Introduction

Smart sensors for IoT
EE-594 - 2022

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EE-594 Content – Internet of Things sensor technology (1)

2 hours per week + 1 hour exercices
prof. C. Enz & prof. A.M. Ionescu

1) Low power sensor technology = BIG DATA GENERATORS

- Motion sensors: accelerometers, magnetometers, gyroscopes (MEMS solutions)
- Biosignals and biosensors:
  ECG, EEG, EMG, EO, blood pressure, pulse wave velocity, SpO2, pH, electrolytes, glucose, hormone and protein sensing
- Gas and particle sensors for exposome and environmental monitoring
- Temperature sensors
- Emerging 2D and 1D nanomaterials for sensing

2) Energy efficient computing technologies

- Low power CMOS and subthermionic transistors
- Flexible electronics
- Neuromorphic computing for Artificial Intelligence @ the Edge

EE-594 Content – Internet of Things sensor technology (2)

3) Energy harvesting and storage for IoT:

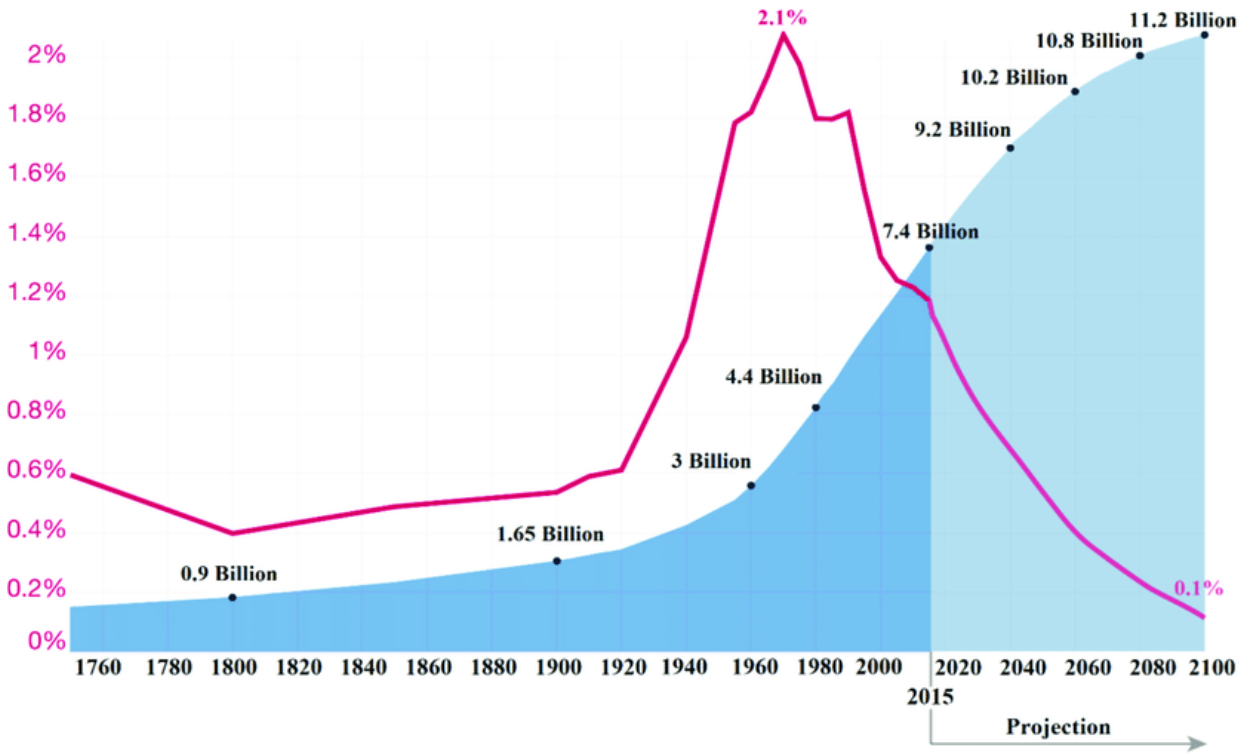
- Energy harvesting from motion
- Energy harvesting from thermal gradients: thermo-electrical-generators (TEGs)
- Energy harvesting from light in indoor and outdoor conditions
- Energy storage and power management: super-caps and thin film batteries.

4) Context-driven embodiments of wearable and IoT systems

- Smart patches and stamps
- Smart garments
- Smart watches
- Smart glasses
- IoT sensors for Industry 4.0 and automotive

5) Sustainable IoT

Introduction

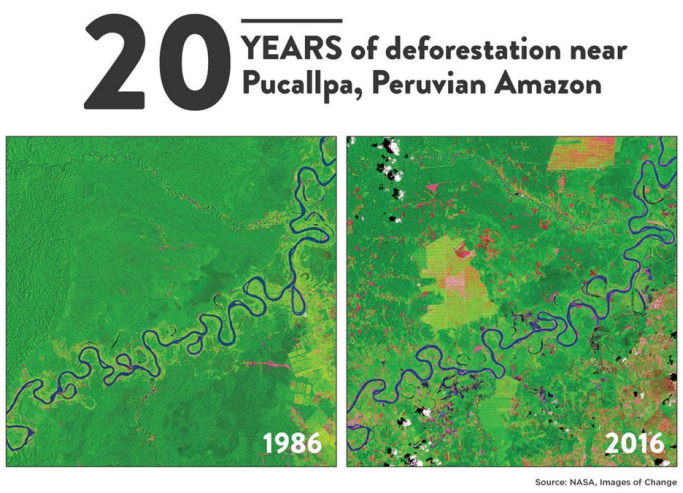


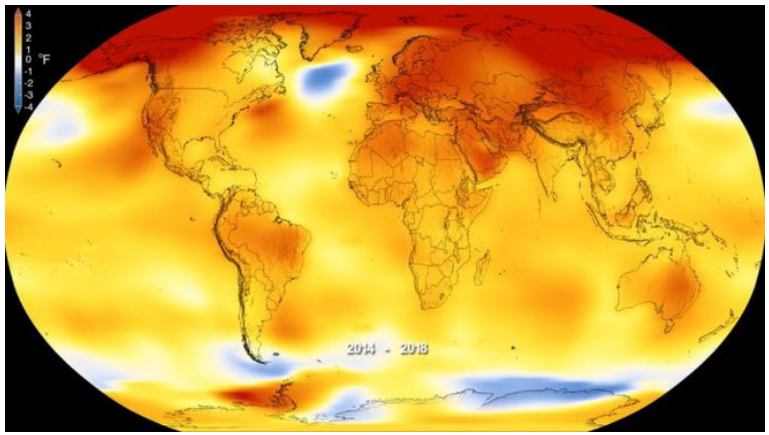
- The United Nations has made projections of the world's population by 2100…
- Can we rely on **technologies such as the internet of things (IoT) to improve the quality of life and avoid negative environmental impact**?

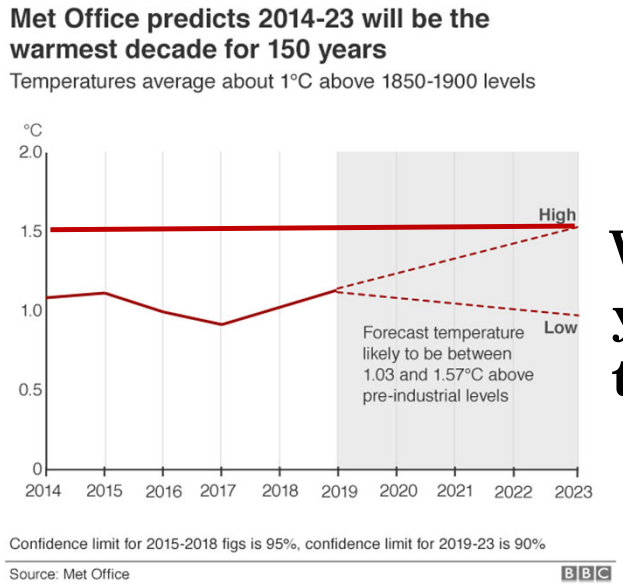
Global Challenges

Climate Change

Greenhouse gas emissions must be drastically reduced within the next decades to stay within 1.5°C of warming above pre-industrial levels and avert the worst impacts of climate change.



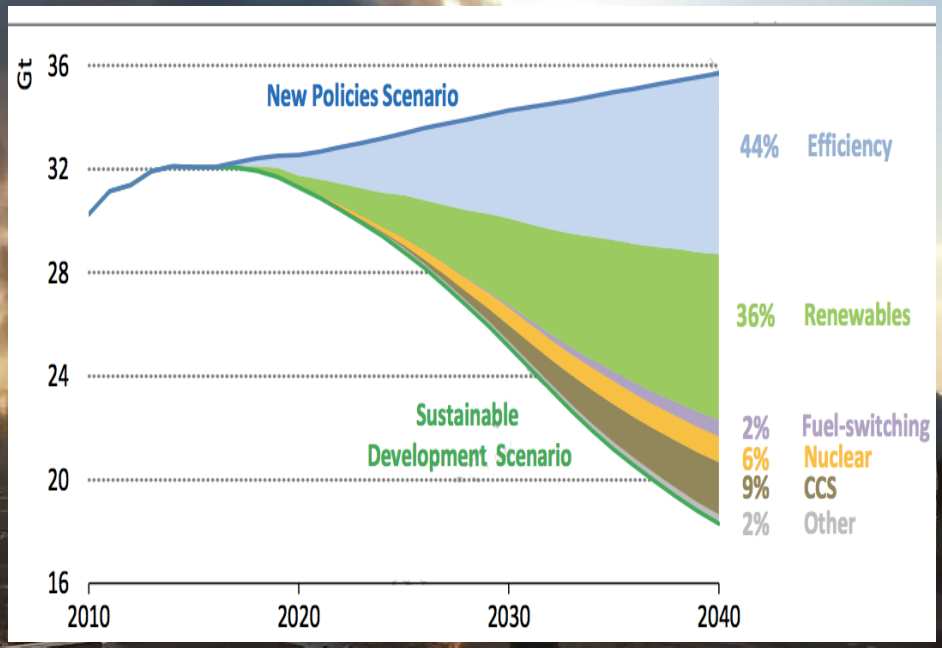




We are not yet almost there!

New policies, efficiency & renewables…

There is an **enormous gap** between **what we need to do** and what we're **actually doing** to prevent dangerous levels of climate change.

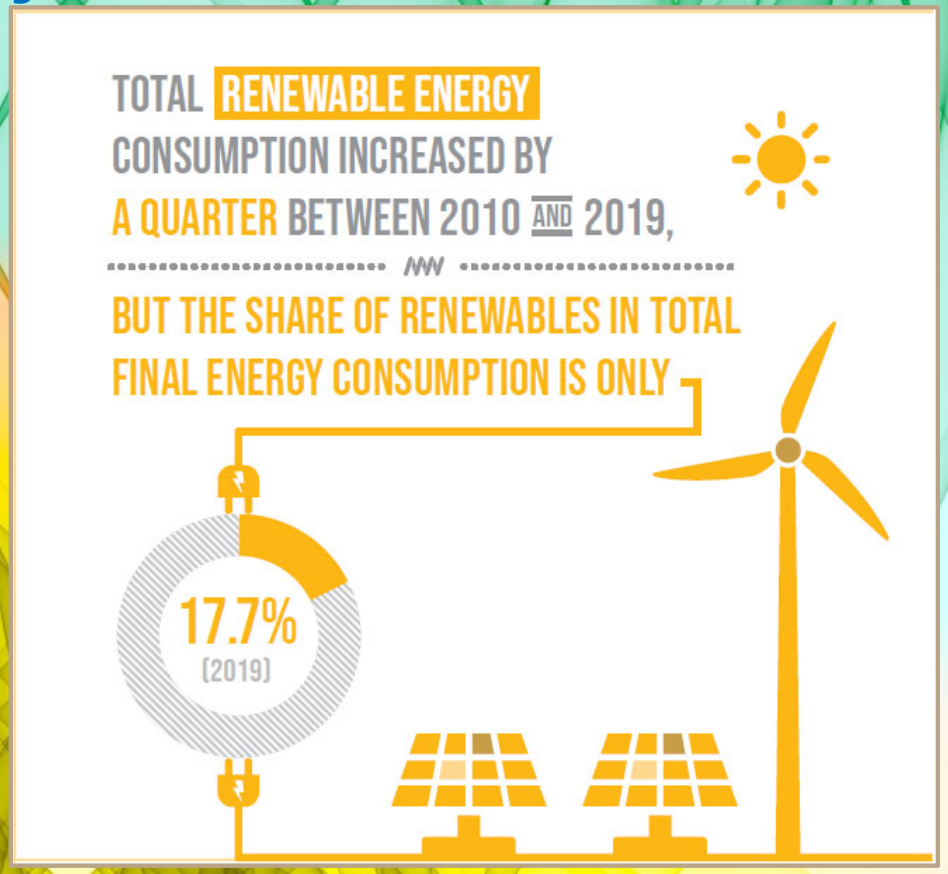


We are not yet almost there!

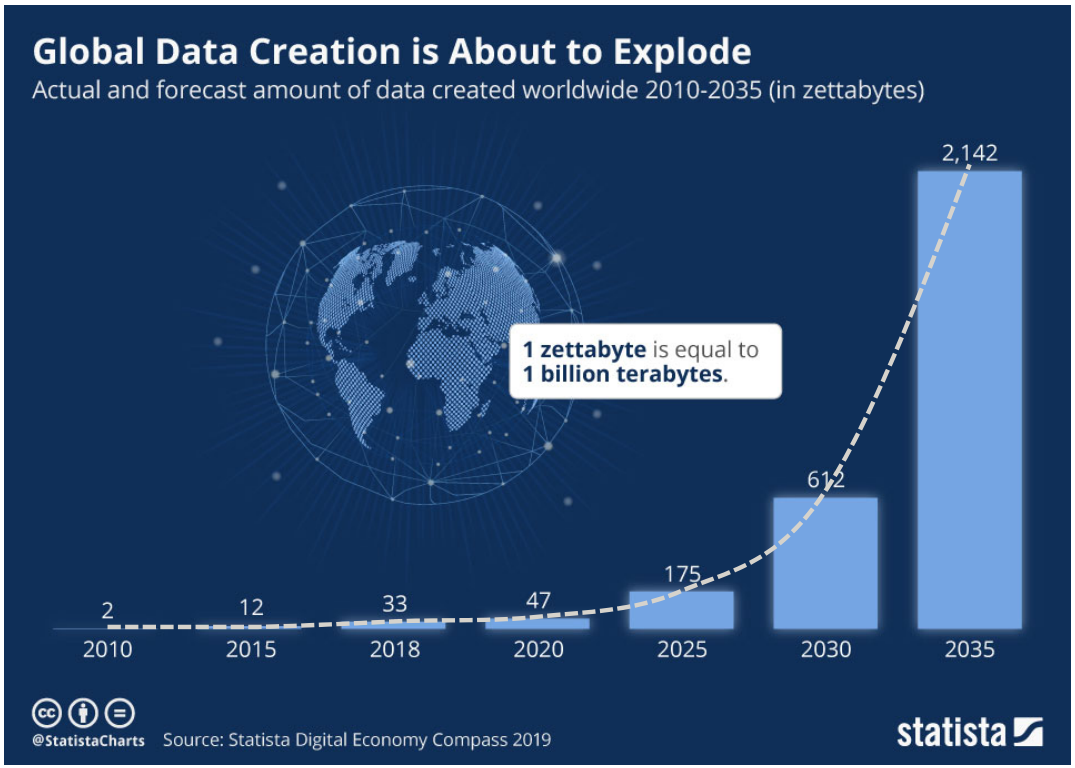
2018 **#EmissionsGap** Report

UN environment

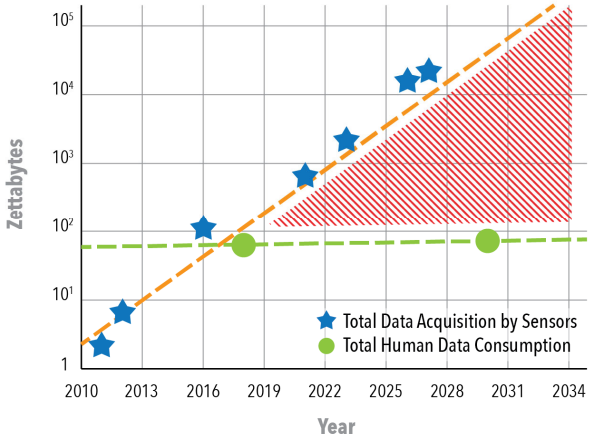
Gaps: energy efficiency and renewables



Gap: energy crisis in the Zettabyte and IoT Era



Global Data via IoT Sensors



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

A sustainable IoT for sustainable applications…

- Technology and environmental sustainability: **mutually exclusive?** Until now digital innovation and sustainability have been disconnected.
- Today's advancements in IoT sensor technologies and wireless connectivity, two concepts of digital innovation and sustainability: **mutually reinforcing**.

→ **pivot to (i) more energy-efficient practices, (ii) use resources more responsibly and (iii) organize processes in ways that reduce waste.**

Sustainable IoT deployment

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

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

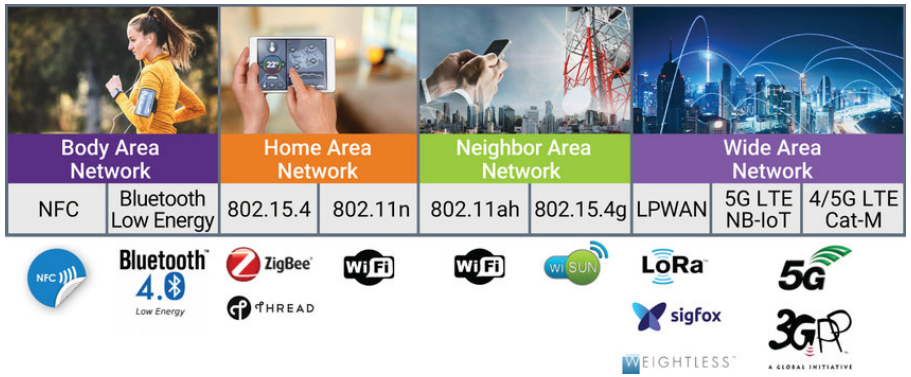
are BOTH simultaneously possible?!

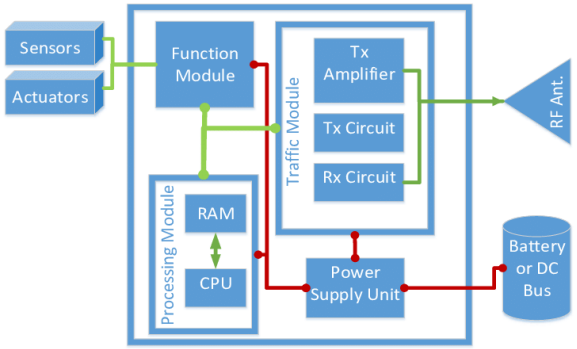
Incremental reduction of IoT sensory node power with traditional technologies

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

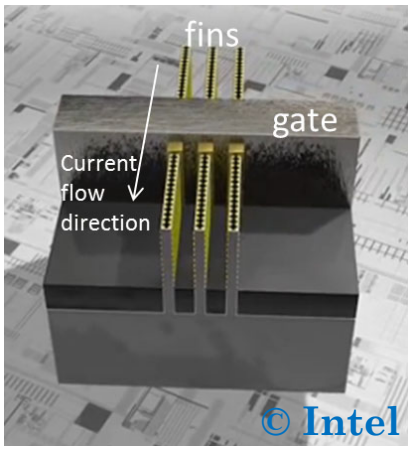




Energy problems @ node level:

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

Nanoelectronics: ~10nm 3D transistors

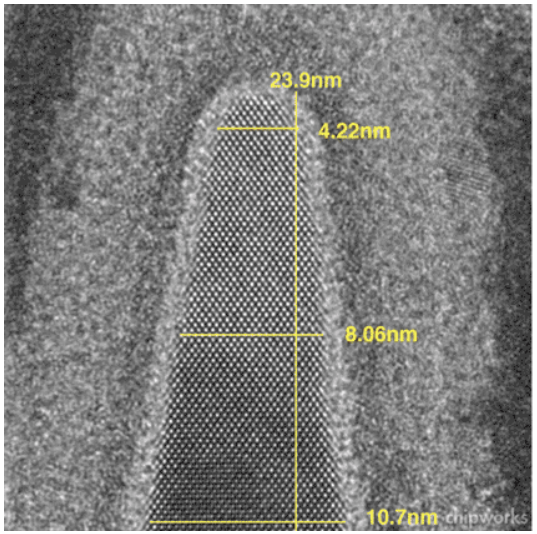


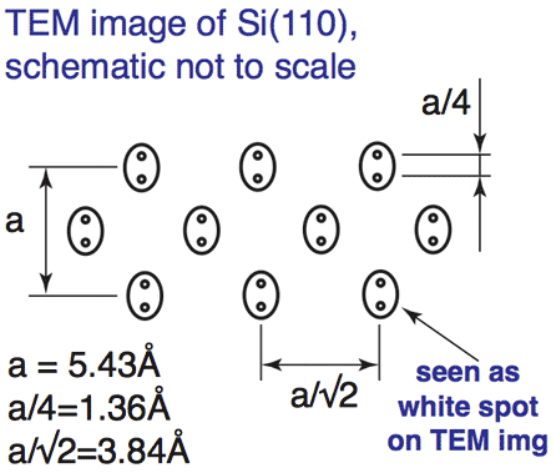
Today: 14 nm:

- **40 millions transistors/mm²**

2019-2020: 10 nm:

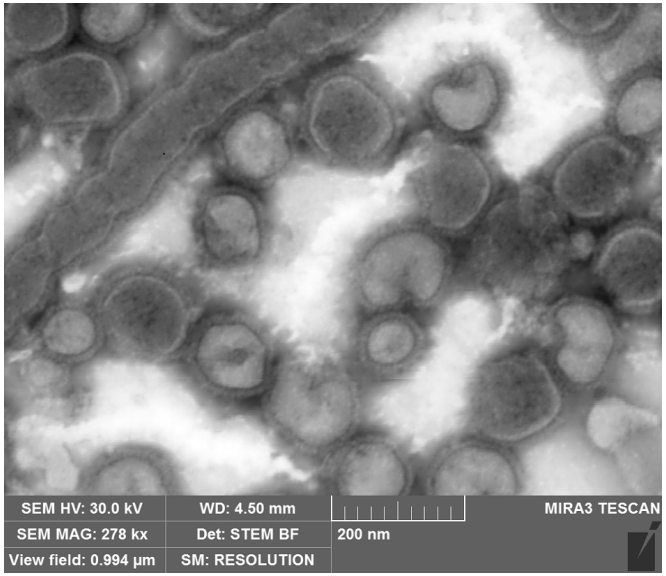
- **100 millions transistors/mm²**





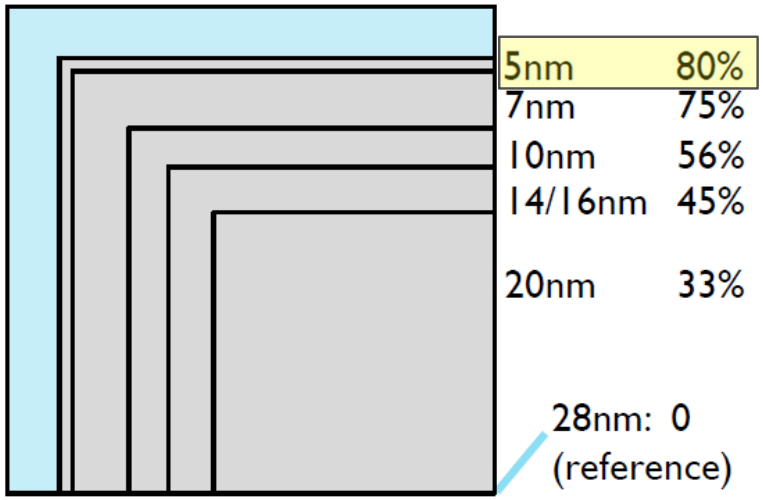
Virus

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

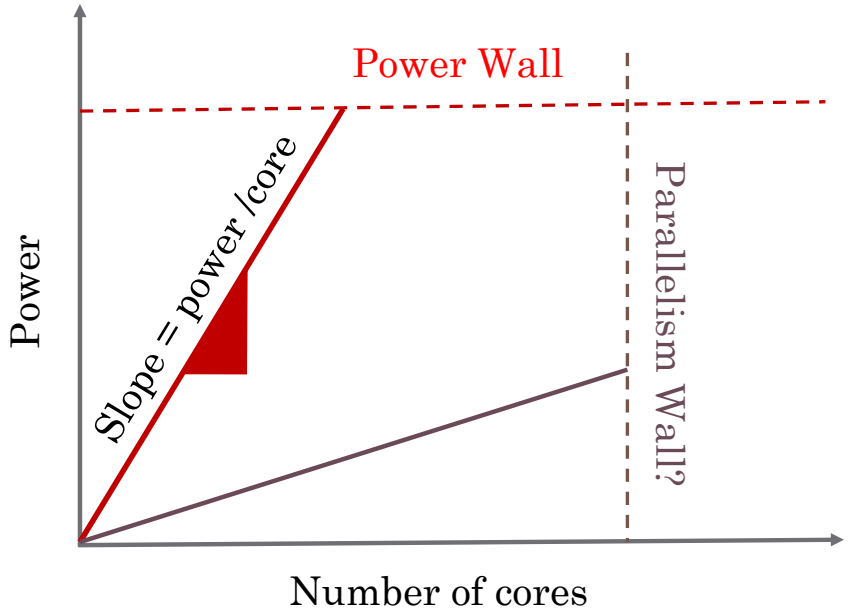


Dark silicon era? Is this so bad?

- ***We get more transistors, we just can't afford to turn them all!***
  Greg Yeric, ARM @ IEDM 2015



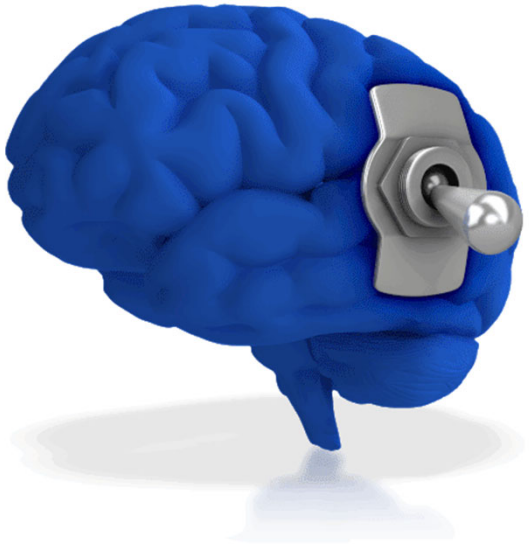
One or two walls?



A dark 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*

P. Lennie, Current Biology, 2003.



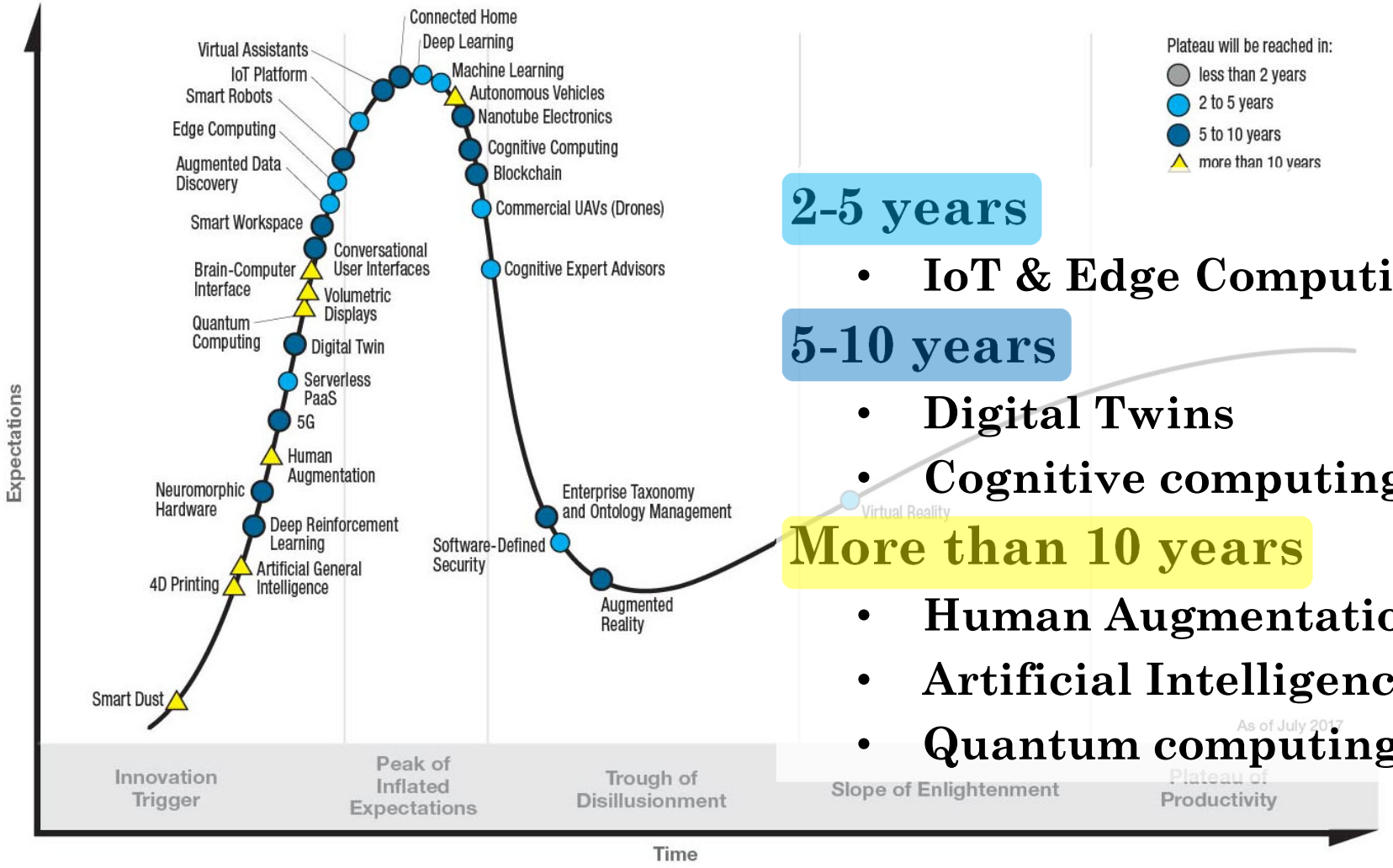
Iphone & Guardian Angels

- First wireless computer with sensors

2007

- Edge of the cloud technologies…

2011



2-5 years

- **IoT & Edge Computing**

5-10 years

- **Digital Twins**
- **Cognitive computing**

More than 10 years

- **Human Augmentation**
- **Artificial Intelligence**
- **Quantum computing**

Source: gartner.com/SmarterWithGartner

Definition(s)

1) Wikipedia:

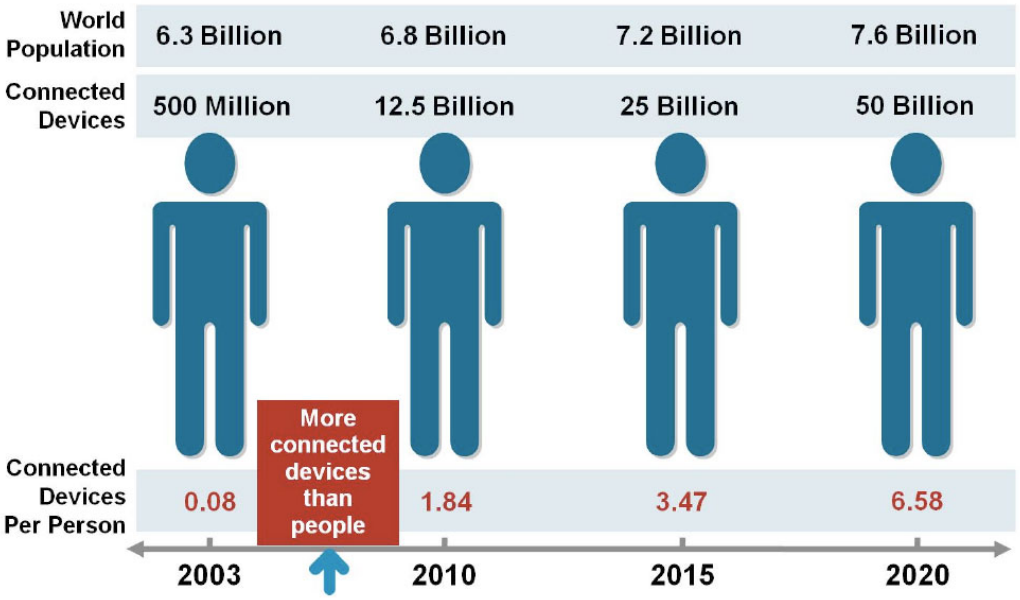
The **Internet of Things (IoT) is a system of interrelated computing devices, mechanical and digital machines, objects, animals or people** that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction.

2) Cisco/Gartner:

The Internet of Things (IoT)is the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment.

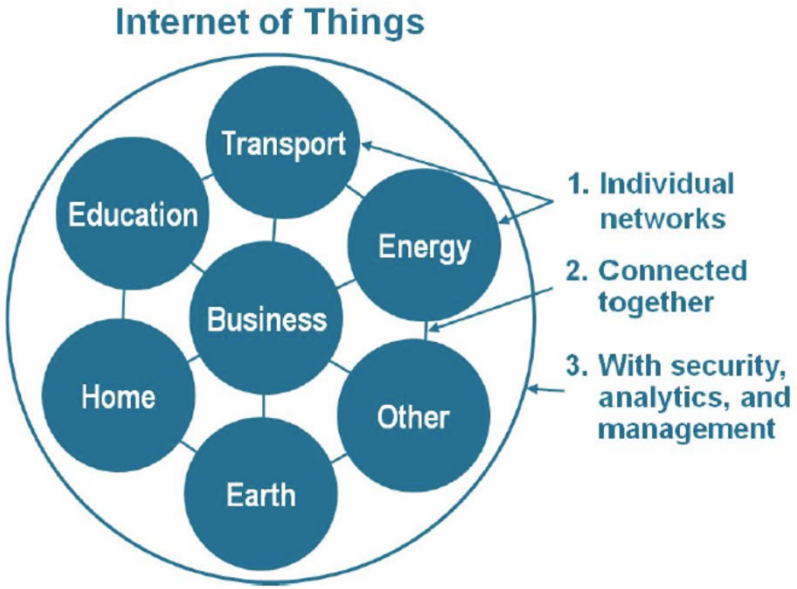
When? Which domains?

Figure 1. The Internet of Things Was "Born" Between 2008 and 2009



Source: Cisco IBSG, April 2011

Figure 2. IoT Can Be Viewed as a Network of Networks



2010: Holly cow!

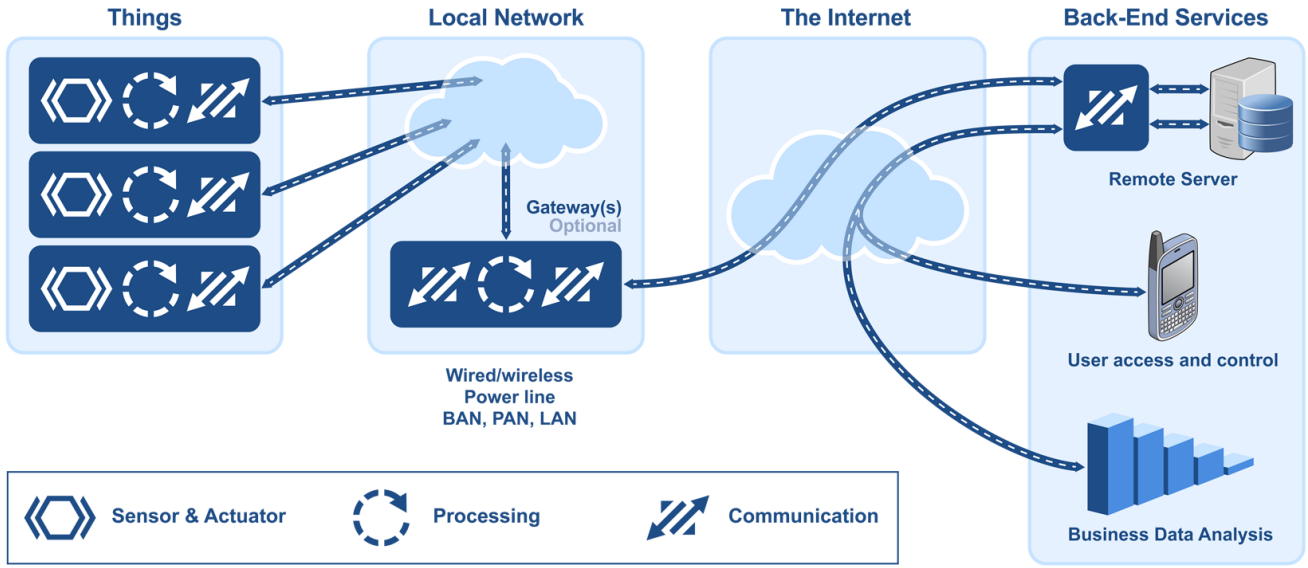
Farmers to monitor cows' health and track their movements, ensuring a healthier, more plentiful supply of meat.
On average, each cow generates about 200 megabytes of information a year…

Source: *The Economist* 2010.

How to think about it?

Four (4) main components of an IoT system:

- The **thing itself** (that is, the device)
- The **local network** (this can include a gateway, which translates proprietary communication protocols to Internet Protocol)
- The **Internet**
- **Back-end services** (enterprise data systems, PCs and mobile devices)



Future: billions of energy efficient IoT edge & fog devices…

CLOUD: Data Centers

Thousands

FOG: Nodes

Millions

EDGE: Devices

Billions

2020:10% of the world's data (Source: IDC).

What is required to compute AI?

ImageNet 1-k benchmark:

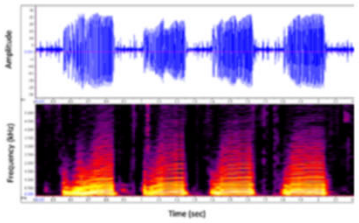
90 epochs – with ResNet-50

→ 10^{18} single precision ops

→ NVIDIA M40 GPU = 14 days!

Audio Analysis:

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



The Cloud

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

Wearable Devices

?

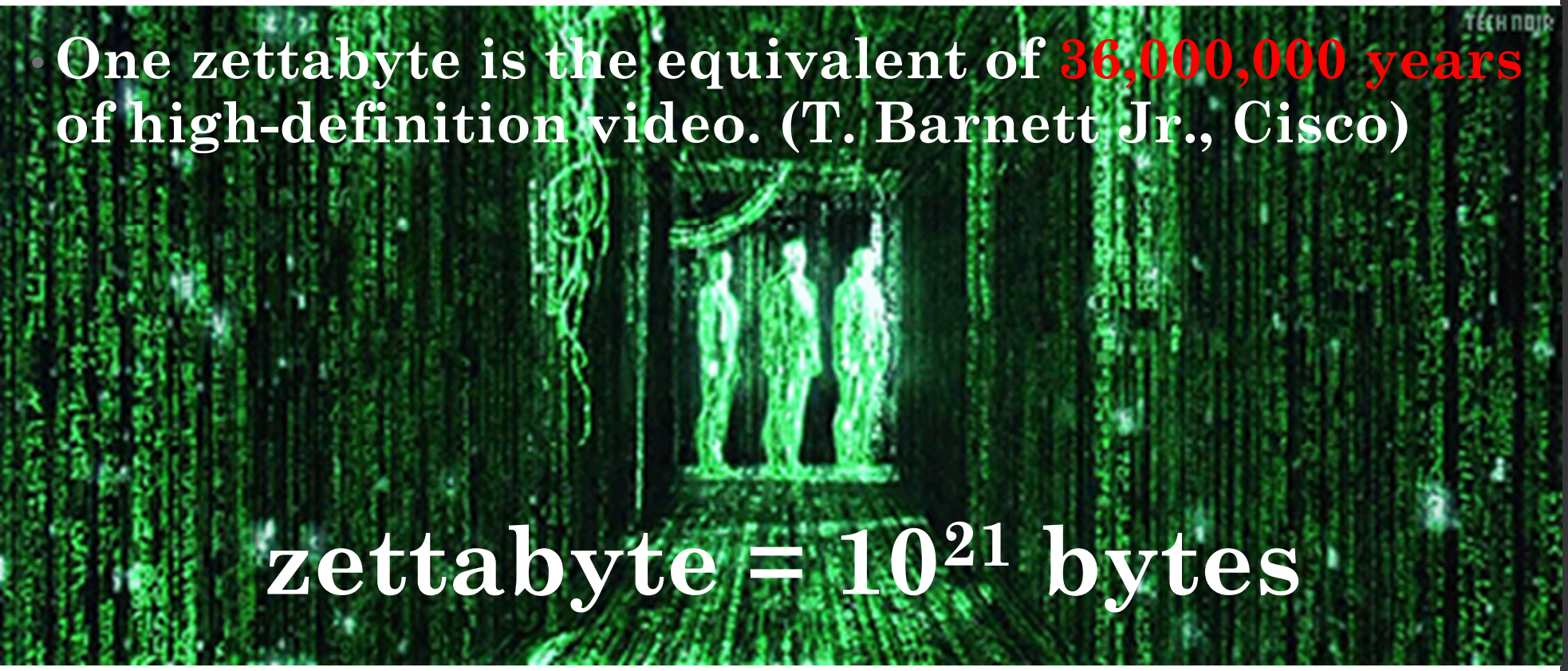
~ x 10^9

~ 10^{17} FLOPS ← → **~ 10^8 IPS**

Moving data is energy expensive!
Computaion @ Edge needed

Source: J. Weiss, IBM.

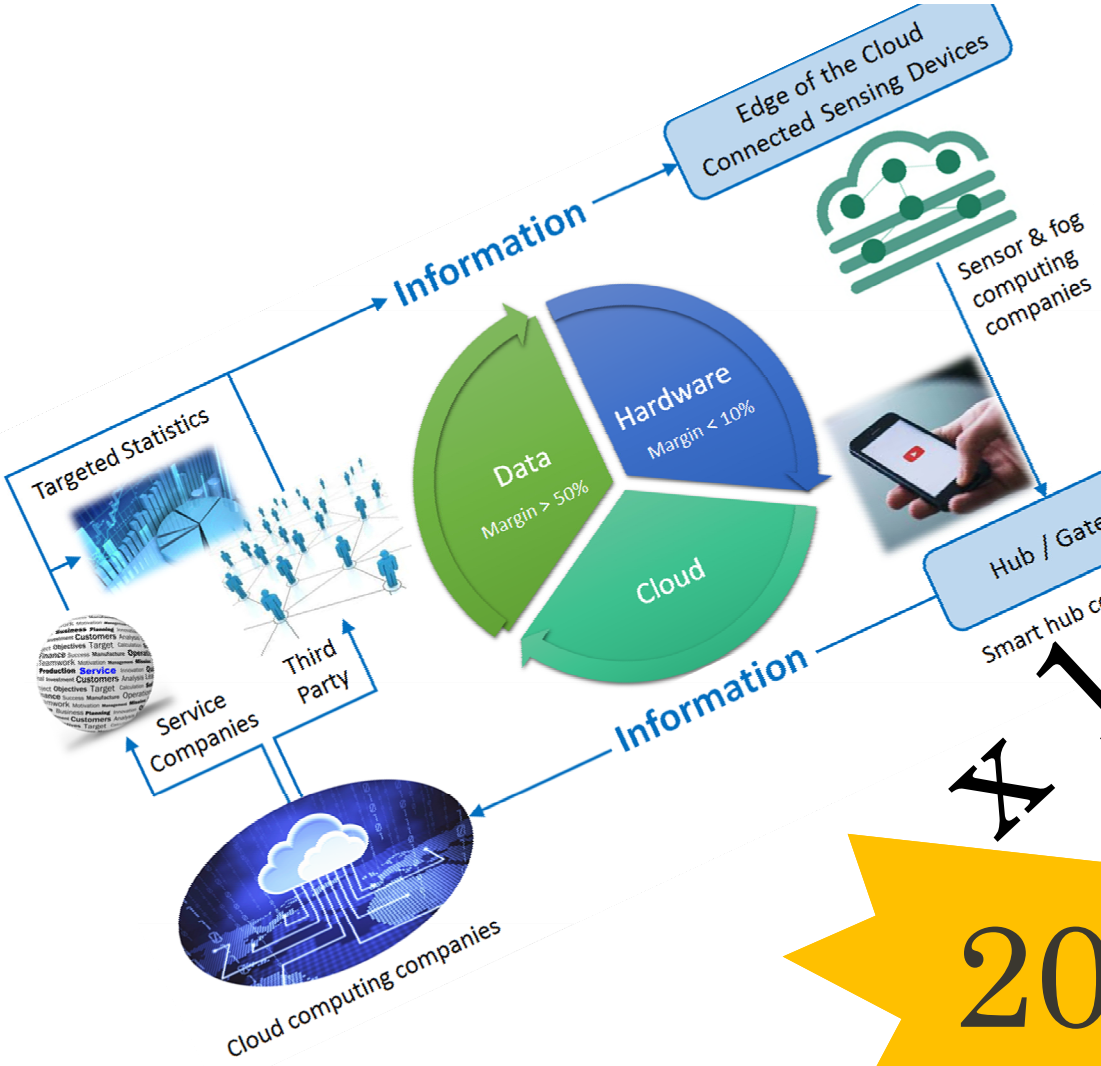
The Zettabyte Era… started in 2010!



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

zettabyte = 10^{21} bytes

The Zettabyte Era



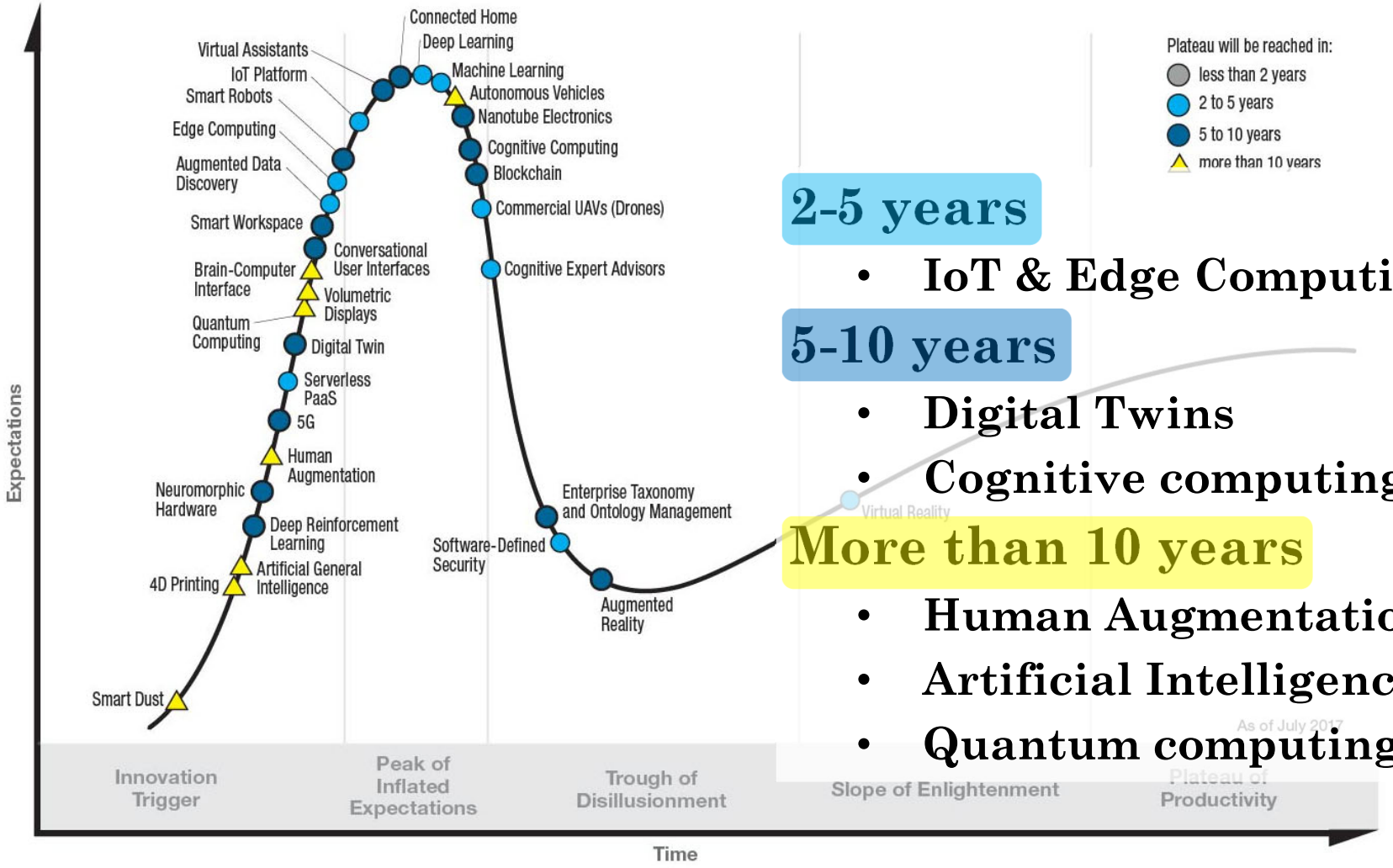
x 1,000,000

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.



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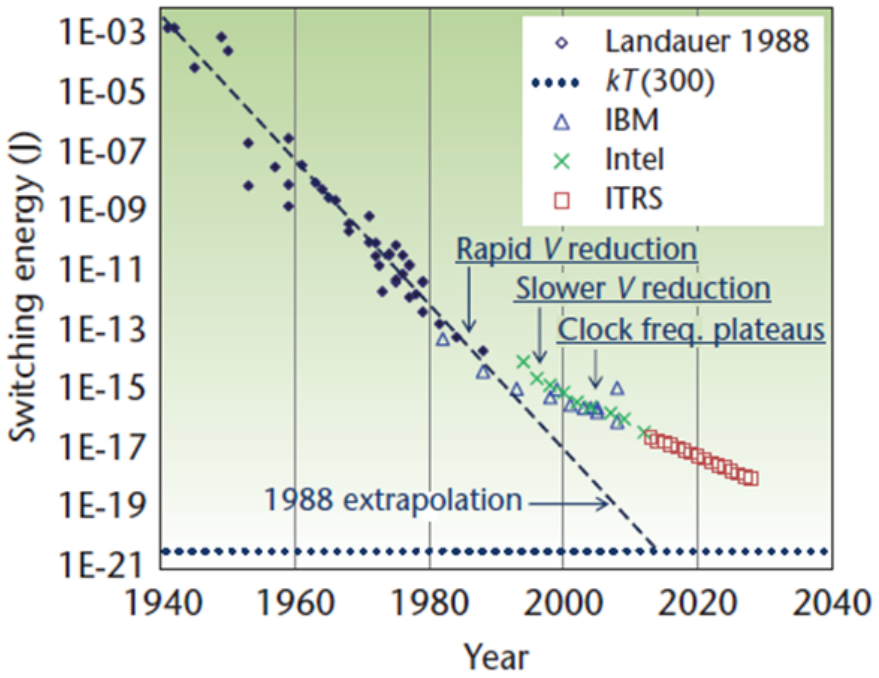
Source: gartner.com/SmarterWithGartner

Silicon technology @ end of nano-scaling

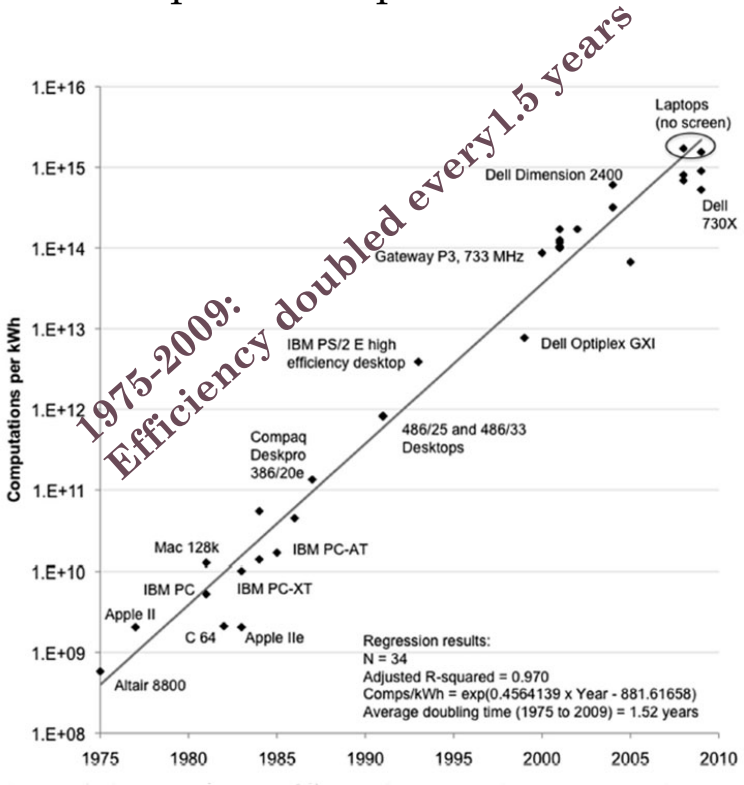
- **Moore's Law**, Dennard's happy scaling
- Silicon is mainstream: 14nm, 7nm, 5nm, … 1nm?

Koomey's law:

computations per killowatt hour

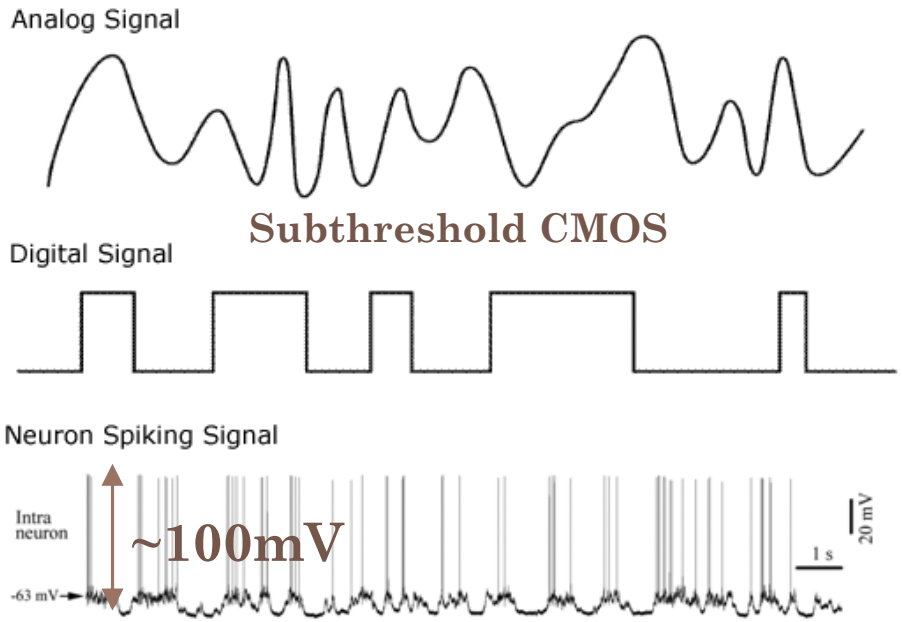


Theis & Wong, Computing in Sci. & Eng., 2017.

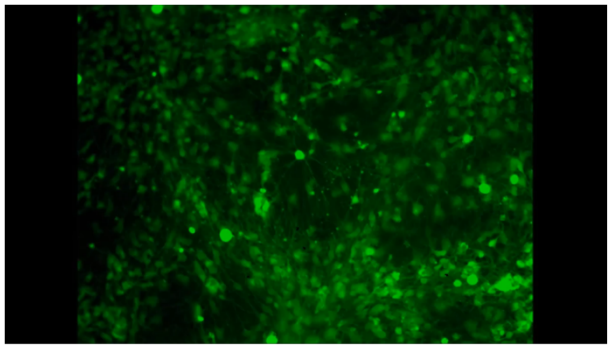


Koomey et al., IEEE Ann. of History of Comp., 2011.

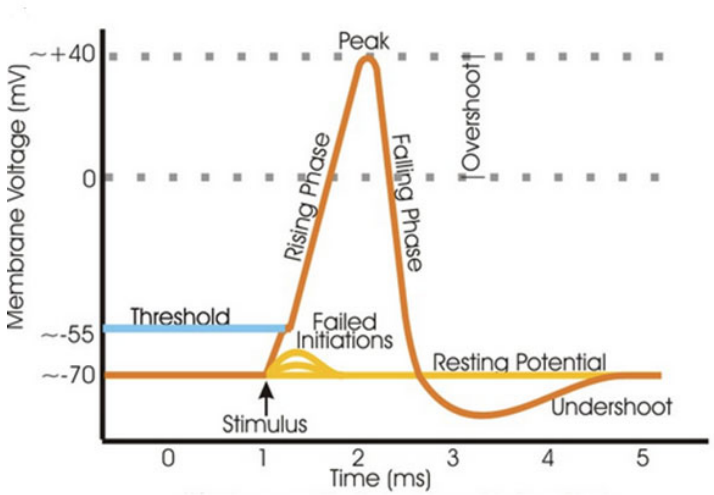
Energy efficient Information processing @ 100mV?



The firing of the neuron

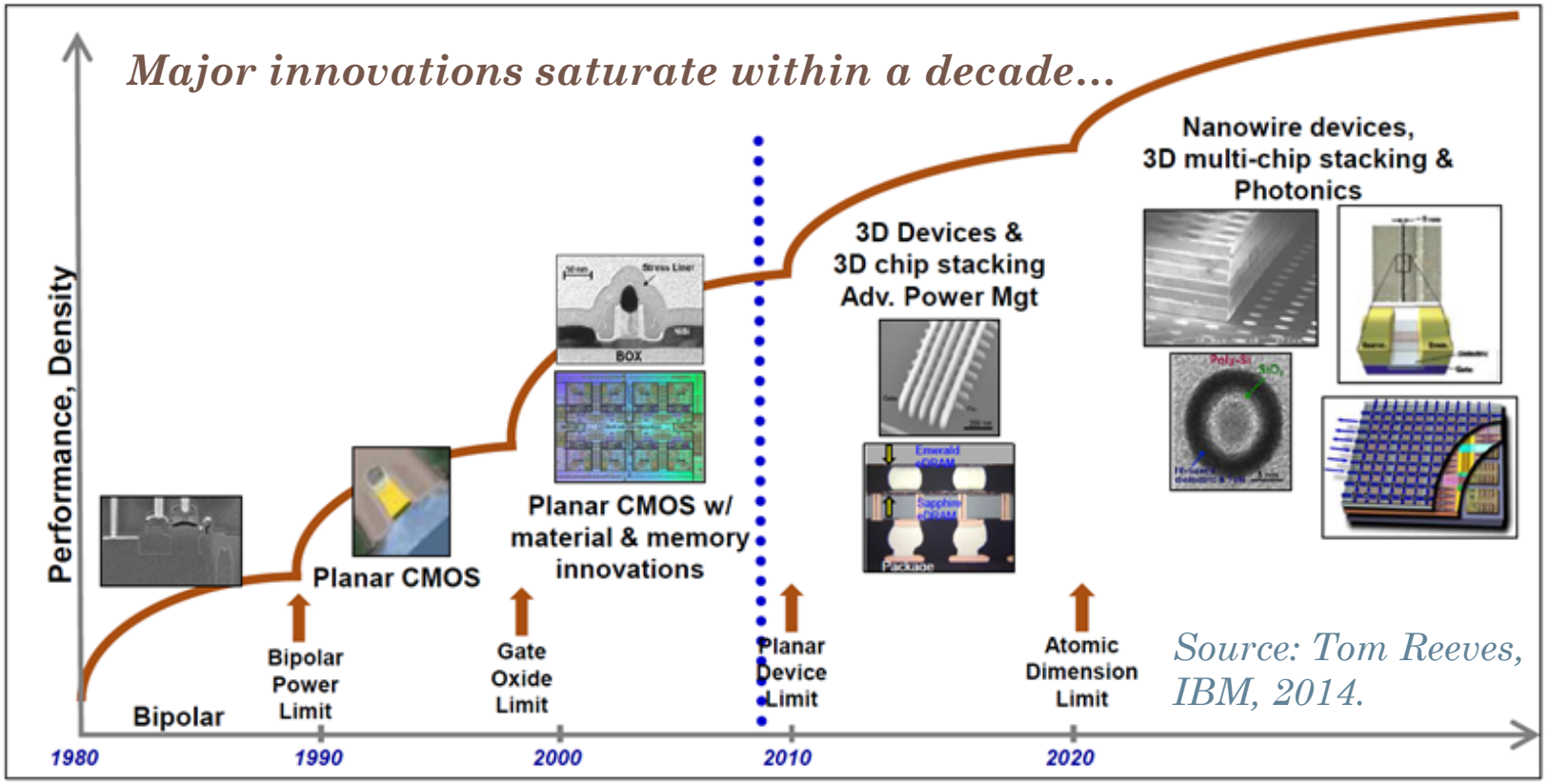


Neuron potential by Na+, K+ ion pumps, is in the order of **+40mV to -70mV**



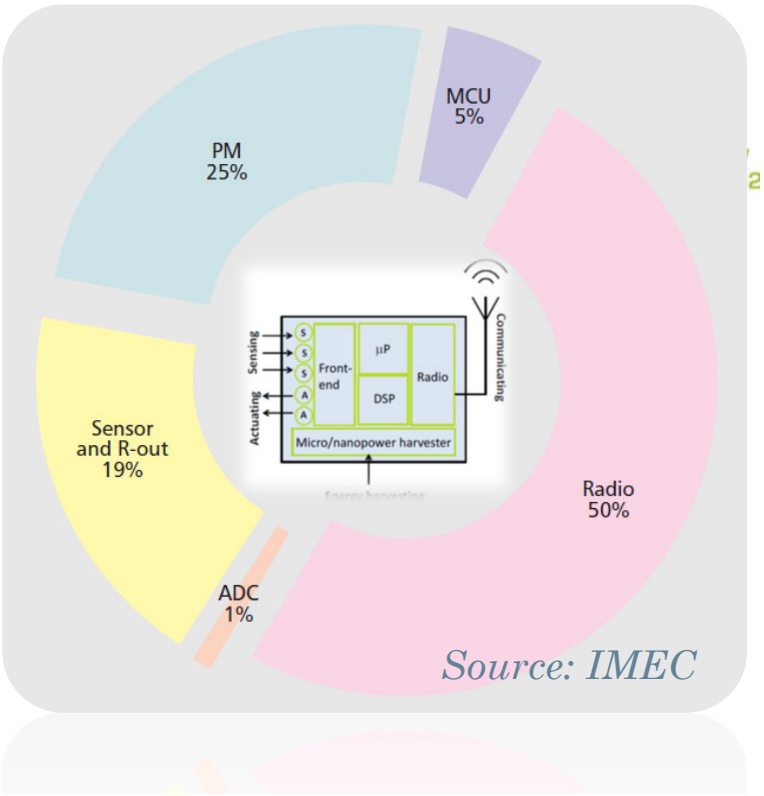
Silicon Technology: a 3D migration into the future

- High-performance, functionally diversified, 3D integrated # technologies

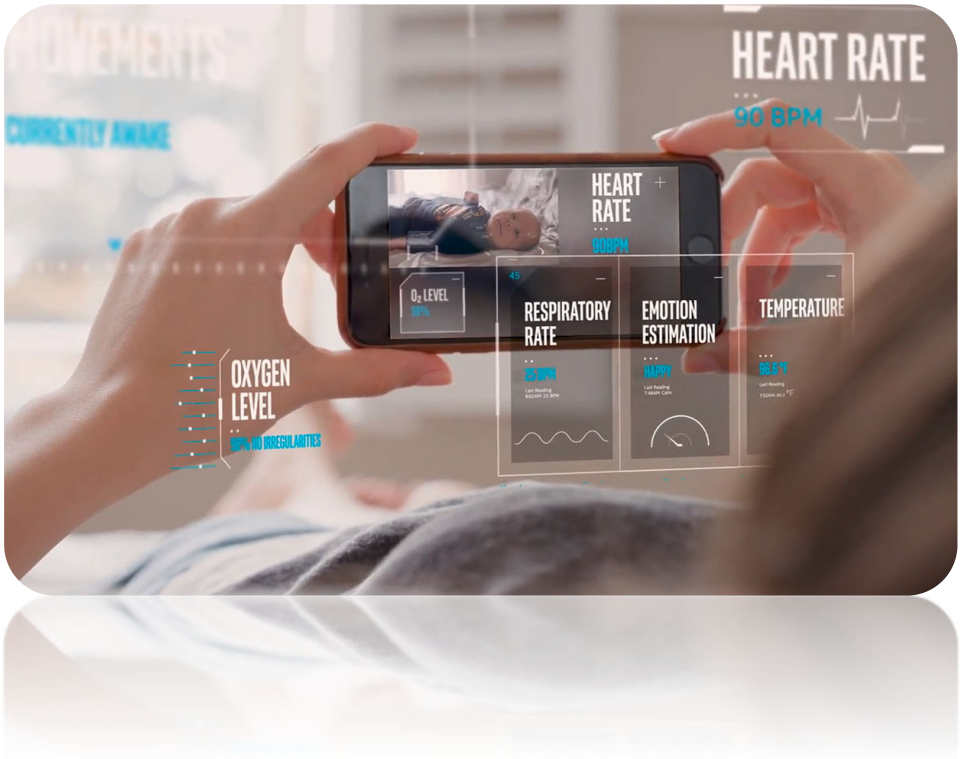


Energy efficient autonomous sensor nodes for Internet of Things

100 microWatt – 10 mW
/ sensor node

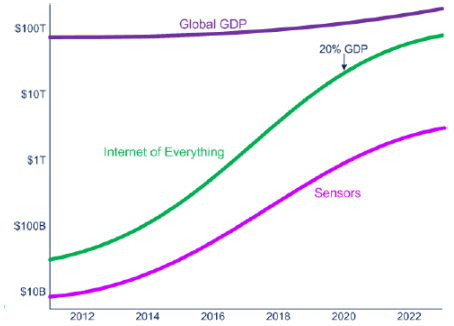


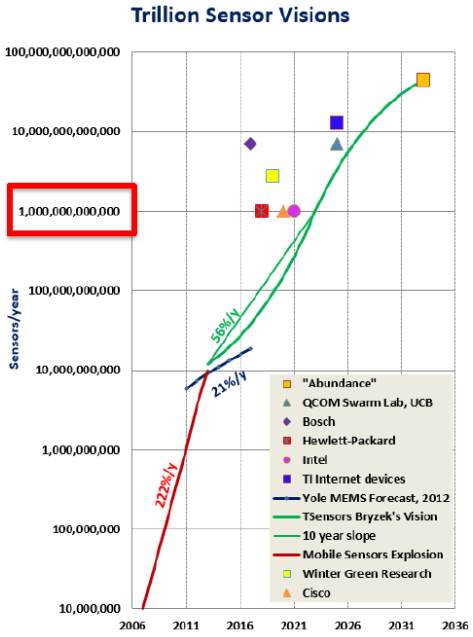
Smart hub: 100mW – 10W
(tens of sensors /hub)



IoT = a sustainable trillion of sensors planet?

- Several visionary organizations created trillions unit forecasts:
  - ❑Explosion to trillion(s) is likely to be driven by new applications?
  - ❑Abundance is expected to be reached in one generation (20 years) and will need (among others) 45 trillion sensors?
- Challenges:
  - Job creation expected indeed but what is the impact on environment and climate? Sustainable? Energy required?
  - Business as usual vision could be detrimental to environment and NOT sustainable!

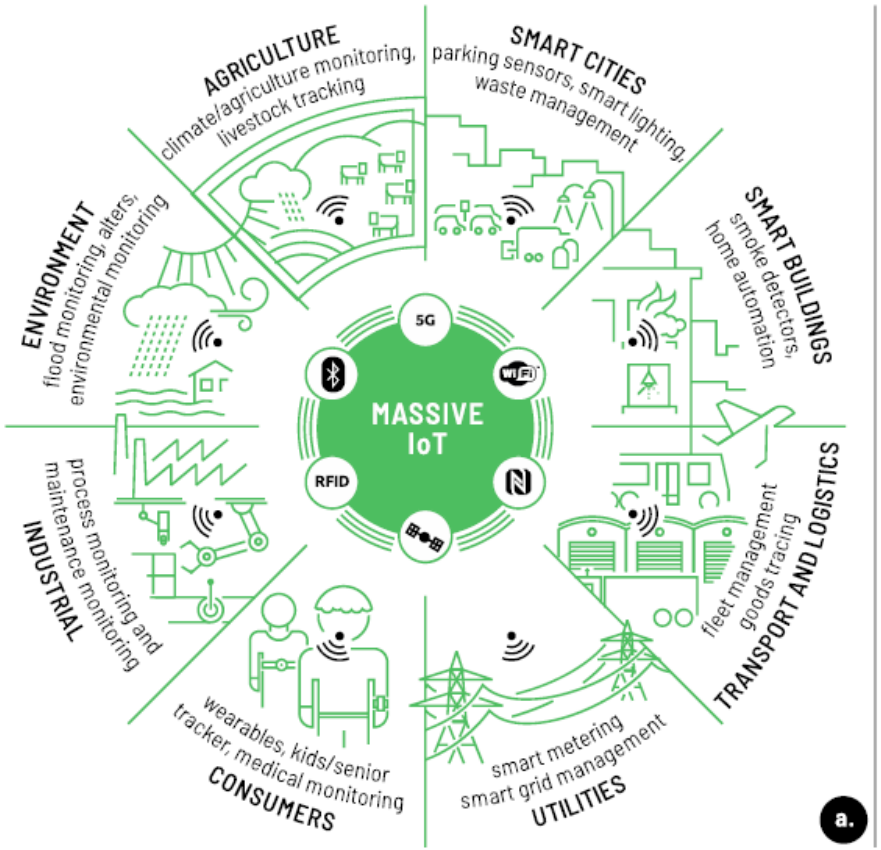


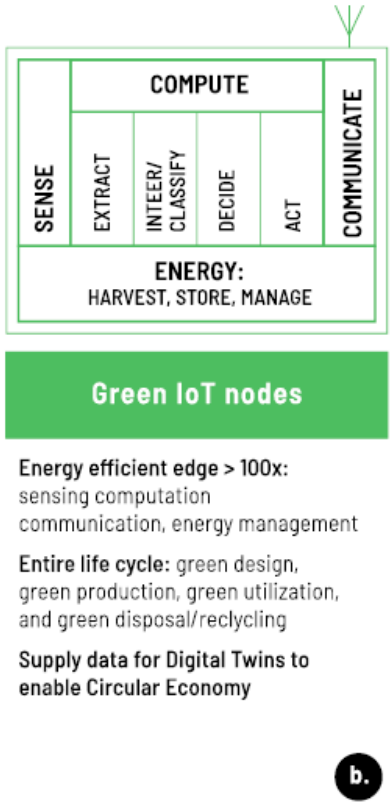


Janusz Bryzek, Chairman and CEO, TSensors Summit

Green IoT nodes

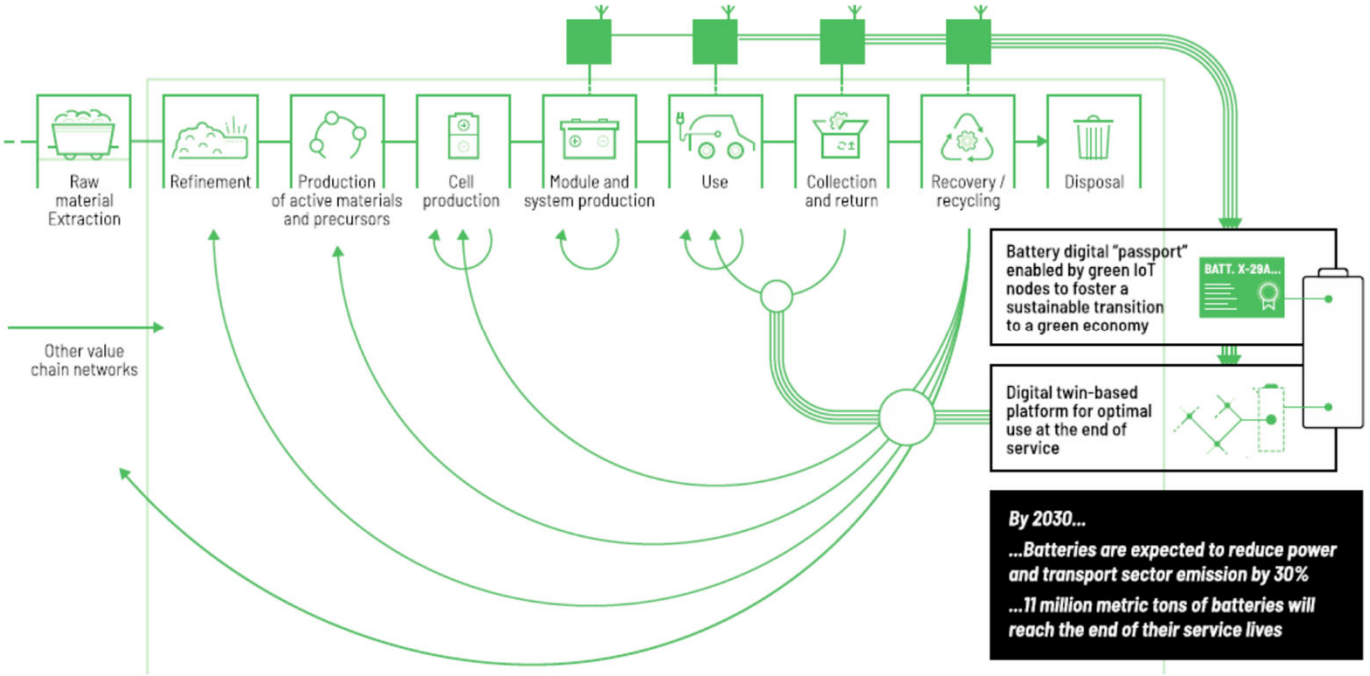
- **Opportunity: Green IoT Nodes as enablers of Circular Economy**: architectures of green IoT node (functional blocks) and the definition of the notion of 'green IoT node' features





Example: IoT & Digital Twins of batteries

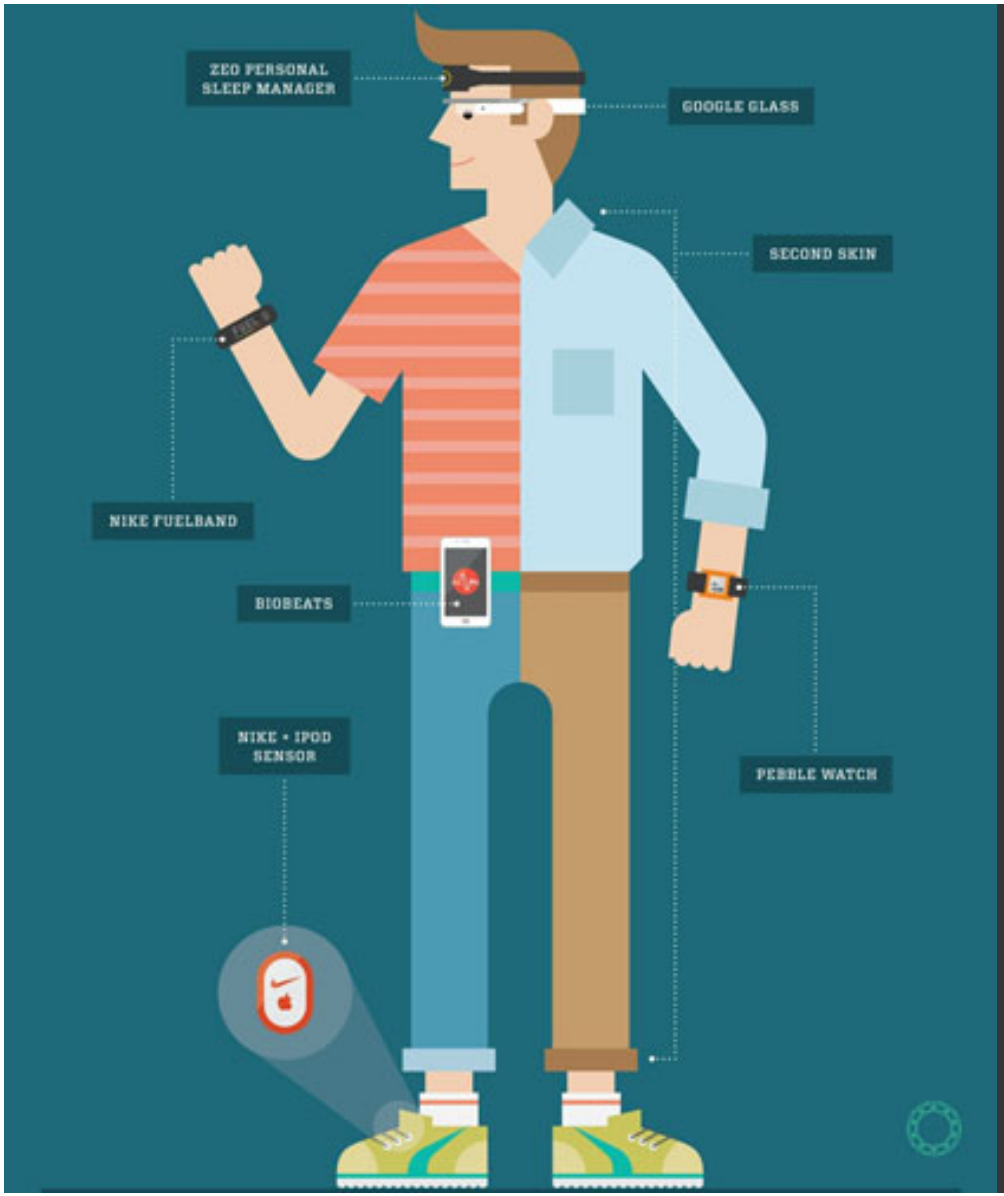
More Resource-Efficient Battery Life Cycles – Digital twin of a battery



Adapted after the illustration from the Circular Economy Initiative Deutschland, 2020, and the World Economic Forum, 2019

Wearable technology: sense your body

- Technology to be worn on the user's body for an extended period of time, significantly enhancing the user's experience
- Four wearable categories:
  - **Fitness and Wellness**
  - **Healthcare and Medical** - *require approval, monitor vital signs and augment senses.*
  - **Industrial and Military**
  - **Infotainment**



Wearables today: mostly activity tracking

Wearable Activity Devices Comparison Chart

There are more options to the right. Use the scroll bar to see additional options.

	Basis B1	BodyMedia Fit Core	Fitbit Flex	Fitbit Force	Fitbit One	Fitbit Z
						
Price	$179.00	$119.00	$99.95	$129.95	$99.95	$59.95
Tracks active minutes	✓	✓	✓	✓	✗	✗
Tracks calories burned	✓	✓	✓	✓	✓	✓
Tracks distance	✗	✓	✓	✓	✓	✓
Tracks elevation/stairs	✗	✗	✗	✓	✓	✗
Tracks heart rate	✓	✗	✗	✗	✗	✗
Tracks sleep	✓	✓	✓	✓	✓	✗
Tracks steps	✓	✓	✓	✓	✓	✓
Wearing the tracker	Wristband	Armband	Wristband	Wristband	Clip	Clip
Battery or chargeable?	Chargeable, recharge every 4 days	Chargeable, recharge every 4 days	Chargeable, recharge every 5 days	Chargeable, recharge every 7 days	Chargeable, recharge every 5 days	Battery lasts 4-6
Accessing your data	Macs, Windows, smartphone	Mac, Windows, Smartphone	Mac, Windows, Smartphone	Mac, Windows, Smartphone	Mac, Windows, Smartphone	Mac, Windows, Sn
Uploading your data	Bluetooth for your phone, USB plugs into your computer	USB plugs into your computer	Bluetooth for your phone, wirelessly for your computer	Bluetooth for your phone, wirelessly for your computer	Bluetooth for your phone, wirelessly for your computer	Bluetooth for your phor for your comp
Tracker display	Real-time data	None	LED progress indicator	Real-time data	Real-time data	Real-time d
	Basis B1	BodyMedia Fit Core	Fitbit Flex	Fitbit Force	Fitbit One	Fitbit Z
	Details	Details	Details	Details	Details	Details

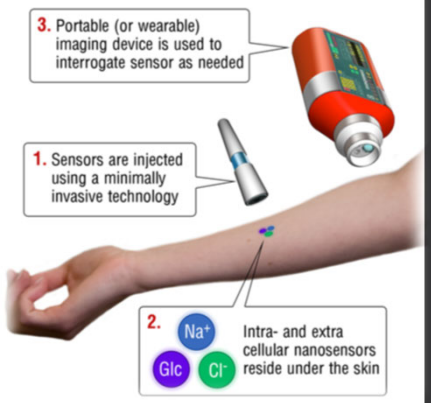
Best waterproof tracker for swimming: Moov Now

3 ATM (30m)

- Stroke detection
- Distance and efficiency in pool
- Run and cycling coaching
- All day step and sleep tracking
- iOS and Android

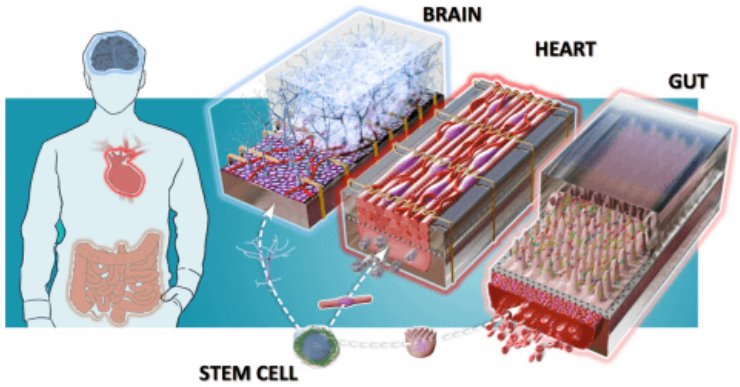
Biosensing as enabler of revolutionary smart wearables, implantanbles & OoCs

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

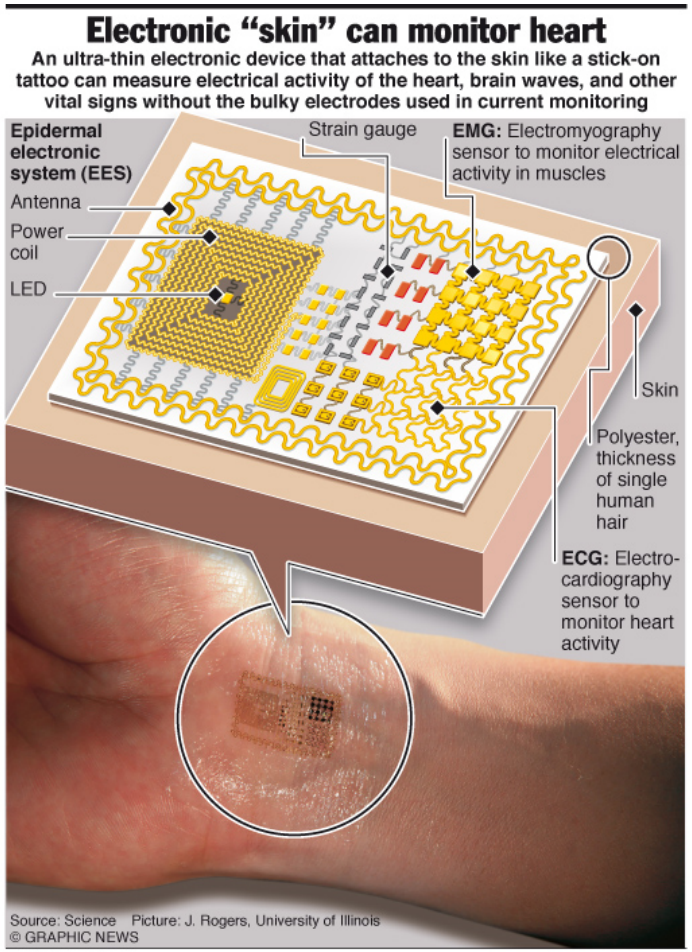


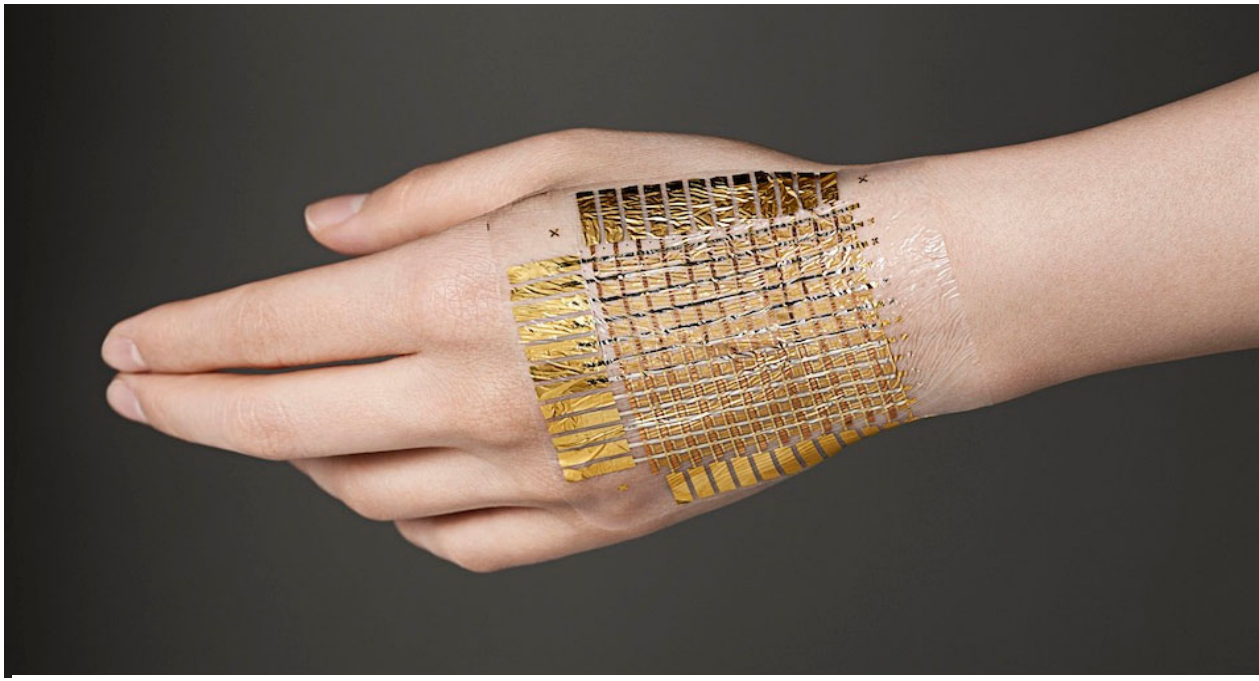
Requirements

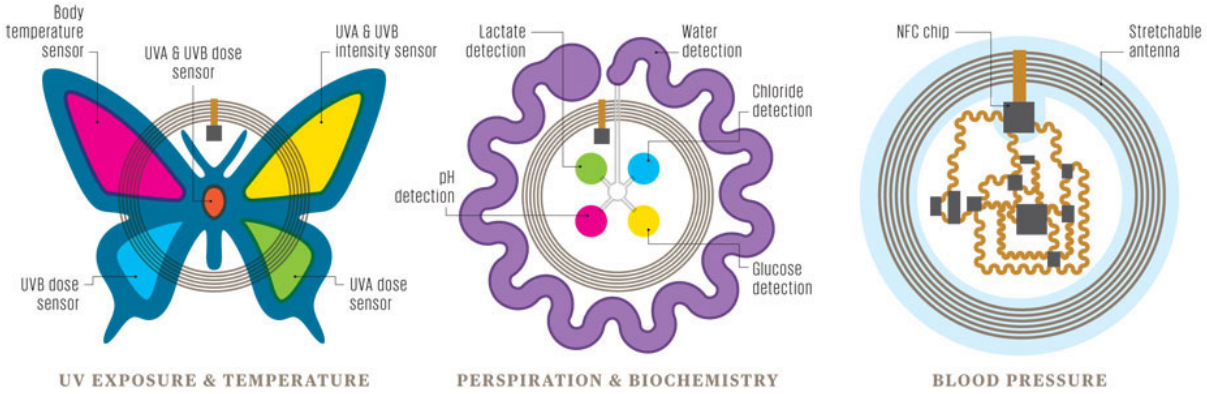
- **High quality data** - multi-parameter sensing
- **Form factor** - frictionless
- **Autonomy** - low power, energy efficiency
- **User acceptance** - data security, privacy
- **Low cost systems** – 3D, on foil integration



Towards sensitive biostamps & tatoos







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

Wearable technology:
sense your environment = exposome

AIR

WATER

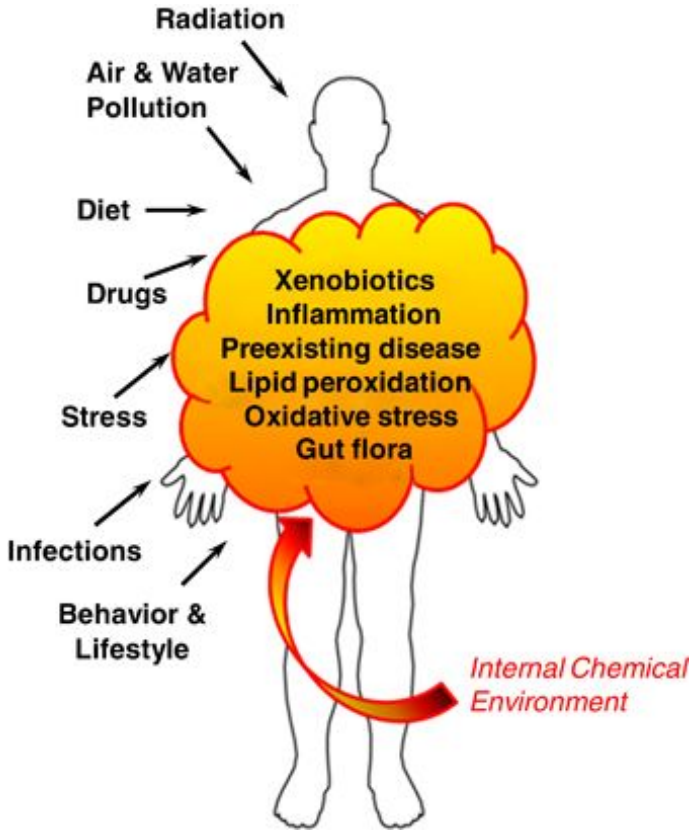
Environmental related diseases:

- **RESPIRATORY INFECTIONS**: Globally more than 1.5 million deaths annually from respiratory infections are attributable to the environment, including at least 42% of lower respiratory infections and 24% of upper respiratory infections in developing countries.
- **CANCER**: environmental causes also account for an estimated 31% of global lung cancer burden.
- **CARDIOVACULAR DISEASES**: 2.5 million people die every year from cardiovascular disease attributable to work-related stress as well as chemical, air pollution, and environmental tobacco smoke exposures.
- **DIARRHOEA**: about 1.5 million deaths per year from diarrhoeal diseases are attributable to environmental factors; WHO recently estimated that 88% of all cases of diarrhoea globally were attributable to water, sanitation and hygiene.
- **MALARIA**
- **INTESTINAL NEMATODE INFECTIONS**
- **HEPATITIS B and C**
- **TUBERCULOSIS**
- …

A schoolgirl with a face mask for protection from smokestack pollution emissions of factories in her neighbourhood in the eastern Mediterranean region.

Credit: Munir NASA/UNEP/Still Pictures

Implications of the exposome for exposure science



Environmental exposures to chemicals arise from both external and internal sources.

The **exposome represents the combined exposures from all sources that reach the internal chemical environment**.

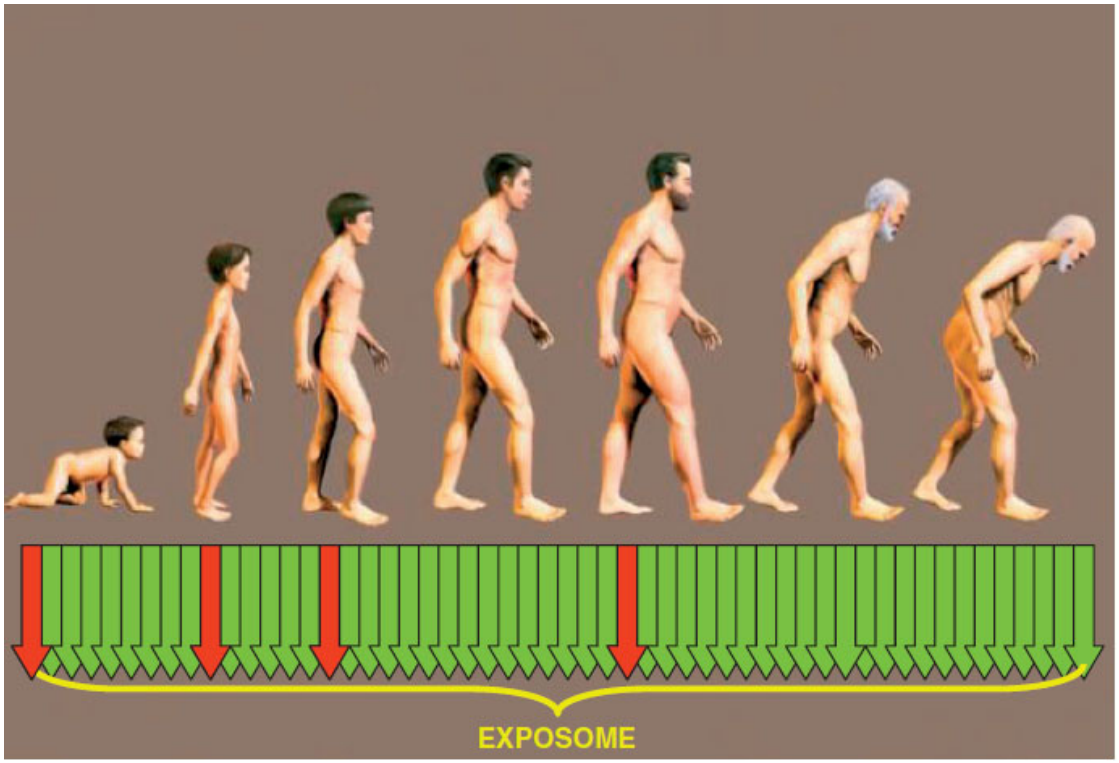
Radiation, stress, infections, behavior and lifestyle factors affect the internal chemical environment due to inflammation, oxidative stress and hormone production.

The exposome: from concept to utility

- **The exposome would require measurements of exposures over time across the lifecourse of an individual**

Table 1 Some examples of approaches and tools to measure the exposome

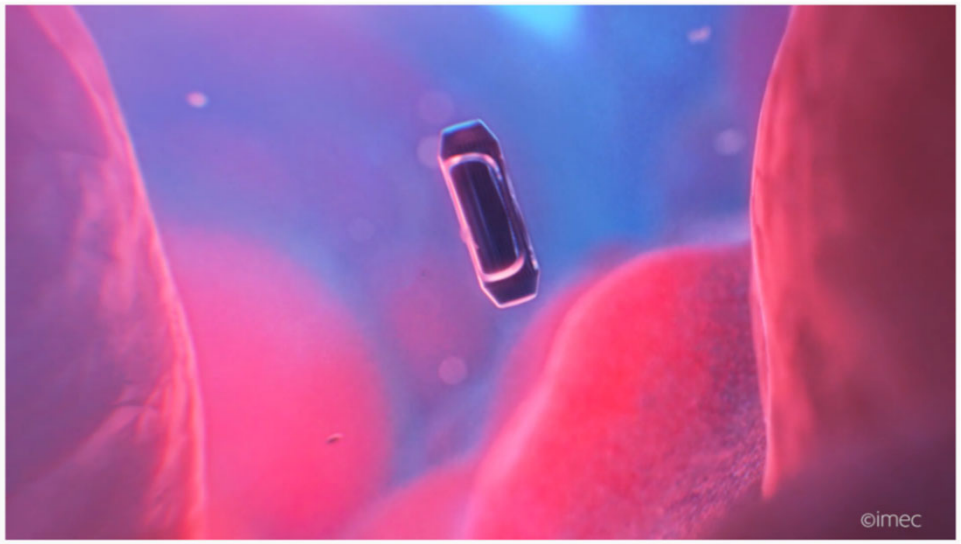
Approach	Tools
Biomarkers (omics)	
General	Genomics, transcriptomics, proteomics, metabolomics, epigenomics
Targeted	Adductomics, lipidomics, immunomics
Sensor technologies (including mobile phones)	Environmental pollutants, physical activity, stress, circadian rhythms, location [global positioning systems (GPS)]
Imaging (including mobile phones, video cameras)	Diet, environment, social interactions
Portable computerized devices (including palmtop computers)	Behaviour and experiences (ecological momentary assessment), stress, diet, physical activity
Improved conventional measurements (combined with environmental measures)	Job-exposure matrices; dietary recall (e.g. EPIC-Soft)



C.P. Wild, International Journal of Epidemiology, 2012.

Ingestibles: time to eat the sensor!

- https://www.imec-int.com/en/ingestibles

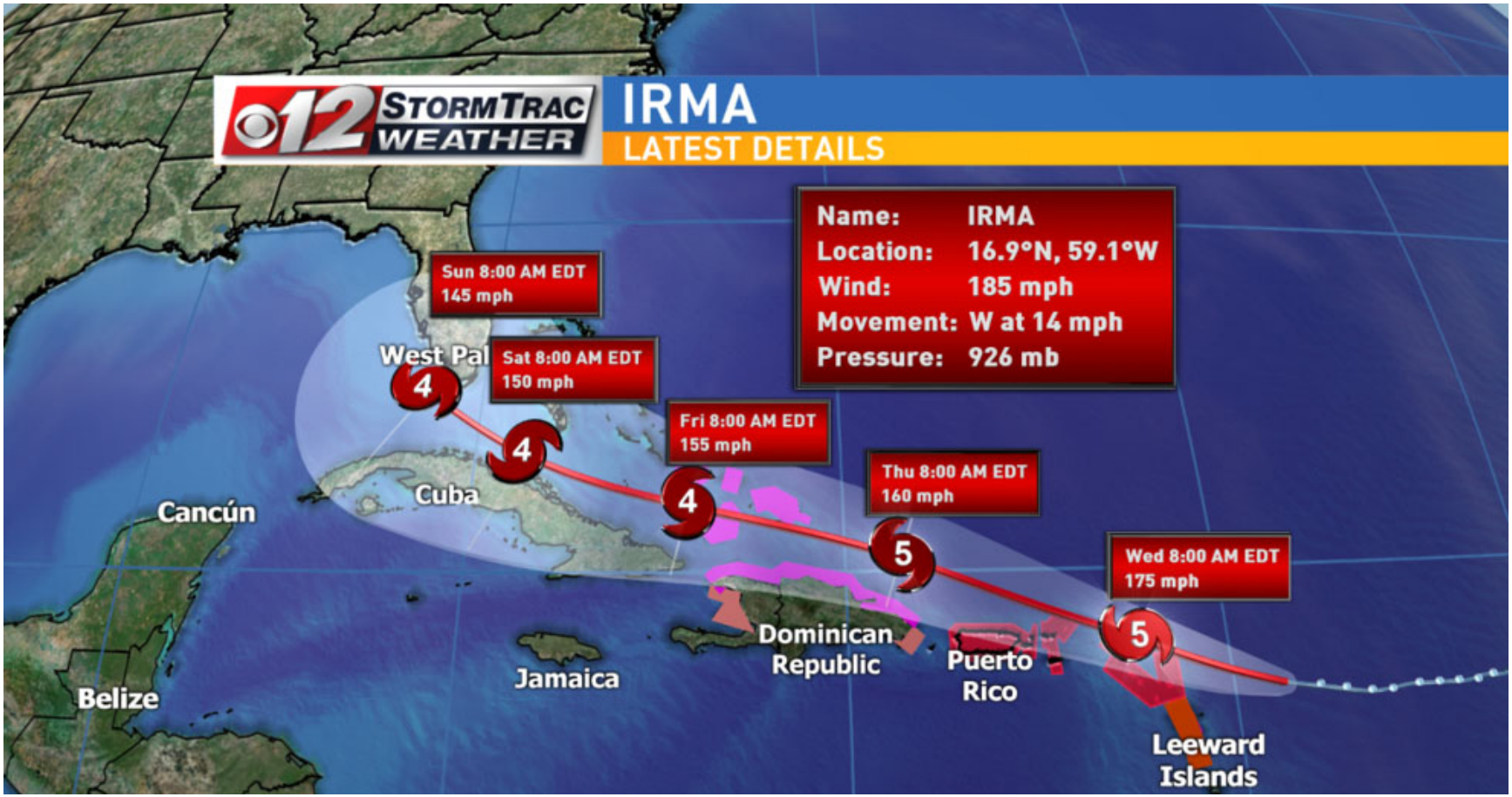


By fixating the ingestible sensors along the gastrointestinal tract, the data they collect could be used to **precisely diagnose** digestive disorders with typically vague complaints: indigestion, gastrointestinal hypermotility and dysmotility, etcetera.

Preventive applications are also possible. Perhaps one day people will regularly take an ingestible sensor with their meal. Not much later, their smartphone will give them a detailed overview of the nutrients, such as fibers, that their body actually absorbed – along with some advice on how to balance their diet.

Today our technology can predict weather…

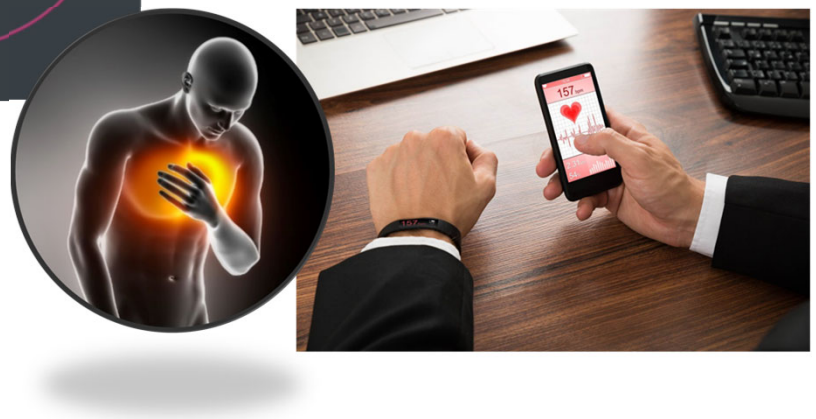
SENSORS → BIG DATA → MODELS → COMPUTING → **WEATHER FORECAST**



Possible to predict healt? Thinking diferent the future of P3 healthcare…

What's the real opportunity for future wearable (Edge AI) technology? P3 healthcare!

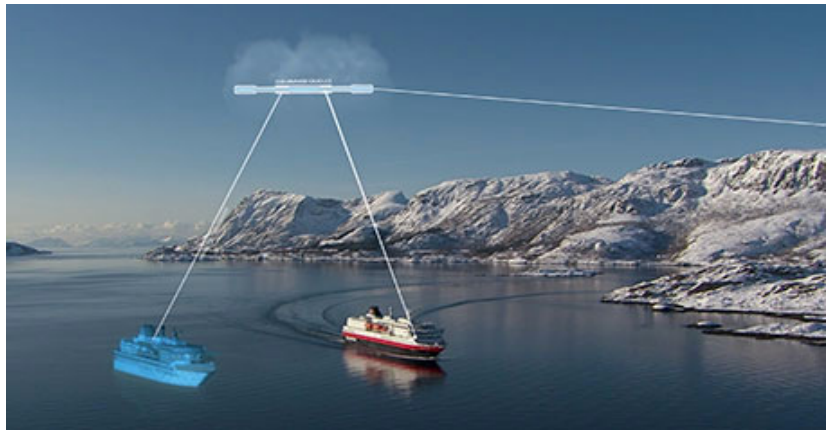
What's the value of **NOT being sick = healthy?**

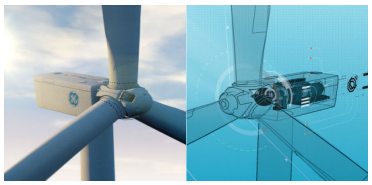


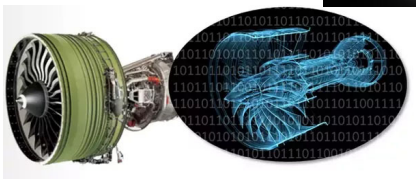
The value of being sick!

2030: From Object to Human Digital Twins

Digital Twins of All Objects





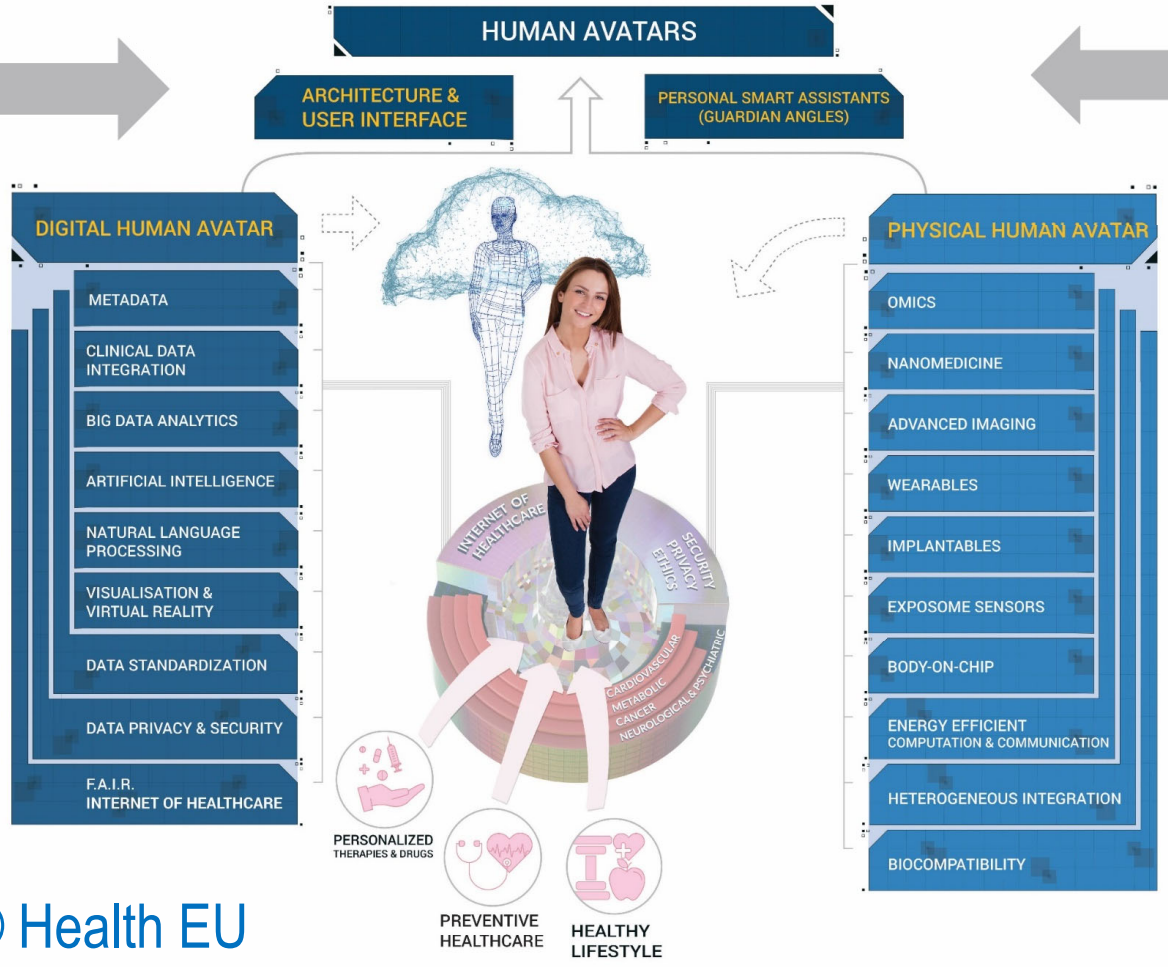


Digital Twins of All Humans

A Truly Personalized and Preventive Healthcare System: ***SUSTAINABLE***

Digital Twins Integrative Technology Platform

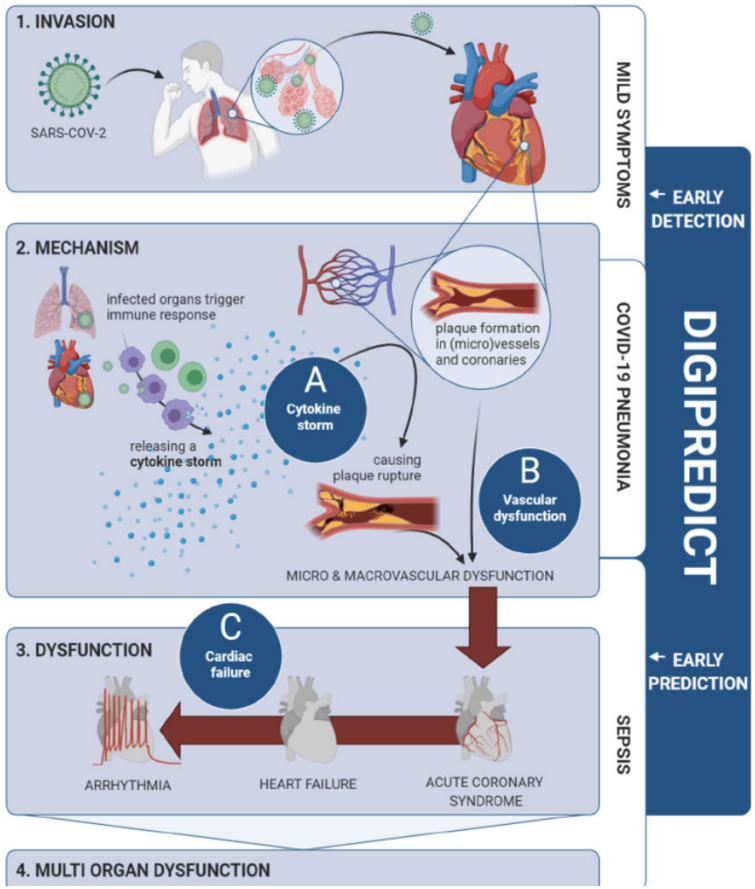
Big
Data
IoH
AI



© Health EU

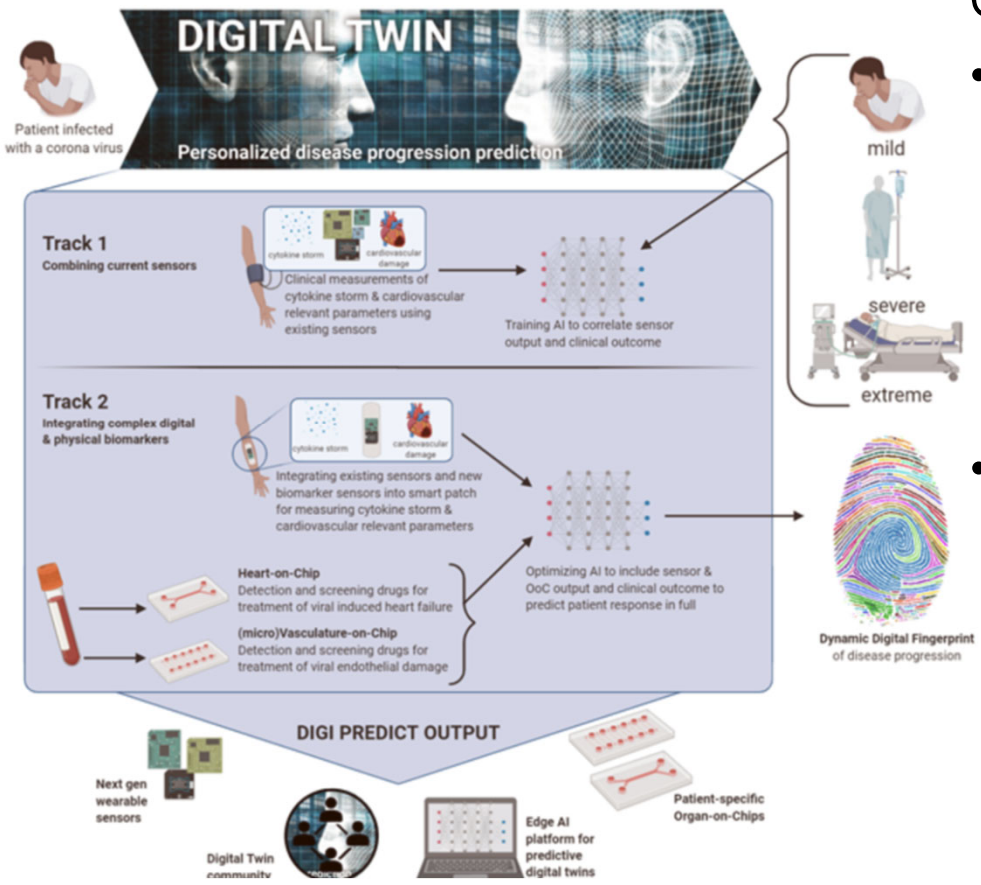
Data
Generator
Technology
Body-On-Chip

DIGIPREDICT: Digital Twins @ the Edge



- **Early detection**: High risk COVID-19 patients can be early identified from **Digital Fingerprints** of complex disease progression and monitored.
- **Personalized therapy**: Supportive therapy as well as referral decisions can be personalized and administered to patients with the highest need.
- **A new Digital Twin tool for P3 Healthcare**: We will empower citizens and provide medical doctors with a new assistive and predictive healtcare tool, the Digital Twin from Edge to Cloud.
- Building a broad **Digital Twin interdisciplinary community** in Europe aiming at sustainable healthcare.

The DIGIPREDICT project



Goals:

- **Develop and deploy Digital Twins at the Edge** for personalized disease progression prediction based on the integration of Digital and Physical biomarkers, Organ-on-Chip and Artificial Intelligence technologies
- **Validation** in clinical path pathologies involving **cytokine storm in COVID-19** and sepsis patients and **cardiovascular** implications

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.

Conclusions

- **Internet of Things involves SENSOR, COMPUTATION & COMMUNICATION physical layers**
- **Energy efficiency and novel functionalities are next drivers** in the zettabyte era.
- **Various enabling technologies co-existing: silicon CMOS, flexible substrates, 3D heterogeneous integration** for abundant data IoT applications @ the edge of the cloud.
- **Green IoT nodes** for sustainable deployment
- **Biosensors: one of the next enabling technology** for smart wearables.
- **Technology (device to system)-data-algorithm interactions** will generate new innovations in IoT and Artificial Intelligence at the Edge.
- **Digital Twins of objects and of all humans**