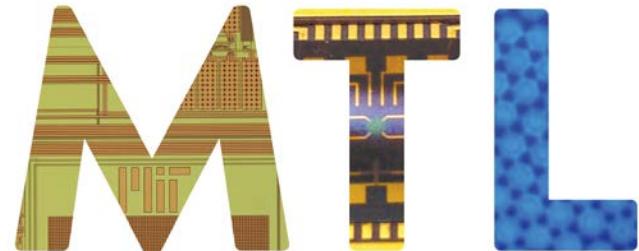


Al 50 aniversario de la Ley de Moore, la nanoelectrónica en una encrucijada

Jesús A. del Alamo

Microsystems Technology Laboratories
Massachusetts Institute of Technology

Universidad Politécnica de Madrid
November 23, 2015

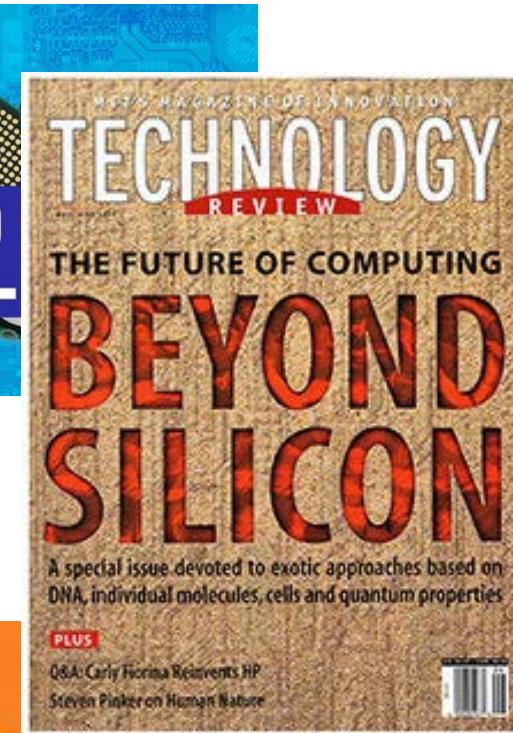
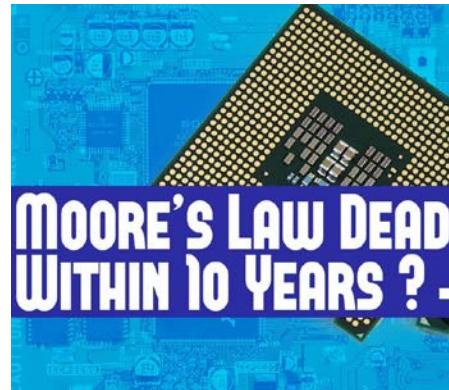
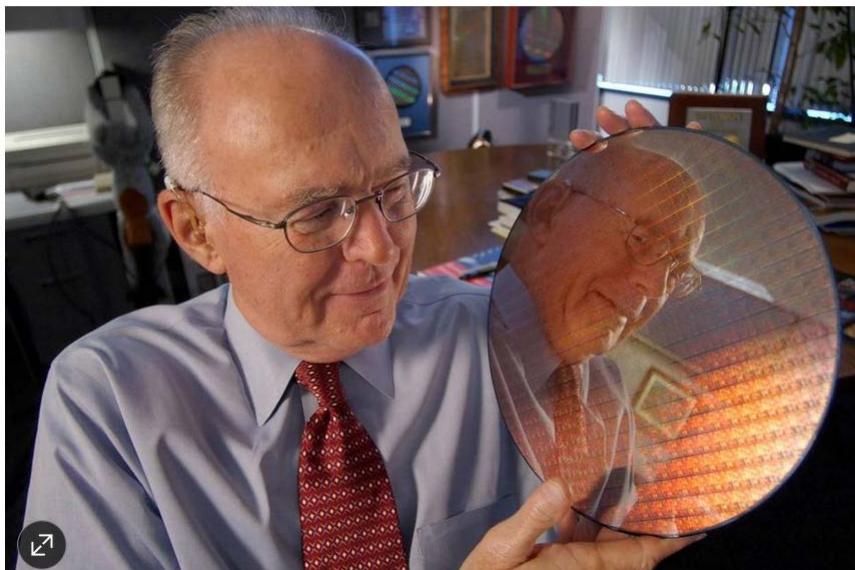


Moore's Law at 50: the end in sight?

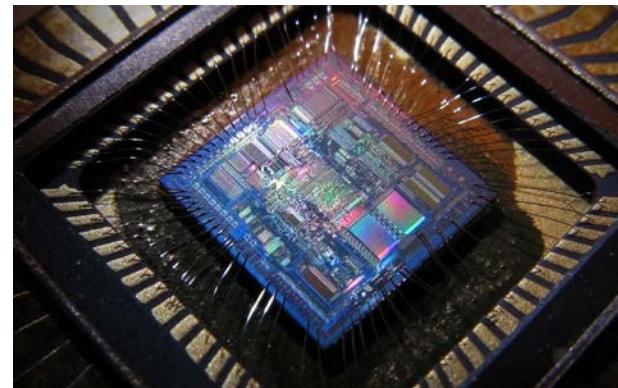
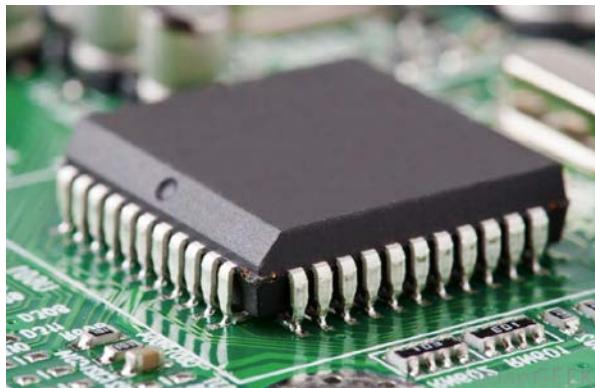
THE WALL STREET JOURNAL

Moore's Law Is Showing Its Age

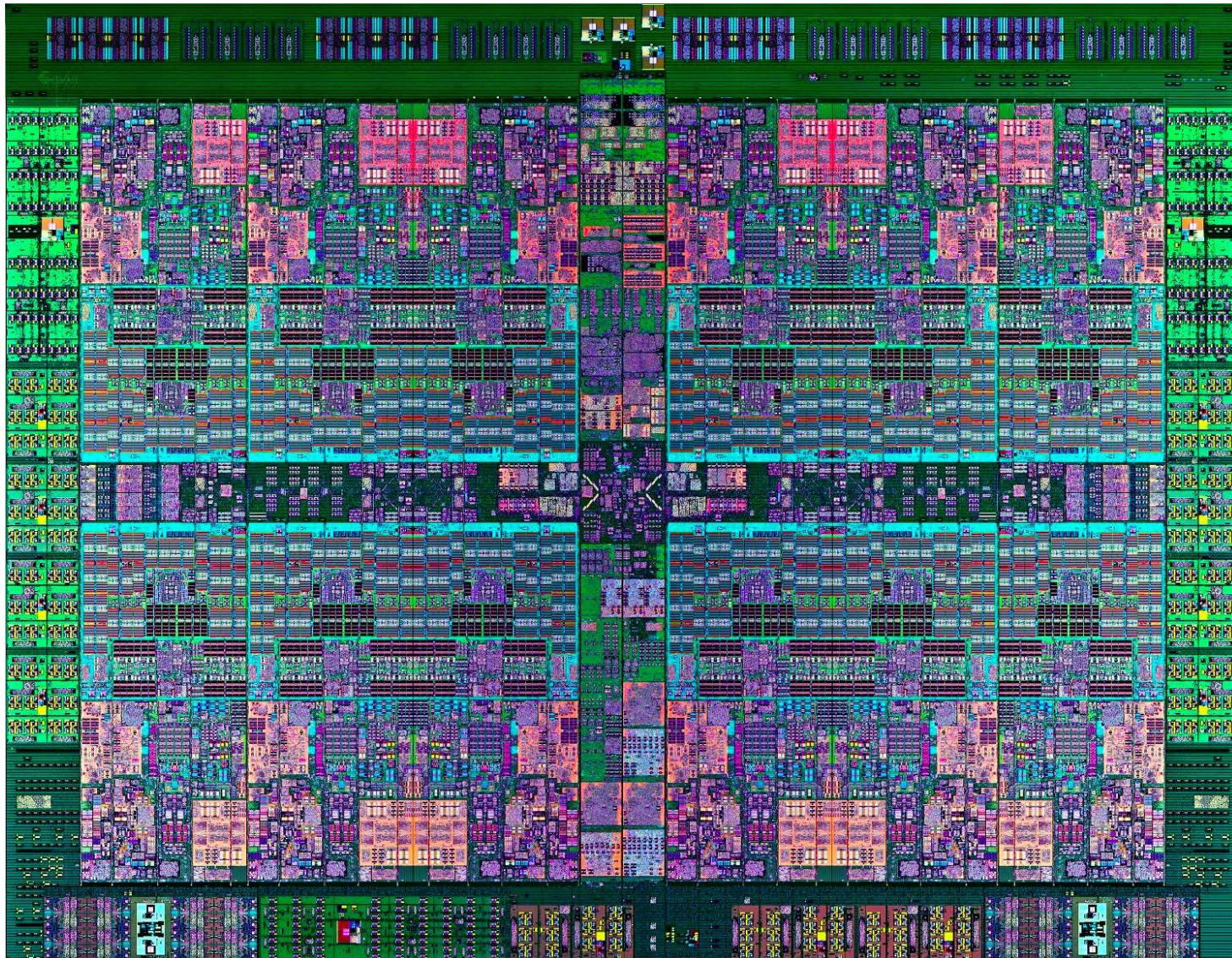
The prediction about squeezing transistors onto silicon has been revised again.



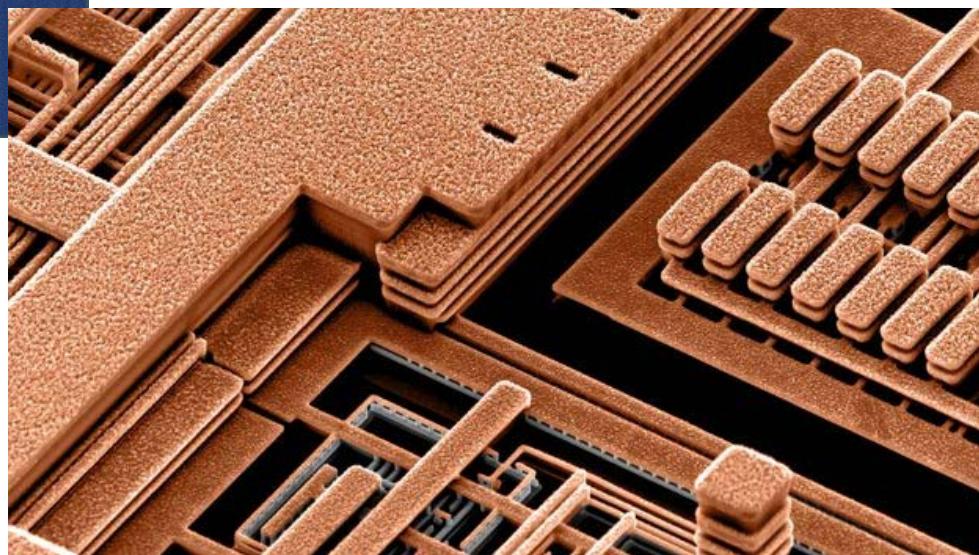
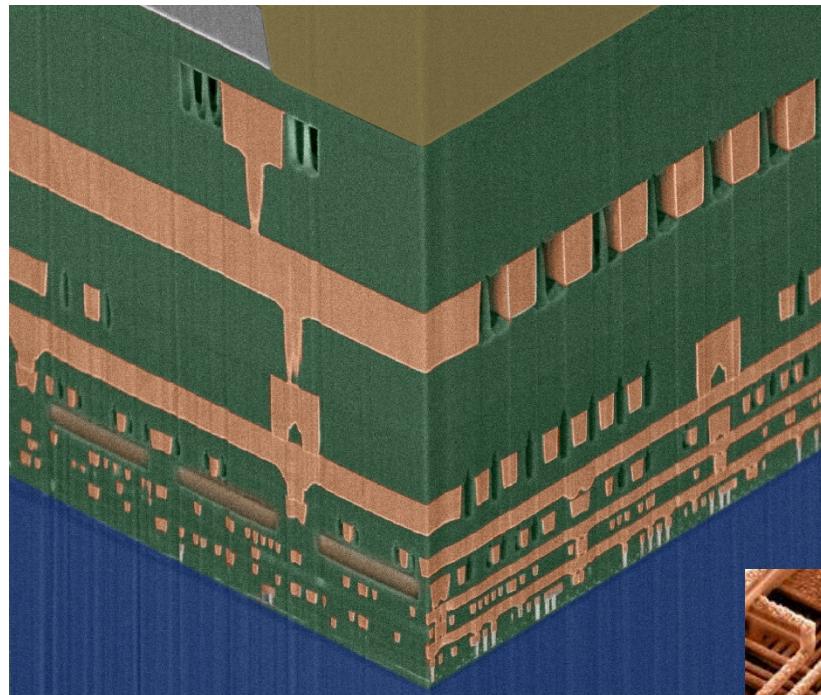
Nanoelectronics: the brains of our information society



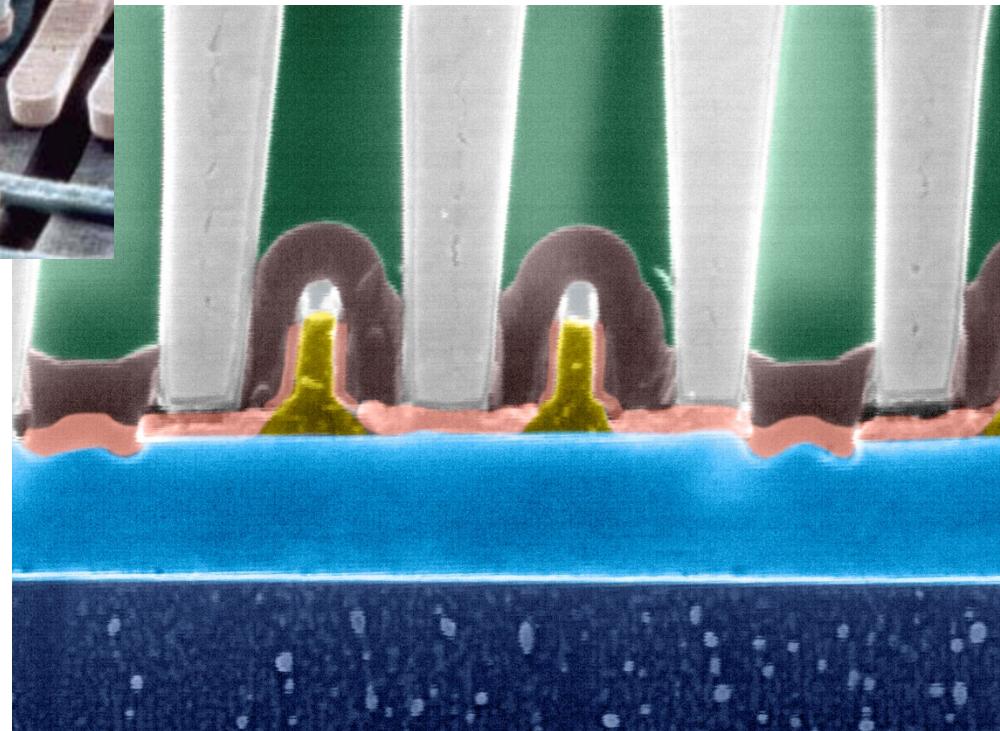
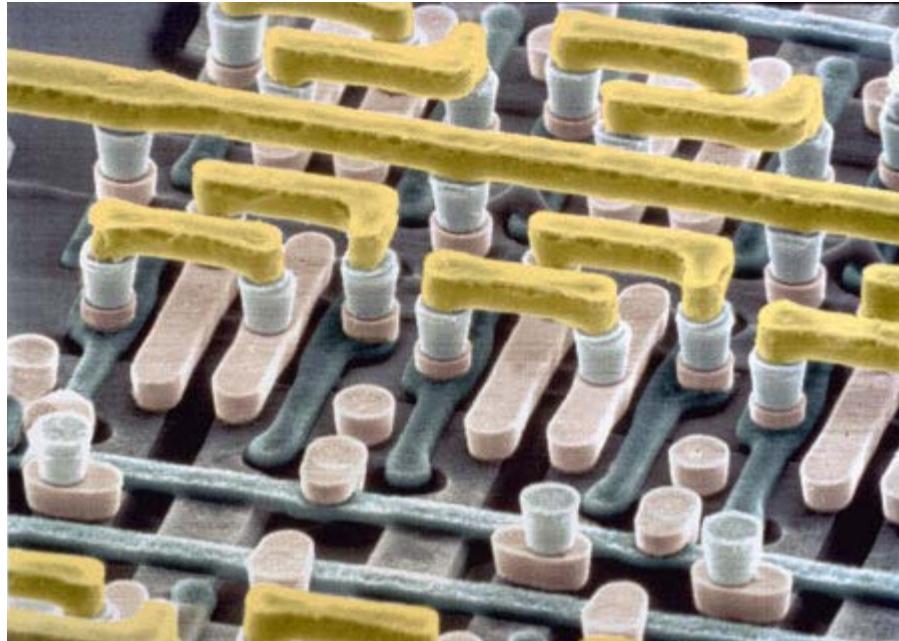
Integrated circuits



Interconnects



Transistors



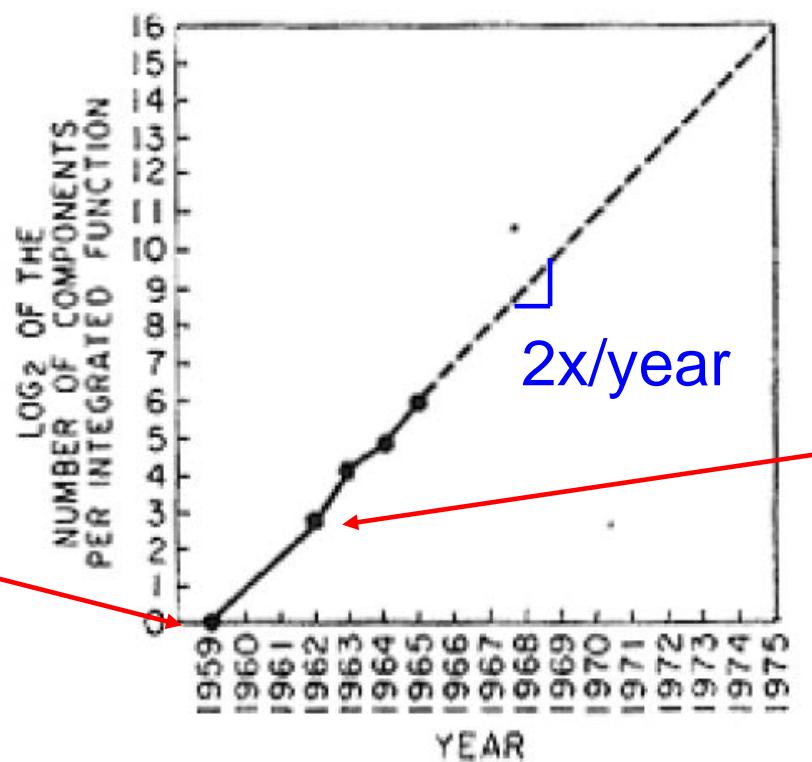
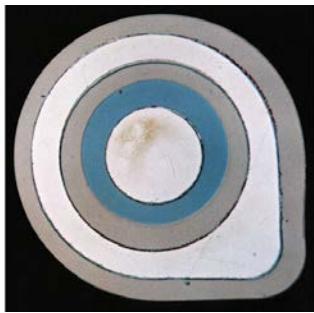
Moore's Law

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

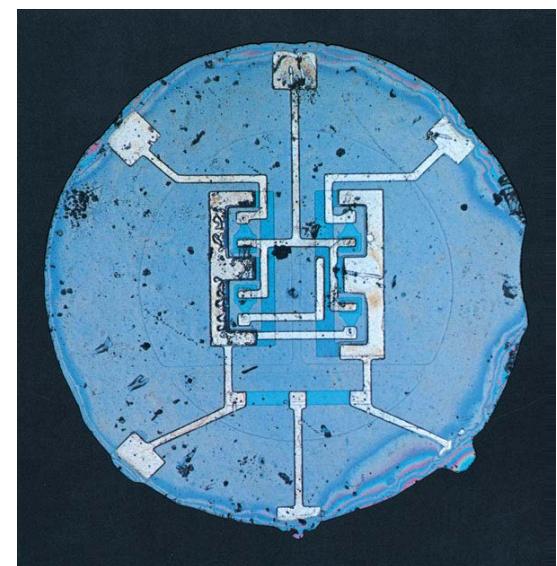
Gordon Moore, IEEE Spectrum 2015

Moore's observation, 1965

first planar
transistor (1959)

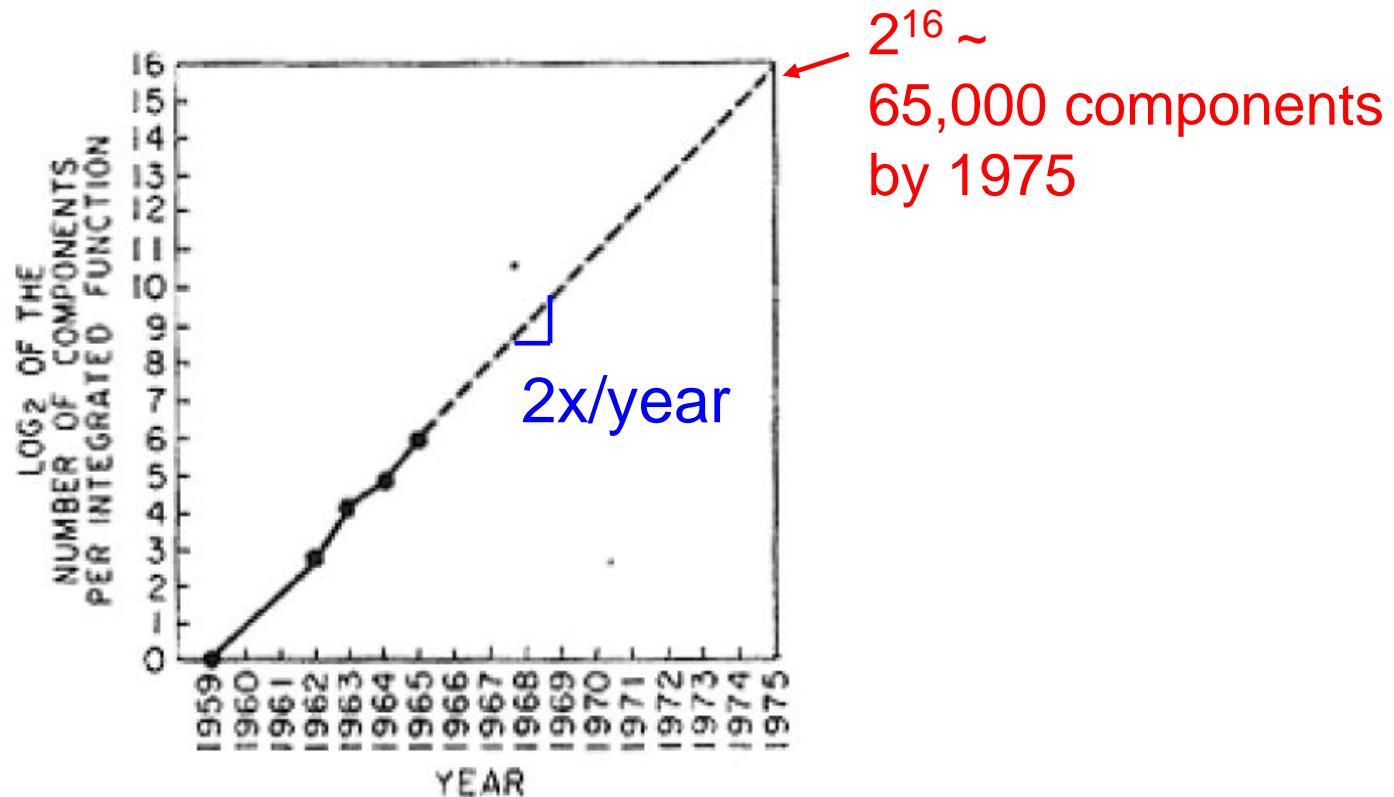


first commercial
integrated circuit (1961)



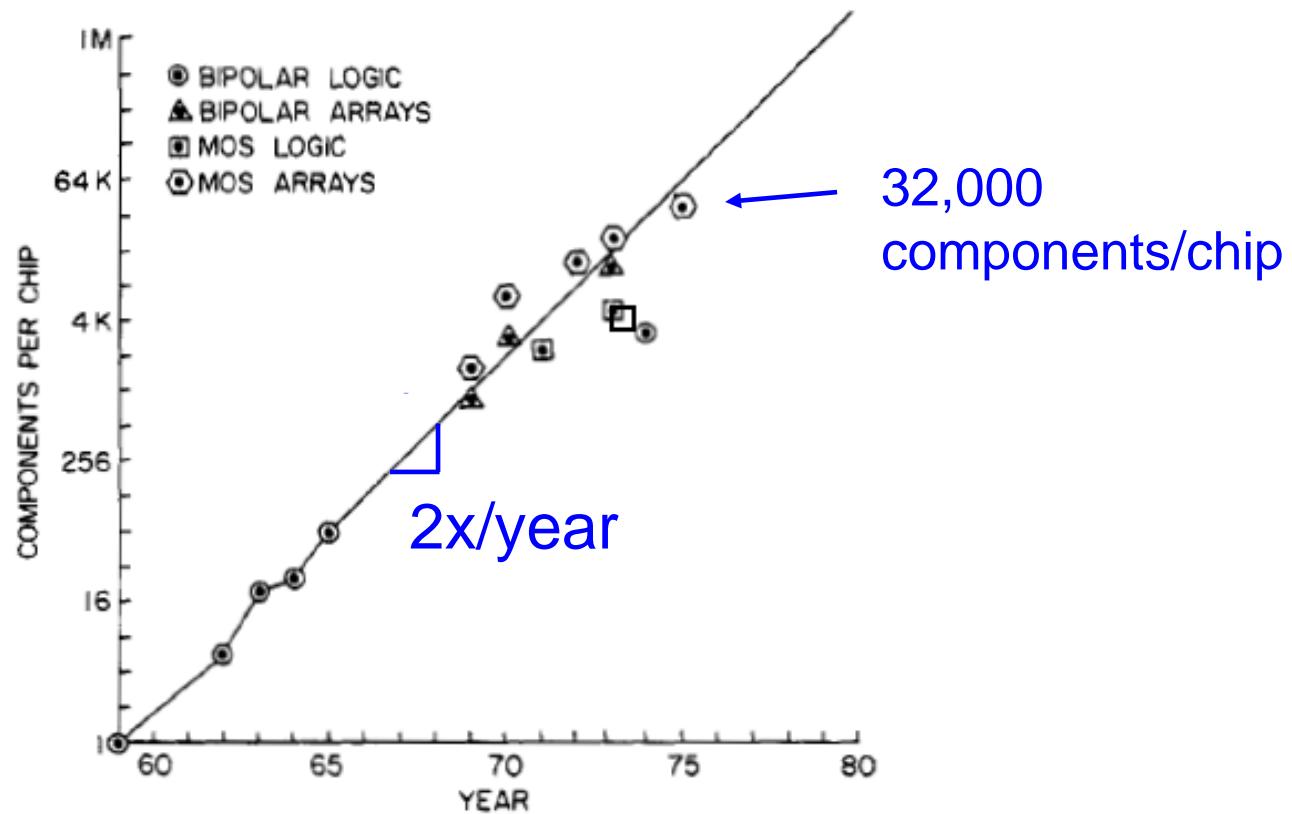
Moore's prediction, 1965

Moore, Electronics 1965

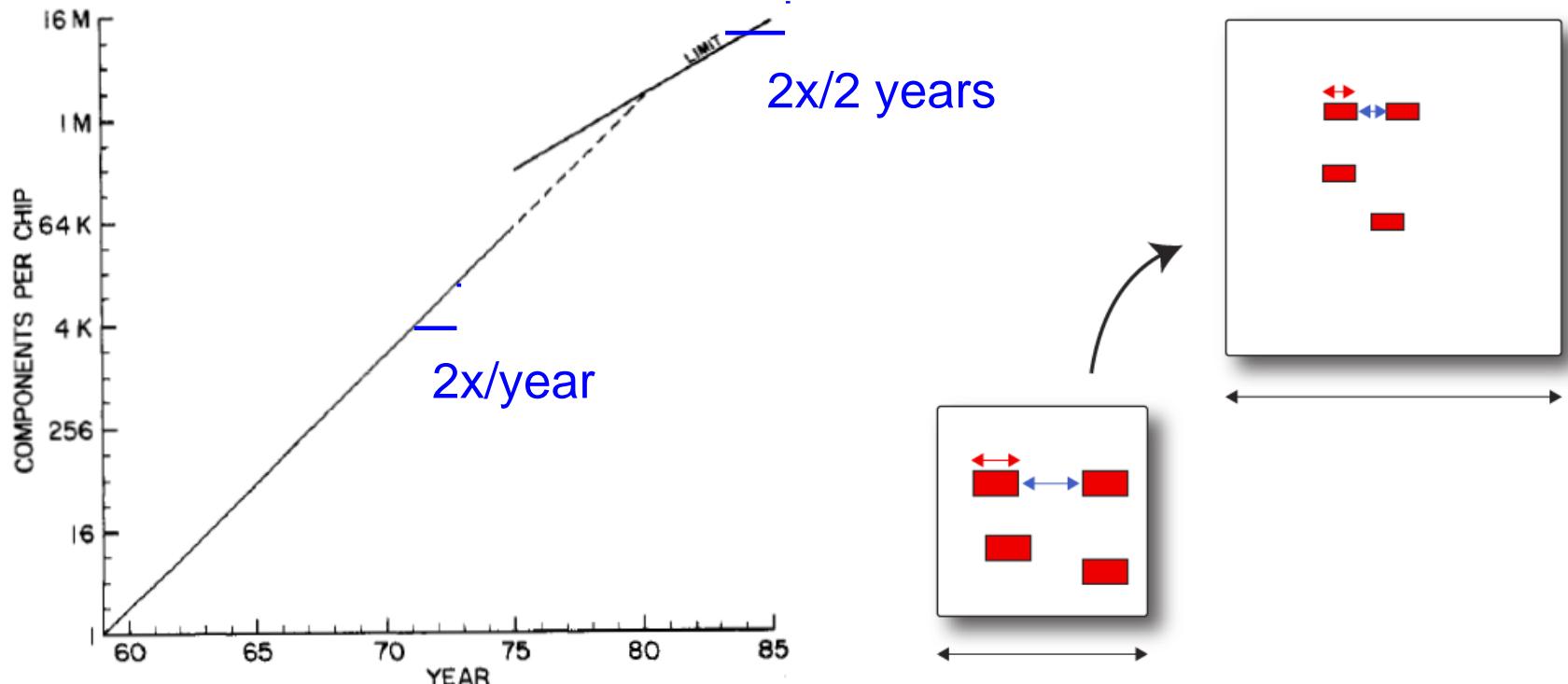


"By 1975, the number of components per integrated circuit for minimum cost will be 65,000."

10 years later...



Moore's revised prediction, 1975



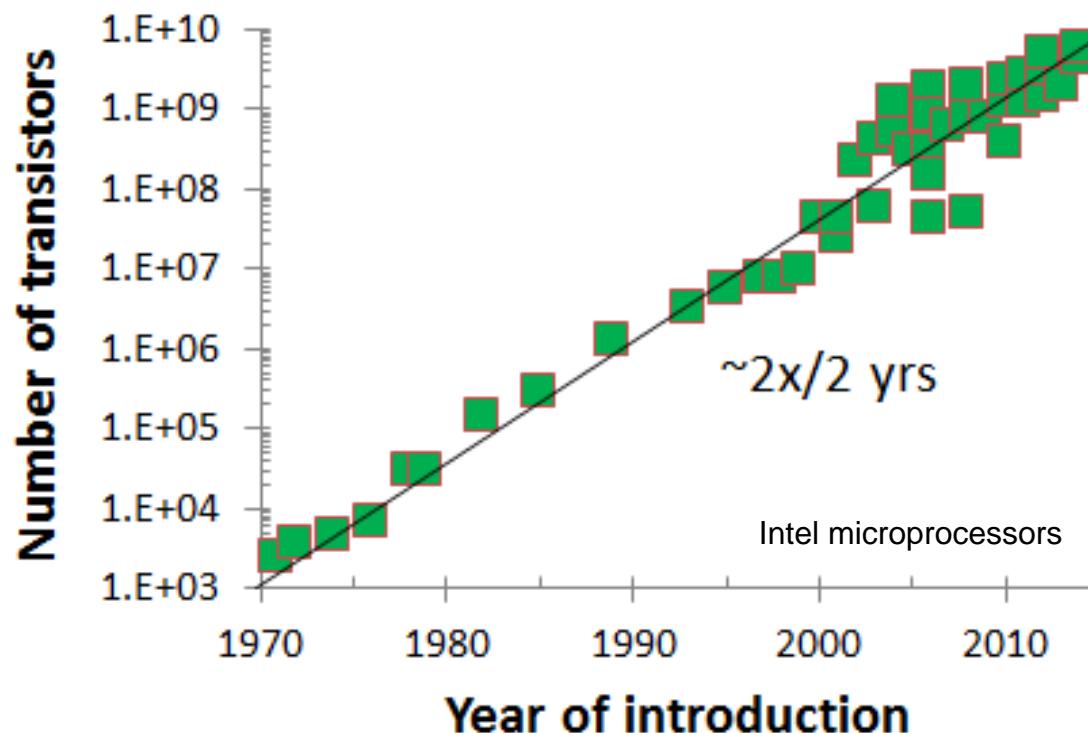
1975 prediction:

Moore, IEDM 1975

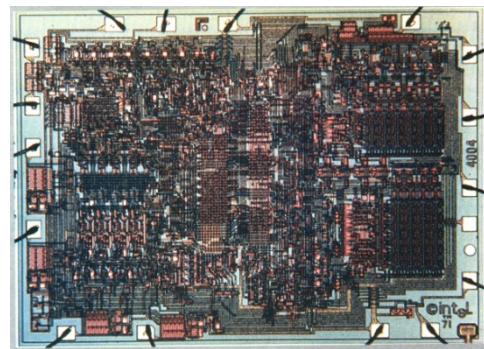
“By the end of the decade, the new slope might approximate a doubling every two years”

Moore's Law: 1970-2015

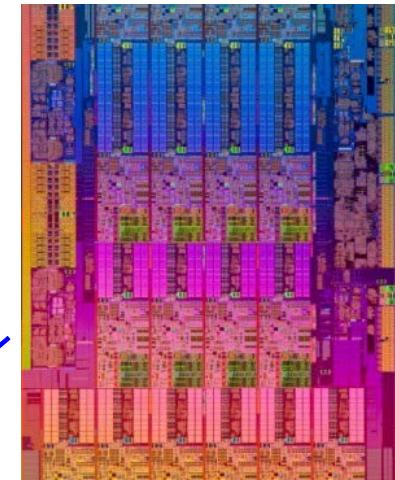
2x/2 years or
>40%/year for 45 years!



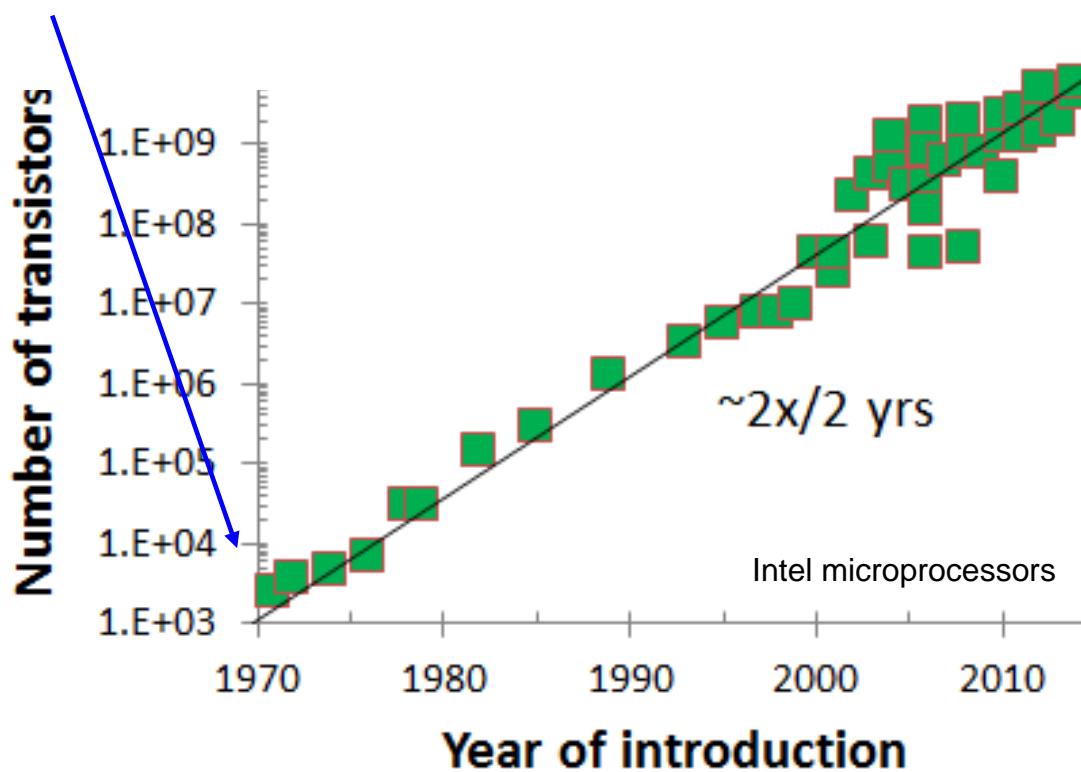
Moore's Law: 1970-2015



1971:
Intel 4004
2250 transistors



2014:
Intel Xeon Haswell-E5
5.6B transistors



After 50 years of Moore's Law



information



medicine



energy



manufacturing



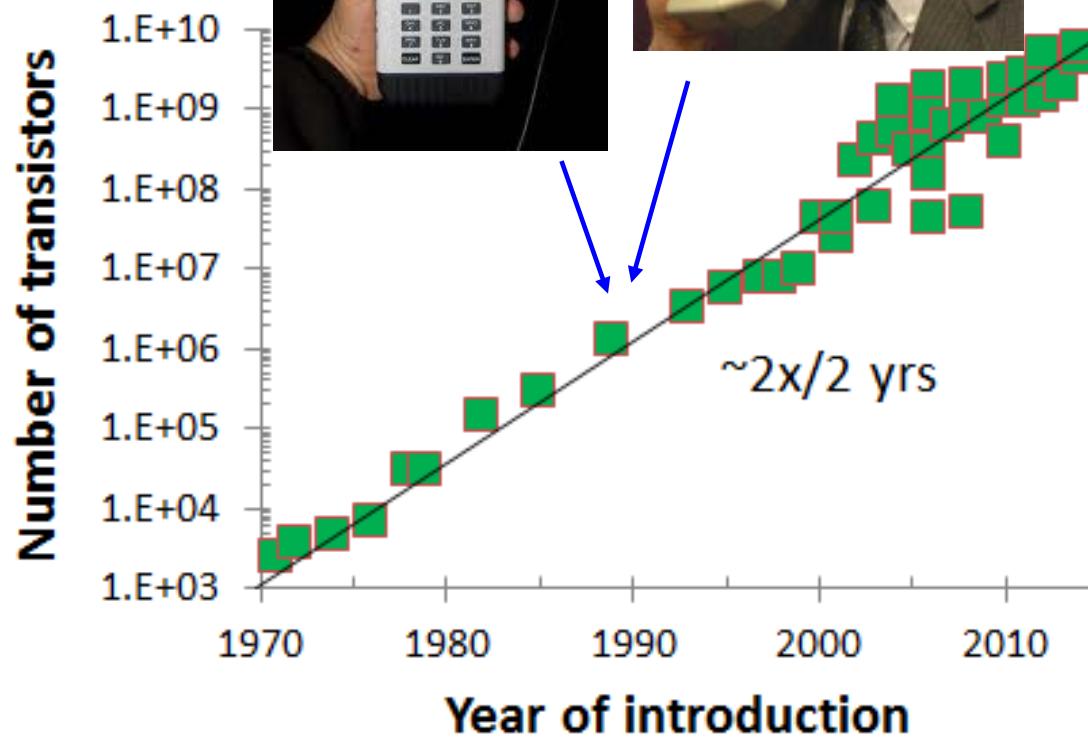
entertainment

What if Moore's Law had stopped in 1990?

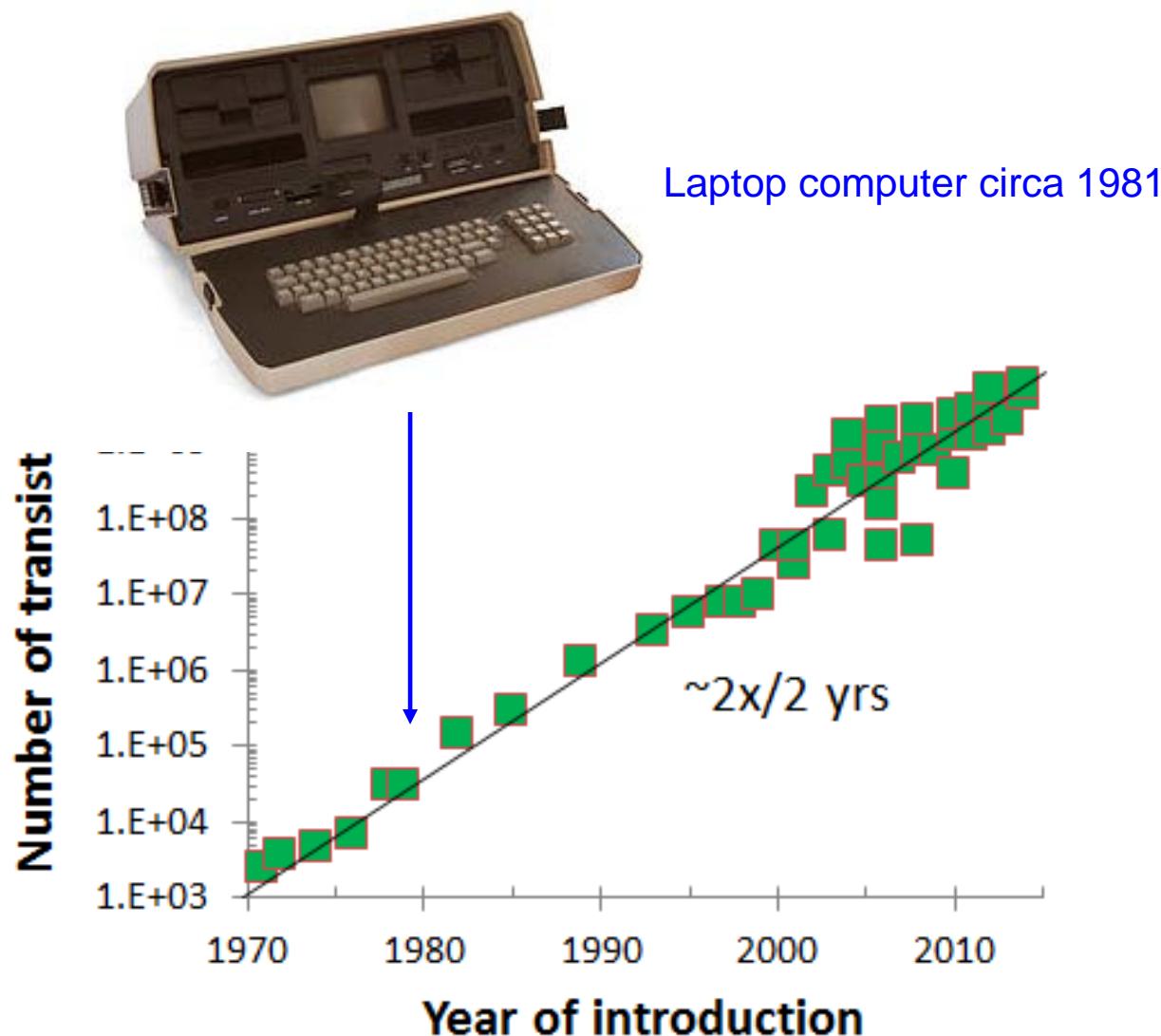
GPS handheld device
circa 1990



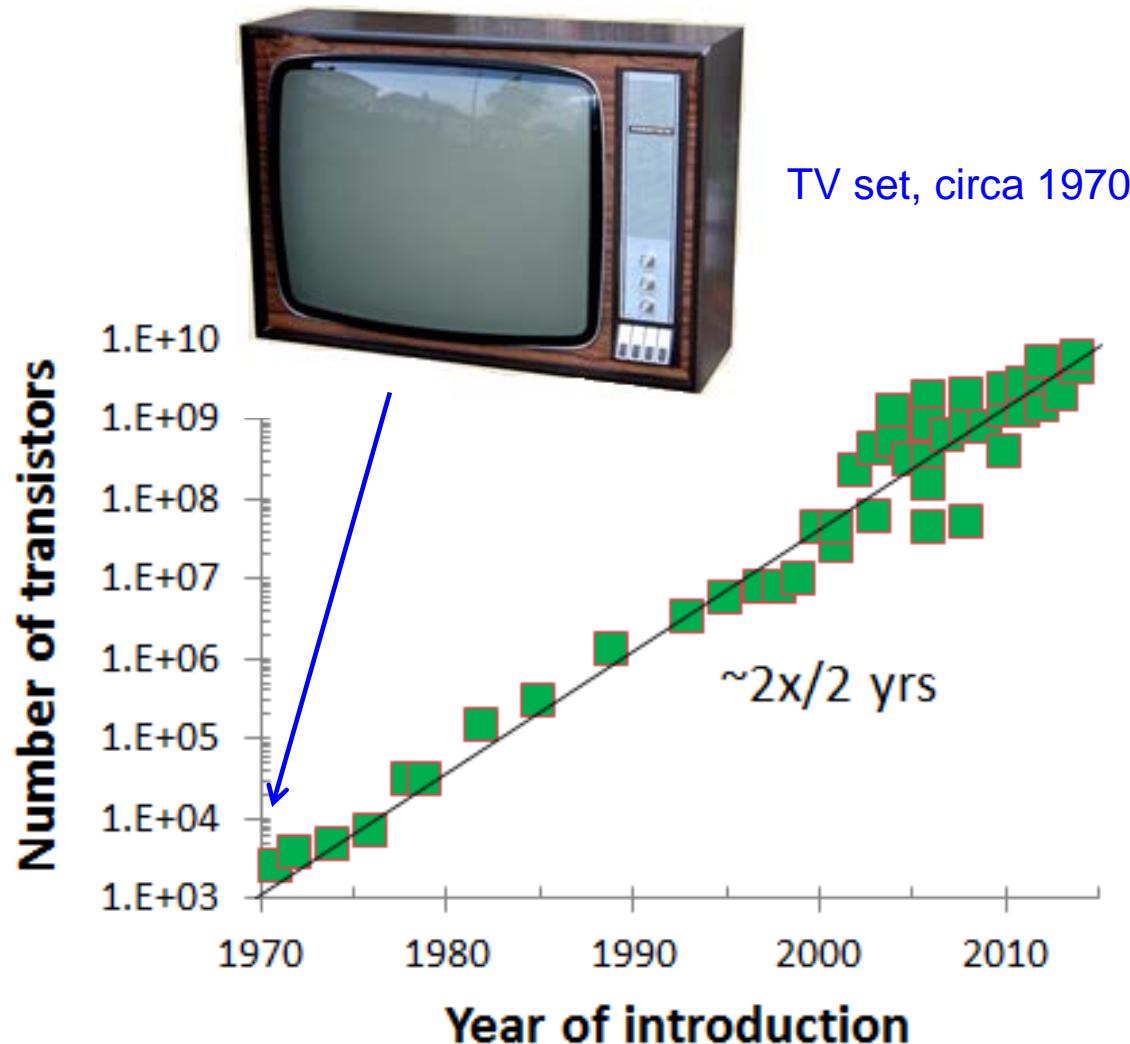
Cell phone circa 1990



What if Moore's Law had stopped in 1980?



What if Moore's Law had stopped in 1970?



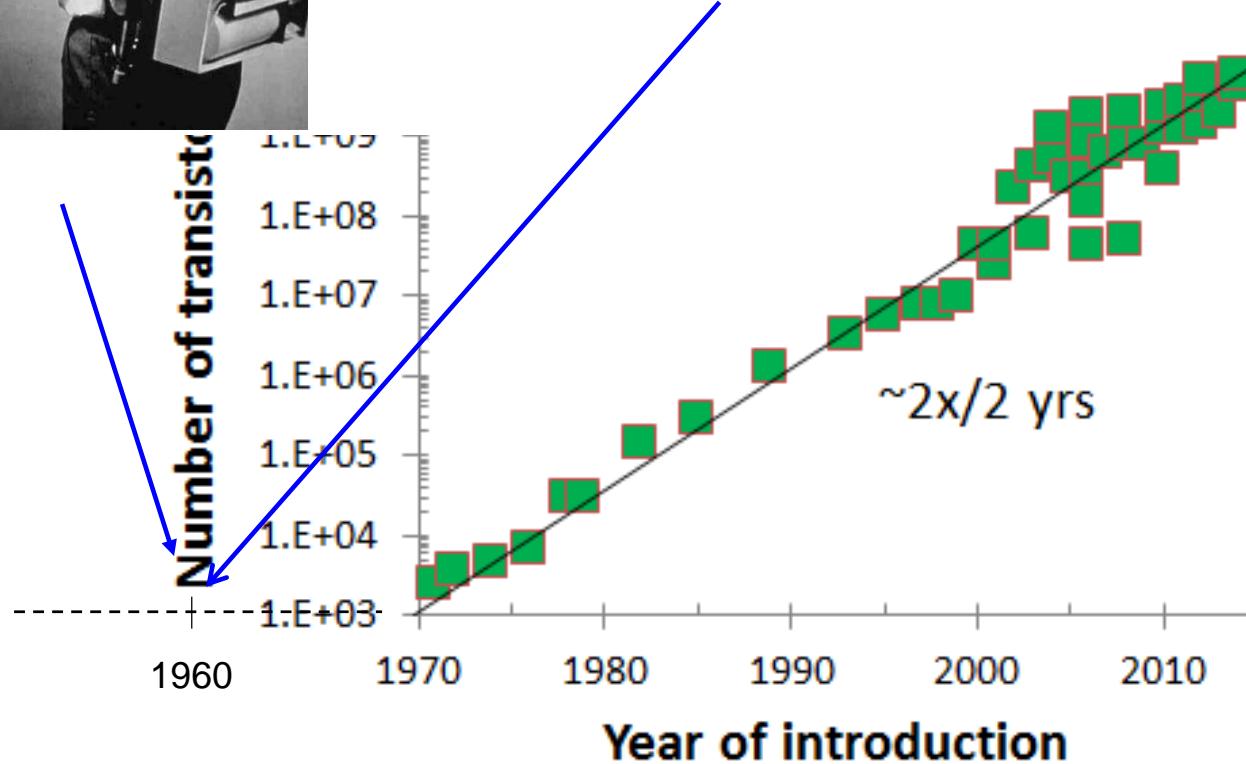
What if Moore's Law had never happened?



Insulin pump circa 1960



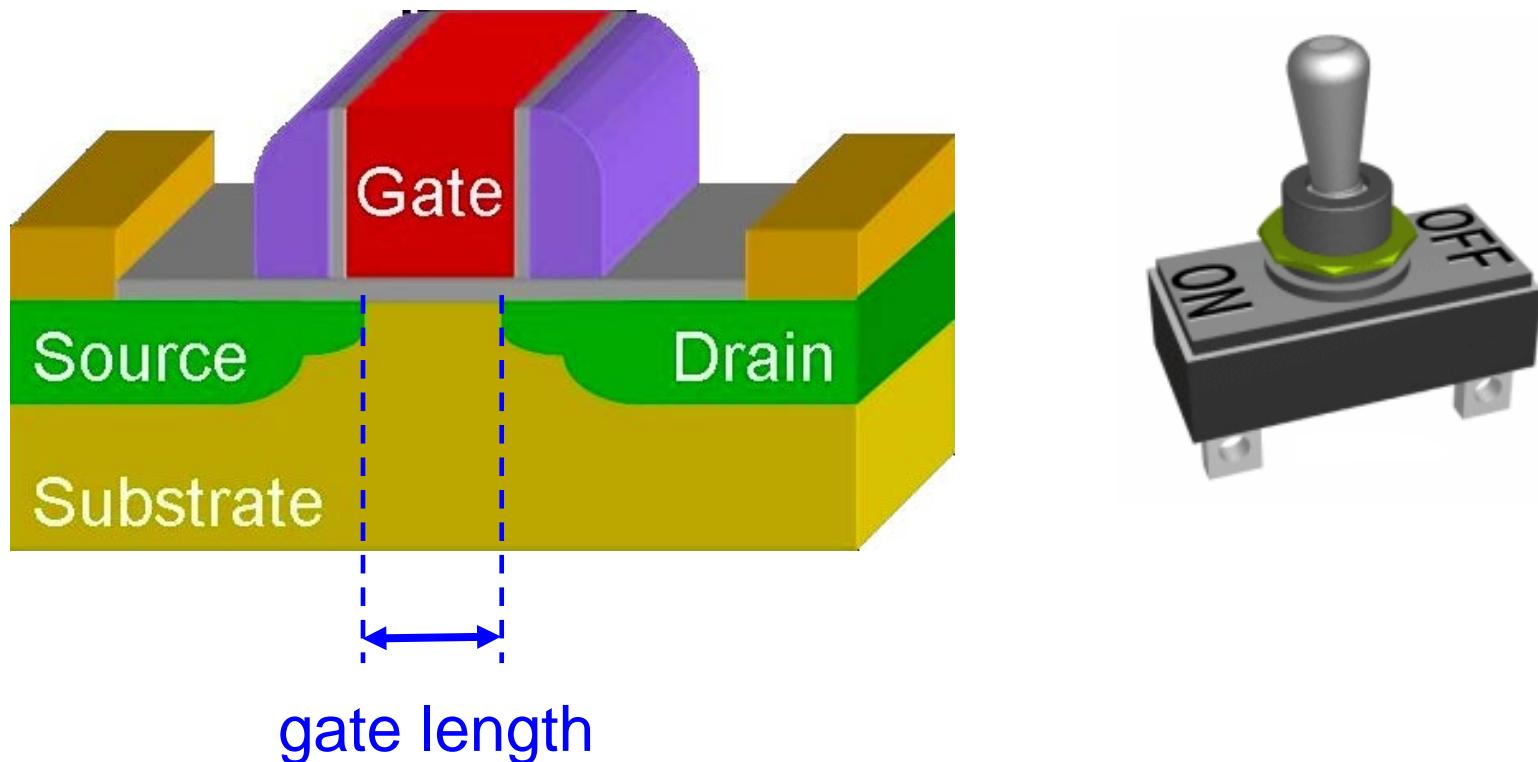
"Personal calculator" circa 1960



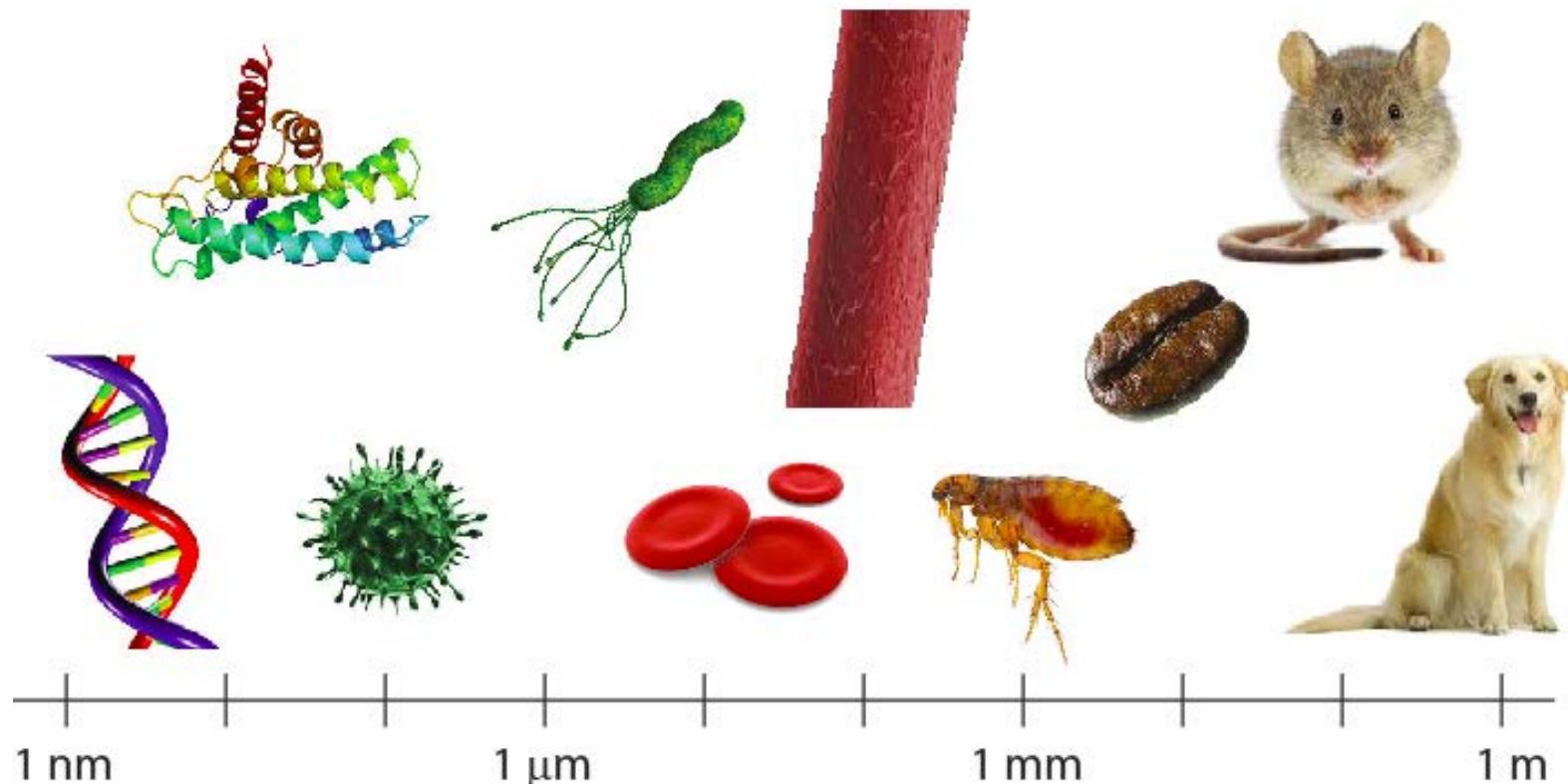
How transistors work

MOSFET =
Metal-Oxide-Semiconductor
Field-Effect Transistor

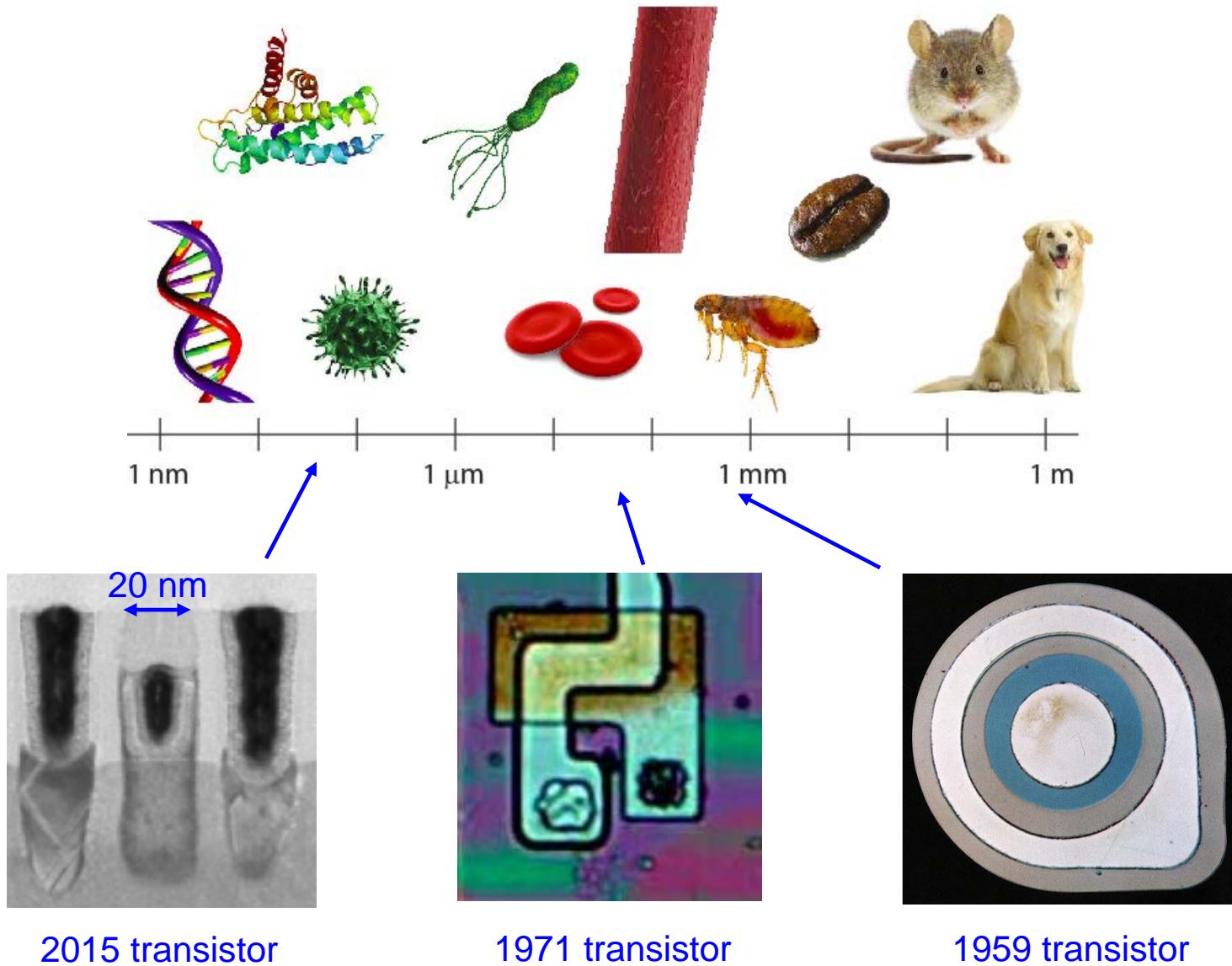
Switch



A sense of scale



A sense of scale



2015 transistor

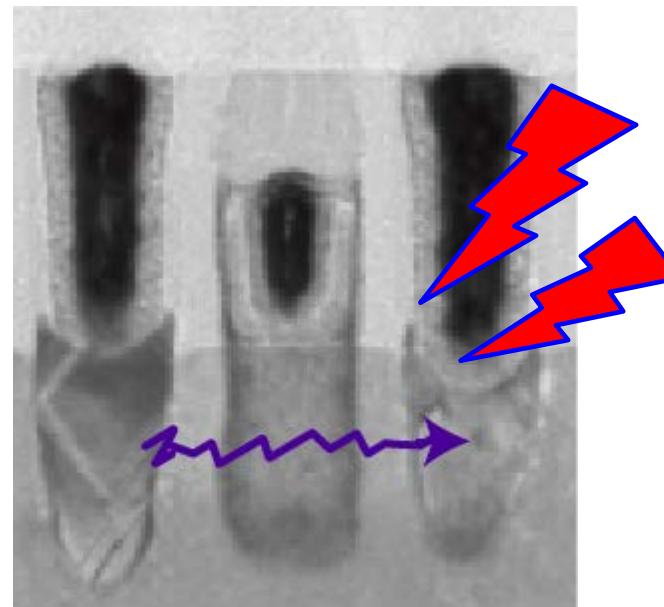
1971 transistor

1959 transistor

Smaller is Better!

MOSFET performance improves as size scales down:

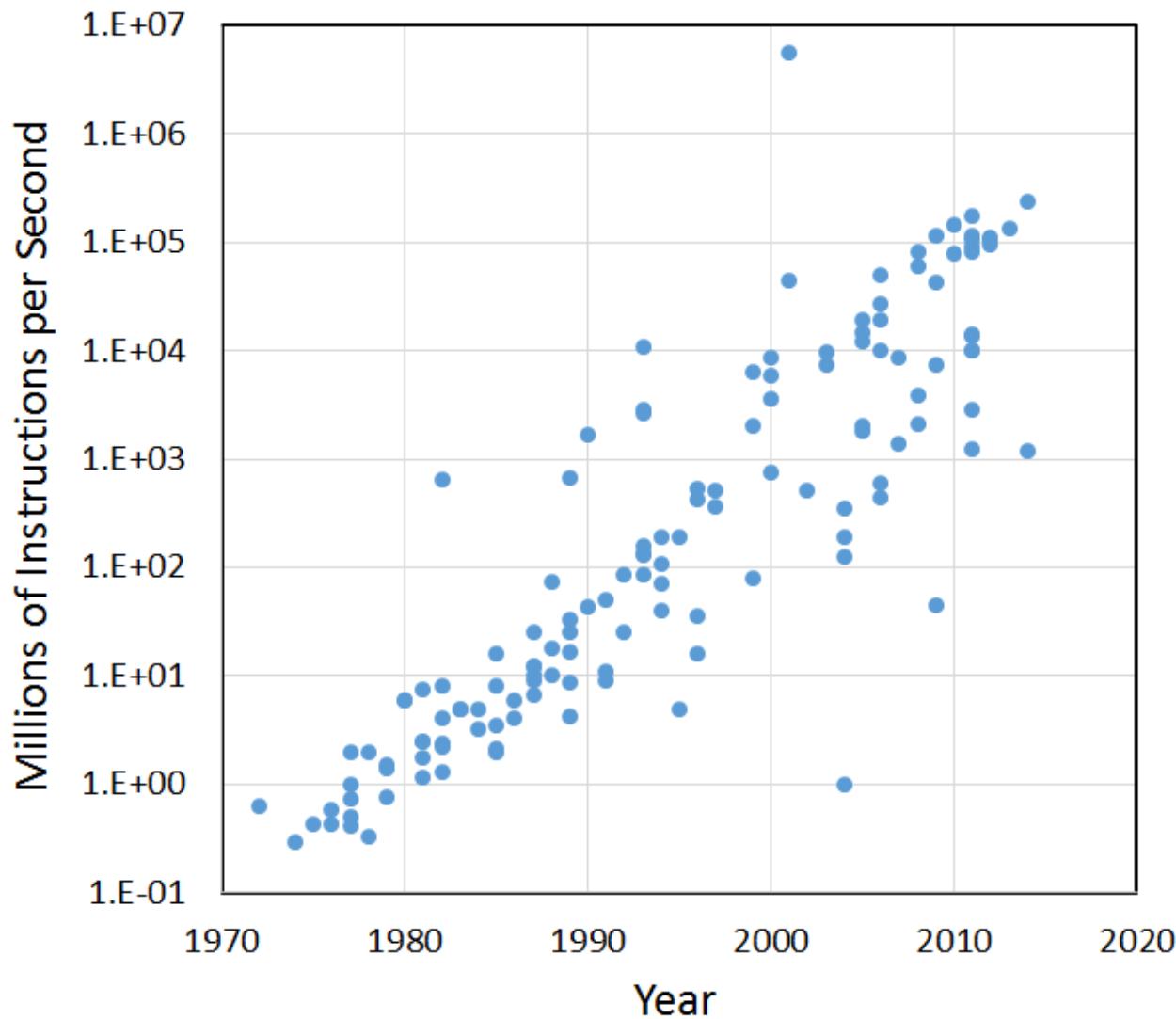
Switching
speed ↑



Energy
consumption ↓

“Triple dividends” of Moore’s Law

- Cost
- Performance
- Energy



Changing transistor architecture



Increasing chemical complexity

1970's

hydrogen 1 H 1.0079	lithium 3 Li 6.941	beryllium 4 Be 9.0122
sodium 11 Na 22.990	magnesium 12 Mg 24.305	
potassium 19 K 39.098	calcium 20 Ca 40.078	
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **

hydrogen 1 H 1.0079	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	helium 2 He 4.0026
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	neon 10 Ne 20.180
potassium 19 K 39.098	calcium 20 Ca 40.078		gallium 31 Ga 69.723	germanium 32 Ge 72.61	tin 33 As 74.922	arsenic 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	antimony 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70	thallium 81 Tl 194.38	mercury 80 Hg 204.59	thallium 82 Pb 207.2	lead 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lutetium 103 Lr [262]	hafnium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [263]	bohrium 107 Bh [264]	hassium 108 Hs [265]
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	euroopium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [246]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]
lanthanide series	europium 63 Eu 151.96	europium 64 Gd 157.25	europium 65 Tb 162.50	europium 66 Dy 164.93	europium 67 Ho 167.26	europium 68 Er 168.93	europium 69 Tm 173.04	europium 70 Yb 173.04
actinide series	curium 96 Cm [247]	curium 97 Bk [247]	curium 98 Cf [247]	curium 99 Es [255]	curium 100 Fm [257]	curium 101 Md [258]	curium 102 No [258]	curium 103 Unq [269]

Increasing chemical complexity

1980's

hydrogen 1 H 1.0079	lithium 3 Li 6.941	beryllium 4 Be 9.0122
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potassium 19 K 39.098	strontium 38 Sr 85.468	barium 56 Ba 132.91
rubidium 37 Rb 87.62	yttrium 39 Y 88.906	lanthanum 57 Lu 137.33
caesium 55 Cs 132.91	zirconium 40 Zr 91.224	hafnium 71 Hf 174.97
francium 87 Fr [223]	niobium 41 Nb 92.906	tantalum 72 Ta 178.49
	chromium 24 Cr 50.942	tungsten 74 W 180.95
	manganese 25 Mn 54.938	rhodium 43 Tc 183.84
	iron 26 Fe 55.845	osmium 76 Os 186.21
	cobalt 27 Co 58.903	iridium 77 Ir 190.23
	nickel 28 Ni 58.693	platinum 46 Pt 192.22
	copper 29 Cu 63.546	gold 78 Au 196.97
	zinc 30 Zn 65.39	mercury 80 Hg 196.97
	gallium 31 Ga 69.723	thallium 81 Tl 199.59
	germanium 32 Ge 72.61	lead 82 Pb 204.38
	arsenic 33 As 74.902	tin 50 Sn 121.76
	selenium 34 Se 78.96	antimony 51 Sb 127.60
	bromine 35 Br 79.904	tellurium 52 Te 126.90
	iodine 36 Xe 131.29	iodine 53 I 131.29
	xenon 37 Kr 131.29	radon 86 Rn [222]

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
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
gallium 31 Ga 69.723	germanium 32 Ge 72.61	cadmium 48 Cd 112.41	germanium 33 As 74.902	selenium 34 Se 78.96	bromine 35 Br 79.904
indium 49 In 114.82	tin 50 Sn 118.71	tin 50 Sn 118.71	arsenic 36 As 121.76	iodine 53 Te 127.60	iodine 54 I 126.90
thallium 81 Tl 207.2	lead 82 Pb 208.98	lead 82 Pb 208.98	antimony 51 Sb 208.98	polonium 84 Po 209.00	astatine 85 At 210.00
thallium 81 Tl 207.2	lead 82 Pb 208.98	lead 82 Pb 208.98	antimony 51 Sb 208.98	polonium 84 Po 209.00	radon 86 Rn 210.00
ununquadium 114 Uuq [269]					

* 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	europeum 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
actinium 89 Ac [227]	thorium 90 Th [232]	protactinium 91 Pa [231]	uranium 92 U [238]	neptunium 93 Np [237]	plutonium 94 Pu [246]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [255]	einsteinium 99 Es [253]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [258]

Increasing chemical complexity

1990's

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potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.966	titanium 22 Ti 47.867	vandium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.903	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	bromine 35 Br 79.904	selenium 36 Se 83.80	krion 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	caesium 55 Cs 132.91	barium 56 Ba 137.33	lutetium 57-70 * 132.91	hafnium 71 Hf 174.97	hafnium 72 Lu 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 196.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	thorium 83 Bi 208.98	polonium 84 Po 209.0	astatine 85 At 210.0	radon 86 Rn [222]	franum 87 Fr [223]	radium 88 Ra [224]	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	euroopium 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	yterbium 70 Yb 173.04	nobelium 89 Ac [227]	actinium 90 Th 232.04	thorium 91 Pa 231.04	protactinium 92 U 238.03	uranium 93 Np [237]	neptunium 94 Pu [246]	plutonium 95 Am [243]	americium 96 Cm [247]	curium 97 Bk [247]	berkelium 98 Cf [255]	californium 99 Es [253]	einsteinium 100 Fm [257]	fermium 101 Md [258]	monelium 102 No [258]
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Increasing chemical complexity

2000's

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sodium 11 Na 22.990	potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.960	titanium 22 Ti 47.867	vandium 23 V 50.942	chromium 24 Cr 51.960	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.903	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.799	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	broxine 35 Br 79.904	krone 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 92.966	molybdenum 42 Mo 95.94	technetium 43 Tc 98.000	rhodium 44 Ru 101.07	osmium 45 Os 101.91	rhodium 46 Pd 102.42	silver 47 Ag 106.42	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	loxiene 53 I 126.90	xenon 54 Xe 131.29		
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francium 87 Fr [223]	radon 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [263]	bohrium 107 Bh [264]	hassium 108 Hs [265]	meitnerium 109 Mt [266]	unkonium 110 Uun [271]	unkonium 111 Uuu [272]	unkonium 112 Uub [277]	unquadium 114 Uuq [285]						

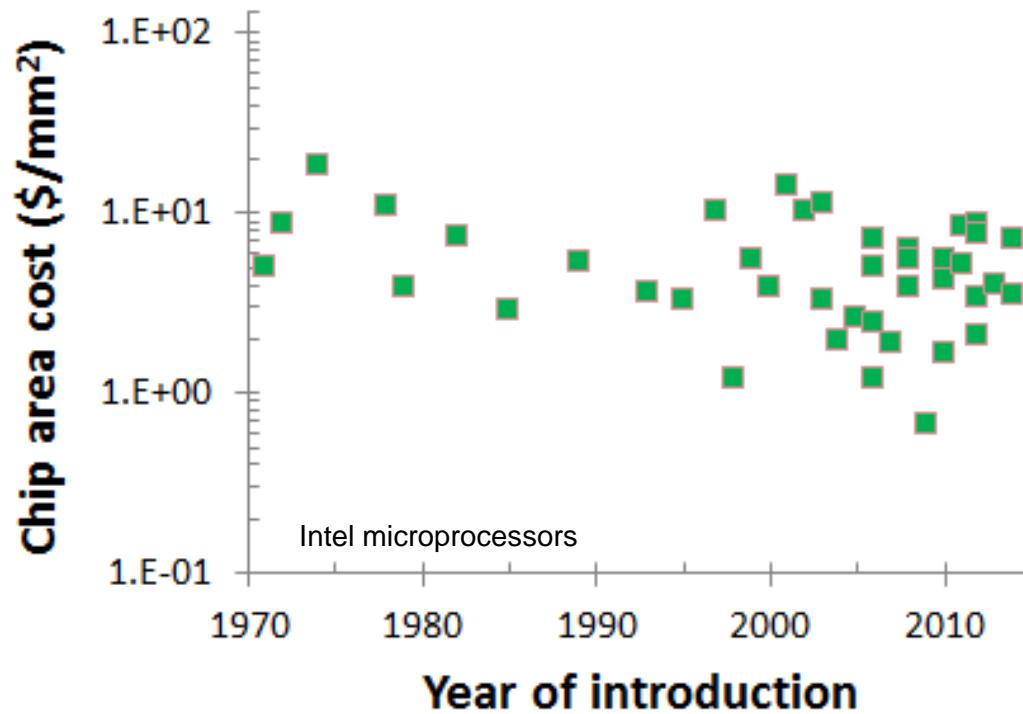
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Increasing manufacturing complexity

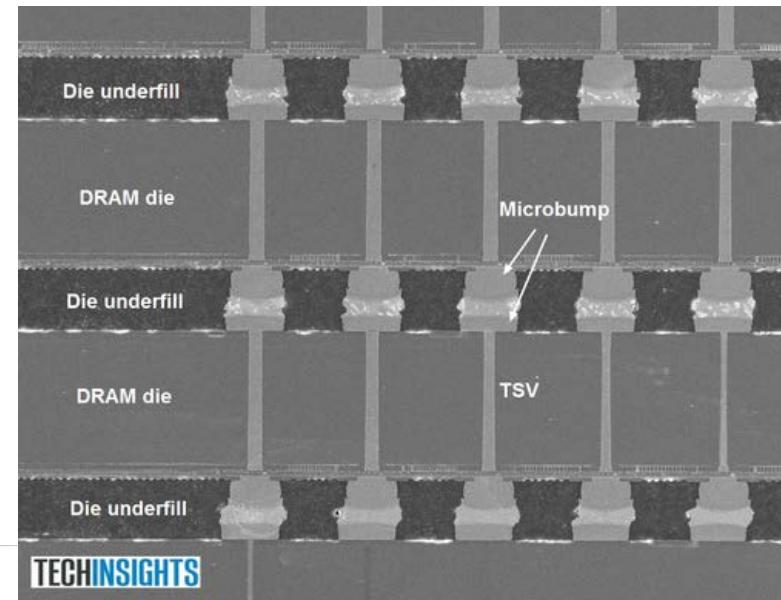
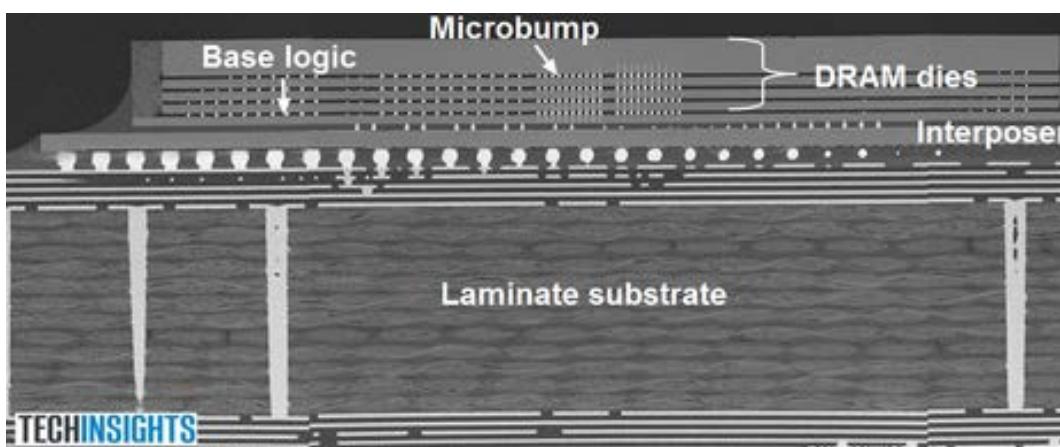
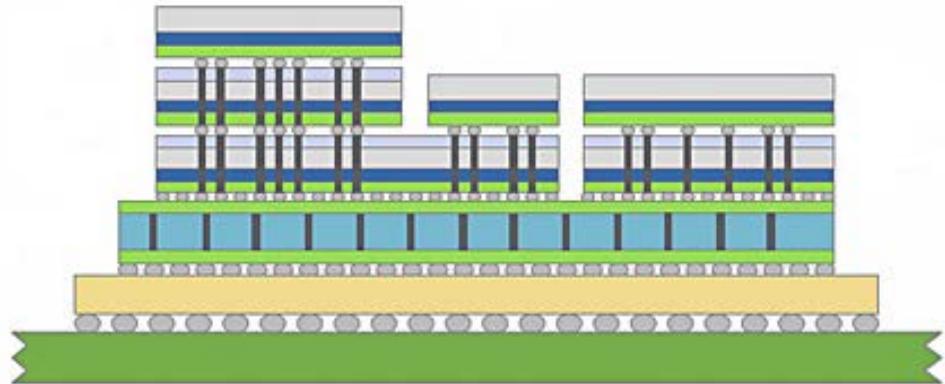


Moore's Law is really about economics





3D System on Chip



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

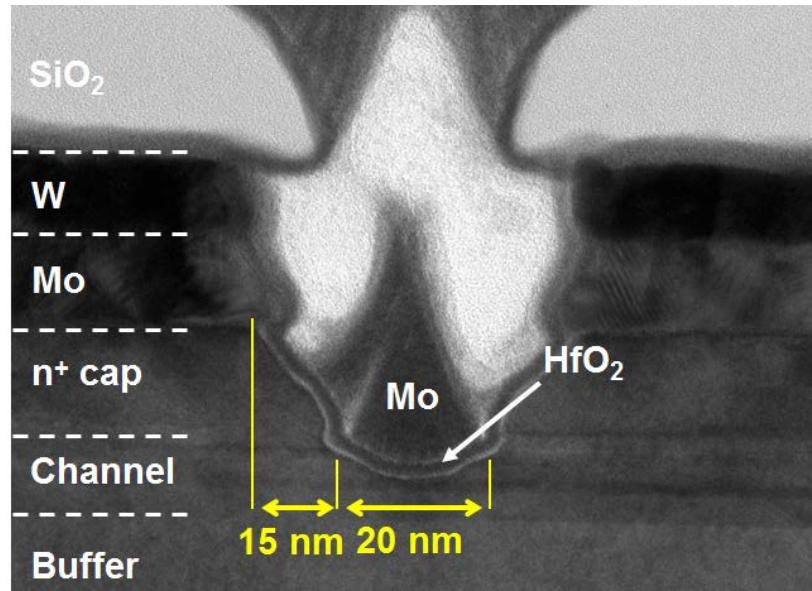
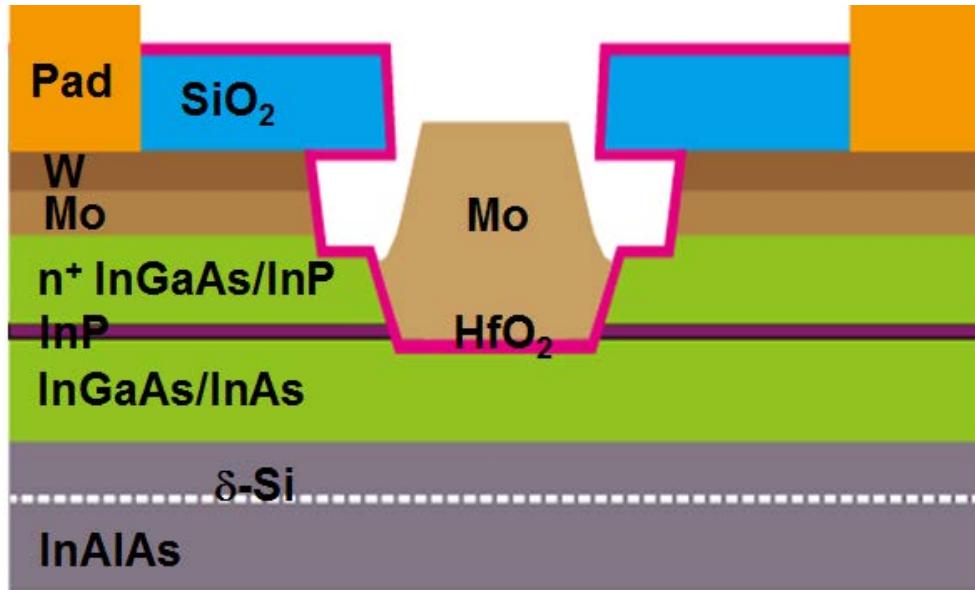
The next computing device?





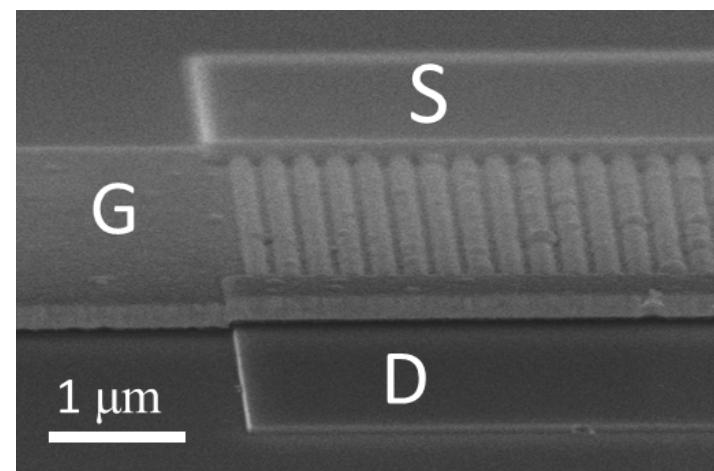
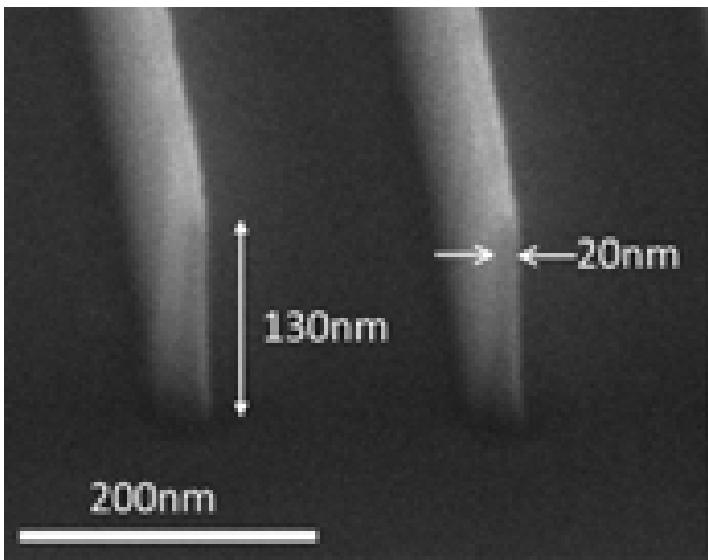
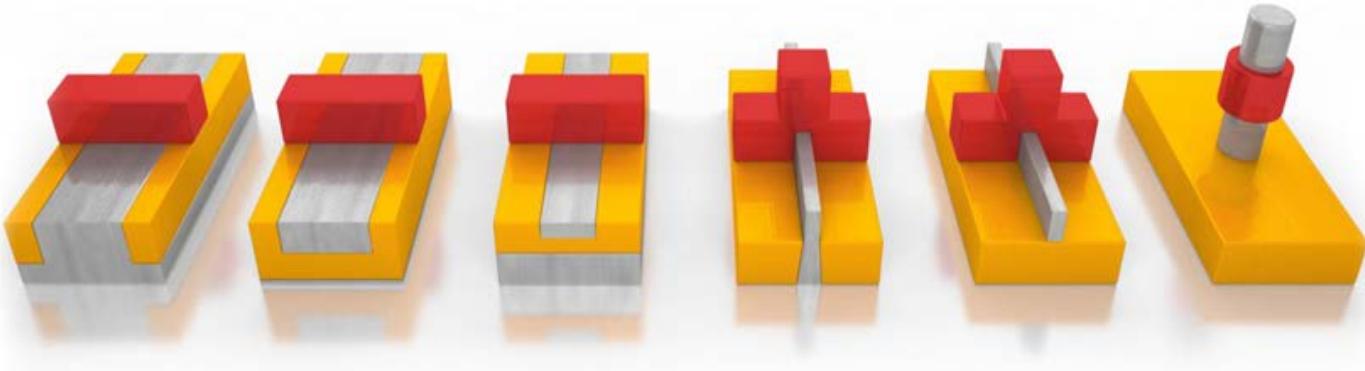
Jianqiang Lin

Planar InGaAs MOSFETs





InGaAs FinFETs



InGaAs Vertical Nanowire MOSFETs



Xin Zhao

