DAC SKYtalk

Design and Manufacturing in 2030

Greg Yeric
Fellow, Arm Research


MOSCONE WEST
MOSCONE WEST
MOSCONE WES
Academy Resource Center - Booth 7337
Meeting Rooms - West 2001-3024
Opening Session (Sunday 8:30am - 10:00am) - West 3002
Where All of Ophthalmology Meets
#aao2019
MOSCONE WEST
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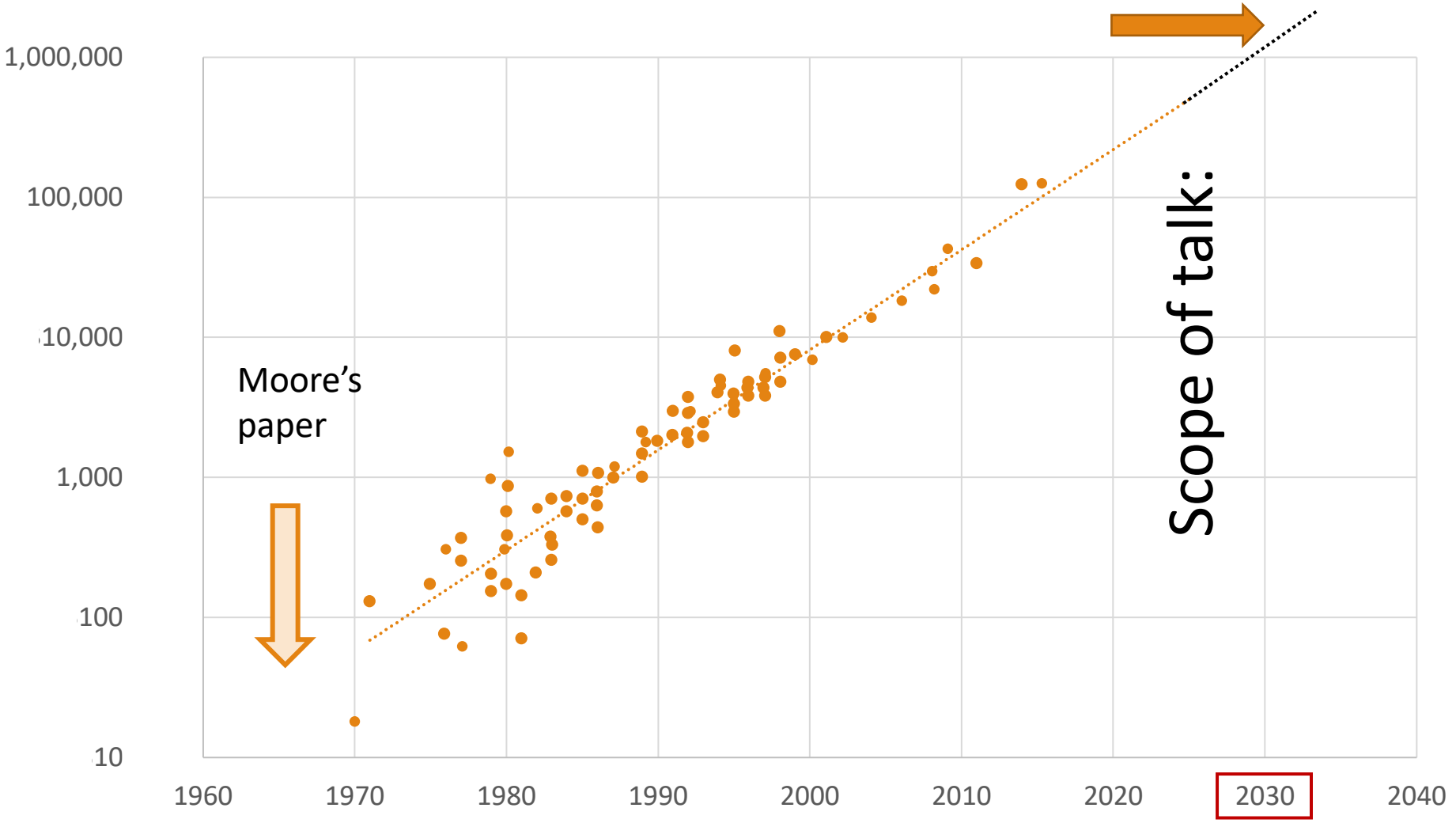
Design and Manufacturing in 2030



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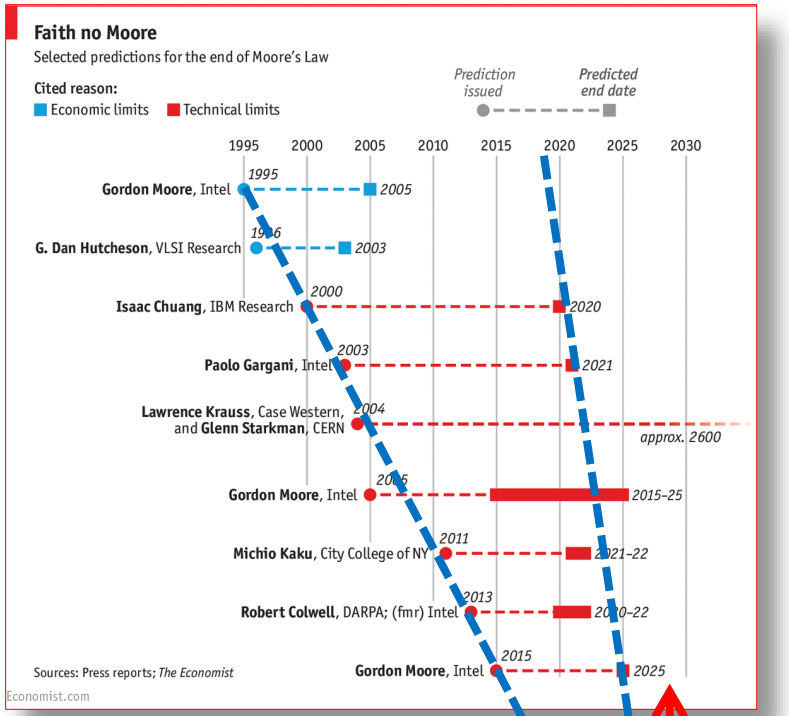
2030 will be “post Moore’s Law”



Yeric, 2015 IEDM
(figure from The Economist)

Moore’s Law ends: 2029

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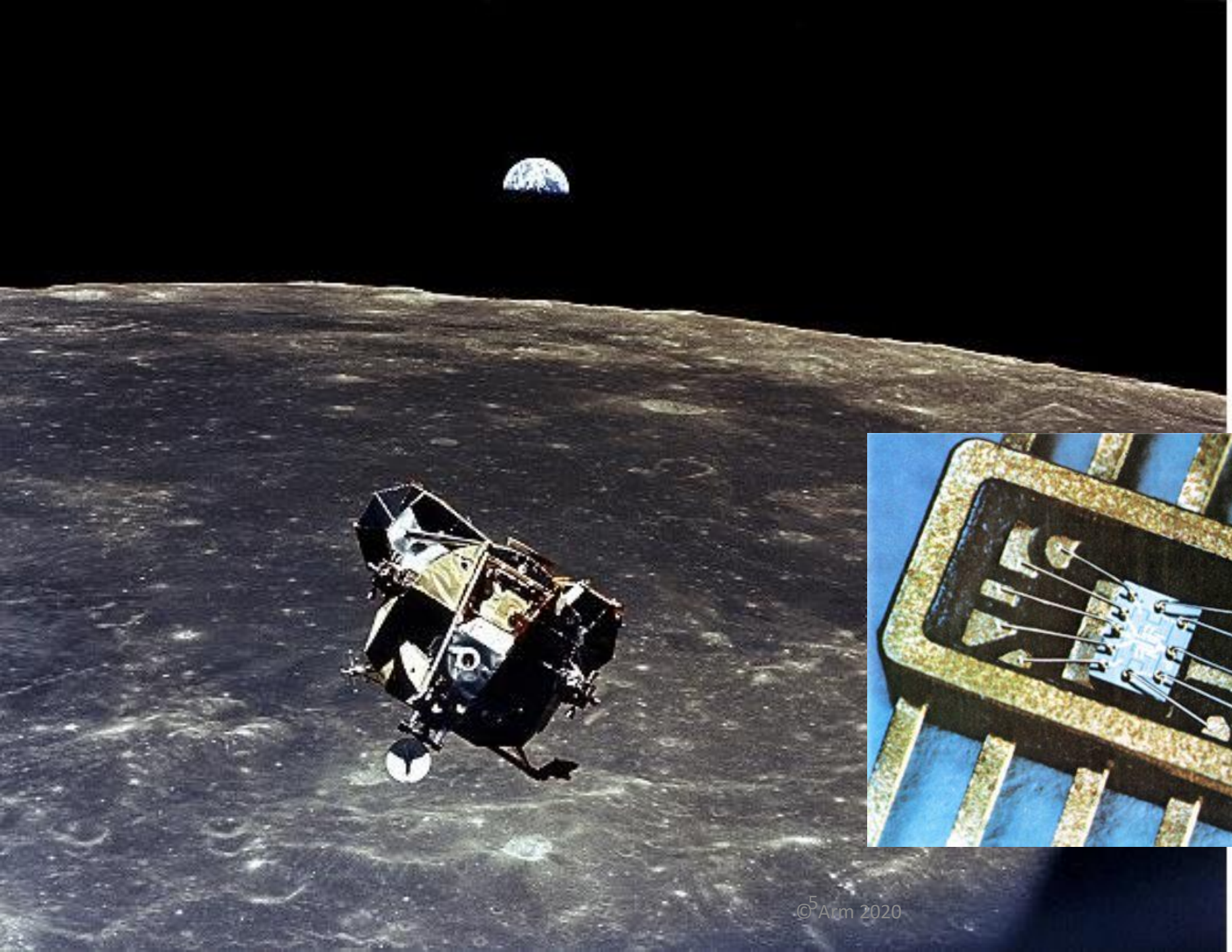

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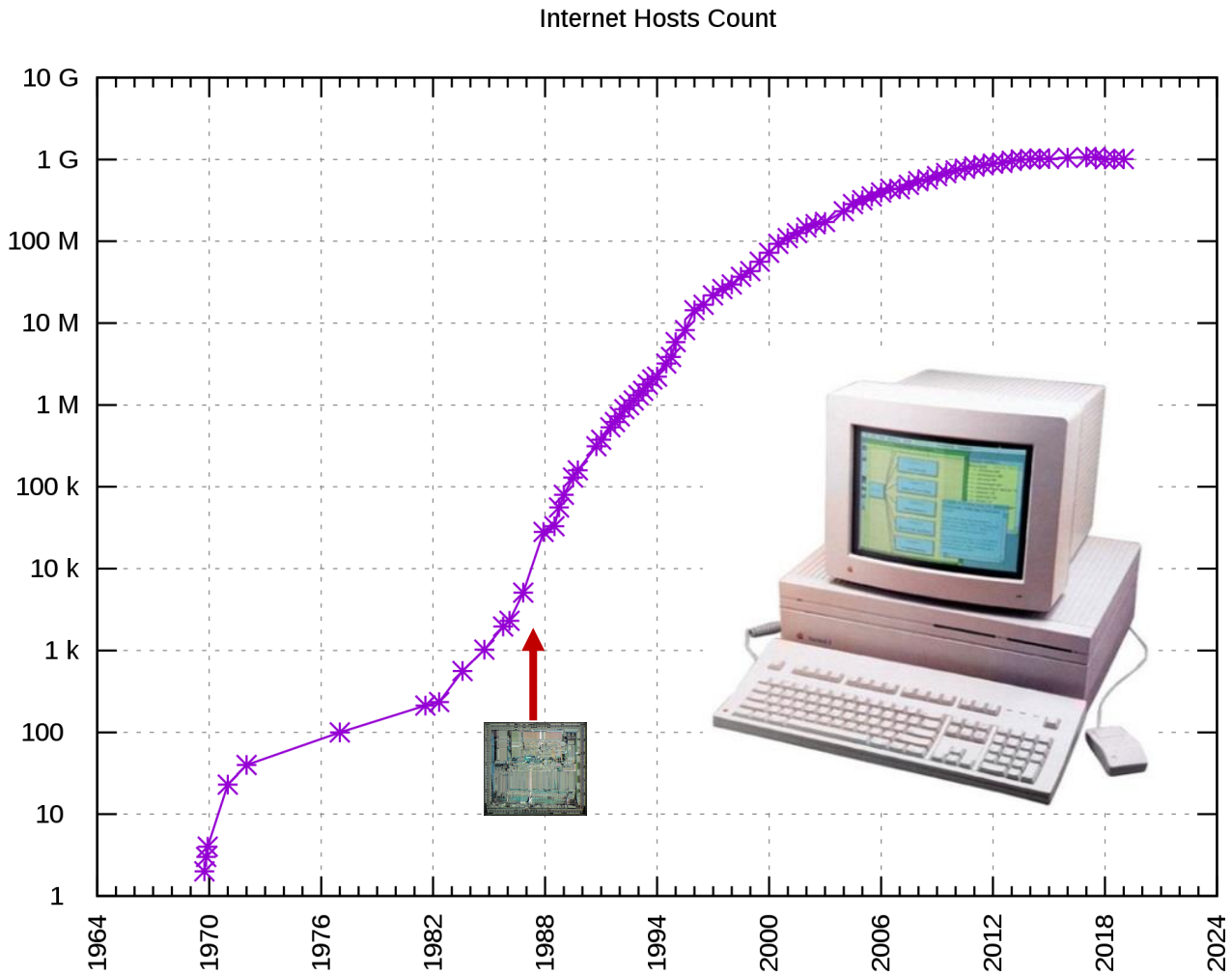

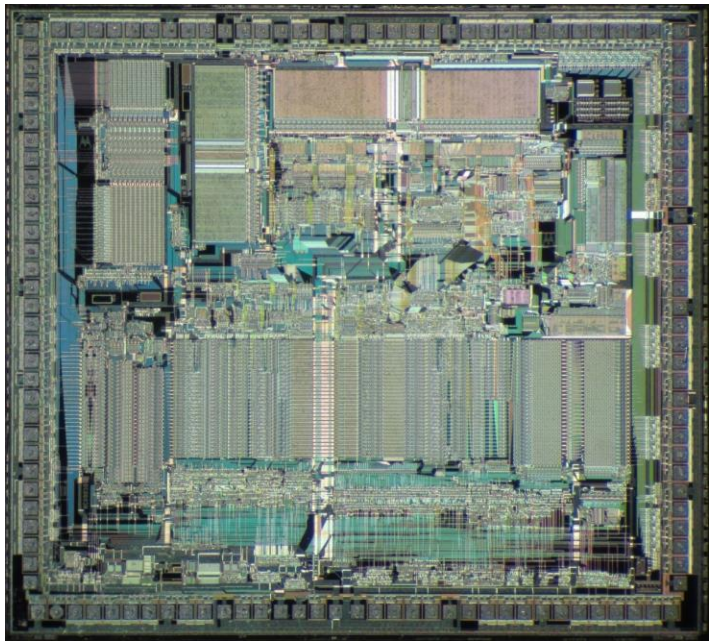

Motorola 68030

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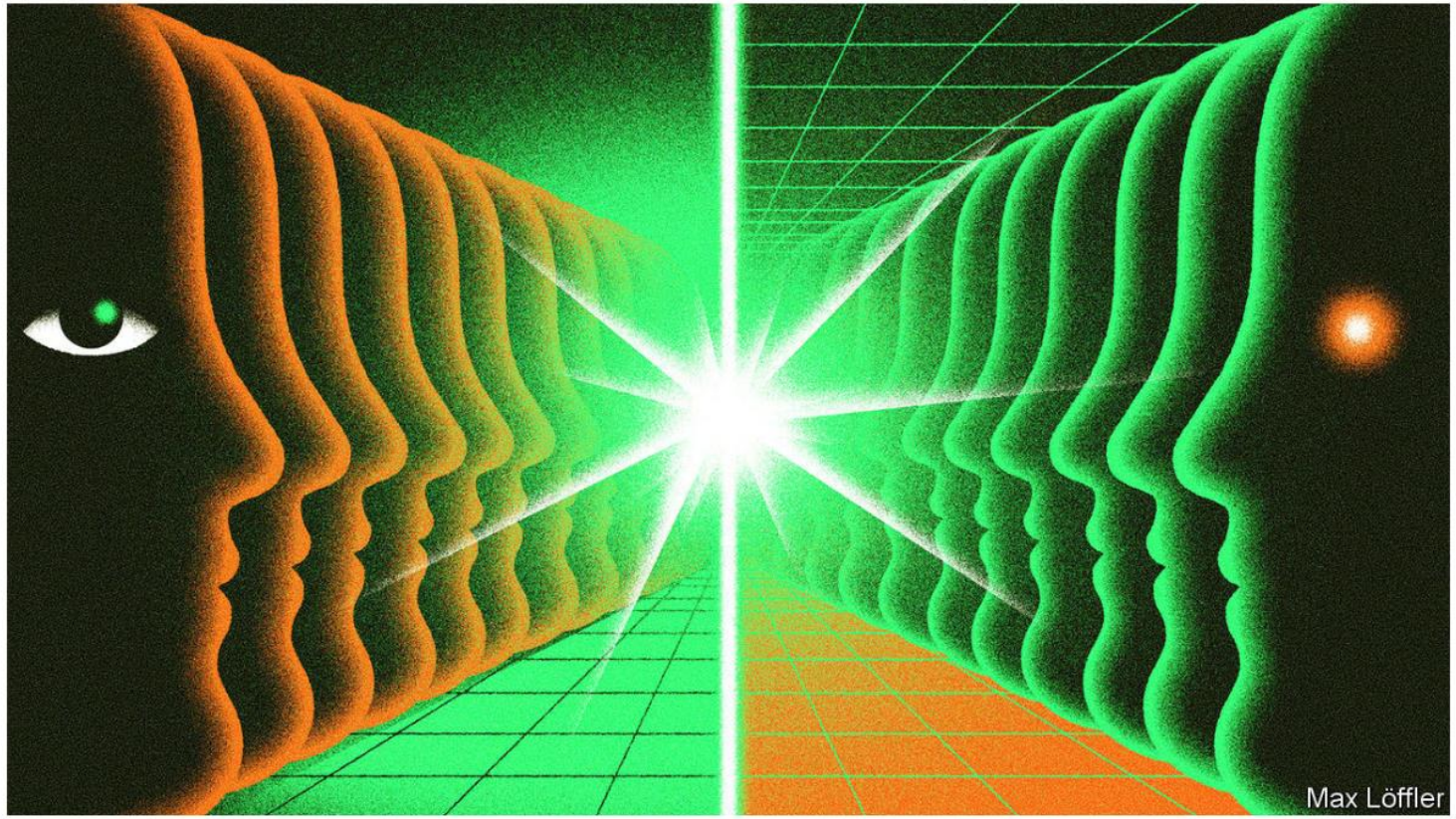

Special report

Feb 20th 2020 edition ›

The Economist

The data economy

A deluge of data is giving rise to a new economy

AWS Graviton2 processor

- 4x the vCPUs
- 7x CPU performance
- ~2x performance/vCPU
- ~30 Billion transistors
- 7nm

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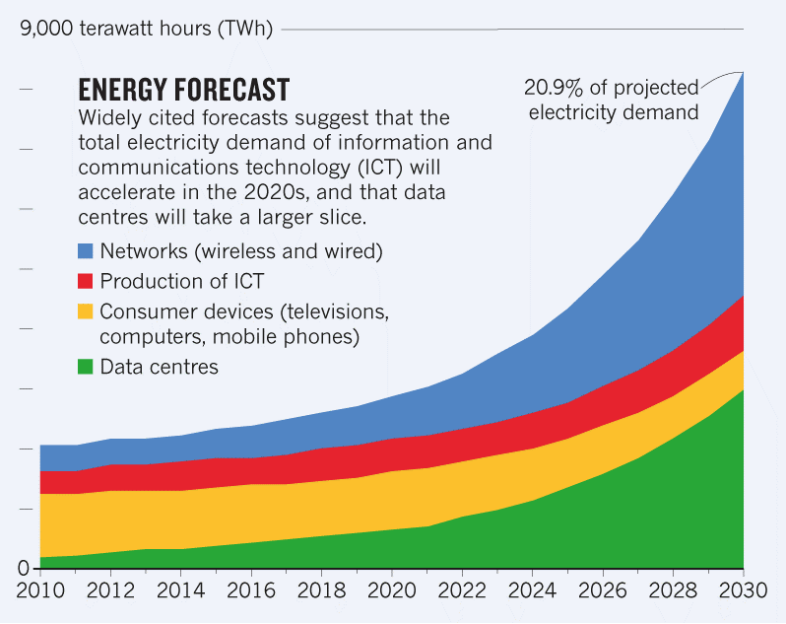
How to stop data centres from gobbling up the world's electricity

The energy-efficiency drive at the information factories that serve us Facebook, Google and Bitcoin.



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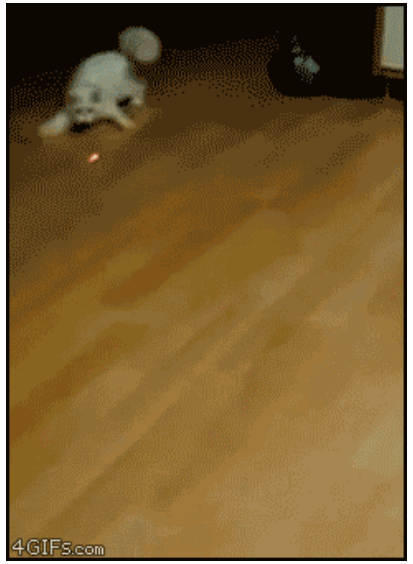
YouTube: 500 hours uploaded every minute



1 billion hours watched per day

2.5 minutes of video = 2 AA batteries

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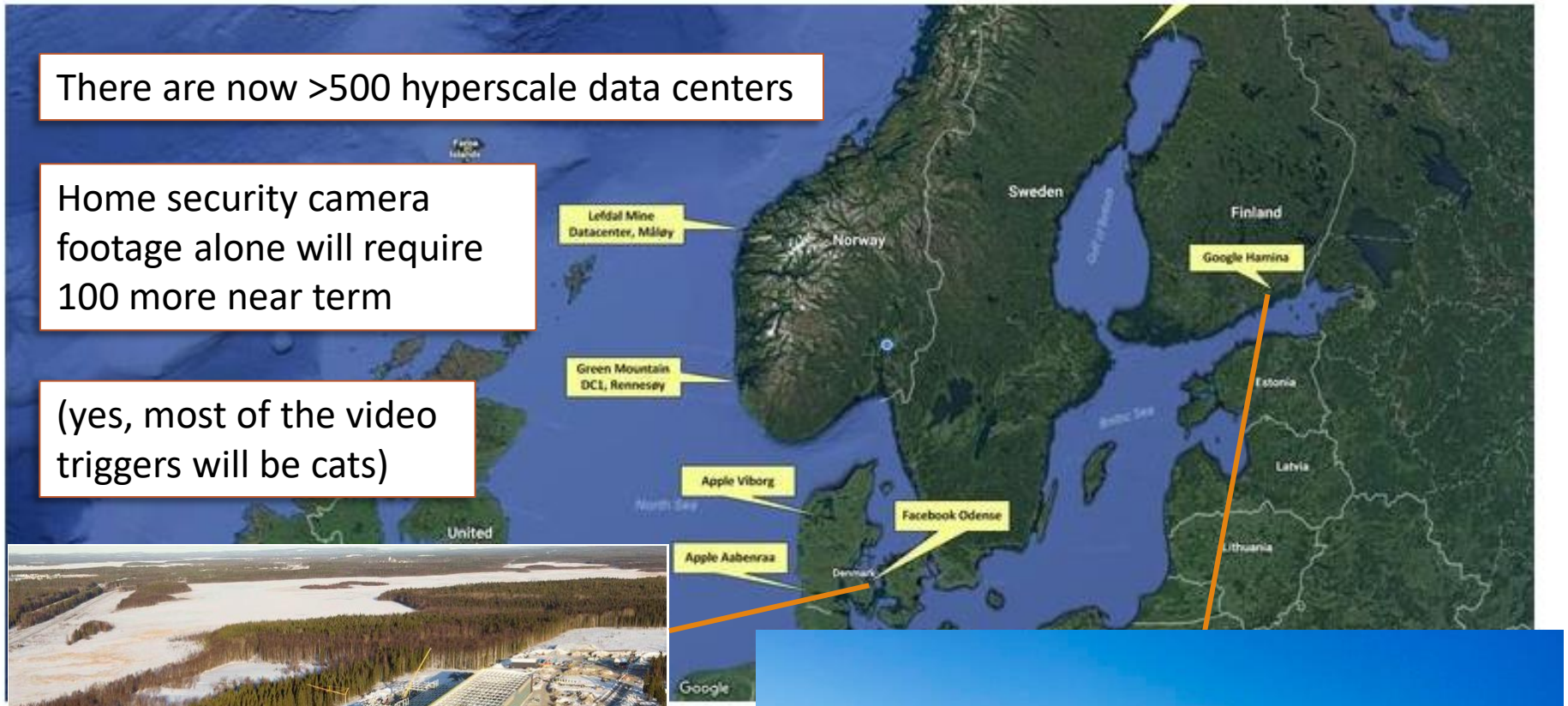
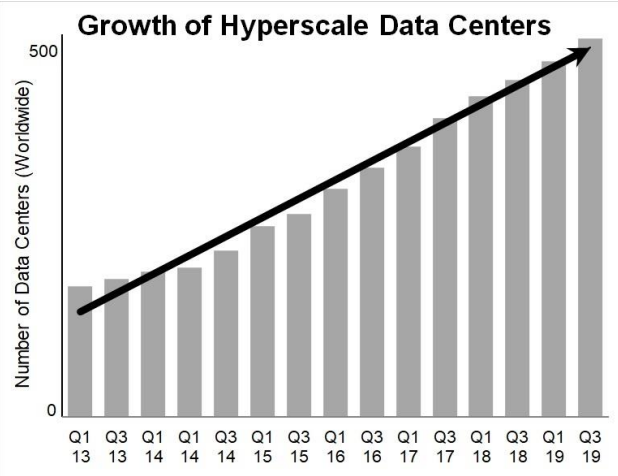
Photos: Inside Apple, Facebook, Google, IBM's frozen Nordic datacenters

There are now >500 hyperscale data centers

Home security camera footage alone will require 100 more near term

(yes, most of the video triggers will be cats)





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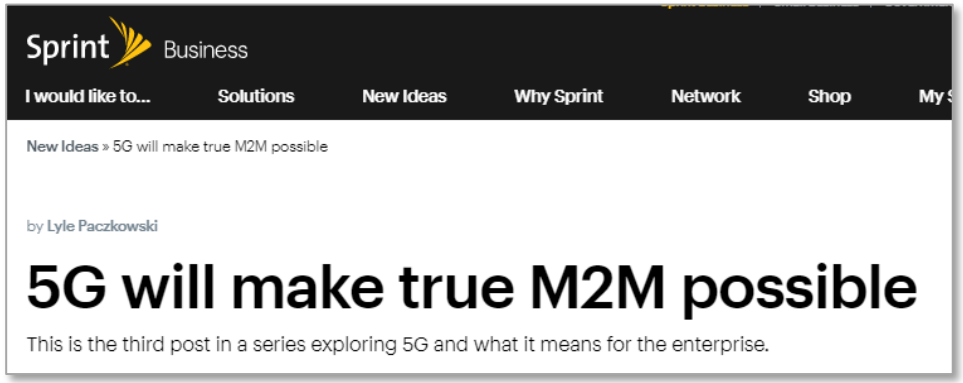


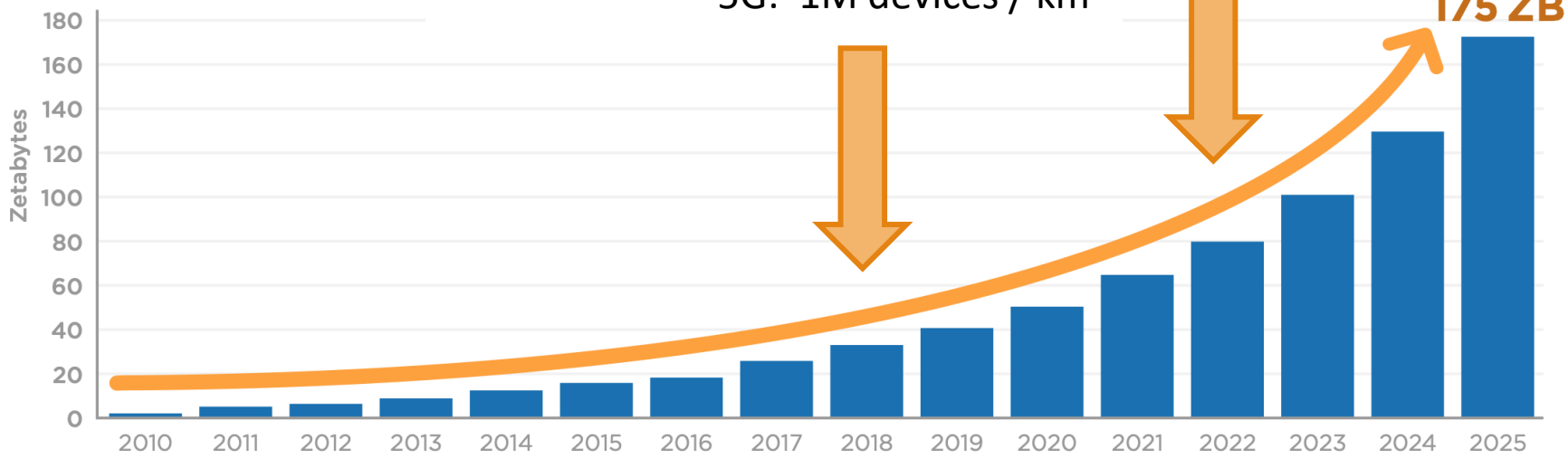
26B+ IoT connections

>50% connections machine-to-machine

5G

Huawei to ship 600,000 5G AAUs

5G: 1M devices / km^2



Source: Data Age 2025, sponsored by Seagate with data from IDC Global DataSphere, Nov 2018

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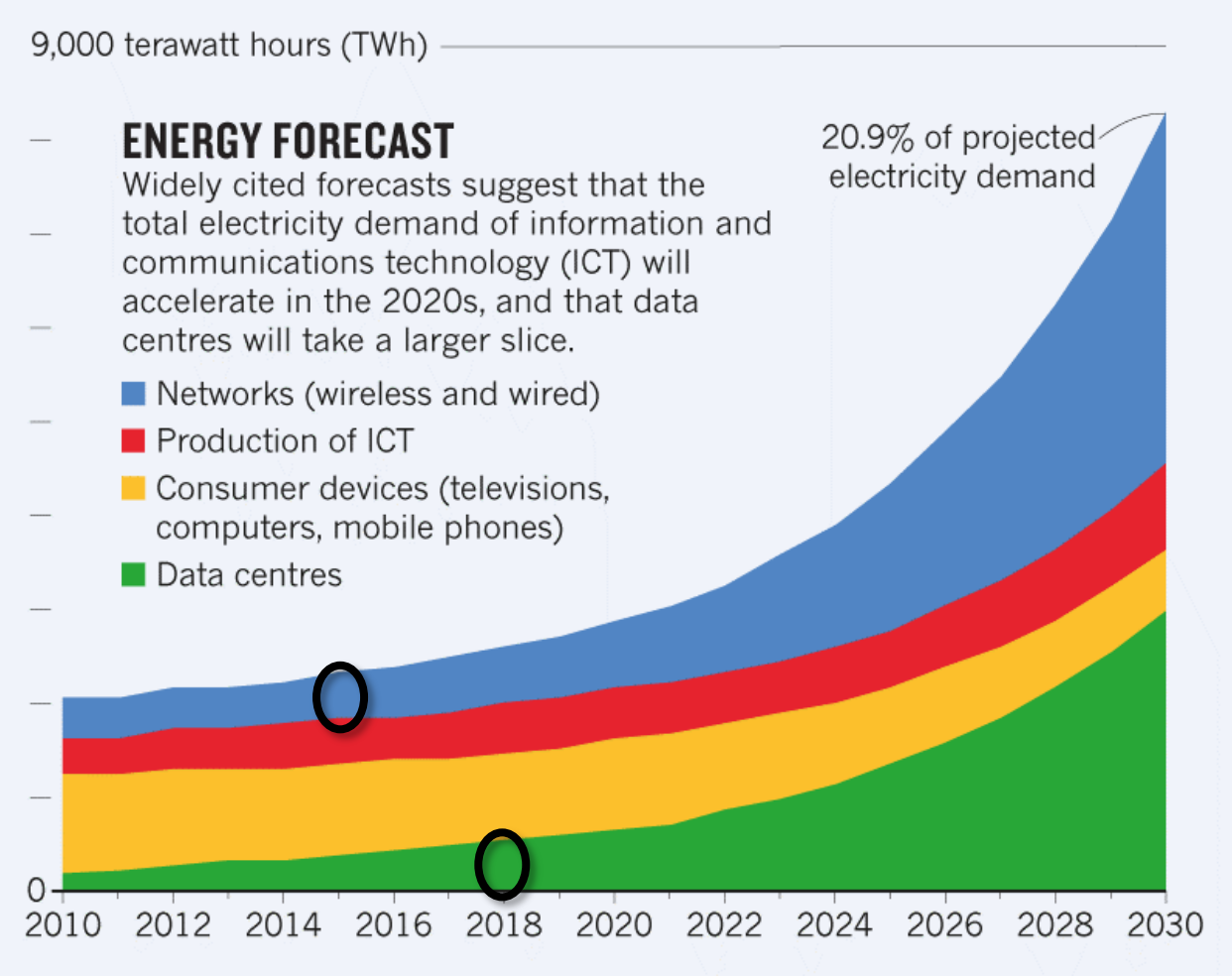
Data poised to dominate



https://www.nature.com/articles/d41586-018-06610-y

2015:
Fixed Access networks: 167 TWh
Wireless networks: 50 TWh

https://www.cfr.org/blog/what-5g-means-energy

2018: Data centers 200 TWh

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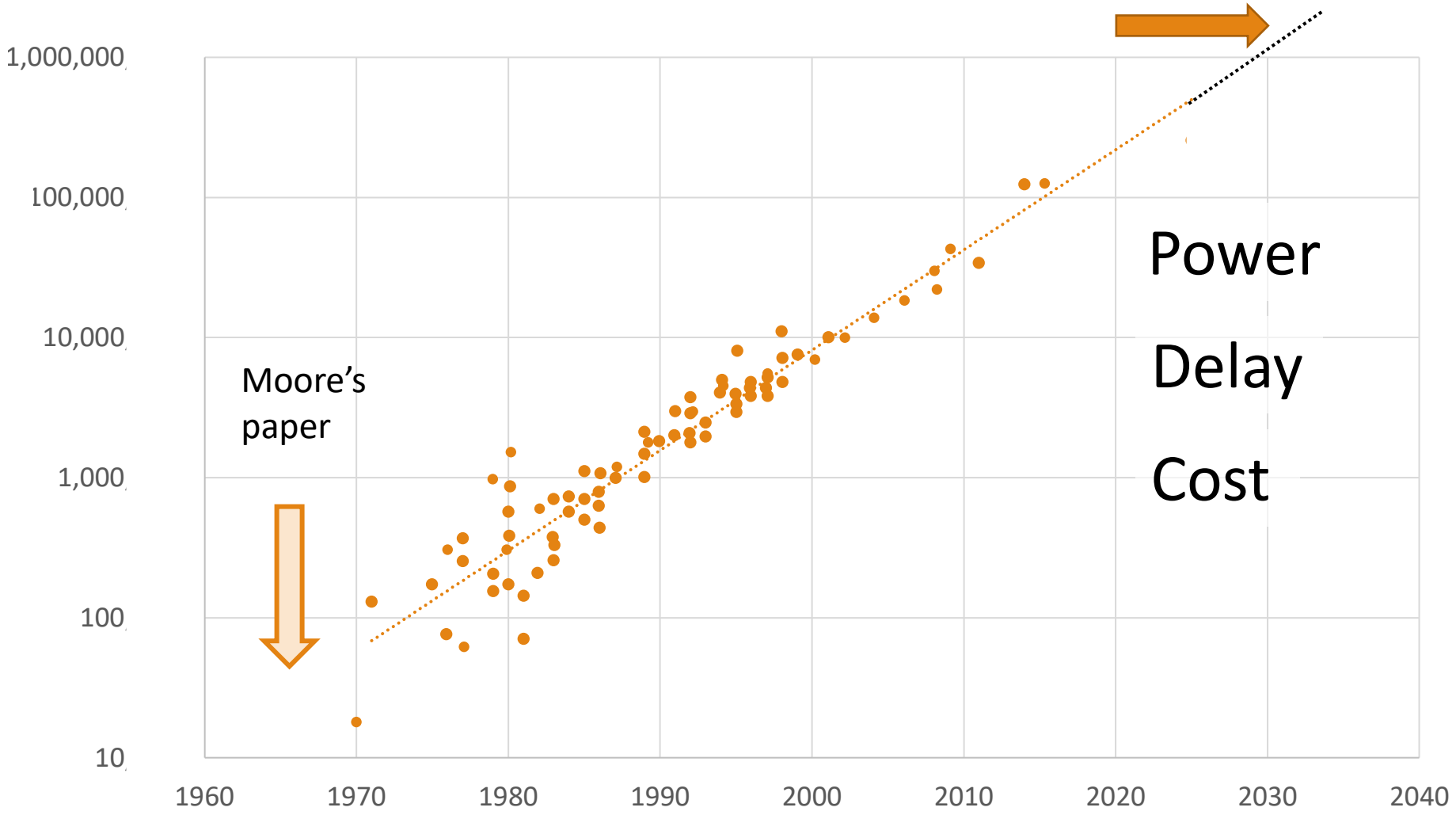
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1980
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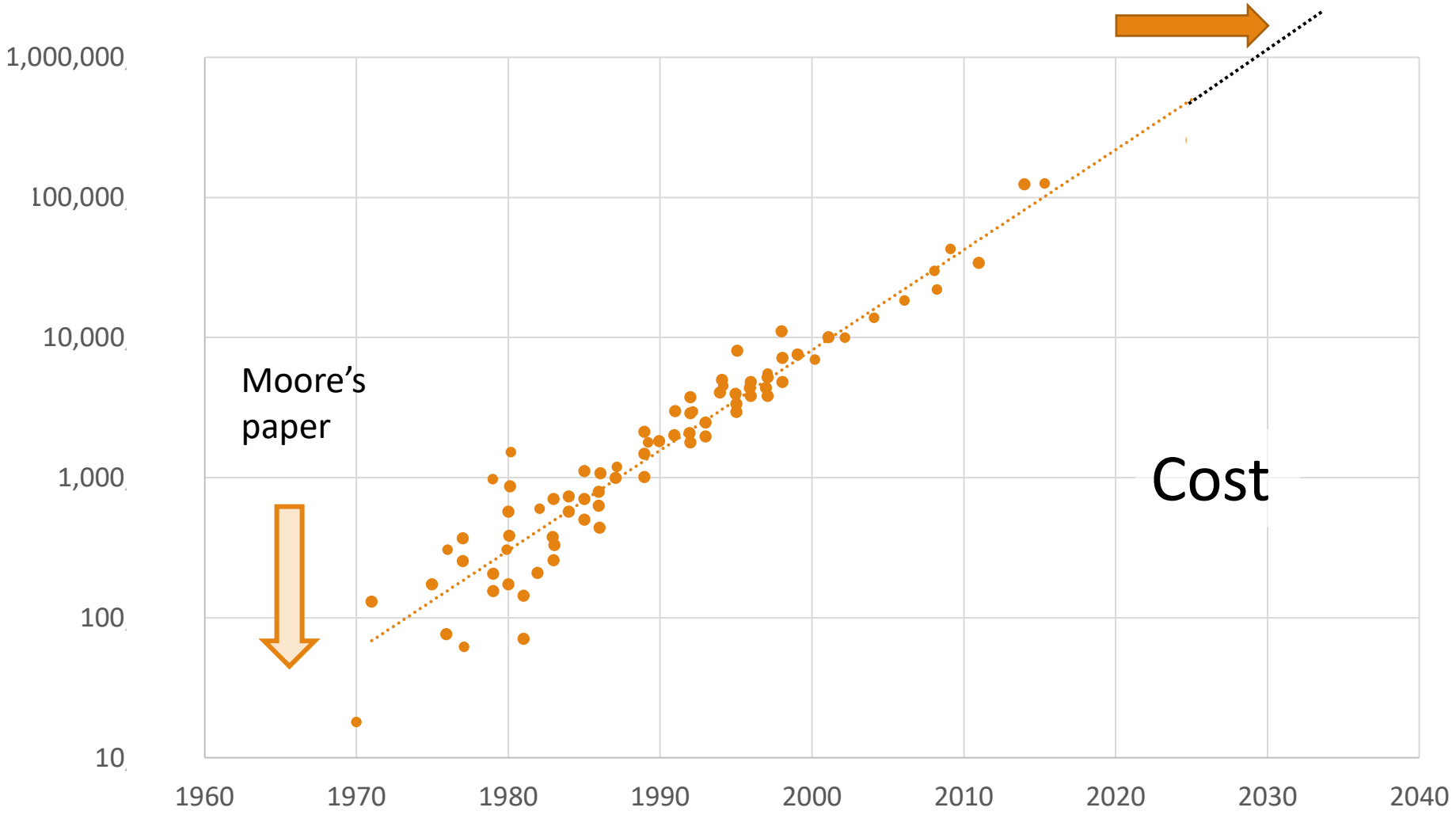
2020
2030
2040
Moore's paper
Power
Delay
Cost

© Arm 2020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Moore's paper
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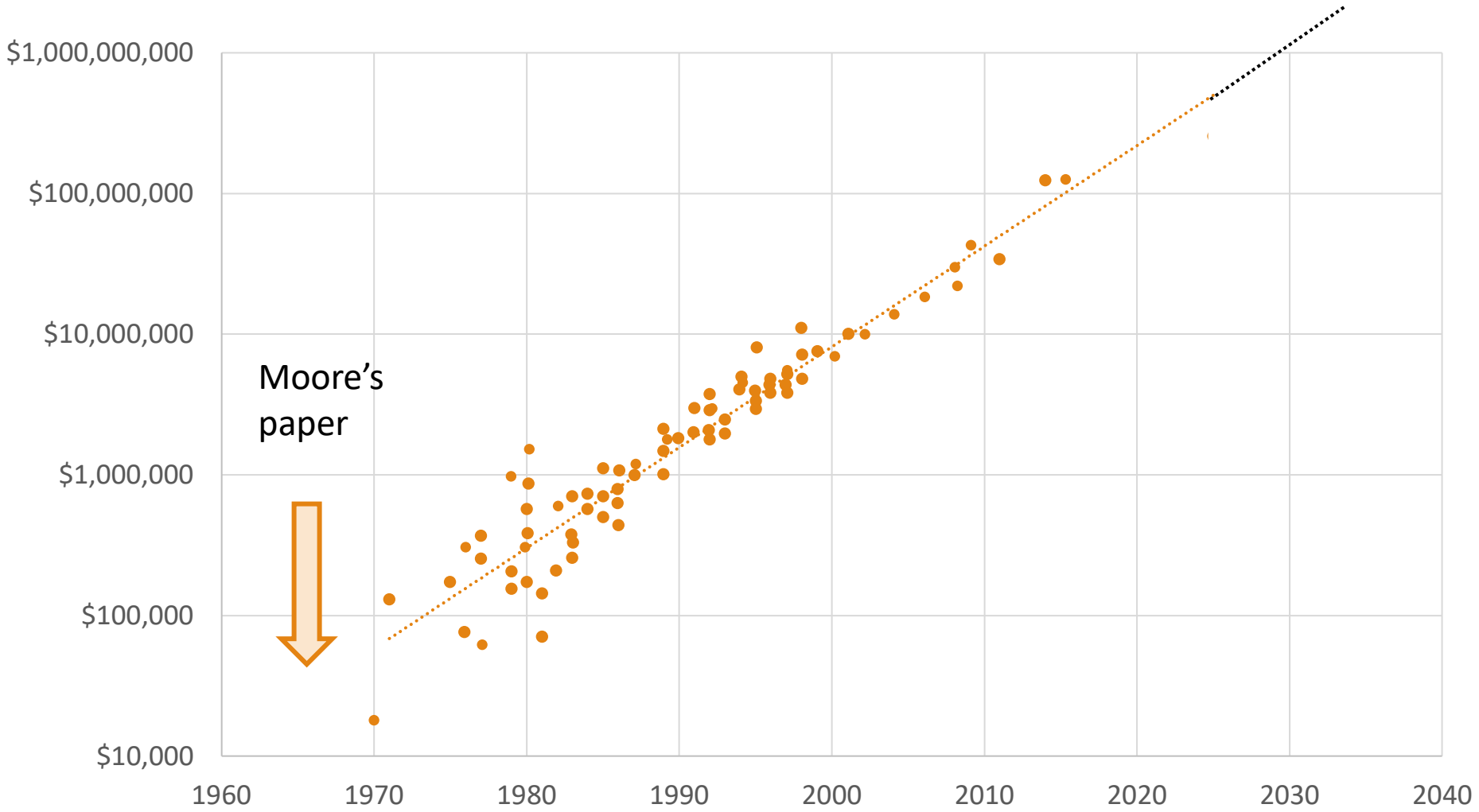
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Moore's paper
1960
1970
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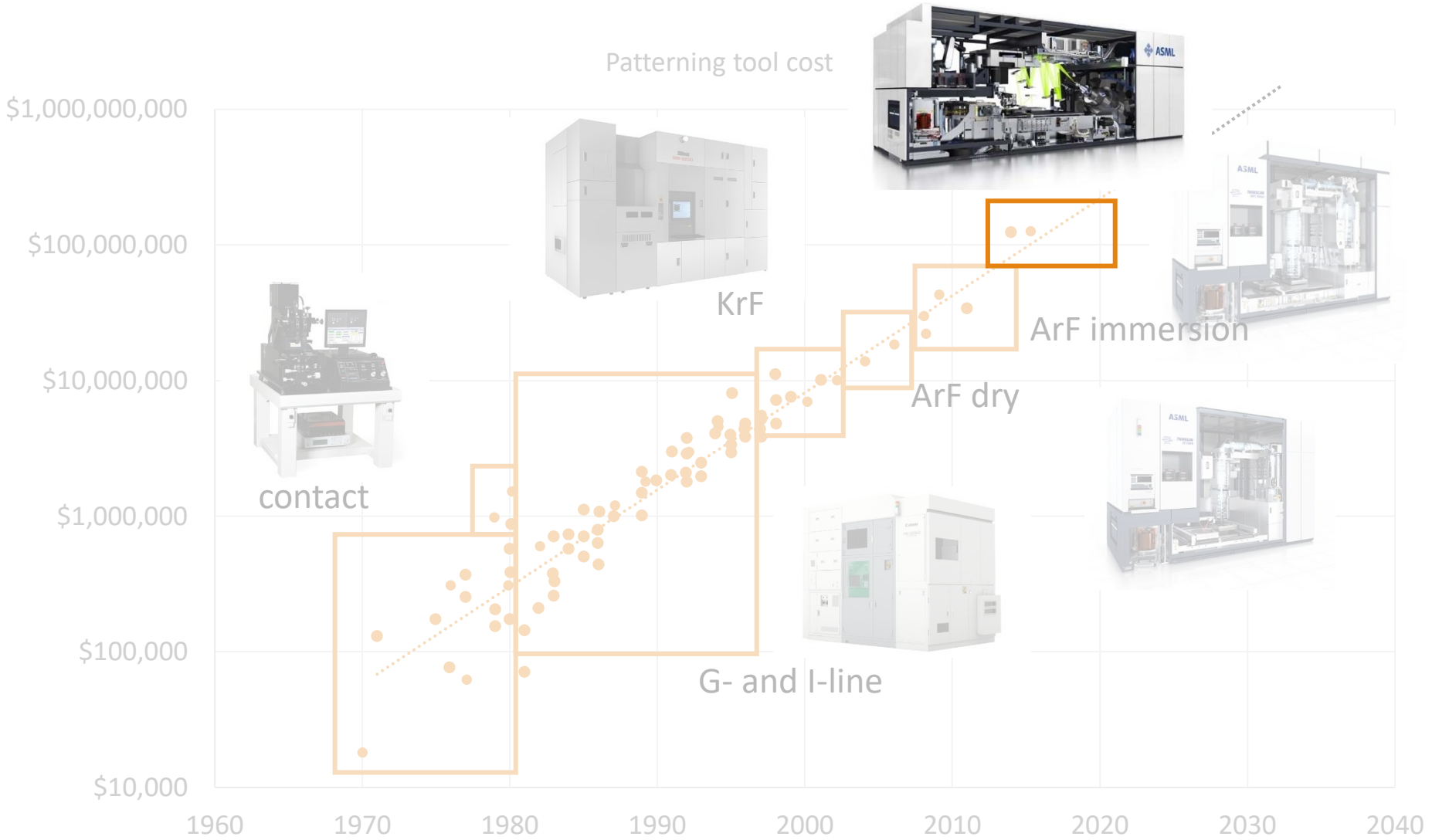
2010
2020
2030
2040

© Arm 2020

EUV: Extreme Ultra-Violet



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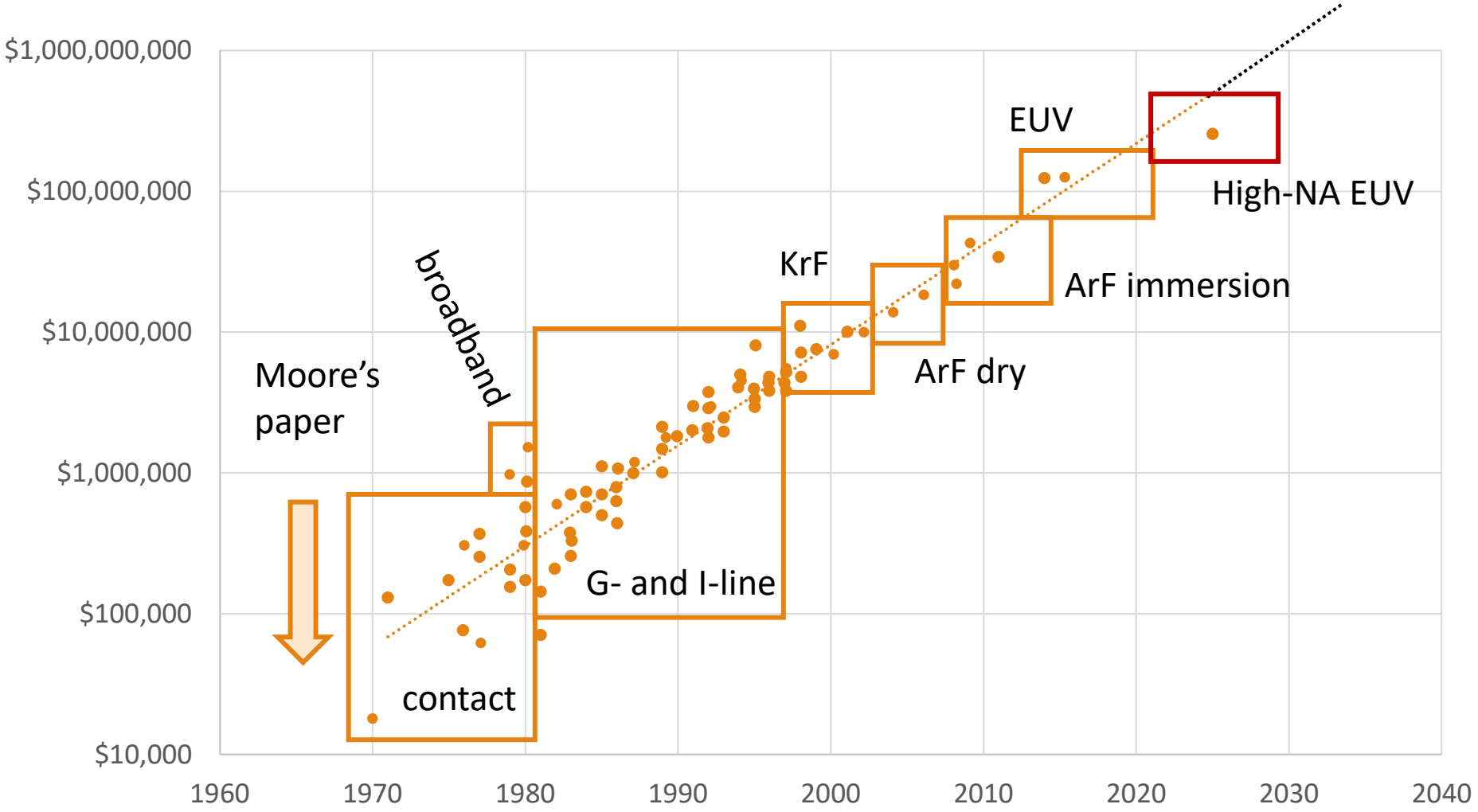

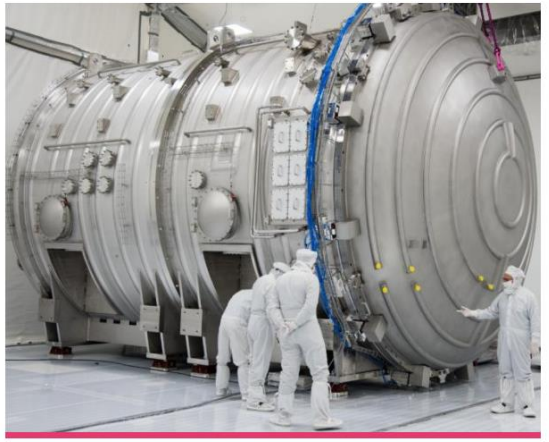

Zeiss will measure high-after-mirrors in this vacuum boiler. They are twice the size of their predecessors and twice more measurement accuracy is required. Source: Zeiss / ASML

See: Moore's 2nd Law, a.k.a. Rock's Law

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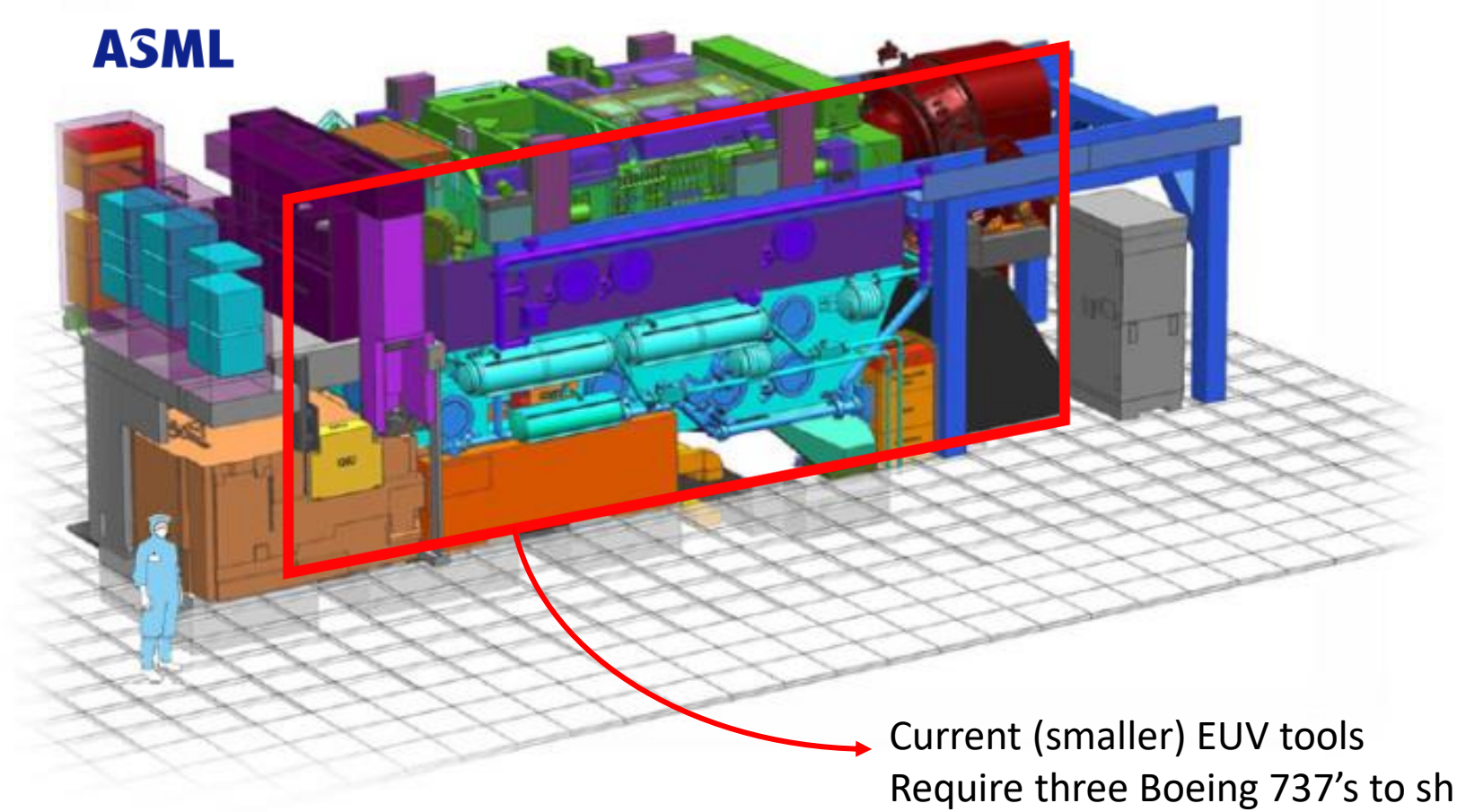
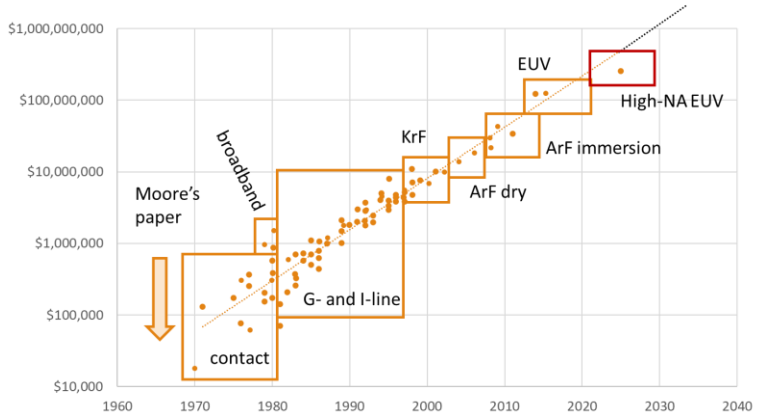
High-NA EUV: a bargain at $255M





Current (smaller) EUV tools
Require three Boeing 737's to ship

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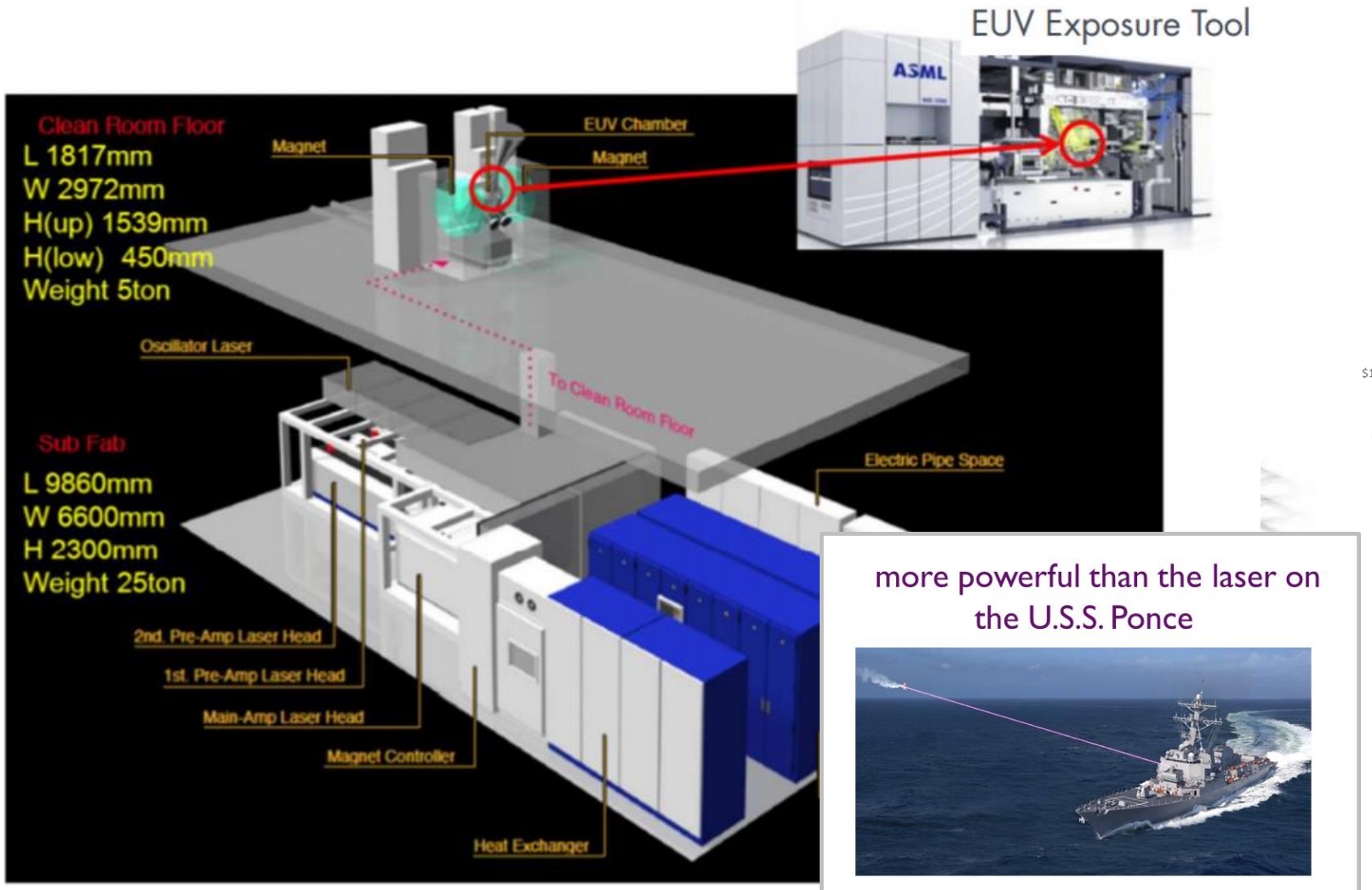
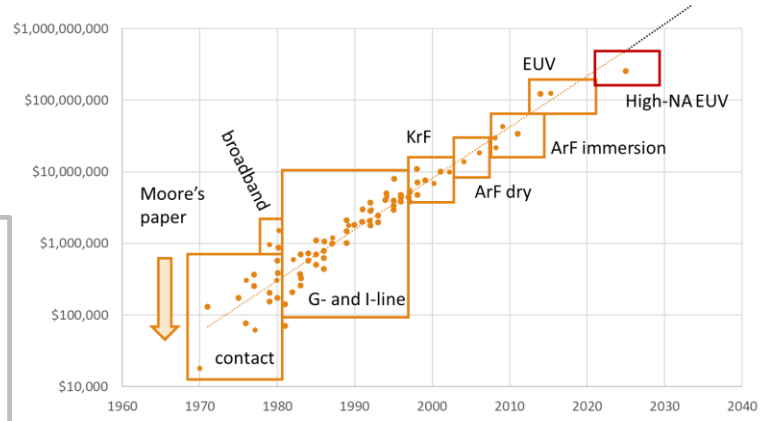
High-NA EUV: a bargain at $255M



more powerful than the laser on the U.S.S. Ponce



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What could come after high-NA EUV?

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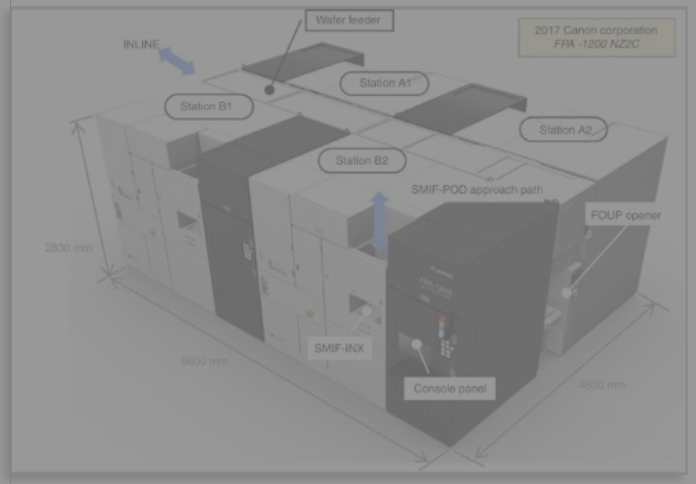
What could come after high-NA EUV?

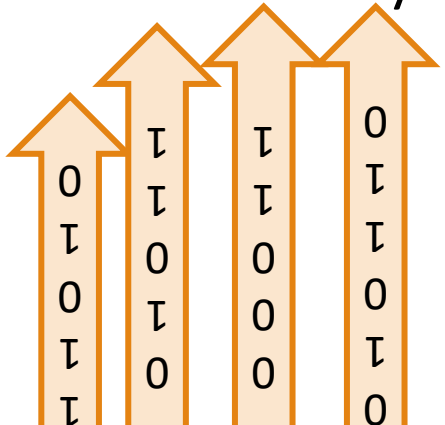
- 6nm EUV 2.0
- Nano-imprint



- e-beam writing

MULTIBEAM

- Self-Assembly



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DNA self-assembly

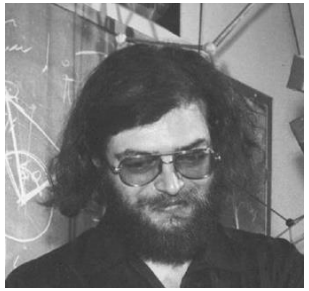
Design and self-assembly of two-dimensional DNA crystals

Erik Winfree*, Furong Liu†, Lisa A. Wenzler† & Nadrian C. Seeman†

* Computation and Neural Systems, California Institute of Technology, Pasadena, California 91125, USA
† Department of Chemistry, New York University, New York, New York 10003, USA

NATURE | VOL 394 | 6 AUGUST 1998

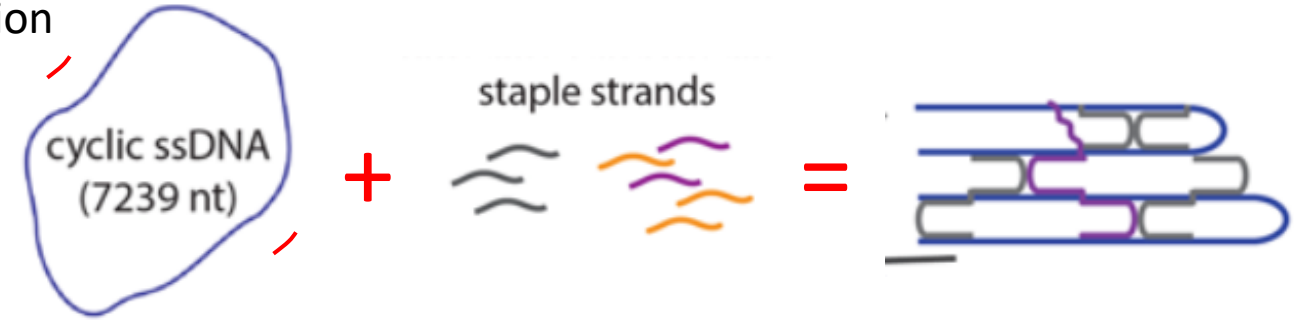
Eric Winfree

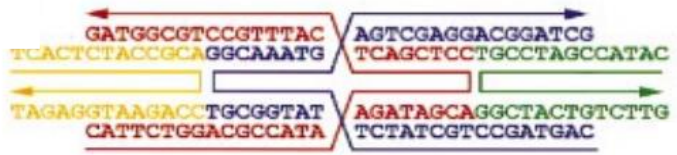


Nadrian Seeman

Paul Rothemund

Binding location





Folding DNA to create nanoscale shapes and patterns

Paul W. K. Rothemund

Nature **440**, 297–302 (2006) | Download Citation

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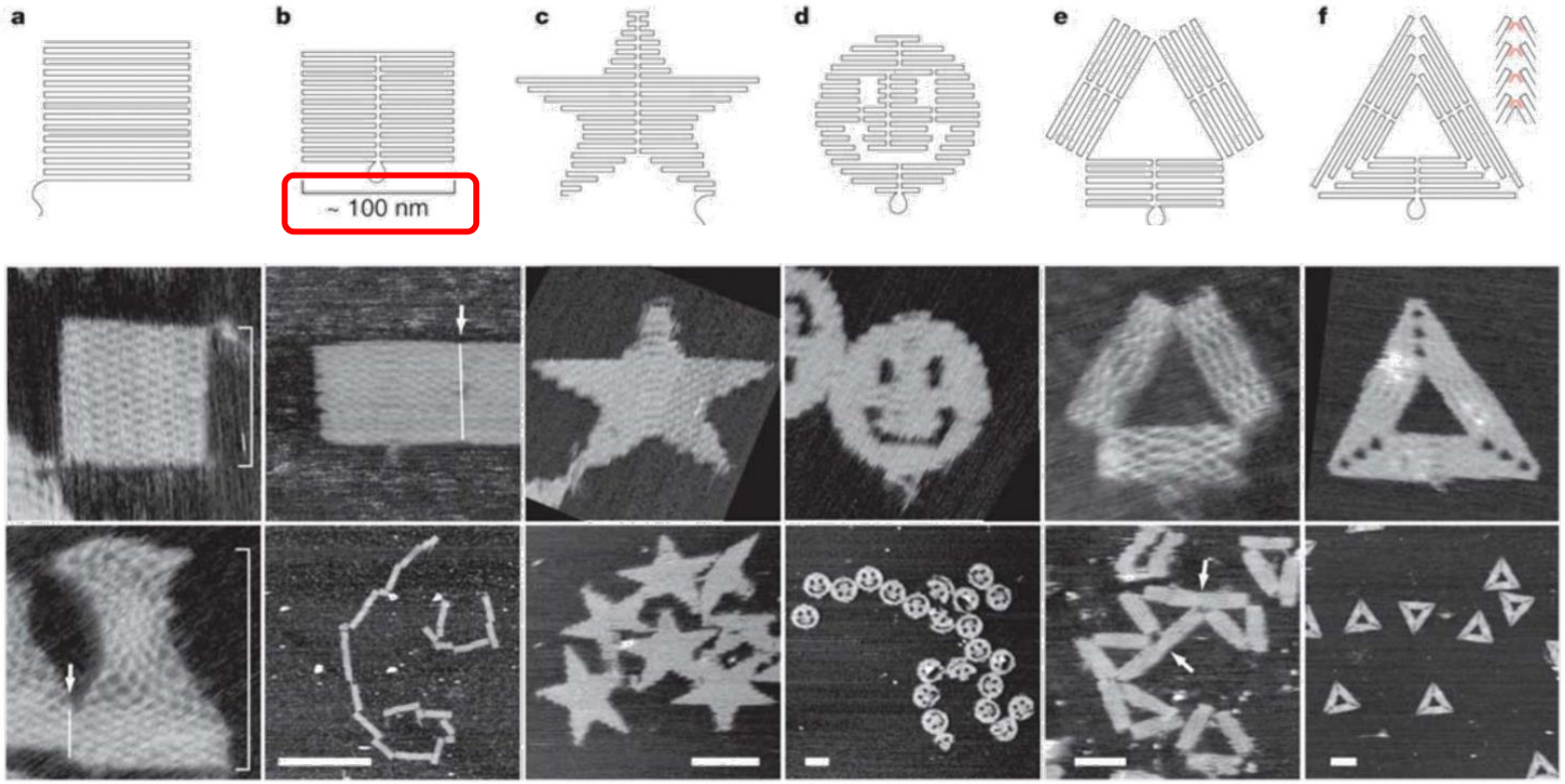
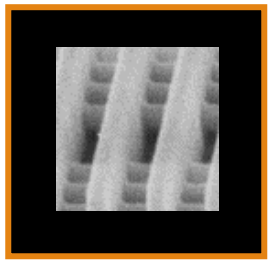
“DNA Origami” tiles





3nm transistors

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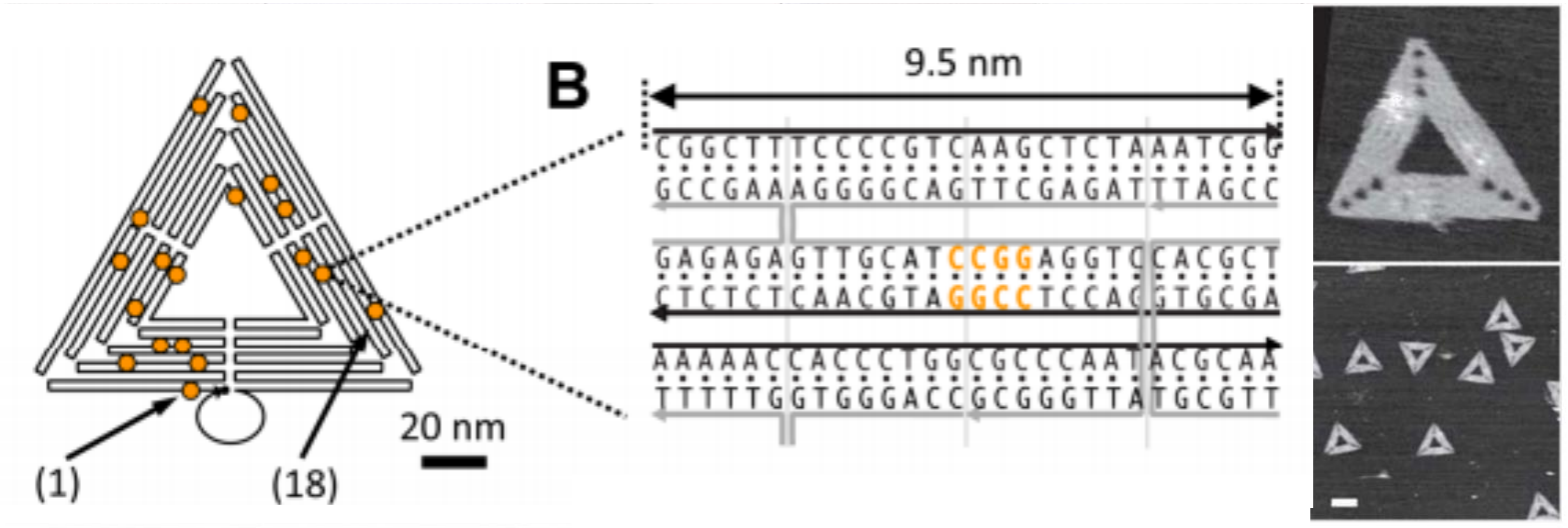
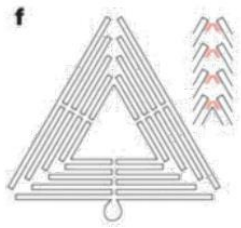
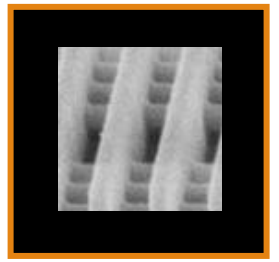
“DNA Origami” tiles

3-5nm precision placement

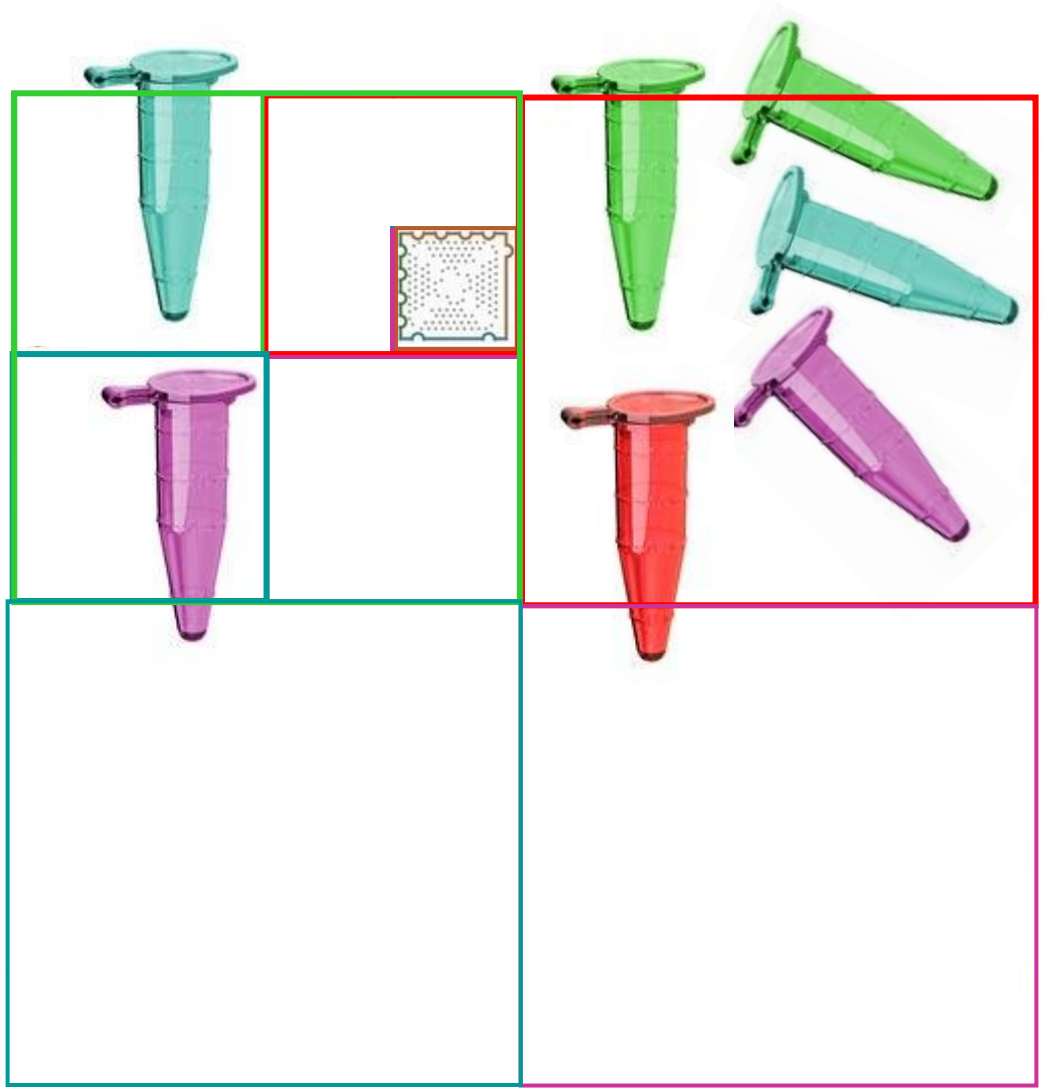


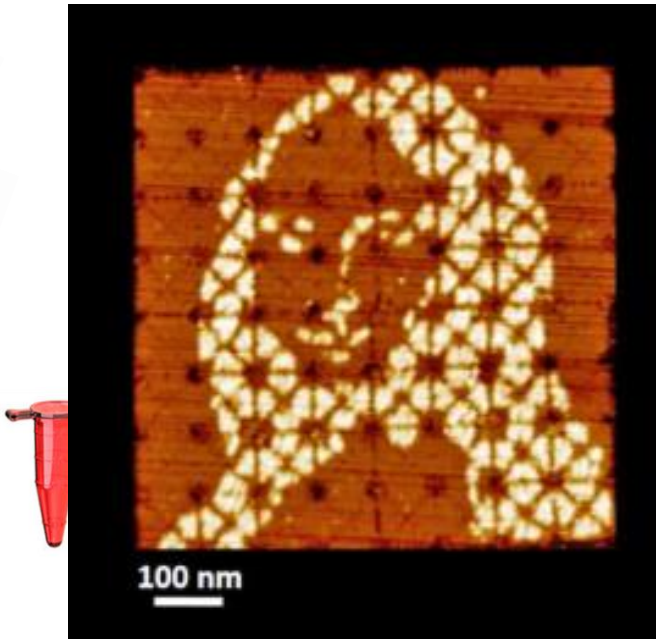


~2
3nm transistors



Fractal assembly of DNA origami





Lulu
Qian

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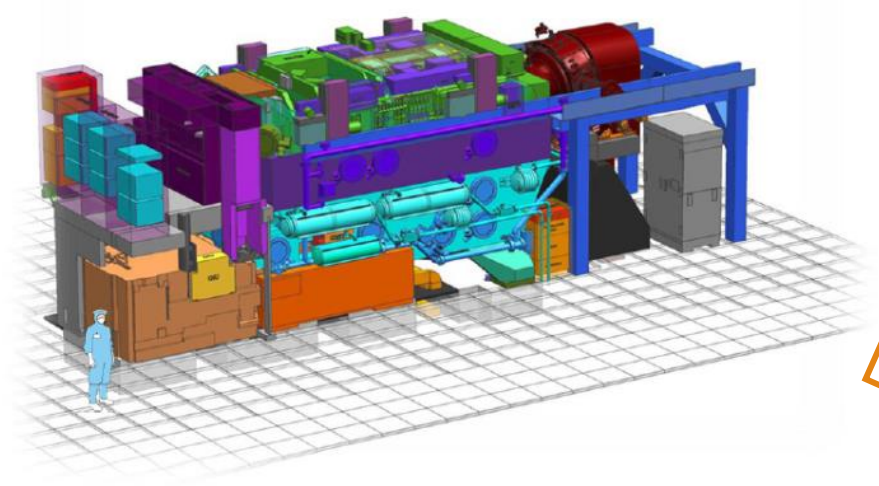
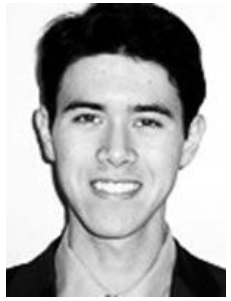
Fractal tiling of DNA origami

$255M



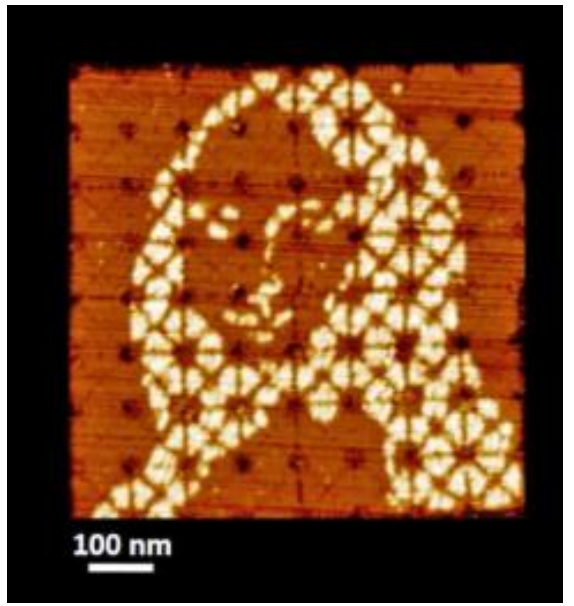
Grigory Tikhomirov

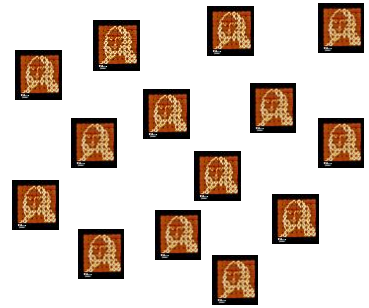


Philip Petersen

	A	B
1	Oligo name 1	ACG TGA TCT AAG TCA AAG TCA
2	Oligo name 2	ACG AAG TCA TGA TCT AAG TCA
3	Oligo name 3	ACG TGA AAG TCA TCT TGA AAG
4	Oligo name 4	ACG TGA TCT AAG TCA AAG TCA
5	Oligo name 5	ACG TGA TCT AAG TGA AAG TCA
6	Oligo name 6	ACG TGA TGA AAG TCT AAG TCA AAG TCA
7	Oligo name 7	ACG TGA TCT AAG TCA TTT TGA AAG
8	Oligo name 8	ACG TGA TCT AAG TCA GAG TTT
9	Oligo name 9	ACG AAG TGA TCT AAG TCA

$20





20 nano-cents

http://qianlab.caltech.edu/FracTileCompiler/

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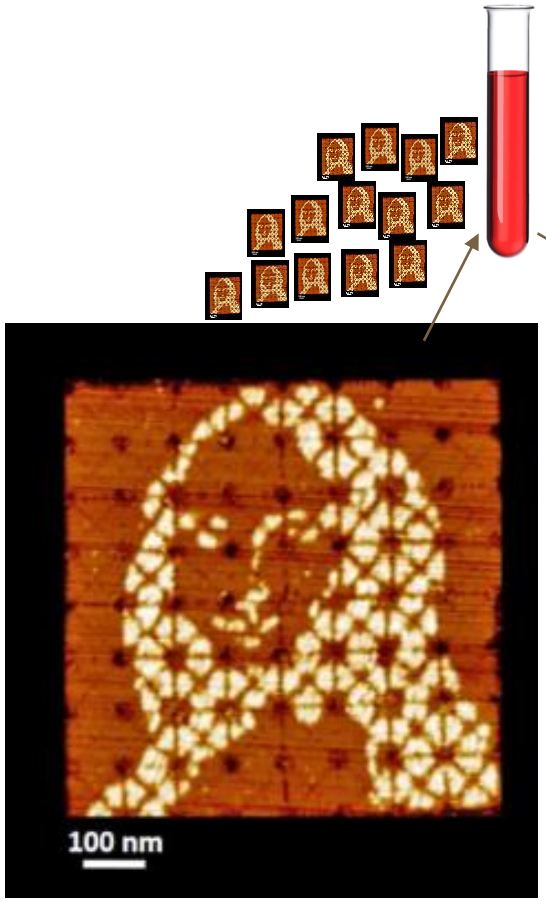
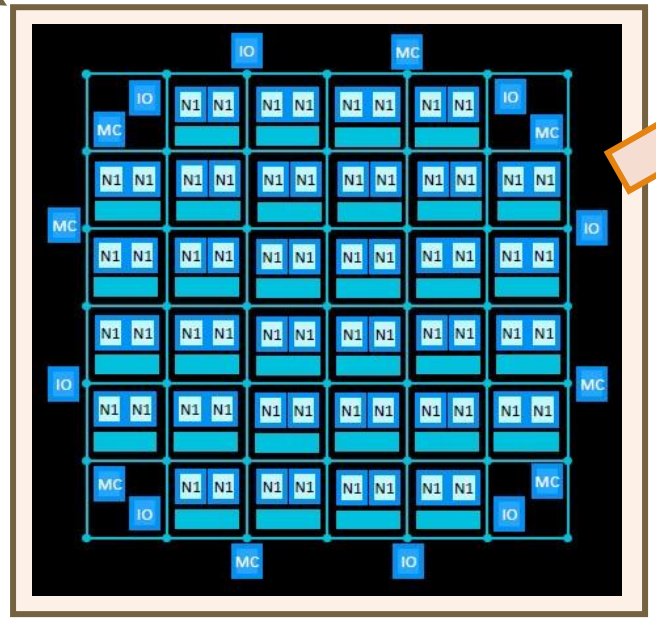
Fractal tiling of DNA origami



NEOVERSE N1

64 cores at 7nm:

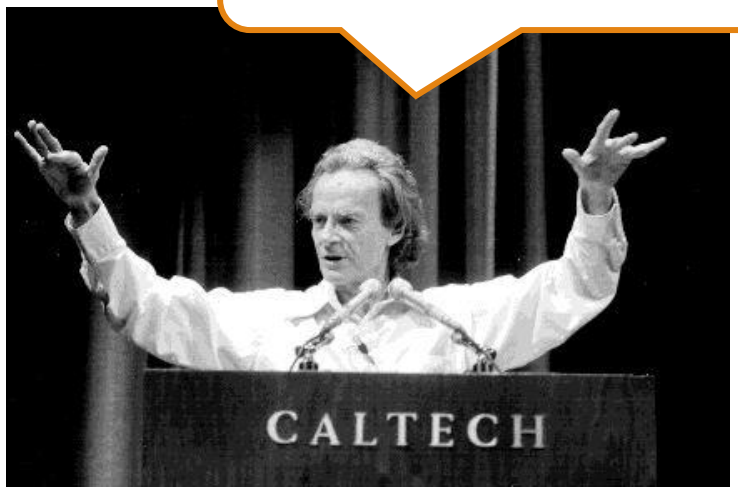
20mm



20mm

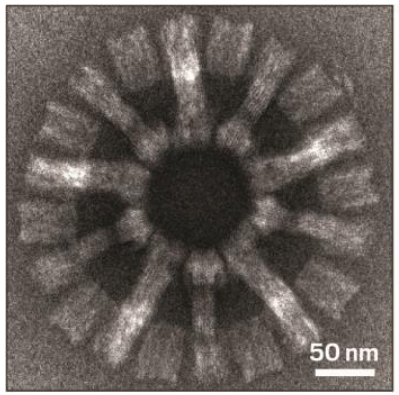
2mm x 2mm

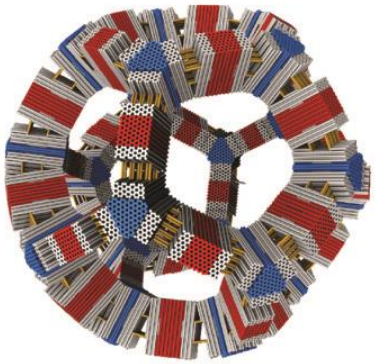
There's plenty of room at the bottom! (1959)



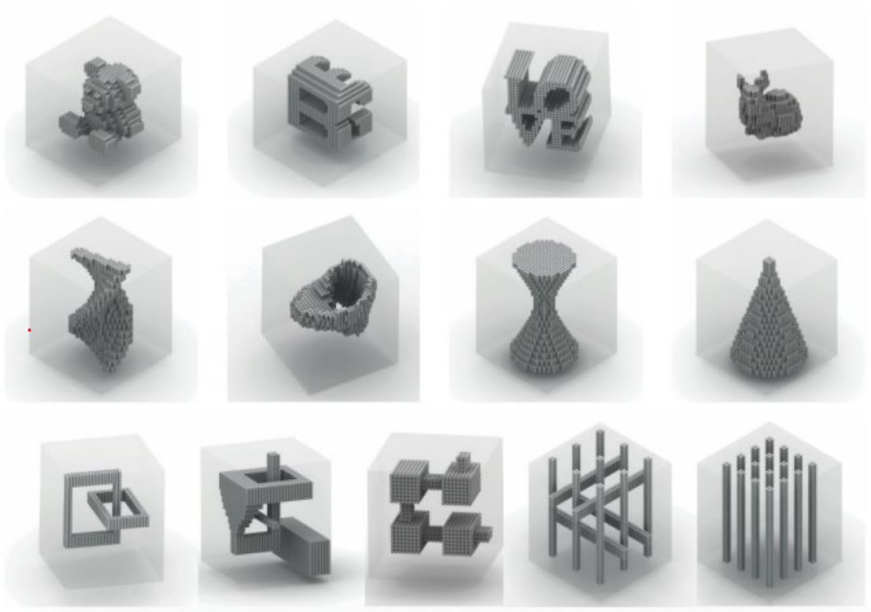
DNA origami doesn’t need to be 2D

Self-assembling dodecahedron (90% yield)
TU Munich





DNA bricks with programmable 3D pixels (voxels):
2.5 x 2.5 x 2.7 nm
Harvard



130µm x 130µm x 130µm

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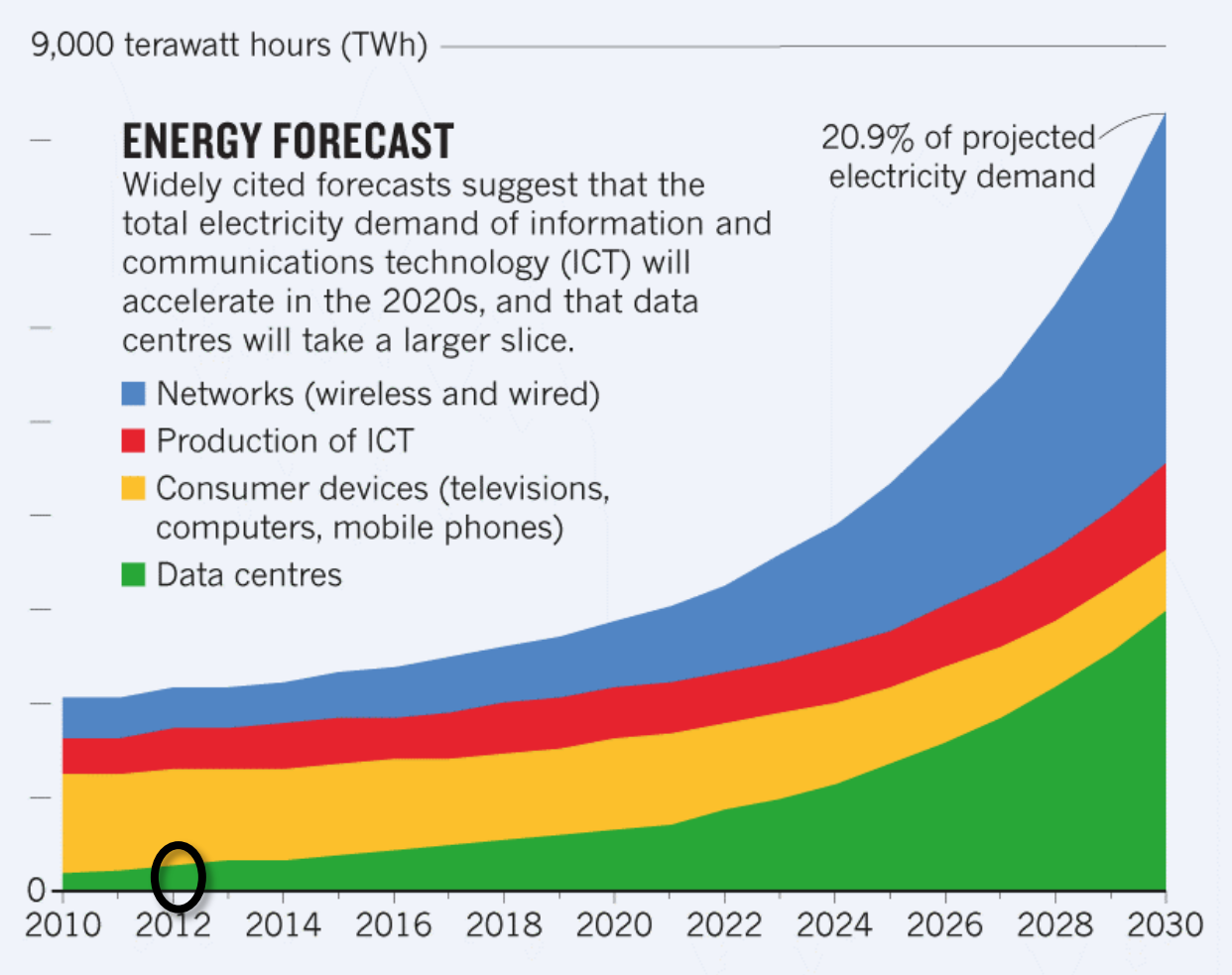
2012: DNN wins ImageNet competition



https://www.nature.com/articles/d41586-018-06610-y

Alex Krizhevsky

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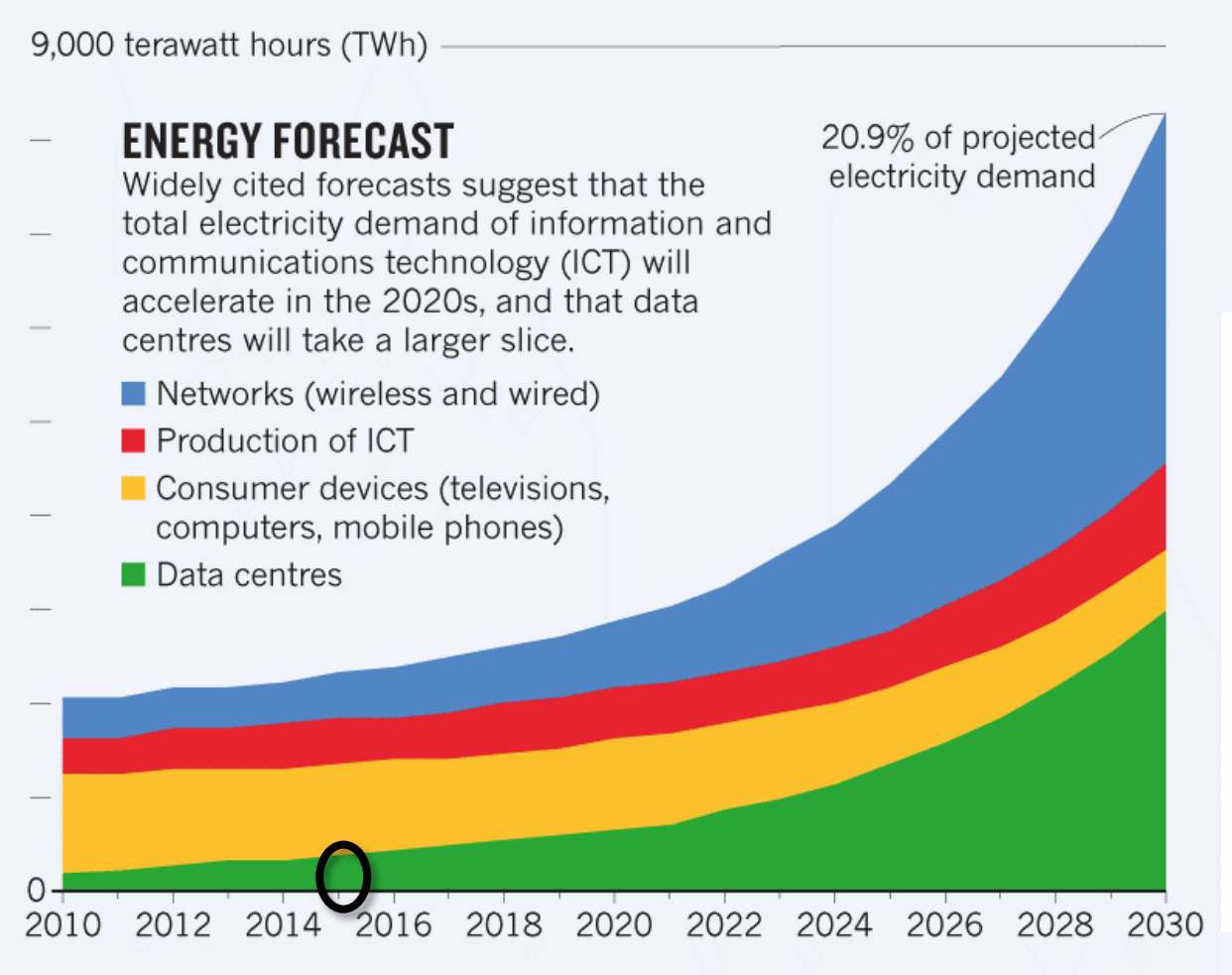
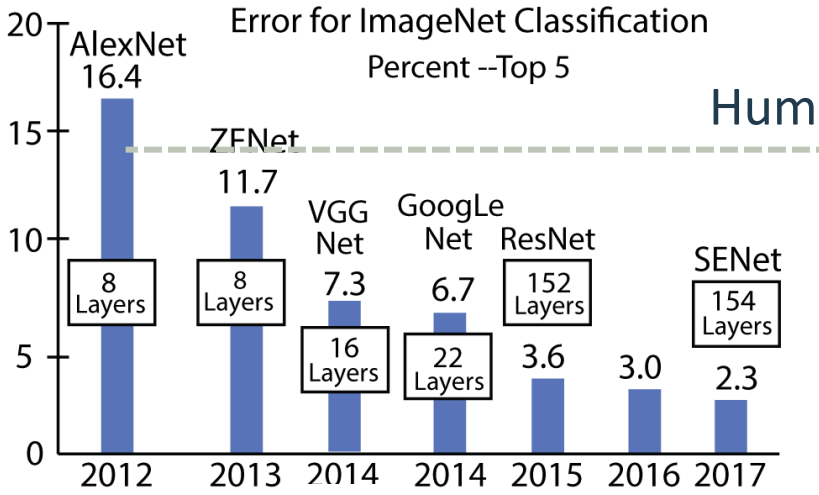
2015: ResNet more accurate than people



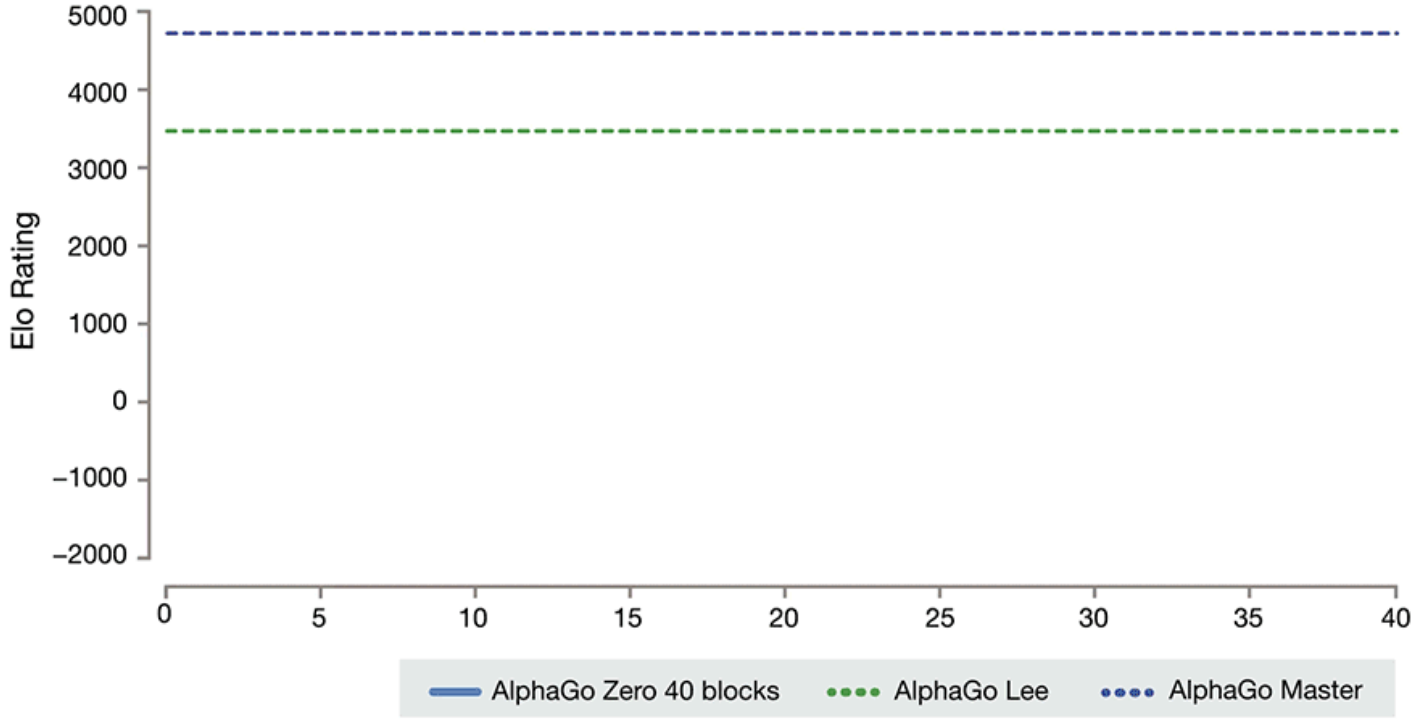
https://www.nature.com/articles/d41586-018-06610-y



ResNet training: 10,000 PF
29 hours using 8 Tesla P100 GPUs
(300W each, so 70kWh total)

© Arm 2020

With $25M hardware, you can play 4.9 million games in 3 days



5000 TPU v1's
40W each

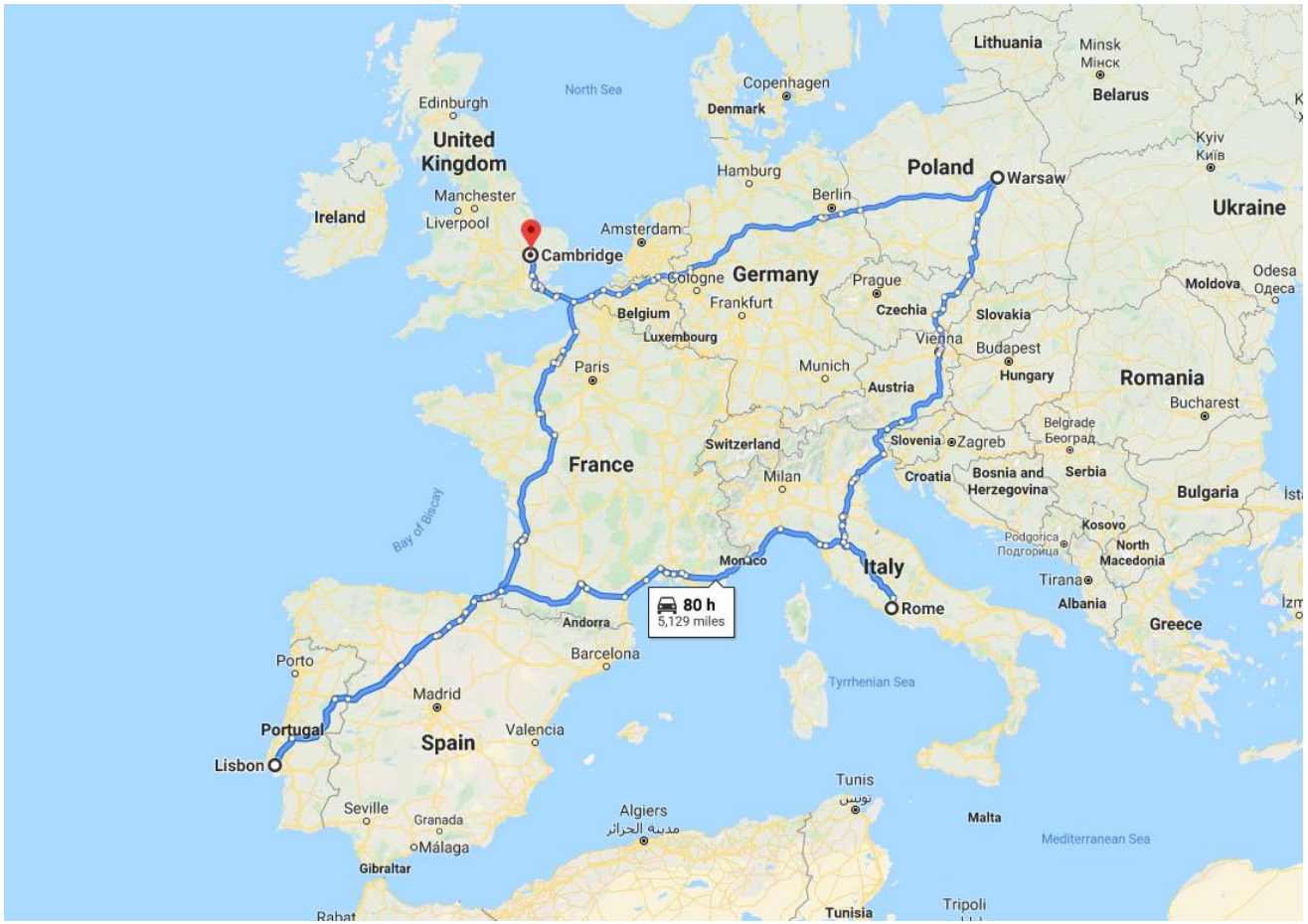
feeding
64 TPU v2's
124W each

40 days

= 216 MWh

© Arm 2020

For the equivalent energy of training AlphaGo:



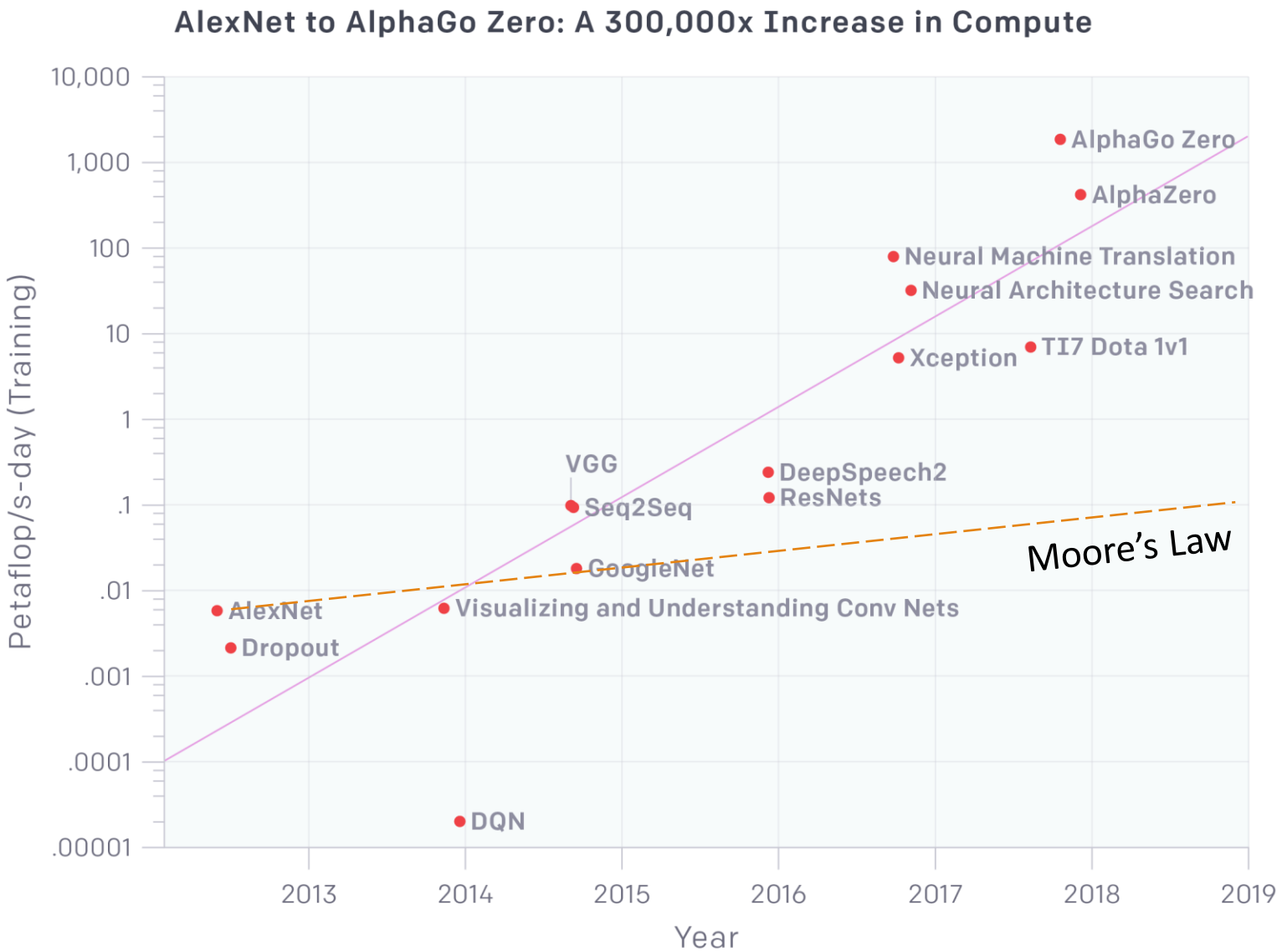
Cambridge to Lisbon to Rome to Warsaw back to Cambridge

(then 146 more loops)

(or power 23 homes for a year)

(or fly for 1000 hours)

© Arm 2020



https://openai.com/blog/ai-and-compute/

This is 7x/year

(and data are actually beyond linear)

If this were to continue,
a quantum computer
in 2029 would be
competing with
2.8e11 PFs-day

280 Yottaflops-day

© Arm 2020

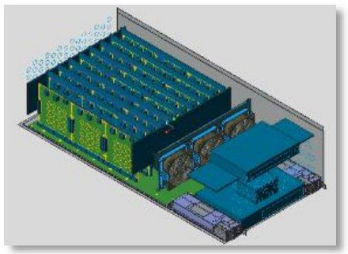
Progress in ~~neuromorphic~~ computing brain inspired

Q4 2017
Wolf Mountain
Remote Access
4 Loihi/Board

Q2 2018
Nahuku
Arria10 Expansion Board
For cloud & local use
8-32 Loihi/Board

Q3 2018
Kapoho Bay
1-2 Loihi
DVS interface
USB host interface

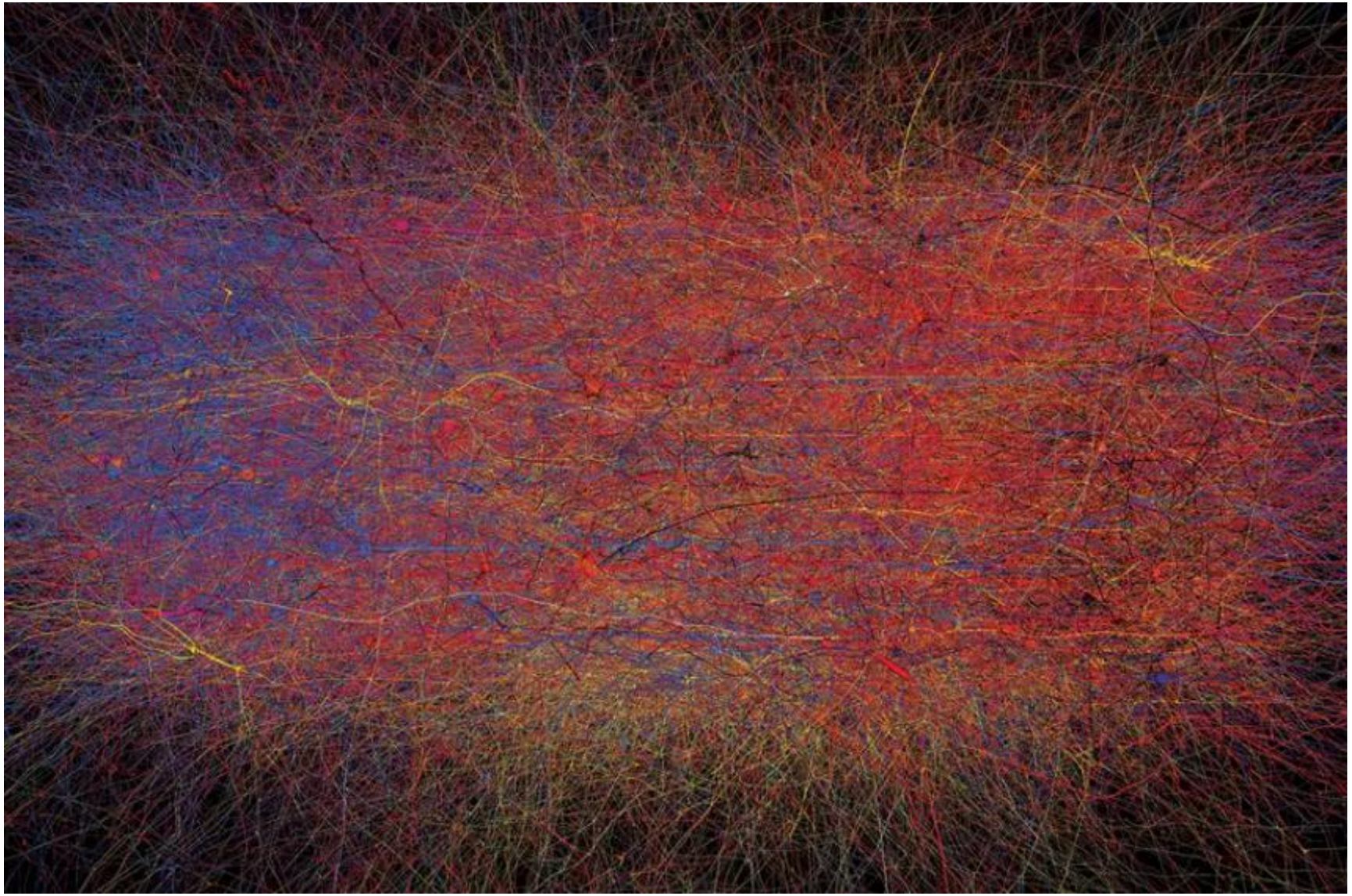
Q2 2019
Pohoiki Springs
Remote Access
Up to 768 chips
(100M neurons)



Intel

© Arm 2020

The “connectome”



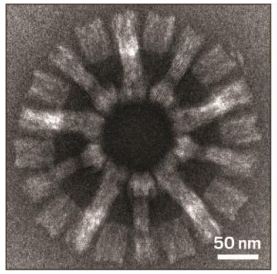
The Blue Brain Project (BBP/EPFL)

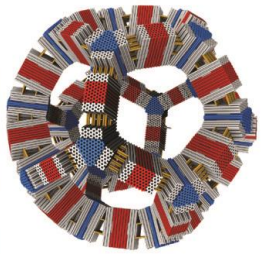
Mouse Brain ~70m neurons

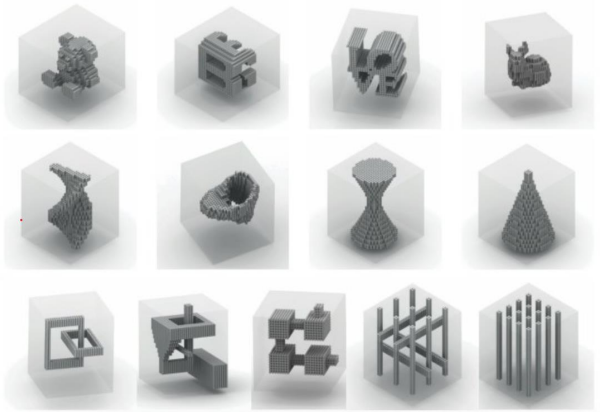
But number of synapses in cerebral cortex 60 trillion

100 - 100,000 inputs per neuron

© Arm 2020







Mukesh Khare
Vice President: IBM Systems Research

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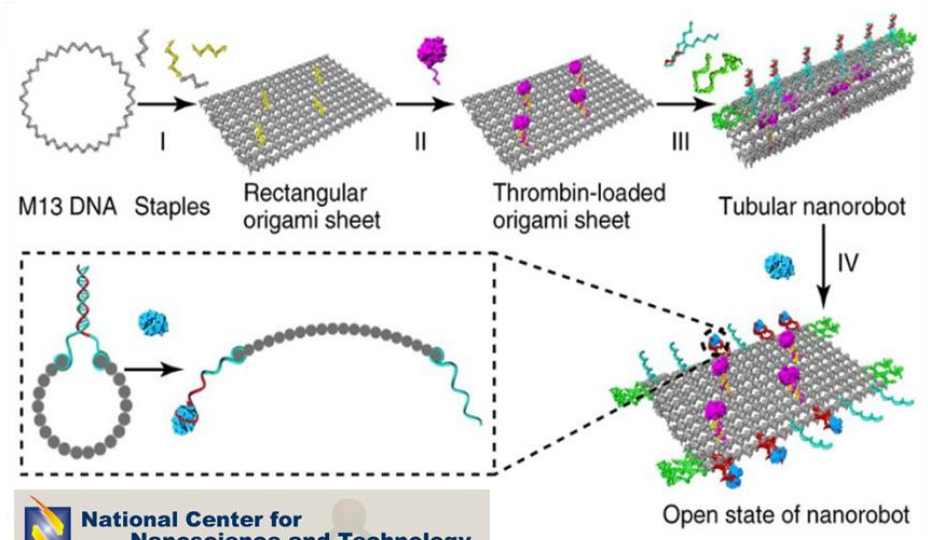
DNA origami doesn't need us

nature biotechnology

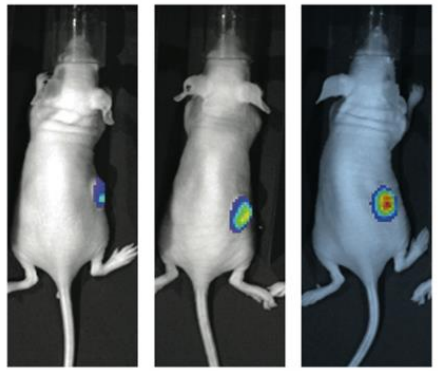
A DNA nanorobot functions as a cancer therapeutic in response to a molecular trigger *in vivo*

Letter | Published: 12 February 2018

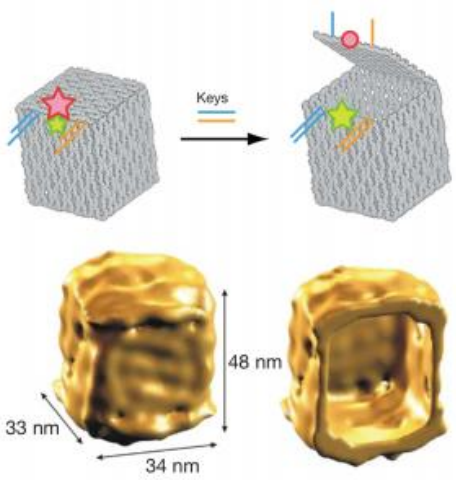


National Center for Nanoscience and Technology

Massachusetts Institute of Technology



Danmarks Grundforskningsfond
Danish National Research Foundation



Energy and Delay scaling

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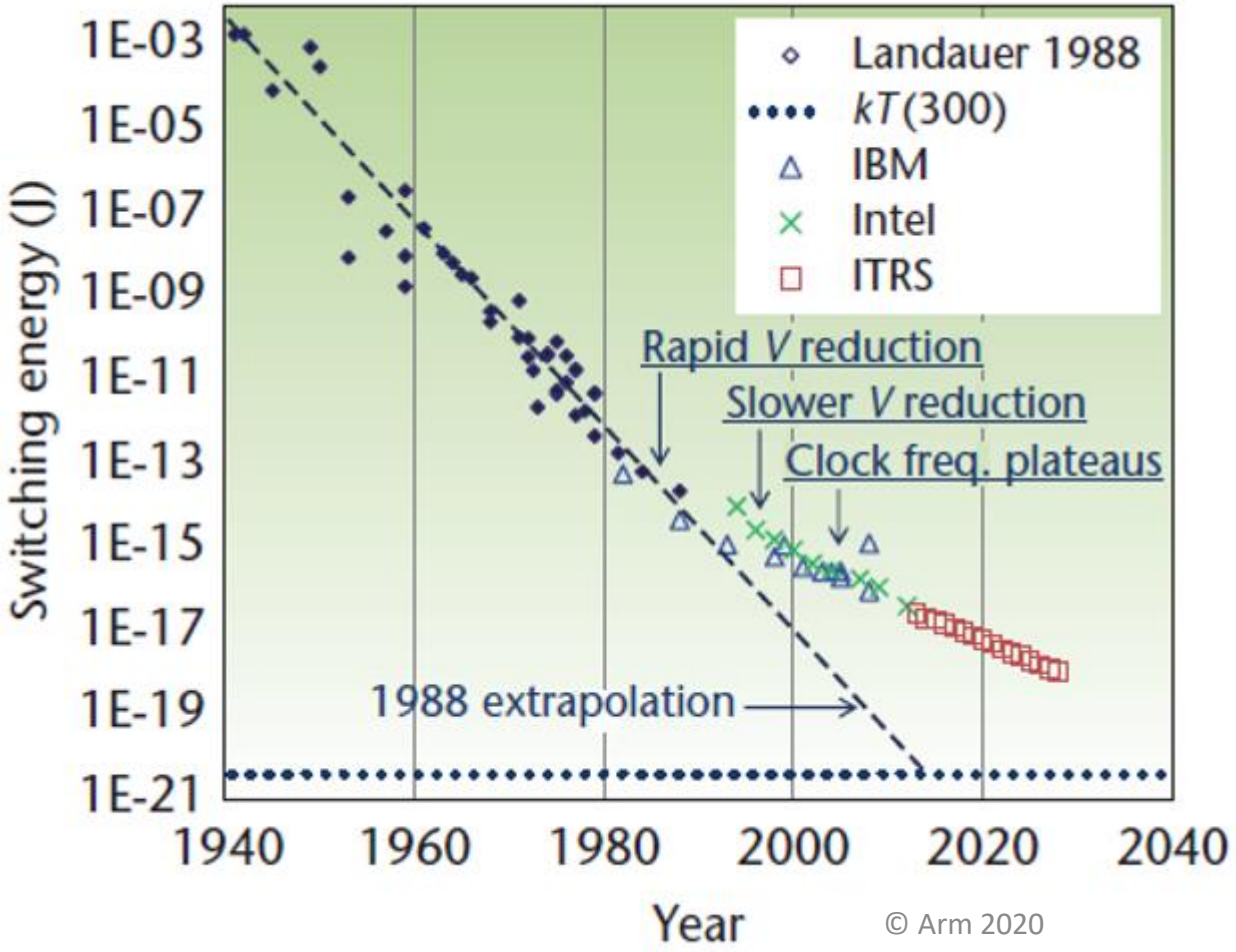
Energy efficient computing and sensing in the Zettabyte era: from silicon to the cloud

IEDM 2017

Adrian M. Ionescu
[1]Nanolab, Ecole Polytechnique Fédérale de Lausanne, Switzerland, email: adrian.ionescu@epfl.ch



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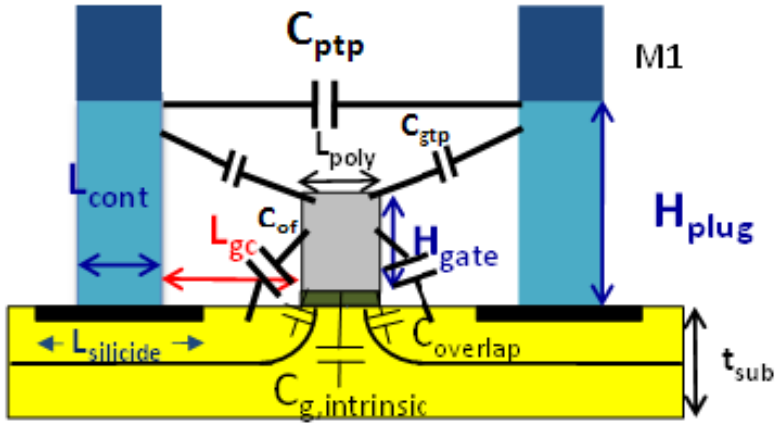
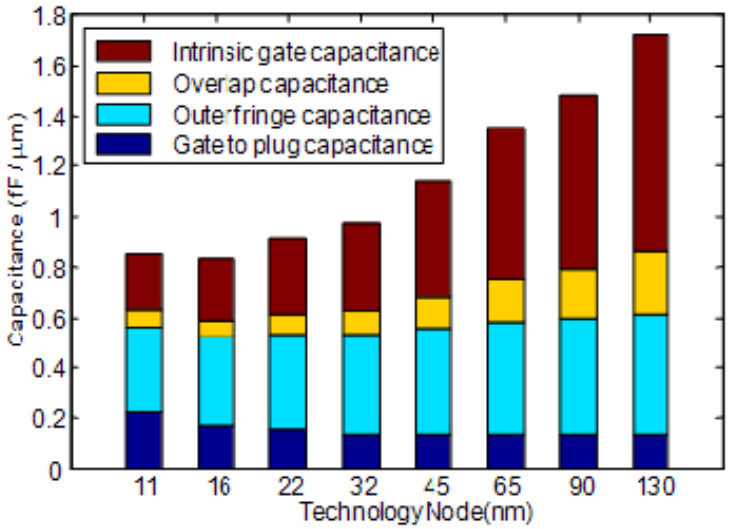
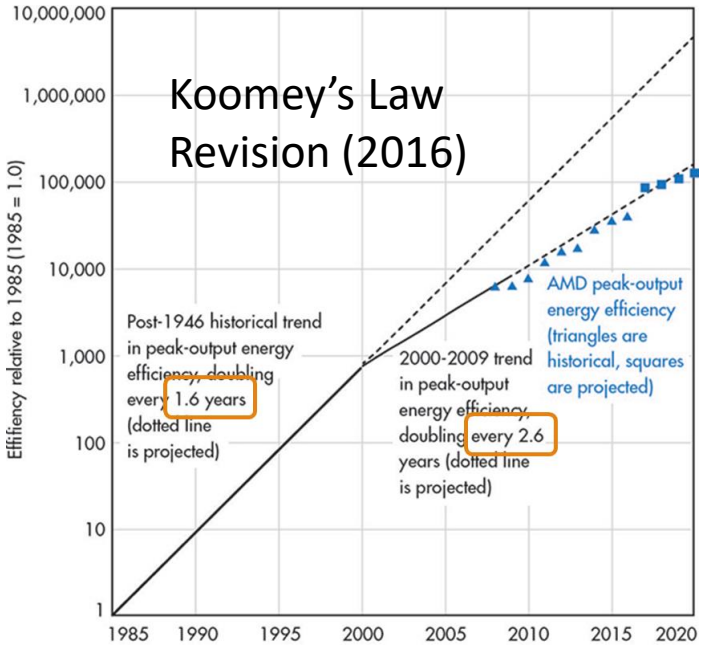
Keynote: Semiconductor Technology: A System Perspective ▶

DR. H. -S. PHILIP WONG
Chief Scientist
Taiwan Semiconductor Manufacturing Company Limited



HS Wong, et al., SISPAD 2009





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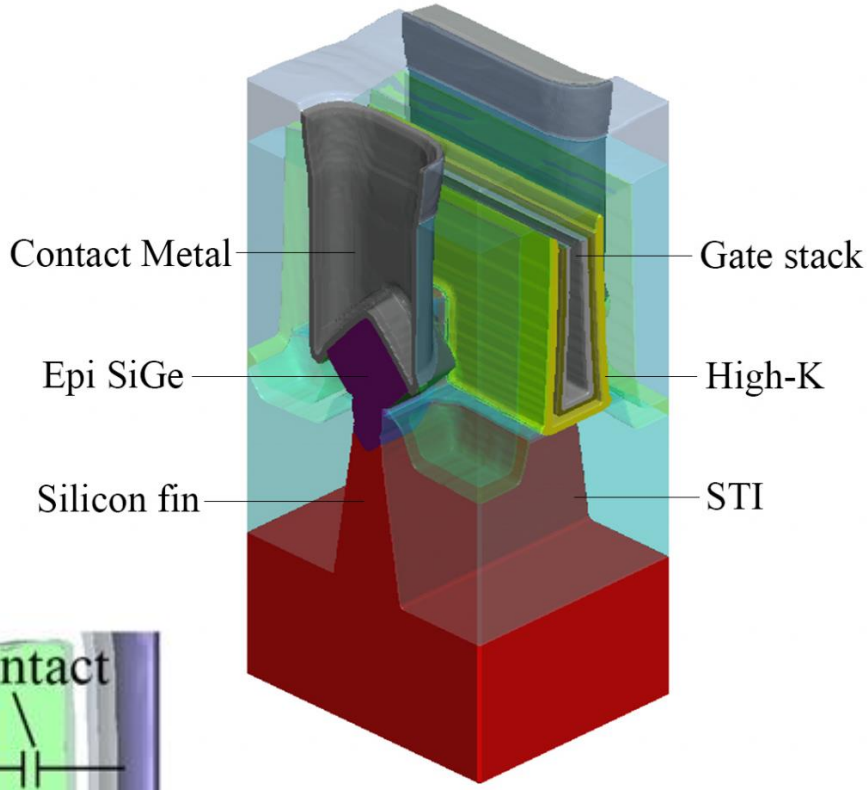
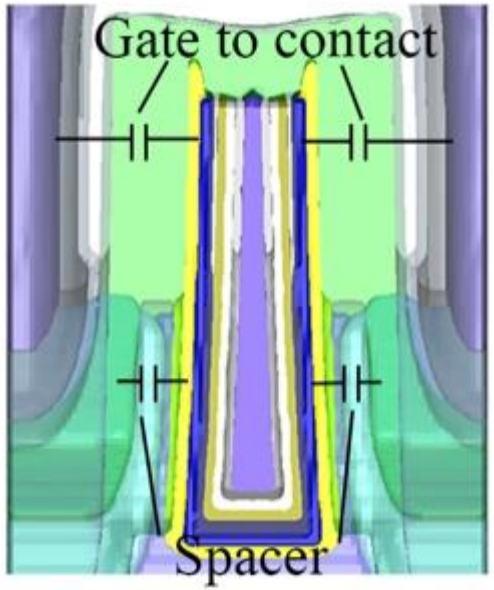
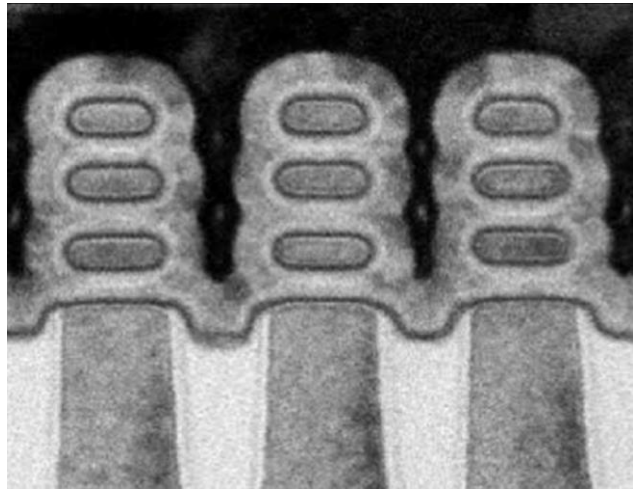




Jacky Huang
coventor.com



https://semiengineering.com/whats-after-finfets/

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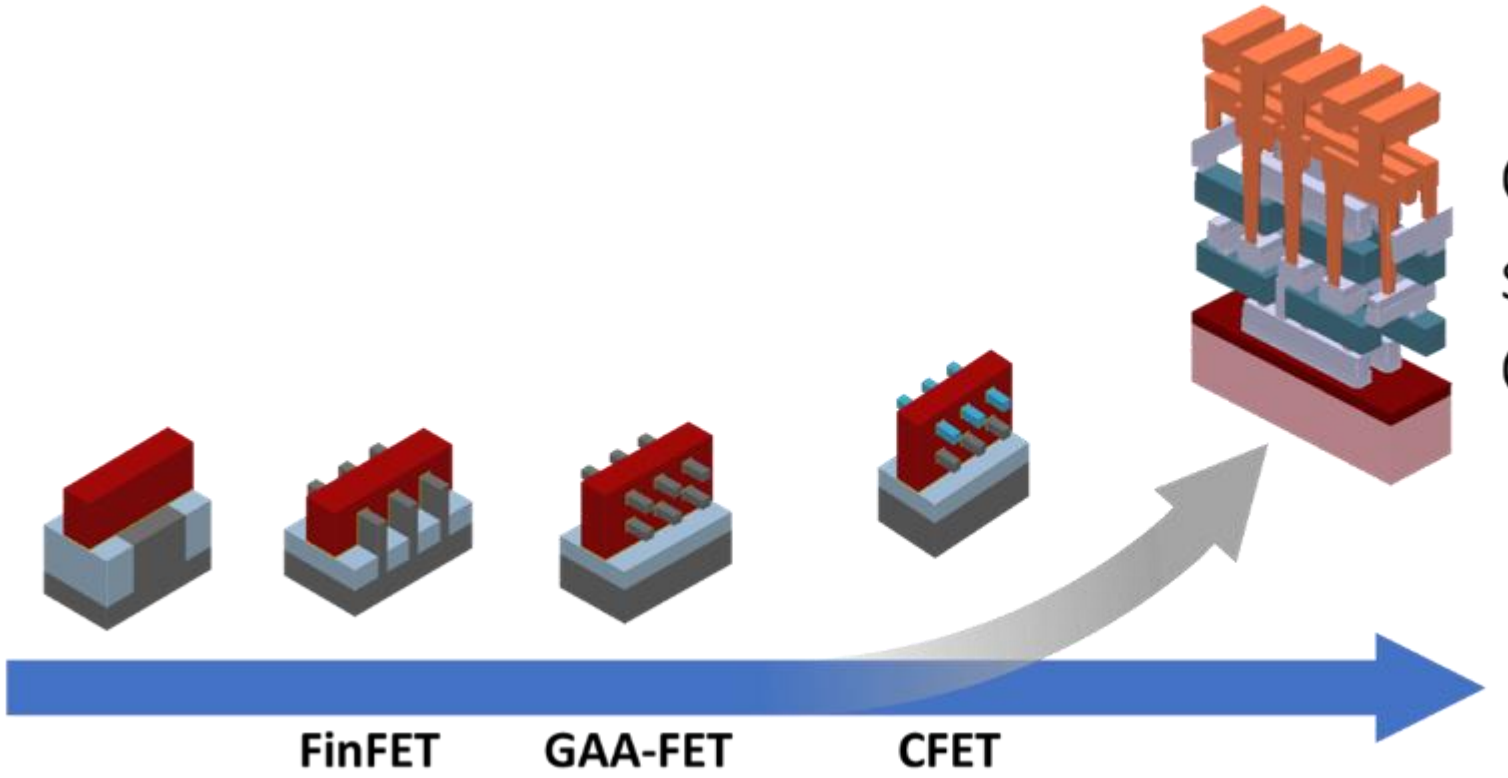
Multi-layer transistor roadmap



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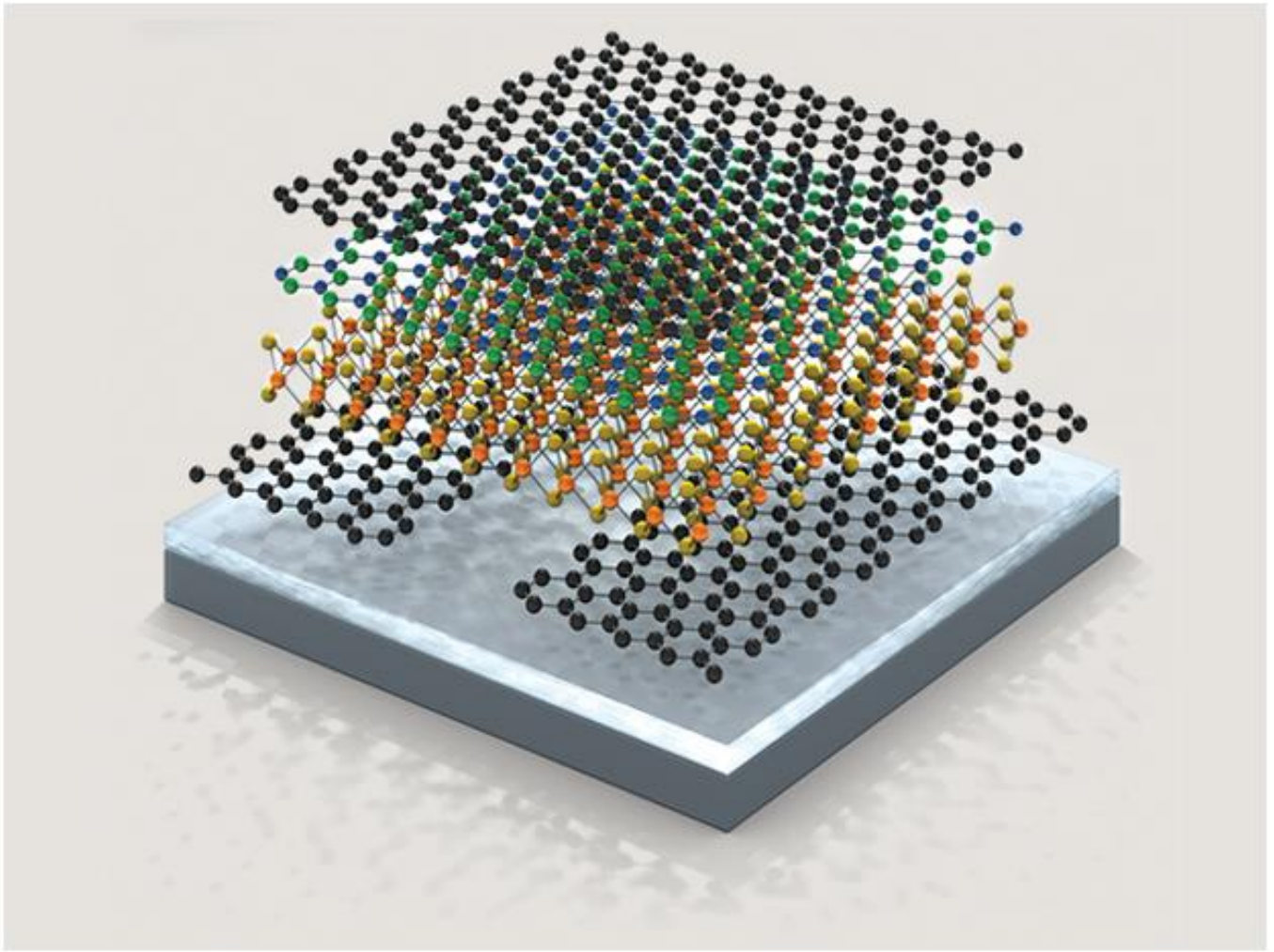


Illustration: Emily Cooper

Transistors Made From 2-D Materials Promise New Class of Electronic Devices

The impact of field-effect transistors made entirely from 2-D materials begins to take shape

By **Dexter Johnson**

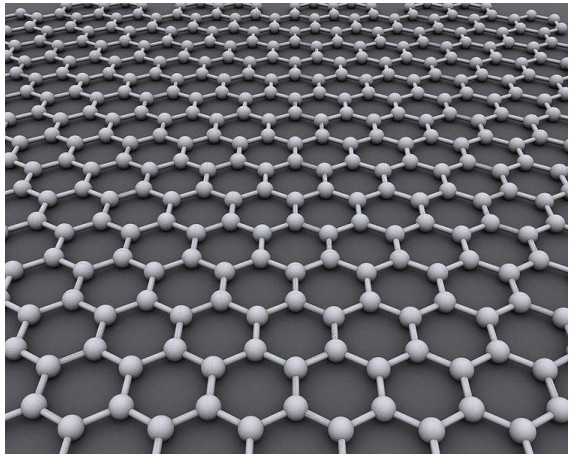
IEEE SPECTRUM

© Arm 2020

Whatever happened to graphene?

Andre Geim

Konstantin Novoselov



2004:  +  = 2010 Nobel Prize 

Band Gap 0V: not a good semiconductor

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51 new 2D semiconductors from one paper

2018

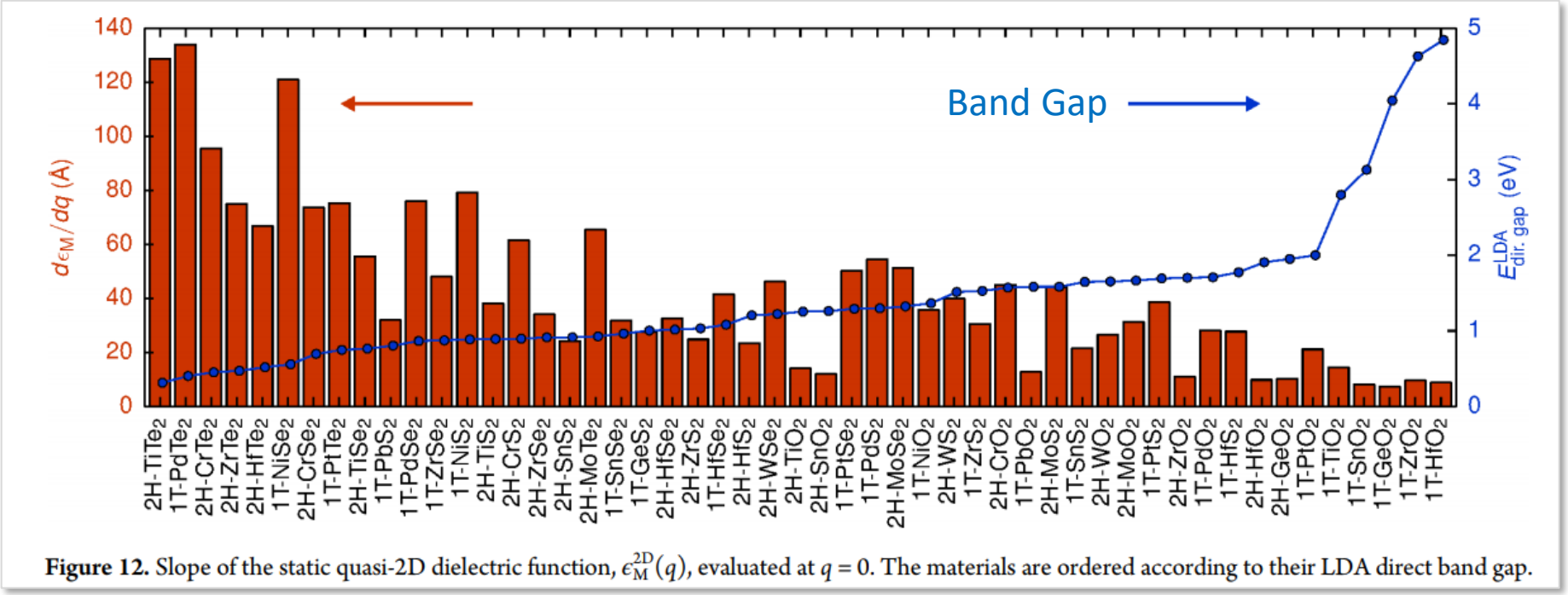

Figure 12. Slope of the static quasi-2D dielectric function, $\epsilon_M^{2D}(q)$, evaluated at $q = 0$. The materials are ordered according to their LDA direct band gap.

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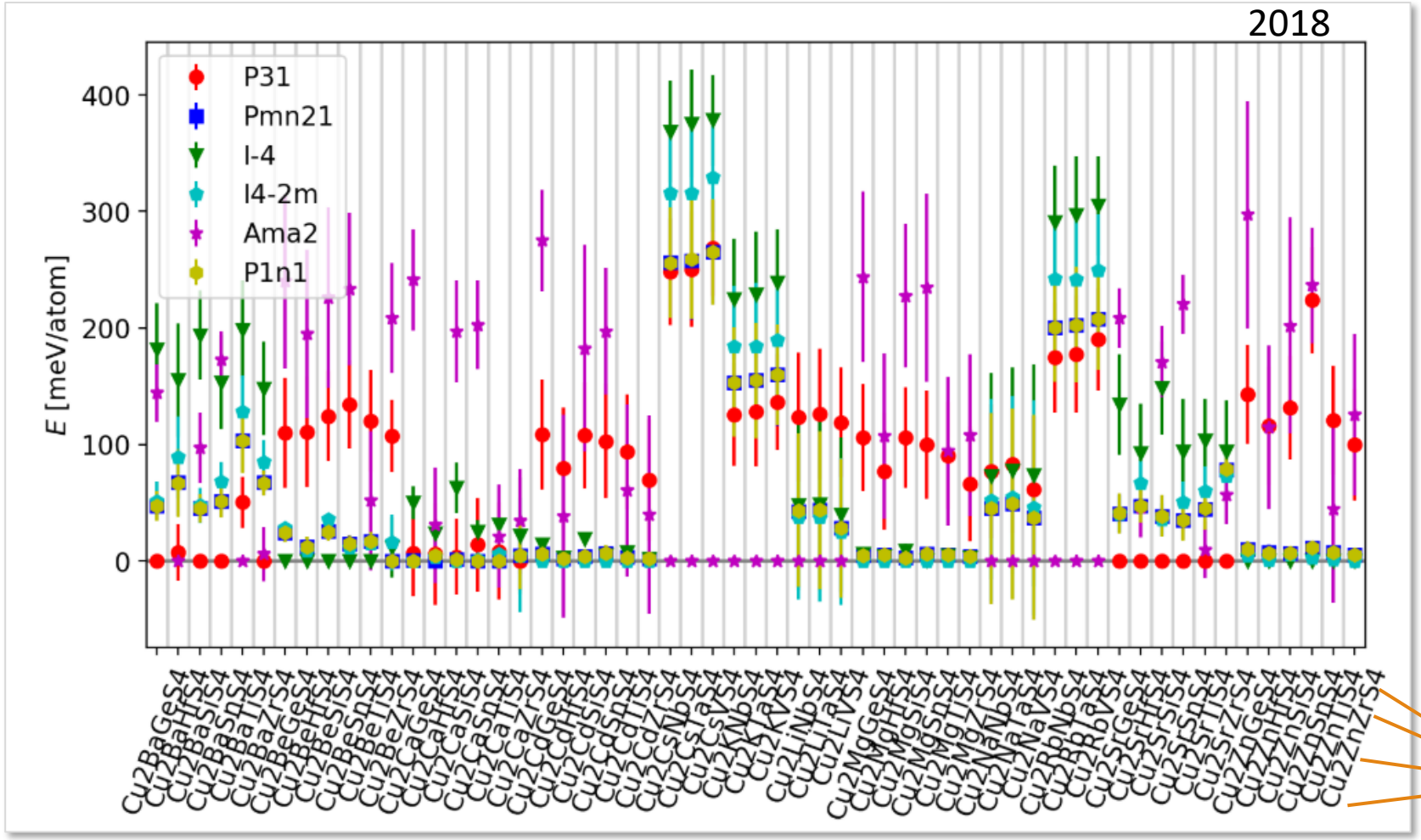
57 new *quaternary** 2D semiconductors



*quaternary: 4 different elements

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The wave of computational materials

THE JOURNAL OF PHYSICAL CHEMISTRY C
Article
pubs.acs.org/JPCC

Computational 2D Materials Database: Electronic Structure of Transition-Metal Dichalcogenides and Oxides

Filip A. Rasmussen and Kristian S. Thygesen*

Center for Atomic-scale Materials Design (CAMD), Department of Physics, and Center for Nanostructured Graphene (CNG), Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark

Promising quaternary chalcogenides as high-band-gap semiconductors for tandem photoelectrochemical water splitting devices: A computational screening approach

Mohnish Pandey and Karsten W. Jacobsen
Phys. Rev. Materials **2**, 105402 – Published 9 October 2018

```
from gpaw.response.gwqeh import *

gspath = '../1/gs/gs_full-hBN.gpw'

GWQEH = GWQEHCorrection(calc=gspath,
                        structure=['hBN',
                                   'graphene'],
                        d = [3.326],
                        gwfile='../1/GW/gw-hBN_results.pckl',
                        bands=(3,5),
                        filename='gwqeh-hBN-graphene',
                        domega0=0.1,
                        omega2=10,
                        include_q0=False
                        )

qp = GWQEH.calculate_qp_energies()
```

1998 Nobel Prize

- DFT: Density Functional Theory (Walter Kohn)
- Computational methods in quantum chemistry (John Pople)

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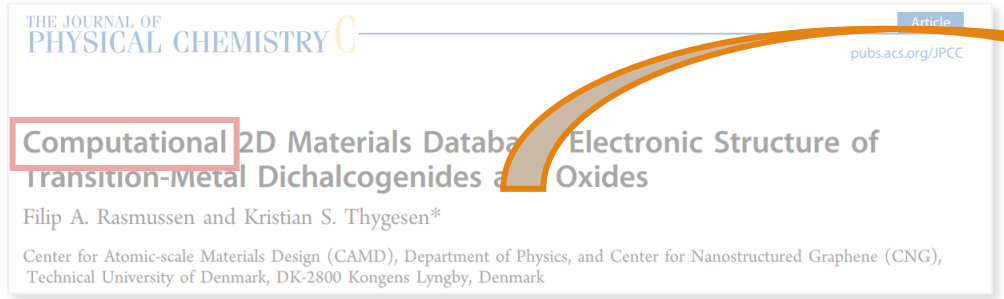
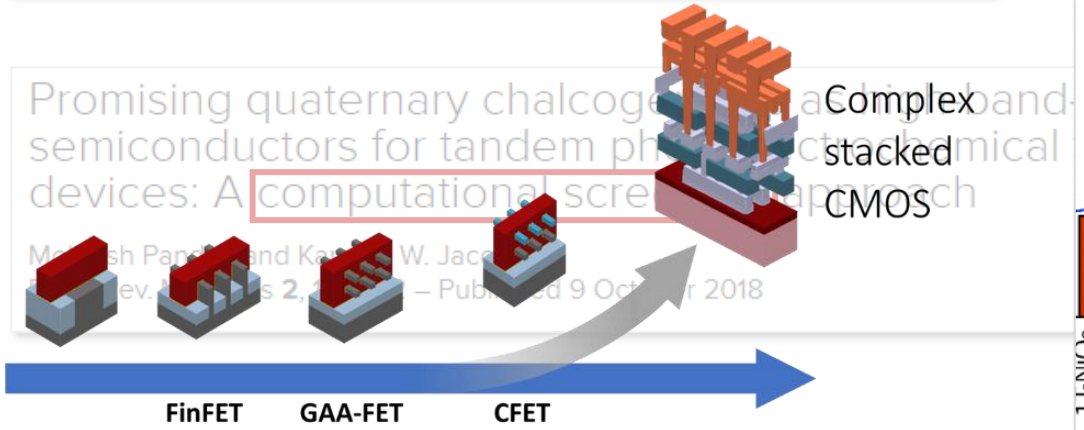
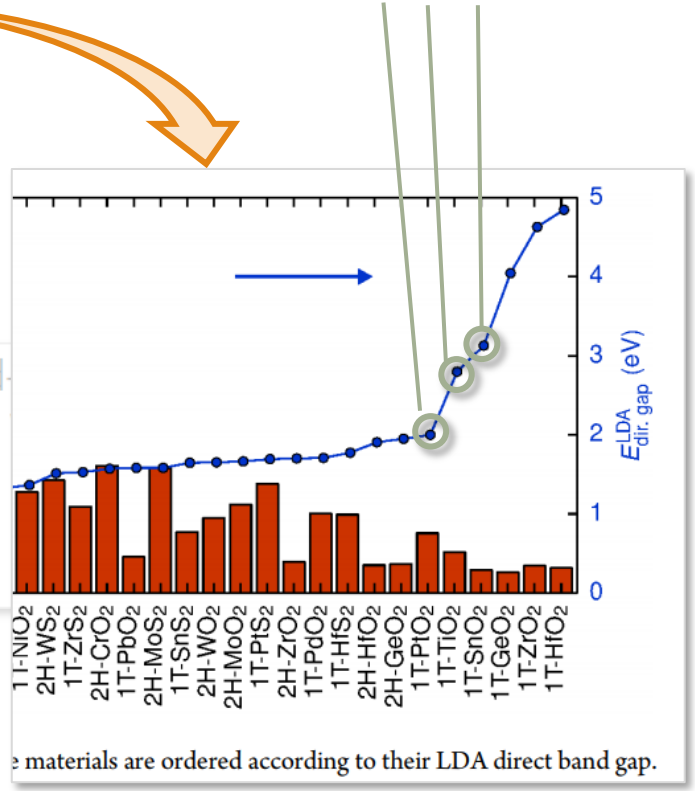
The wave of computational materials

3 days simulation per point







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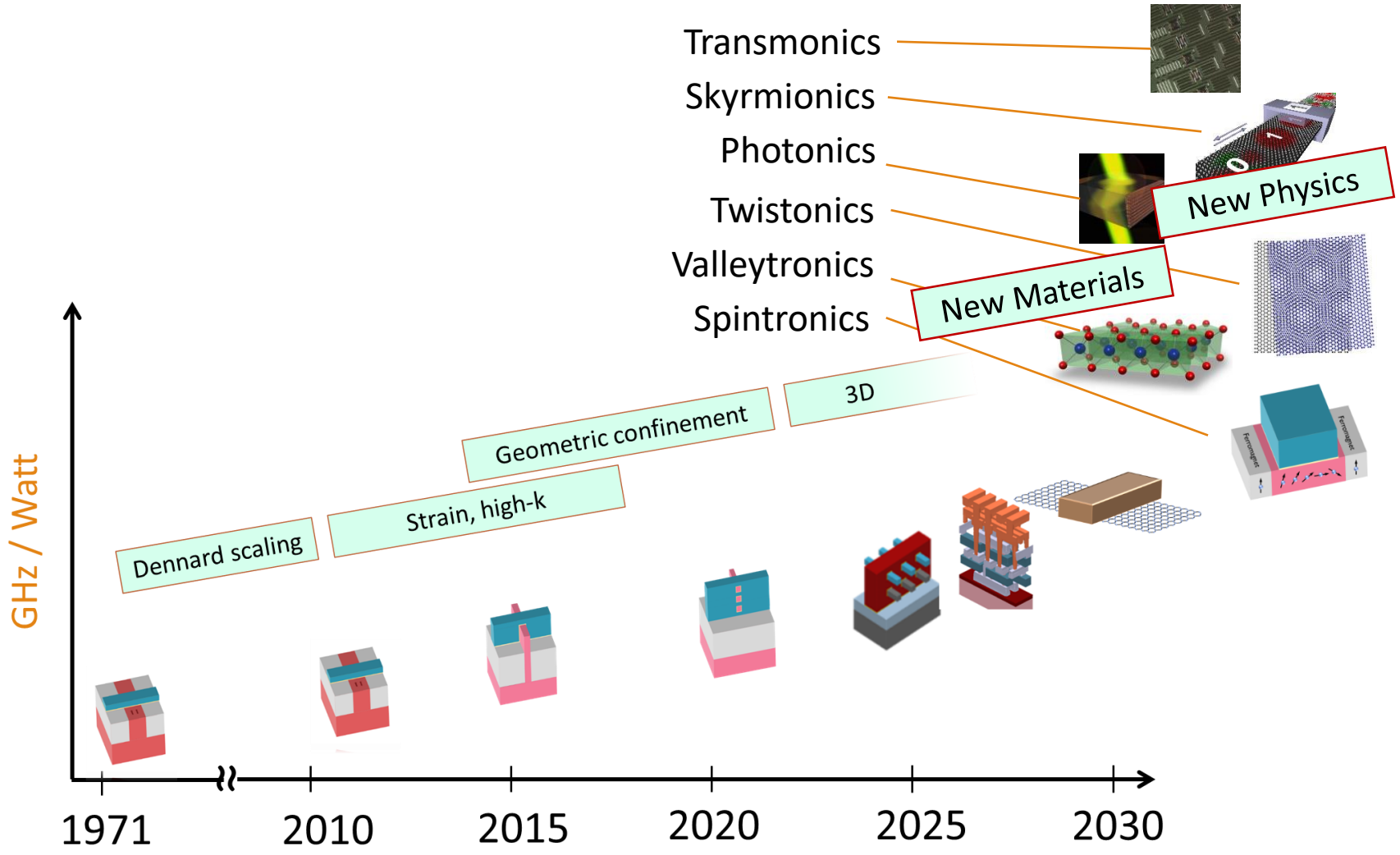
The –ic's of 2030?



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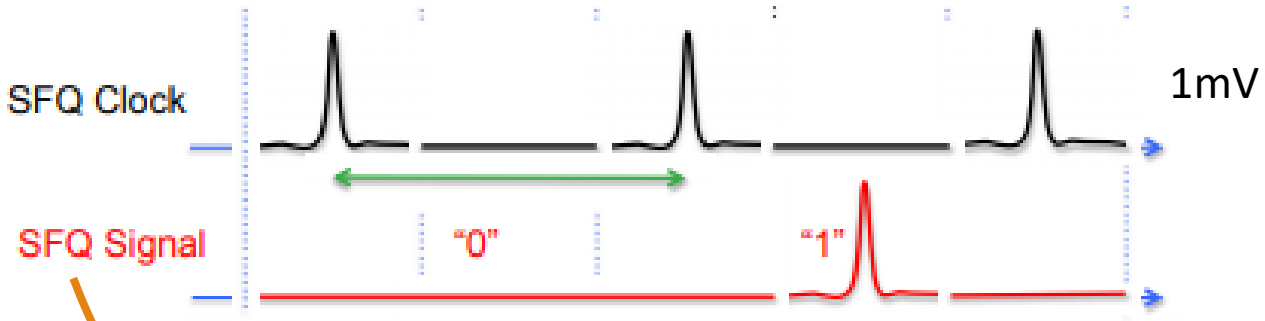
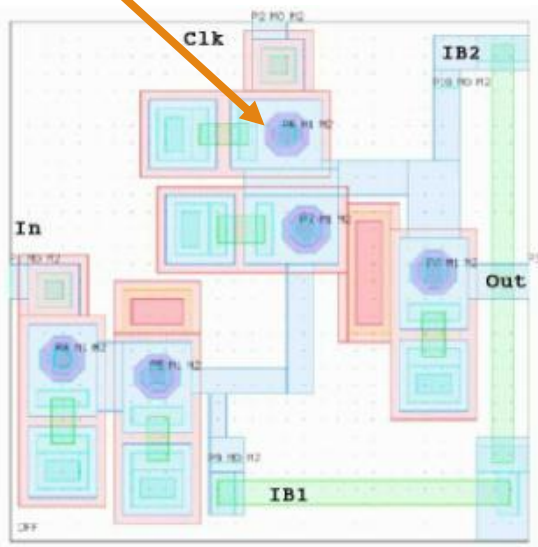
Superconducting electronics (SCE)



Flip-Flop: just 5 JJ's
(up to 750GHz)



Demonstration of a 120 GHz single-flux-quantum shift register circuit based on a 10 kA cm^{-2} Nb process

H Akaike[1], T Yamada[1], A Fujimaki[1], S Nagasawa[2], K Hinode[2], T Satoh[2], Y Kitagawa[2] and M Hidaka[2]

Published 16 March 2006 • IOP Publishing Ltd

Superconductor Science and Technology, Volume 19, Number 5

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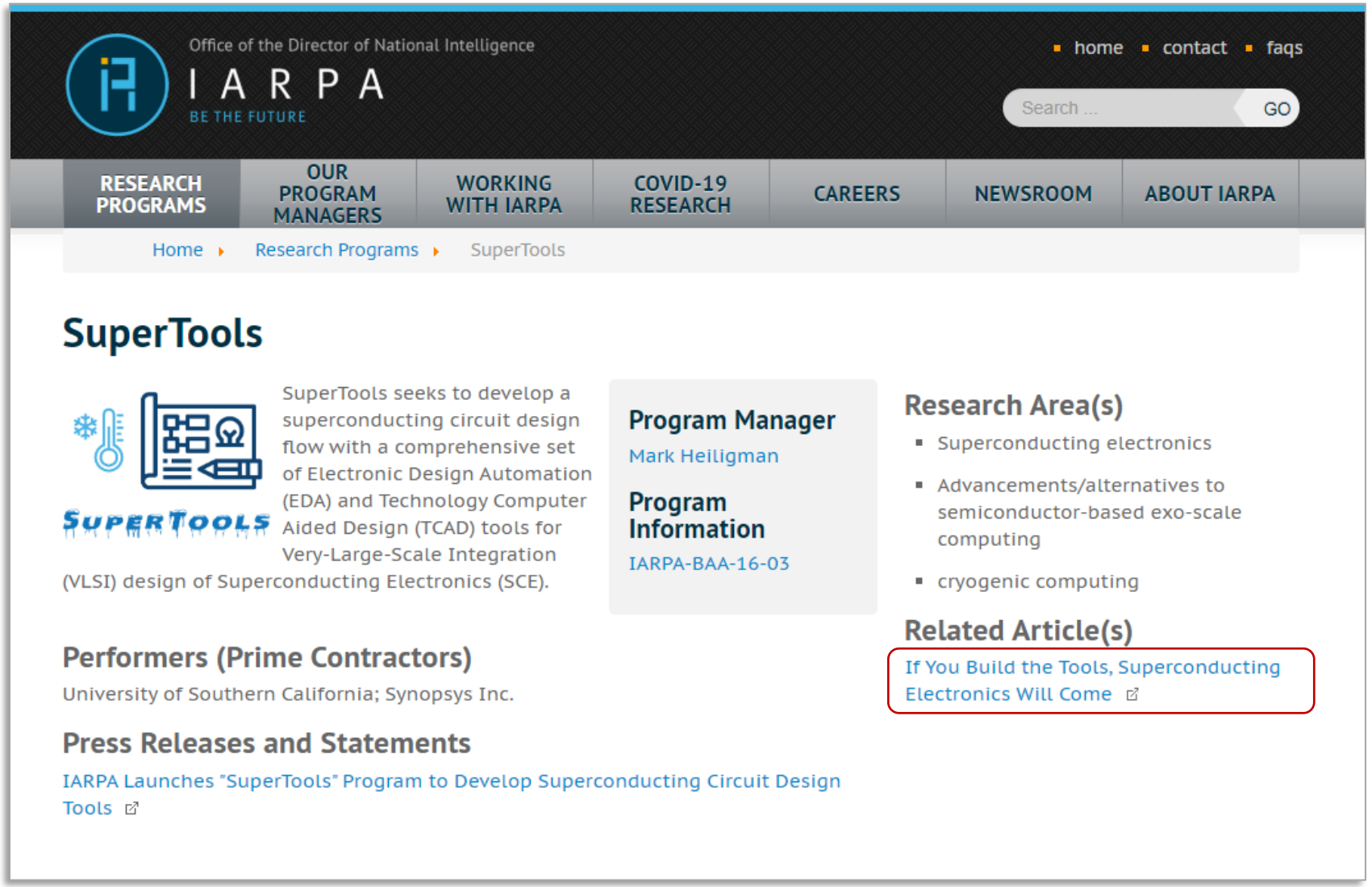

https://www.iarpa.gov/index.php/research-programs/supertools

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Disruptive technology toward 2030

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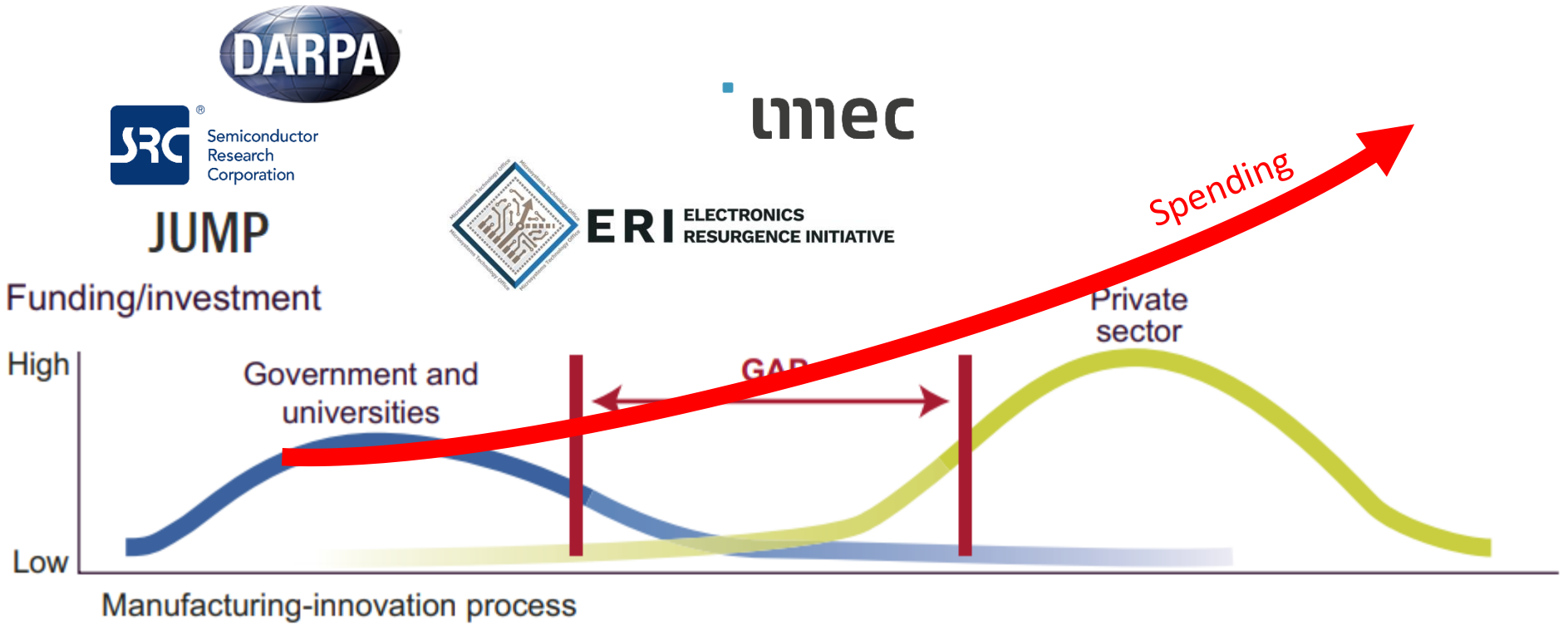
From Lab to Fab



← Lab to Fab →

Basic manufacturing research	Proof of concept	Production in laboratory	Capacity to produce prototype	Capability in production environment	Demonstration of production rates

GAO-14-406SP (2014)

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FYI
SCIENCE POLICY NEWS FROM AIP
Bulletin

Lawmakers Propose Multibillion Dollar Semiconductor R&D Push

SHARE THIS

Publication date: 24 June 2020 Number: 61

A bipartisan group of lawmakers recently introduced legislation that would channel billions of dollars into manufacturing incentives and new R&D streams to bolster U.S. semiconductor manufacturing in the face of increasing international competition.

Image credit – Randy Montoya / Sandia National Lab

"Research is critical to advancing semiconductor innovation in the U.S. American semiconductor design and manufacturing companies invest approximately one-fifth of revenue in R&D, almost $40 billion in 2019, representing the second-highest rate of research investment of any industry."

American Foundries Act Would Provide Needed Investments in U.S. Semiconductor Manufacturing, Research

Thursday, Jun 25, 2020, 4:50pm
by **Semiconductor Industry Association**

Bipartisan legislation would advance domestic production and research of chips critical to America's economy and national security

WASHINGTON—June 25, 2020—The Semiconductor Industry Association (SIA) today applauded introduction in the Senate of the American Foundries Act of 2020, legislation that would provide federal investments totaling tens of billions of dollars for semiconductor manufacturing and research to help ensure America's continued leadership in chip technology, which is fundamental to our country's economy and national security. The bipartisan bill was introduced today by Sens. Tom Cotton (R-Ark.), Chuck Schumer (D-N.Y.), Jim Risch (R-Idaho), Jack Reed (D-R.I.), Josh Hawley (R-Mo.), Angus King (I-Maine), Susan Collins (R-Maine), Kirsten Gillibrand (D-N.Y.), Marco Rubio (R-Fla), and Doug Jones (D-Ala.).

"U.S. companies have led the world in semiconductor technology for decades, but over the years governments of overseas competitors have offered aggressive incentives for advanced chip manufacturing to relocate," said Keith Jackson, President, CEO, and Director of ON Semiconductor and 2020 SIA chair. "To reverse that trend and keep America in front in chip technology, we need to invest ambitiously in domestic semiconductor manufacturing and research. We commend the bipartisan group of bill sponsors for their leadership in addressing this challenge and urge Congress to move forward with legislation to incentivize semiconductor manufacturing and expand semiconductor research."

The U.S. currently maintains a stable chip manufacturing footprint, but the trend lines are concerning. There are commercial semiconductor manufacturing facilities, or "fabs," in 18 states, and semiconductors ranked as our nation's fifth-largest export in 2019. Significant semiconductor manufacturing incentives, however,

© Arm 2020

Example from Arm Research

Arm Leads Project to Develop an Armpit-Sniffing Plastic AI Chip

In a quest for penny-priced plastic sensors, Arm and its partners are demonstrating a stripped-down form of machine learning

By **Samuel K. Moore**

IEEE SPECTRUM

arm

Unilever

© Arm 2020

Example from Arm Research

Arm Leads Project to Develop an Armpit-Sniffing Plastic AI Chip

In a quest for penny-priced plastic sensors, Arm and its partners are demonstrating a stripped-down form of machine learning

By Samuel K. Moore

Application
Software
Algorithms
Architecture
Microarchitecture
Circuits
Device
Process integration
Materials

Unilever

arm

PragmatIC

MANCHESTER 1824
The University of Manchester

"materials to systems"
"atoms to applications"

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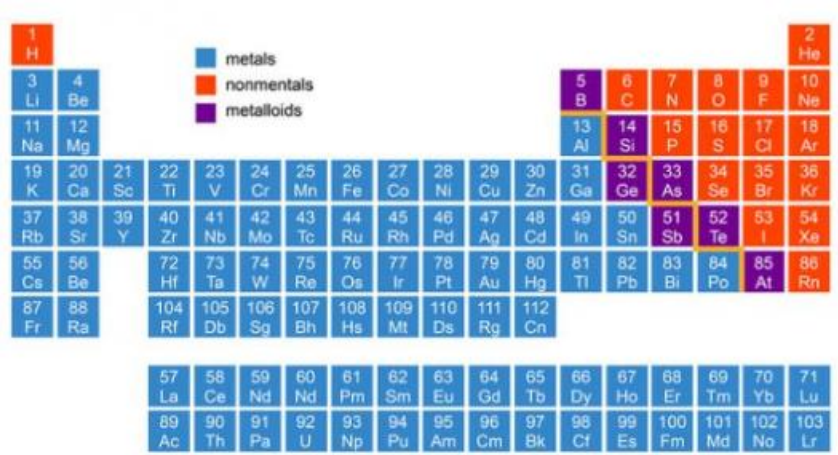
Example from Arm Research: CeRAM

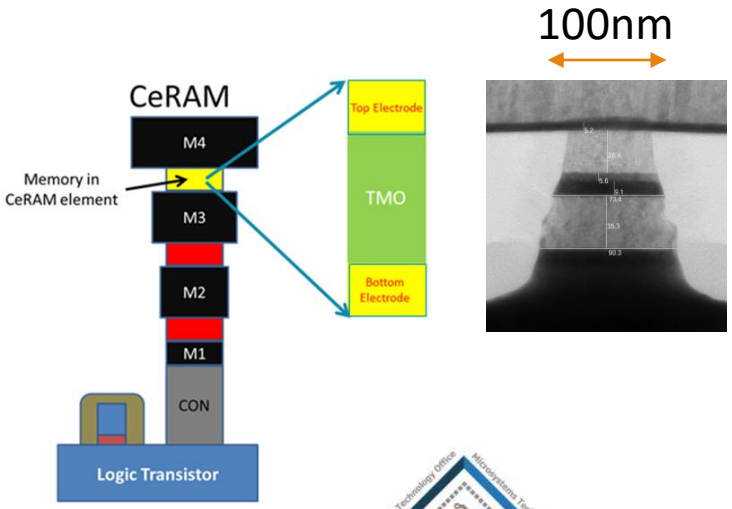
Applied, ARM to develop CeRAM for neuromorphic applications

July 24, 2018 // By Peter Clarke 0 Comments

Email print Share Share reddit



Semiconductor manufacturing equipment maker Applied Materials Inc. has been selected by DARPA to work with ARM Ltd. and research firm Symetrix Corp. to develop a switch that functions like the neuron and synapses of the human brain, based on Correlated-Electron RAM (CeRAM) technology.



ELECTRONICS RESURGENCE INITIATIVE

arm symetrix

University Of British Columbia

University of Colorado Colorado Springs

University of Colorado Boulder

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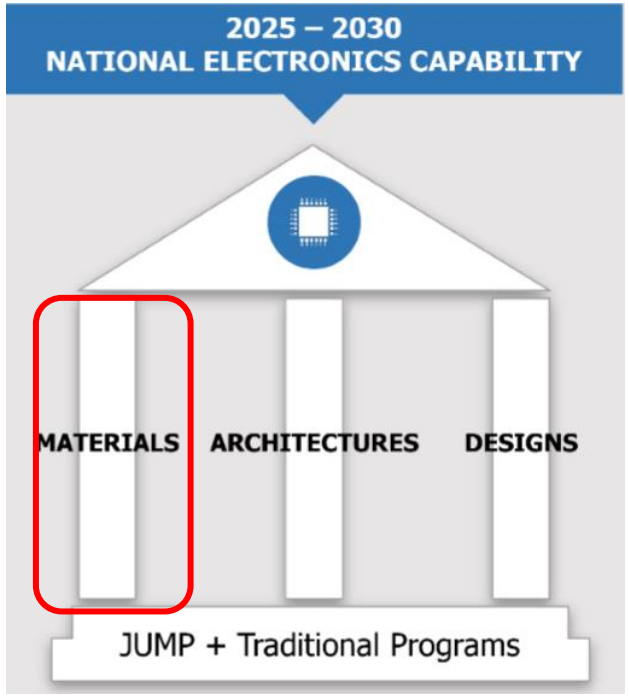
DARPA's Electronics Resurgence Initiative



https://www.darpa.mil/work-with-us/electronics-resurgence-initiative

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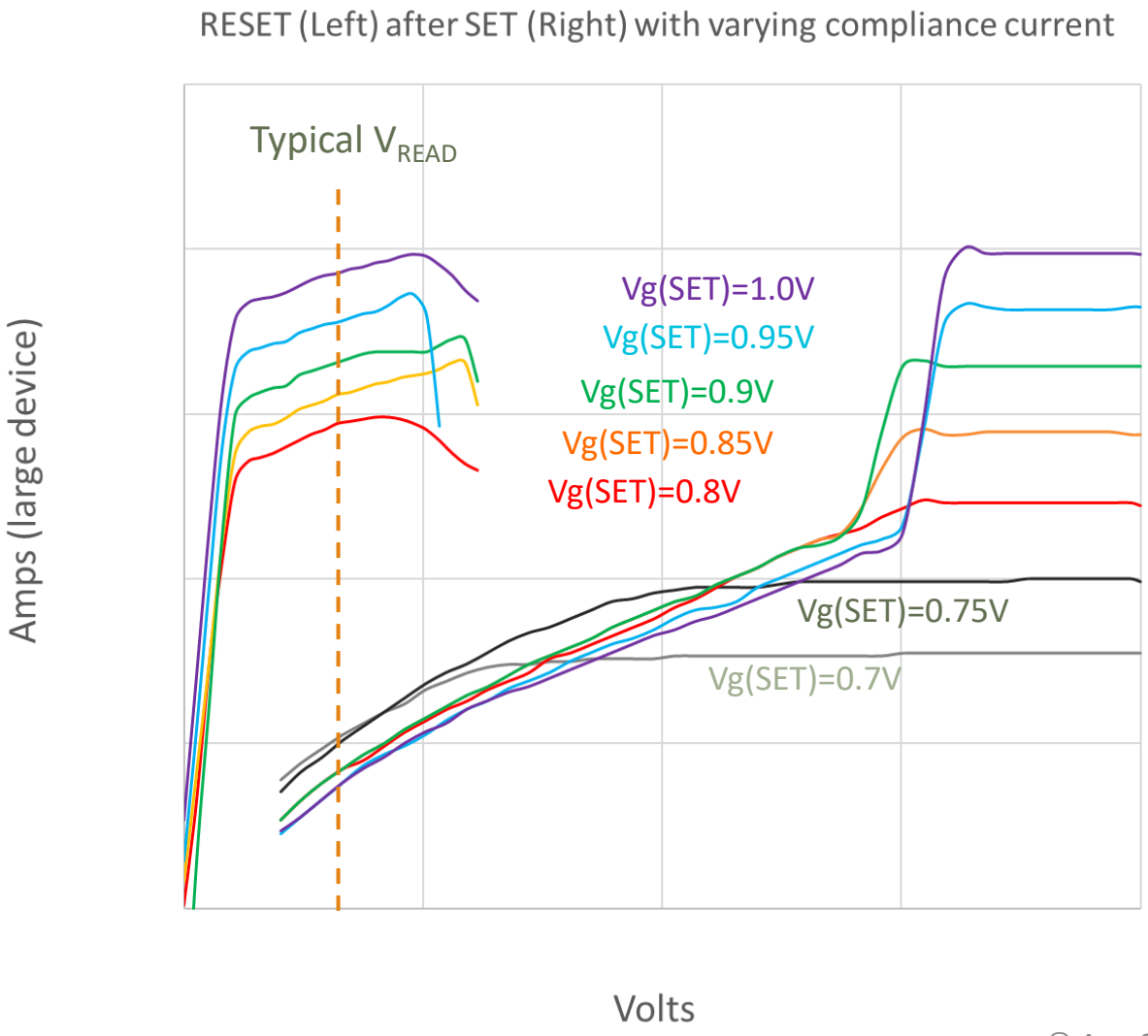
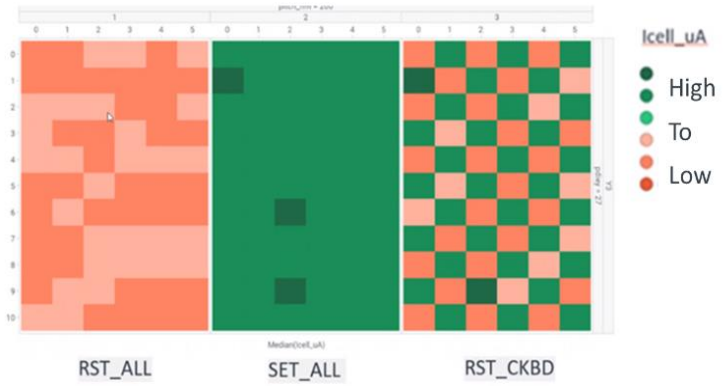
Multi-level cell (MLC) memory



- 300mm wafers
- Sub-100nm dots
- Low Power
- Speed: < 10nS



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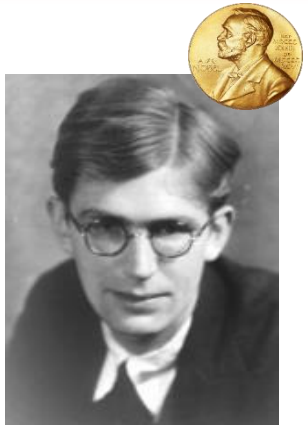
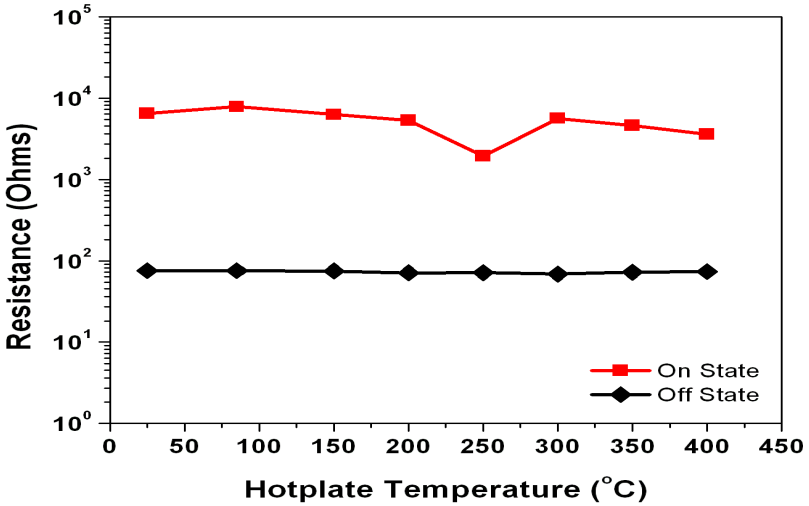
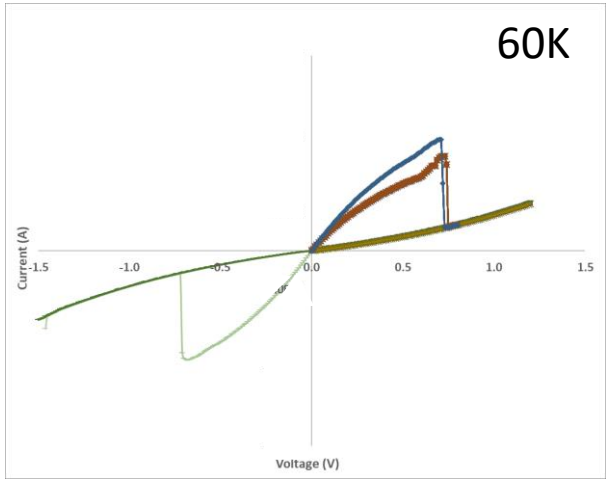
Correlated Electrons

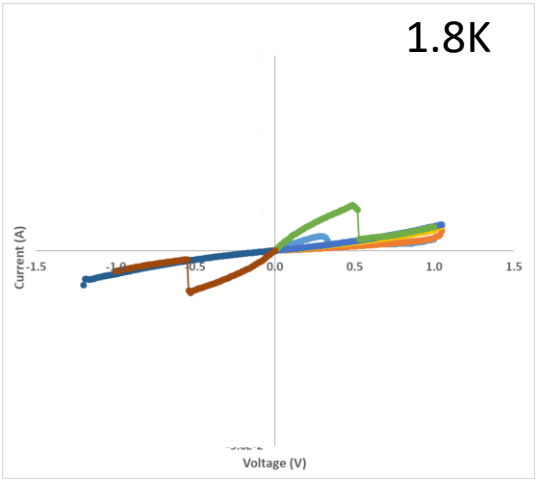
A true quantum phase transition is adiabatic



Nevill Mott
1954-1971







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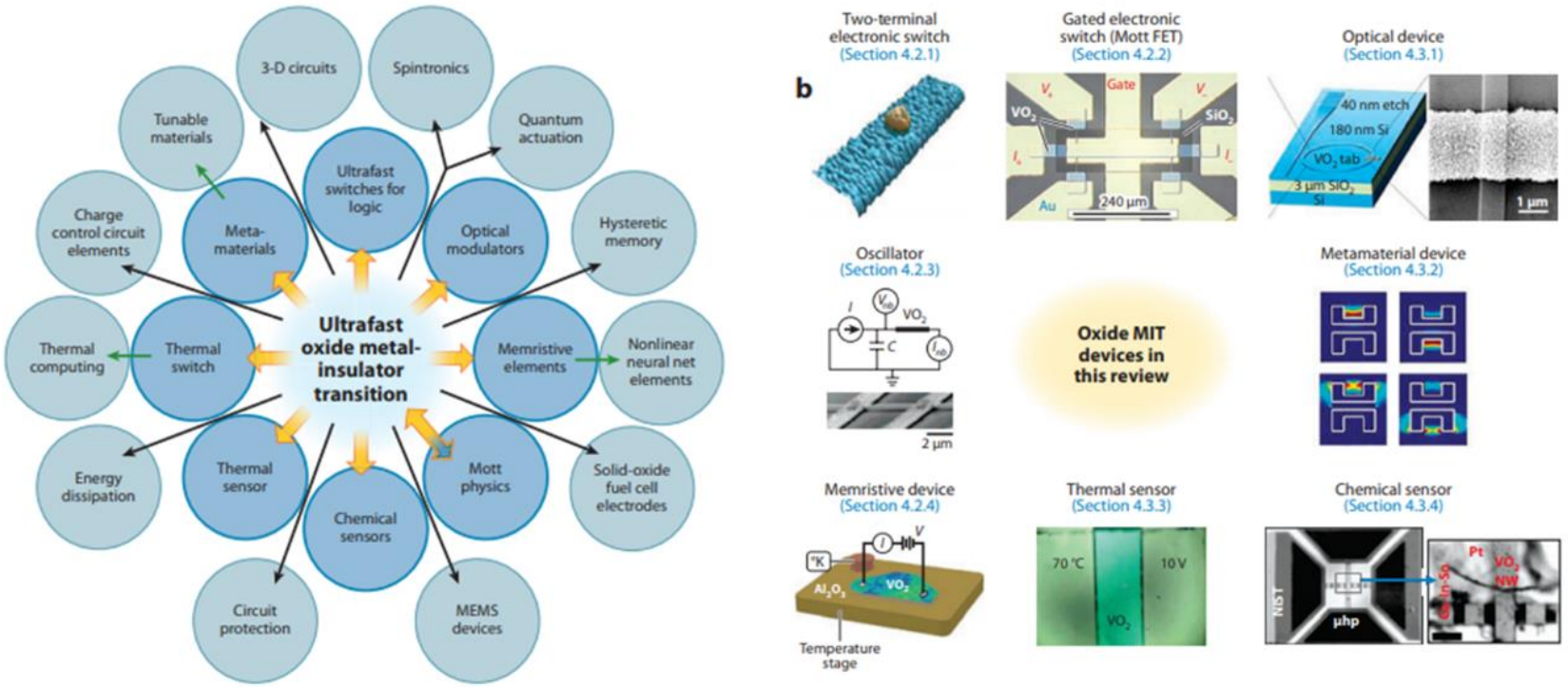
New physics, new opportunities



Oxide Electronics Utilizing Ultrafast Metal-Insulator Transitions, Harvard, *Ann. Rev. Mat. Rsh* (2011)

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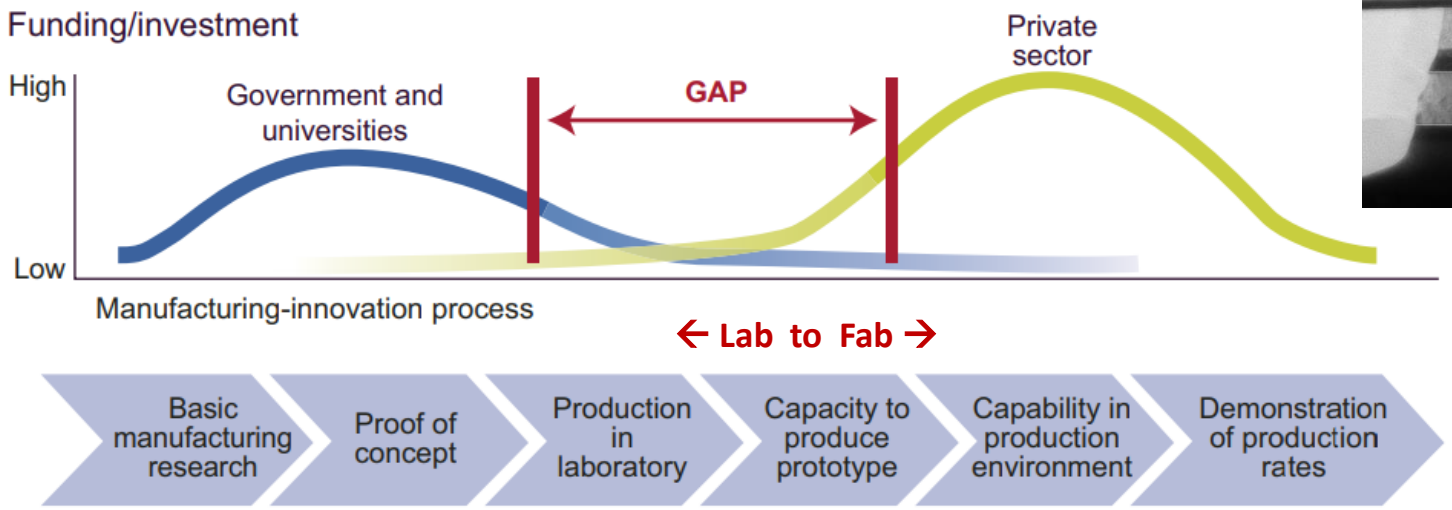
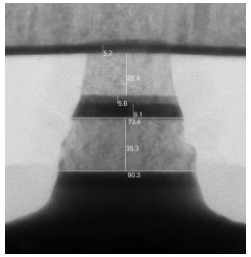
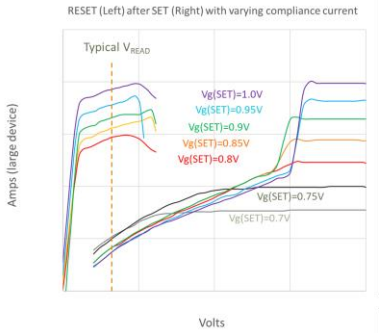
NVM MLC example





MLC is all about variation control

- Best deposition/cost tradeoff?
- PVD, CVD, ALD …
- How do you etch it?



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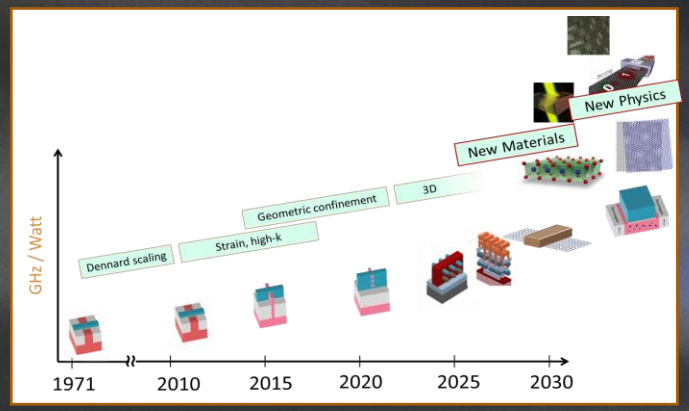
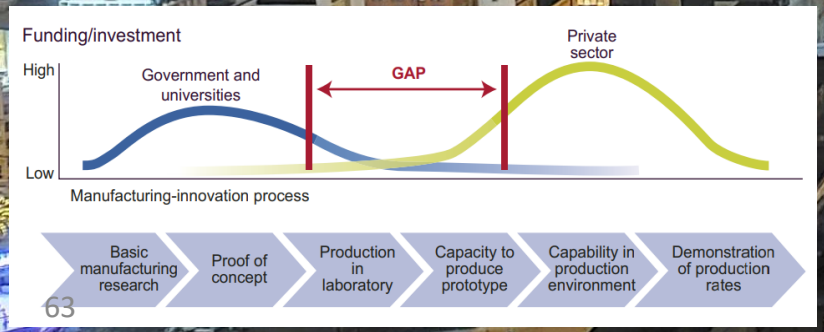


- Application
- Software
- Algorithms
- Architecture
- Microarchitecture
- Circuits
- Device
- Process integration
- Materials



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Questions

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