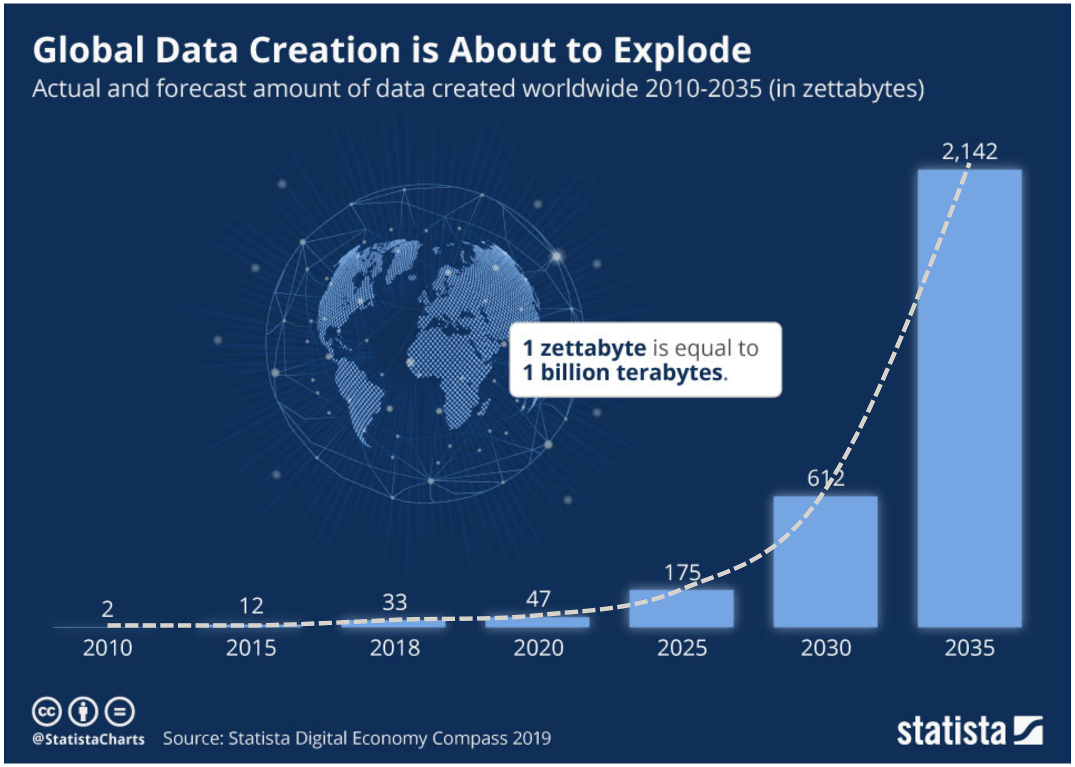
1985
Storage 21PB
Coms 59PB
Comp 0.74PIPS

2007
Storage 277EB
Coms 537EB1
Comp 195PIPS

2020
Storage 140 ZB
Coms 272 ZB
Comp 2'590 ZIPS
Edge IoT >50 ZB

M. Hilbert, P. López, Science, 2011.
Z.-W. Xu, J. of Comp. Sci. and Tech., 2014

Gap: energy crisis in the Zettabyte and IoT Era



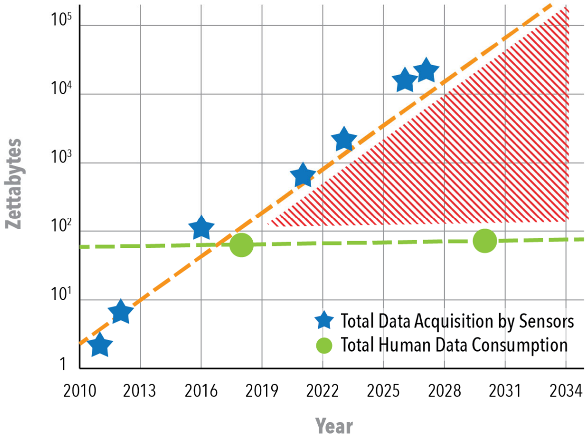
Global Data Creation is About to Explode

Actual and forecast amount of data created worldwide 2010-2035 (in zettabytes)

1 zettabyte is equal to **1 billion terabytes**.

Source: Statista Digital Economy Compass 2019

Global Data via IoT Sensors



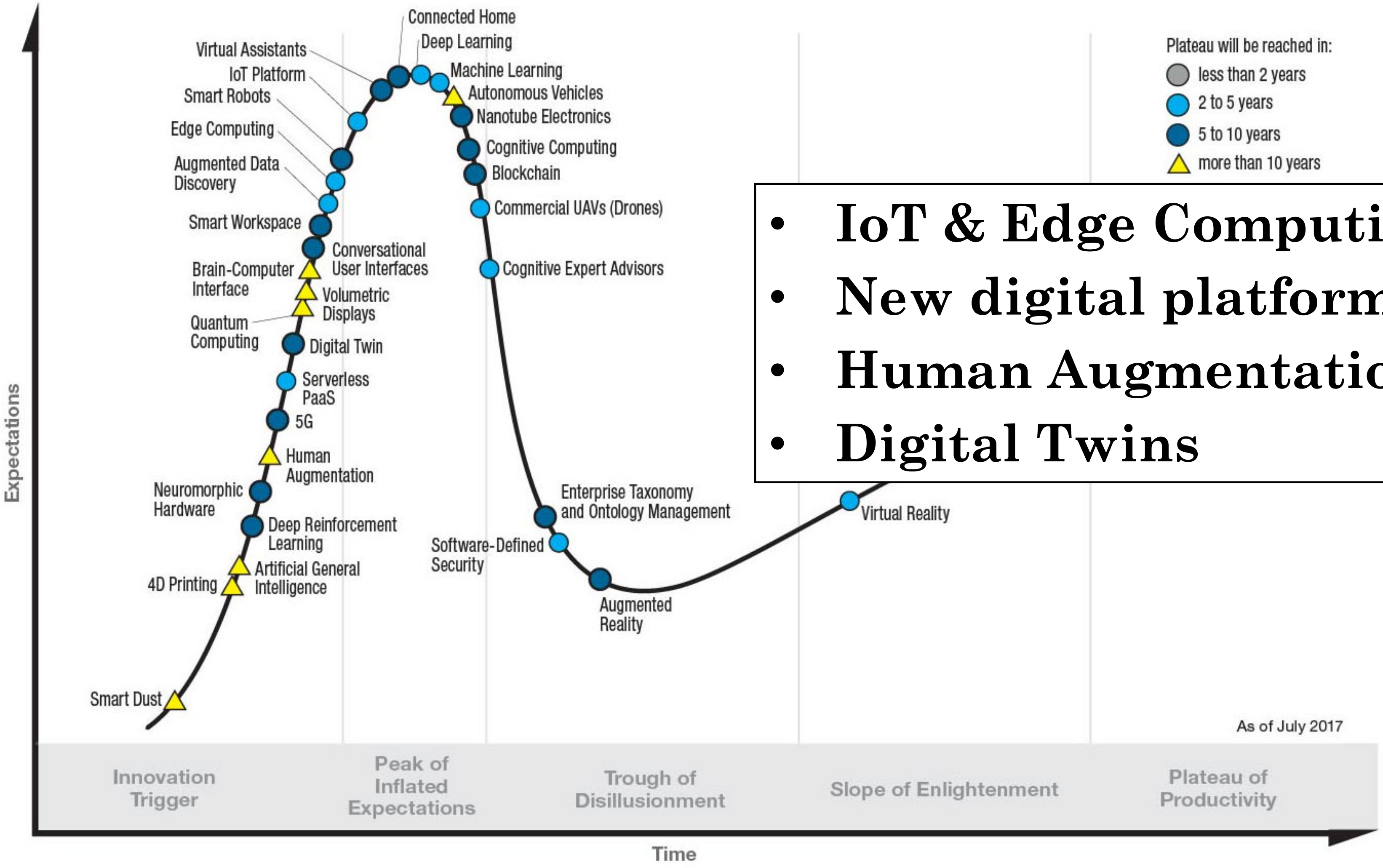
+ 1 trillion IoT devices by 2035
with annual growth >20% (© ARM)

Sustainable IoT deployment

I. **Massive reduction** of IoT sensory node **power** by ~1000x

II. **Massive reduction** in **data** proliferation

BOTH NEEDED!

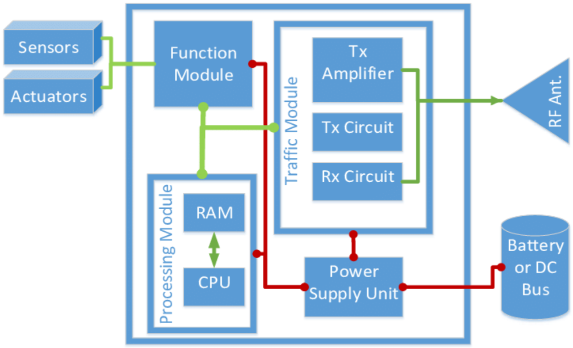


- **IoT & Edge Computing**
- **New digital platforms**
- **Human Augmentation**
- **Digital Twins**

Source: gartner.com/SmarterWithGartner

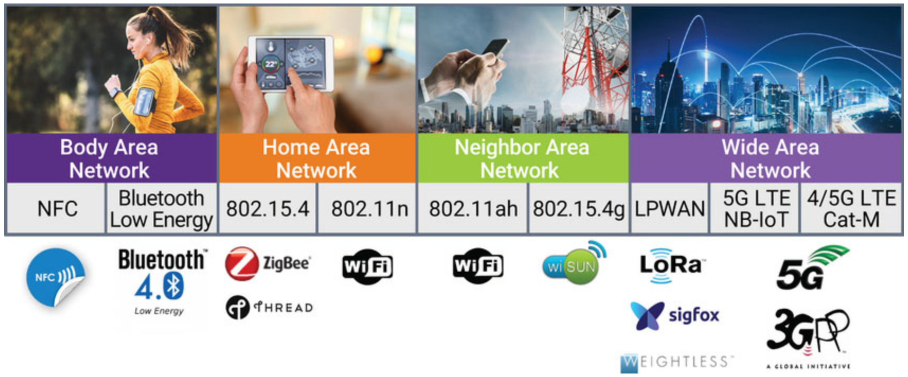
Incremental reduction of IoT sensory node power with traditional technologies

Industrial IoT node size and power consumption: mm^3 to cm^3 with 100’s uW to 10’s mW.



Silicon = only solution for all IoT Node Devices?

- Sensing
- Processing
- Communications

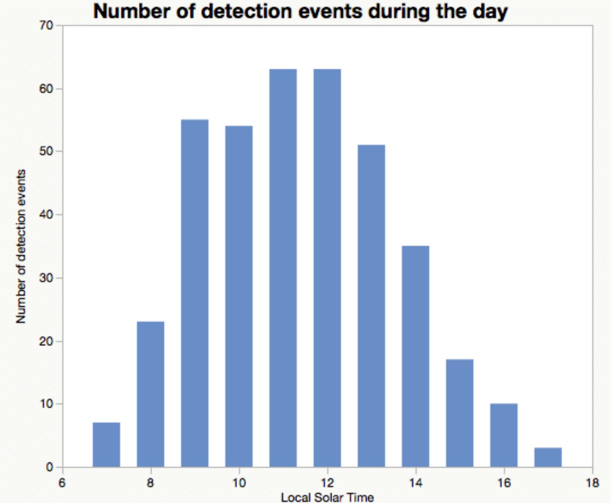


Energy problems @ node level:

- **No digital data reduction**
- **Expensive ADC and digital processing**
- **Expensive data communication**

Massive reduction in IoT data proliferation

- **bio-inspiration**
- no digital, no ADC → time-domain **spikes**
- no sensed bits transmitted → **event/tasks**

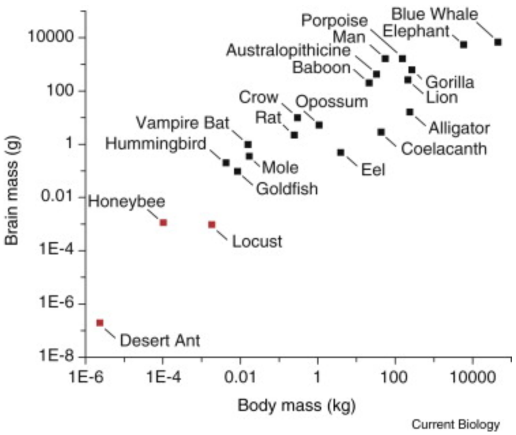


The most energy efficient IoT node

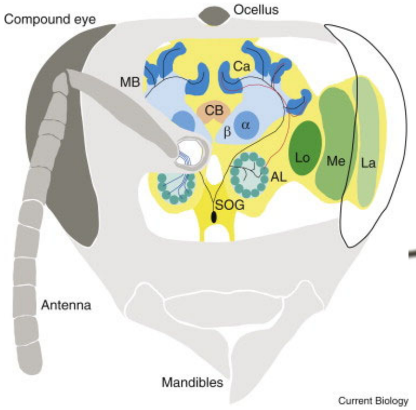
The honeybee

Are Bigger Brains Better?

The brain of a honey bee has 960 000 neurons and is 1 mm^3 in size.



Current Biology



Current Biology

Lars Chittka and Jeremy Niven, Current biology, 2009.

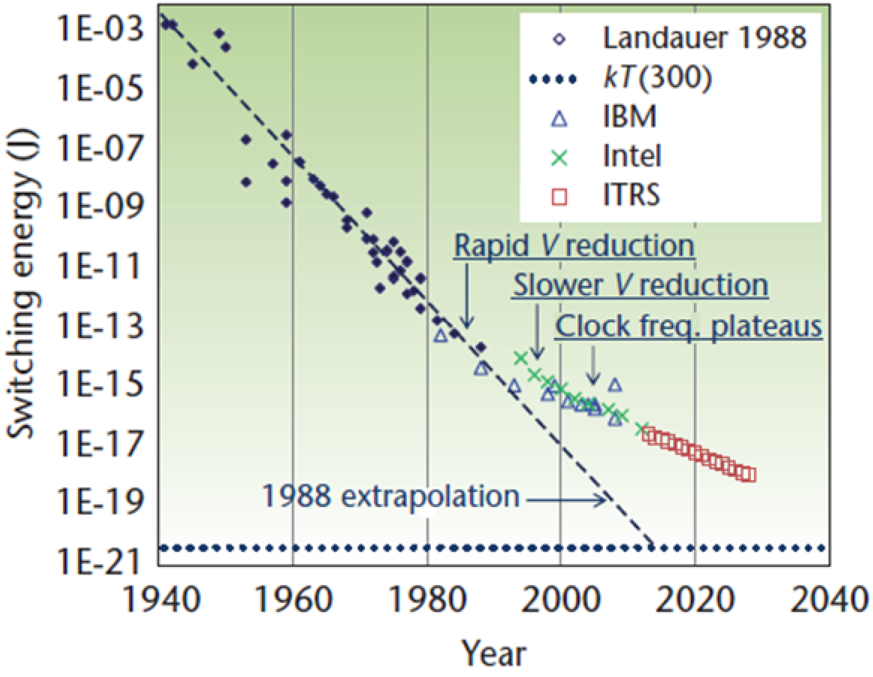
Neural network analyses show that **cognitive features found in insects, such as numerosity, attention and categorisation-like processes, may require only very limited neuron numbers.**

Silicon technology @ end of nano-scaling

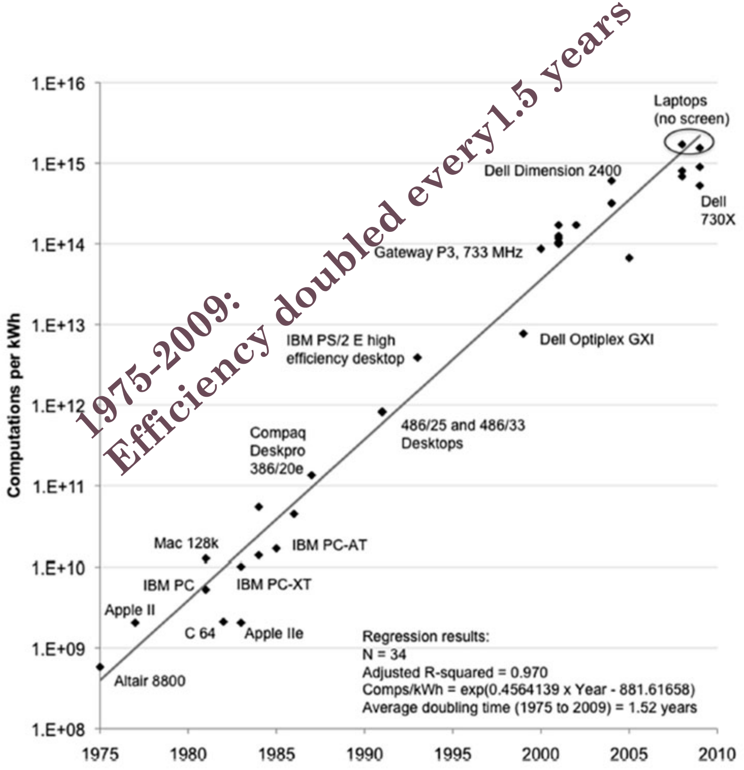
- **Moore's Law**, Dennard's happy scaling
- Silicon is mainstream: 14nm, 7nm, 5nm, … 1nm?

Koomey's law:

computations per killowatt hour



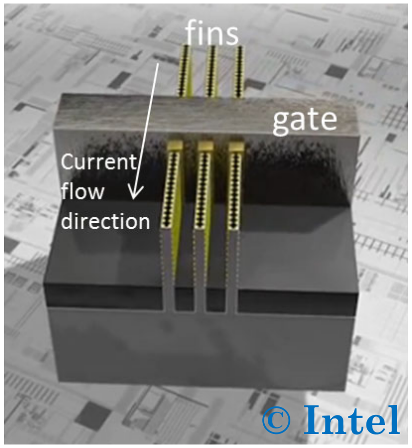
Theis & Wong, Computing in Sci. & Eng., 2017.



1975-2009:
Efficiency doubled every1.5 years

Koomey et al., IEEE Ann. of History of Comp., 2011.

Nanoelectronics: ~10nm 3D transistors



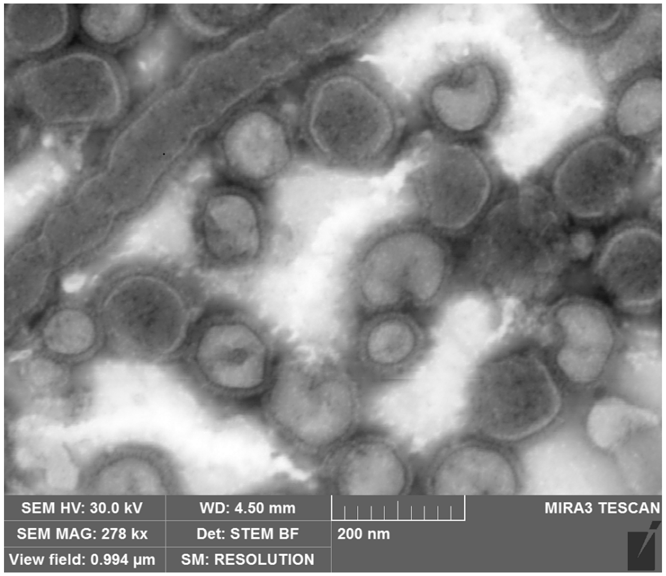
© Intel

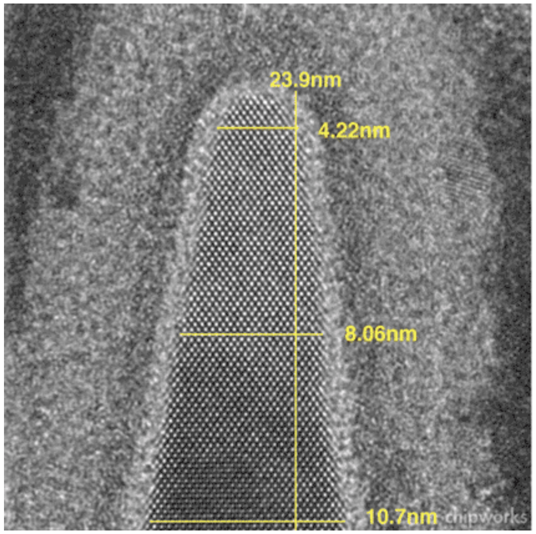
Today: 14 nm:
- ❑ **40 millions transistors/mm²**

10 nm:
- ❑ **100 millions transistors/mm²**

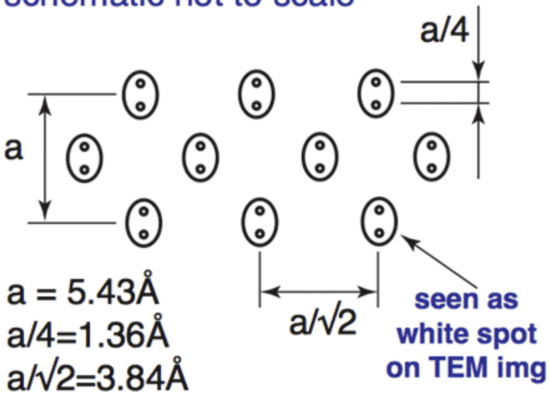
Virus

Negatively stained Influenza Virus, usually spherical or ovoid in shape, 80 to 150 nm.



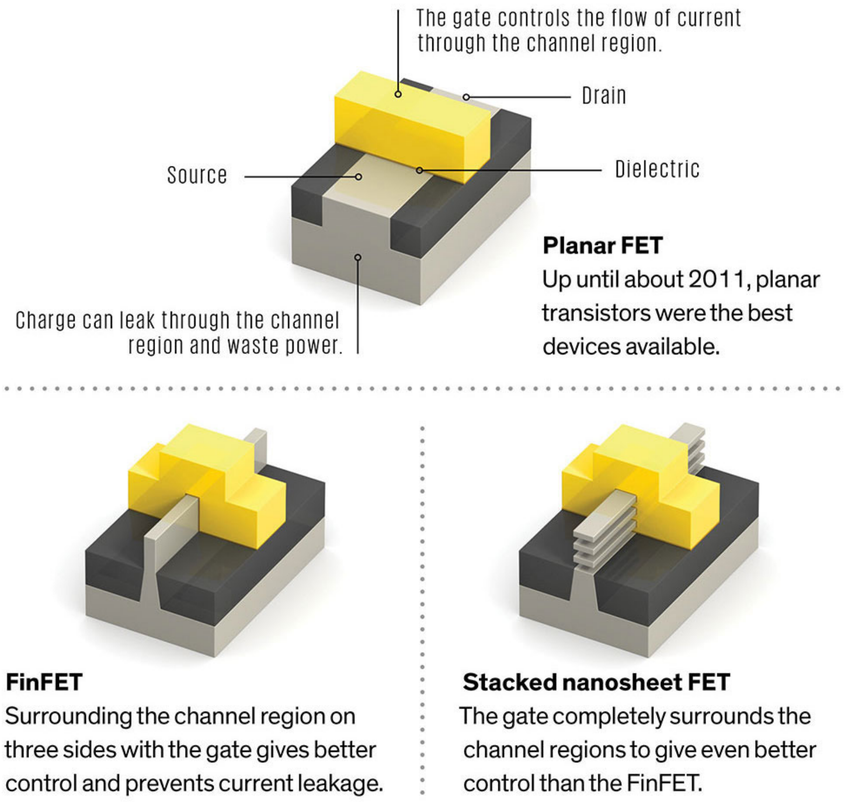


TEM image of Si(110), schematic not to scale



a = 5.43Å
a/4=1.36Å
a/√2=3.84Å

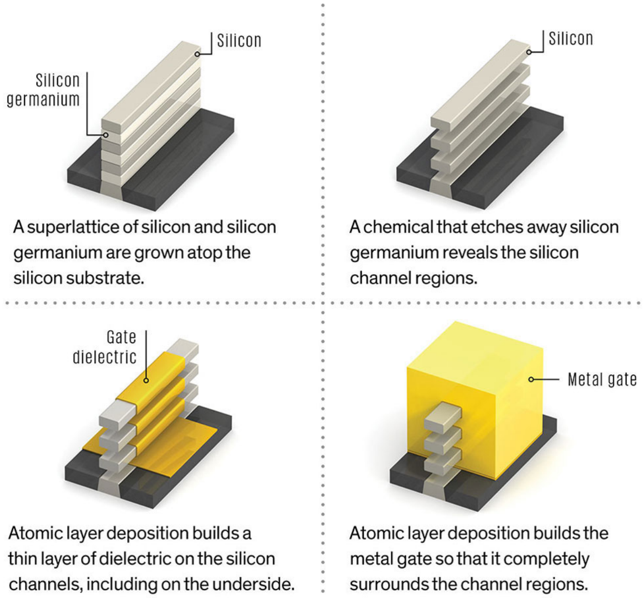
Stacked nanosheet transistors down to 2nm?



Planar FET
Up until about 2011, planar transistors were the best devices available.

FinFET
Surrounding the channel region on three sides with the gate gives better control and prevents current leakage.

Stacked nanosheet FET
The gate completely surrounds the channel regions to give even better control than the FinFET.

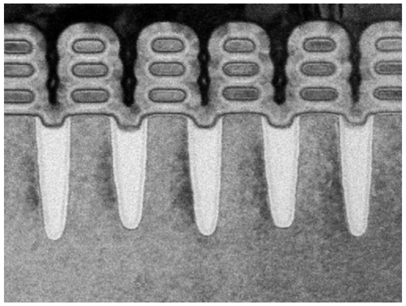


A superlattice of silicon and silicon germanium are grown atop the silicon substrate.

A chemical that etches away silicon germanium reveals the silicon channel regions.

Atomic layer deposition builds a thin layer of dielectric on the silicon channels, including on the underside.

Atomic layer deposition builds the metal gate so that it completely surrounds the channel regions.

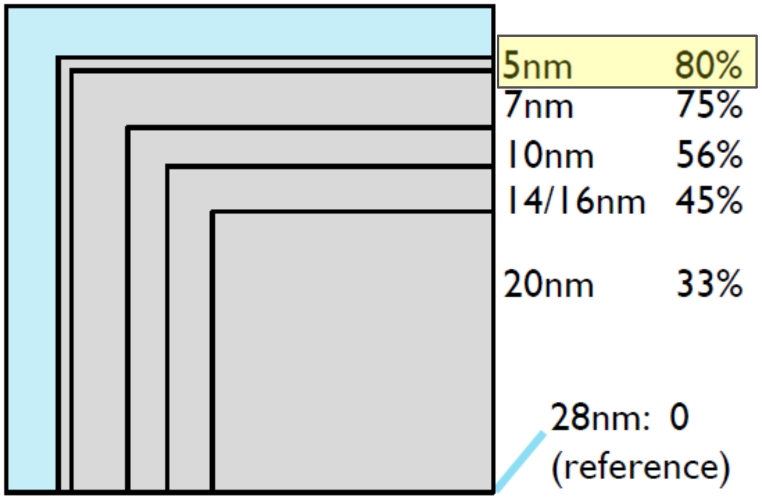


From IEEE Spectrum, 2021.

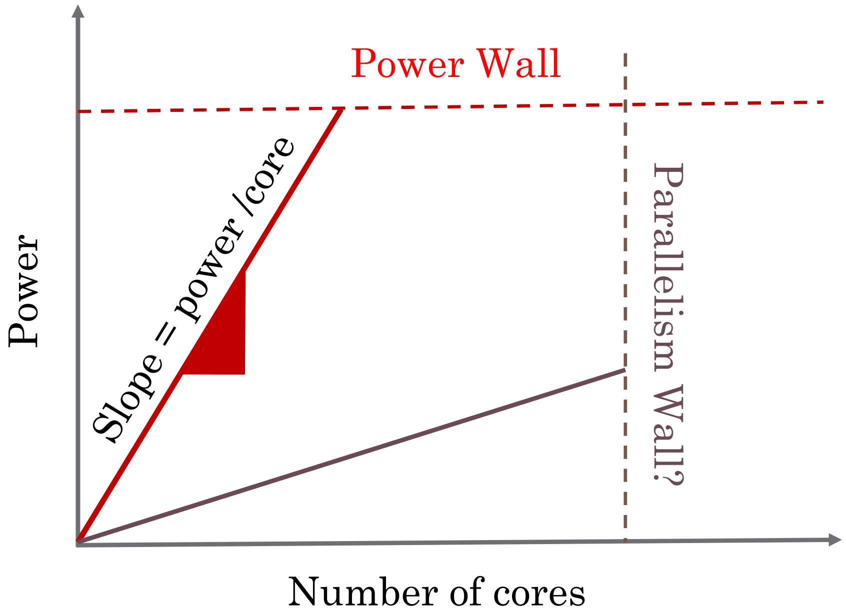
Dark silicon era? Is this so bad?

- *We get more transistors, we just can't afford to turn them all!*

  Greg Yeric, ARM @ IEDM 2015



One or two walls?

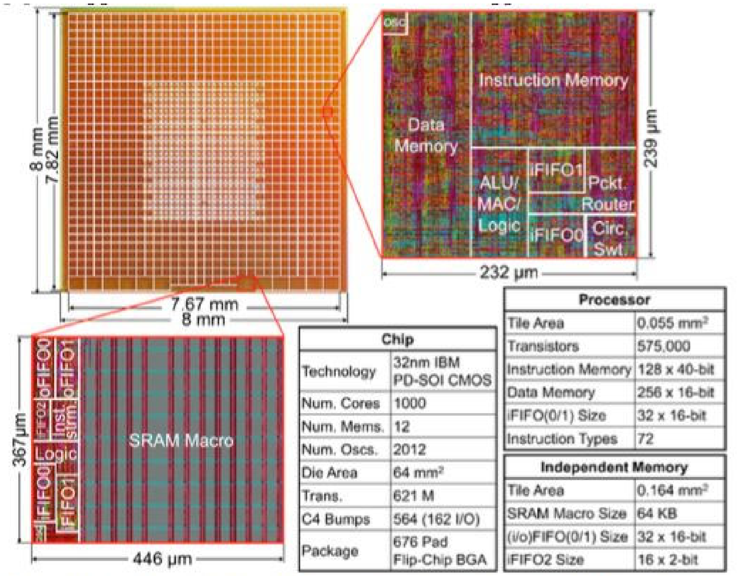


Future kilo-core processors?

- UC Davis' Kilocore: Bohnenstiehl at al., *5.8 pJ/Op 115 Billion Ops/sec to 1.78 Trillion Ops/sec*

1000 cores execute 1 trillion instructions/sec while dissipating 13.1 W!

More cores? What else?

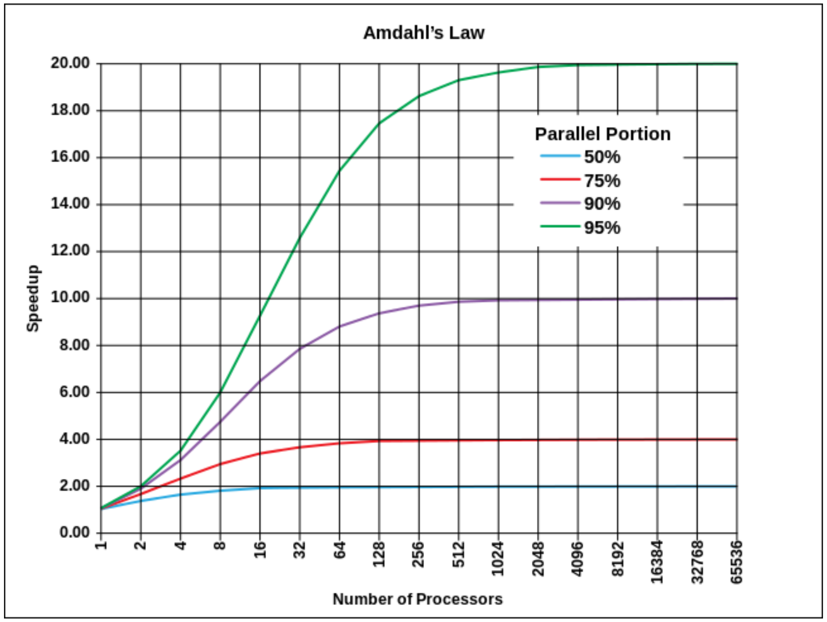


Chip	
Technology	32nm IBM PD-SOI CMOS
Num. Cores	1000
Num. Mems.	12
Num. Oscs.	2012
Die Area	64 mm^2
Trans.	621 M
C4 Bumps	564 (162 I/O)
Package	676 Pad Flip-Chip BGA

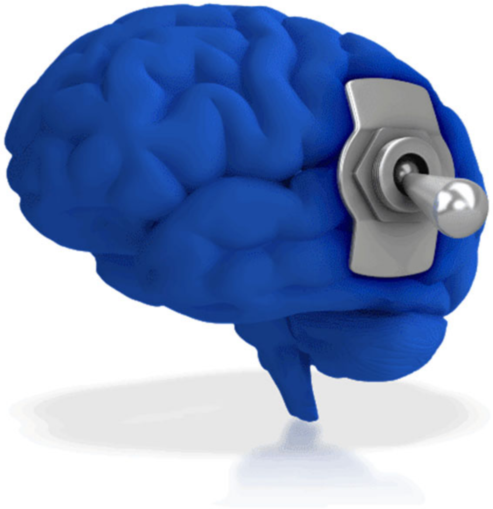
Processor	
Tile Area	0.055 mm^2
Transistors	575,000
Instruction Memory	128 x 40-bit
Data Memory	256 x 16-bit
iFIFO(0/1) Size	32 x 16-bit
Instruction Types	72

Independent Memory	
Tile Area	0.164 mm^2
SRAM Macro Size	64 KB
(i/o)FIFO(0/1) Size	32 x 16-bit
iFIFO2 Size	16 x 2-bit

Fig. 1: Die photo of the KiloCore array, and annotated layout plots of a single processor tile and a single independent memory tile.



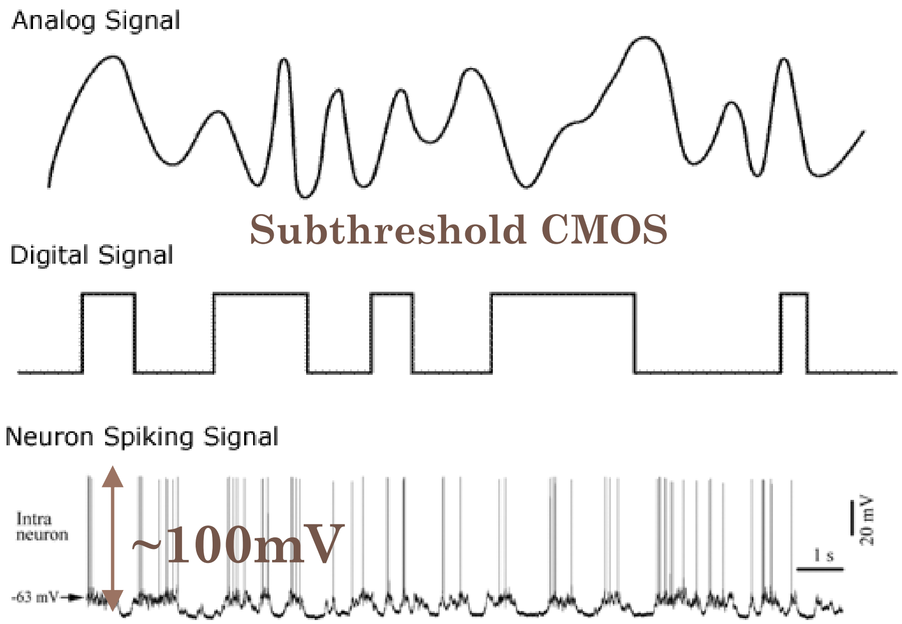
A dark biological brain?



- only about 3% of the neurons in the brain can be highly active at one time
- *visual processing accounts for 44% of the brain's energy consumption*

- **The brain works with 20 Watts. This is enough to cover our entire thinking ability.**
- **IBM's Watson? About 20,000 Watts.**

Information processing @ 100mV?

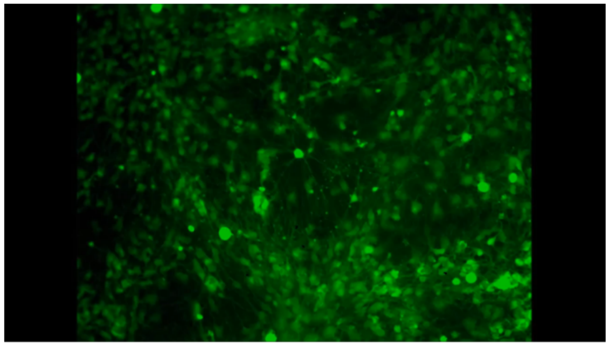


Subthreshold CMOS

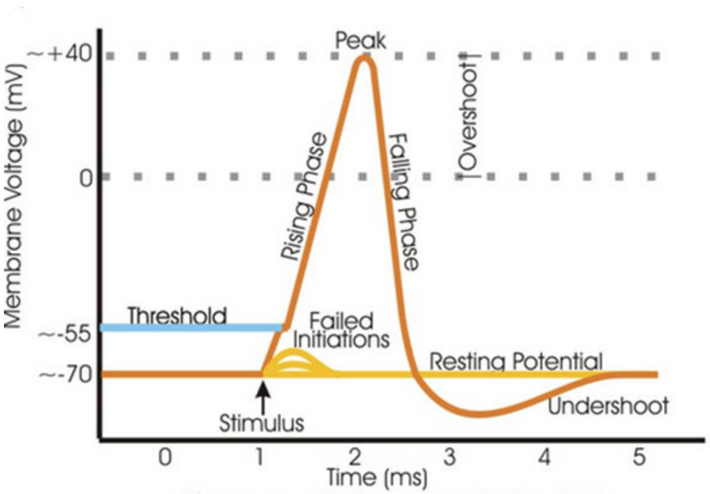
~100mV

- The coding principles used to represent sensory information in the cortex are not well understood.
- Neural activity is very costly.

The firing of the neuron



Neuron potential by Na+, K+ ion pumps, is in the order of **+40mV to -70mV**



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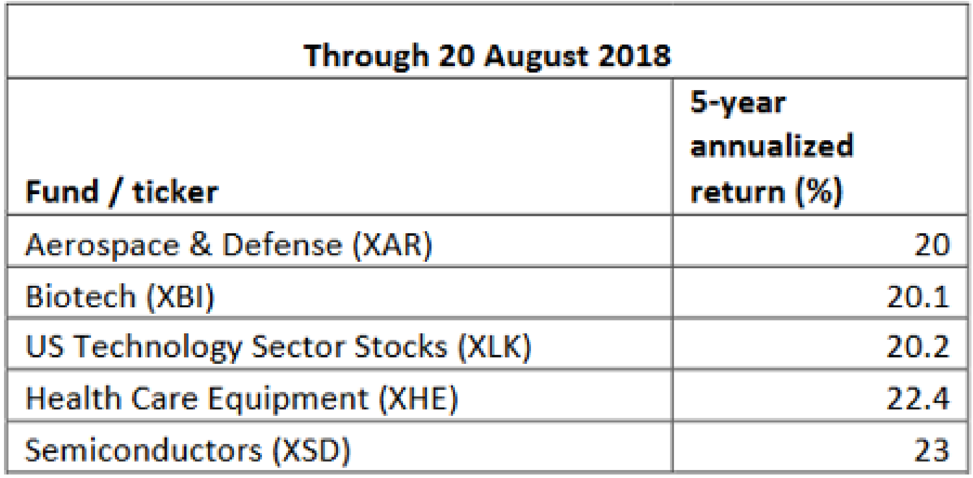
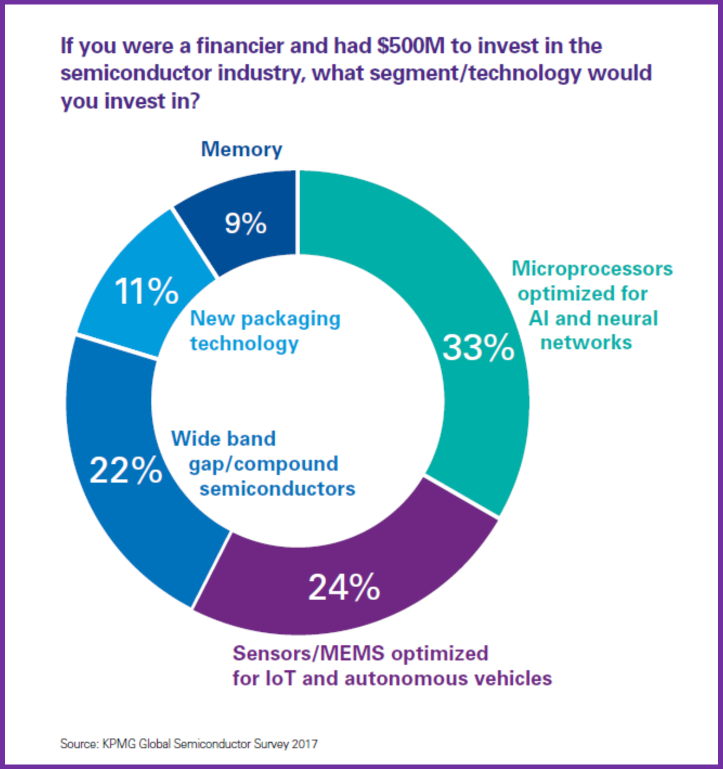
Semicons are the best performing industry over the past five years



Through 20 August 2018	
Fund / ticker	**5-year annualized return (%)**
Aerospace & Defense (XAR)	20
Biotech (XBI)	20.1
US Technology Sector Stocks (XLK)	20.2
Health Care Equipment (XHE)	22.4
Semiconductors (XSD)	23

- The industry is evolving to more of a portfolio model — selling chips into many different products, spreading returns across a greater number of assets.

What’s next?



If you were a financier and had $500M to invest in the semiconductor industry, what segment/technology would you invest in?

Source: KPMG Global Semiconductor Survey 2017

AI-related semiconductors will see growth of about 18 percent annually over the next few years, $67 billion in 2025

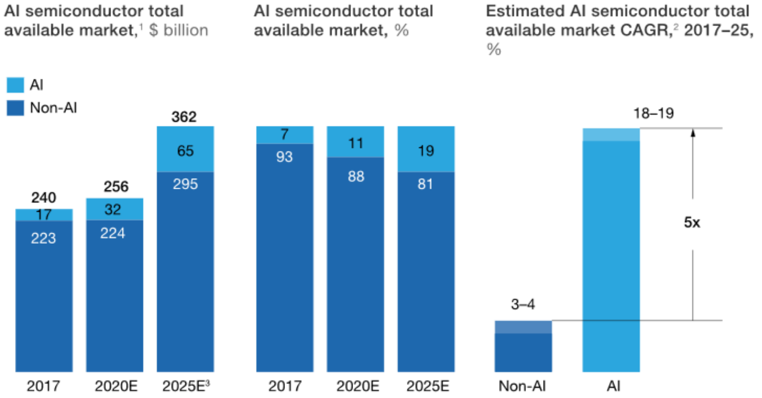
5X greater CAGR than non-AI applications!

Artificial-intelligence hardware:
the New opportunity for semiconductors

- AI could allow semiconductor companies to capture 40 to 50% of total value: the best opportunity in decades!

- Semiconductor companies must undertake **a new value-creation strategy** that focuses on enabling **customized, end-to-end solutions for specific industries, or “microverticals.”**

Growth for semiconductors related to artificial intelligence (AI) is expected to be five times greater than growth in the remainder of the market.



AI semiconductor total available market,[1] $ billion

AI semiconductor total available market, %

Estimated AI semiconductor total available market CAGR,[2] **2017–25,** %

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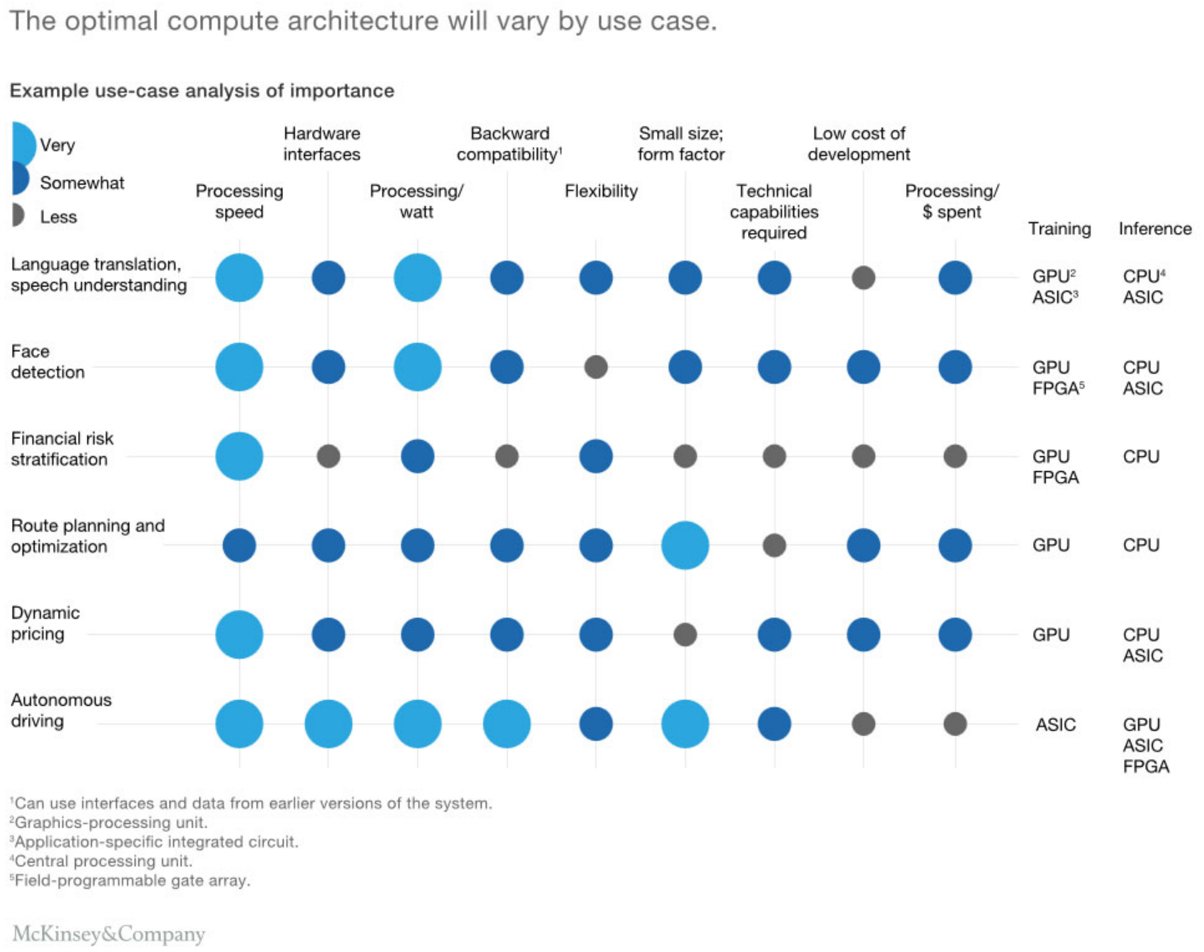
[1] Total available market includes processors, memory, and storage; excludes discretes, optical, and micro-electrical-mechanical systems.
[2] Compound annual growth rate.
[3] E = estimated.

Source: Bernstein; Cisco Systems; Gartner; IC Insights; IHS Markit; Machina Research; McKinsey analysis

McKinsey&Company

Anticipating what is the real future optimal computing



The optimal compute architecture will vary by use case.

Example use-case analysis of importance

⬤ Very
● Somewhat
• Less

	Processing speed	Hardware interfaces	Processing/ watt	Backward compatibility[1]	Flexibility	Small size; form factor	Technical capabilities required	Low cost of development	Processing/ $ spent	Training	Inference
Language translation, speech understanding	⬤	●	⬤	●	●	●	●	•	●	GPU[2] ASIC[3]	CPU[4] ASIC
Face detection	⬤	●	⬤	●	•	●	●	●	●	GPU FPGA[5]	CPU ASIC
Financial risk stratification	⬤	•	●	•	●	•	•	•	•	GPU FPGA	CPU
Route planning and optimization	●	●	●	●	●	⬤	•	●	●	GPU	CPU
Dynamic pricing	⬤	●	●	●	●	•	●	●	●	GPU	CPU ASIC
Autonomous driving	⬤	⬤	⬤	⬤	●	⬤	●	•	•	ASIC	GPU ASIC FPGA

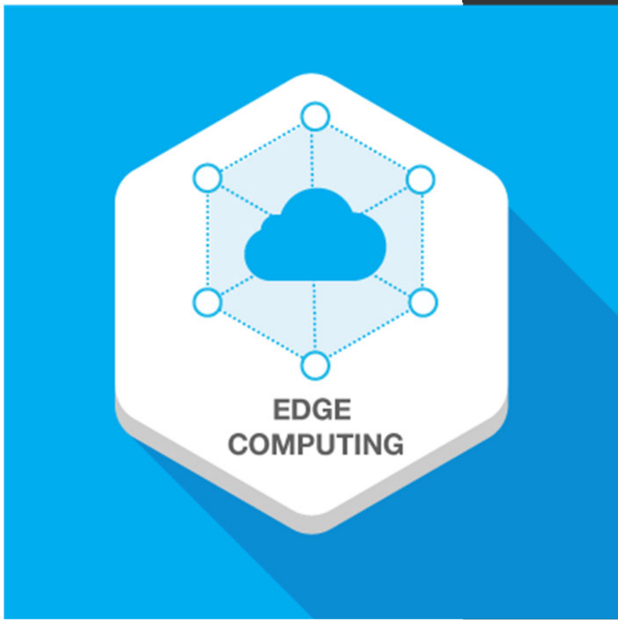
[1] Can use interfaces and data from earlier versions of the system.
[2] Graphics-processing unit.
[3] Application-specific integrated circuit.
[4] Central processing unit.
[5] Field-programmable gate array.

McKinsey&Company

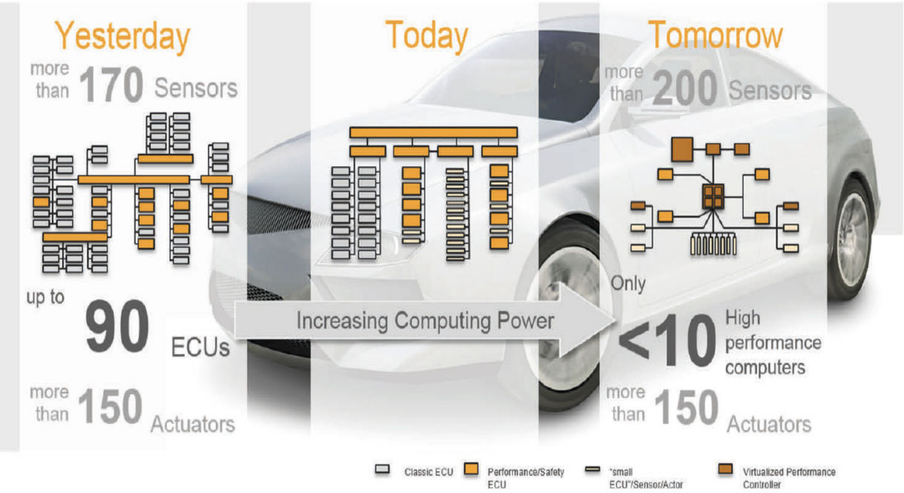
Decentralizing is next!

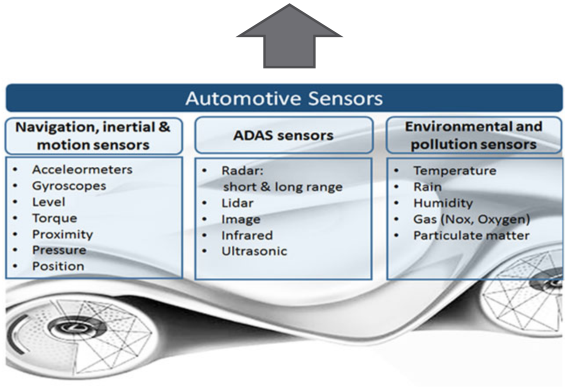
This is the breathing in and out of the computer industry.

Edge computing is a natural next step from cloud computing.



Automotive: example of future electronics impact





Automotive Sensors

Navigation, inertial & motion sensors	ADAS sensors	Environmental and pollution sensors
Accelerometers	Radar: short & long range	Temperature
Gyroscopes	Lidar	Rain
Level	Image	Humidity
Torque	Infrared	Gas (Nox, Oxygen)
Proximity	Ultrasonic	Particulate matter
Pressure		
Position		

Miniaturized smart MEMS sensor technologies **-** more than 200 individual sensors per fully automated cars.

Technology and packaging - *more closely related* by automotive requirements from-transistor-to-housing, which will include multi-domain co-design (chip, package, system) and high reliability.

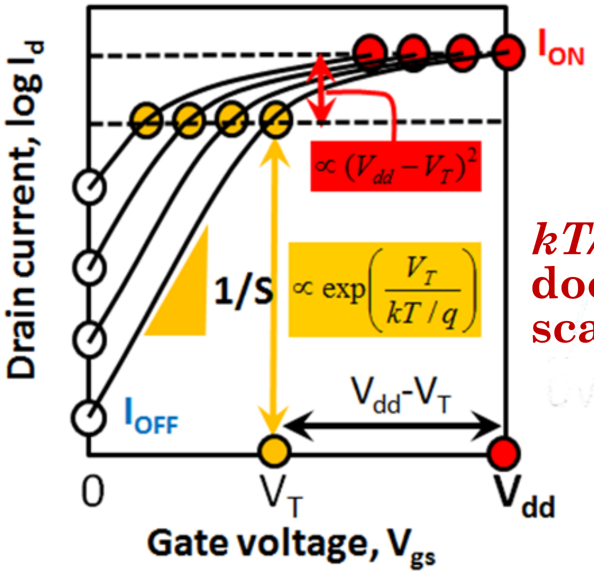
Semiconductor power technologies –Intelligent Power Devices based on silicon or on post-silicon technology (GaN, SiC) are expected to offer solutions for engine control devices and vehicle safety control devices.

ADAS systems –a key enabling technology for the progression of autonomous driving to levels 4/5.

Holistic Connectivity and Artificial Intelligence at the Edge – the future car = AI Edge device, where the holistic connectivity and local intelligence/processing will play increasingly important roles.

Leakage Power & Estimated Minimum Power Supply of CMOS

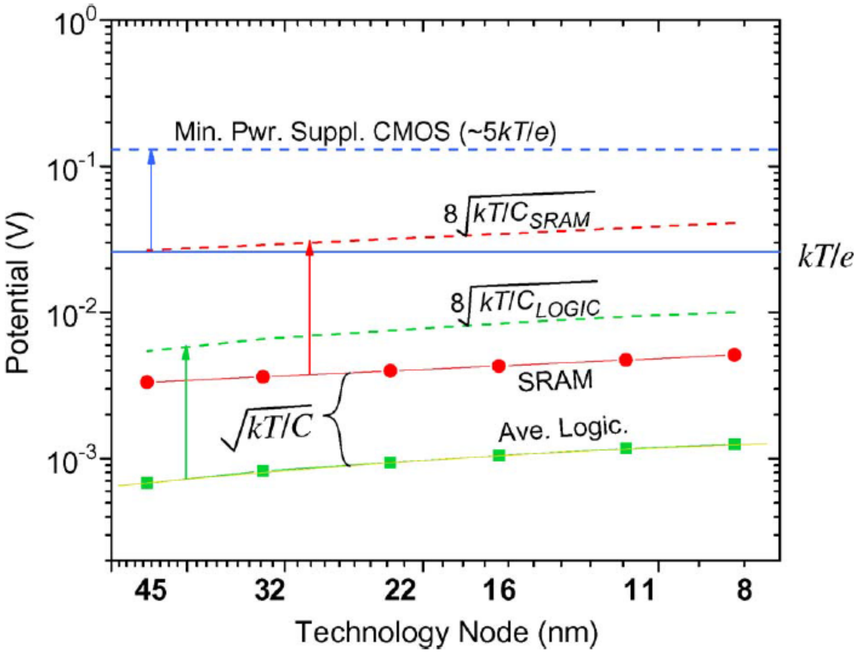
- **Leakage power** due to incompressible subthreshold swing of MOSFET: 60mV/dec @ RT
- Vdd scaling saturated **@ ~0.7-0.8V**



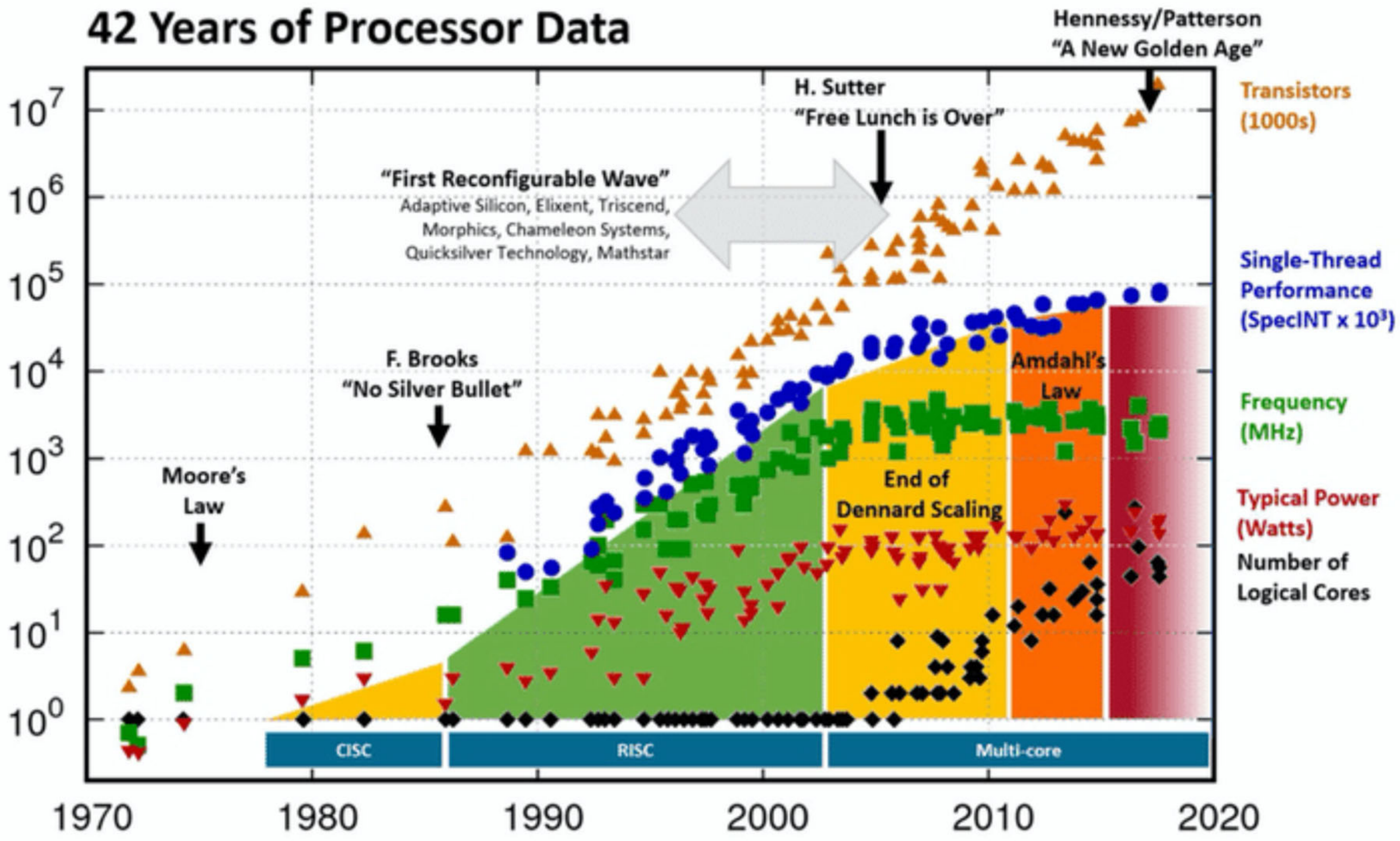
***kT/q* does not scale!**

Ionescu & Riel, Nature, 2011.

Estimated minimum power supply for CMOS ~5*kT/q* ~ 130mV



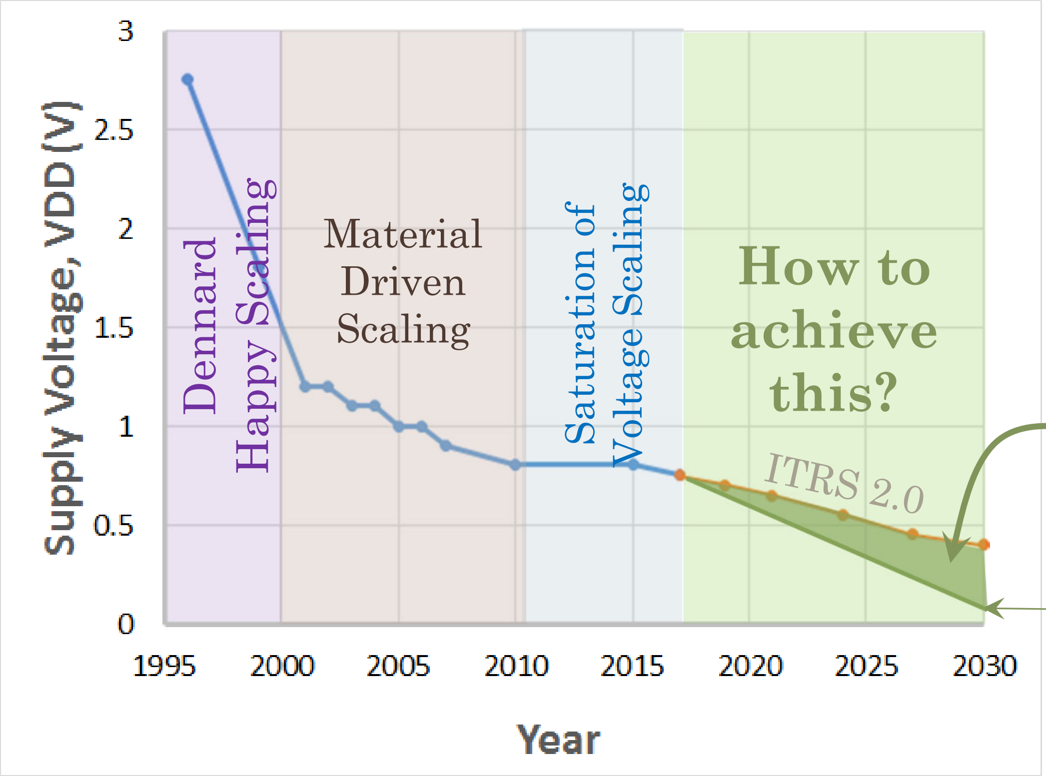
Theis & Solomon, IEEE Proc., 2009.



Hennessy and Patterson, Turing Lecture 2018, overlaid over "42 Years of Processors Data"
https://www.karlrupp.net/2018/02/42-years-of-microprocessor-trend-data/;"First Wave" added by Les Wilson, Frank Schirrmeister
Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

Supply voltage scaling limits in CMOS Era

- 2000-2015, V_{DD} scaled @ $2k_BT/q$ = 50mV/year, saturated now
- Need ~**400 mV V_{dd} scaling by 2025**



$$I_{on} = C_g v_{eff}(V_{dd} - V_{th})$$

$$I_{off} = I_0 10^{-V_{th}/SS}$$

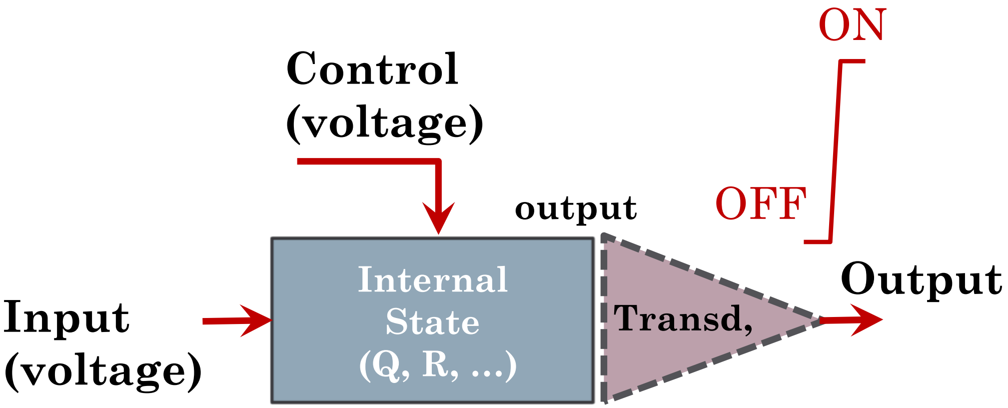
$$\text{SS} = \frac{dV_g}{dlog(I_d)} > 60\text{mV/dec @ RT}$$

- New physics / boosters
- ***Steep Slope Devices: SS < 60mV/dec @ RT***

V_{dd} ~ 5 kT/q (=130mV)

Steep slope switches

- Voltage control of an ***abruptly*** and ***fast*** switching internal state
- Efficient transduction mechanism



Control (voltage)

Input (voltage)

Internal State (Q, R, …)

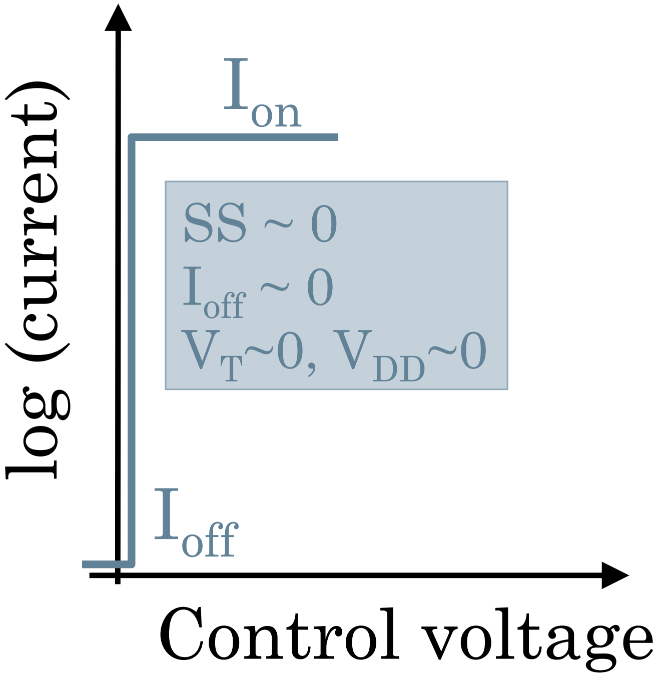
output

Transd,

Output

ON

OFF



SS ~ 0

I_{off} ~ 0

V_T~0, V_{DD}~0

The (inverse) subthreshold slope

- Re-engineering the swing of the FET

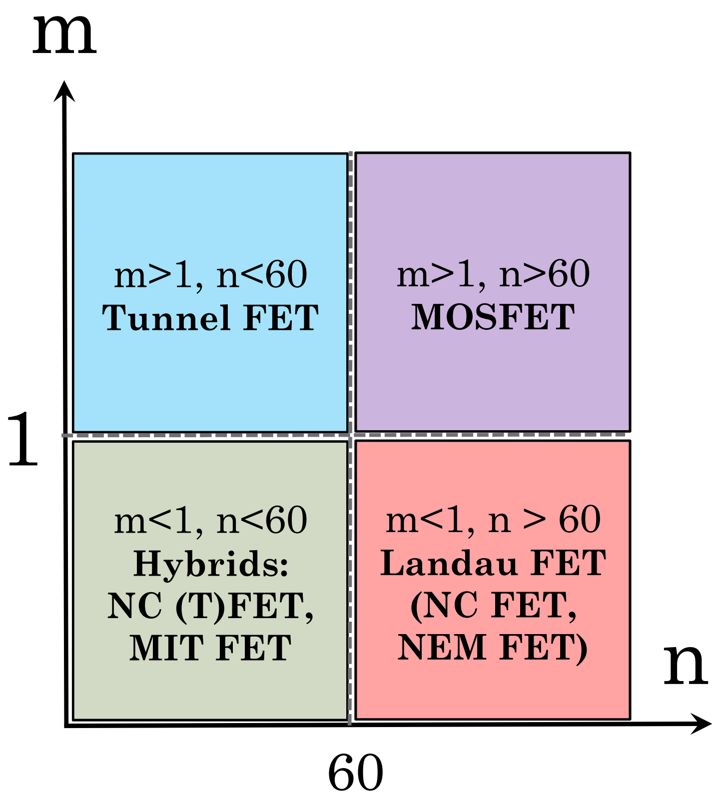
$$S = \frac{\partial V_g}{\partial(\log I_d)} = \underbrace{\frac{\partial V_g}{\partial \psi_S}}_{m}\underbrace{\frac{\partial \psi_S}{\partial(\log I_D)}}_{n} = (1+\frac{C_s}{C_{ins}})\frac{kT}{q}\ln 10 = m \times n$$

- ***Steep (subthermionic) slope:***

  m < 1 *and/or*

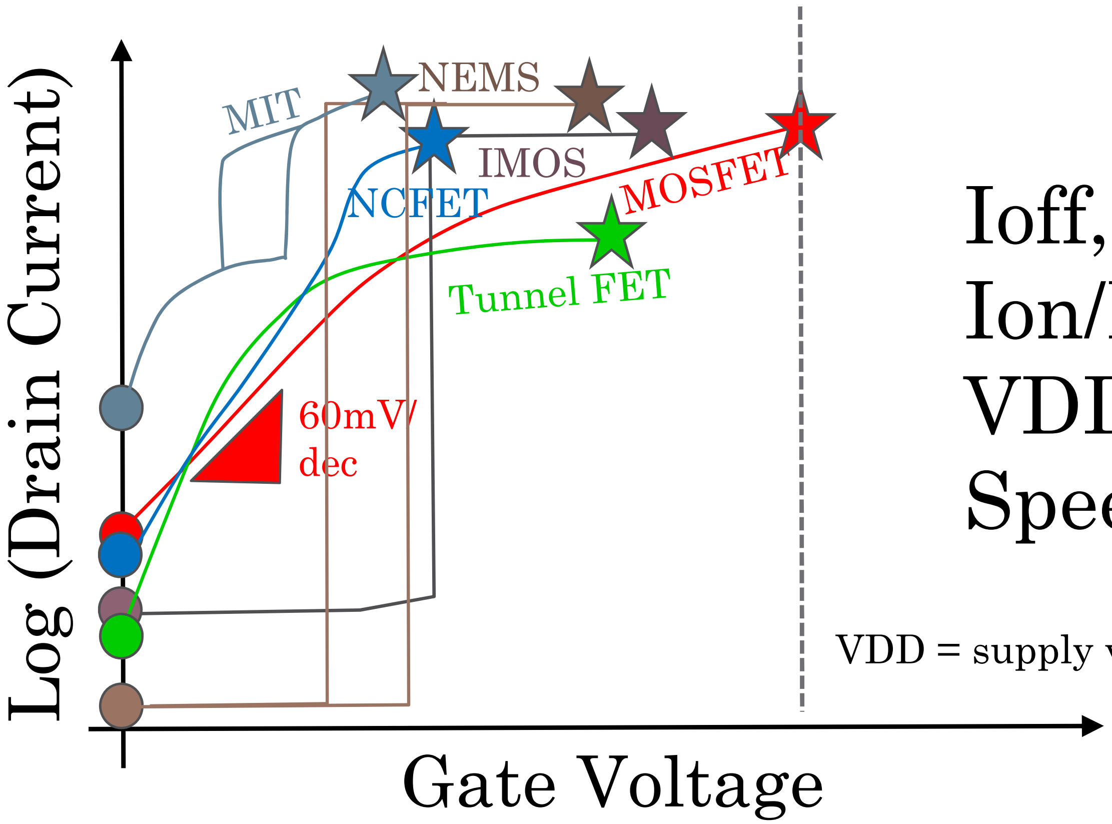
  n < kT/q ln10 = 60mV/dec @ RT

  by new physics and new device architecture.



Quest for a 100 millivolt switch

- Steep slope devices: a **Zoo** of Physics and Technology!



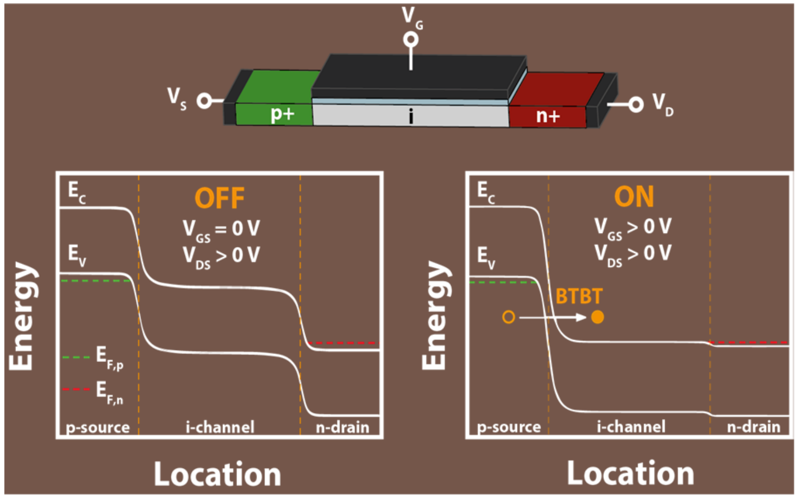
VDD = supply voltage

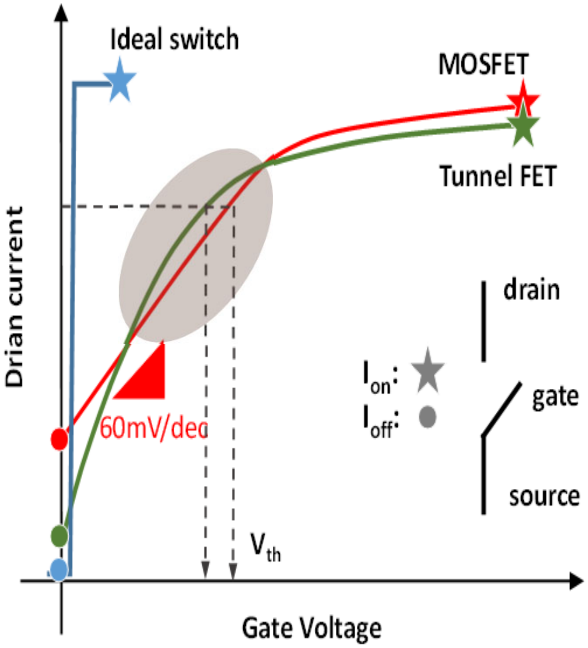
Ioff, Ion,
Ion/Ioff,
VDD
Speed?

Tunnel FETs: $n < kT/q \ ln2$

- Gated diode, energy filter: Band-To-Band-Tunneling offers sub-thermionic current swing!
- CMOS additive technology boosters applicable for improved performance.

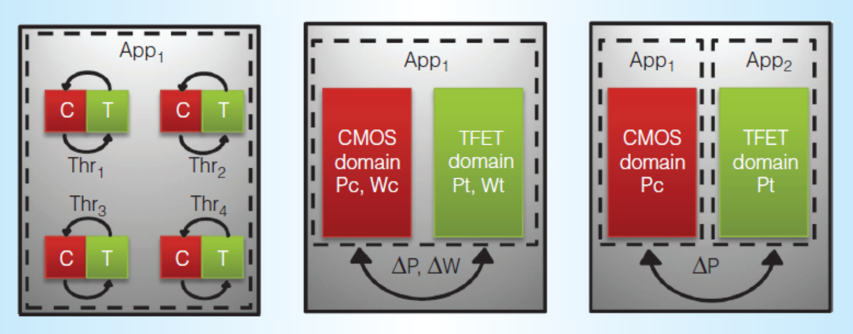
$$I_{on} \sim T^{WKB}_{tunneling} = \exp\left(-\frac{4\lambda\sqrt{2m^*}\,E_G^{3/2}}{3qh\left(\Delta\Phi + E_G\right)}\right)$$

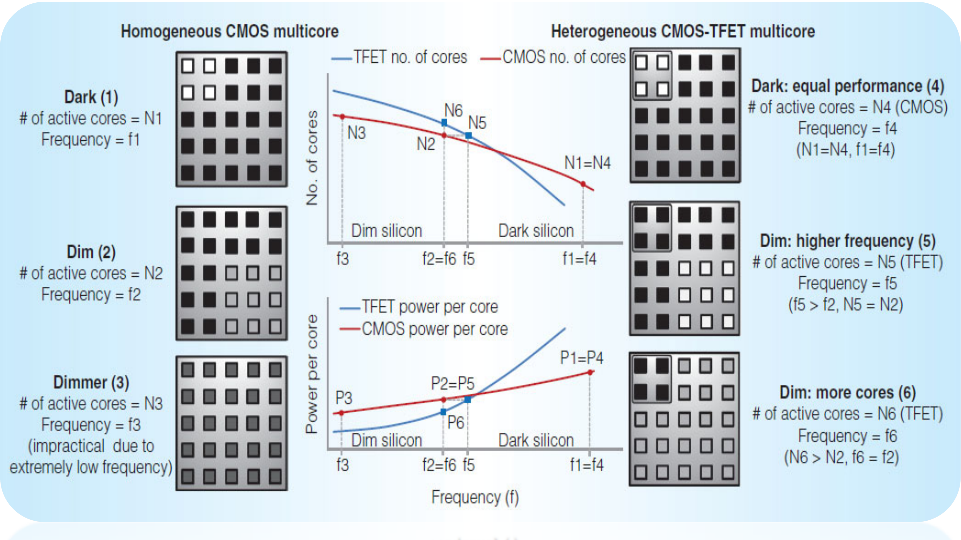




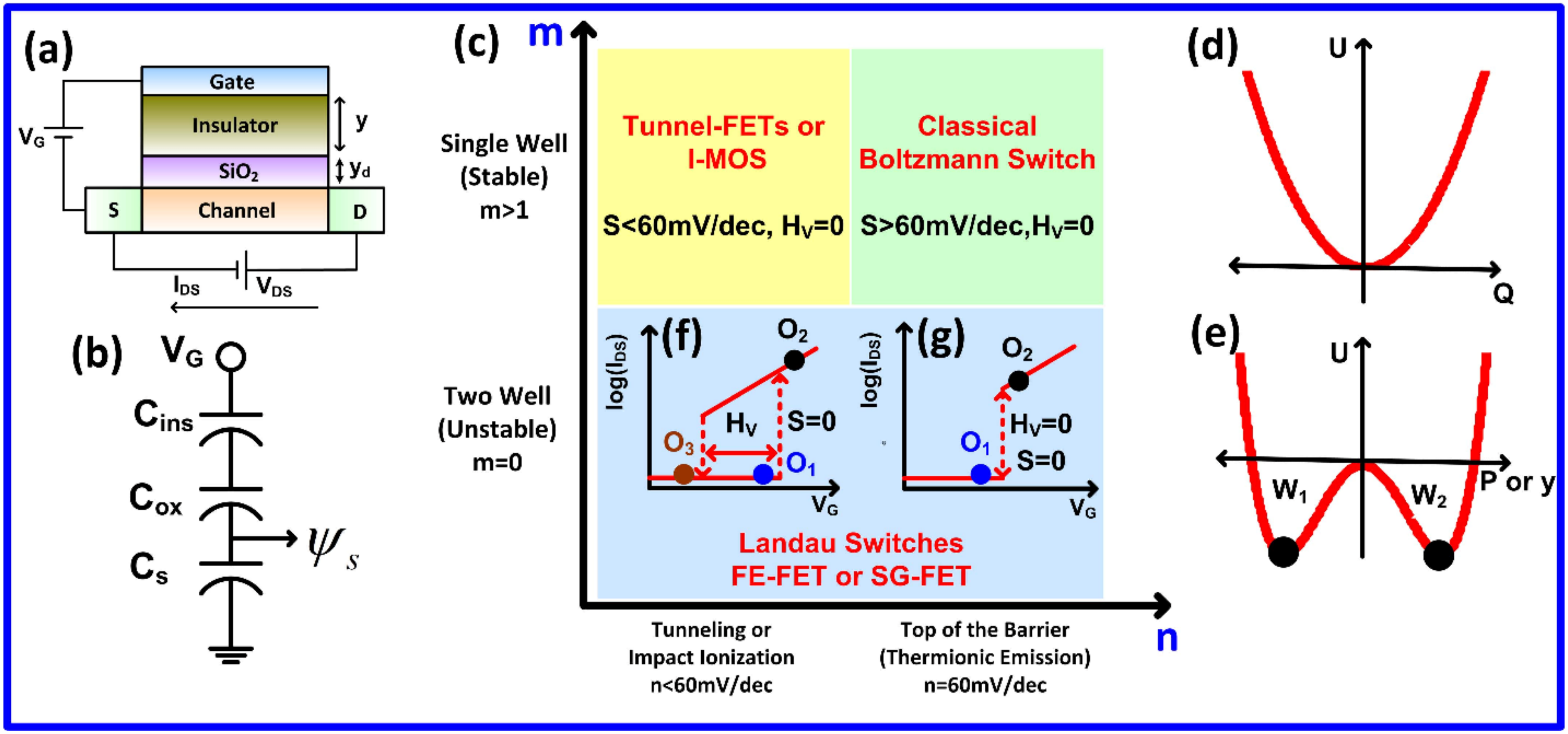
Tunnel FET applications in foreseeable future

- **Heterogenous CMOS-Tunnel FET multi-core processor design:** *better energy efficiency*
- **IoT sensors nodes based on Tunnel FETs:**
  - Analog/RF Tunnel FETs for energy efficient IoT nodes operating @ 100mV
  - Ultra sensitive new tunnel FET sensors for IoT nodes (<10-100microW/node)
- **Neuromorphic design with Tunnel FETs**

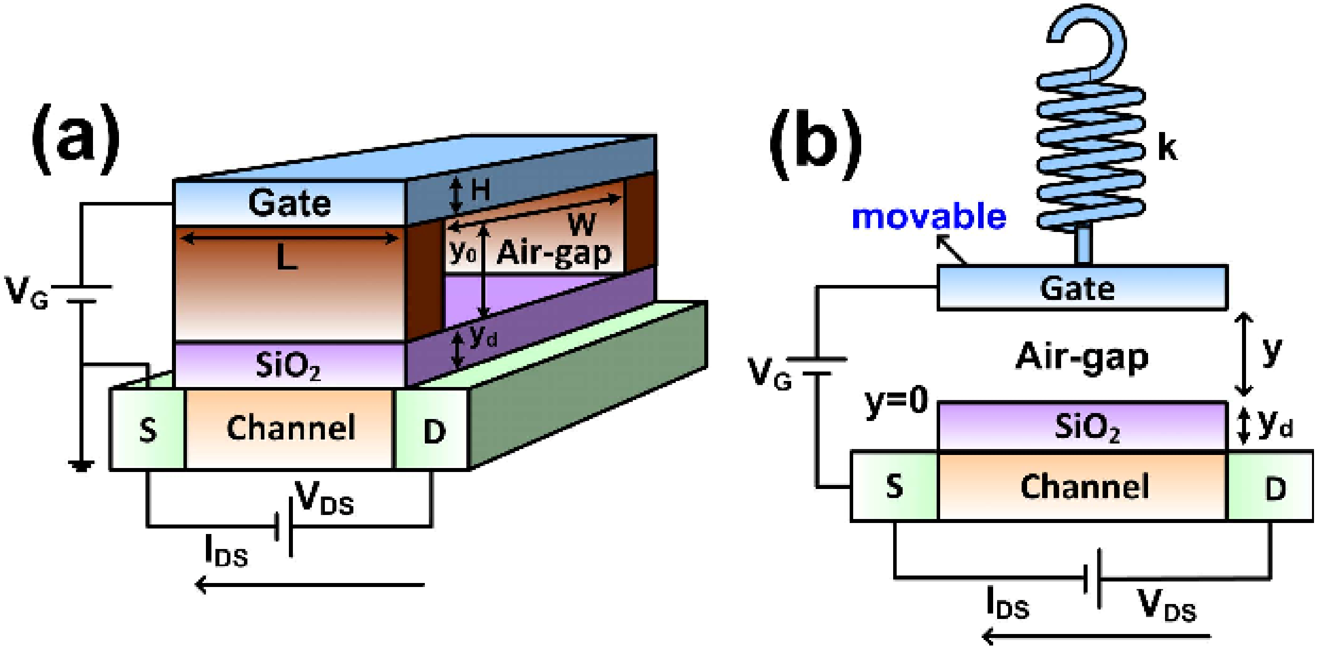




Landau switches: *m<1*



Landau switches: *m<1*



DOI:10.1109/TED.2013.2286997

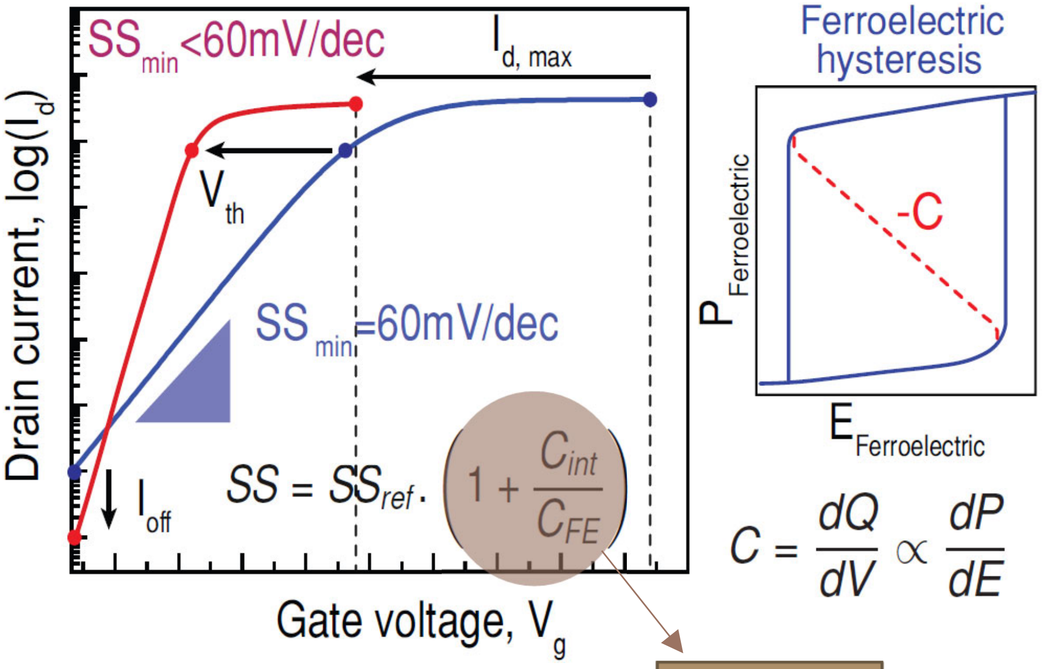
A. Alam, Prospects of Hysteresis-Free Abrupt Switching (0mV/decade) in Landau Switches

Negative capacitance as technology booster for MOSFETs & Tunnel FETs

Sub-1 body factor by negative capacitance:

- Ferroelectric gate stack
- Reduced V_{th}
- Improved overdrive
- Steeper slope

Can be used as additive technology booster on any type of Field Effect Transistor!



$$SS = SS_{ref} \cdot \left(1 + \frac{C_{int}}{C_{FE}}\right)$$

$$C = \frac{dQ}{dV} \propto \frac{dP}{dE}$$

A. Saeidi et al, IEEE EDL 2017.

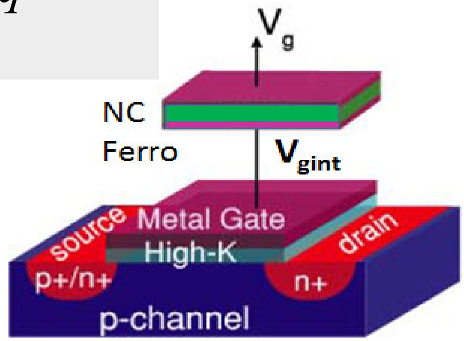
$m < 1$

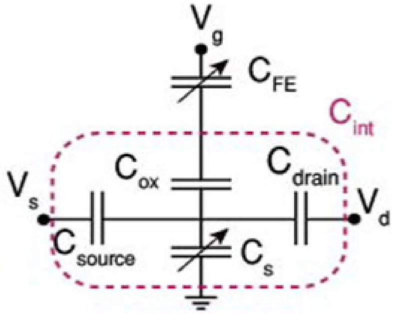
Hybrid steep slope devices…

- Combine multiple principles of switching in a single device architecture.

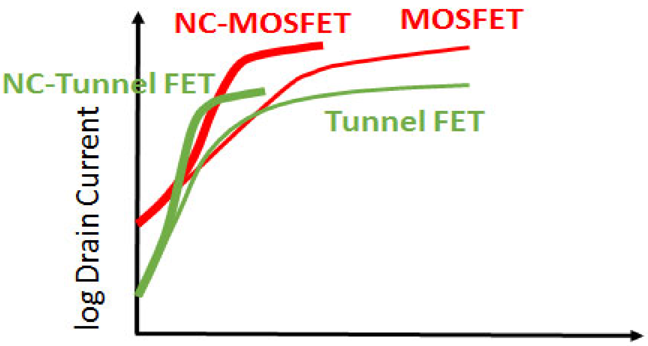
$$S = \frac{\partial V_g}{\partial(\log I_d)} = \underbrace{\frac{\partial V_g}{\partial \psi_S}}_{m} \underbrace{\frac{\partial \psi_S}{\partial(\log I_D)}}_{n} = (1 + \frac{C_s}{C_{ins}}) \frac{kT}{q} \ln 10$$

m <1 and n < 1





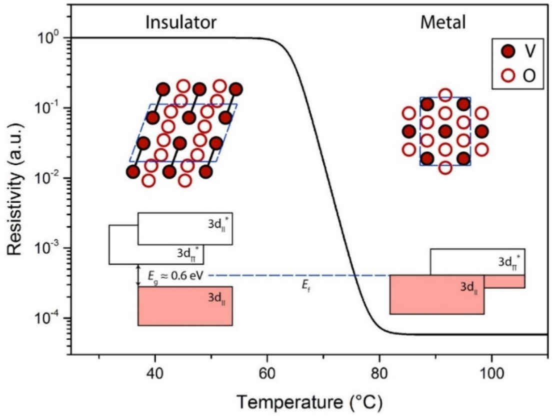
Q: can negative capacitance significantly boost the weak performance of Tunnel FET?



When a metal is not a metal!
Beyond metals, insulators & semiconductors

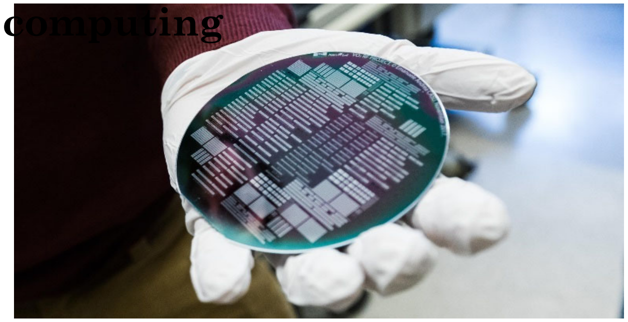
- **Mott insulators**: Metal that stops conducting under certain conditions (low temperature or high pressure), despite classical theory predicting conduction. Flaw in central approximation in band theory: **inter-electron forces are not negligible!**

- Steven C. Erwin (Nature, Vol. 441, 2006) - Materials that owe their insulating nature to correlations in the motions of different electrons.



Vanadium dioxide, VO_2, undergoes a structural **phase transition at ~68 °C**.
The monoclicic phase: **bandgap ~0.6 eV.**
The tetragonal phase: **metallic behavior.**
Fast transition ~ns.

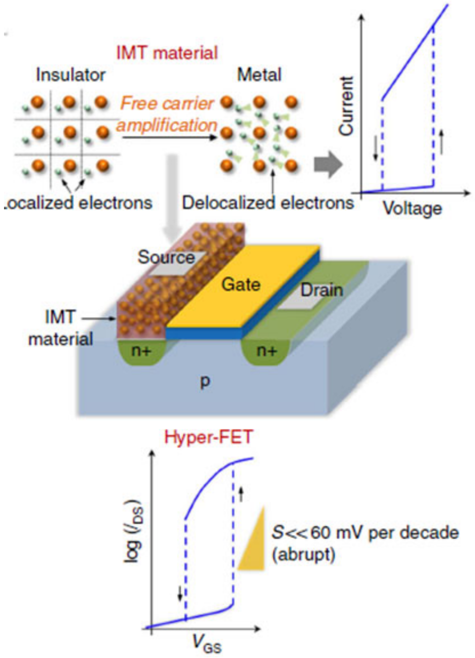
A revolutionary material for aerospace and neuromorphic computing

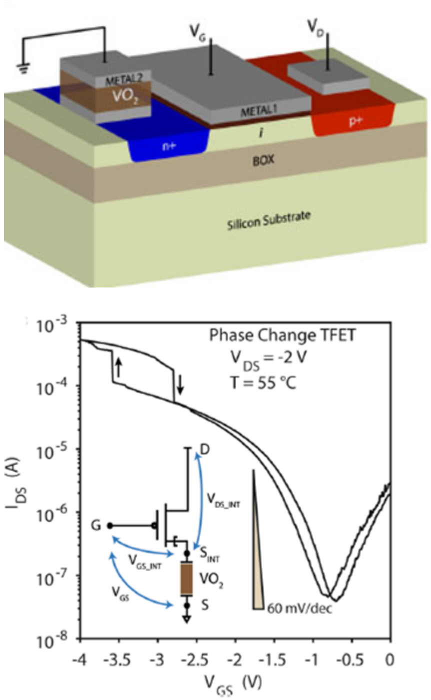


https://actu.epfl.ch/news/a-revolutionary-material-for-aerospace-and-neuro-8/

Sub-unity body factor with with phase change device architectures…

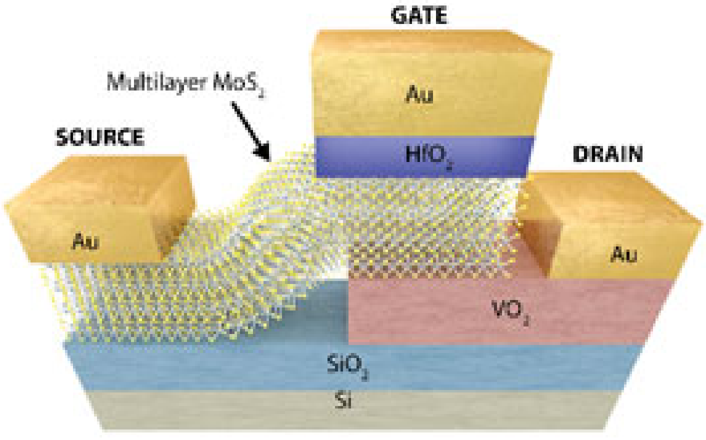
Phase change materials as steep slope booster - internal amplication in source config.





N. Shukla et al., Nature Comms., 2015.
W. Vitale et al., Scientific Reps., 2016.

vdW MoS_2/VO_2 FieldEffect Transistors

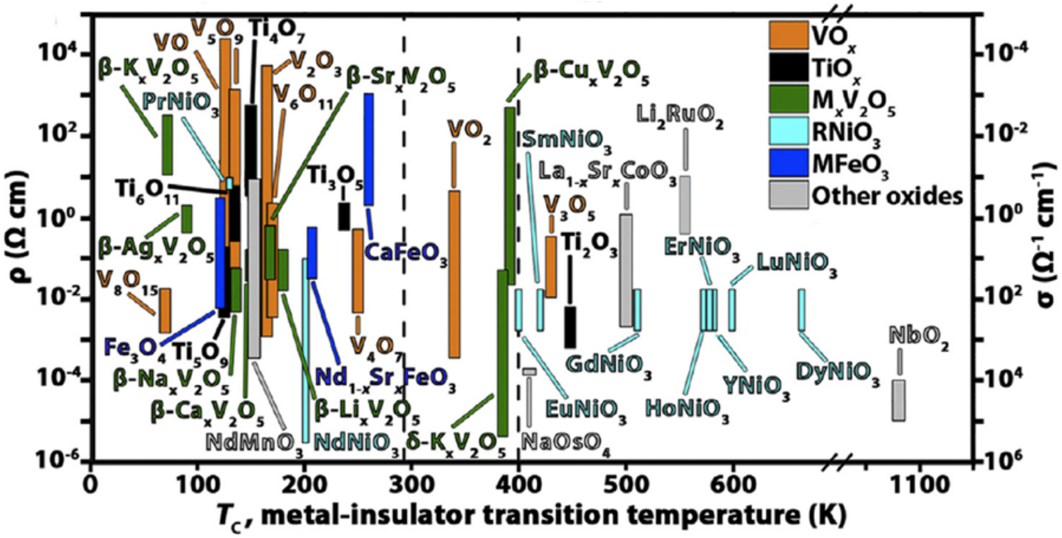


- Ultra low Ioff hybrid junctions
- N-N junction switchable into Schottky junctions
- 2D/phase change FET with steep slope

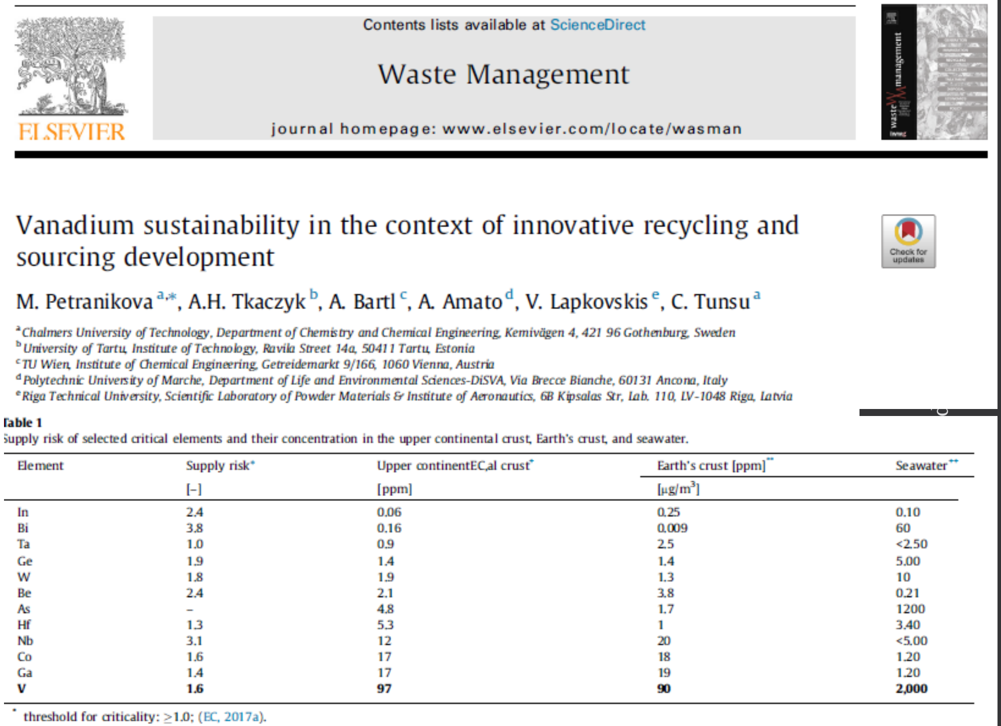
N. Oliva et al., IEDM 2017.

Sustainability of materials and processes

IMT/MIT materials:
choices for the future…



In the earth's crust vanadium is a rather abundant element.
It shows a concentration of just under 100 ppm.



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Vanadium sustainability in the context of innovative recycling and sourcing development

M. Petranikova [a,*], A.H. Tkaczyk [b], A. Bartl [c], A. Amato [d], V. Lapkovskis [e], C. Tunsu [a]

[a] Chalmers University of Technology, Department of Chemistry and Chemical Engineering, Kemivägen 4, 421 96 Gothenburg, Sweden
[b] University of Tartu, Institute of Technology, Ravila Street 14a, 50411 Tartu, Estonia
[c] TU Wien, Institute of Chemical Engineering, Getreidemarkt 9/166, 1060 Vienna, Austria
[d] Polytechnic University of Marche, Department of Life and Environmental Sciences-DiSVA, Via Brecce Bianche, 60131 Ancona, Italy
[e] Riga Technical University, Scientific Laboratory of Powder Materials & Institute of Aeronautics, 6B Kipsalas Str, Lab. 110, LV-1048 Riga, Latvia

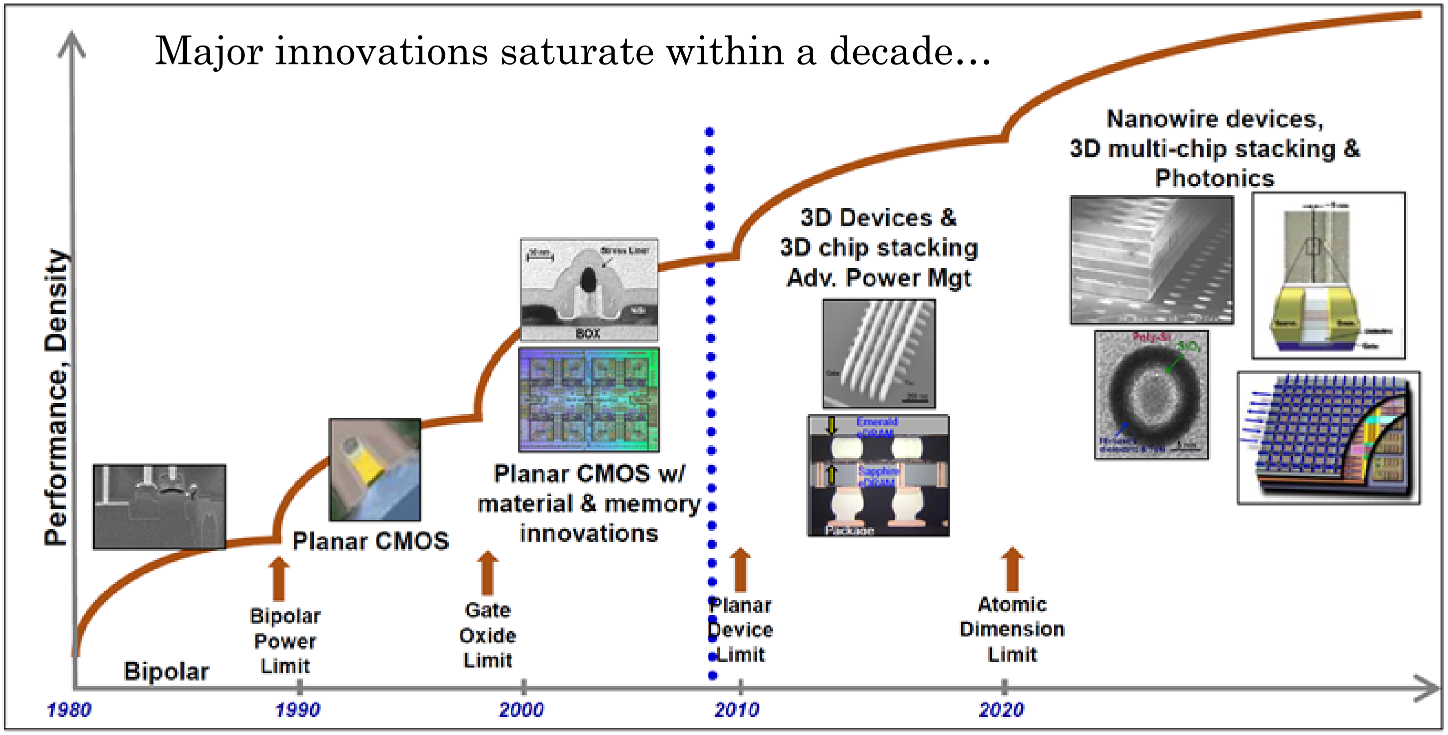
Table 1
Supply risk of selected critical elements and their concentration in the upper continental crust, Earth's crust, and seawater.

Element	Supply risk*	Upper continentEC,al crust*	Earth's crust [ppm]**	Seawater**
	[–]	[ppm]	[μg/m^3]	
In	2.4	0.06	0.25	0.10
Bi	3.8	0.16	0.009	60
Ta	1.0	0.9	2.5	<2.50
Ge	1.9	1.4	1.4	5.00
W	1.8	1.9	1.3	10
Be	2.4	2.1	3.8	0.21
As	–	4.8	1.7	1200
Hf	1.3	5.3	1	3.40
Nb	3.1	12	20	<5.00
Co	1.6	17	18	1.20
Ga	1.4	17	19	1.20
V	**1.6**	**97**	**90**	**2,000**

* threshold for criticality: ≥1.0; (EC, 2017a).

Silicon Technology: a 3D migration into the future?

- High-performance, 3D integrated # technologies

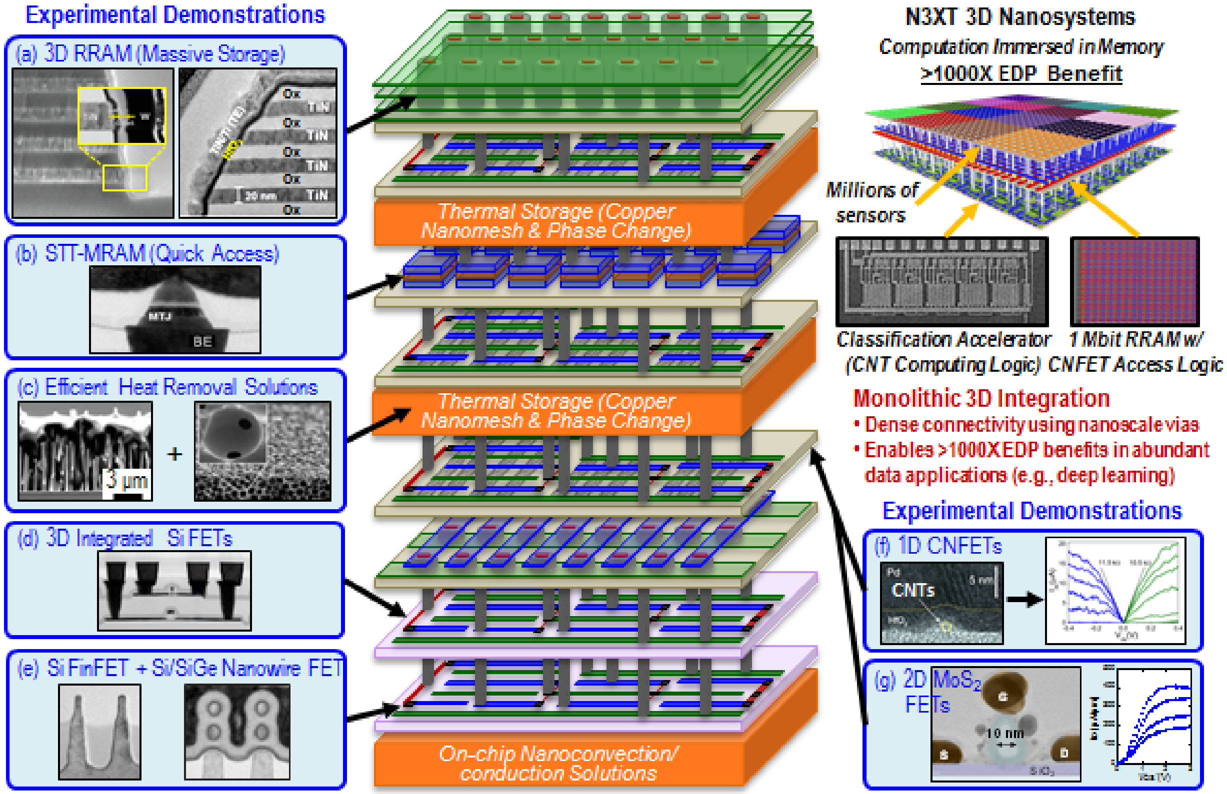


Major innovations saturate within a decade…

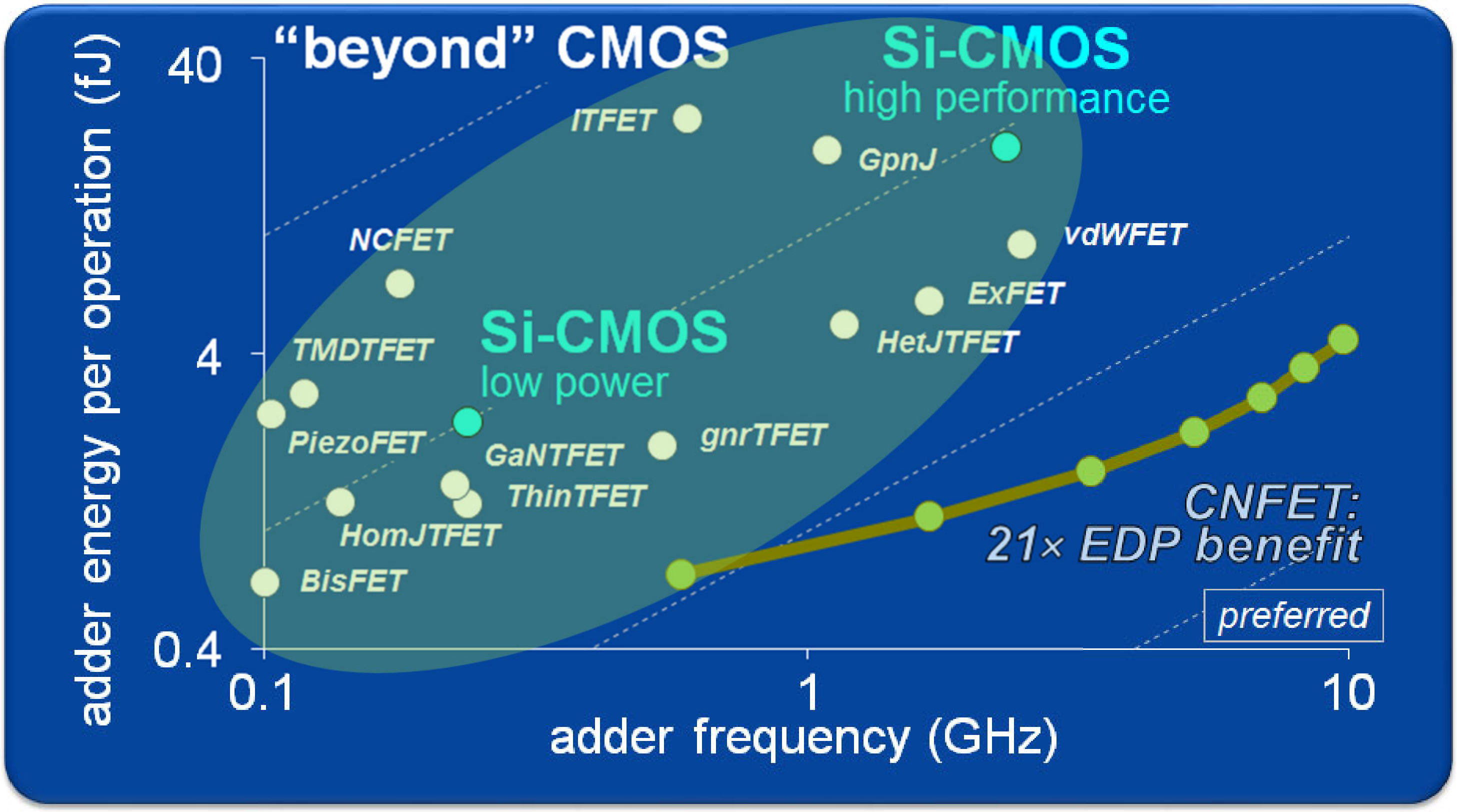
Source: IBM

3D integration with ultra-dense connectivity: N3XT concept

- Computation Immersed in Memory
- 1000x EDP benefits
- Can serve abundant future data applications
- Top active layers: CNT or 2D FETs

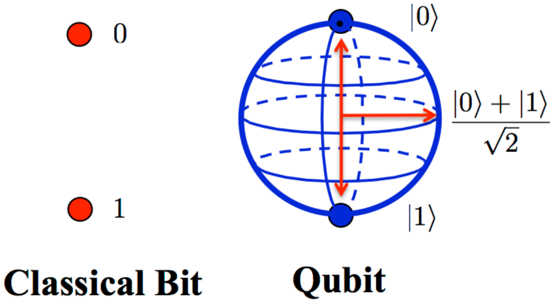


N3XT chip with CNT transistors



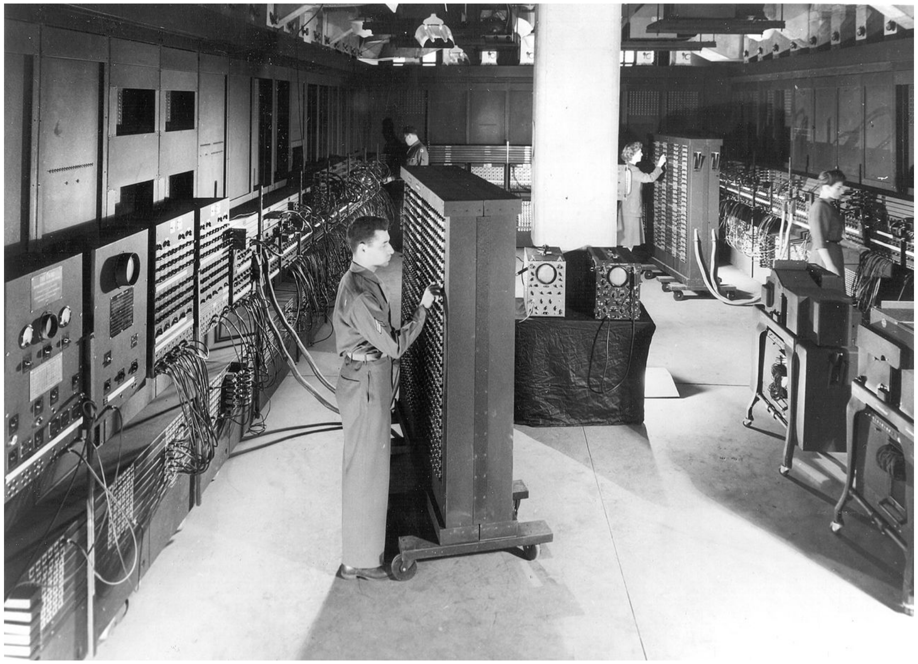
Outline

- **Introduction to future electronic technologies in the Zettabyte era**
- The New Ecosystem of **Digital Transformation in Zettabyte Era**
- **Energy efficiency**: from devices to architectures
- **Cloud and Quantum Computing**
- **Edge Artifical Inteligence and Neuromorphic Computing**
- **Digital Twins**



It’s the 1940s again…

Quantum Computing is an immature technology but…
an entirely new category of hardware that has its own strengths, its own weaknesses, and a huge potential for powerful apps…



A DISCONTUINITY!

Qubits

- ***What is the principle?***

  a small number of particles in superposition states can carry an enormous quantity of information:

  1,000 particles in superposition $2^{1,000}$ (~10^{300}) numbers

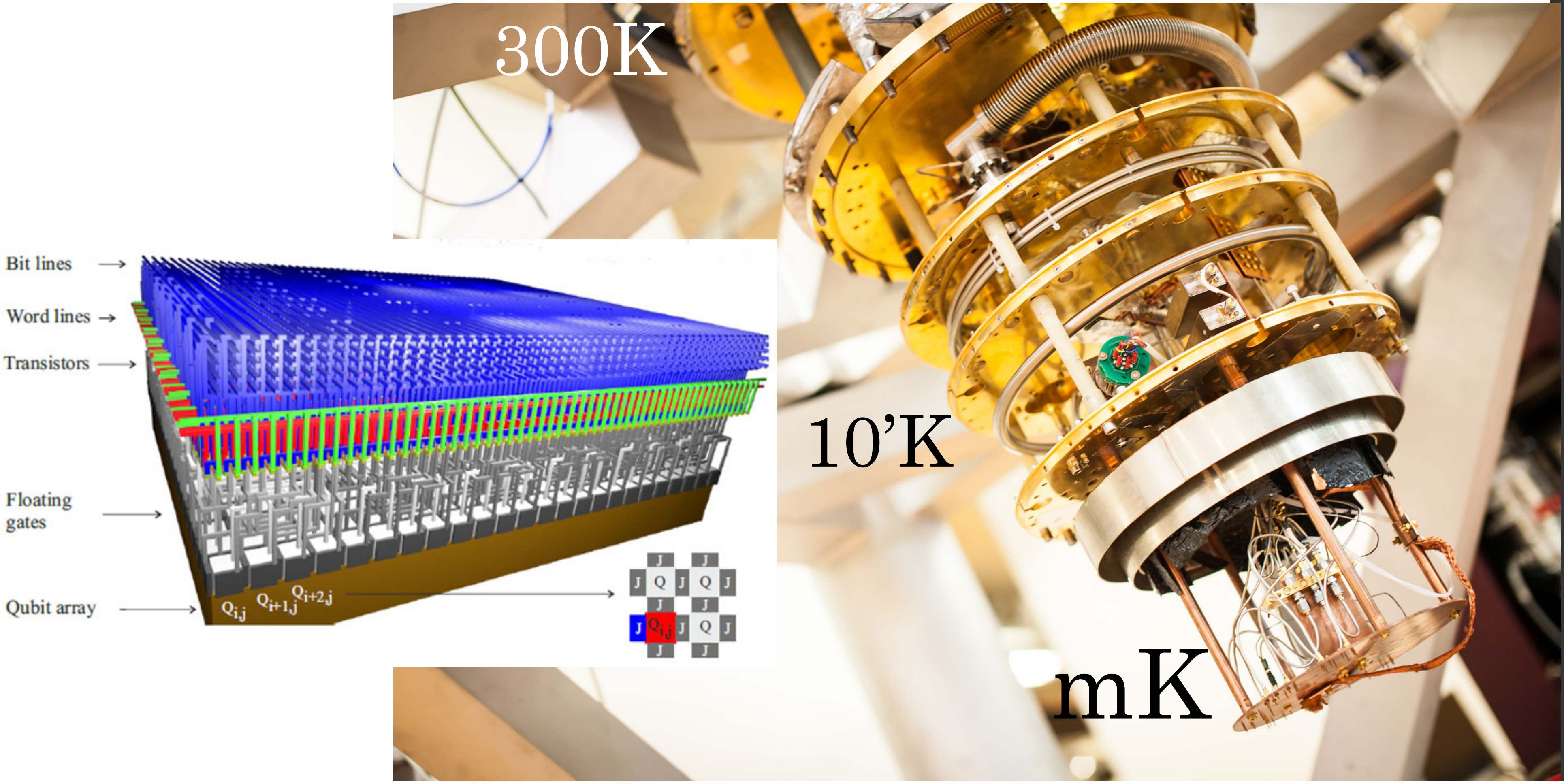
  and QC can manipulate these numbers in parallel.

  challenge: *measure and pick-out one possibility! @milliK!*
- ***What type of computational problems?***
  - factorization or simulations of quantum physics!
- ***How many qubits are needed for a computer***?
  - *Tens of thousands to millions*
- ***Existing technologies?***
  - *trapped ions, electron/hole spin in semic., single dopants in silicon, nitrogen-vac, in diamond*

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

a superposition of both states at the same time

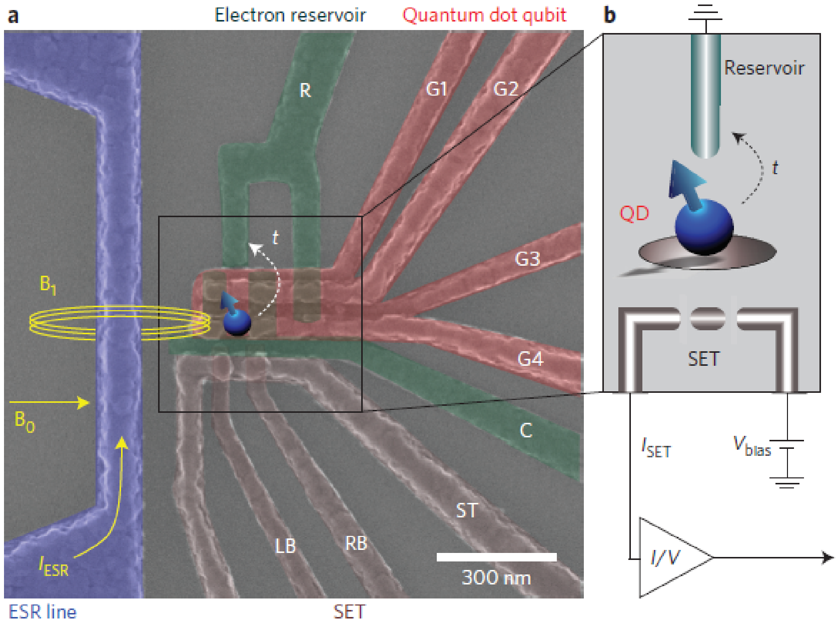
Quantum computer architecture…



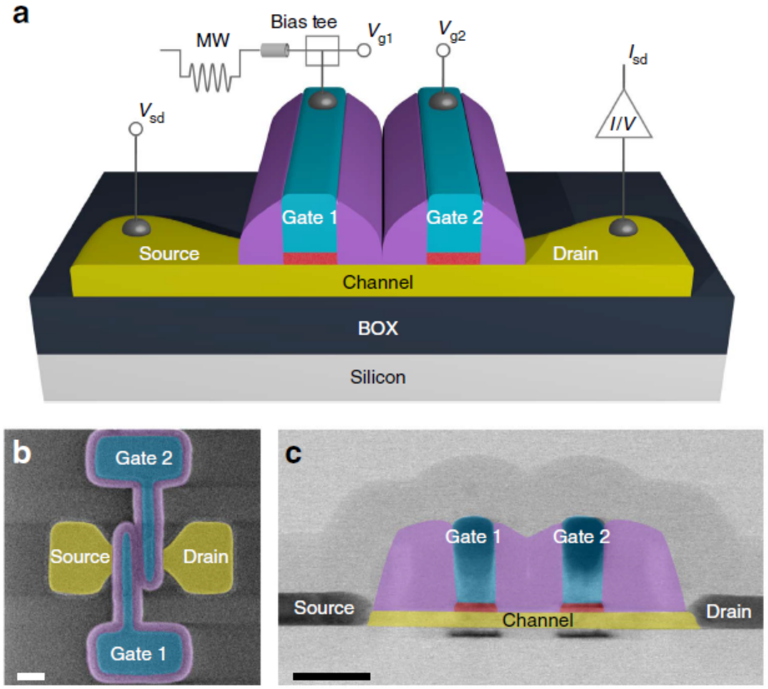
Technologies to read-out qubits

A gate-addressable quantum dot qubit in isotopically engineered silicon with SET readout

CMOS qubit device on FD SOI



M. Veldhorst et al., Nature Nanotech, 2014.



R. Maurand et al., Nature Coms., 2014.

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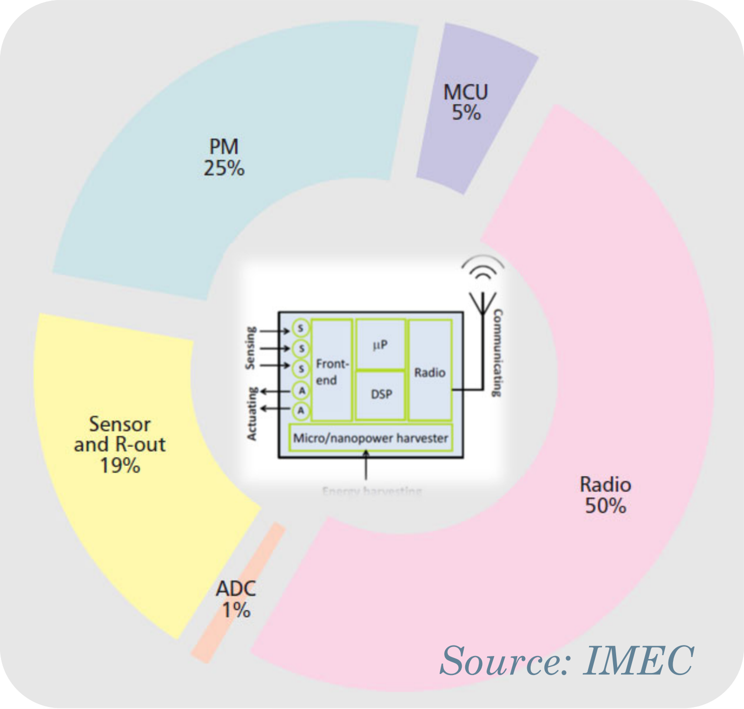
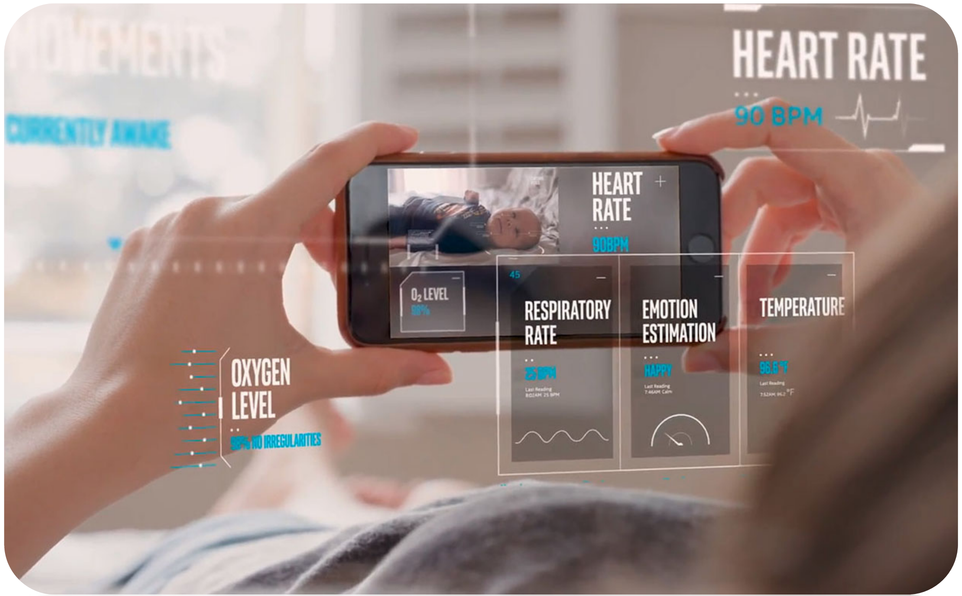
Energy efficient autonomous sensor nodes for Internet of Things

100 microWatt – 10 mW
/ sensor node



Source: IMEC

Smart hub: 100mW – 10W
(tens of sensors /hub)

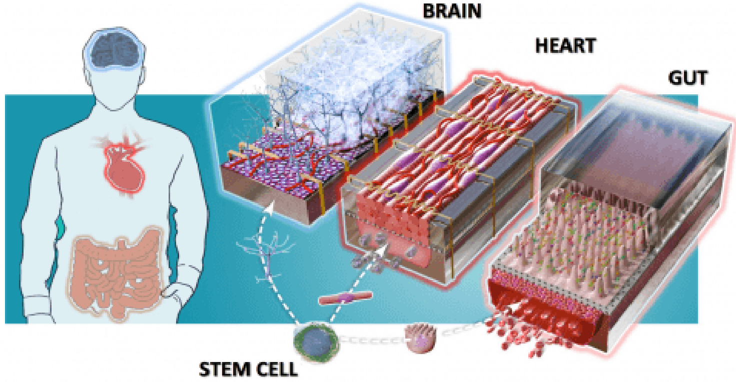


Key challenges for biosensors

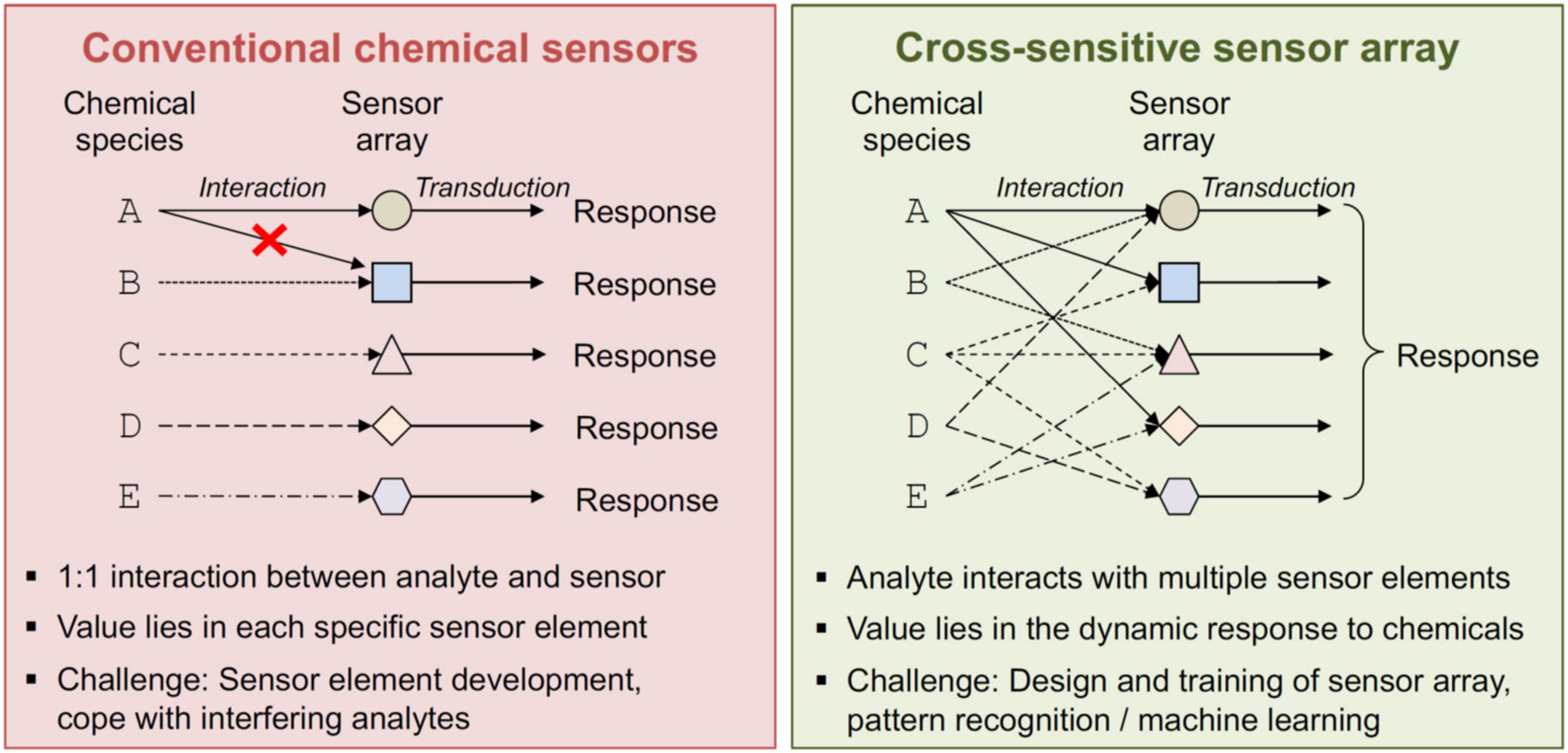
- **Wearable** biosensors: ECG, EEG, EMG, SpO2, blood pressure, pH, glucose, various analytes in biofluids, …
- **Implantable** sensors and transducers
- **Organs on Chip** with embedded sensors!

Requirements

- **High quality data** - multi-parameter sensing
- **Form factor** - frictionless
- **Autonomy** - low power, energy efficiency
- **User acceptance** - data security, privacy
- **Low cost systems** – 3D, on foil integration



Edge AI sensors: from conventional to cross sensitive sensor arrays & dynamic signatures



Conventional chemical sensors

- 1:1 interaction between analyte and sensor
- Value lies in each specific sensor element
- Challenge: Sensor element development, cope with interfering analytes

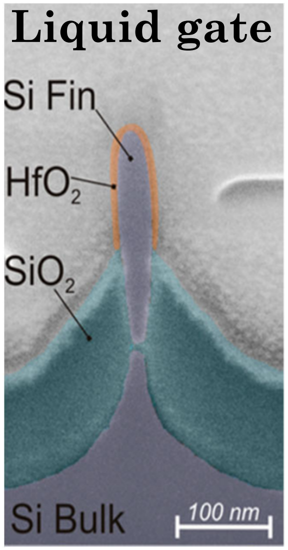
Cross-sensitive sensor array

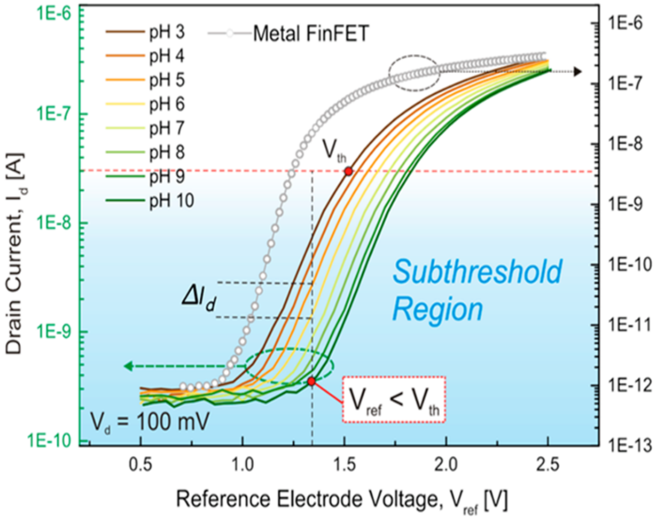
- Analyte interacts with multiple sensor elements
- Value lies in the dynamic response to chemicals
- Challenge: Design and training of sensor array, pattern recognition / machine learning

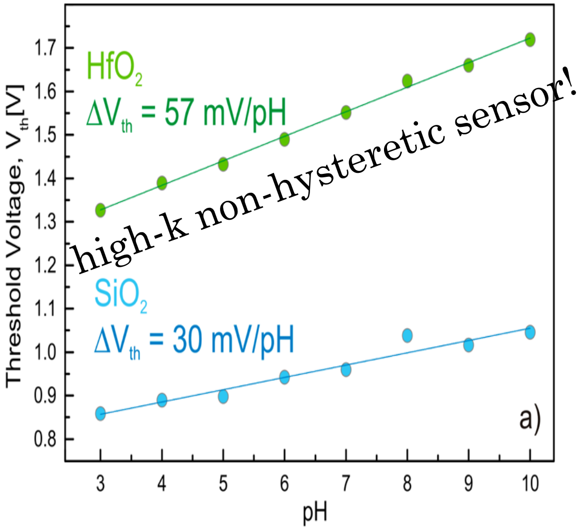
Source: J. Weiss, IBM Zürich Resaerch, Tutorial @ Transducers 2019.

Biosensing with computing technology

- From metal-gate FinFET to **liquid-gate FinFET** biosensor







high-k non-hysteretic sensor!

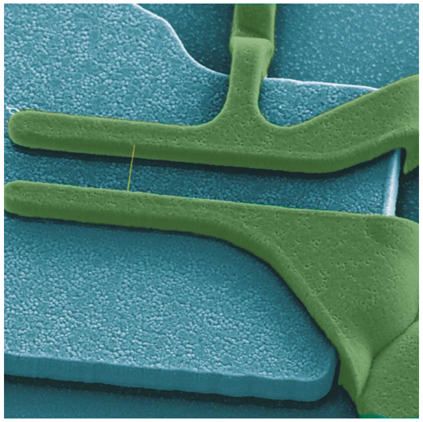
S. Rigante et al., ACS Nano 2015.

Wearables: bio and environmental co-monitoring for air and water quality!

Environmental related diseases:

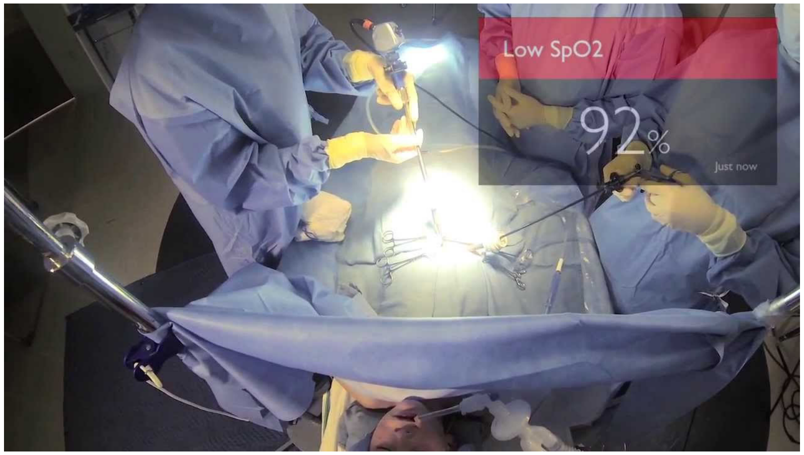
- **RESPIRATORY INFECTIONS:** more than 1.5 million deaths annually from respiratory infections due to environment.
- **CANCER:** environmental accounts for an estimated 31% of global lung cancer burden.
- **CARDIOVACULAR DISEASES:** 2.5 million people die every year from cardiovascular disease attributable to chemical and air pollution.
- **DIARRHOEA:** about 1.5 million deaths per year from diarrhoeal diseases; 88% of all cases of diarrhoea attributable to water, sanitation and hygiene.
- **MALARIA, INTESTINAL NEMATODE INFECTIONS, HEPATITIS B and C, TUBERCULOSIS, etc.**

CNT Gas Sensor



Source: C. Hierold, ETHZ

Context driven wearable technology



Frictionless sweat sensing

- An emerging frontier for wearable biosensors

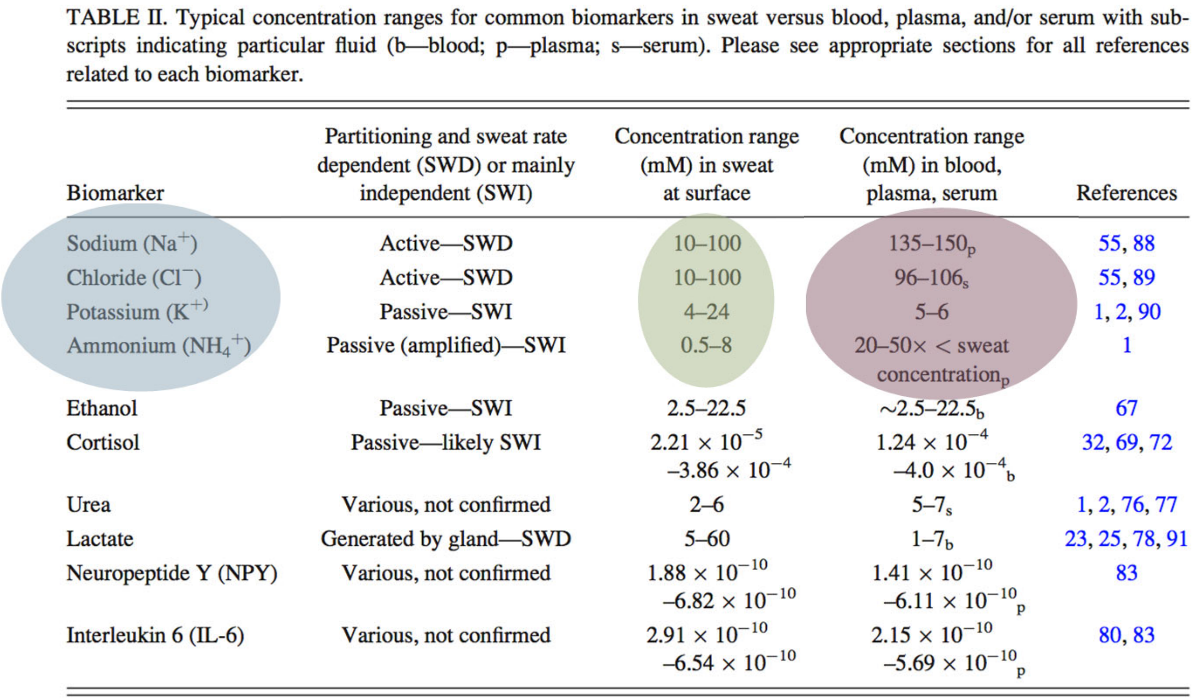
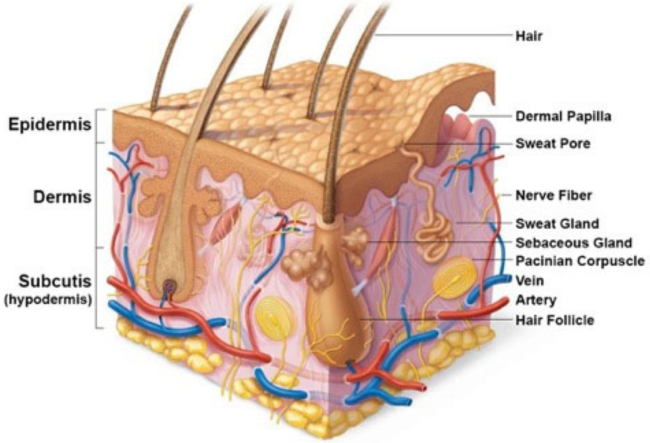


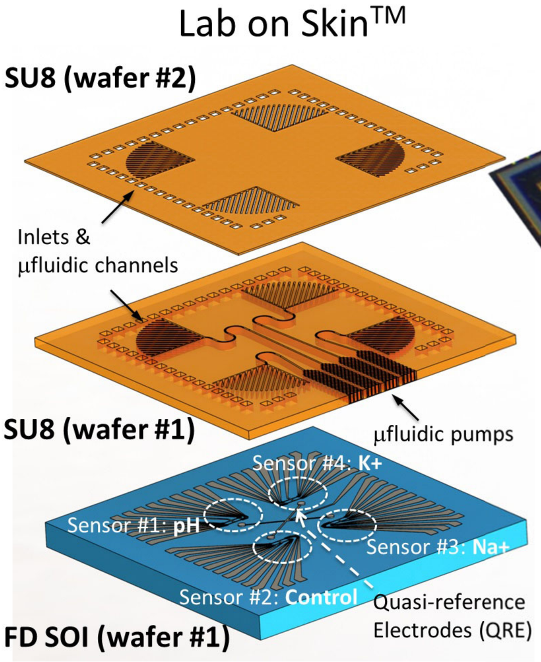
TABLE II. Typical concentration ranges for common biomarkers in sweat versus blood, plasma, and/or serum with subscripts indicating particular fluid (b—blood; p—plasma; s—serum). Please see appropriate sections for all references related to each biomarker.

Biomarker	Partitioning and sweat rate dependent (SWD) or mainly independent (SWI)	Concentration range (mM) in sweat at surface	Concentration range (mM) in blood, plasma, serum	References
Sodium (Na^+)	Active—SWD	10–100	$135–150_p$	55, 88
Chloride (Cl^-)	Active—SWD	10–100	$96–106_s$	55, 89
Potassium ($K^{+)}$	Passive—SWI	4–24	5–6	1, 2, 90
Ammonium ($NH_4{}^+$)	Passive (amplified)—SWI	0.5–8	20–50× < sweat concentration_p	1
Ethanol	Passive—SWI	2.5–22.5	$\sim 2.5–22.5_b$	67
Cortisol	Passive—likely SWI	2.21×10^{-5} $–3.86 \times 10^{-4}$	1.24×10^{-4} $–4.0 \times 10^{-4}{}_b$	32, 69, 72
Urea	Various, not confirmed	2–6	$5–7_s$	1, 2, 76, 77
Lactate	Generated by gland—SWD	5–60	$1–7_b$	23, 25, 78, 91
Neuropeptide Y (NPY)	Various, not confirmed	1.88×10^{-10} $–6.82 \times 10^{-10}$	1.41×10^{-10} $–6.11 \times 10^{-10}{}_p$	83
Interleukin 6 (IL-6)	Various, not confirmed	2.91×10^{-10} $–6.54 \times 10^{-10}$	2.15×10^{-10} $–5.69 \times 10^{-10}{}_p$	80, 83

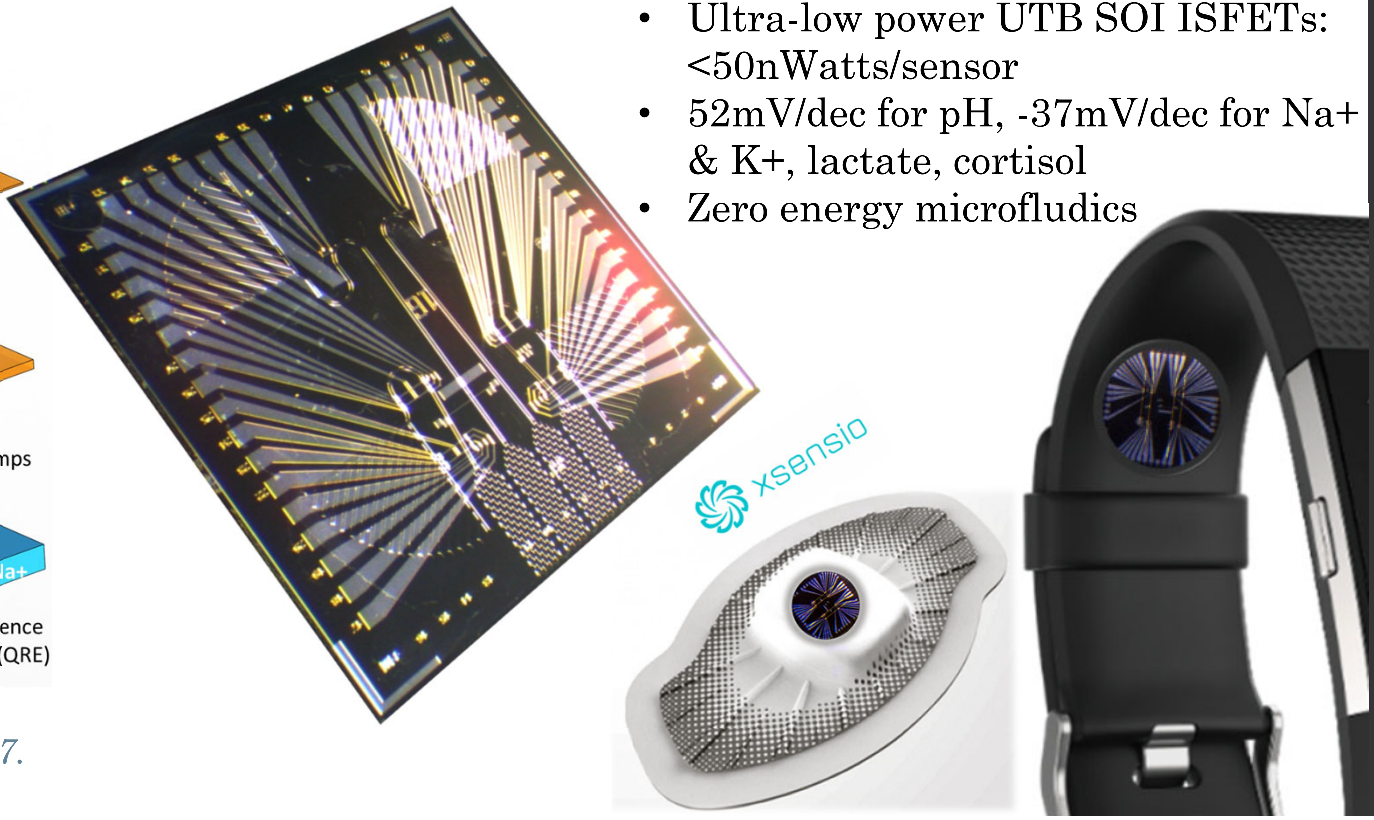


Real-time sweat analysis with Lab On Skin^{TM}

- Embeddable unique Xsensio's **Lab-On-Skin^{TM} electronic stamp technology**: minute by minute non-invasive multi-biomarker sensing

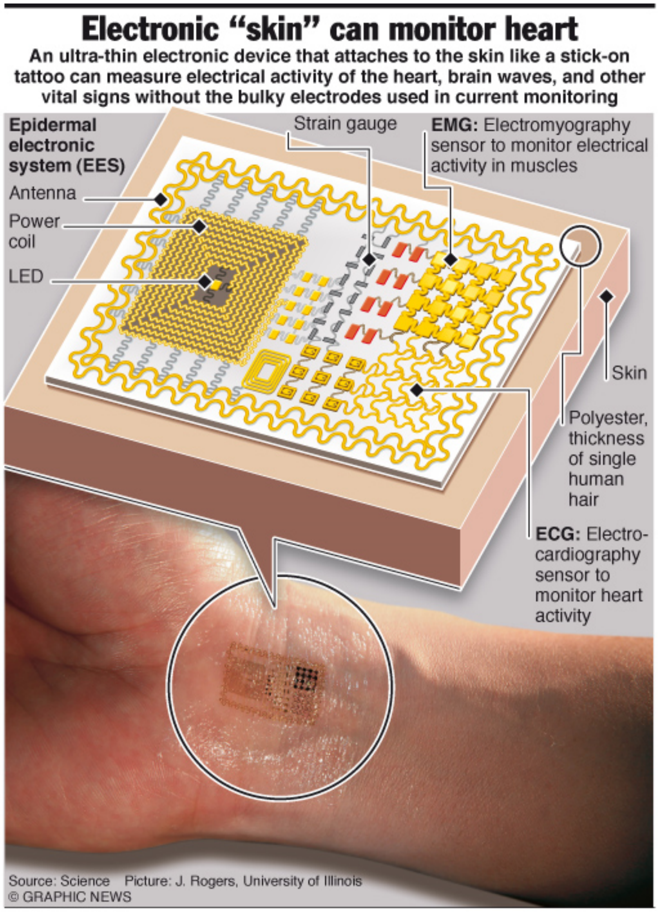


- Ultra-low power UTB SOI ISFETs: <50nWatts/sensor
- 52mV/dec for pH, -37mV/dec for Na+ & K+, lactate, cortisol
- Zero energy microfludics



F. Bellando et al., IEDM 2017.

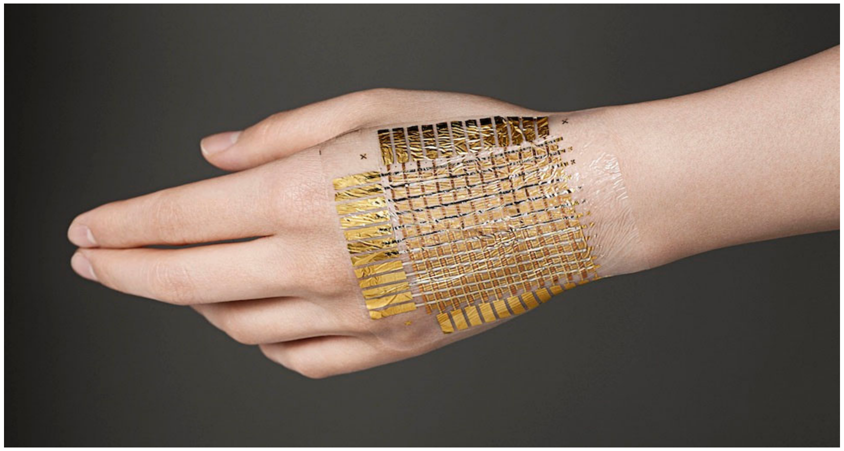
Towards sensitive biostamps & tatoos

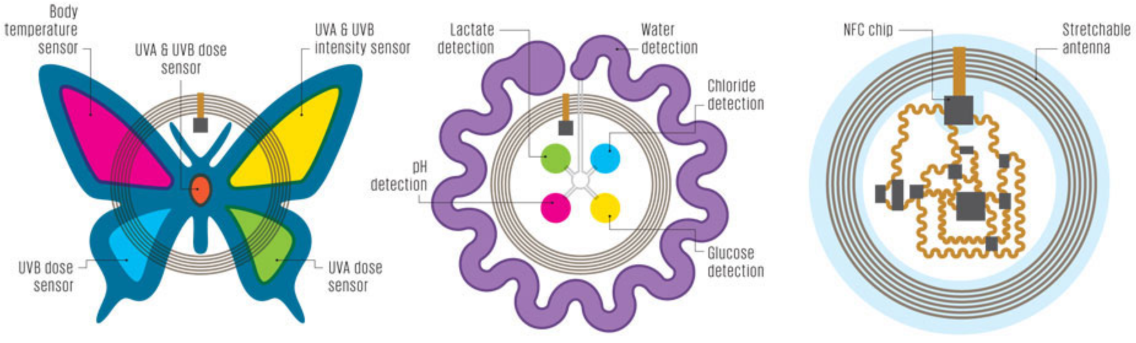


Electronic “skin” can monitor heart

An ultra-thin electronic device that attaches to the skin like a stick-on tattoo can measure electrical activity of the heart, brain waves, and other vital signs without the bulky electrodes used in current monitoring

Source: Science Picture: J. Rogers, University of Illinois
© GRAPHIC NEWS





UV EXPOSURE & TEMPERATURE

PERSPIRATION & BIOCHEMISTRY

BLOOD PRESSURE

John A. Rogers, Science, 2011 & IEEE Spectrum. 2015.

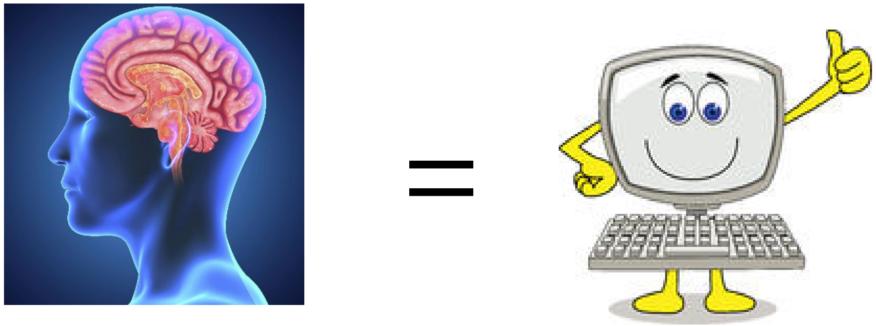
Neuromorphic computing: what is and what is not?!

Goal: build computers that learn and generalize in broad variety of tasks, much as human brains - *Todd Hylton*

Cognitive computing:

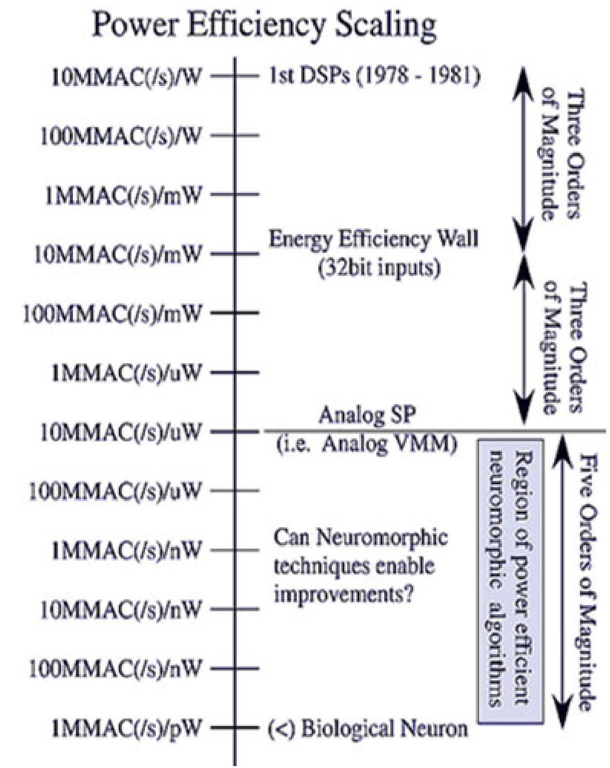
BRAIN = COMPUTER

THINKING = EXECUTION OF ALGORITHMS !



A neuromorphic computer is not a brain but **a brain-like energy efficient system** to do machine learning & AI.

Computational efficiency of various technologies

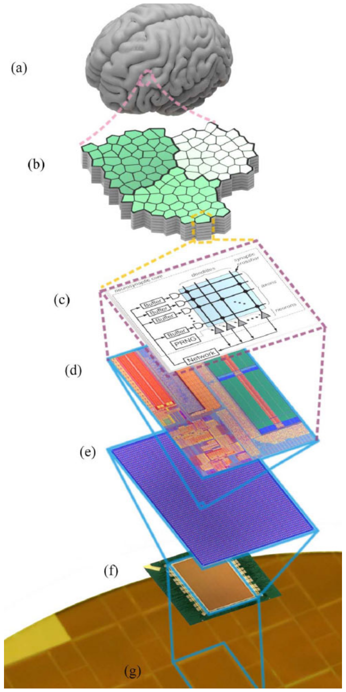


MAC = Multiply-Accumulate Instr.

J. Hasler, B. Marr, " Frt. Neurosc., 2013.

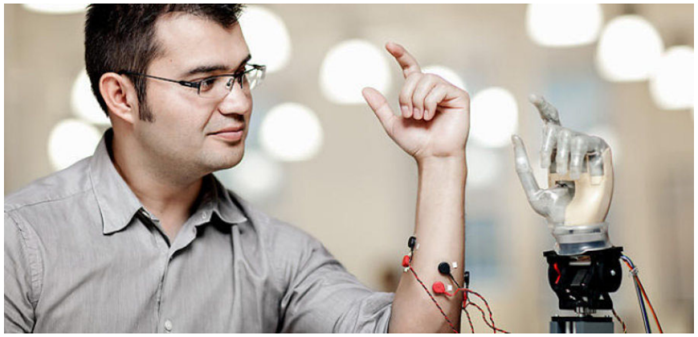
Tremendous recent progress in neuromorphic computers…

- Key feature: fundamental reorganization of memory and processing (co-location).
- **IBM’s TrueNorth** (DARPA’s SyNAPSE project)
  65 mW real-time neurosynaptic processor, 4’096 neurosynaptic cores tiled in 2-D array, **1 million digital neurons** and **256 million synapses,** with **computational energy efficiency = 400 GSOPS/Watt.**
- **Intel’s Liohi** (September 2017)
  130’000 neurons, 130 million synapses



F. Akopyan et al., IEEE TCAD, 2015

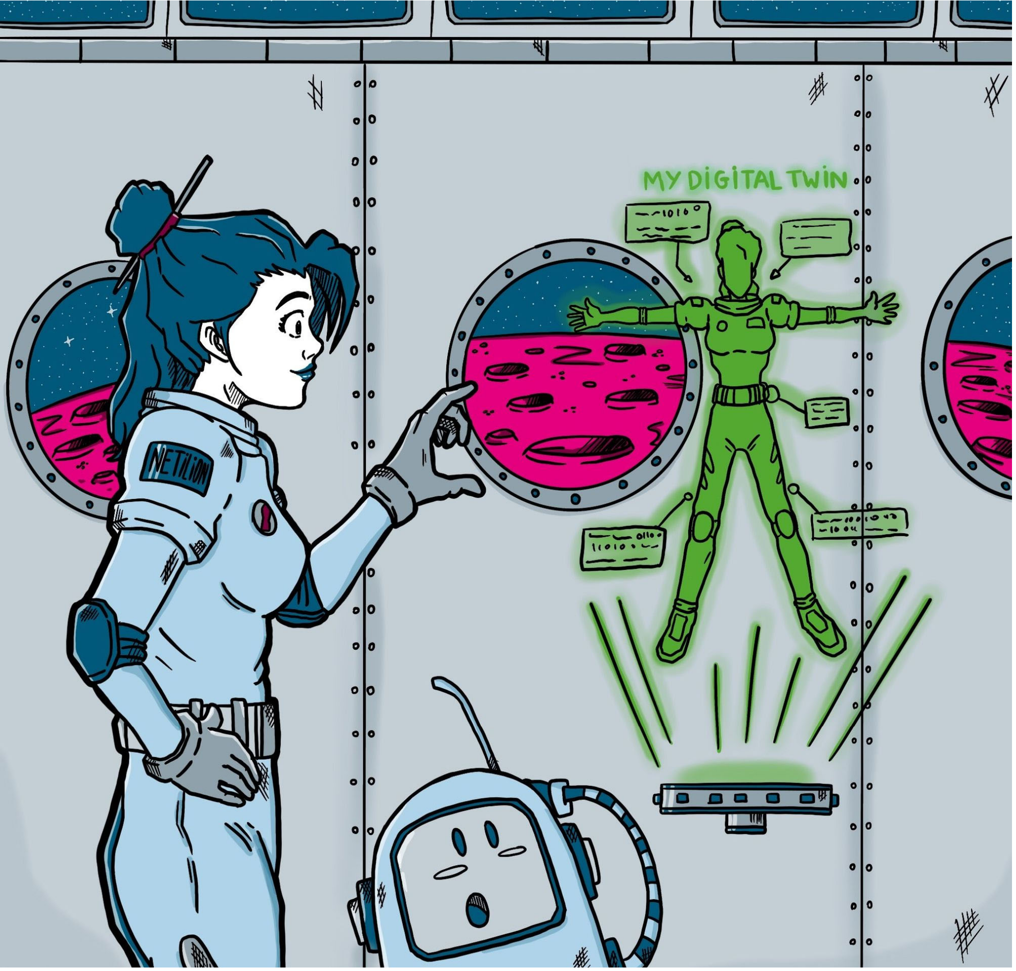
Potential future applications:
cognitive prostetics, BMI, wearables, smart in situ imaging facilities.



Outline

- **Introduction to future electronic technologies in the Zettabyte era**
- The New Ecosystem of **Digital Transformation in Zettabyte Era**
- **Energy efficiency**: from devices to architectures
- **Cloud and Quantum Computing**
- **Edge Artifical Inteligence and Neuromorphic Computing**
- **Digital Twins**

Digital Twins as mainstream technology for digitalisation

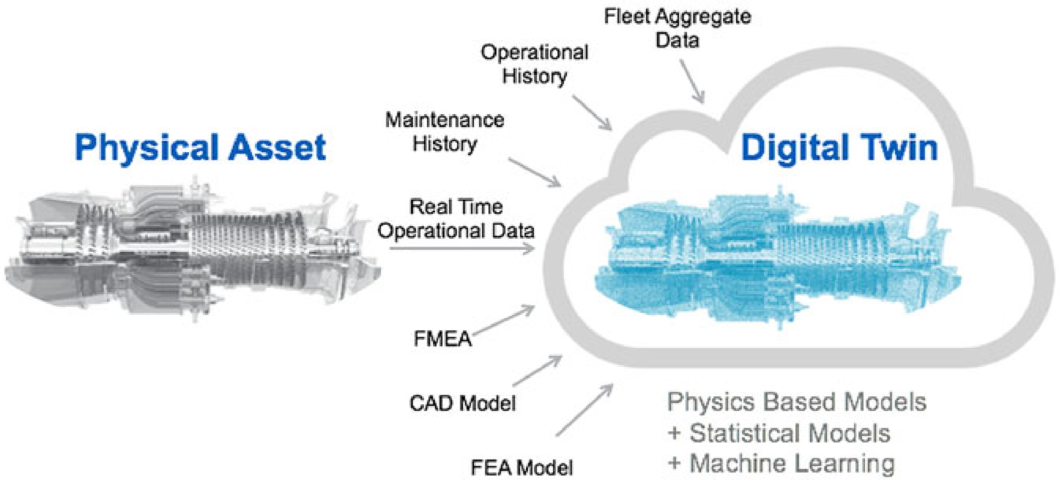


- **digital replica** of an object or a process in the physical world…

One source of truth…

Three main purposes to implement a DT:

- A **PRODUCT Digital Twin** – to guarantee reliable design in product development and improvements.
- A **PRODUCTION Digital Twin** – to improve production planning and manufacturing.
- A **PERFORMANCE Digital Twin** – to capture, analyse and act on data while an asset is in operation.



Key components:

- **MODEL**
- **TIME SERIES DATA**
- **UNIQUE IDENTIFIER**
- **MONITORING CAPABILITY**

Expected benefits

- Enhances efficiency and productivity:
  - ☐ Using digital twins, businesses no longer need to fully experiment with physical objects to improve processes.
  - ☐ Don't need to halt ongoing processes and can simply run simulations in the lab to understand the risks and benefits
- Reduces product quality issues:
  - ☐ Digital twins simulate different "what-if" real-world scenarios
- Lowers maintenance costs:
  - ☐ Digital twins predict maintenance failures via simulation models that capture information about various risk factors
  - ☐ They save costs, improve equipment reliability, reduce downtime, and extend the equipment life span.
- Improves employee training:
  - ☐ Employees can be also trained to handle equipment that isn't physically close or is too costly to be given hands-on training.
  - ☐ Digital twins can recreate real-life hazardous situations to train employees.
- **What about Digital Twins and Sustainability?**

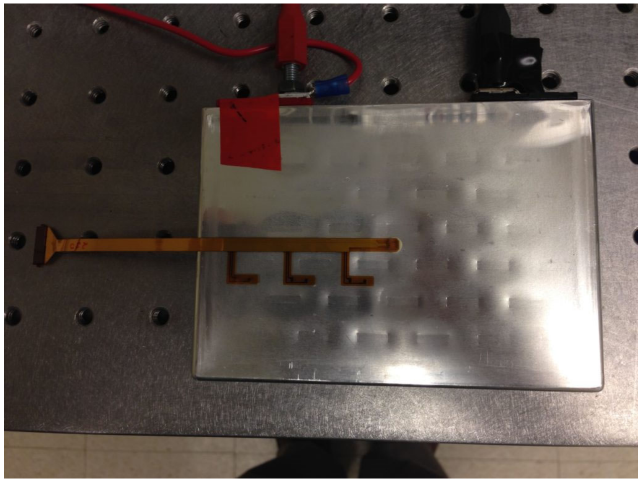
Can Digital Twins Transform Cities Environment in a more Sustainable way?

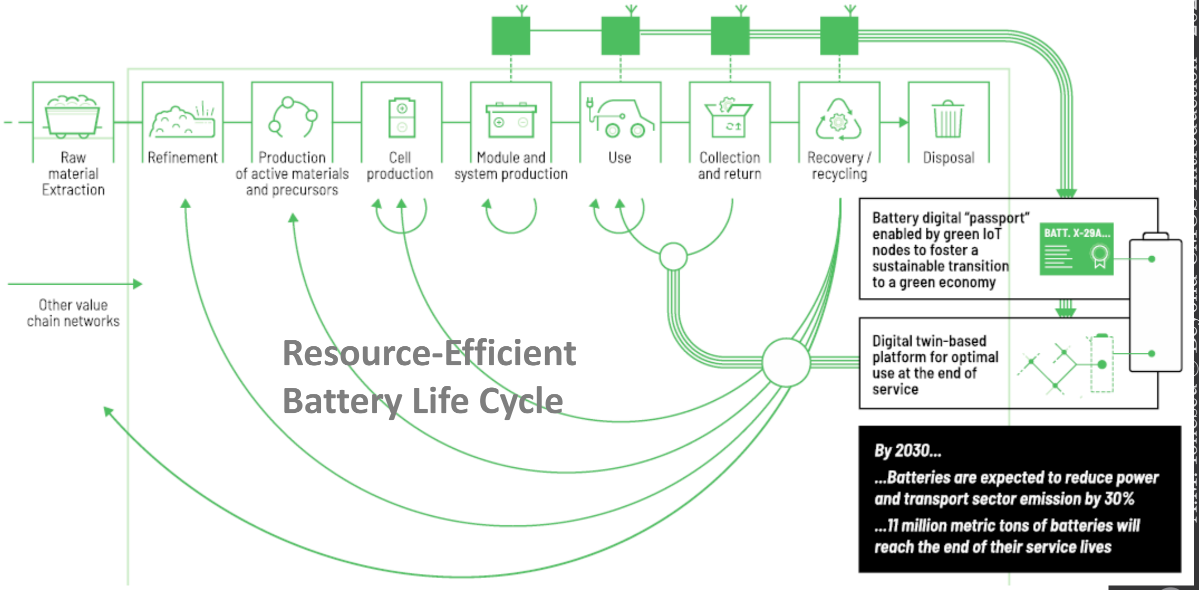
- **City = A complex case of systems-of-systems, the DT needs to incorporate the data from the physical twin in real time to model real-world processes.**
- Recent developments in sensors, wireless communications, and processors enabled Smart Cities Digital Twins.

Virtual Singapore

Digital twins for smart batteries

- https://www.ge.com/news/reports/scientists-built-a-digital-twin-of-a-car-battery-to-make-it-last-longer
- shrink the battery size, shave production expenses by 15%, all while maintaining long-term re





Battery digital "passport" enabled by green IoT nodes to foster a sustainable transition to a green economy

Digital twin-based platform for optimal use at the end of service

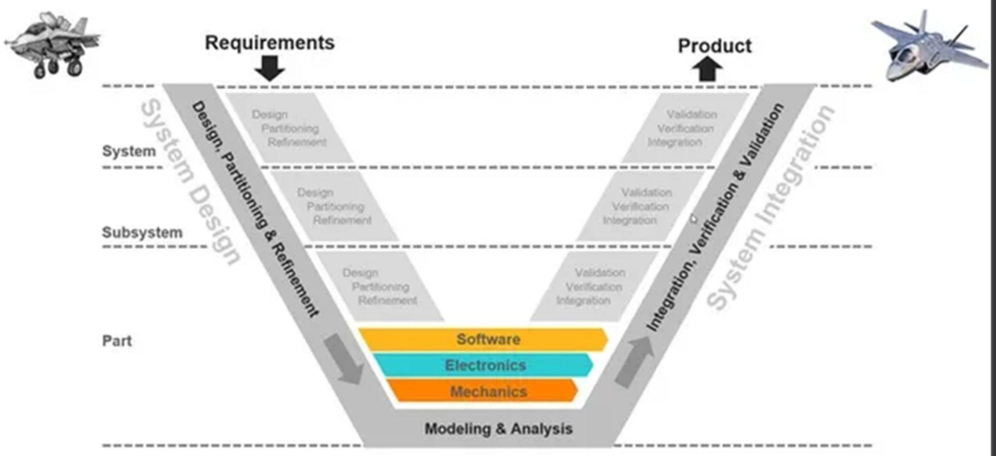
By 2030...

...Batteries are expected to reduce power and transport sector emission by 30%

...11 million metric tons of batteries will reach the end of their service lives

System-of-Systems need Digital Twins: the F-35

- **200,000 parts** made by **1,600 suppliers**
- houses **3,500 integrated circuits**
- **>20,000,000 lines of software** code.
- designers face **hugely intricate hardware/software interaction** and interactions at the system level across **multiple domains**—mechanical, electronic, thermal, etc.

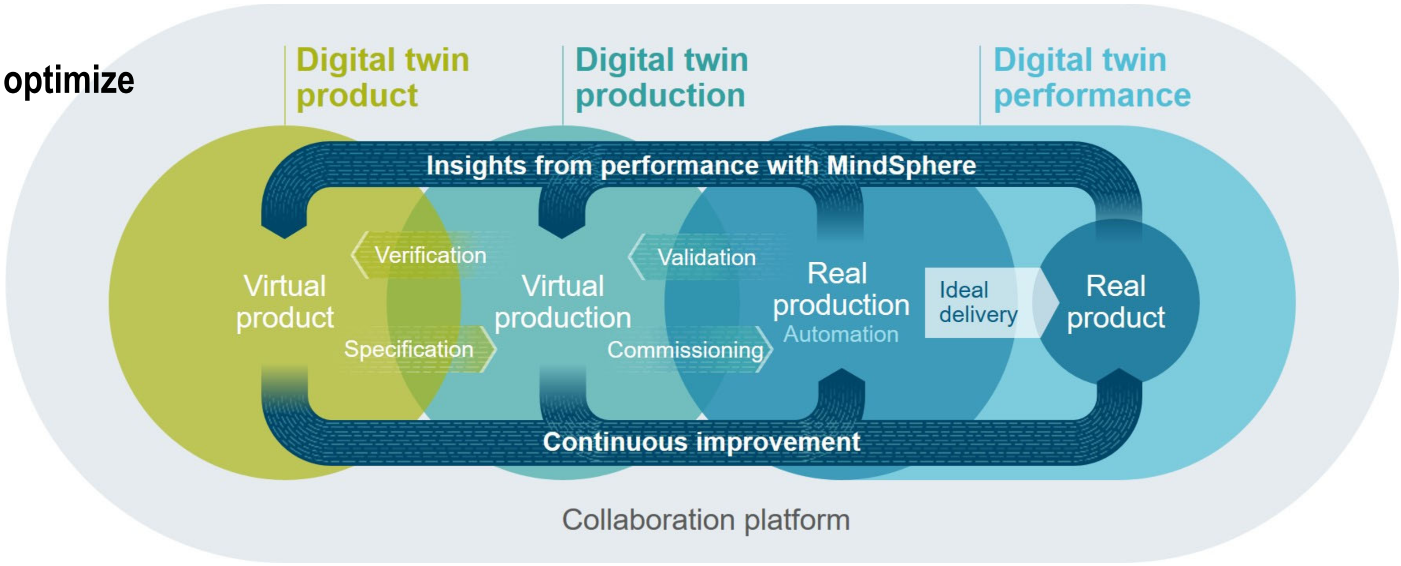


Digital twins of performance

Siemens manufacturers implement the **in conjunction with IIoT** to eliminate the unknowns and make near real-time production optimization decisions.

The **performance twin** involves capturing and sending back live performance data of the production line and of product itself, at a customer location. This **near real-time data** allows engineers to determine if the production line and product behave as they were intended. If not, this information will quickly drive **actionable insights** and informed decision making back into the product and production line design.

Closing the loop to optimize decision making



Digital Twins of All Humans

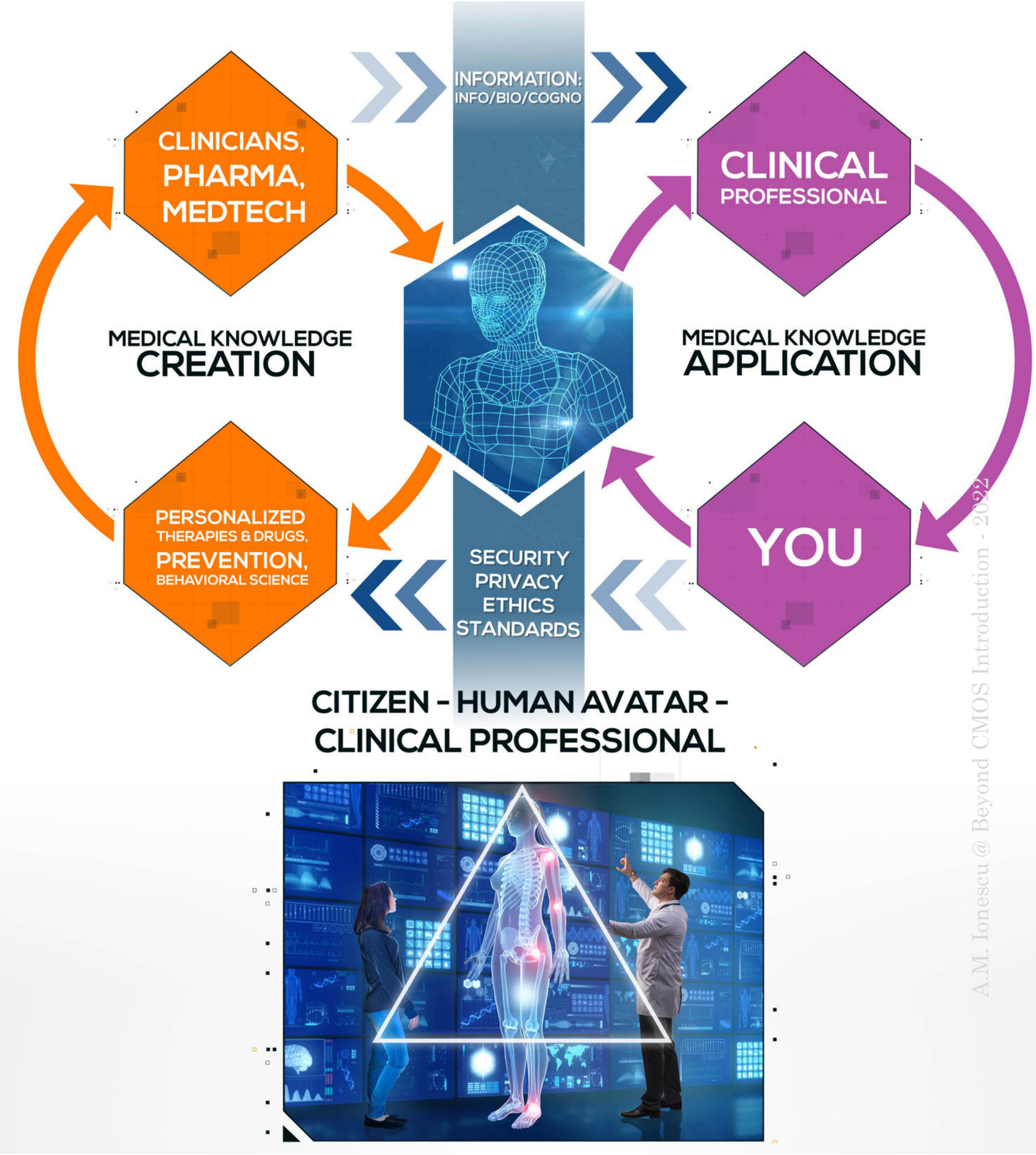
- Reactive healthcare is unsustainable
- Digital twins will apply to people too
- Towards a more sustainable Personalized, Preventive and Participatory (P3) Healthcare

The missing link…

… for breaking barriers between Medical Knowledge Creation and Medical Knowledge Application

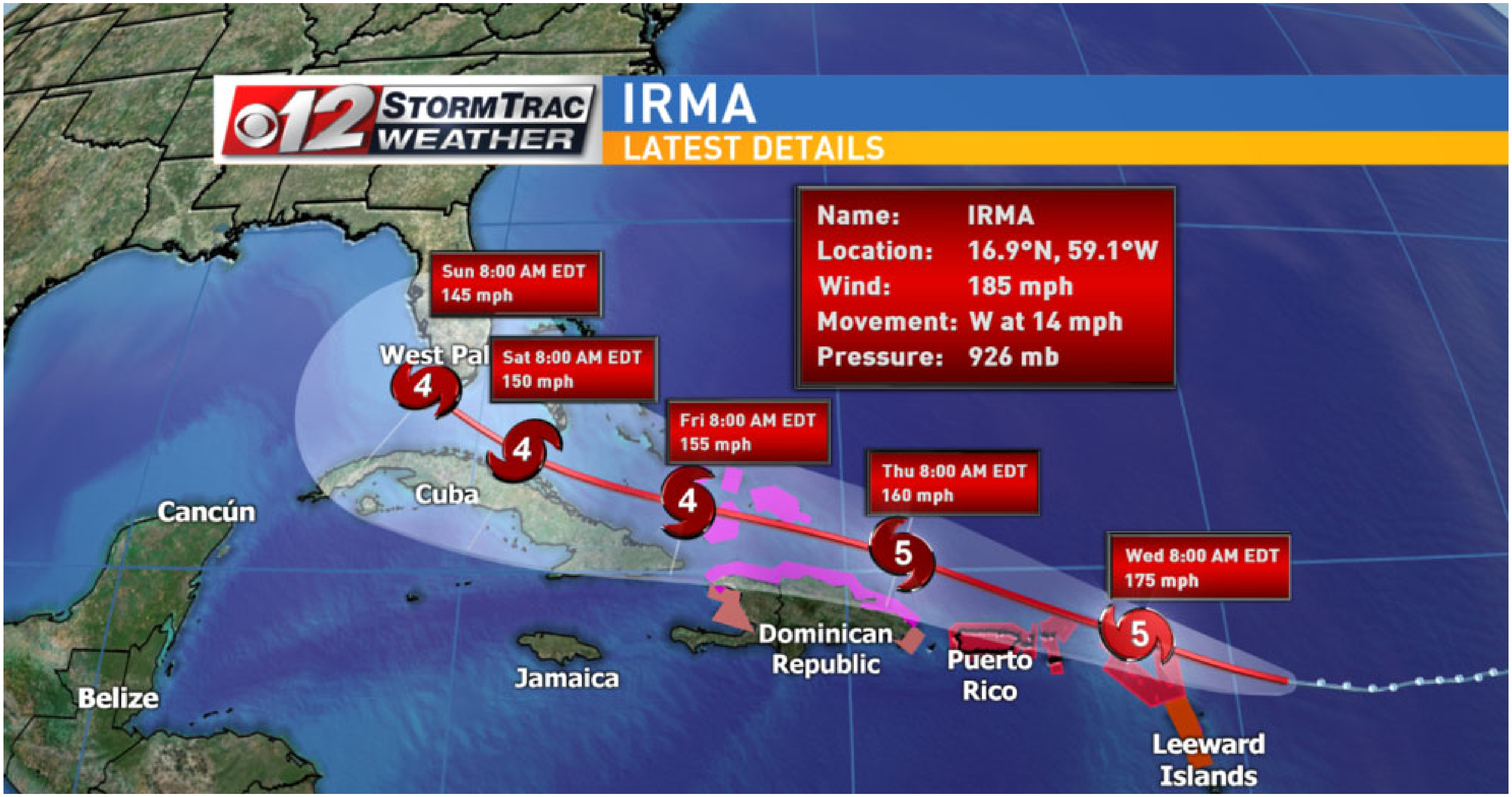
… for creating the triangle Citizen – Human Avatar – Clinical Professional

… for a sustainable healthcare in 21st Century



Today our technology can predict weather…

SENSORS → BIG DATA → MODELS → COMPUTING → **WEATHER FORECAST**



Re-thinking the future of P3 healthcare with DT

- What's the real opportunity for future Digital Twins in P3 healthcare?

$75bn

Creation

New ways to discover drugs

$7.2tr

Diagnosis

Diagnose at earlier stages, saving lives and money

?

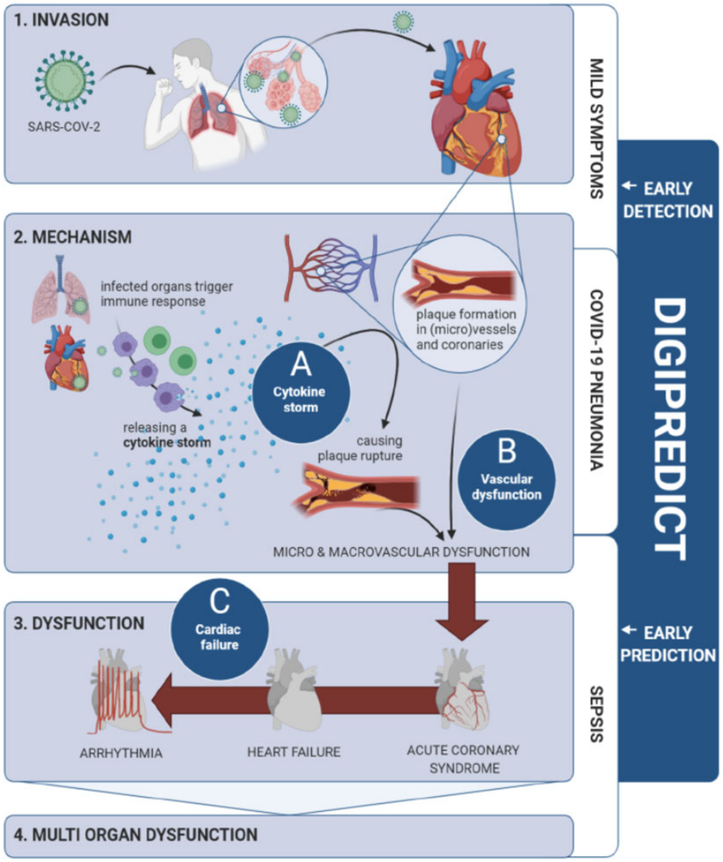
Prevention

Whole-life tracking, management and health

The value of NOT being sick = healthy?

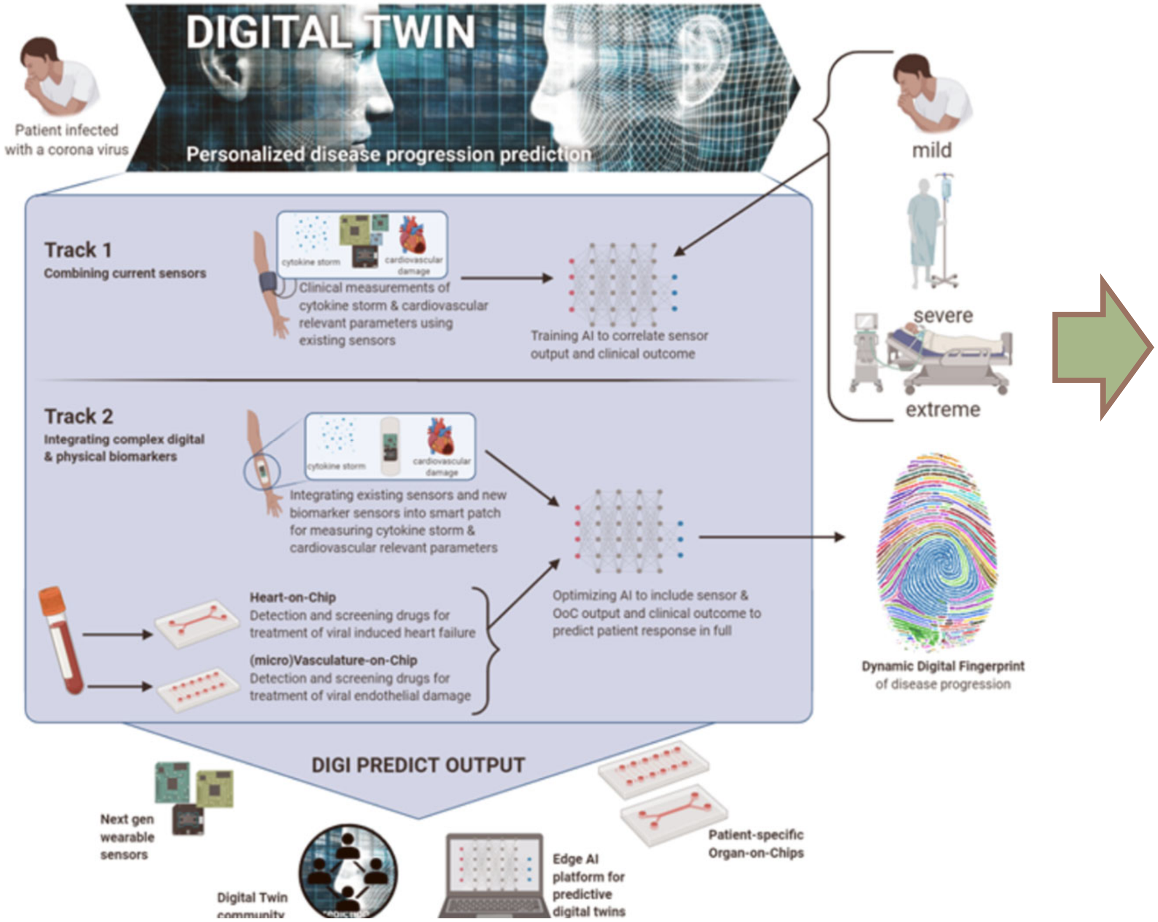
The value of being sick

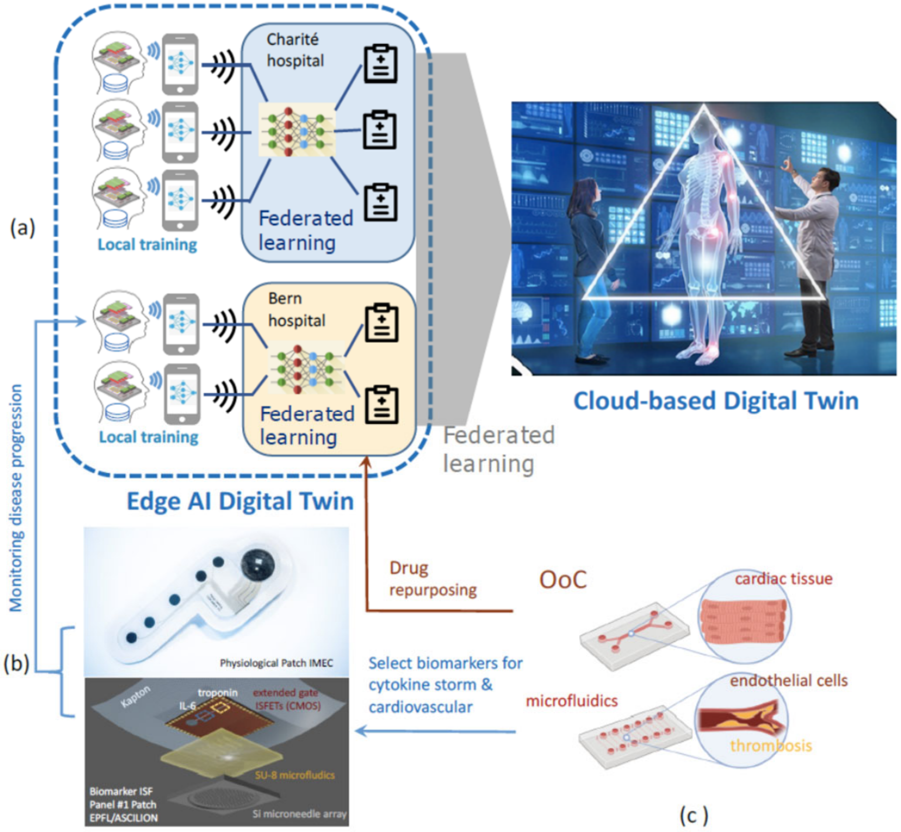
DIGIPREDICT FET Proactive: Digital Twins @ the Edge



- **Early detection**: High risk COVID-19 patients can be early identified from **Digital Fingerprints**
- **Personalized therapy**: Supportive therapy and referral decisions can be personalized to patients with highest need.
- **A new Digital Twin tool for P3 Healthcare**: empowers citizens and medical doctors with a new assistive and predictive healtcare tool.
- Build a **Digital Twin community** in Europe.

The DIGIPREDICT concept

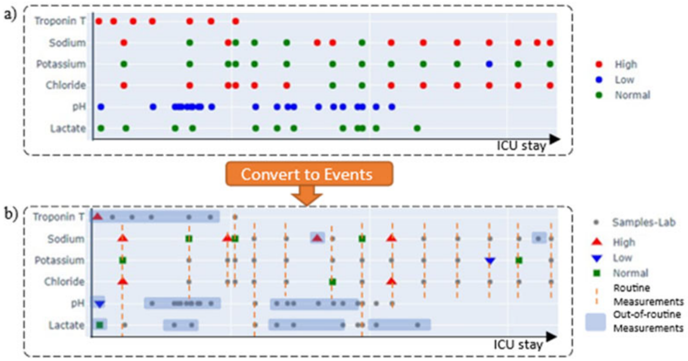




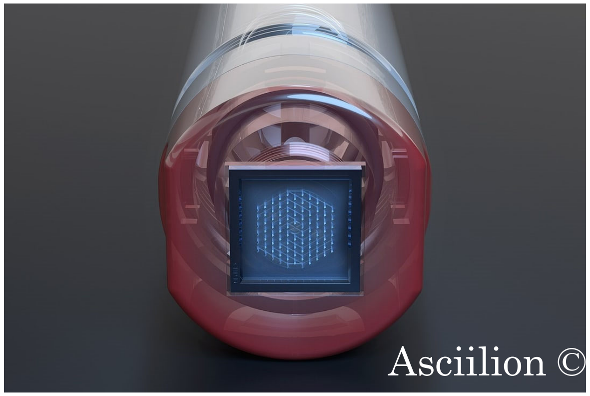
DIGIPREDICT biomarker smart patch

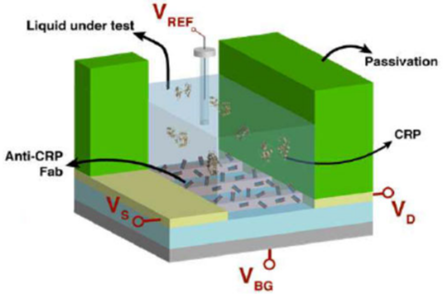
Develop **sensors co-integrated with MEMS needle arrays for collecting ISF and detecting biomarkers** for cytokine storm :

- Multimodal sensing: inflammation proteins
- Dynamics of change/monitoring
- Near real-time monitoring
- Wirelessly connected
- ML algorithm & visualisation interface

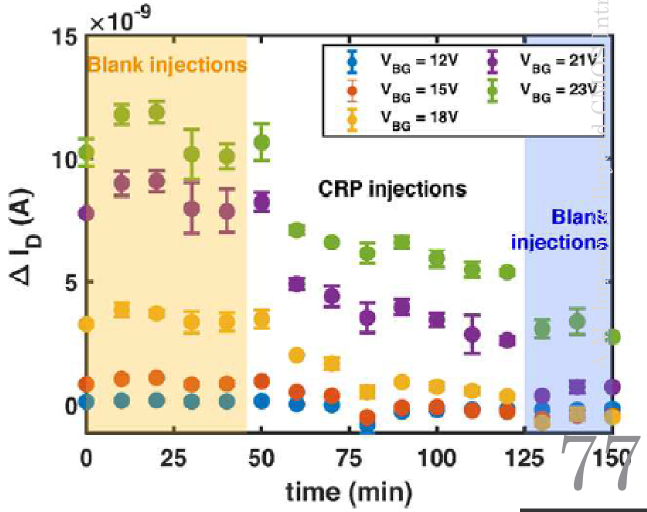


CRP detection: EPFL + CEA-LETI + Xsensio SA

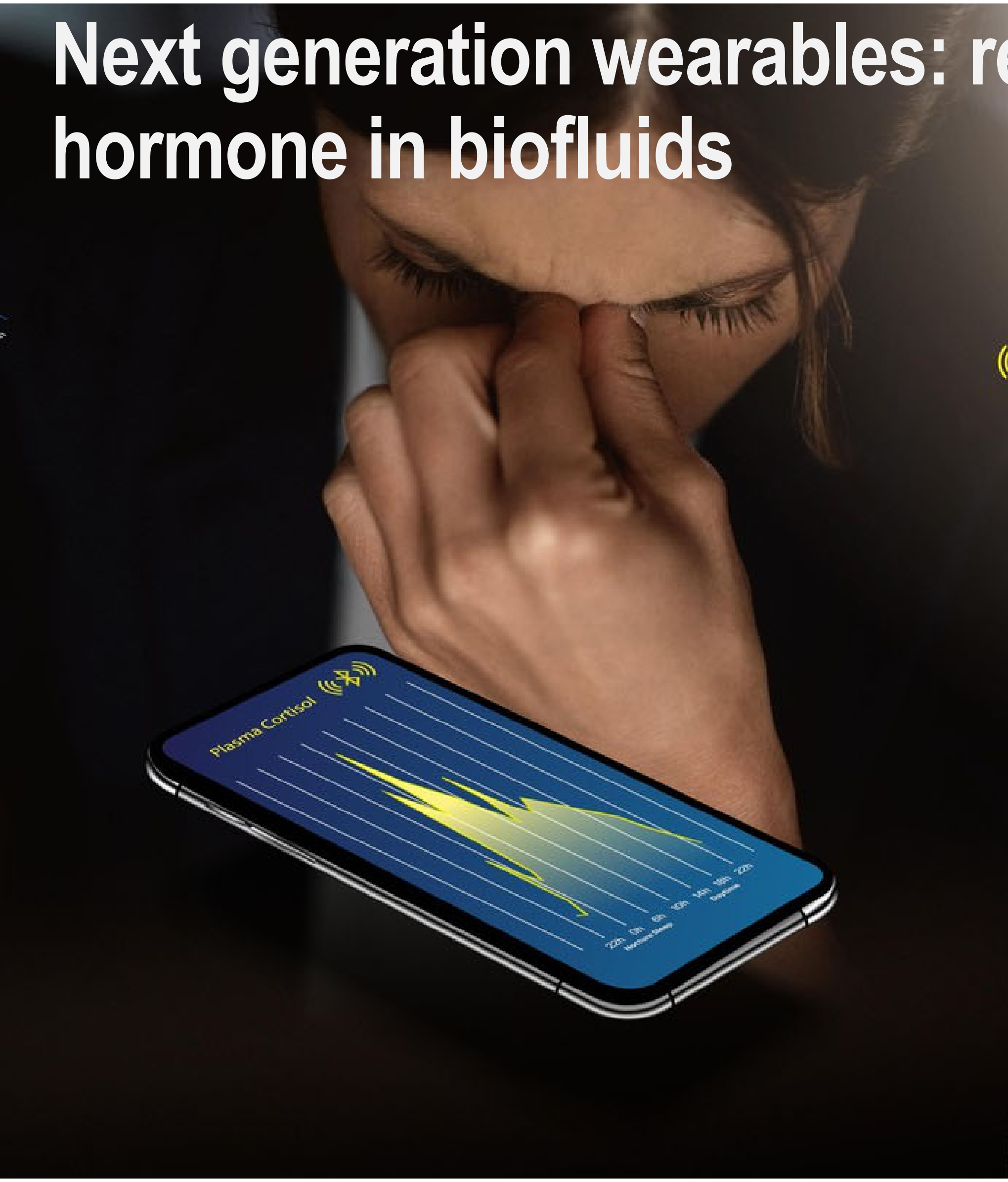


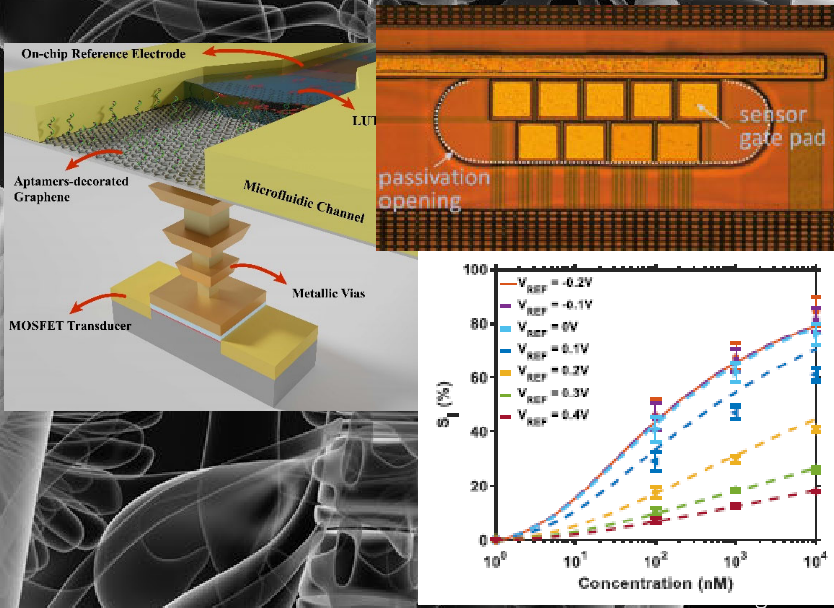


L. Capua et al., IEDM, 2021.



Next generation wearables: real-time sensing of stress hormone in biofluids

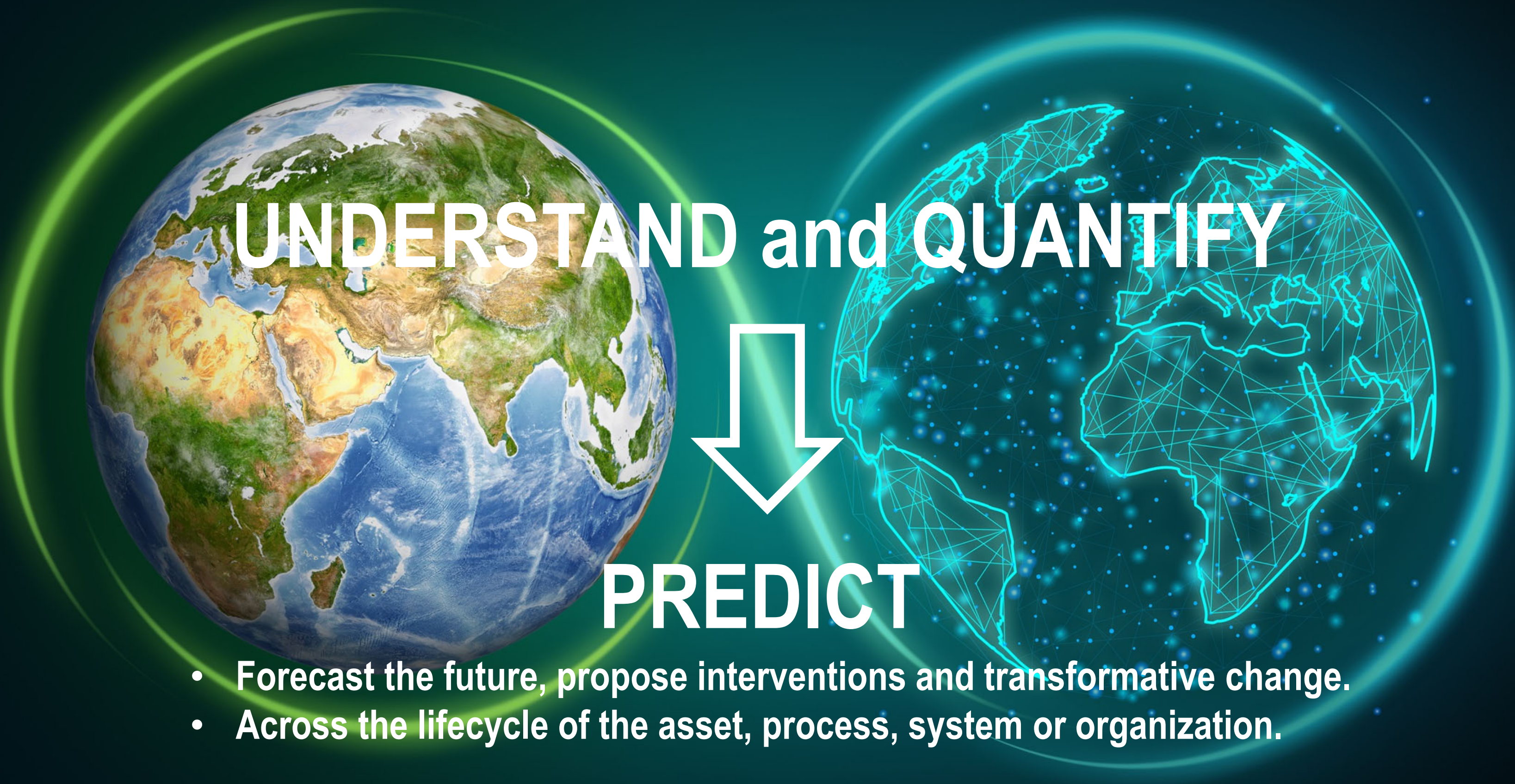




Sheibani et al. Extended gate field-effect-transistor for sensing cortisol stress hormone. Commun Mater 2, 10 (2021)

Overcoming sustainability challenges with digital twins

https://global.royalhaskoningdhv.com



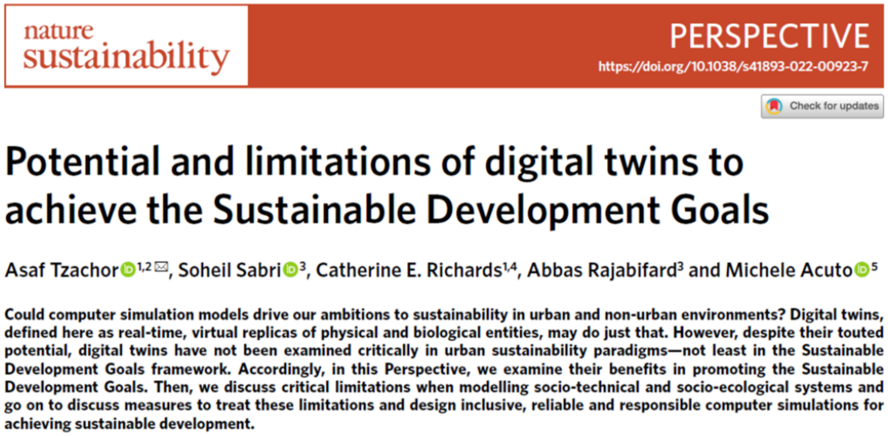
UNDERSTAND and QUANTIFY

PREDICT

- Forecast the future, propose interventions and transformative change.
- Across the lifecycle of the asset, process, system or organization.

Perspective: Sustainable Development Goals

- Possible **ONLY with** two key digitalization components: **IoT and Digital Twins!**
- Sustainable chips & software



nature sustainability

PERSPECTIVE

https://doi.org/10.1038/s41893-022-00923-7

Check for updates

Potential and limitations of digital twins to achieve the Sustainable Development Goals

Asaf Tzachor[1,2] ✉, Soheil Sabri[3], Catherine E. Richards[1,4], Abbas Rajabifard[3] and Michele Acuto[5]

Could computer simulation models drive our ambitions to sustainability in urban and non-urban environments? Digital twins, defined here as real-time, virtual replicas of physical and biological entities, may do just that. However, despite their touted potential, digital twins have not been examined critically in urban sustainability paradigms—not least in the Sustainable Development Goals framework. Accordingly, in this Perspective, we examine their benefits in promoting the Sustainable Development Goals. Then, we discuss critical limitations when modelling socio-technical and socio-ecological systems and go on to discuss measures to treat these limitations and design inclusive, reliable and responsible computer simulations for achieving sustainable development.

Digital twins for the SDGs

Target 17.9
Improve scientific and policy partnerships between diverse stakeholders

Target 1.5
Explore climate-change-resilient pathways in urban infrastructures and services

Target 2.4
Digital twins for smart farming

Target 3.b
Digital twins of vaccine production processes

Target 4.a
Simulations as educational tools in future learning environments

Target 5.b
Inform stakeholders on ICT development that empowers women

Target 6.4
Predictive maintenance and sustainable refurbishment of water infrastructures

Target 7.b
Resource optimization in process operations of electricity systems and smart grids

Target 8.4
Develop industrial ecology business models across industries

Target 9.4
Promote circular economy models in the construction sector

Target 10.6
Ensure ICT resources are available for developing countries

Target 11.2
Improve transportation for vulnerable and marginalized communities

Target 12.5
Generate scenarios and strategies for waste management

Target 13.1
Predictive models for disaster risk reduction in critical systems

Target 14.1
Improve oil and gas and seabed mining operations to prevent marine pollution

Target 15.2
Simulate ecosystems for monitoring, conservation and eco-restoration

Target 16.10
Adoption of open-data principles in digital twins and attributing land tenure rights to ensure transparency

Conclusions

- Energy efficiency technologies form the next driver in the zettabyte era.
- The future of computing will be hybrid, with CMOS, neuromorphic and quantum computing serving the edge, fog and cloud.
- IoT, combining computation and sensing is the basis of a new industrial ecosystem and new business.
- Technology-data-algorithm interactions will generate new innovations and progress in AI
- A revolution in personalized, preventive and participatory healthcare is coming via nanotechnology and artificial intelligence.