جامعة الملك سعود
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Systematics of Making things Smaller

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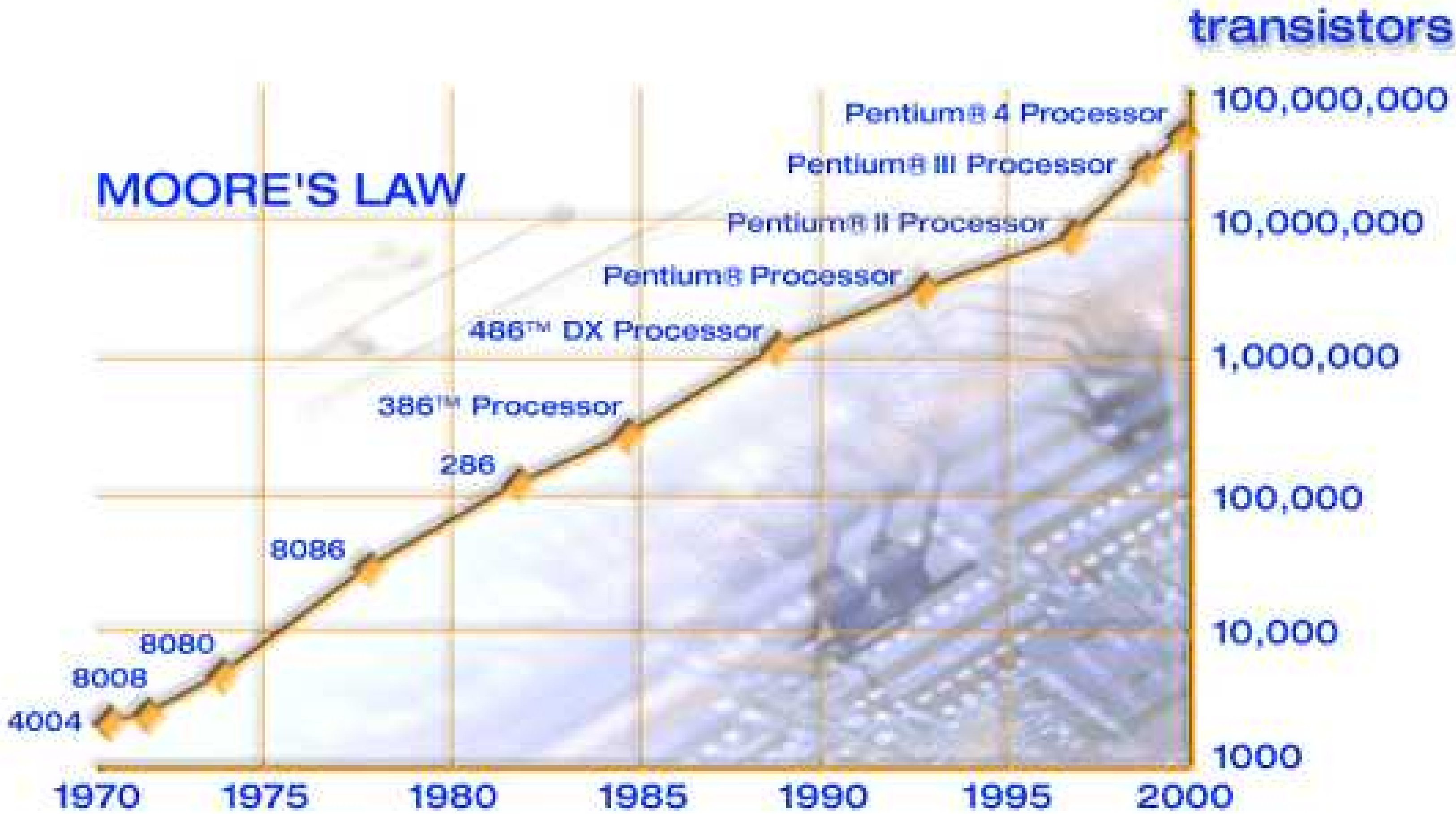
Why is Small Good?

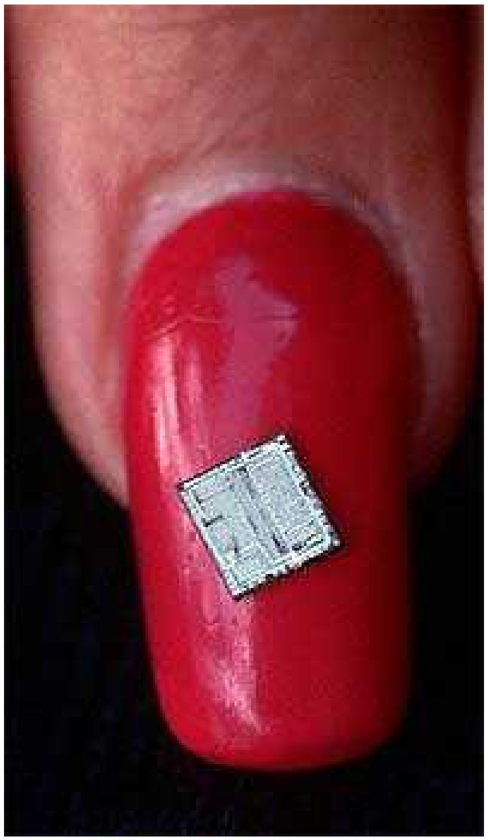
- Faster
- Lighter
- Can get into small spaces
- Cheaper
- More energy efficient
- Different properties at very small scale

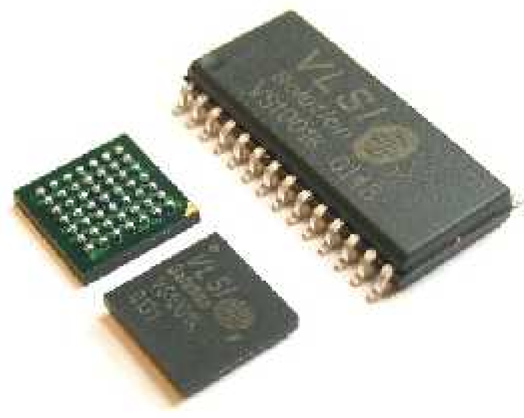
Moore's Law



transistors
MOORE'S LAW
100,000,000
10,000,000
1,000,000
100,000
10,000
1000
Pentium® 4 Processor
Pentium® III Processor
Pentium® II Processor
Pentium® Processor
486™ DX Processor
386™ Processor
286
8086
8080
8008
4004
1970
1975
1980
1985
1990
1995
2000

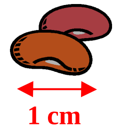
IC Technology





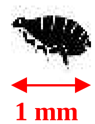
How small is a nanometer? (and other small sizes)

Start with a centimeter.



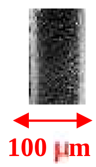
A centimeter is about the size of a bean.

Now divide it into 10 equal parts.



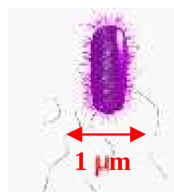
Each part is a millimeter long. About the size of a flea.

Now divide that into 10 equal parts.



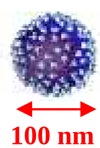
Each part is 100 micrometers long. About the size (width) of a human hair.

Now divide that into 100 equal parts.



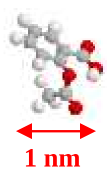
Each part is a micrometer long. About the size of a bacterium.

Now divide that into 10 equal parts.



Each part is a 100 nanometers long. About the size of a virus.

Finally divide that into 100 equal parts.



Each part is a nanometer. About the size of a few atoms or a small molecule.

1. Mechanical Frequencies Increase in Small Systems

$$\omega = \left(\frac{g}{l}\right)^{0.5}$$

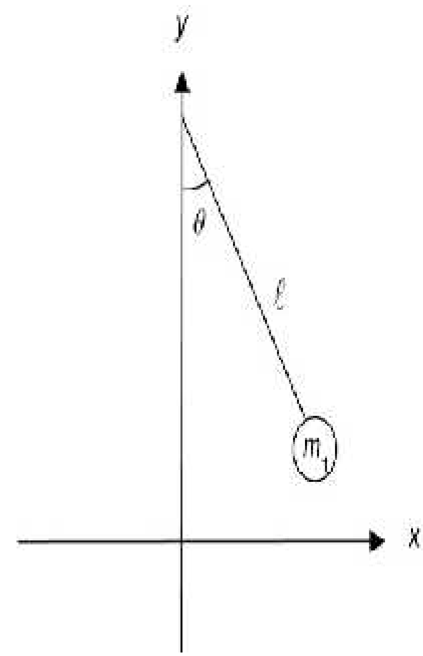
- For l= 98 cm
  ω= 3.16 Hz

- For l = 9.8 μm

ω= 1000 Hz ~ 1kHz

- For l= 9.8 nm

ω= 31,622 Hz ~ 32 kHz



Simple Pendulum

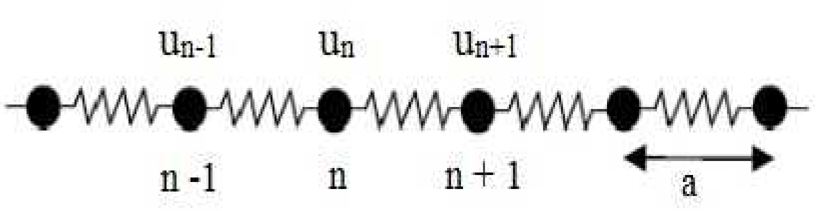
2. Simple Harmonic Oscillation (SHO)

- In nanophysics, which is needed when the mass m is on an atomic scale, the frequency and energy can be calculated as

$$\omega = \left(\frac{k}{m}\right)^{0.5}$$

$$E_n = (n + 1/2)\hbar\omega$$

It can be seen that the materials are more energy efficient at the nanoscale



Monatomic Lattice

3. Mechanical Strength for small systems

- For atomic chain of N masses of length L and connected by a spring of constant k Young´s modulus can be expressed in microscopic quantities as,

$$Y = \rho K a^2/m$$

Where,
ρ is the mass per unit length
a is the spring length

- A connection between macroscopic and nanometer scale descriptions can be made by considering L=Na

4. Spectral variations on a Linear Atomic Chain of Length L=Na

- The sound speed in a solid material

$$v = (Y/\rho)^{1/2}$$

- The longitudinal resonant frequency of 0.1 m brass rod

$$f = v/2L$$

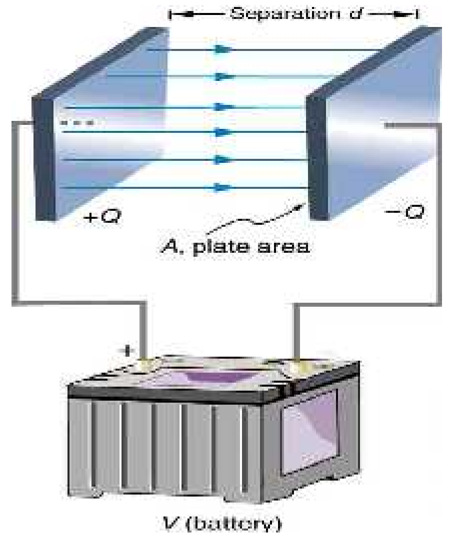
Where v=3000 m/s , then f = 15 kHz (ultrasonic range)

- If one could shorten the brass rod to 0.1 μm in length

$$f = 15 \text{ GHz}$$

- Which corresponds to electromagnetic wave with 2 cm, this huge change in frequency allow completely different applications to be addressed, achieved simply by changing the size of the device.

5. Scaling Relations Illustrated by Simple Circuit Elements



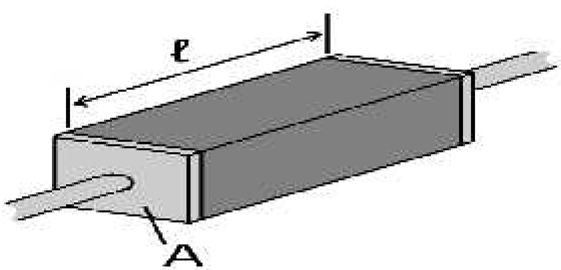
CAPACITOR

- Under isotropic scaling the capacitance scales as L

$$C = \varepsilon_0 A/d$$

- If the capacitor is diacharged through a resistor R the time constant τ=RC

- Science the resistance $R=\rho l/A$ where ρ is the resistivity, the resistance scales as L^{-1}

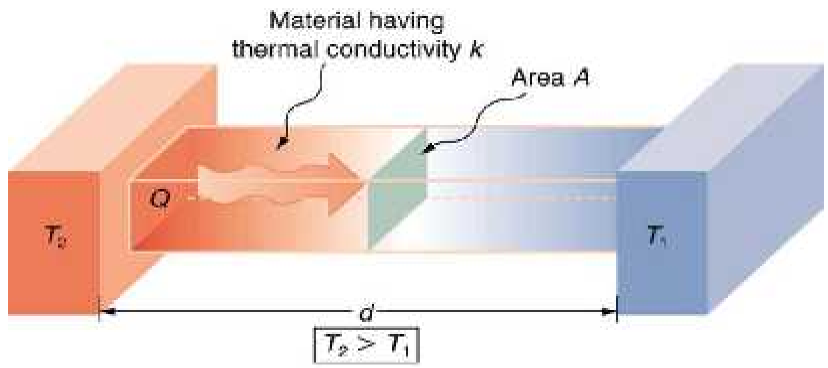


RESISTOR

- Thus the resistive time constant scales as L^0

- The resistive electrical power produced in the discharge $dU/dt= U/RC$ remains constant under scale changes

6. Scaling Relation for Temperature Differences



- In the steady state the temperature difference is related to the heat flow dQ/dt as,

$$(T_2 - T_1) = (dQ/dt)\ (d/K_T A)$$

Where K_T is the thermal conductivity

- The typical temperature difference $(T_2 - T_1)$ scales in three dimensions, as L.

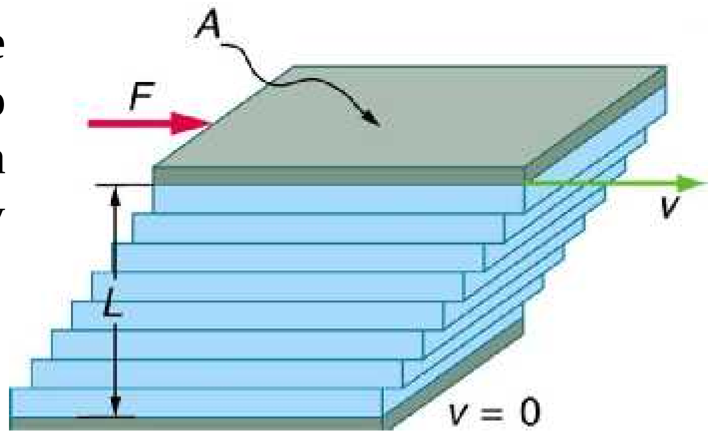
<u>Temperature differences are reduced as the size scale is reduced.</u>

7. Viscous Forces Become Dominant For Small Particles in Fluid Media

- The most relevant property of the medium is the viscosity η defined in terms of force necessary to move a flat surface of area *A* parallel to an extended surface at spacing *L* relative to a velocity *v* can be expressed as,

$$F = \eta v A/L$$

  - *The viscous force scales as* L^{-1}



  - Following Stokes law the velocity for a falling sphere of radius R can be obtained as,

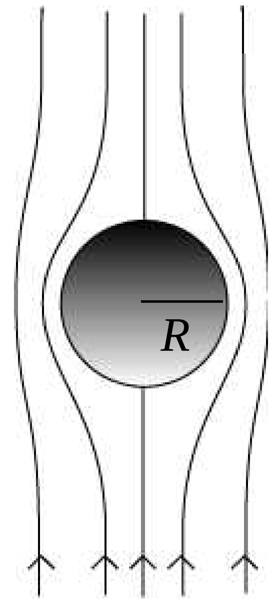
$$v = mg/6\pi\eta R$$

  - For the nanometer scale Brownian motion to be present with particle diffusivity is

$$D = kT/6\pi\eta R$$

  - The diffusion length is large for the nanometer scale as,

$$x_{rms} = (4Dt)^{1/2}$$



- The microelectronics process is able to make complex planar structures containing millions of working components in a square centimeter. This process is adaptable to make essentially planar mechanical machines with components on a micrometer scale.

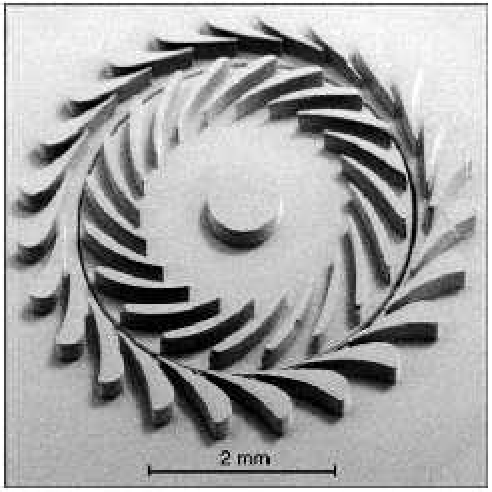


Figure 3.7 Turbine wheel produced on silicon wafer with deep reactive ion etching.