

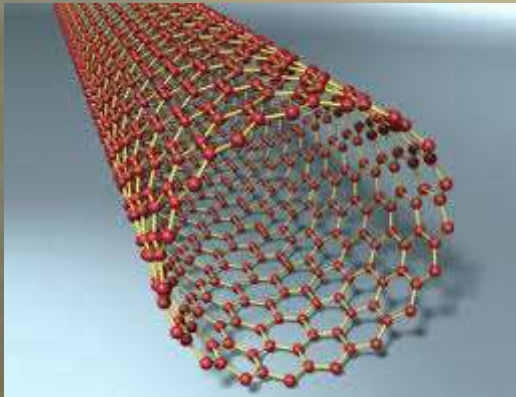
Carbon nanotubes as electromechanical resonators

Single-electron tunneling, nonlinearity, and high-bandwidth readout

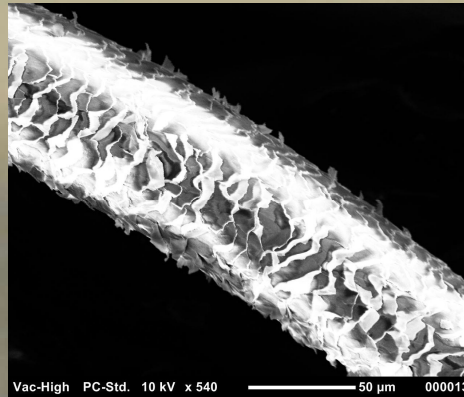
Harold Meerwaldt



Nano?



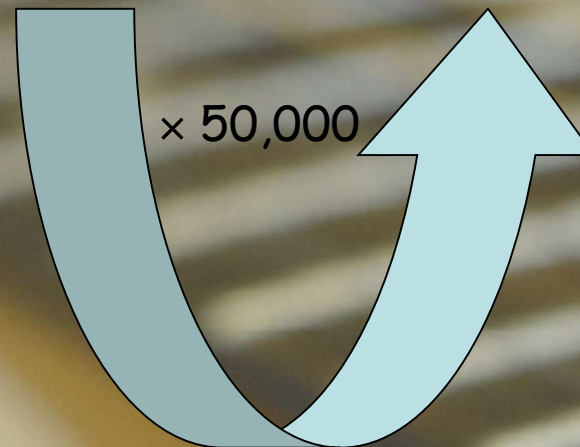
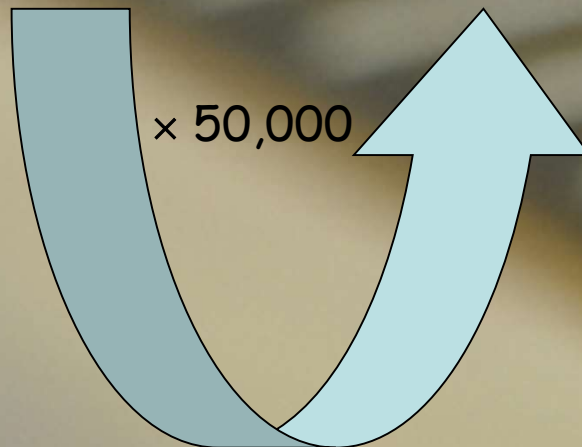
nanotube: 1 nanometer



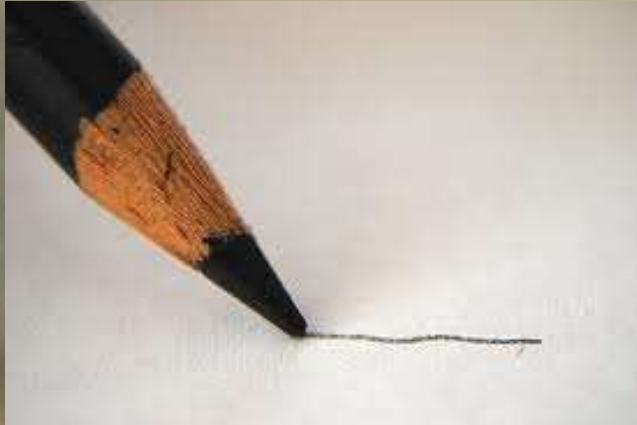
hair: 0.05 millimeter



pipe: 2.5 meter



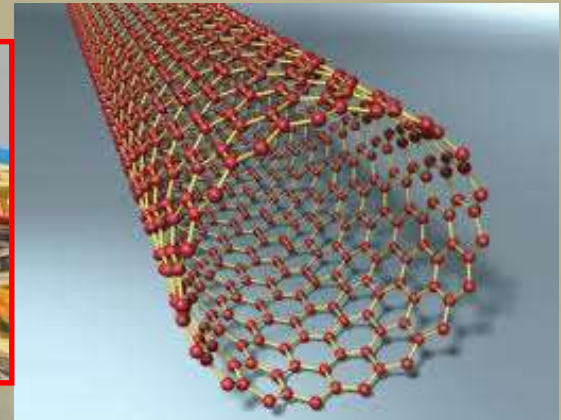
How do we make carbon nanotubes?



graphite

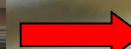
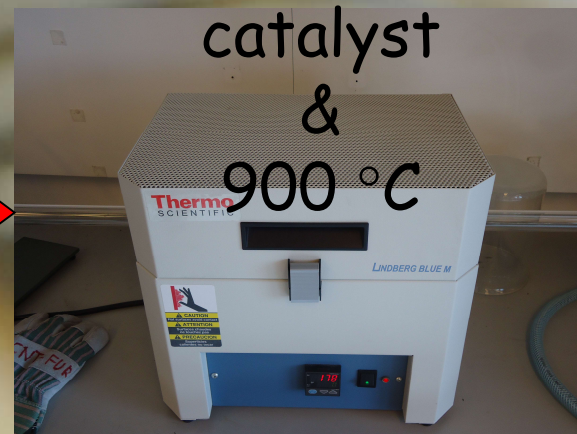


graphene



carbon nanotube

- hydrogen
- methane



What's so special about carbon nanotubes?

- Strongest material known
- A very light material



Resonators

"A resonance is a vibration that occurs only at a certain frequency."



- heavier is lower
- more tension is higher

a carbon nanotube is

- longer is lower

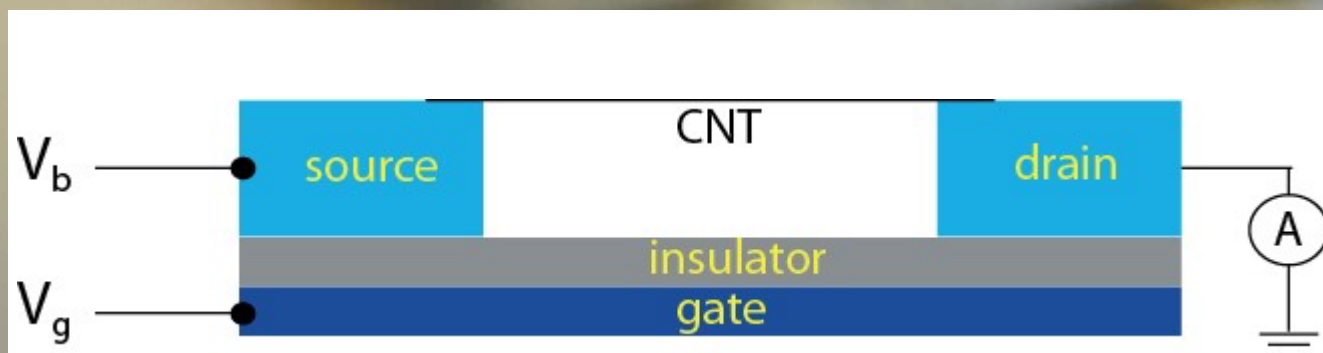
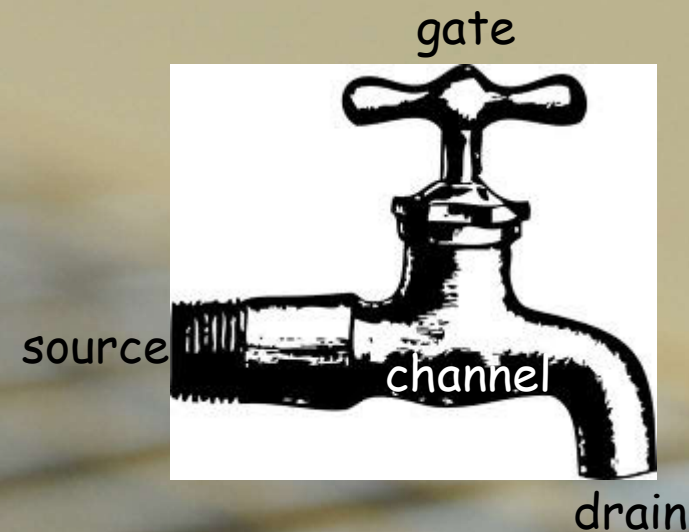
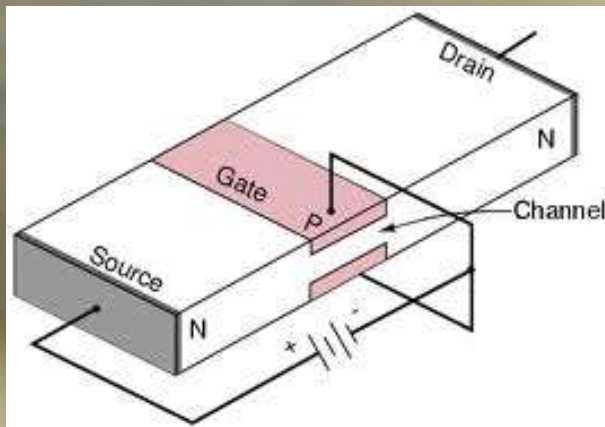
- stiffer is higher

- light
- under tension
- long
- and stiff

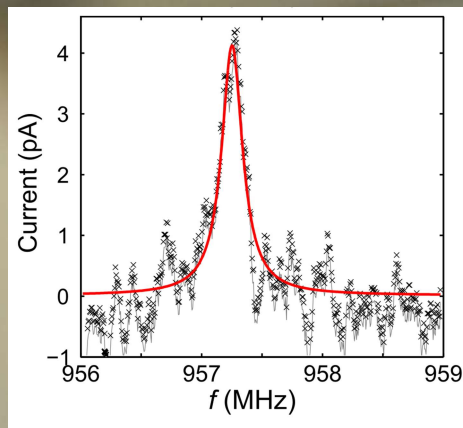
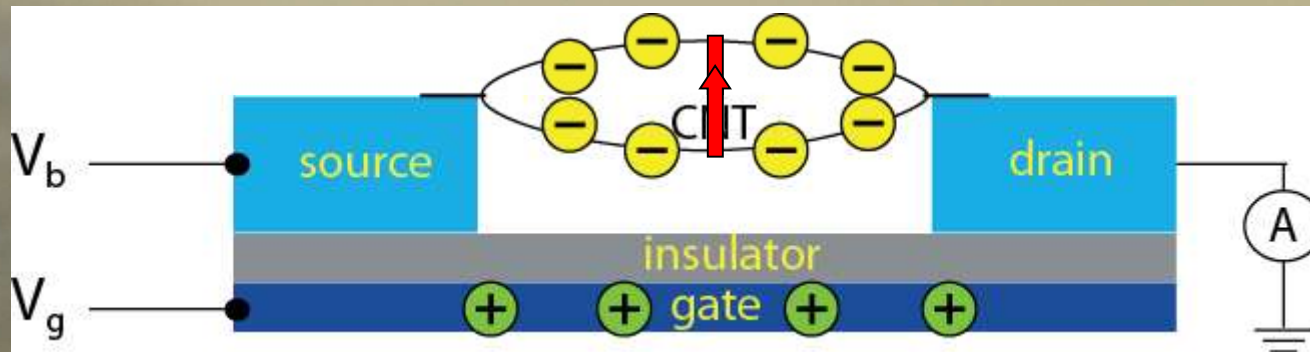
→ high frequency

Electro...

- A nanotube is a transistor



...mechanical

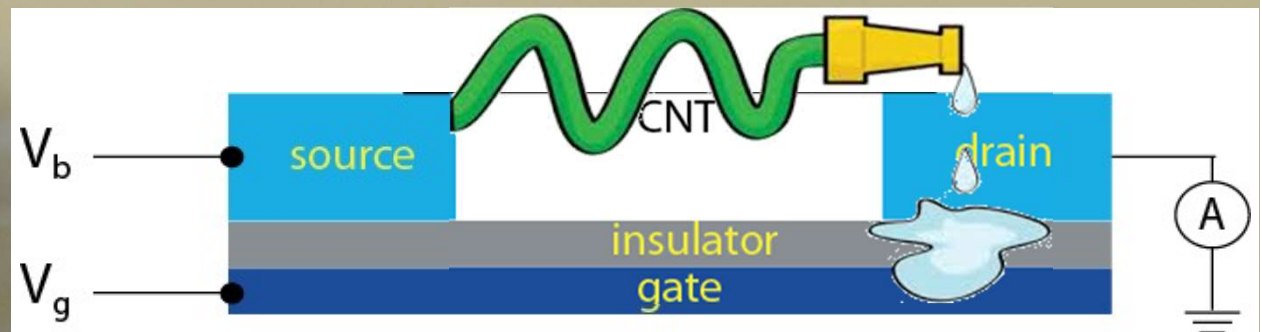
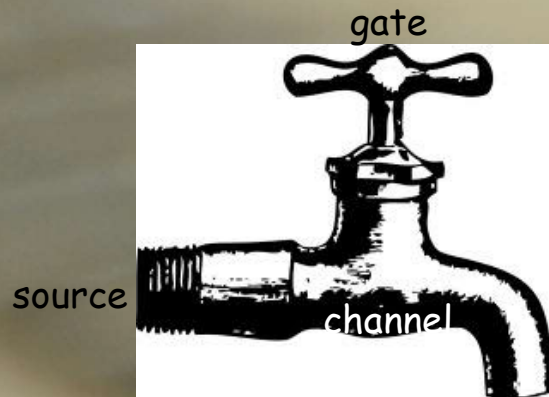


957,000,000 oscillations per second

82 - 880 oscillations per second

Single-electron tunneling

at $-273\text{ }^{\circ}\text{C}$



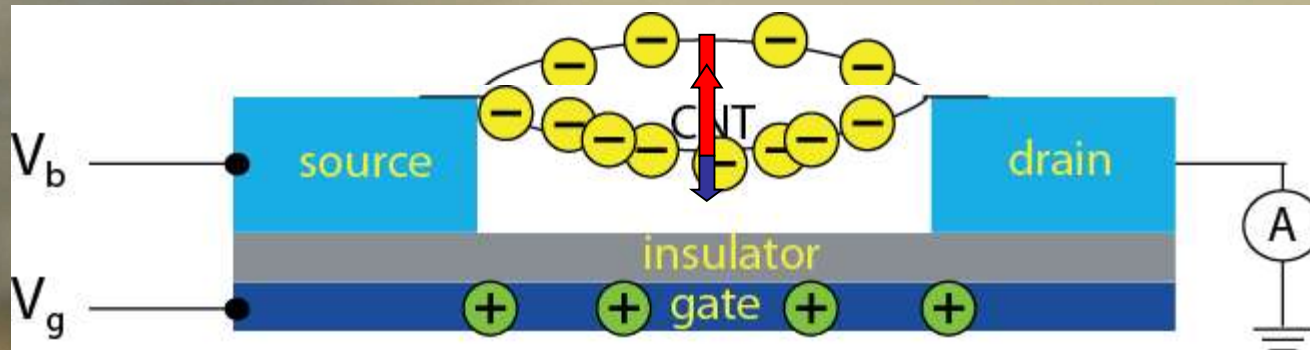
drain



957,000,000 oscillations per second

100,000,000,000 electrons per second

Single-electron tunneling

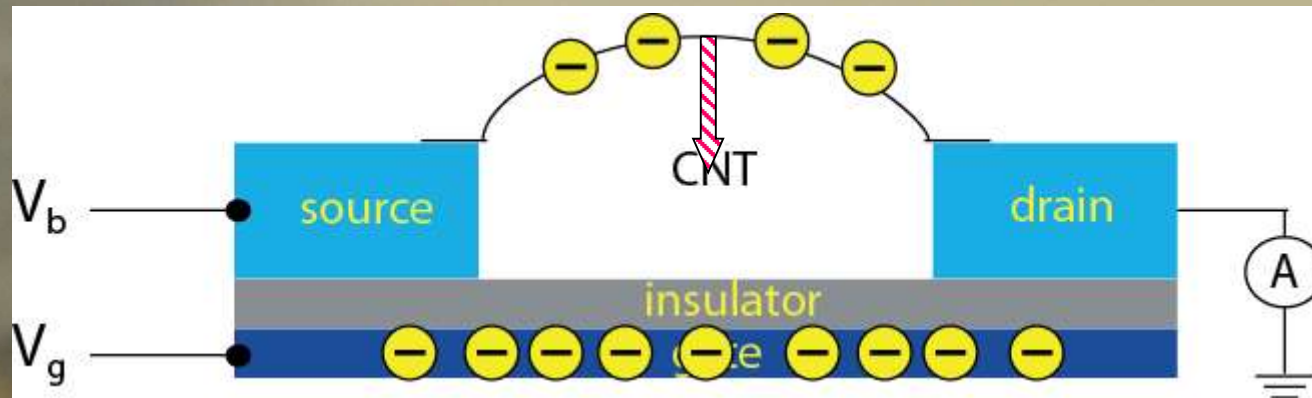


Single-electron tunneling → a lower resonance frequency

Nonlinearity

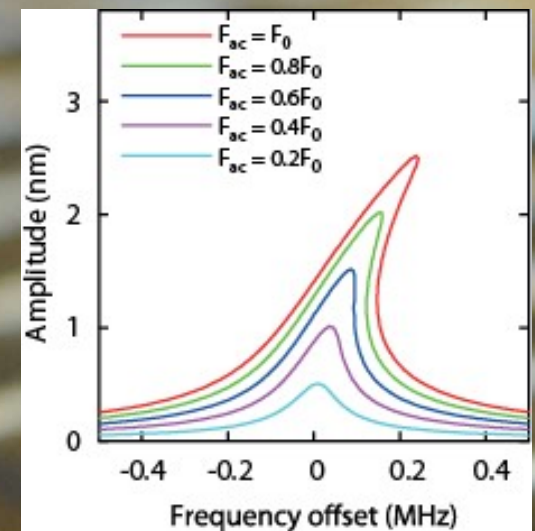
- linear:

restoring force = - spring constant \times displacement



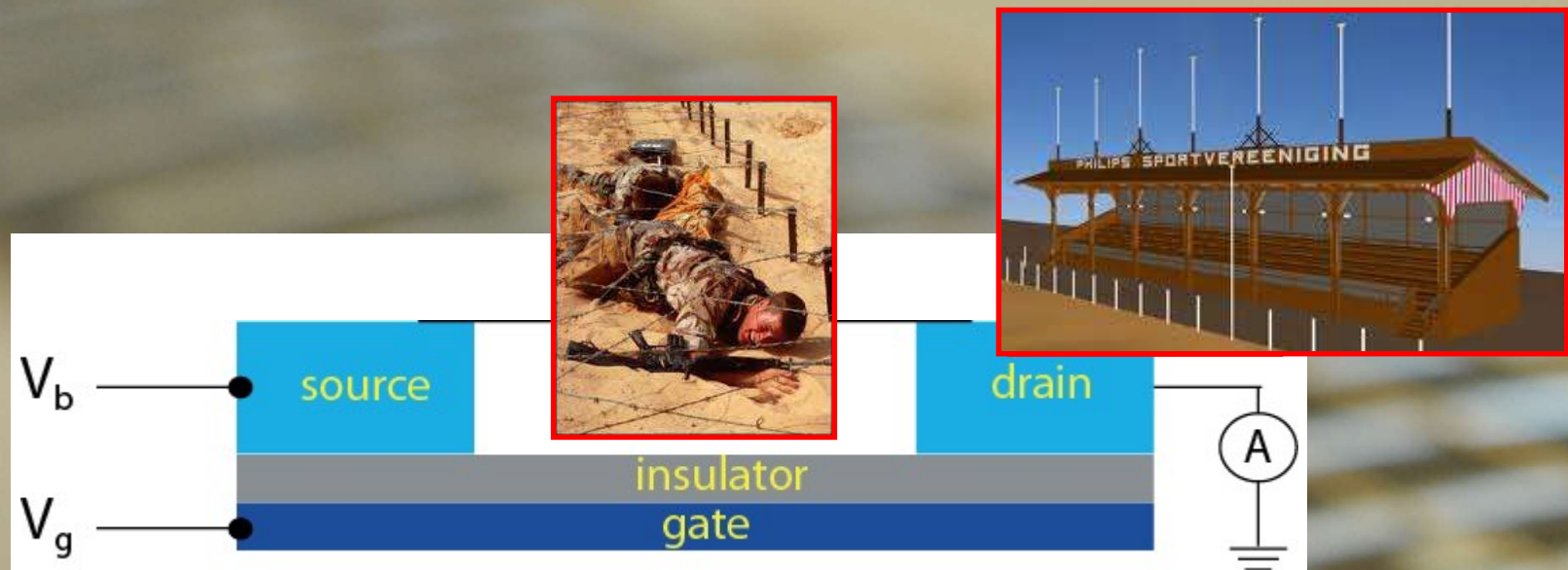
- nonlinear:

restoring force = - NL constant \times displacement³



High-bandwidth readout

"measure really, really fast"



previously: measure 0.1 s

now: measure 0.000001 s

Take-home messages

1. Nanotubes are cool
2. Nanotubes are awesome
3. Nanotubes got me to my defence in 4 years!!!

Thank you for your attention