An Alliance with Mother Nature in the Quest for Ever More Complex Integrated Nanosystems

Alex Zettl
Department of Physics, University of California at Berkeley,
Materials Sciences Division, Lawrence Berkeley National Laboratory

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Building a Pyramid

Natural pyramids in Pyramid Lake, Nevada

Building a Pyramid

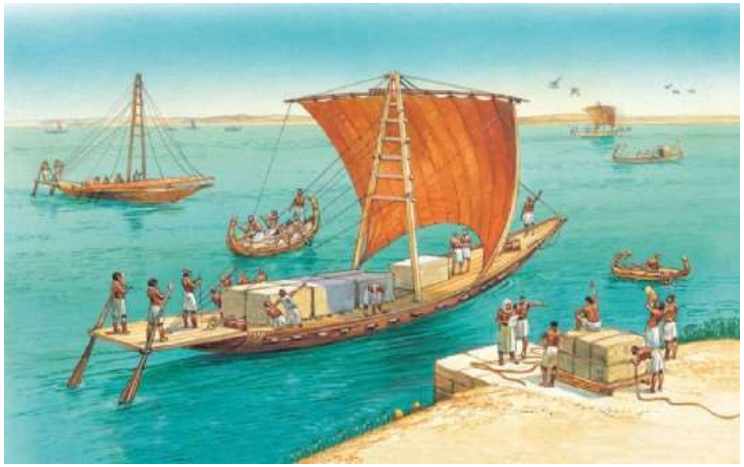
Natural pyramids in Pyramid Lake, Nevada

Building a Pyramid

Artificial pyramids in Giza, Egypt

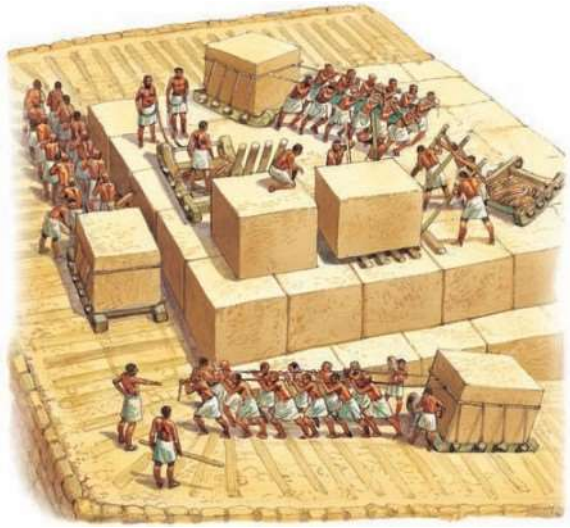
Precise Manufacturing

Source building material



Transport

Manufacture-compliant architecture



Assembly/Integration

Nature Does Better at Smaller Scale

1 cm

Quartz Crystals

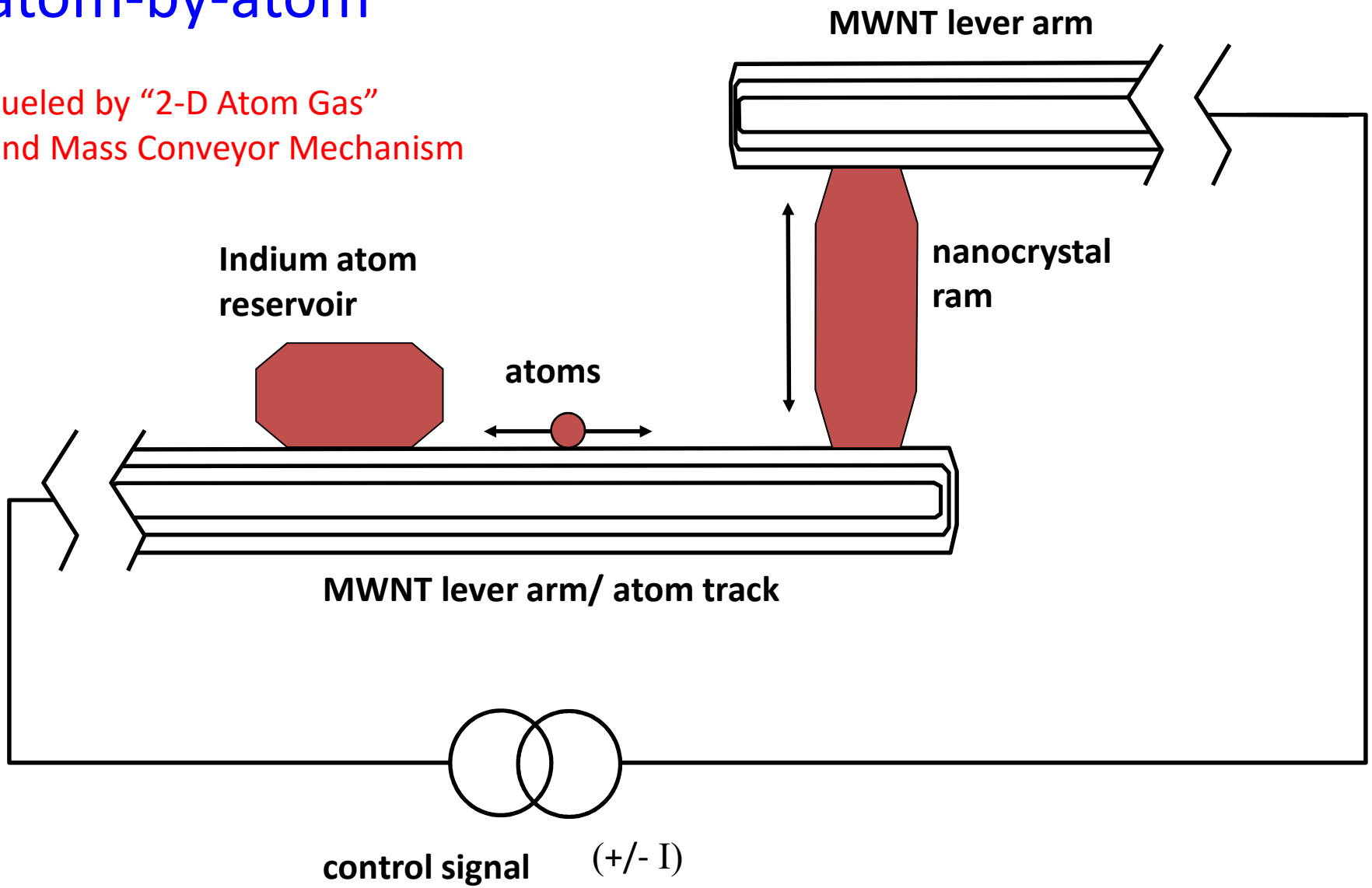
Can we work with nature to enable precise, atomic-scale assembly?

We require

1. Source material
   (atom/molecule/nanoparticle) reservoir
2. Transport mechanism
3. Compliant architecture
4. Fault-tolerant assembly method

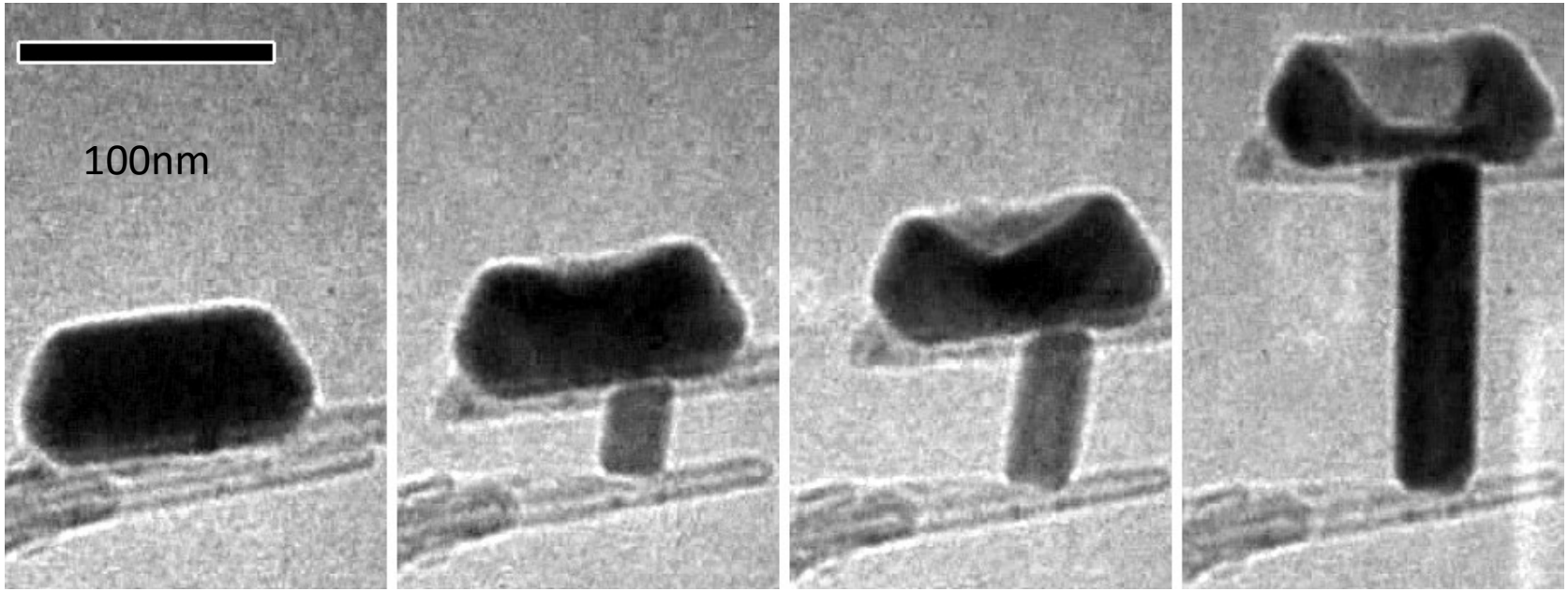
Assembling (and disassembling) a nanocrystal, atom-by-atom

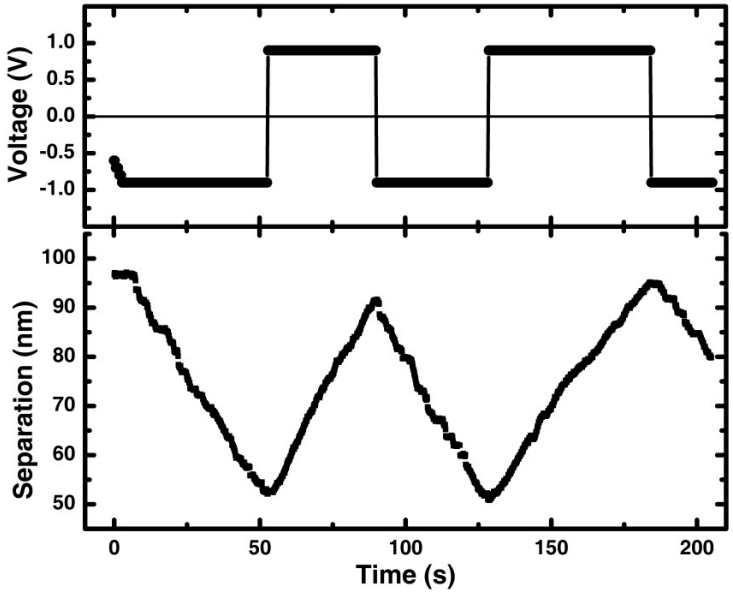
Fueled by "2-D Atom Gas"
and Mass Conveyor Mechanism



Zettl Group
Nanocrystal Actuator

Nanocrystal ram motor is fully controllable, reversible





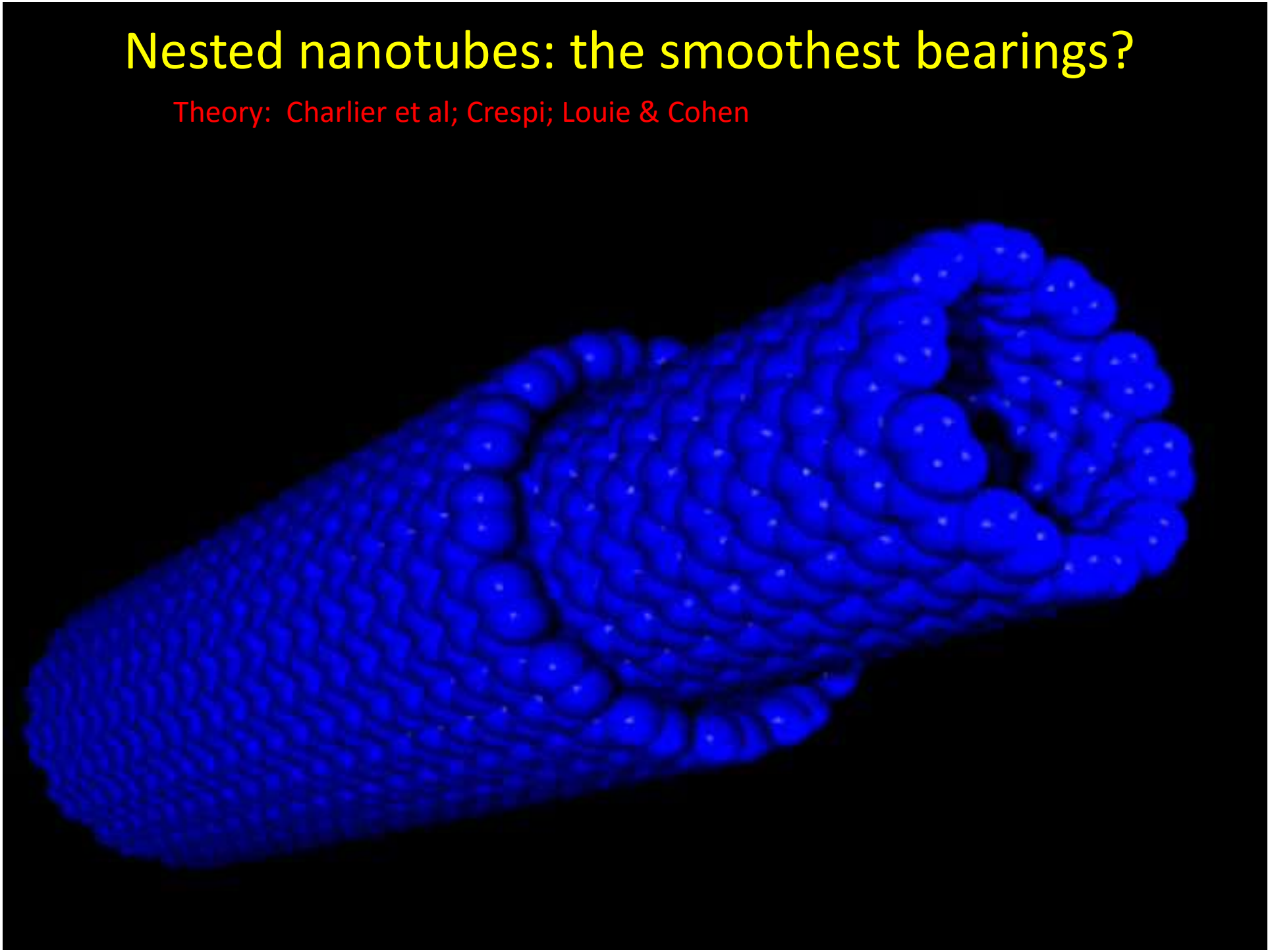
Nanocrystal ram is regrown each cycle-- No wear or fatigue

Power density: 3 GW/m^3
Biomotors, automobiles: .03 GW/m^3)

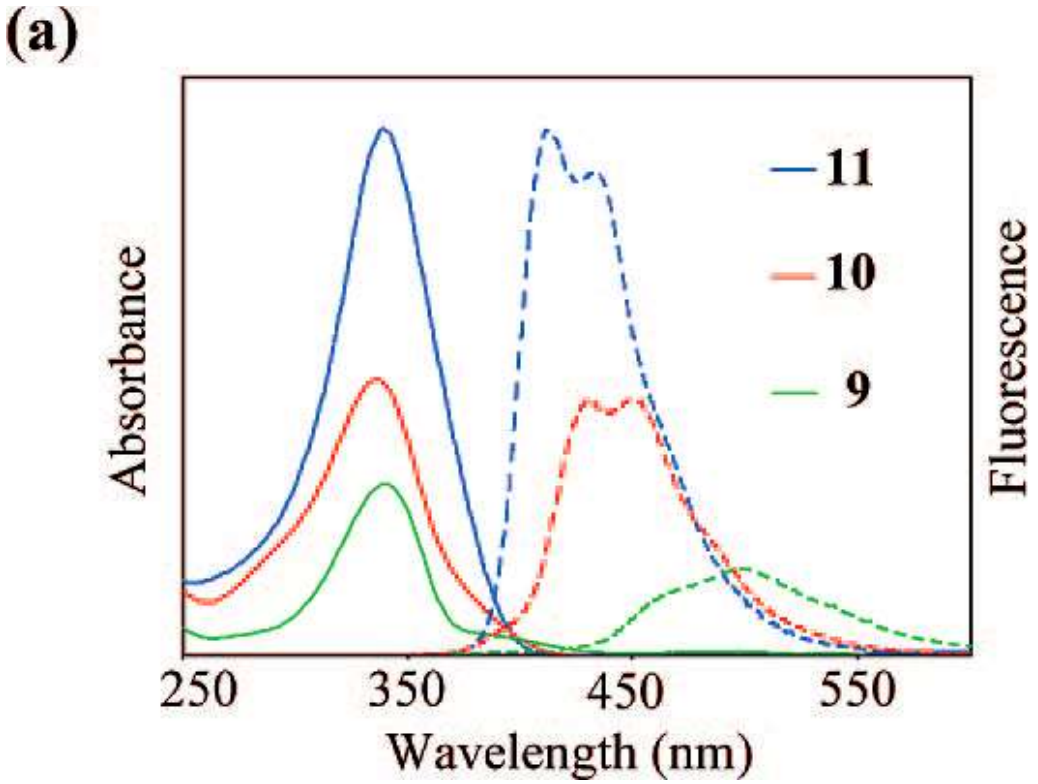
Regan, Aloni, Jensen, Zettl, *Nature* (2005); *Nanoletters* (2005)

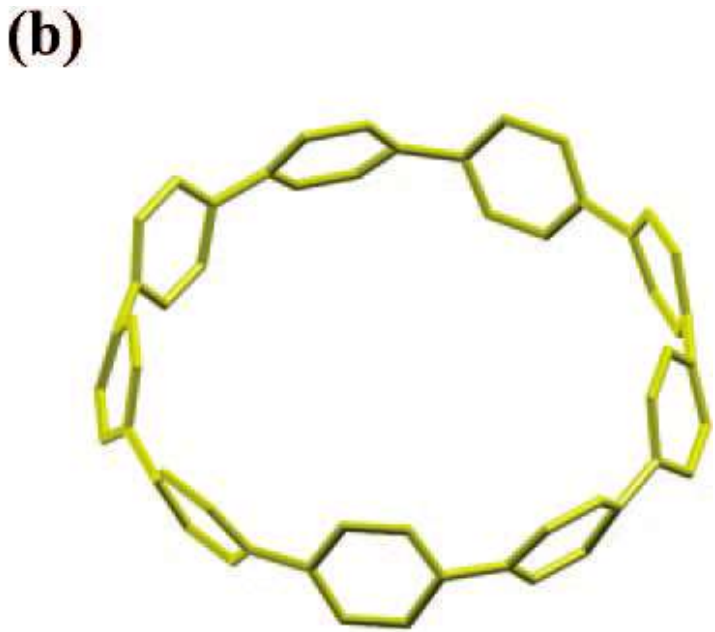
Nested nanotubes: the smoothest bearings?

Theory: Charlier et al; Crespi; Louie & Cohen



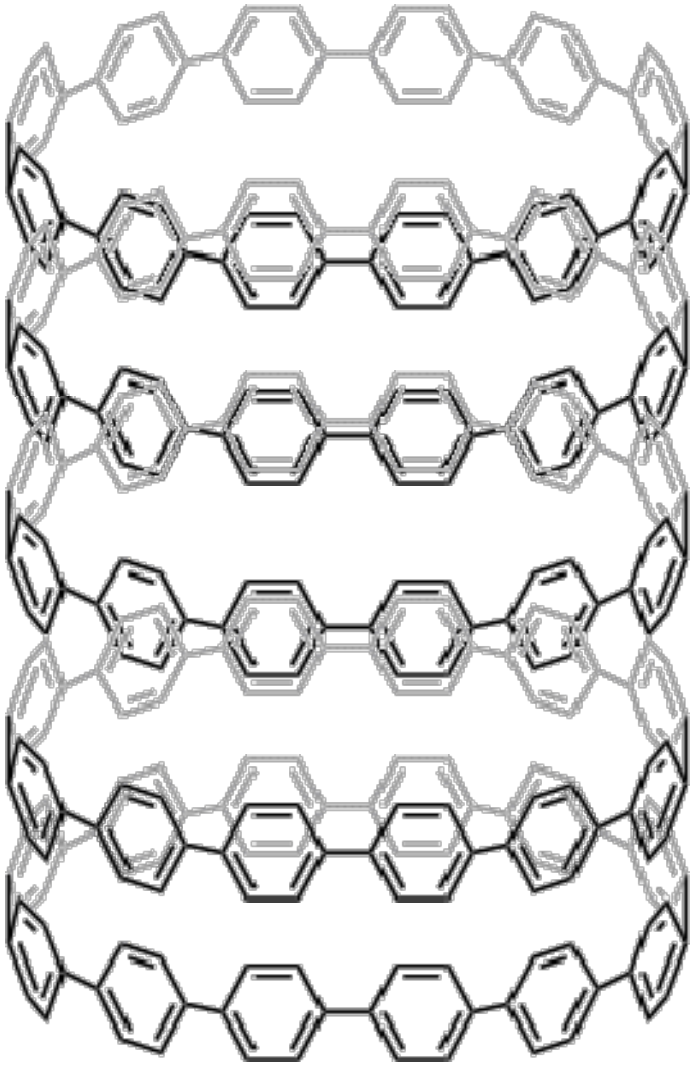
Organic Chemistry Route to Carbon Nanotubes



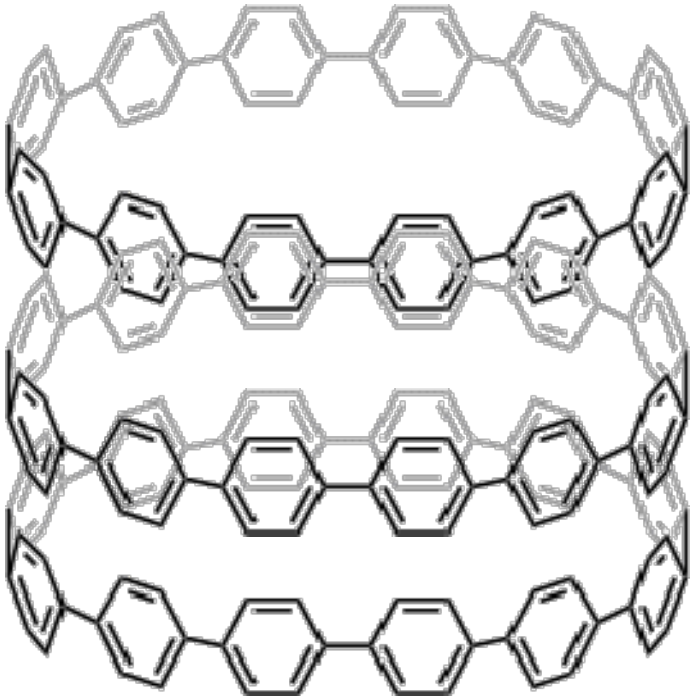


R. Jasti, C. Bertozzi, Neaton et al, JACS (2008)

Proposed stack



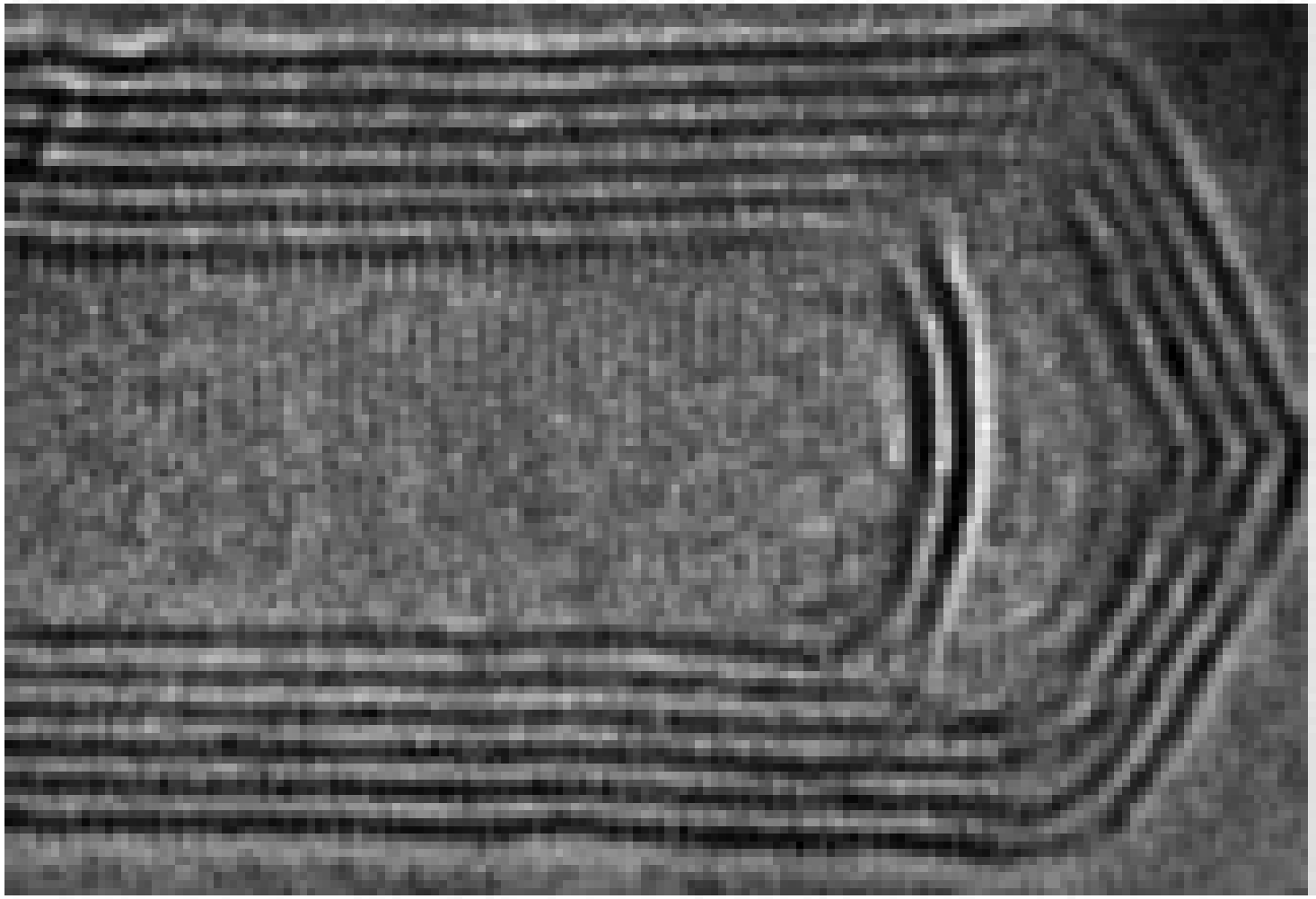
Realized stack



After 7 years of very sophisticated organic chemistry…

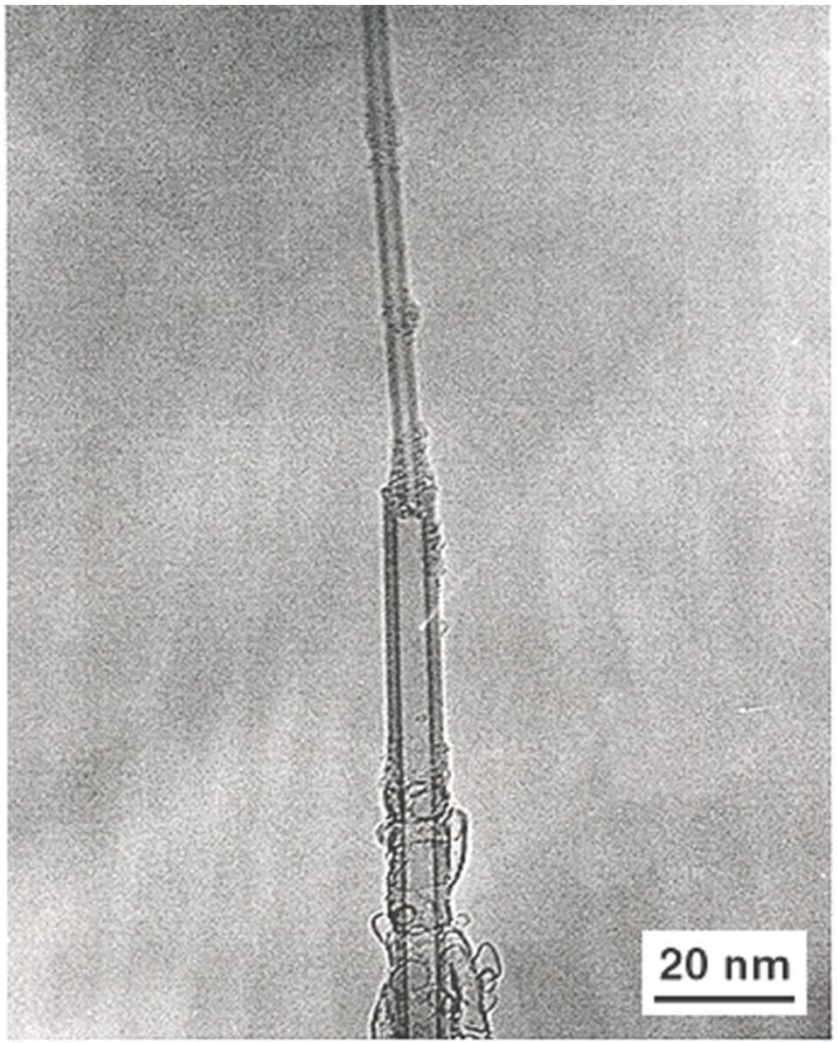
stack is 3 units high

Non-equilibrium (plasma) synthesis of nested carbon nanotubes

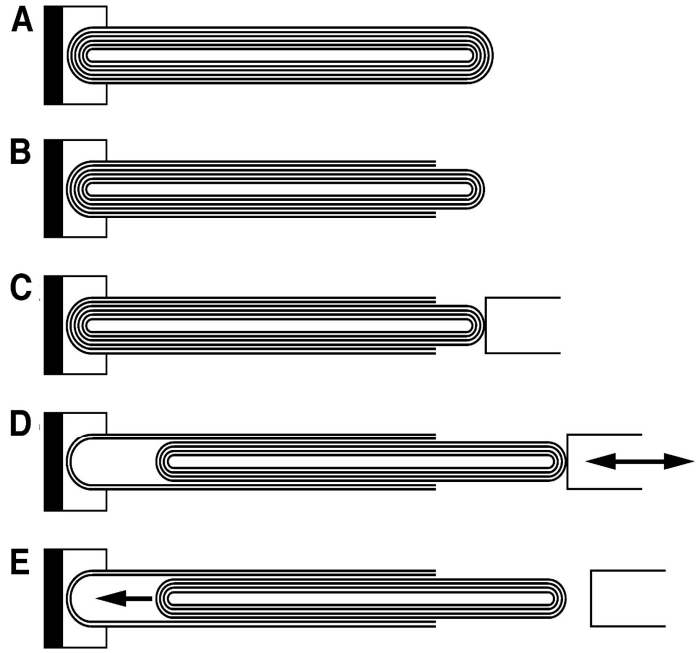


Terrones, M. Annu. Rev. Mater. Res. 2003, 33, 419

Nanoscale Linear/Rotational Bearing



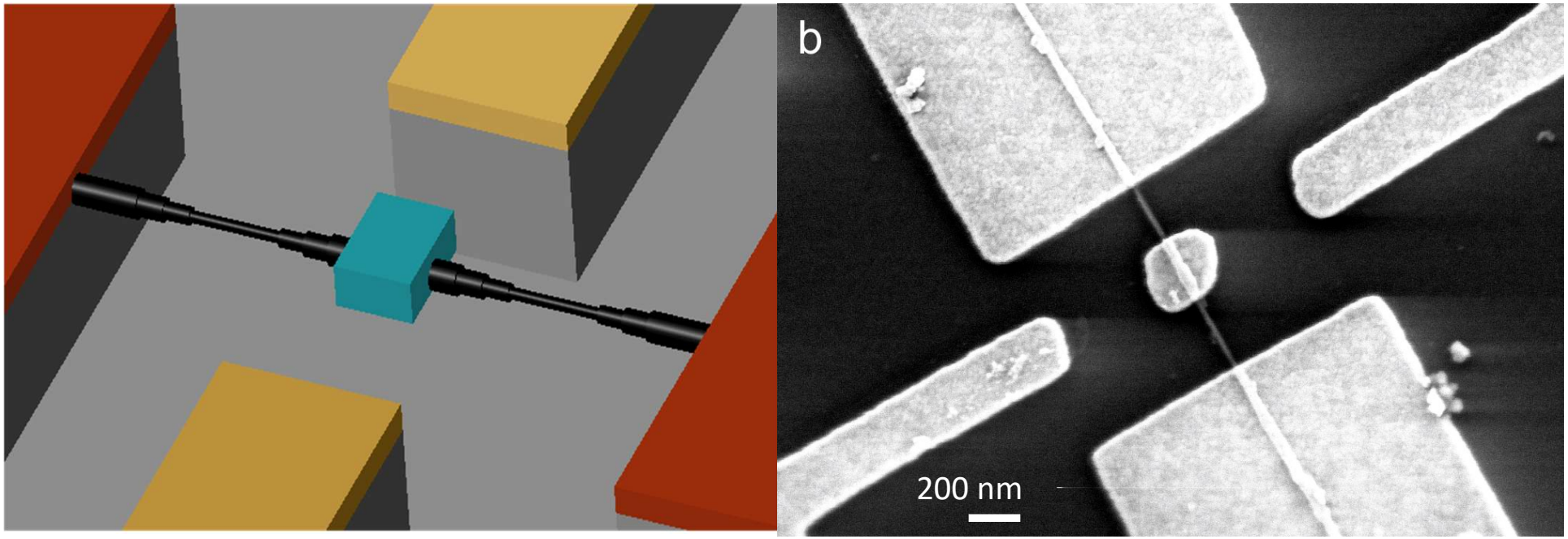
9 walls = 4 (core) + 5 (housing)



Measured friction: $F_f < 10^{-16}$ N/atom
(lowest friction ever measured)

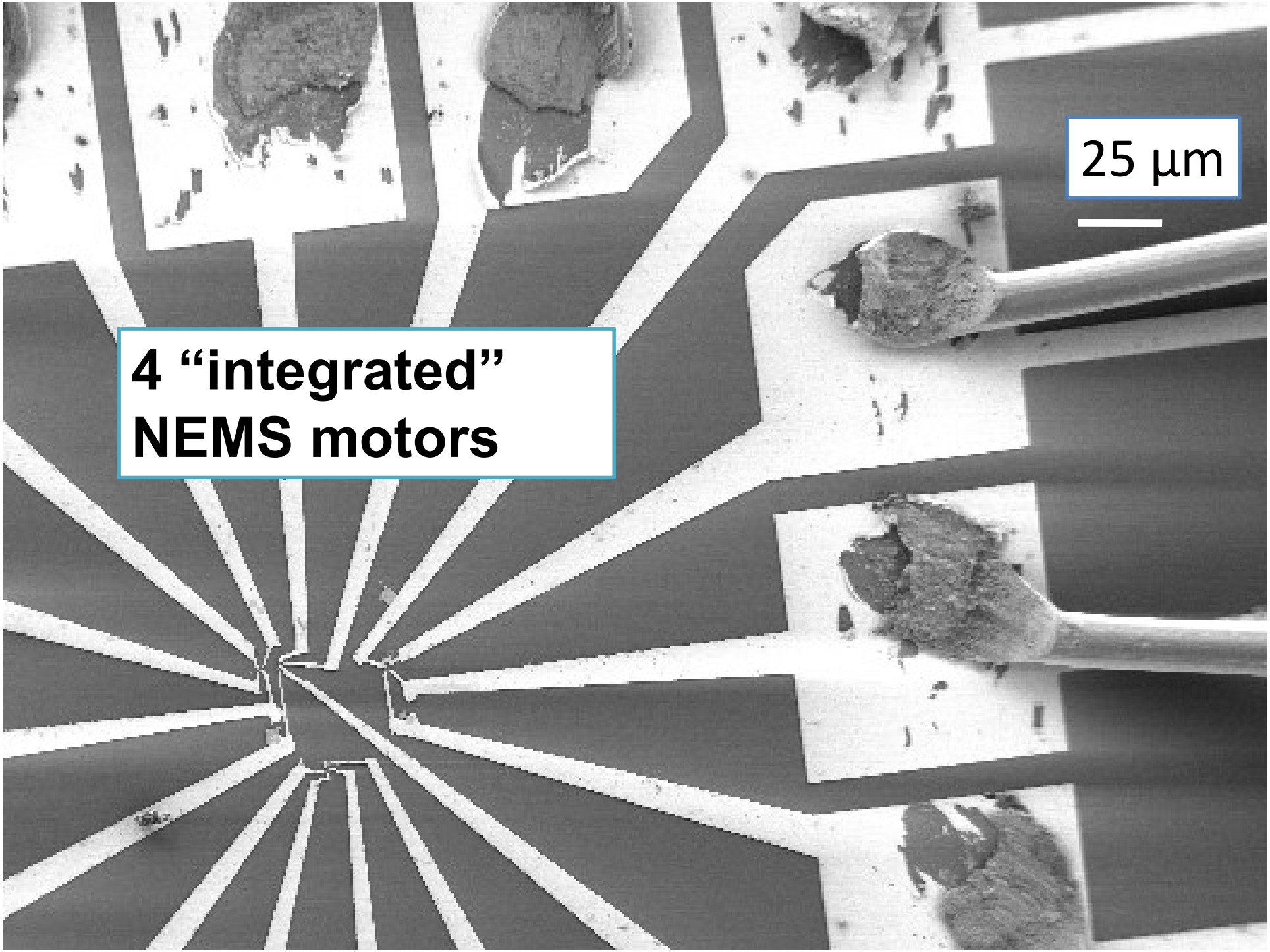
Cumings & Zettl, *Science* (2000), Kis & Zettl, *PRL* (2006)

Nanotube-bearing based rotational electric nanomotor

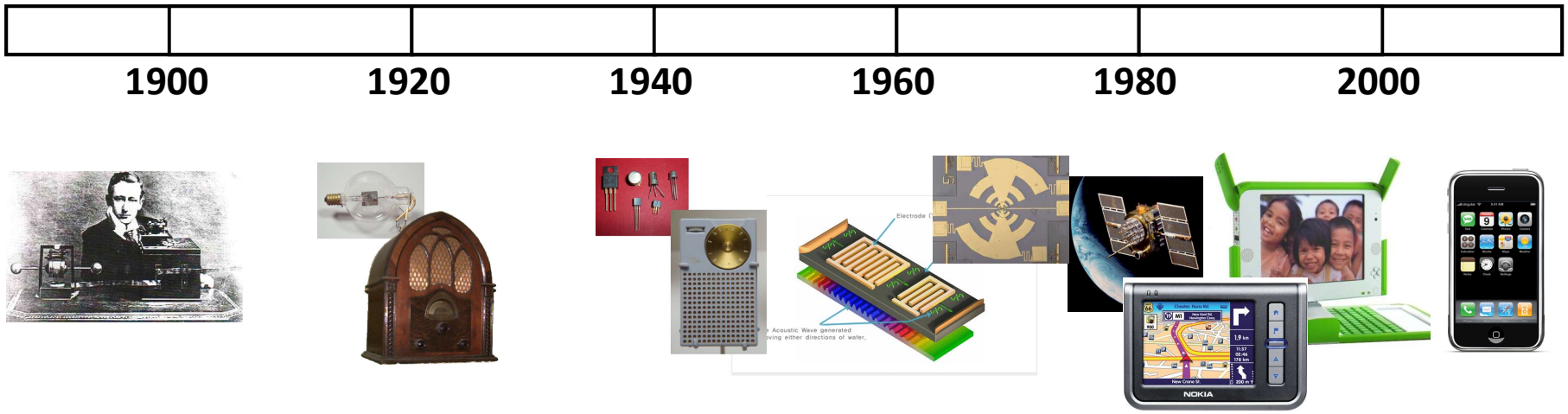


E-Beam lithography, Si processing

Fennimore, Yuzvinsky, Zettl, *Nature* 2003


25 µm
4 “integrated”
NEMS motors

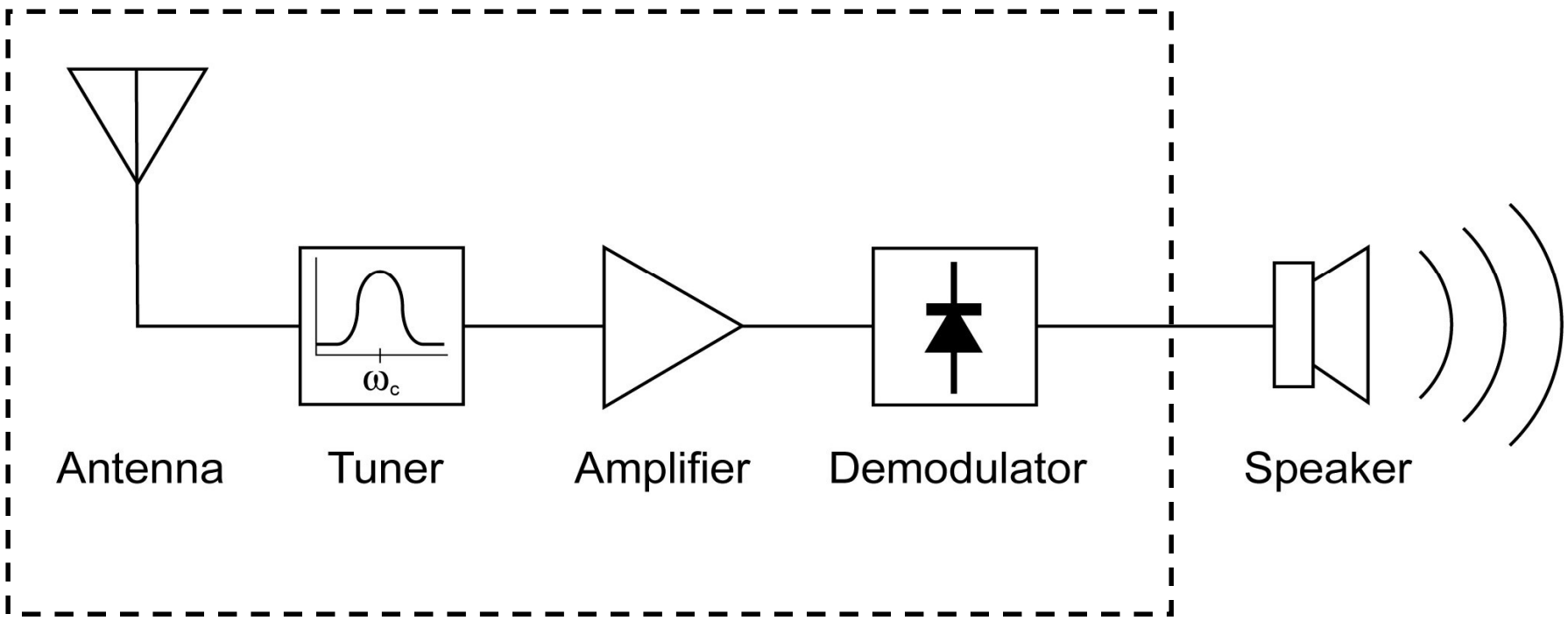
History of Radio Technology



Key developments:

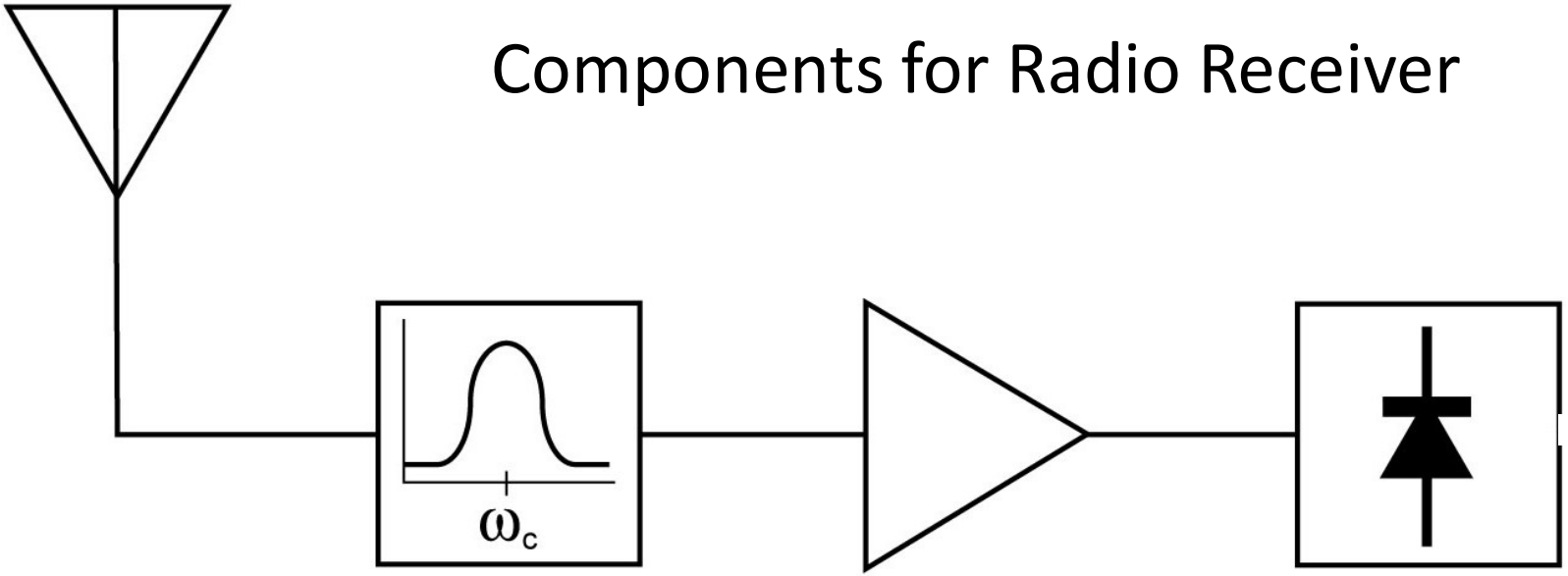
- Theory (EM, quantum mechanics)
- Materials (semiconductors)
- Integration (on-chip architecture)

Multi-component System: Radio

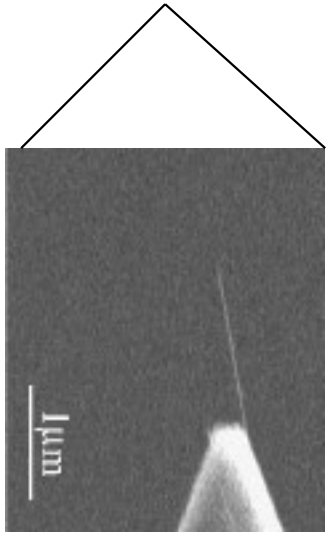


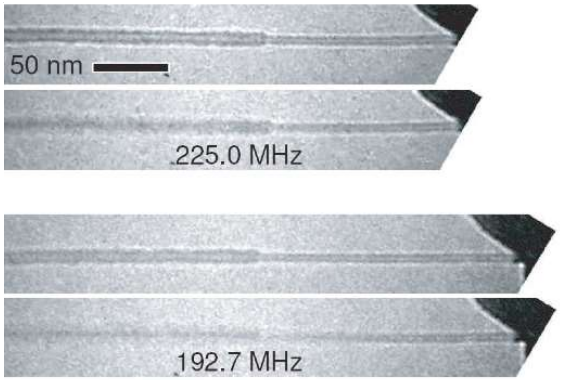
Radio Receiver

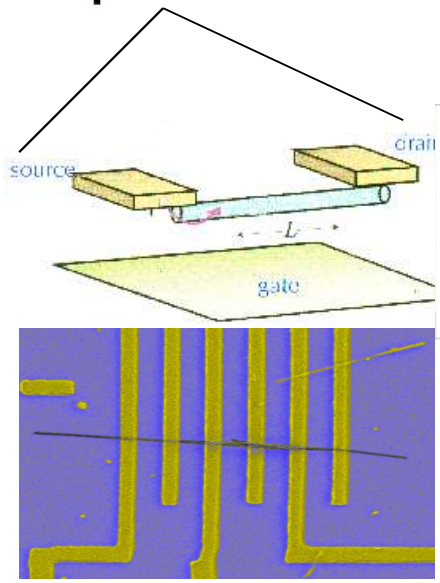
Components for Radio Receiver

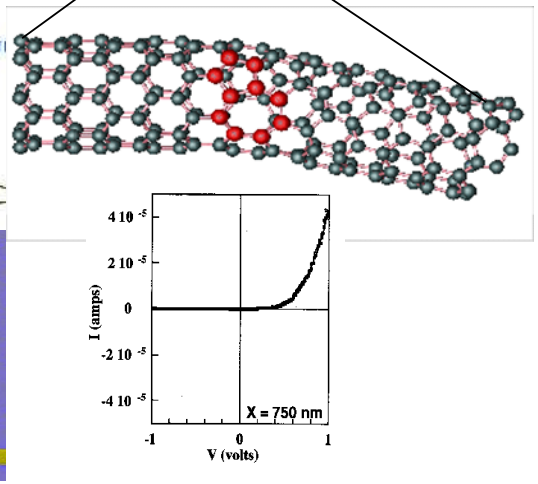


Antenna Tuner Amplifier Demodulator



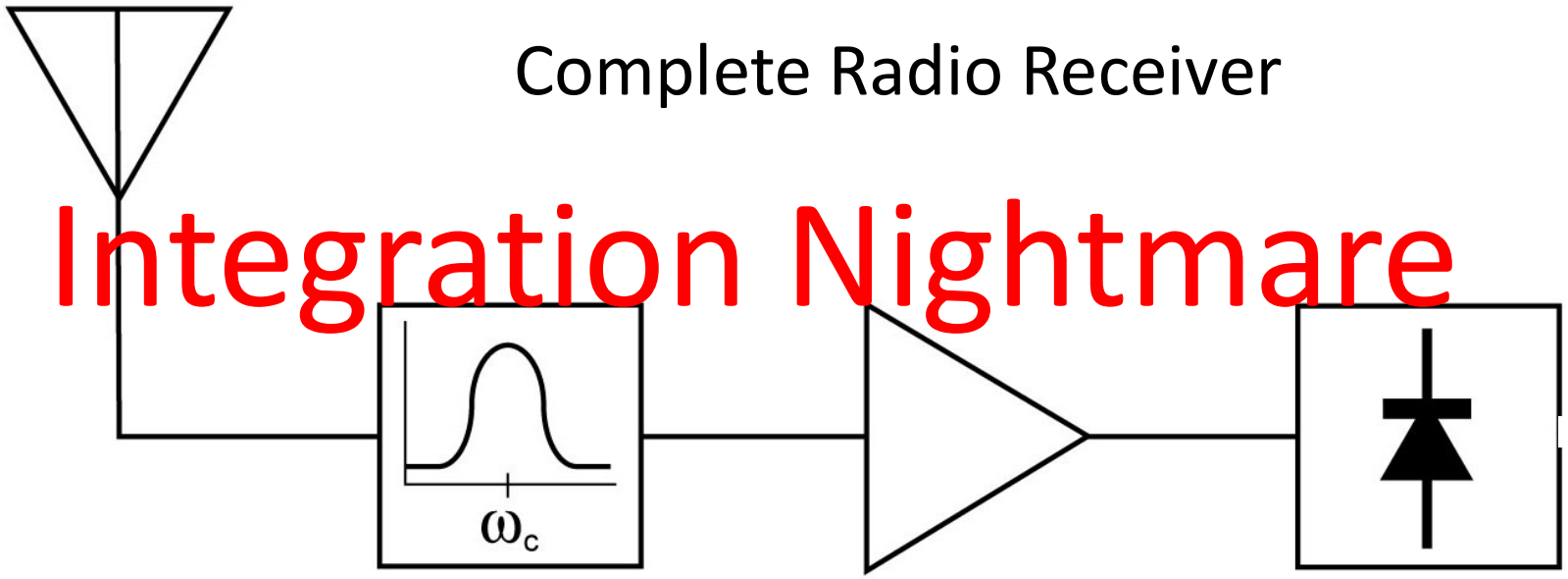




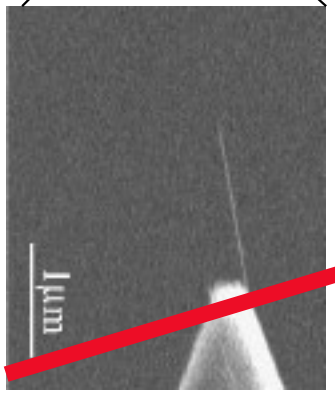


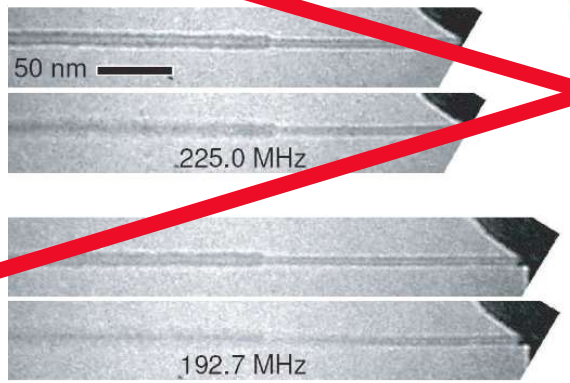
Complete Radio Receiver

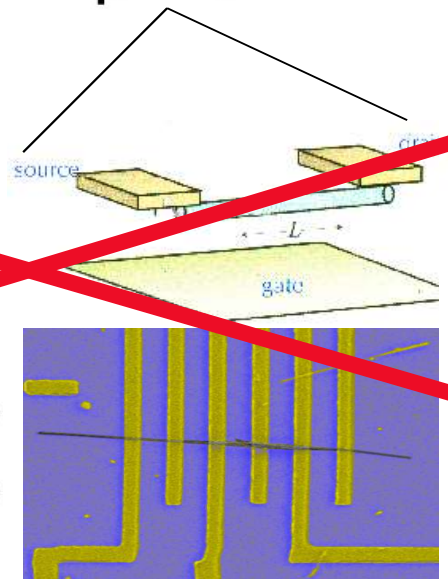
Integration Nightmare

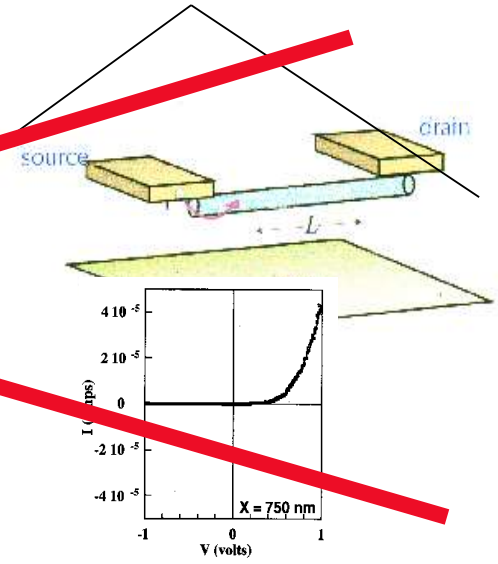


Antenna Tuner Amplifier Demodulator

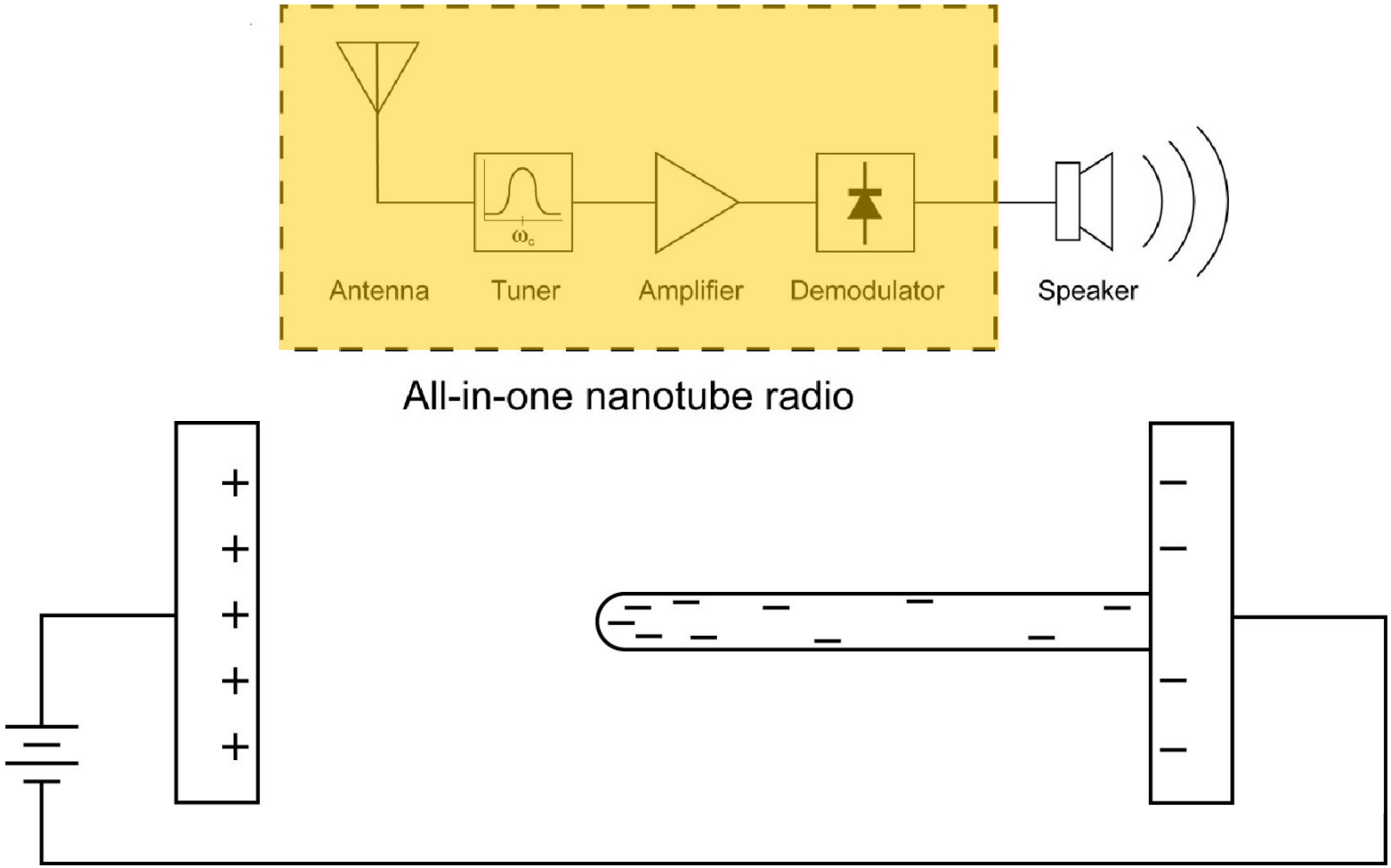




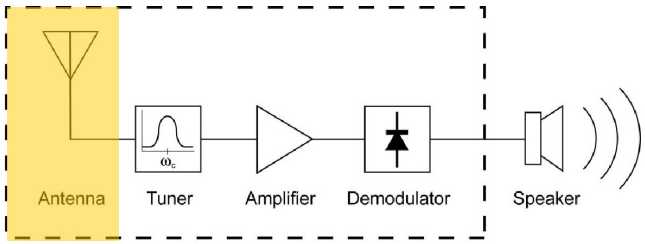




Ultimate Integration: One-Molecule Device



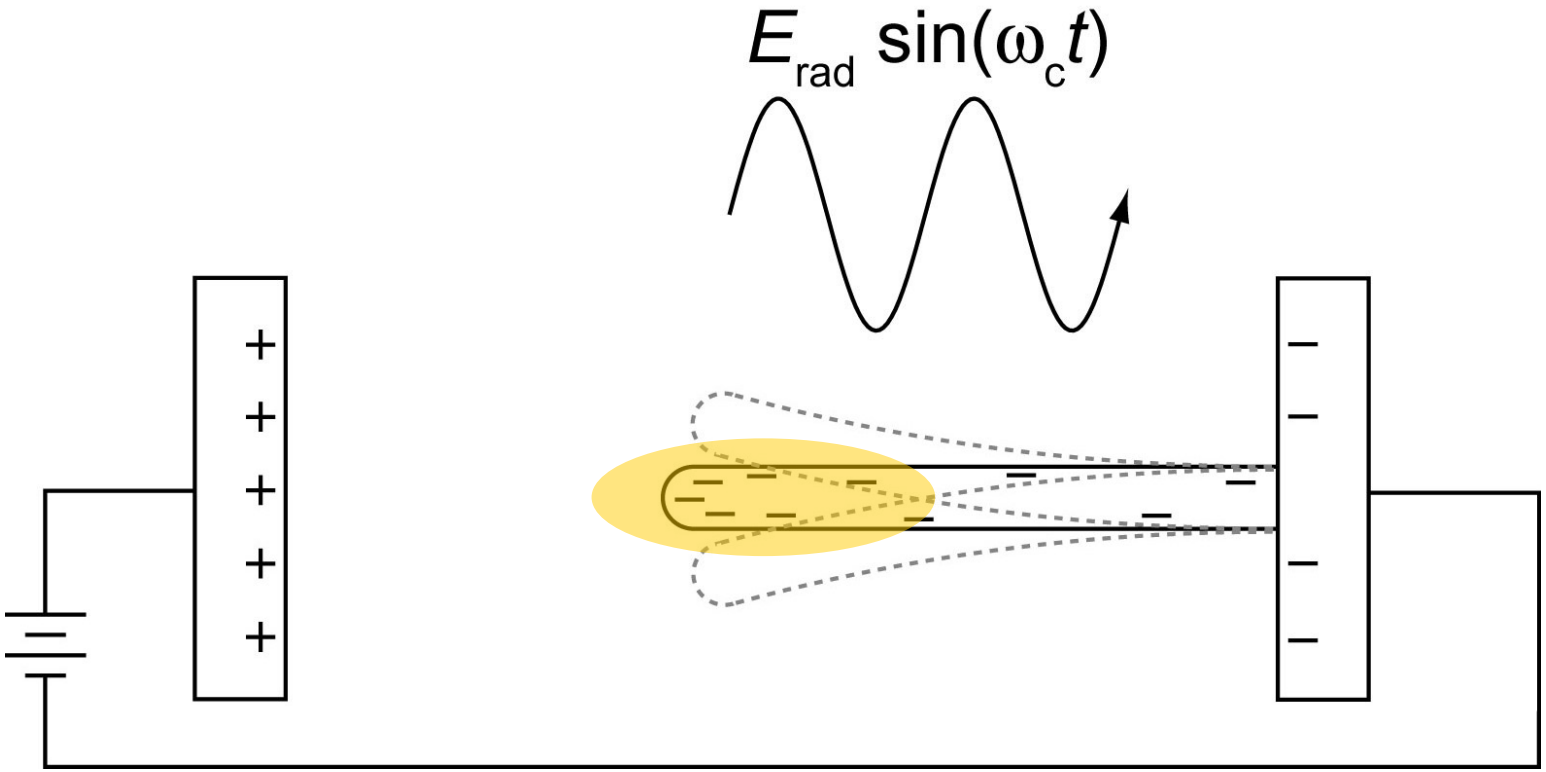
Entire radio implemented with one nanotube.

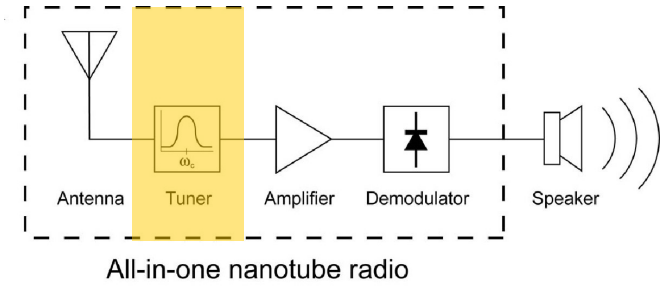


All-in-one nanotube radio

Antenna

Charged tip of nanotube is sensitive to external *E* fields.

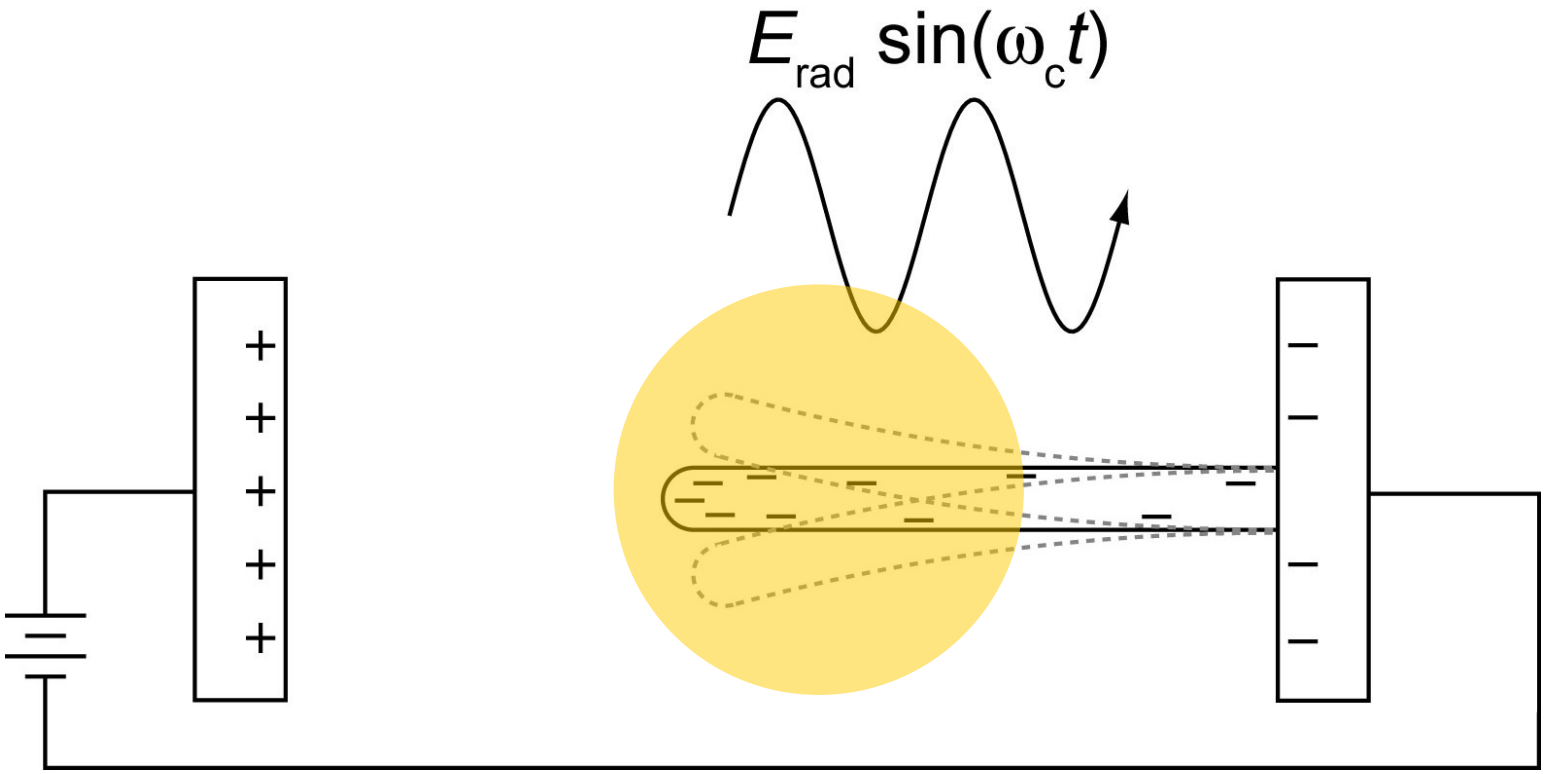


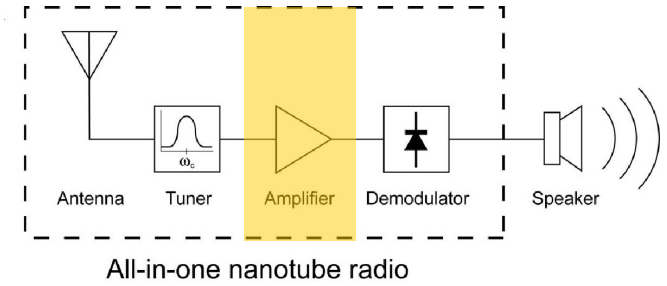


All-in-one nanotube radio

Tuner

Vibrates when radio signal matches resonance frequency.

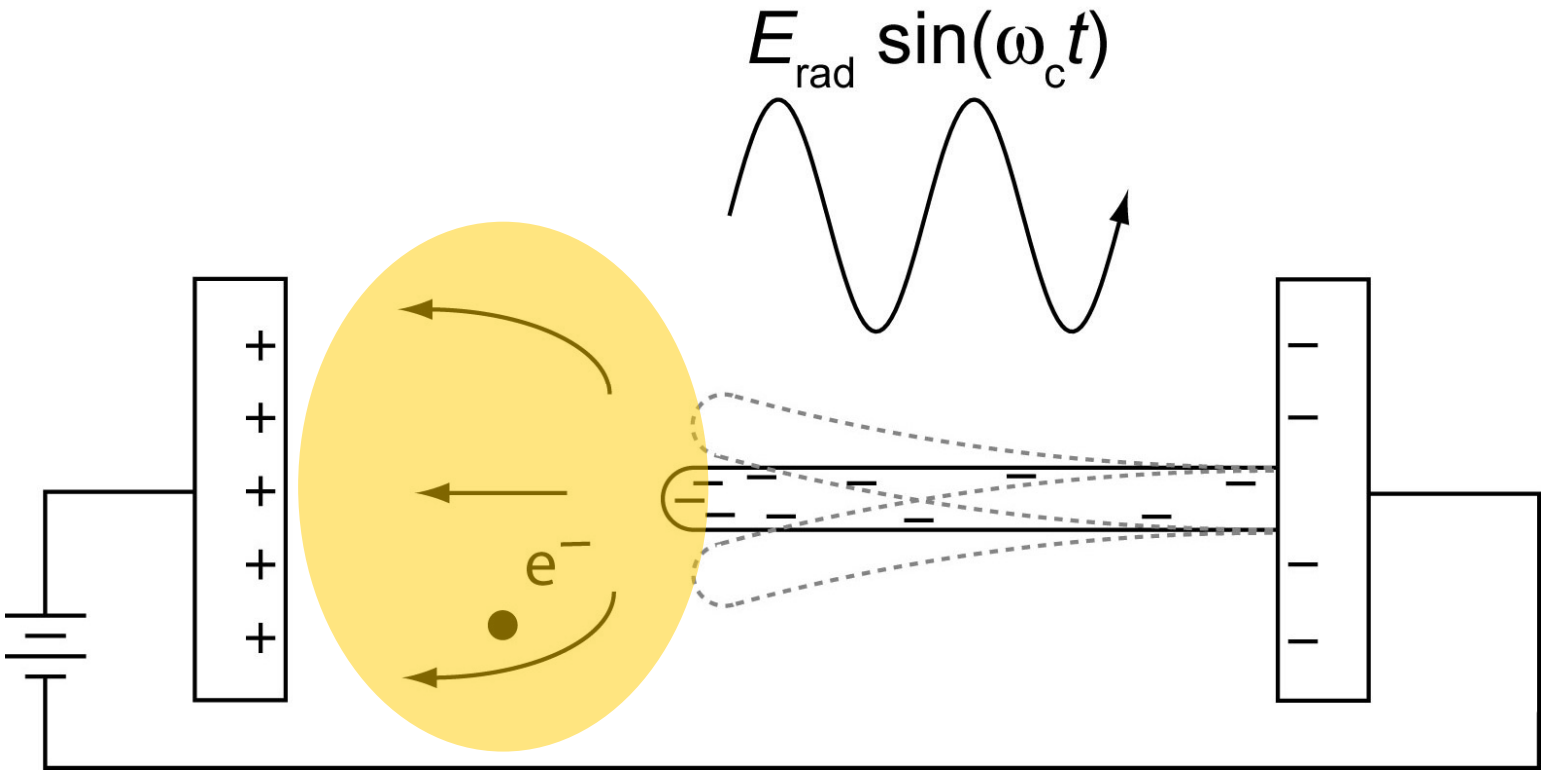


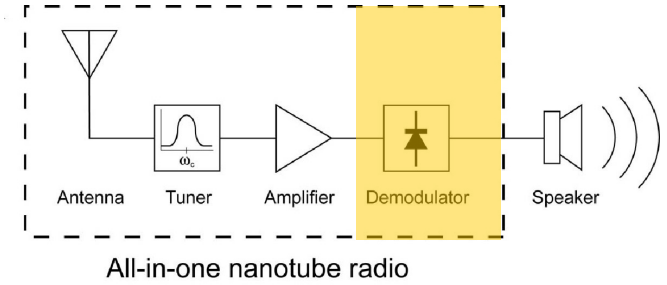


All-in-one nanotube radio

Amplifier

Vibrating tube modulates field emission current.

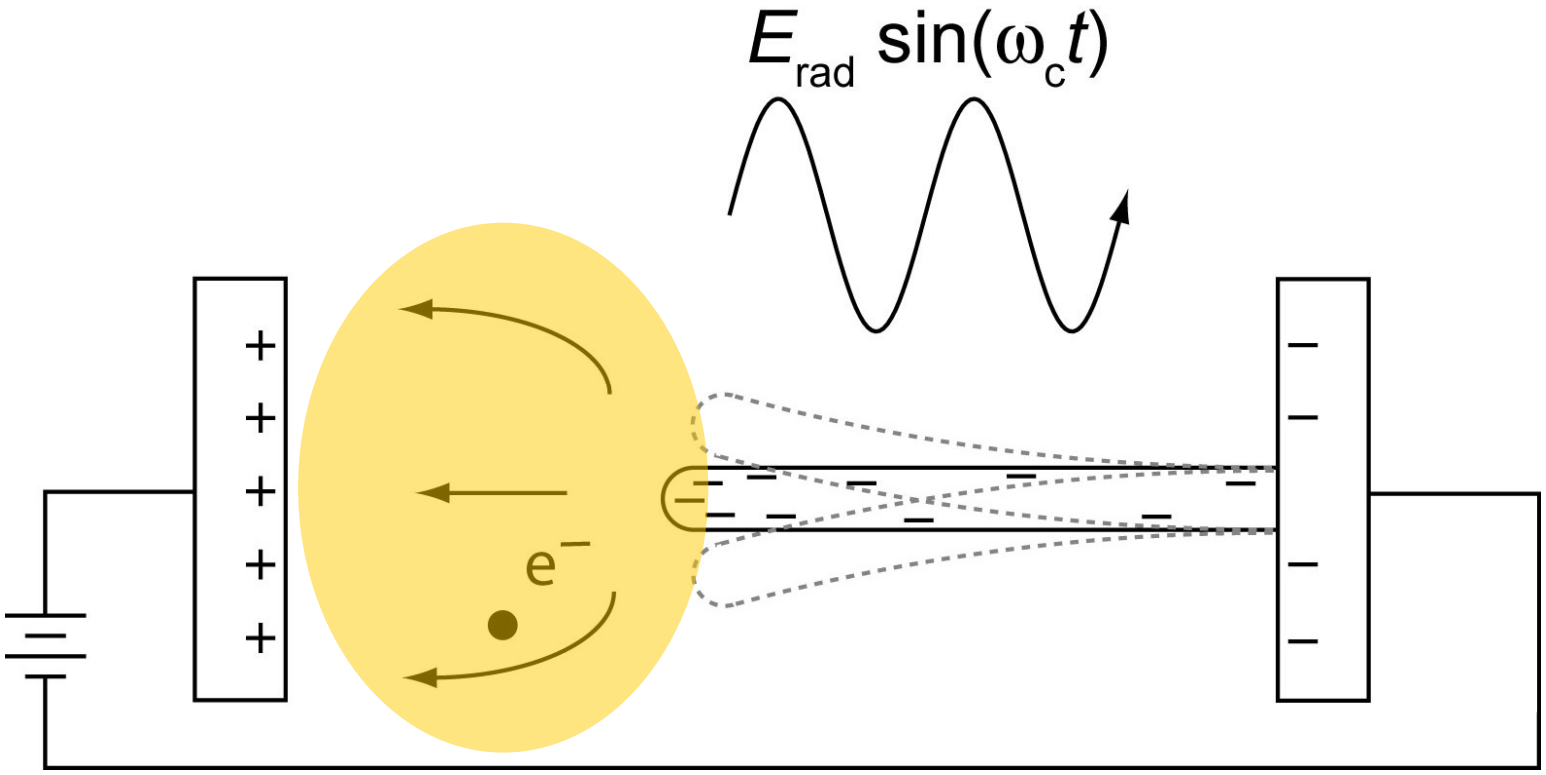


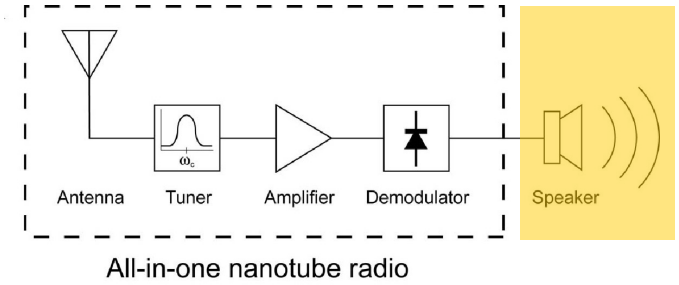


All-in-one nanotube radio

Demodulator

Field emission nonlinearities demodulate radio signal.

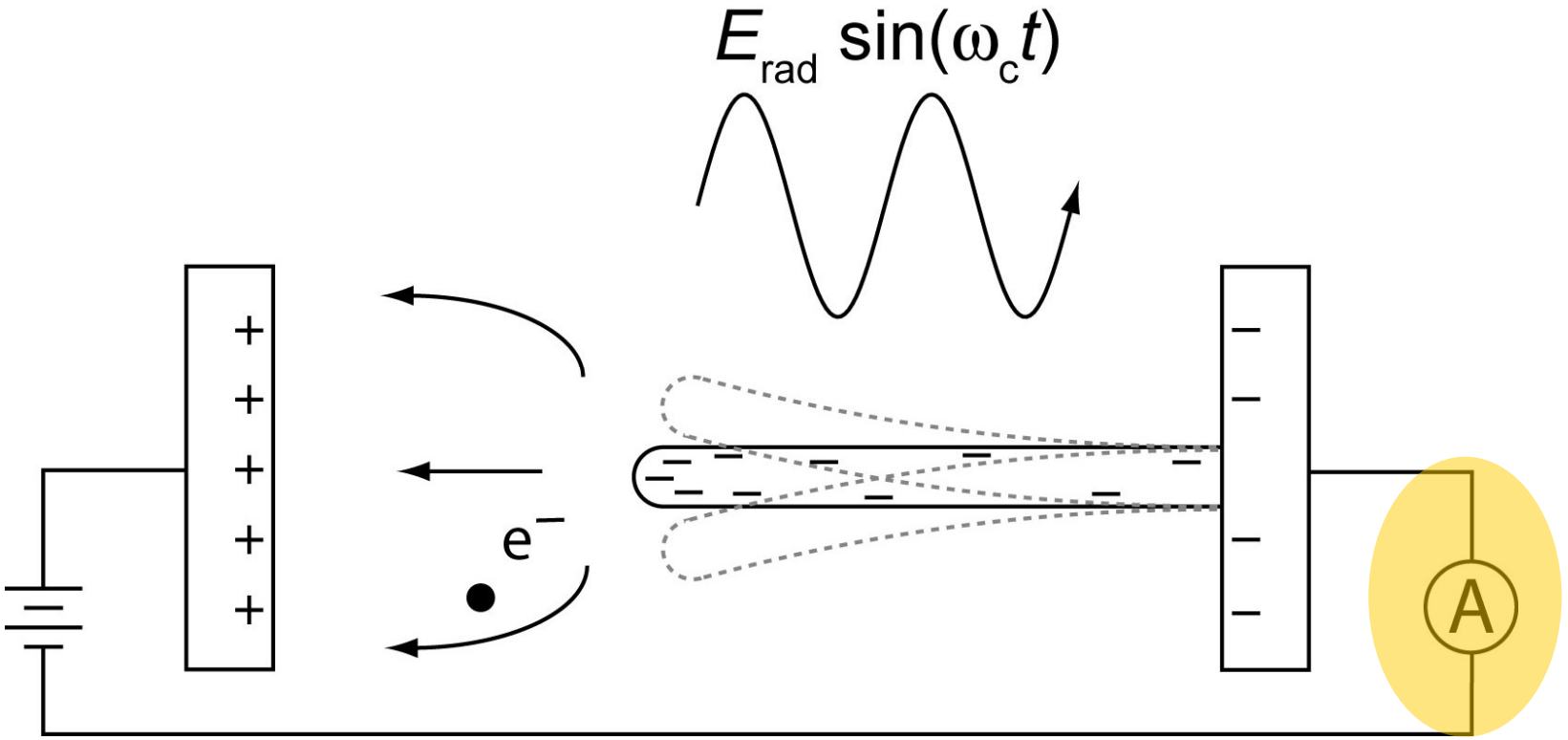




All-in-one nanotube radio

Output

Measure current with sensitive ammeter.

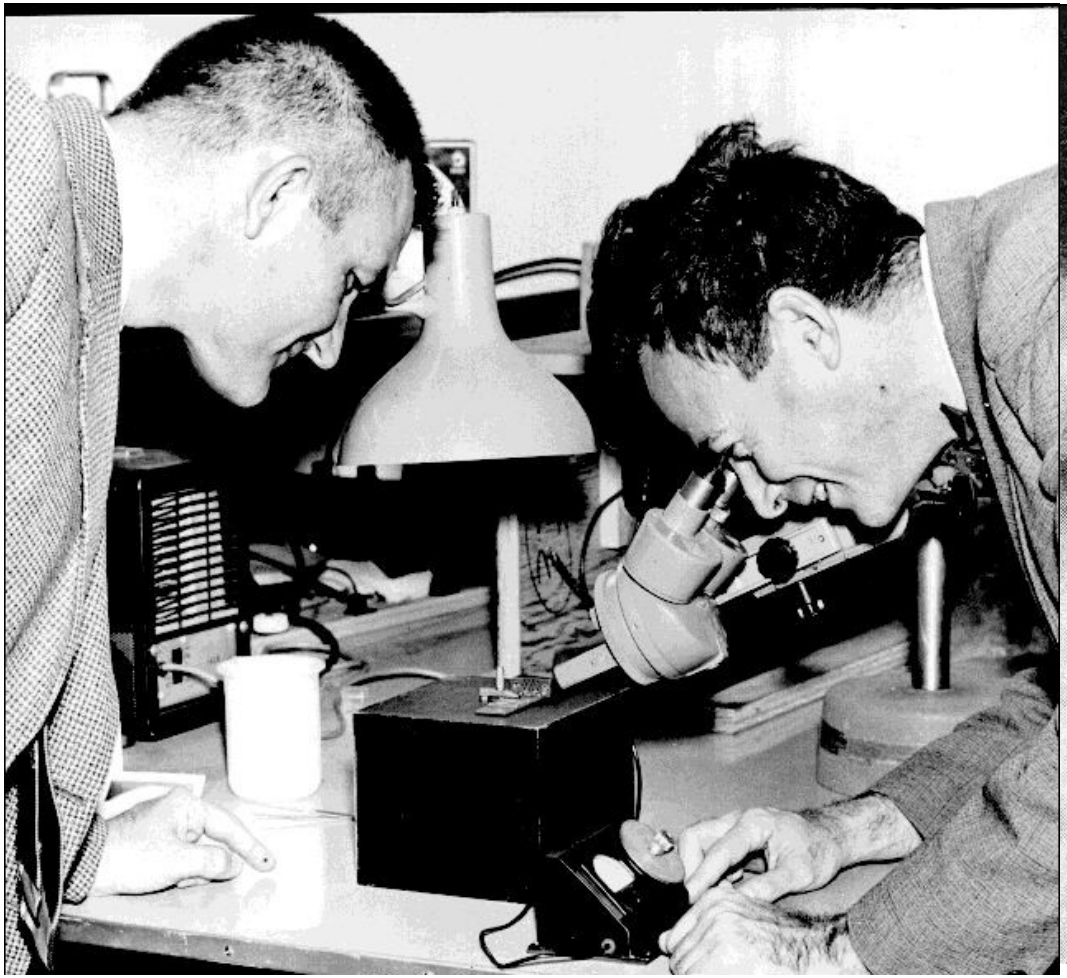


A Miniaturization Challenge

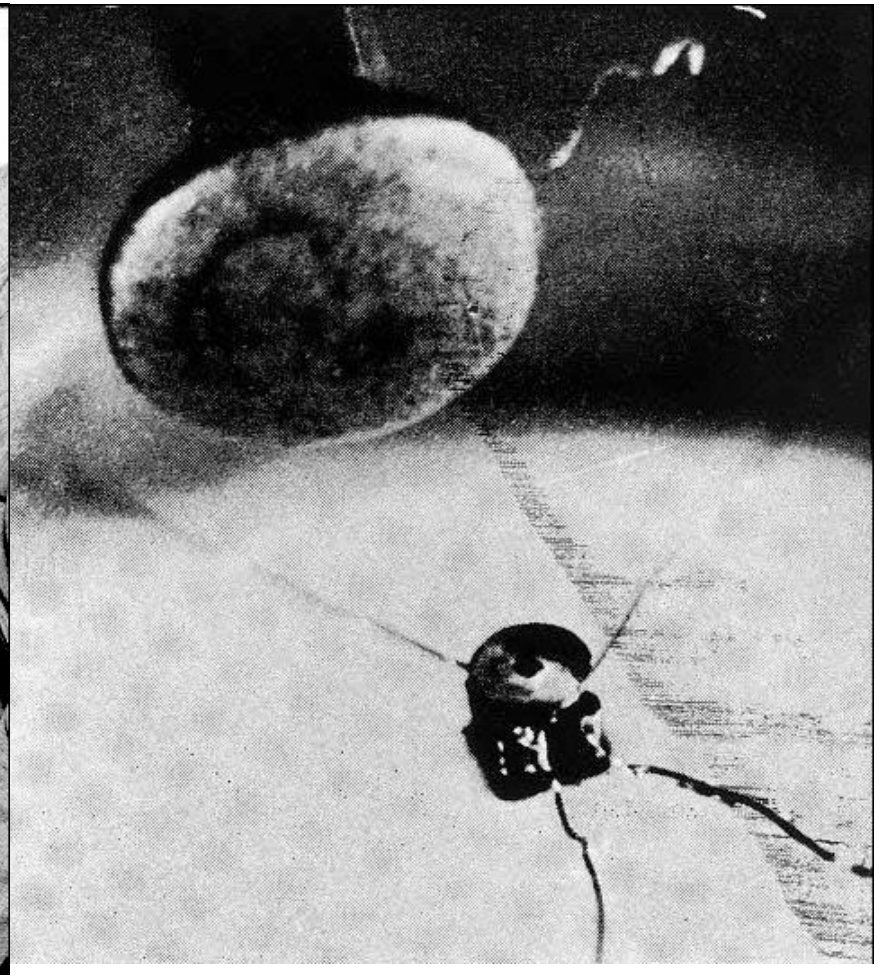
"...$1,000 to the first guy who makes an operating electric motor---a rotating electric motor which can be controlled from the outside and, not counting the lead-in wires, is only 1/64 inch cube."

Richard P. Feynman, 1959

(1960)



William McLellan (left) and
Richard Feynman



1 mm

1/64” = 0.397mm = 397µm = 397,000 nm

Don’t fight nature– exploit it!