

Al 50 aniversario de la Ley de Moore, la nanoelectrónica en una encrucijada

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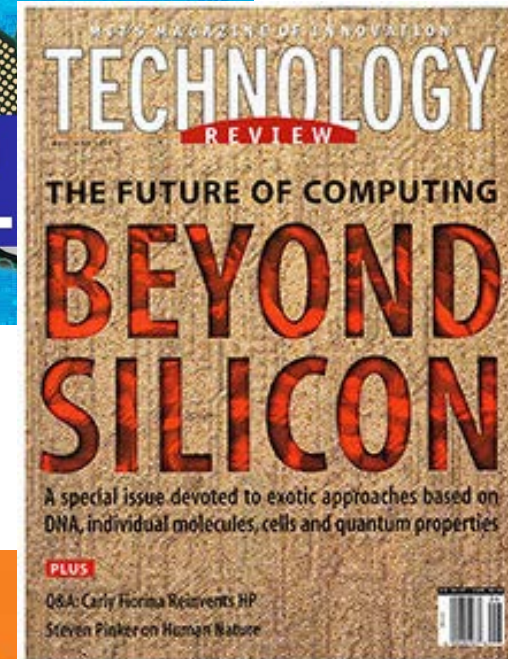
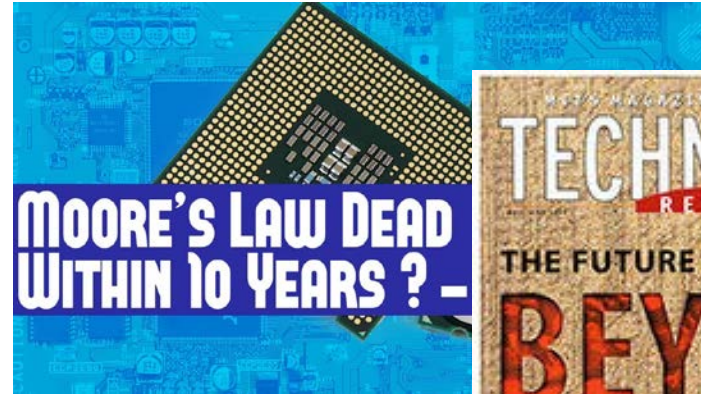
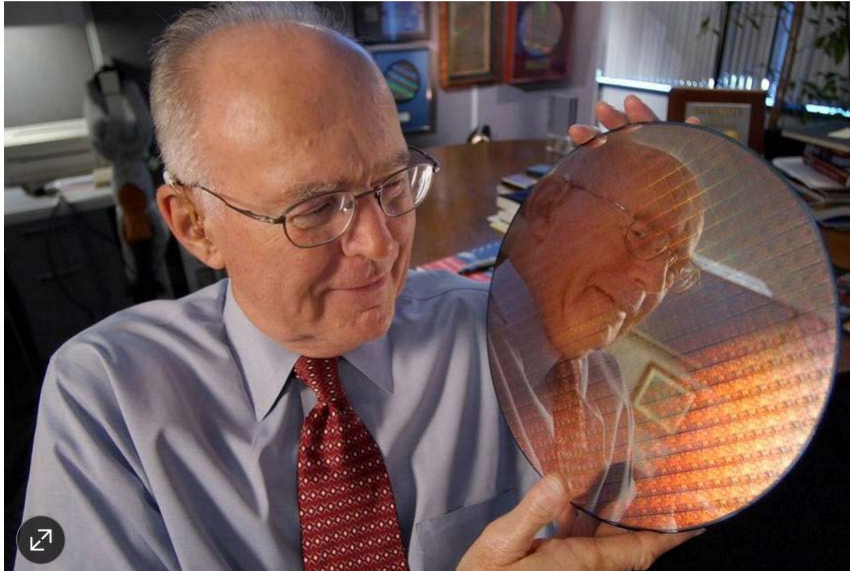


Moore's Law at 50: the end in sight?

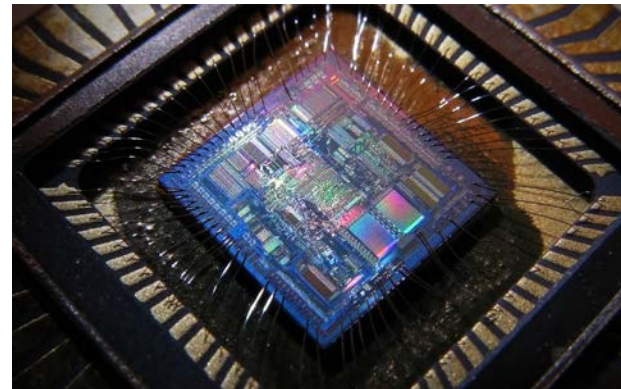
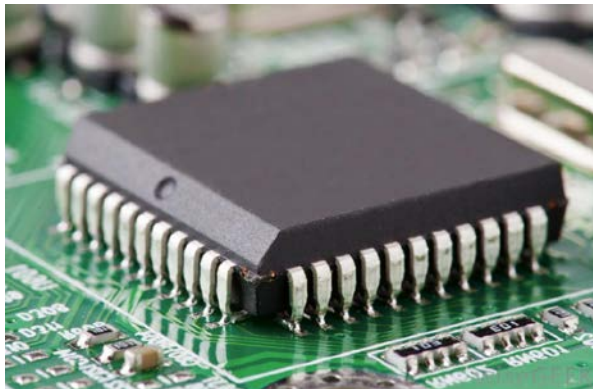
THE WALL STREET JOURNAL

Moore's Law Is Showing Its Age

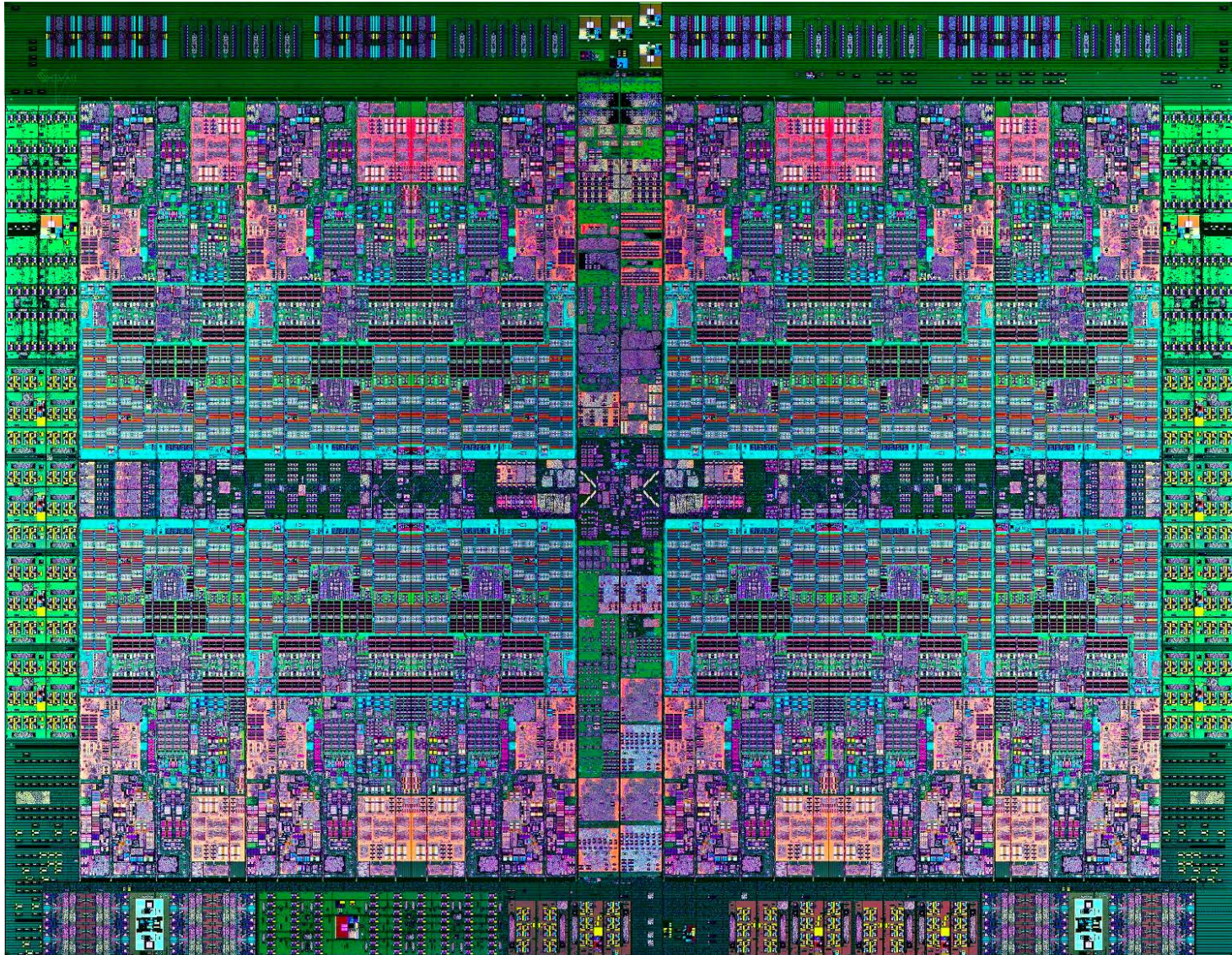
The prediction about squeezing transistors onto silicon has been revised again.



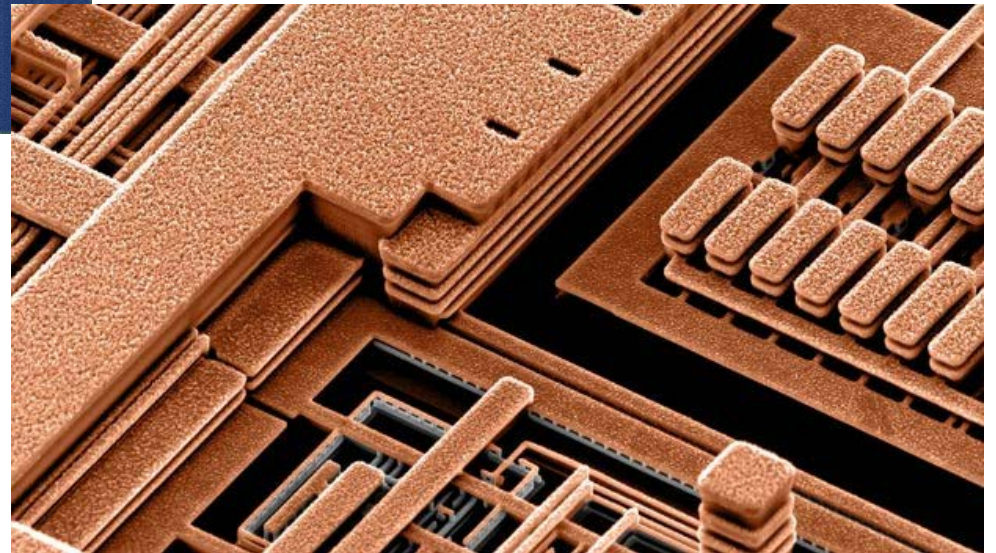
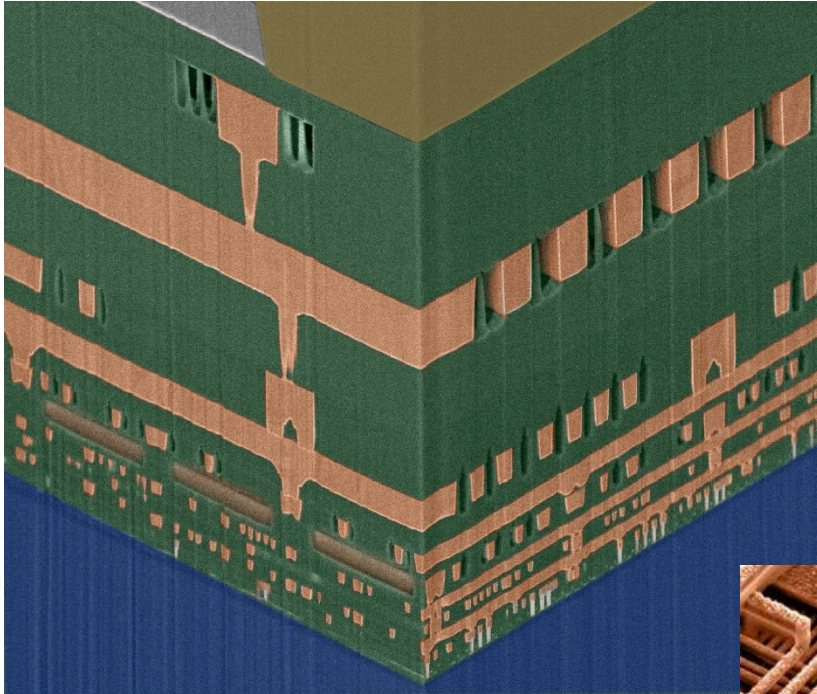
Nanoelectronics: the brains of our information society



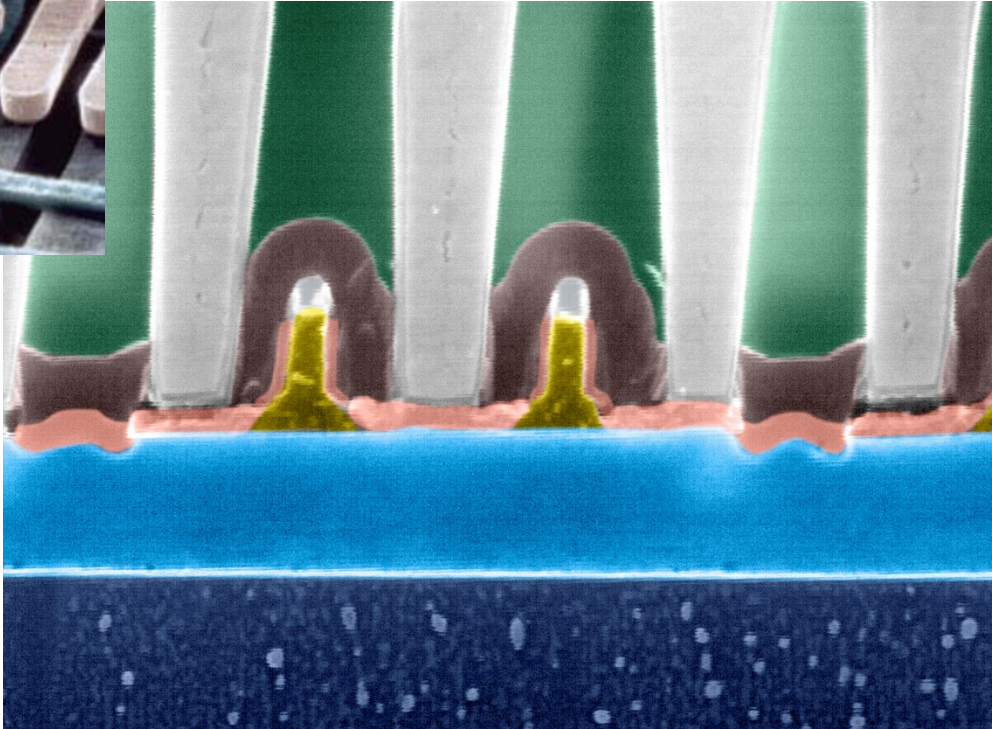
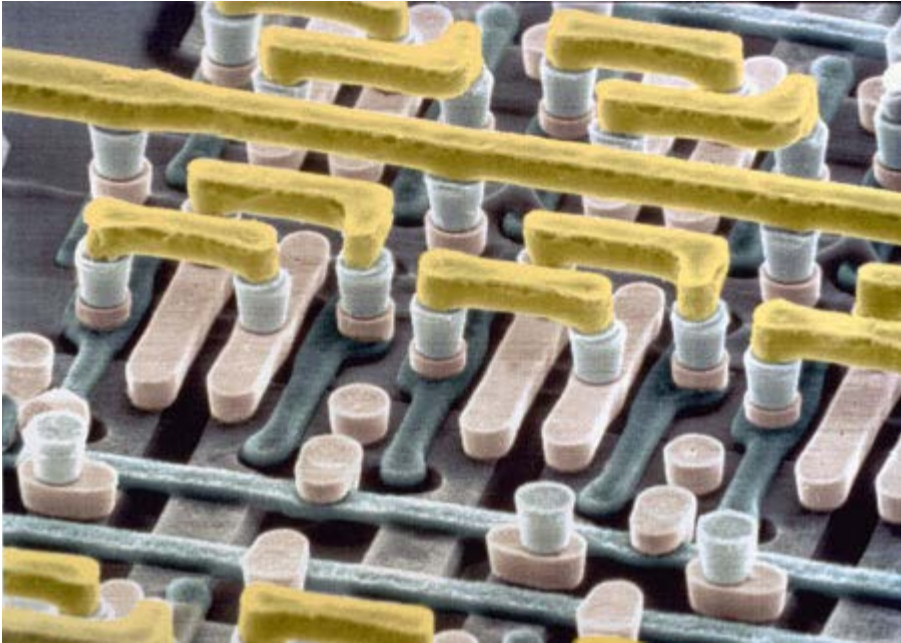
Integrated circuits



Interconnects



Transistors



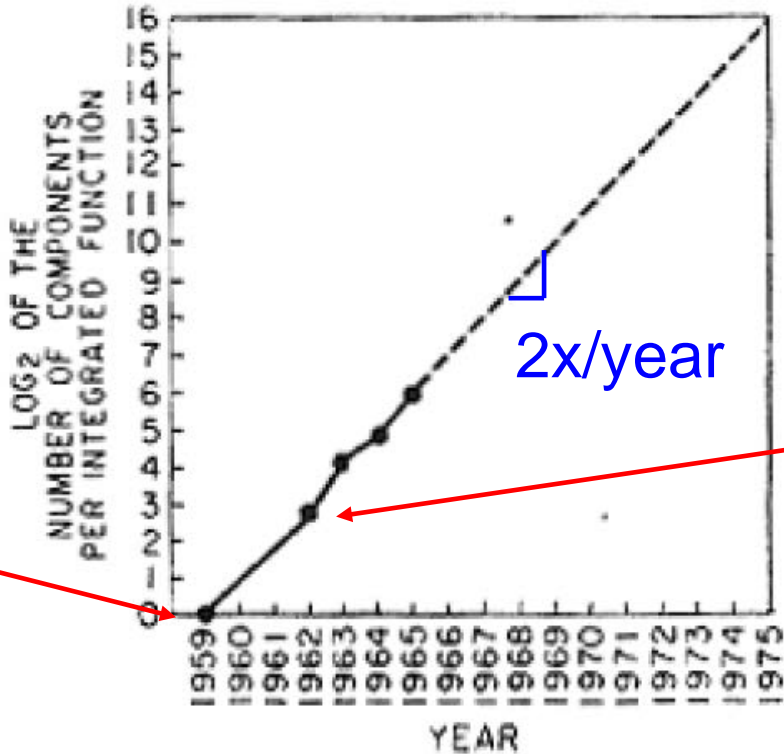
Moore's Law

“It's not a law in any real respect. It was an observation and a projection.”

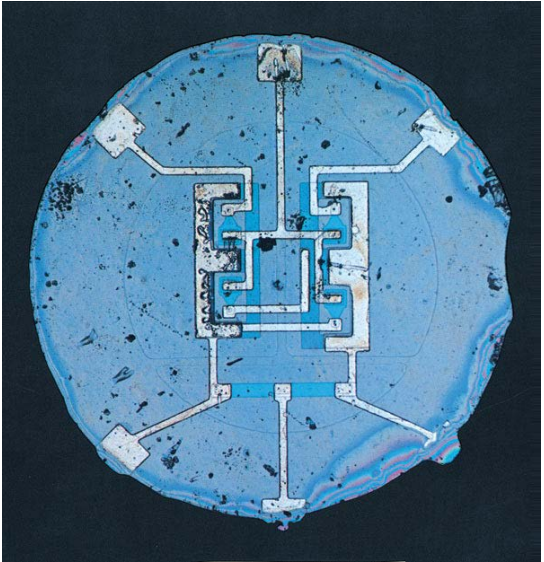
Gordon Moore, IEEE Spectrum 2015

Moore's observation, 1965

first planar transistor (1959)

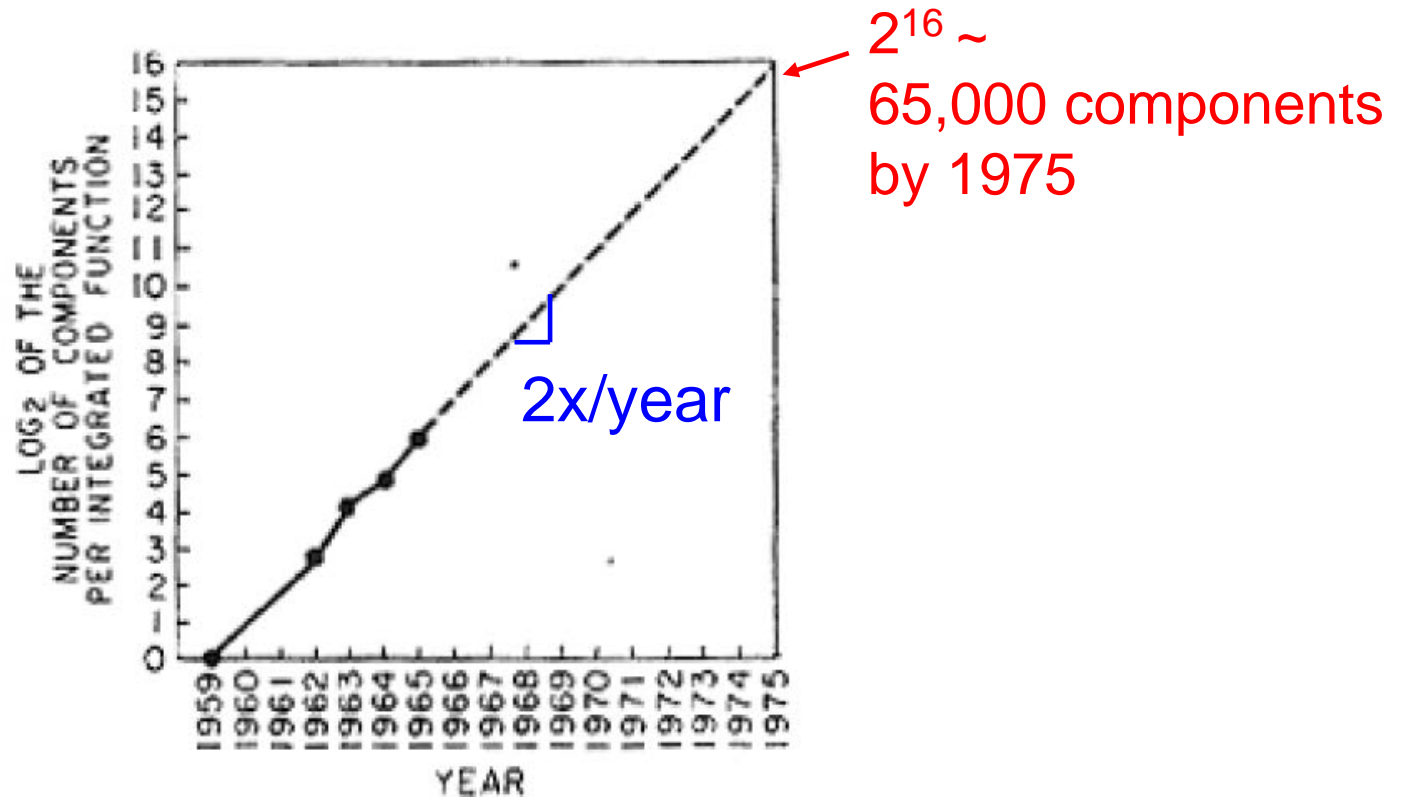


first commercial integrated circuit (1961)



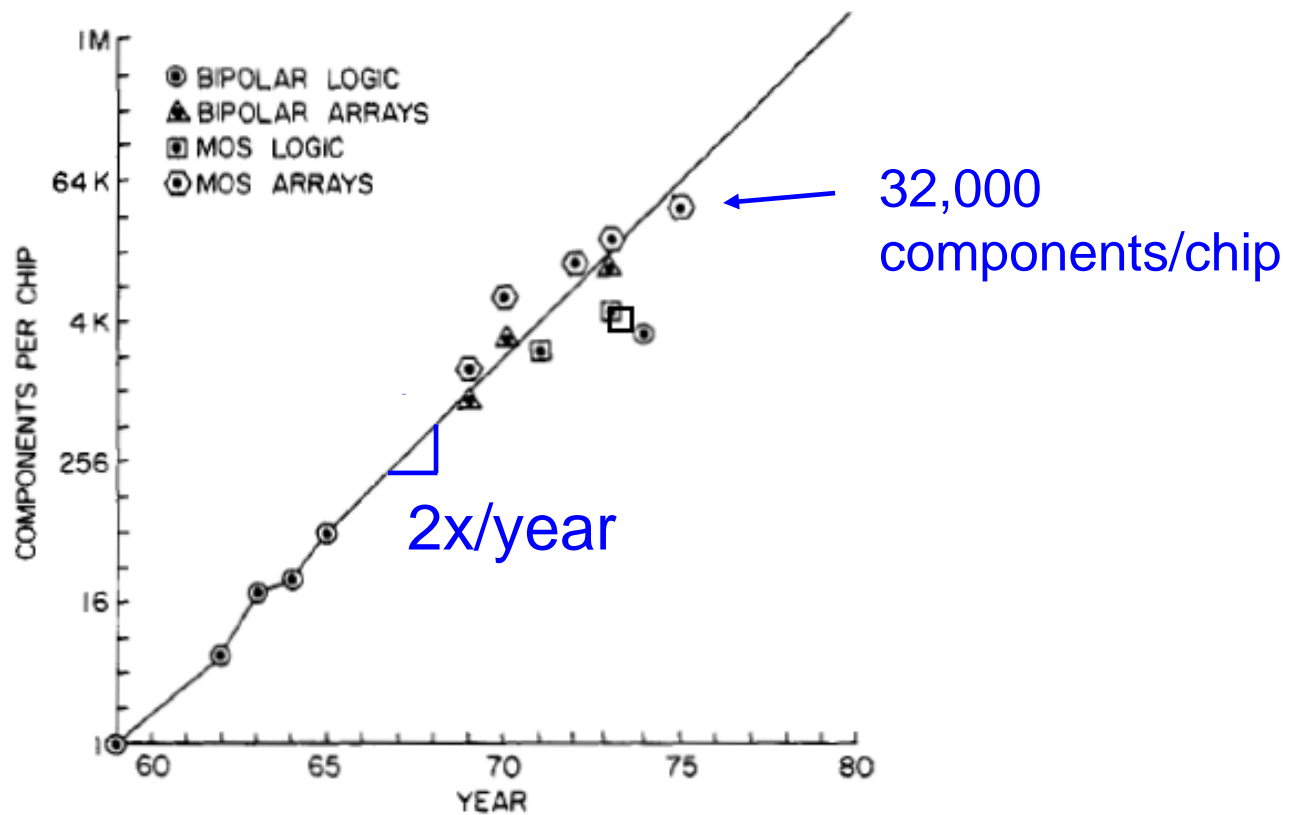
Moore's prediction, 1965

Moore, Electronics 1965

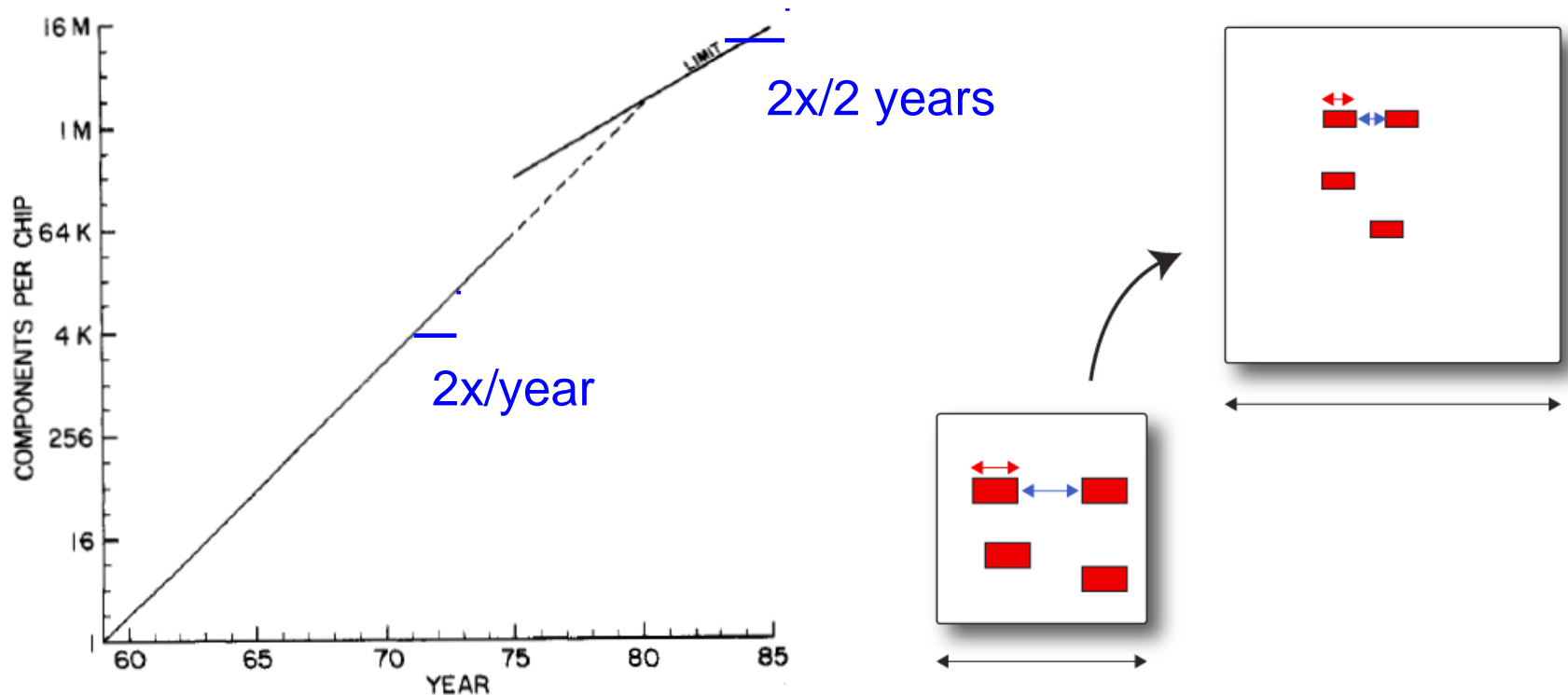


“By 1975, the number of components per integrated circuit for minimum cost will be 65,000.”

10 years later...



Moore's revised prediction, 1975



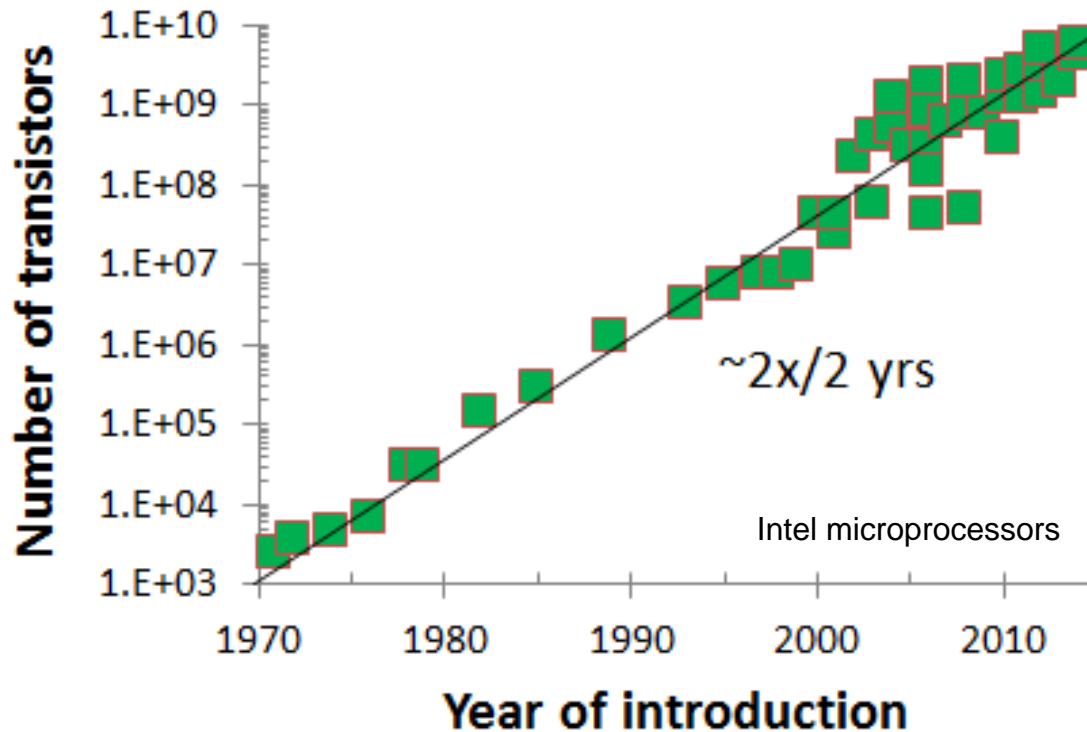
1975 prediction:

Moore, IEDM 1975

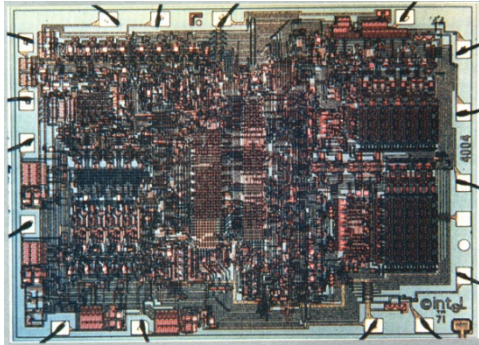
“By the end of the decade, the new slope might approximate a doubling every two years”

Moore's Law: 1970-2015

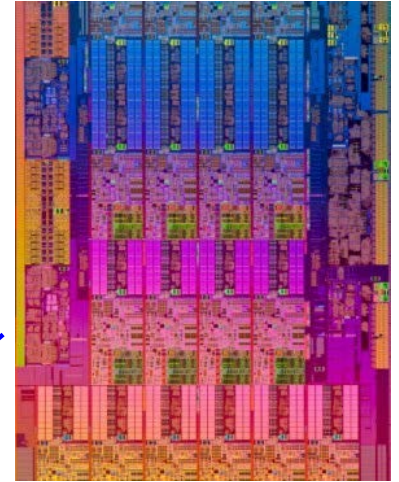
2x/2 years or
>40%/year for 45 years!



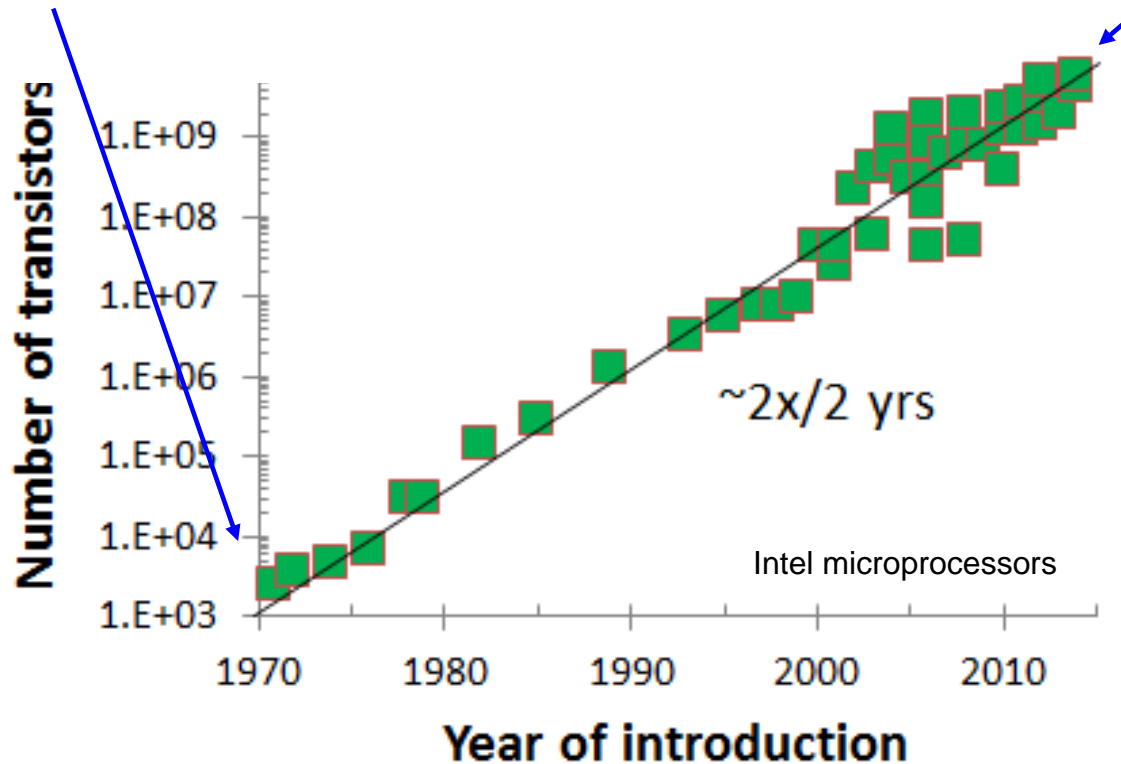
Moore's Law: 1970-2015



1971:
Intel 4004
2250 transistors



2014:
Intel Xeon Haswell-E5
5.6B transistors



After 50 years of Moore's Law



transportation



information

energy



medicine



manufacturing



entertainment

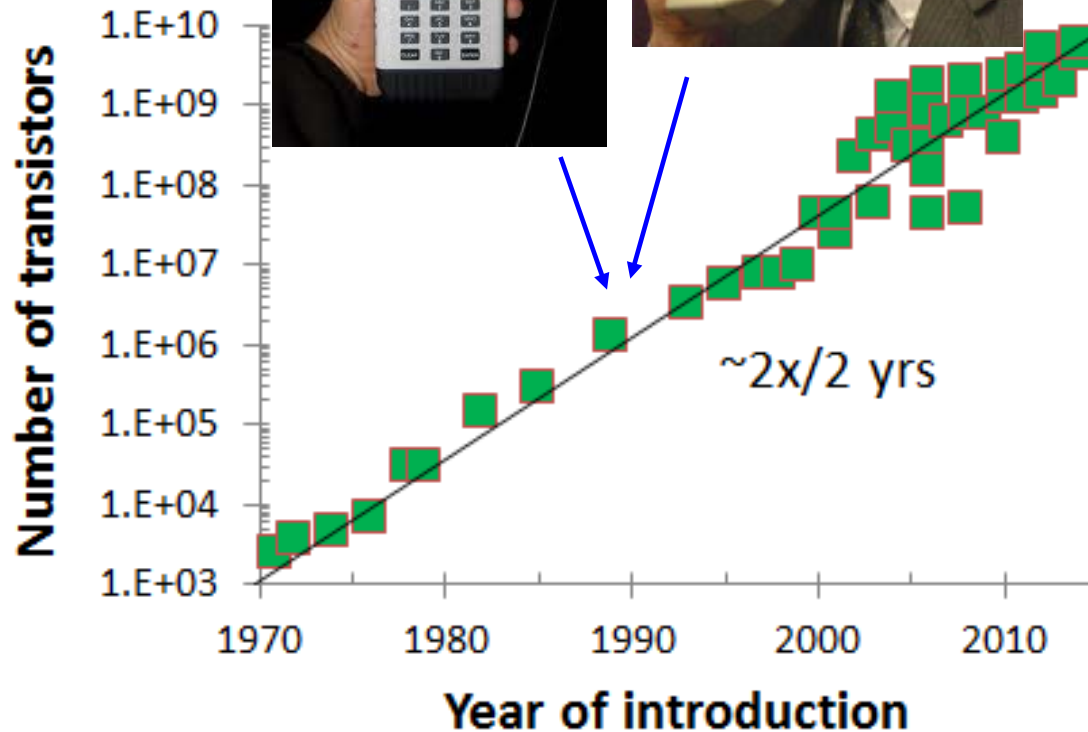


What if Moore's Law had stopped in 1990?

GPS handheld device
circa 1990



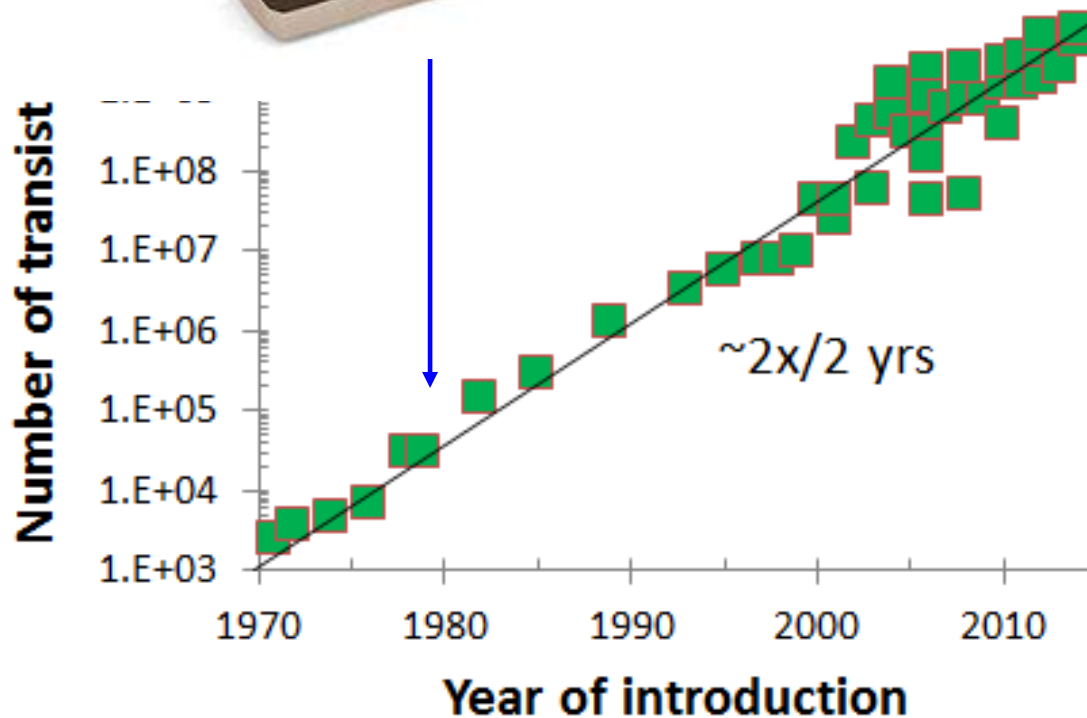
Cell phone circa 1990



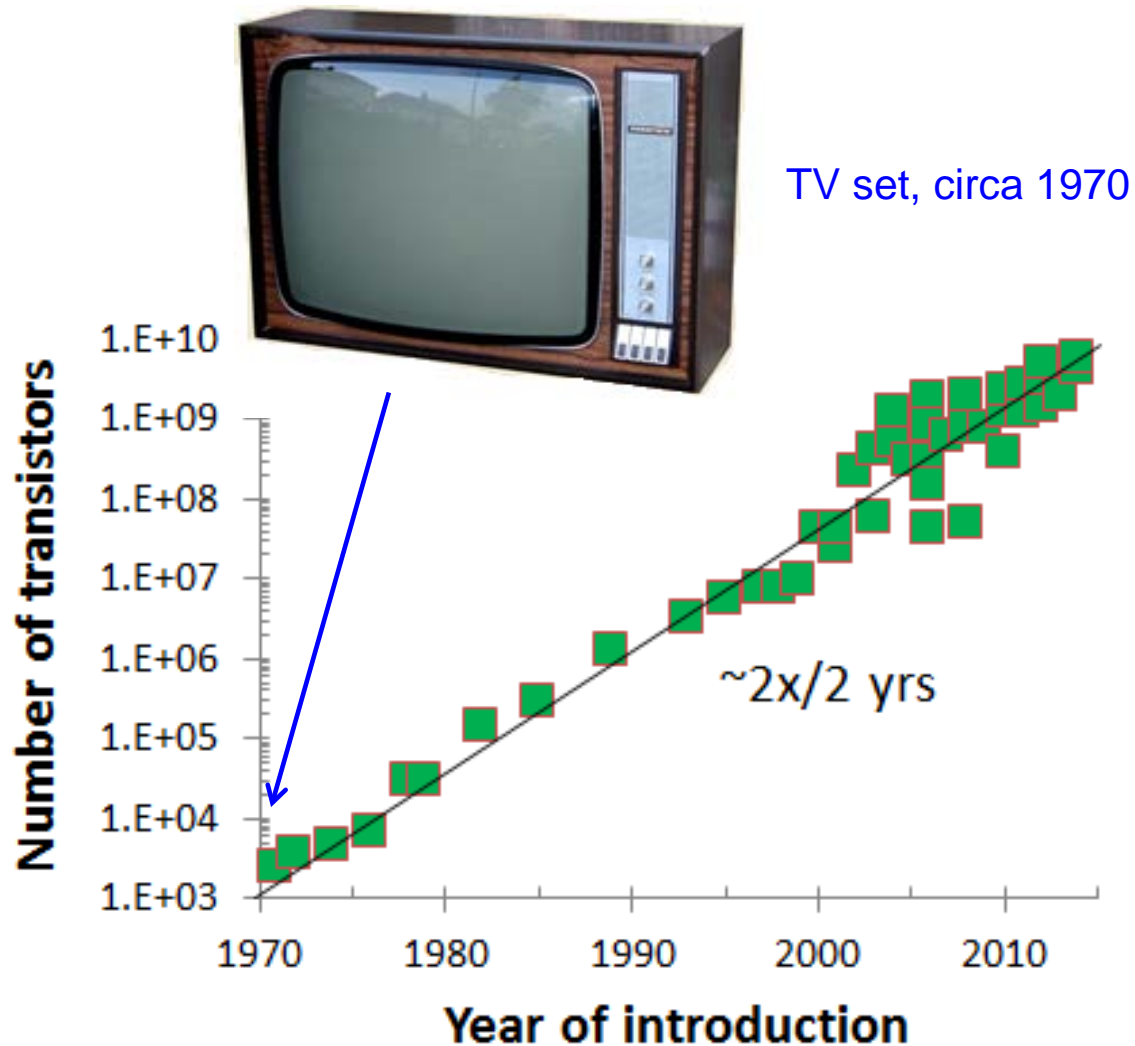
What if Moore's Law had stopped in 1980?



Laptop computer circa 1981



What if Moore's Law had stopped in 1970?

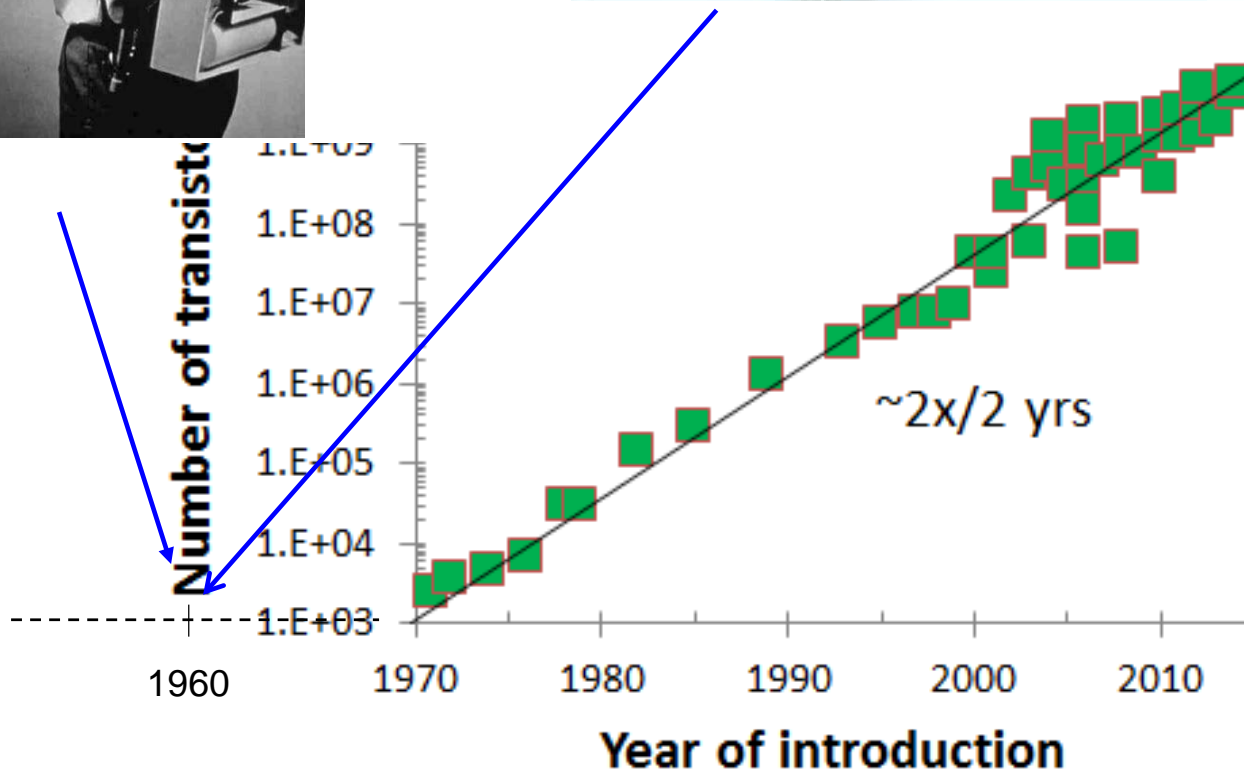


What if Moore's Law had never happened?



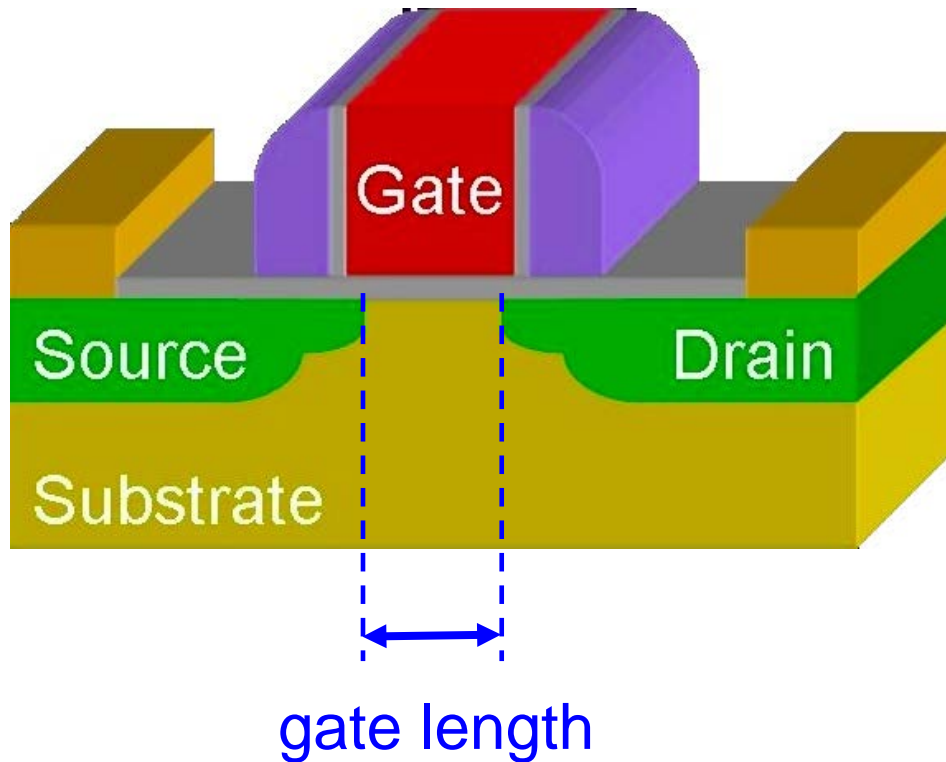
Insulin pump circa 1960

"Personal calculator" circa 1960



How transistors work

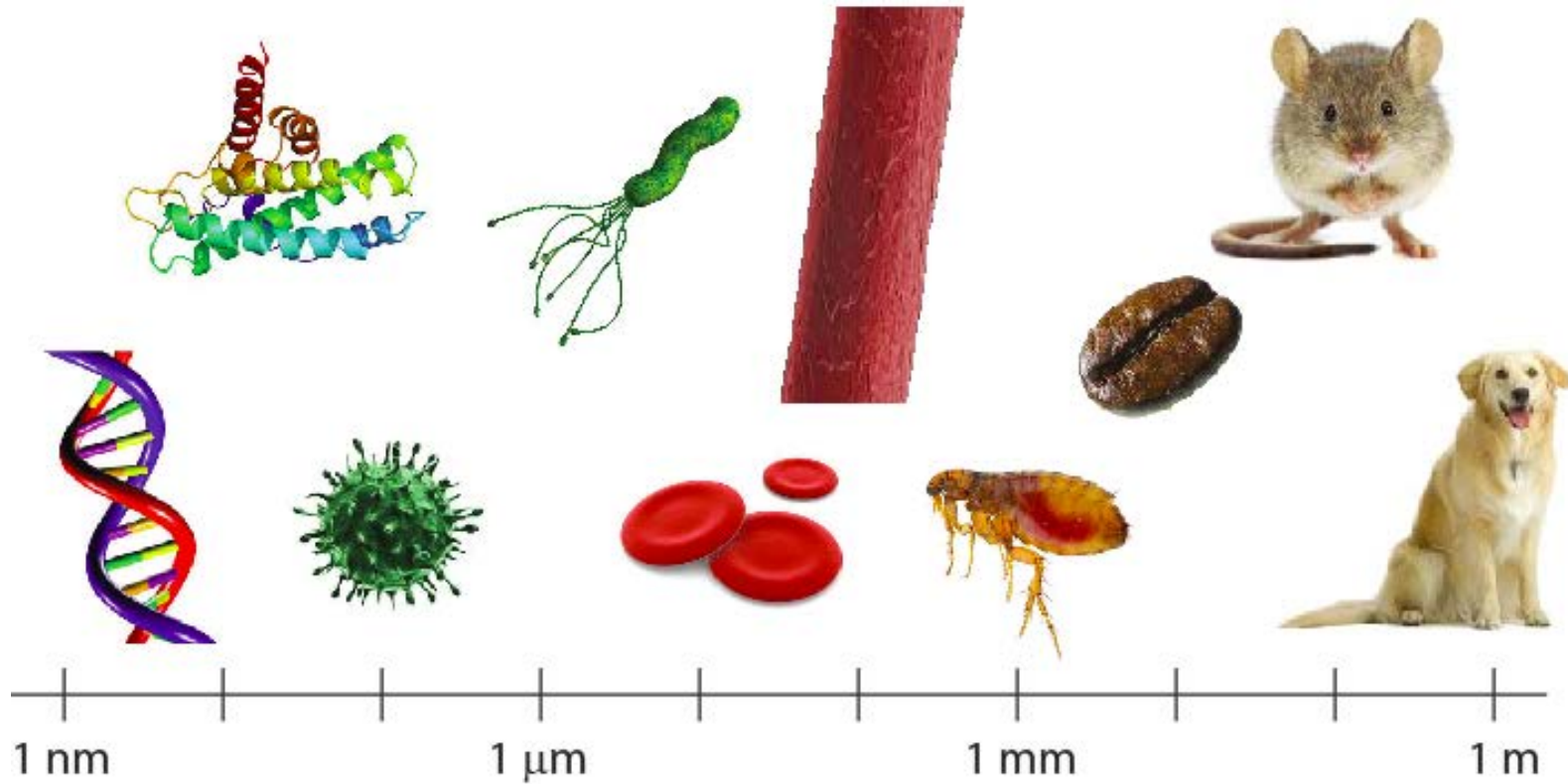
MOSFET =
Metal-Oxide-Semiconductor
Field-Effect Transistor



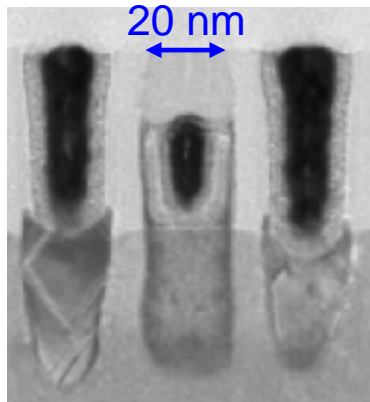
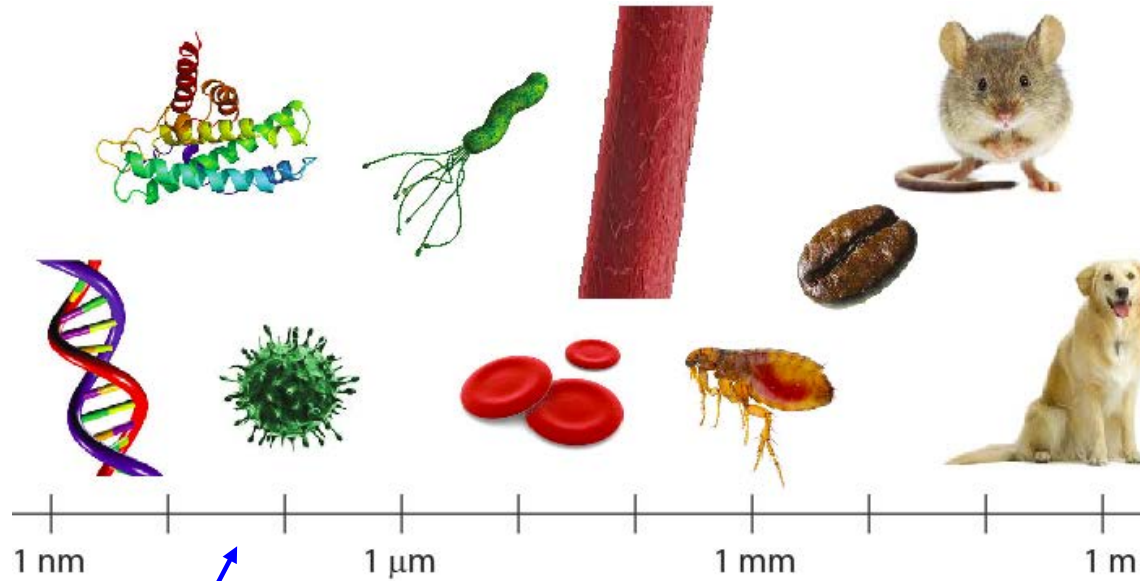
Switch



A sense of scale



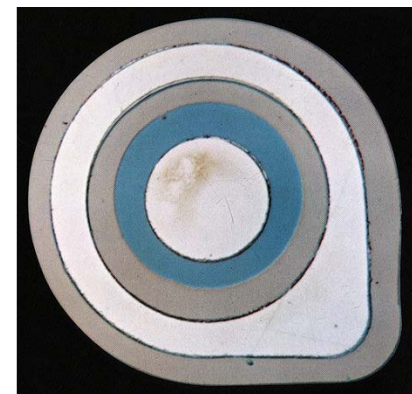
A sense of scale



2015 transistor



1971 transistor

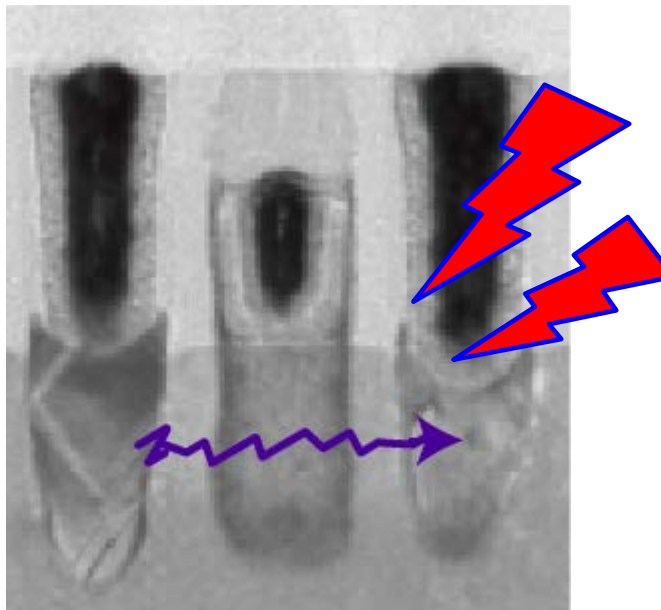


1959 transistor

Smaller is Better!

MOSFET performance improves as size scales down:

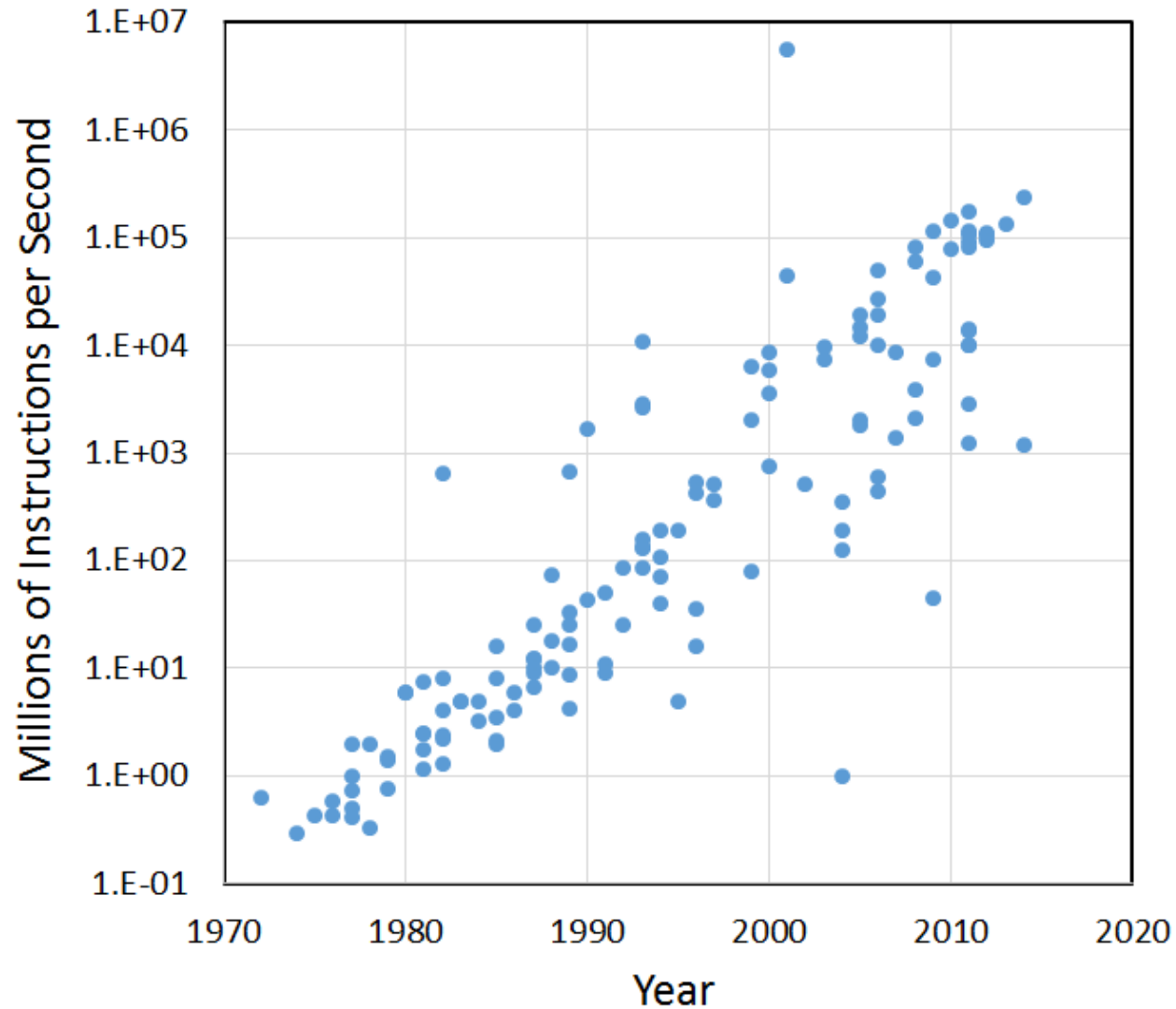
Switching
speed \uparrow



Energy
consumption \downarrow

"Triple dividends" of Moore's Law

- Cost
- Performance
- Energy



Changing transistor architecture



Increasing chemical complexity

1970's

hydrogen 1 H 1.0079																		helium 2 He 4.0026												
lithium 3 Li 6.941		beryllium 4 Be 9.0122																		boron 5 B 10.811		carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180				
sodium 11 Na 22.990		magnesium 12 Mg 24.305																		aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948					
potassium 19 K 39.098		calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80											
rubidium 37 Rb 85.468		strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29											
cesium 55 Cs 132.91		barium 56 Ba 137.33	* 57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]											
francium 87 Fr [223]		radium 88 Ra [226]	* 89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [268]	meitnerium 109 Mt [268]	unnilium 110 Uun [271]	ununium 111 Uuu [272]	unbibium 112 Uub [277]	unwequadim 114 Uuq [289]																

* Lanthanide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
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** Actinide series

Increasing chemical complexity

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rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29	
cesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
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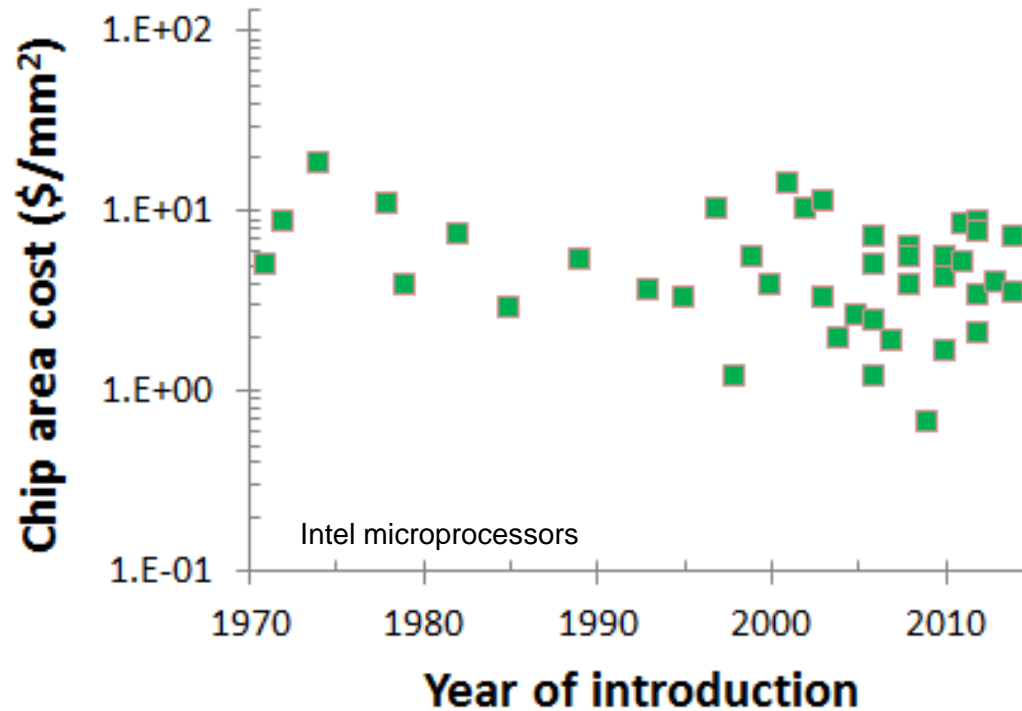
** Actinide series

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Increasing manufacturing complexity

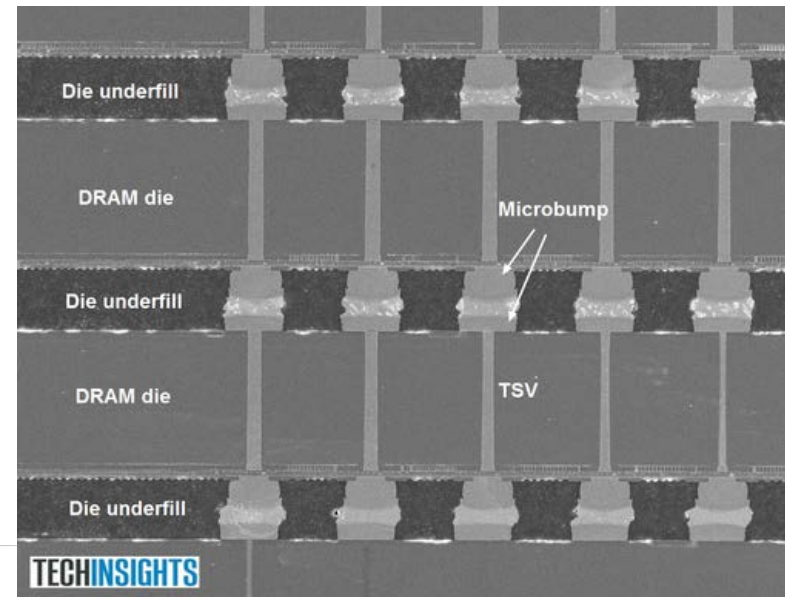
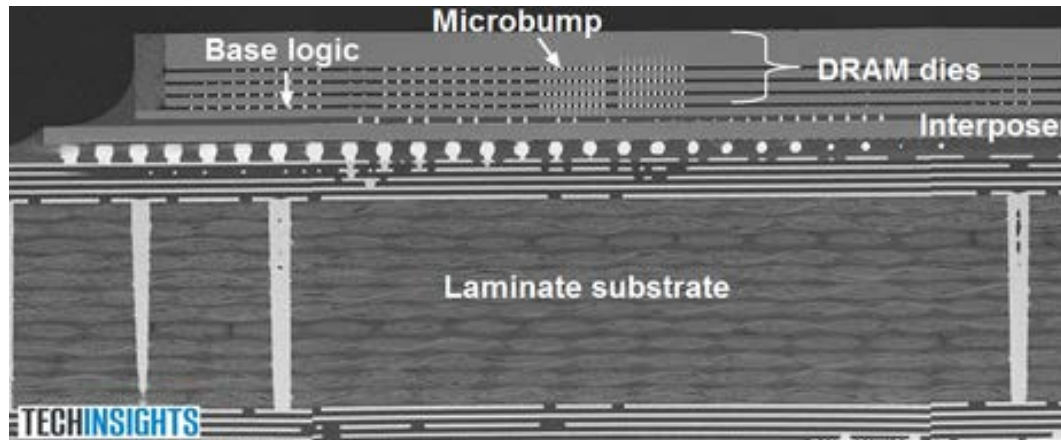
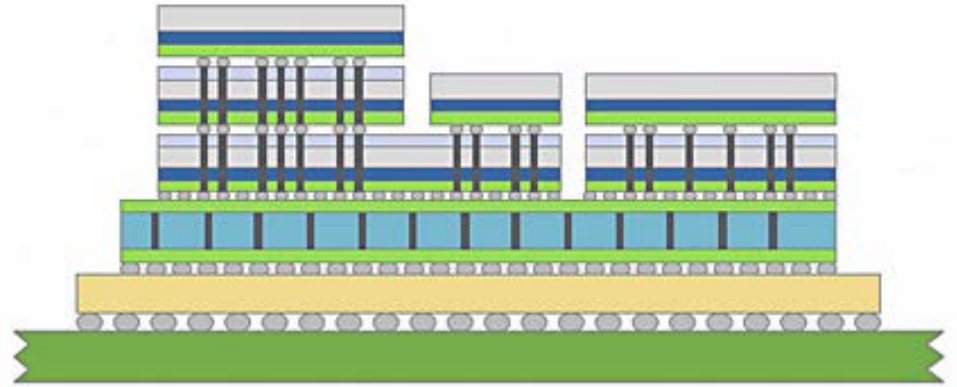
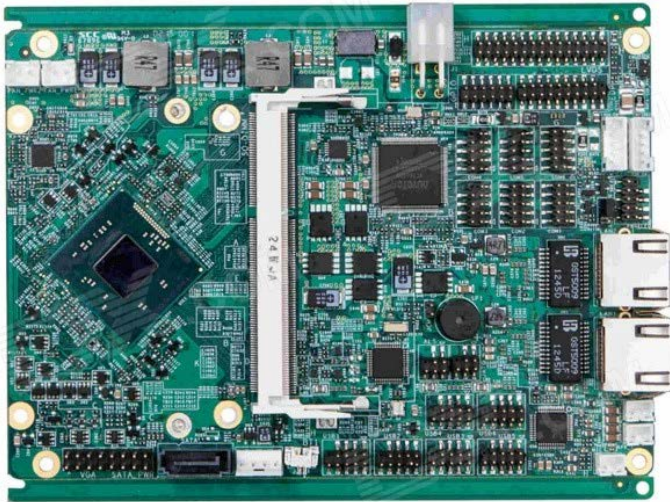


Moore's Law is really about economics





3D System on Chip



Cadence
Hynix

Effective parallel computing

4K-by-4K Matrix Multiplication benchmark
on state-of-the-art Intel processor:

Python

```
for i in xrange(n):  
    for j in xrange(n):  
        for k in xrange(n):  
            C[i][j] += A[i][k] * B[k][j]
```

	Implementation	Time (s)	Speedup
1	Python	25,552.48	1
2	Java	2,372.68	11
3	C	542.67	47
4	Parallel loops	69.80	366
5	Parallel divide-and-conquer	3.80	6,724
6	+ vectorization	1.10	23,230
7	+ AVX intrinsics	0.41	62,323
8	Strassen	0.38	67,243

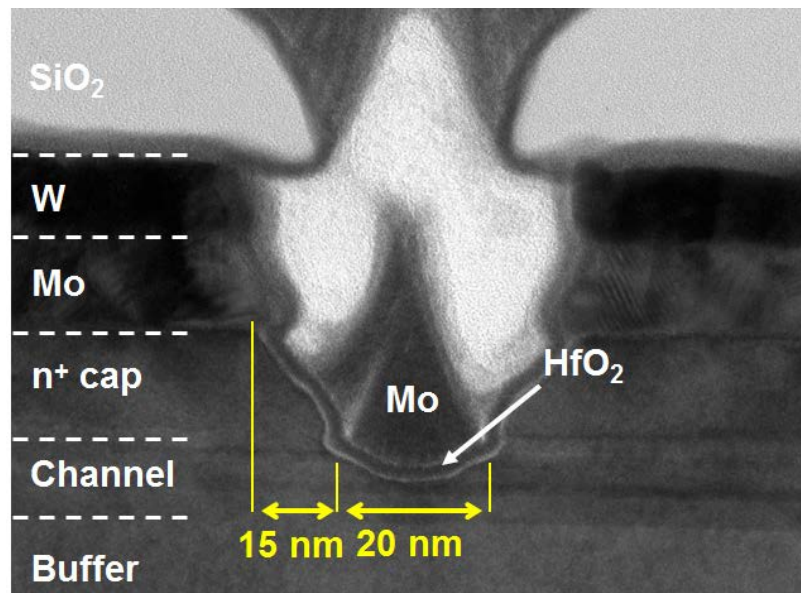
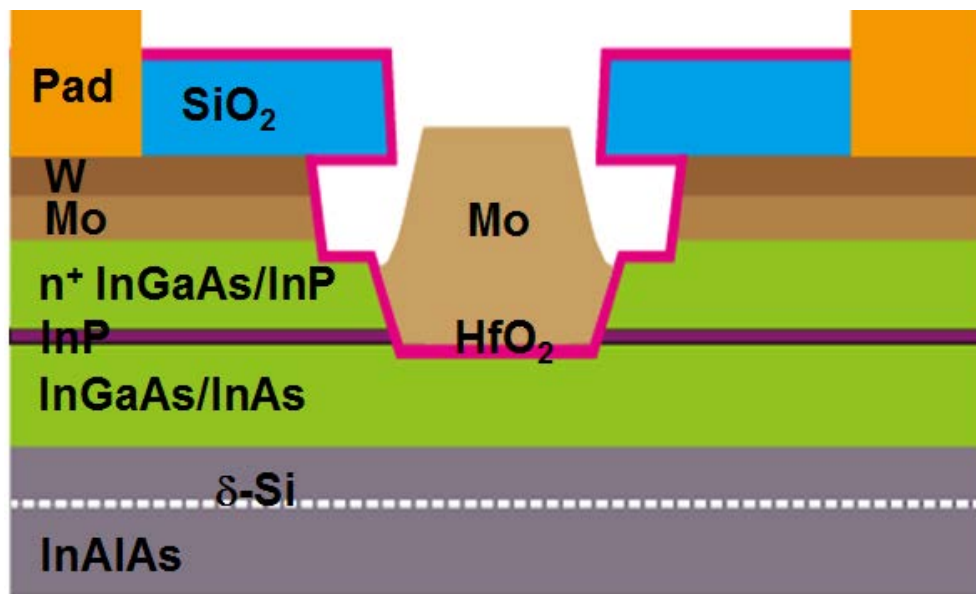
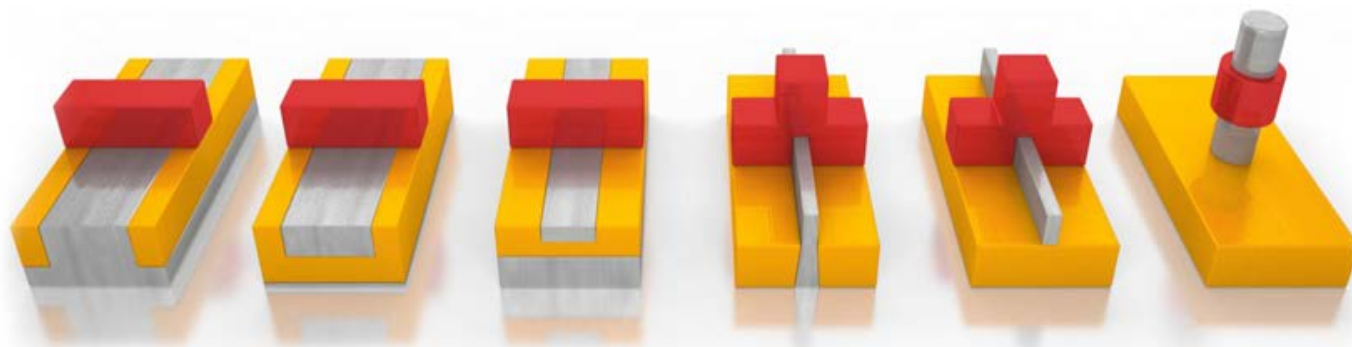
The next computing device?





Jianqiang Lin

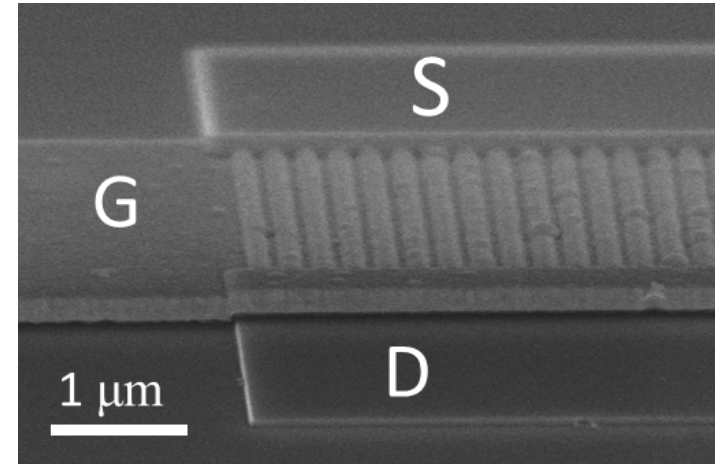
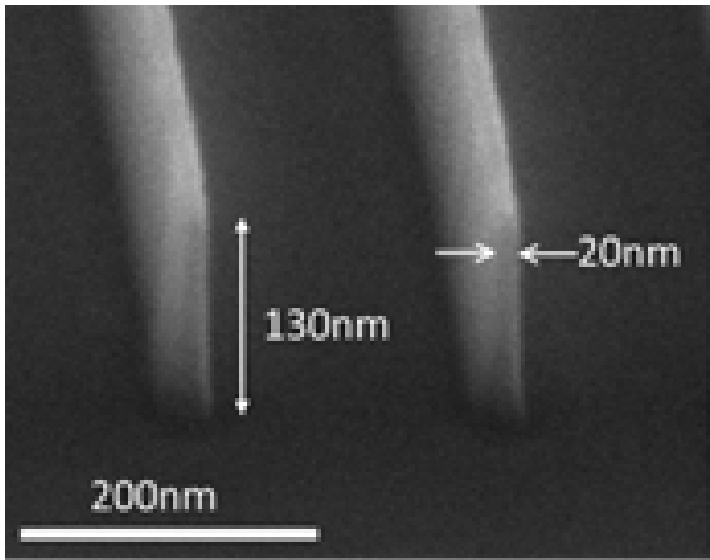
Planar InGaAs MOSFETs





Alon Vardi

InGaAs FinFETs



Vardi, DRC 2014, IEDM 2015

InGaAs Vertical Nanowire MOSFETs

