NCN Nanotechnology 101 Series

Nanoelectronics 101

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1) Introduction
2) Transistors
3) CMOS
4) Integrated Circuits
5) 21C Electronics?

NCN

www.nanohub.org

PURDUE UNIVERSITY

1. The importance of transistors (and chips)

supercomputers

iPods

PCs

cell phones

PDAs

1. The scale of things

1 meter
(1 billion nm)

people

things

1 millimeter
(1 million nm)

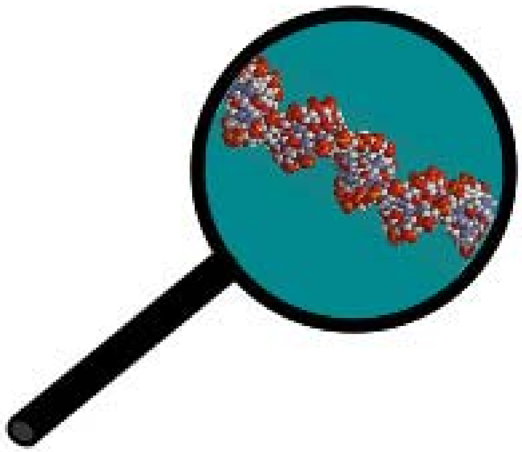
ants

dust

1 micrometer
(1 thousand nm)

cells

1 nanometer



molecules

(e.g. DNA)

1. What is a billion?

A billion seconds ago it was 1959.

A billion minutes ago Jesus was alive.

A billion hours ago our ancestors were living in the StoneAge.

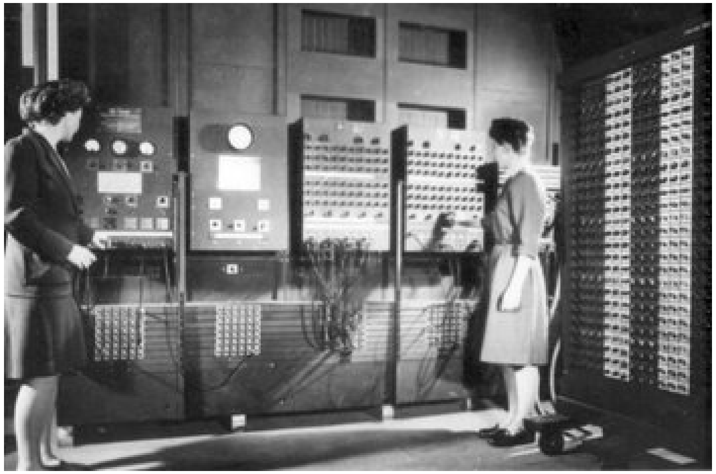
A billion days ago no-one walked on two feet on earth.

1. Vacuum tube electronics

Vacuum Tube

ENIAC

(1945, Mauchly and Echkert, U Penn)



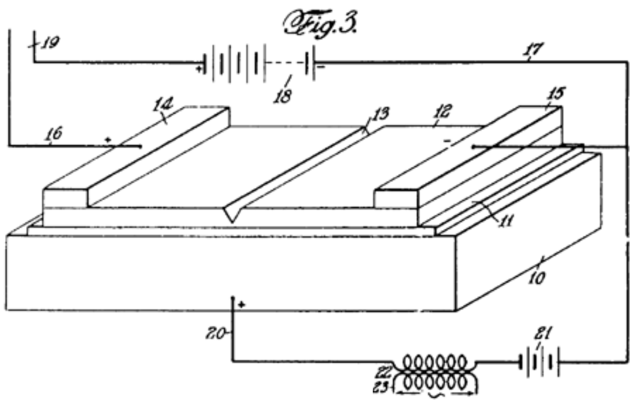
http://en.wikipedia.org

Edison effect (Edison, 1883)
cathode rays (Thompson, 1897)
diode (Fleming, ~1900)
triode (De Forest, 1906)

18,000 vacuum tubes
1000 sq. feet of floor space
30 tons
150 KW
~50 vacuum tubes / day

2. Transistors

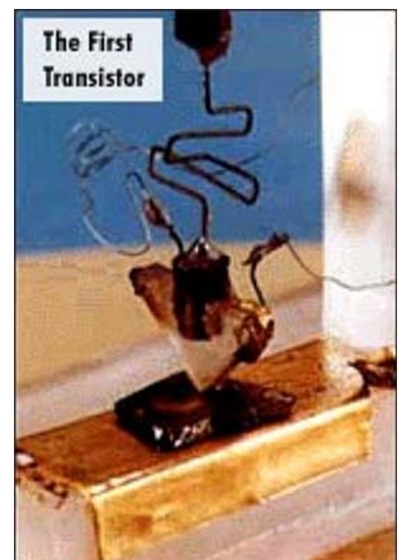
Field-Effect Transistor
Lillienfield, 1925
Heil, 1935



Bardeen, Schockley, and Brattain, 1947

“The transistor was probably the most important invention of the 20th century,”

Ira Flatow, Transistorized!
www.pbs.org/transistor



2. Transistors

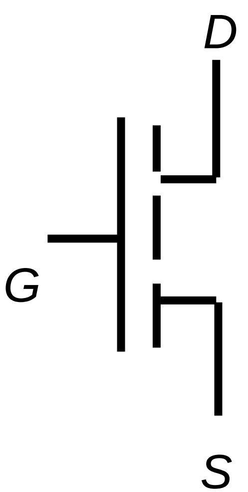
transistors

Sony TR-63
6-transistor
shirt pocket radio
1957

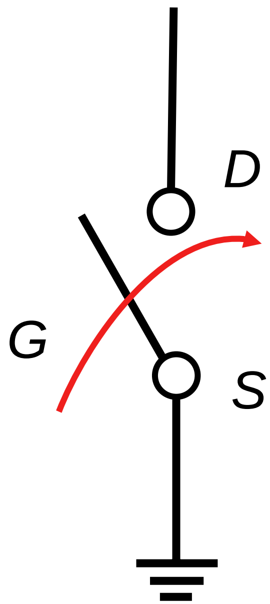
http://www.etedeschi.ndirect.co.uk/early.sony.htm

2. Transistors

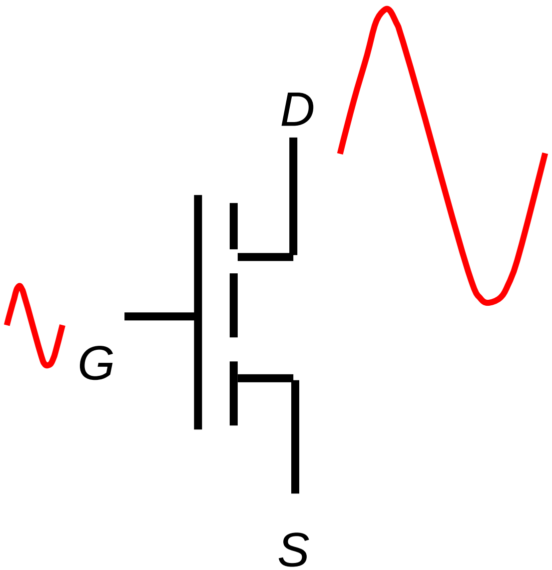
symbol



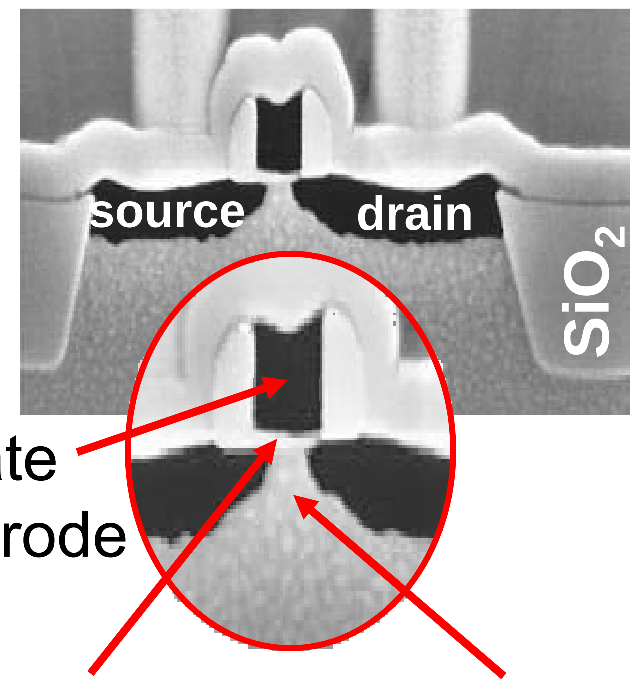
switch



amplifier

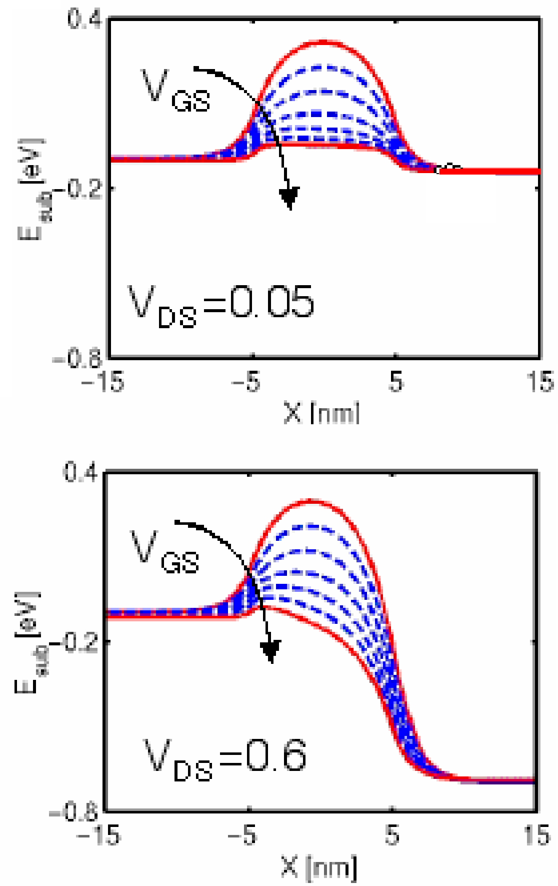


2. Transistors



electron energy vs. position

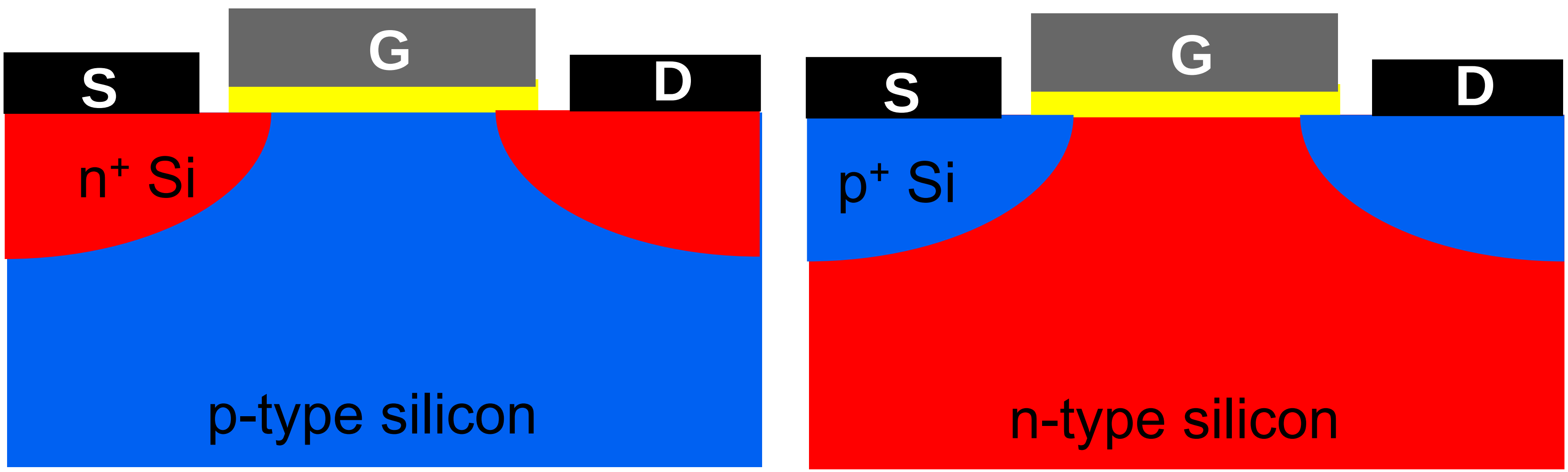
$$E = -q\,V$$



$V_D \approx 0V$

$V_D = V_{DD}$

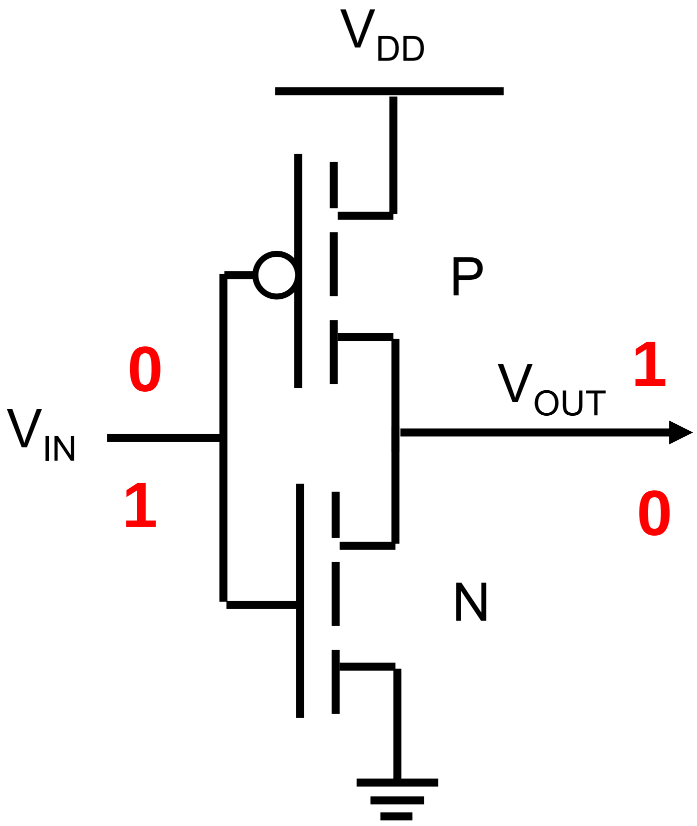
3. CMOS

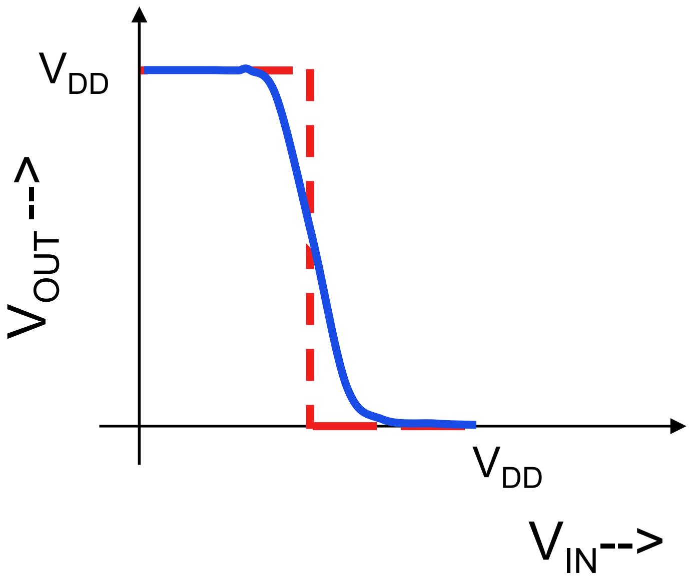


n-MOS: $V_{GS} > 0$

p-MOS: $V_{GS} < 0$

3. CMOS



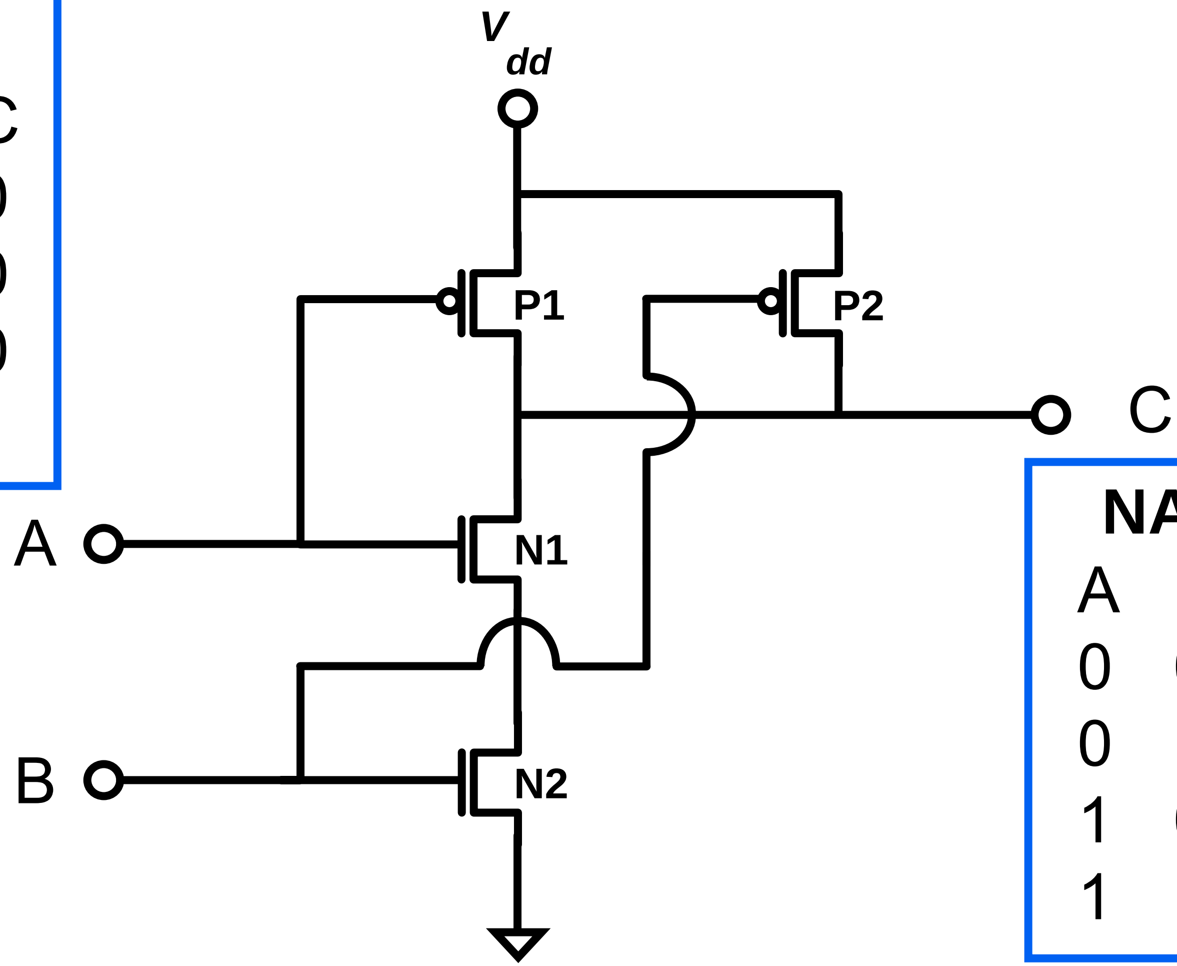


"transfer characteristic"

3. 2-input CMOS NAND gate

AND

A	B	C
0	0	0
0	1	0
1	0	0
1	1	1



NAND

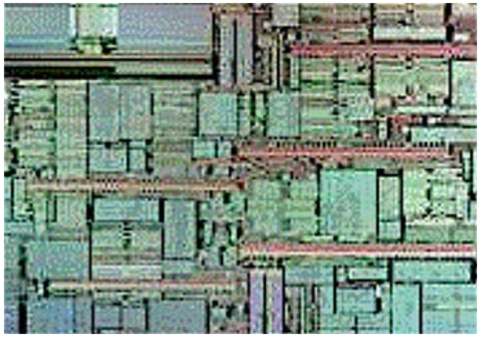
A	B	C
0	0	1
0	1	1
1	0	1
1	1	0

4. Integrated circuits

integrated circuit

Kilby and Noyce (1958, 1959)

Intel 4004

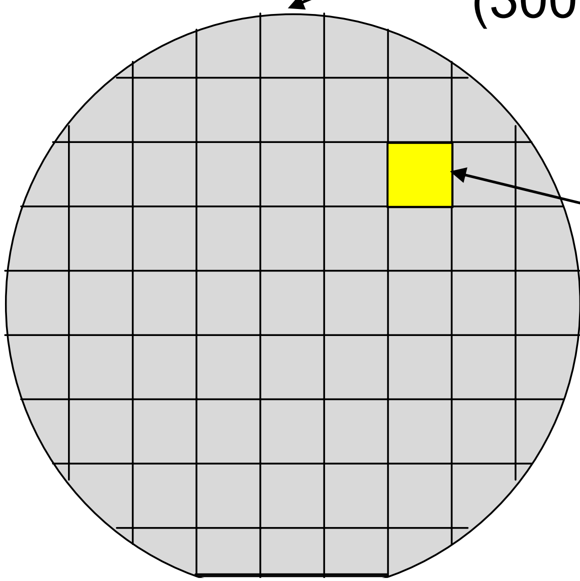


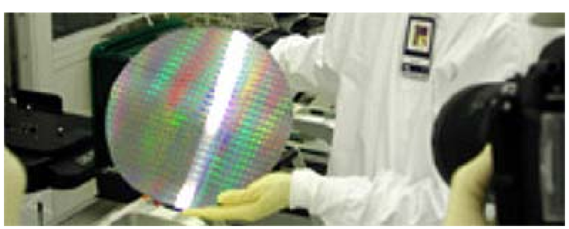
Hoff and Faggin (1971)

~2200 transistors

4. Microelectronics

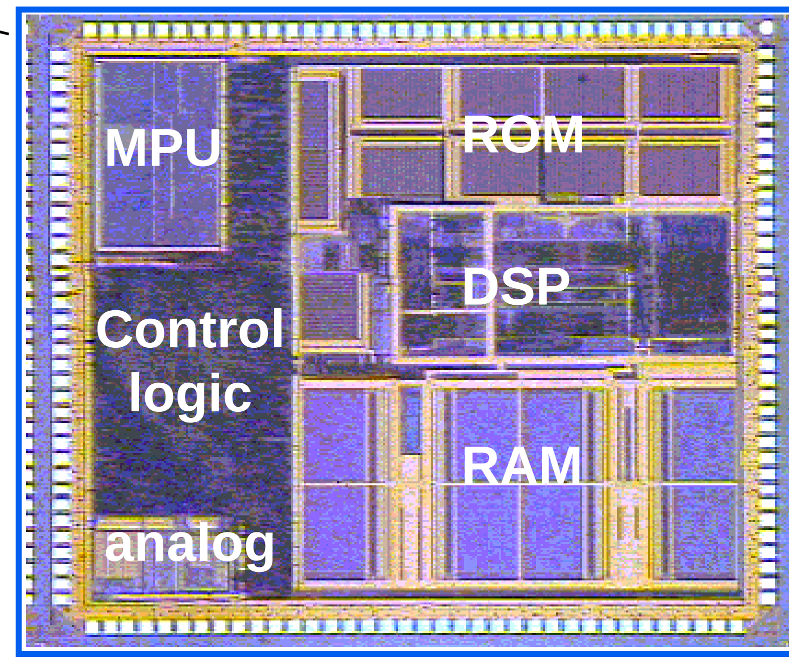
Silicon wafer
(300 mm)





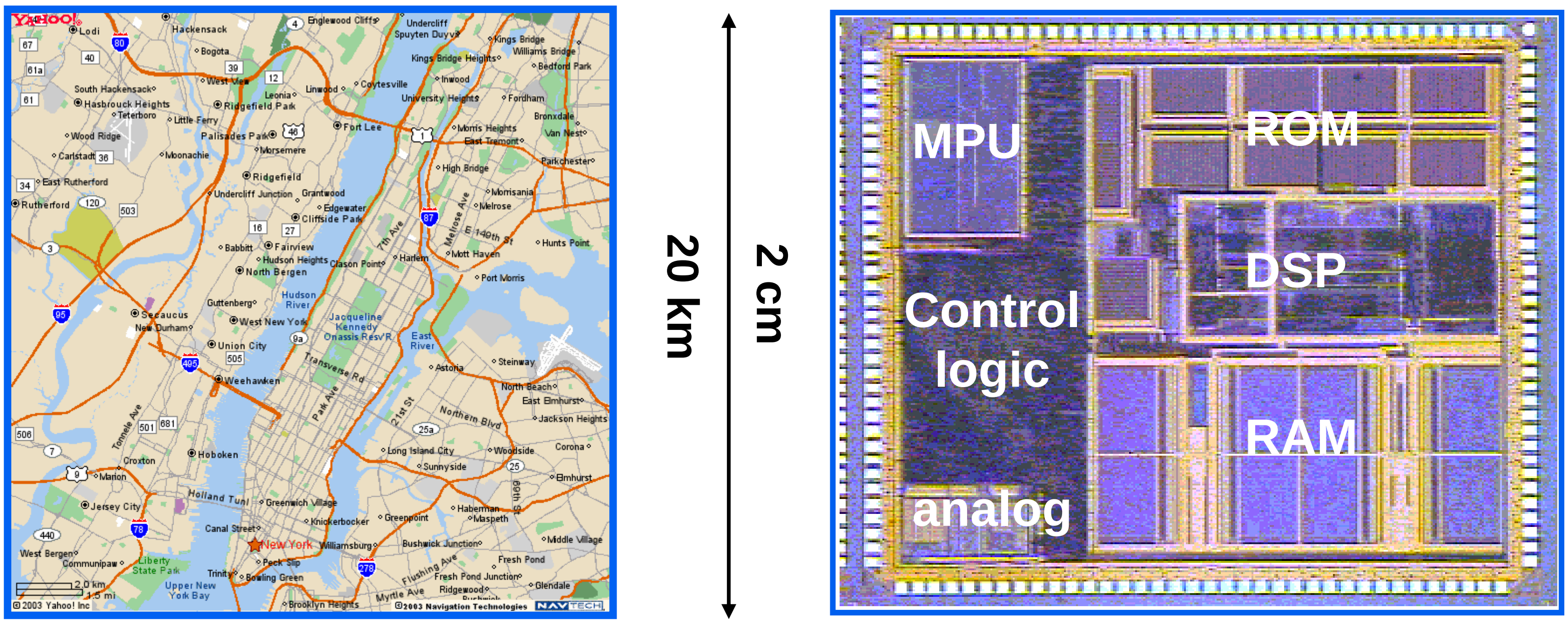
Intel

Silicon "chip"
(~ 2 cm x 2 cm)



TI cell phone chip

4. What if a chip were the size of New York City?

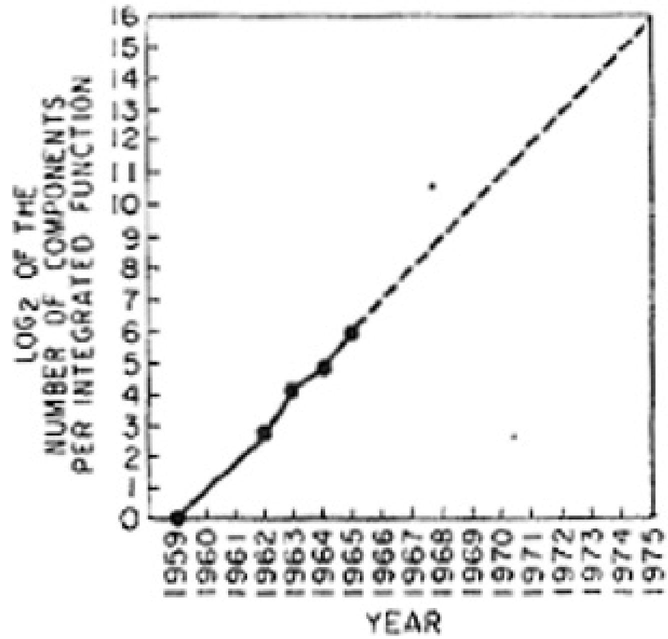


- Transistor gate length would be 4 cm.
- Feature edges would would be specified to the nearest mm.
- There would be 200,000 km of wires (total) on the 8 levels of metal.

From Bob Doering, Texas Instruments, Jan. 2004

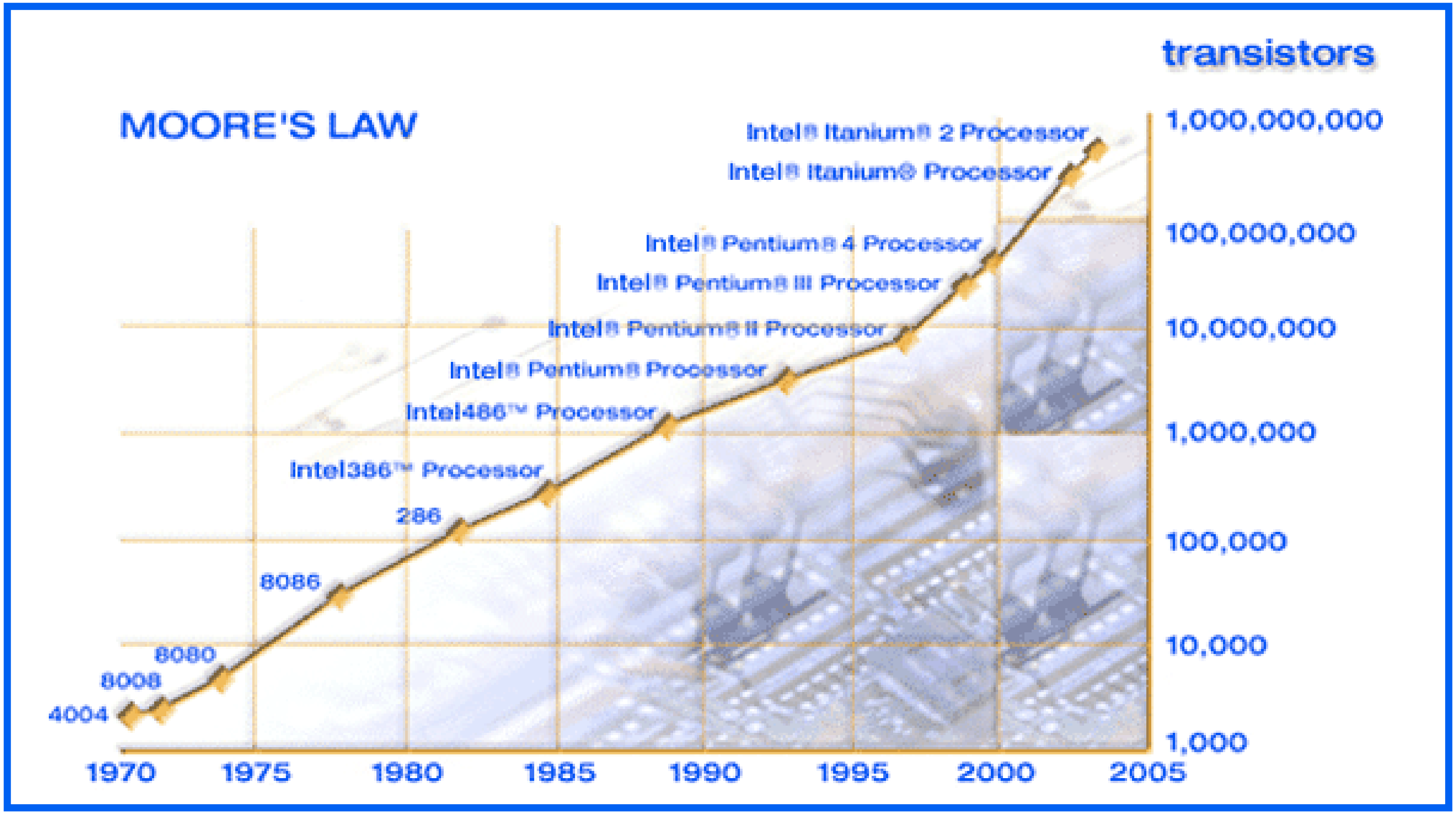
4. Moore's Law

Gordon E. Moore
Co-founder, Intel Corporation



Electronics, vol. 38,
April 19,1965

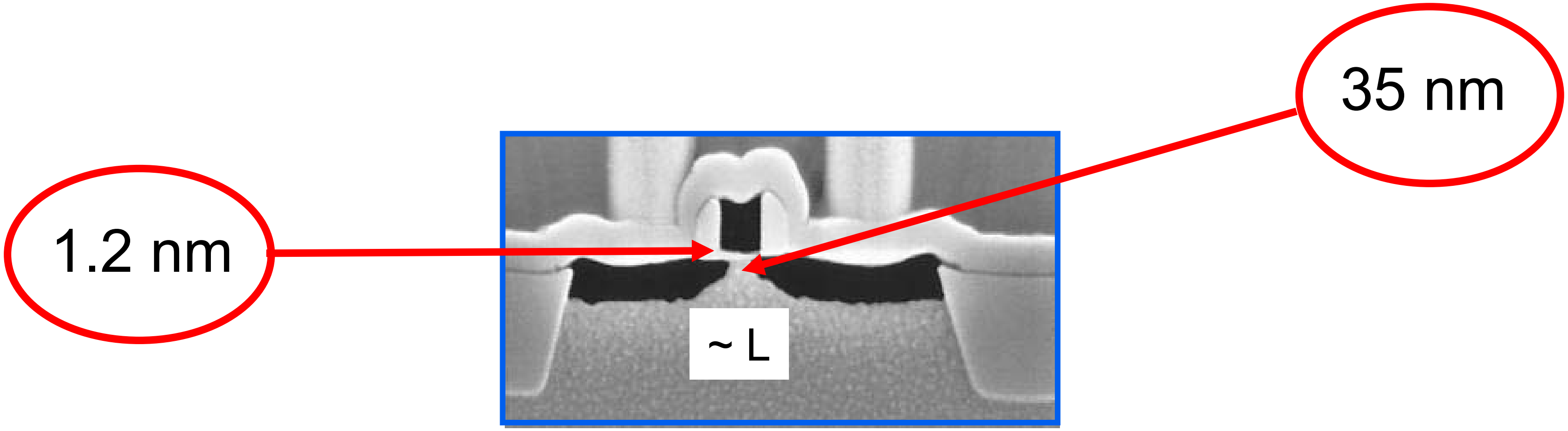
4. Moore's Law



more transistors per chip means:

higher performance / lower cost

4. Transistor scaling



Each technology generation: **(device scaling)**

$$L \rightarrow L/\sqrt{2} \qquad A \rightarrow A/2$$

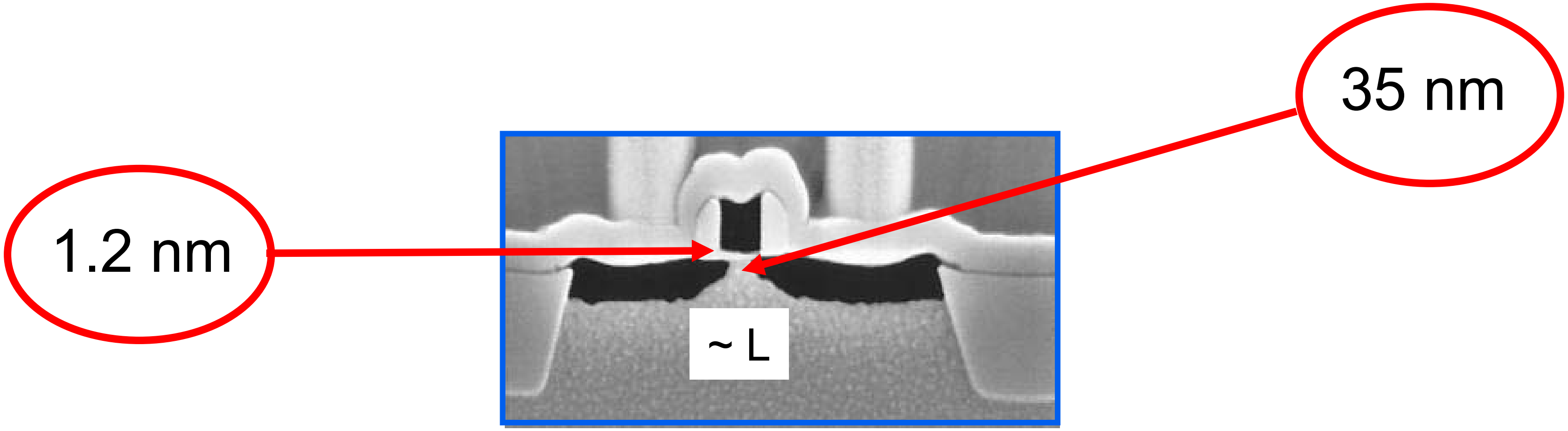
Number of transistors per chip doubles **(Moore's Law)**

4. Nanoelectronics

*Working at the length scale of 1-100 nm in order to create materials, devices, and systems **with fundamentally new** properties and functions because of their nanoscale size.*

paraphrased from www.nano.gov

4. Transistor scaling



Each technology generation: **(device scaling)**

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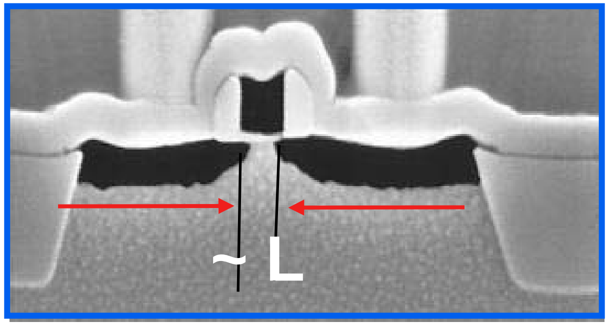
4. Scaling challenges



1) low voltage operation
2) high on-current
3) low off-current
4) series resistance
5) device variability

4. More than Transistors

Metal 7

Metal 6

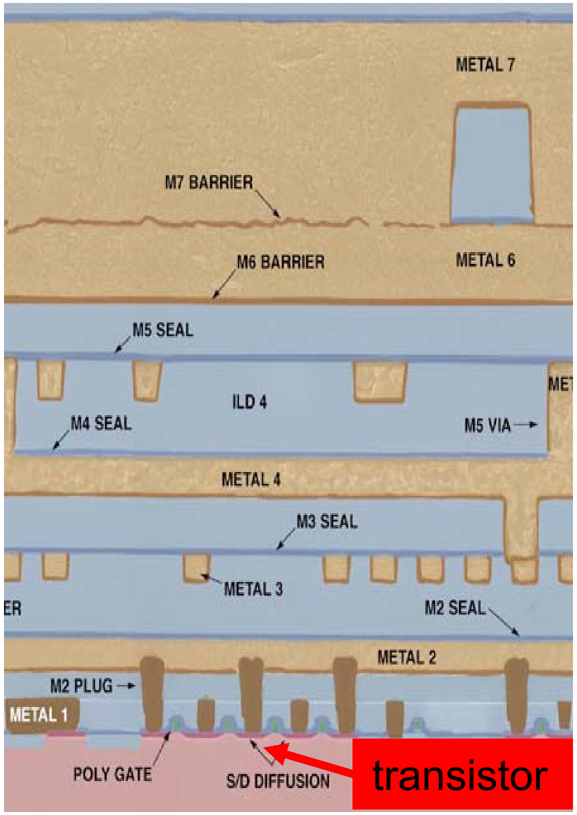
Metal 5

Metal 4

Metal 3

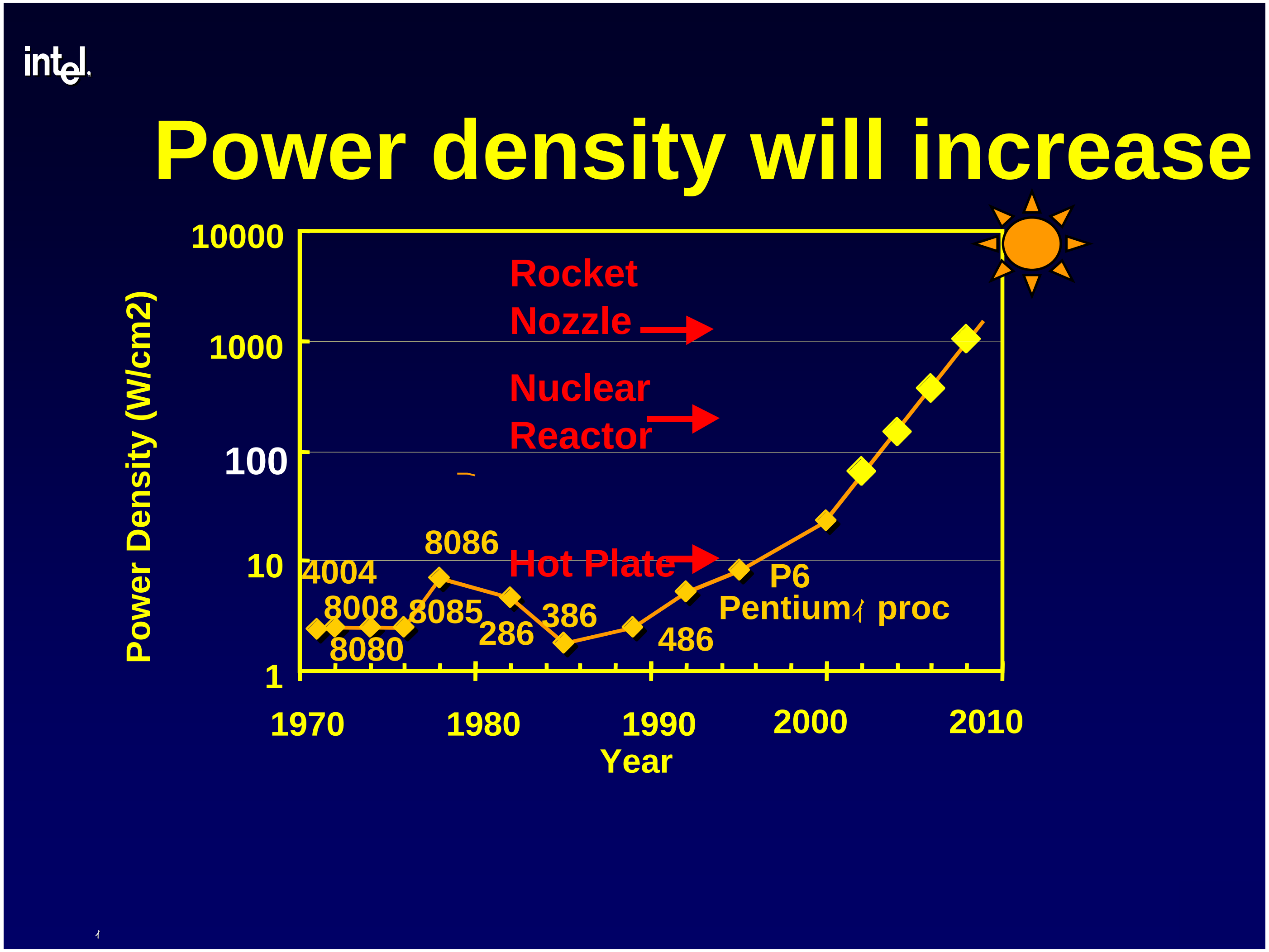
Metal 2

Metal 1



Silicon wafer

4. The power crises



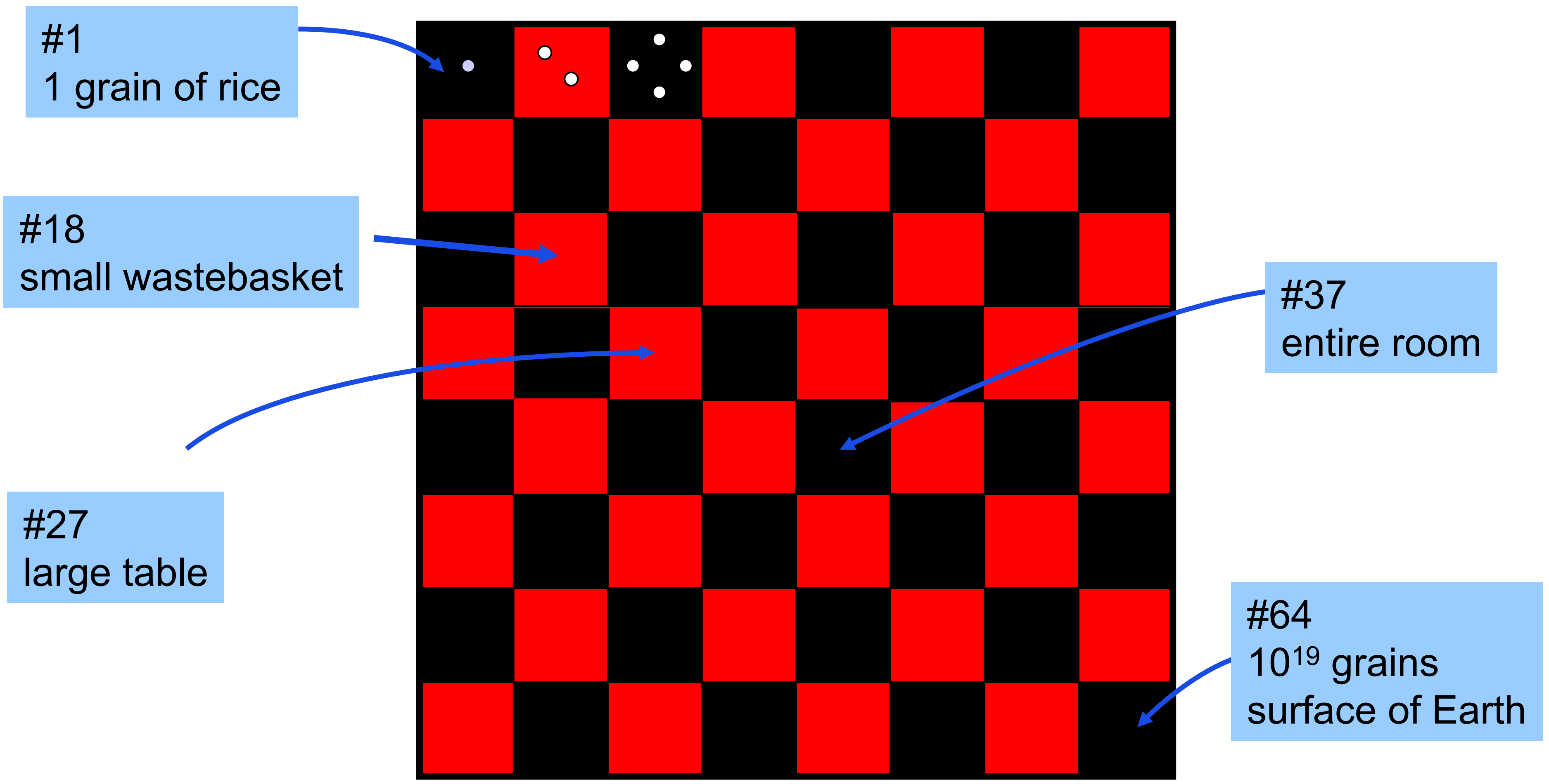
4. Design challenges

1) power
2) interconnects
3) device variability
4) reliability
5) complexity

4. Exponential Growth

1	90 nm	1B/chip
2		2B
3		4B
4		8B
5		16B
6		32B
7		64B
8		128B
10		256B
11		512B
12		**1T**

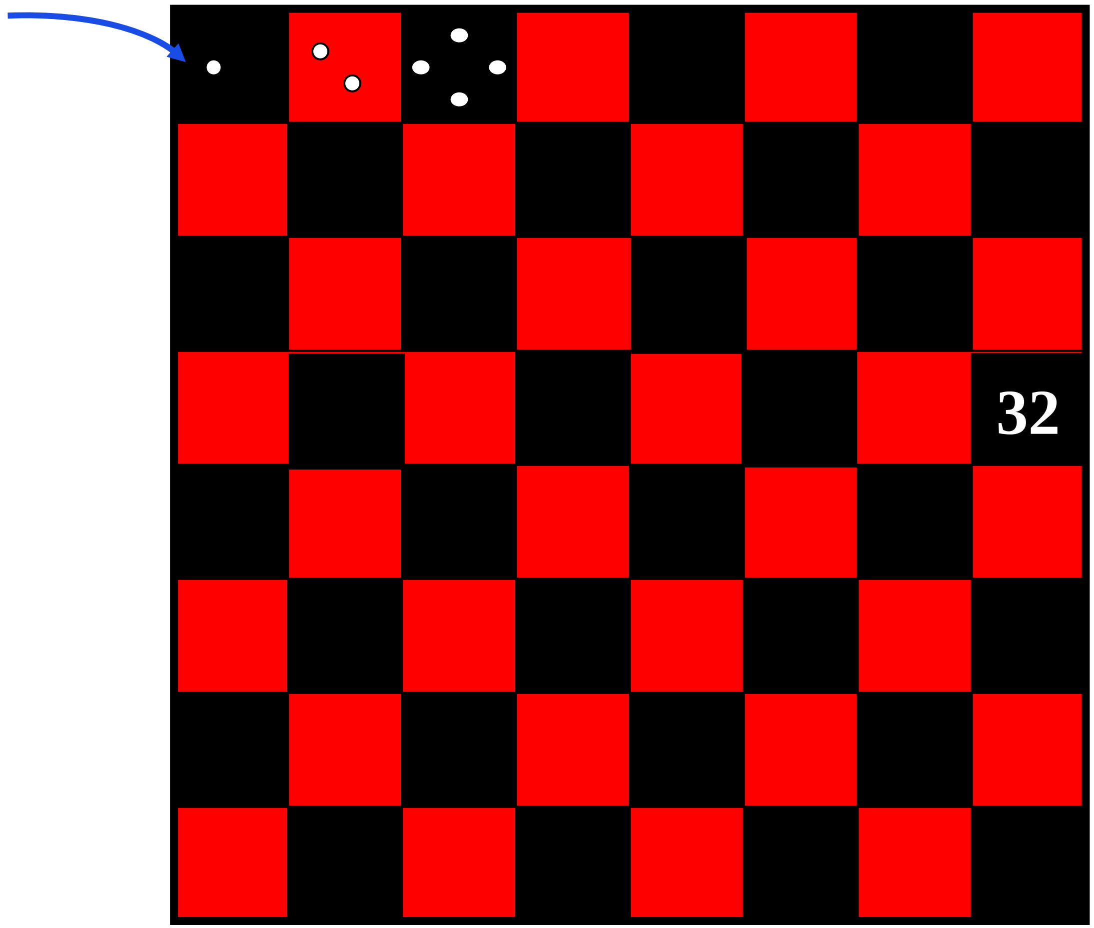
4. Exponential Growth



from "Digital Immortal," by R.W. Lucky, *New Republic*, Nov. 8. 1999

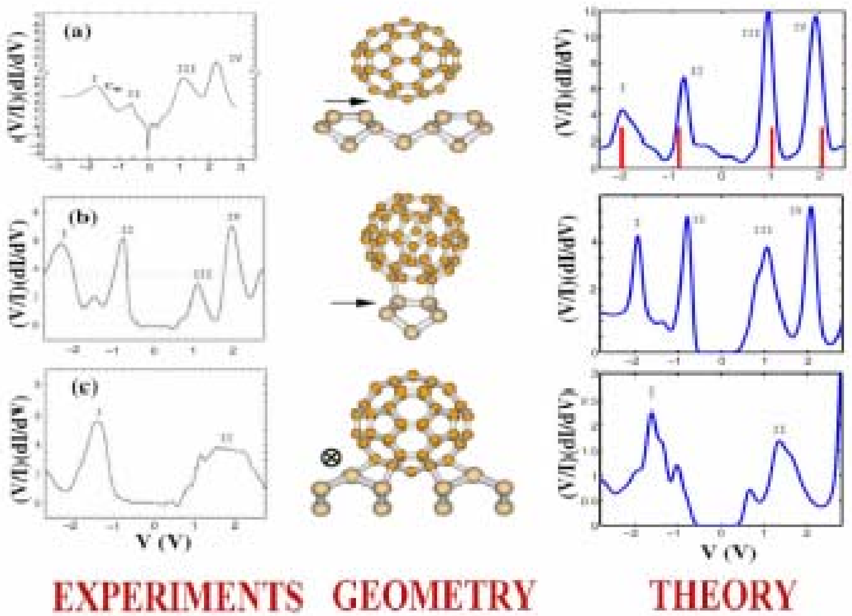
4. Exponential Growth

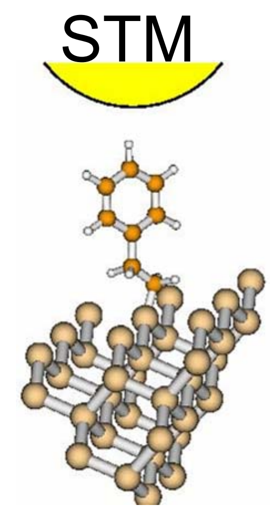
#1
First IC
(1959)

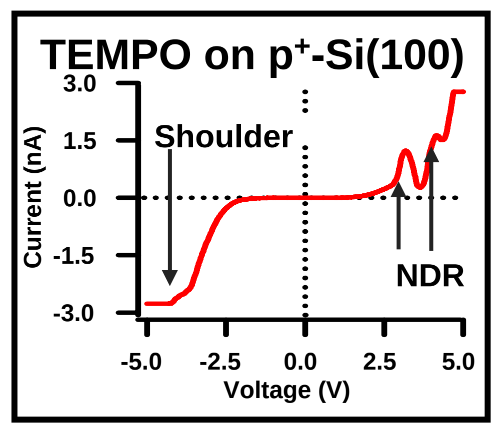


5. Beyone Silicon CMOS: Molecular electronics?

C_{60} on Si(100) 2x1



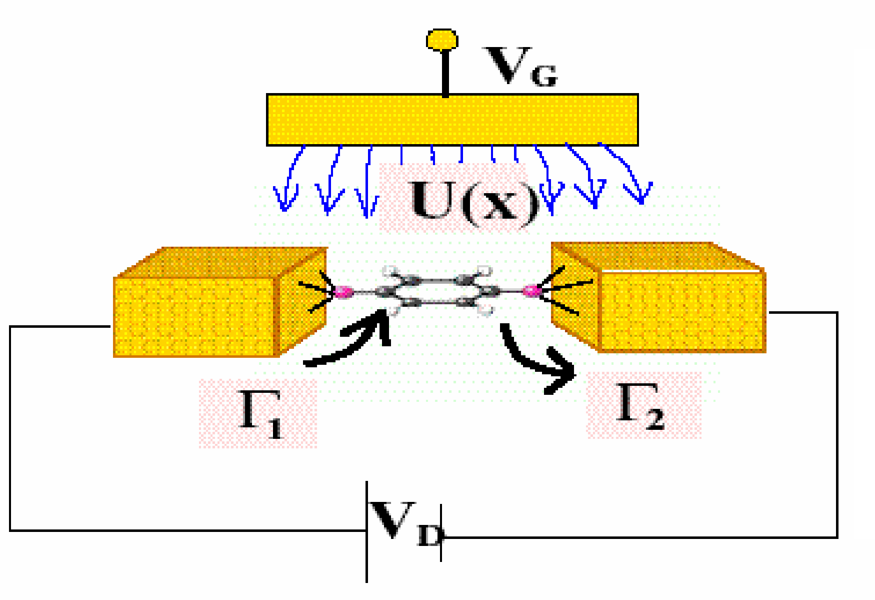


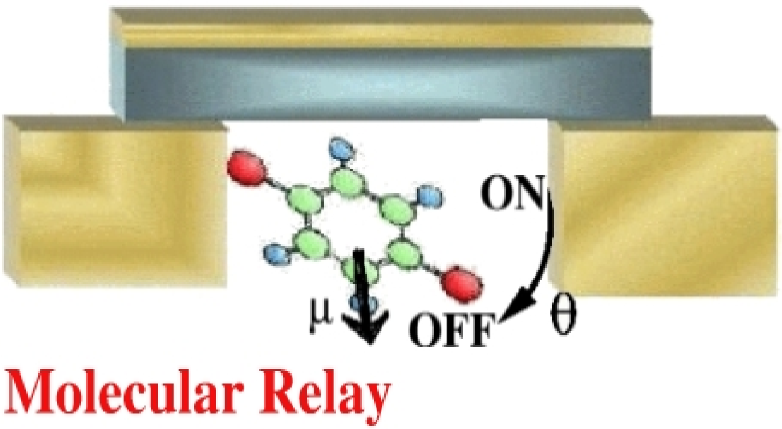


(Liang and Ghosh)

Hersam, Datta, Purdue

5. Beyond Silicon CMOS: Molecular transistors?

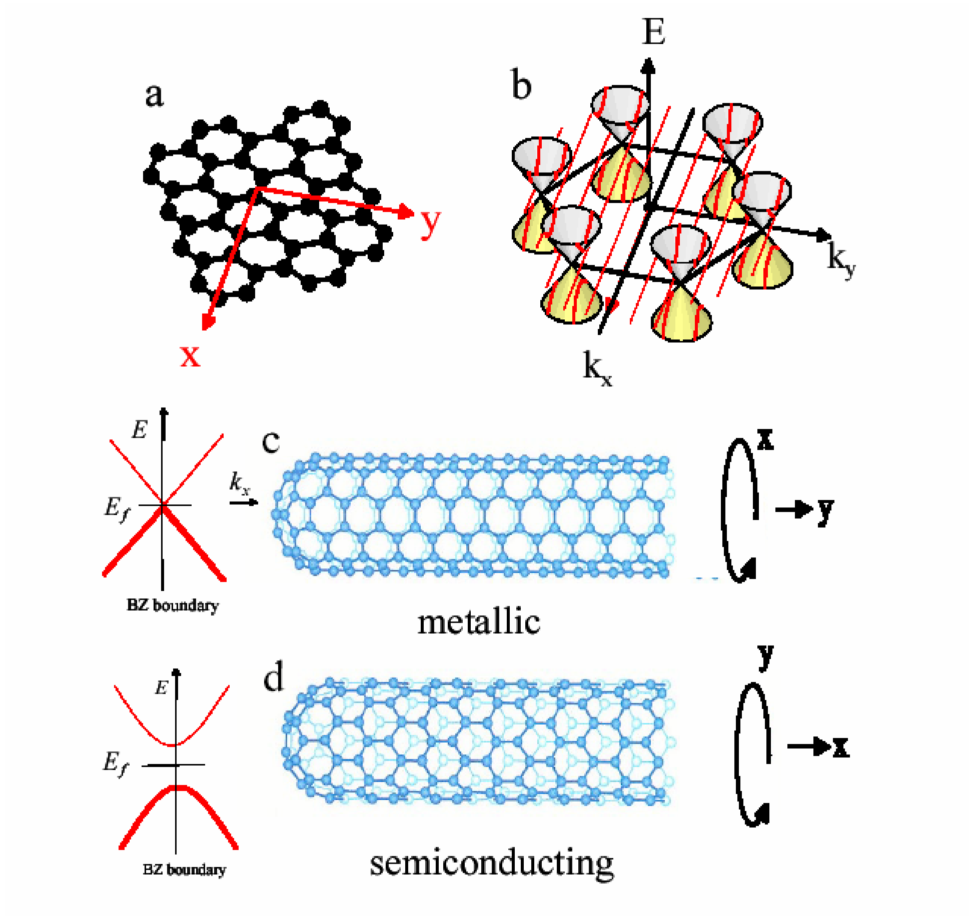




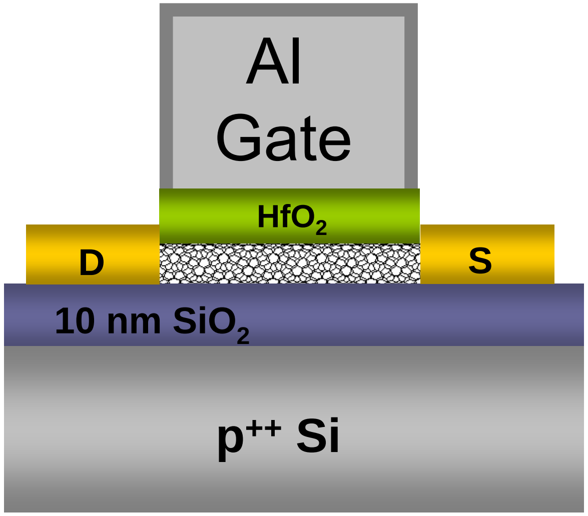
S. Datta, A. Ghosh, P. Damle, T. Rakshit

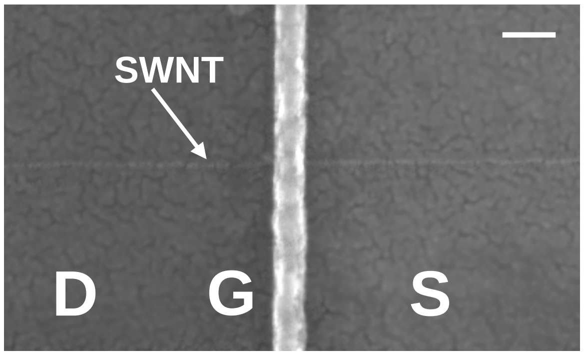
Ghosh, Rakshit, Datta,
Nanoletters **4**, 565, 2004

5. Beyond Silicon CMOS: Carbon nanotube transistors?



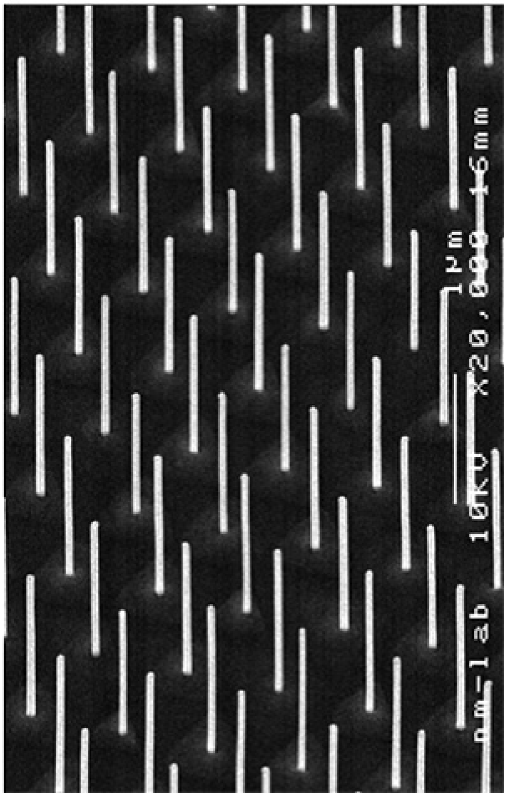
McEuen et al., *IEEE Trans. Nanotech*., **1** , 78, 2002.



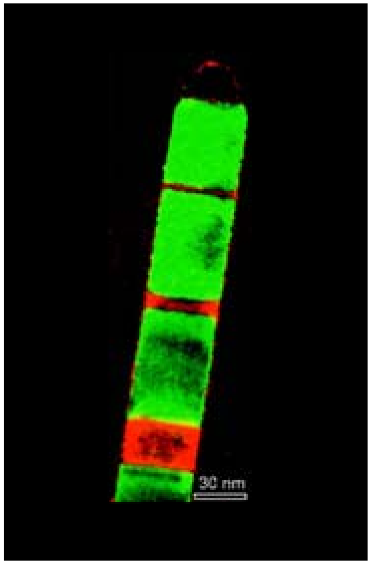


Hongjie Dai group, Stanford

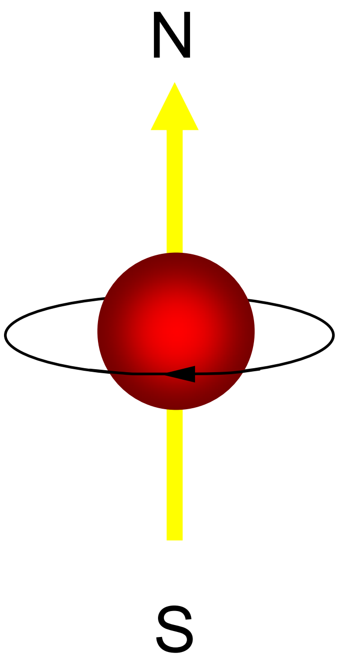
5. Beyond Silicon CMOS: Nanowire transistors?



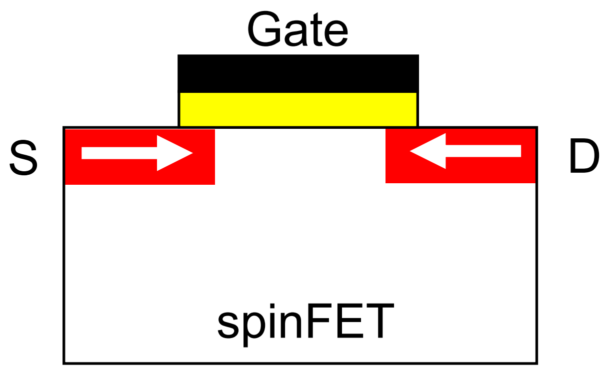
Samuelson Group
Lund



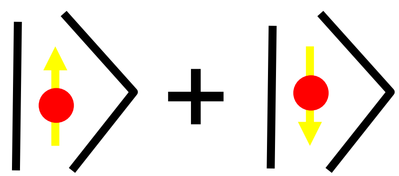
5. Beyond transistors?



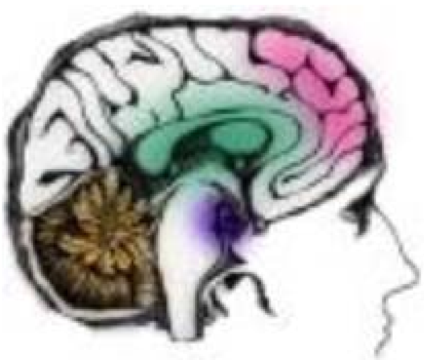
spin



qubit



quantum computing



5. 21st Century Electronics

1) CMOS devices face serious challenges

leakage, variations, interconnects, …

2) Power dissipation limits device density

not our ability to make devices small

3) CMOS will operate near ultimate limits

no transistor can be fundamentally better

4) CMOS will provide more devices than can be used

increasingly, design will drive progress

5. 21st Century Electronics

5) New tools, assembly techniques, and understanding *will help push CMOS to its limits*

6) Beyond CMOS devices will add functionality to CMOS

non-volatile memory, opto-electronics, sensing….

7) Beyond CMOS technology will address new markets

macroelectronics, bio-medical devices, …

8) Biology may provide inspiration for new technologies

bottom-up assembly, human intelligence

Nanoelectronics 101

Questions?