2023 edition

MICRO-470

Scaling laws in micro & nanosystems

Prof. Herbert Shea

Moodle: https://moodle.epfl.ch/course/view.php?id=15794

Class planning 2024

Week #	Date of Week	Lecture Content (2 x 45 min)
1	09.09.2024	Introduction to Scaling Laws
2	16.09.2024	*(Jeûne Fédéral)*
3	23.09.2024	Mechanical scaling 1
4	30.09.2024	Mechanical scaling 2
5	07.10.2024	Electrostatic Actuation 1
6	14.10.2024	Electrostatic Actuation 2
7	21.10.2024	*vacances mi-semestre*
8	28.10.2024	Thermal Effects
9	04.11.2024	Thermal Effects
10	11.11.2024	Electromagnetics
11	18.11.2024	Microfluidics 1
12	25.11.2024	Microfluidics 2
13	02.12.2024	*no class this week*
14	09.12.2024	Piezo scaling Failure Mechanisms 1
15	16.12.2024	Failure Mechanisms 2

Videos from 2020 on MediaSpace

https://mediaspace.epfl.ch/channel/MICRO-470%2BScaling%2Blaws%2Bin%2Bmicro%2B%2526%2Bnanosystems/30236

2 ECTS

Few students: should we have 4h/week, every 2nd week?

Or 4 hr in a row too much?
3 hours better?

Oral exam (100% of your grade). Jan/Feb 2024

See file “exam themes 2023” on moodle for example topics and exam modality.

A sign-up sheet will be made available online once the exam dates are announced for you to choose a time slide.

Oral exam:

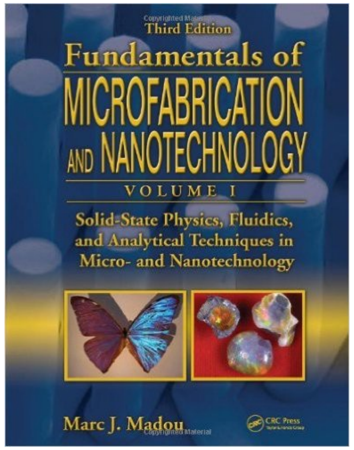
- When you enter the exam room, you will receive a page with two or three questions.
- You will then have 20 minutes to prepare. You can write notes and answers directly on this page.
- You will not have access to your lecture notes or any other documentation. **Closed book**
- you will have 20 minutes of oral exam to discuss the questions with the professor

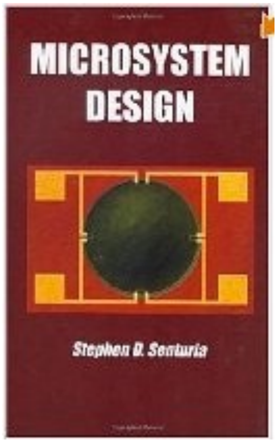
Textbooks- can recommend: (more are listed in the moodle, some for download)

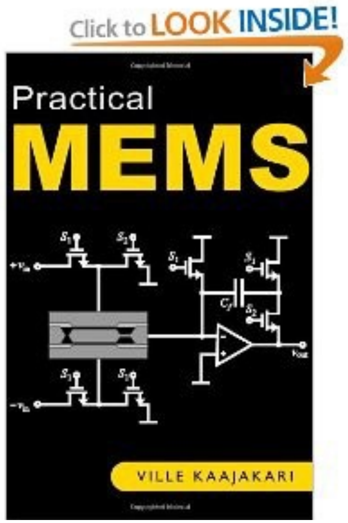
- **Fundamentals of Microfabrication and Nanotechnology**, by *Marc Madou*, CRC Press; 3rd edition (2012)

- **Microsystem Design** by *Stephen D. Senturia*, Springer (2004)

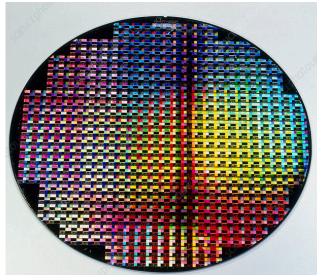
- **Practical MEMS**: Design of microsystems, accelerometers, gyroscopes, RF MEMS, optical MEMS, and microfluidic systems, by *Ville Kaajakari*, Small Gear Publishing (2009)







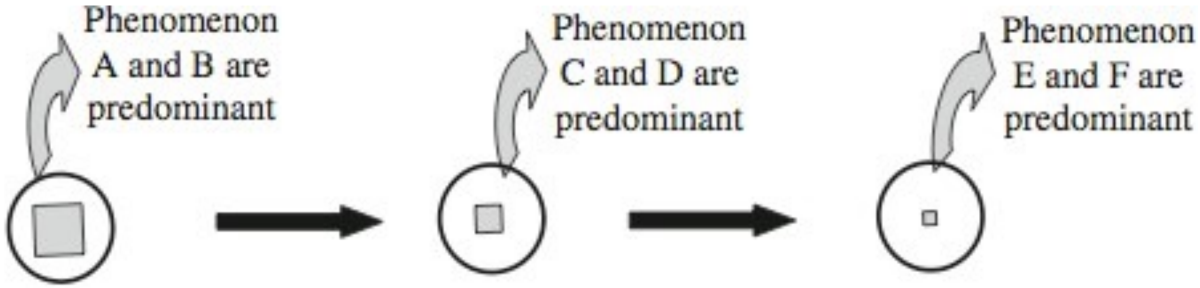
Motivation for miniaturization and MEMS



- Smaller size (or more components, large arrays, …)
- Less material, better materials (ex: single crystal Si)
- Lower energy consumption
- Better performance (when well-fabricated)
- Cheaper (when mass produced)
- Different physical phenomena dominate

What happens at smaller size scales ?

- Competing physical effects do not follow the same scaling
- Simple scaling ?
- Continuum breakdown ?
- Quantum-like breakdown ?



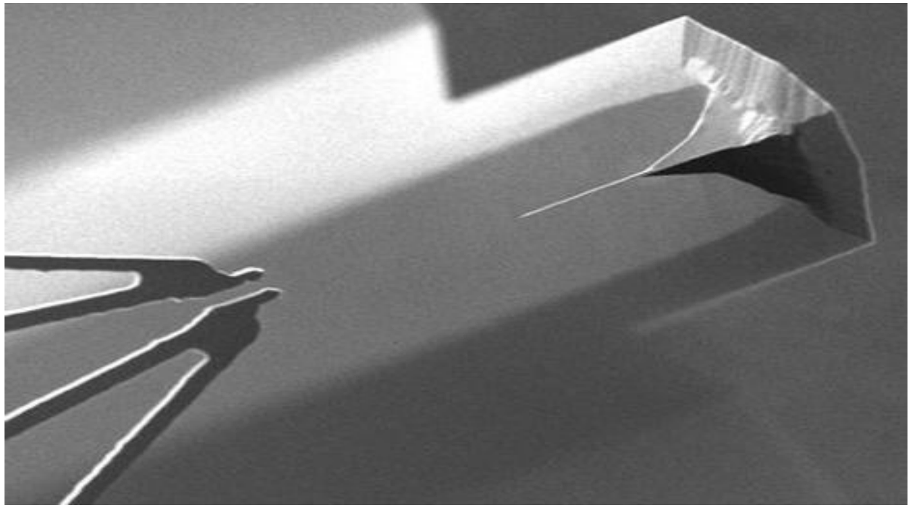
Change in predominance of phenomena with varying scale

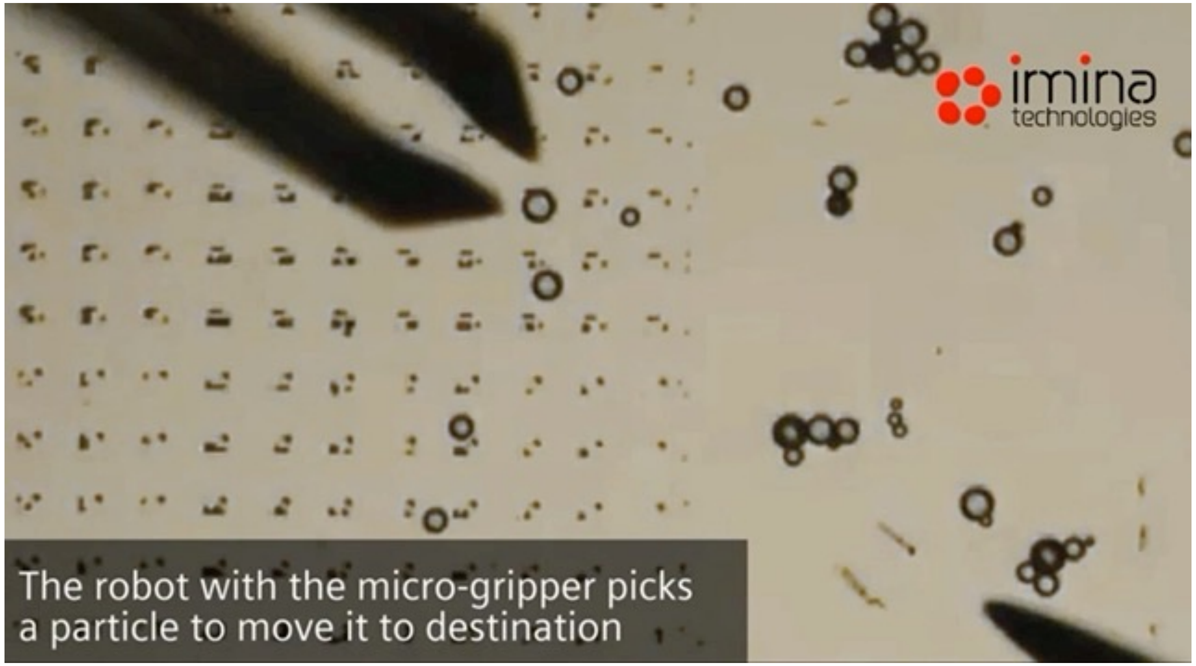
R1: Mechanics Over Micro and Nano Scales, Suman Chakraborty, Springer 2011

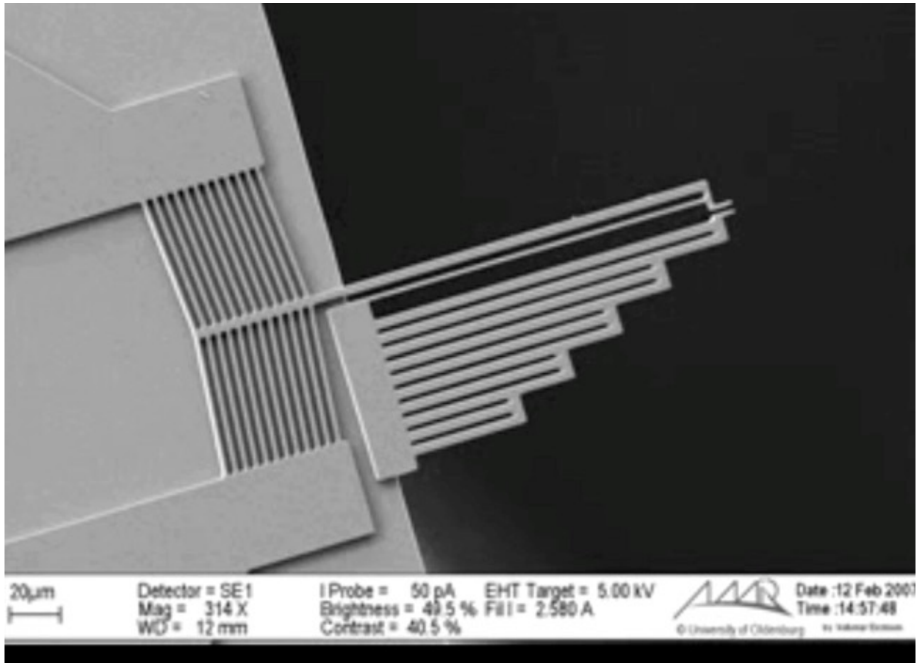
Real fly on a ceiling

Objectives of this course

- Understand scaling-related effects for different physical principles
- Establish simple scaling rules
- Lean how to make simple models of MEMS and NEMS
- Explore examples where scaling effects are exploited
- *Enable you to choose an appropriate actuation/sensing principle adapted to the application that you are developing*




imina
technologies
The robot with the micro-gripper picks
a particle to move it to destination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Fil I = 2.580 A
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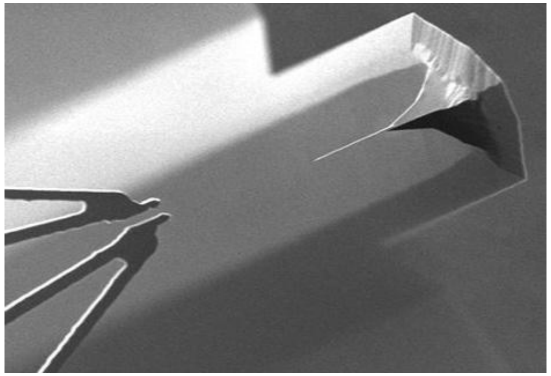
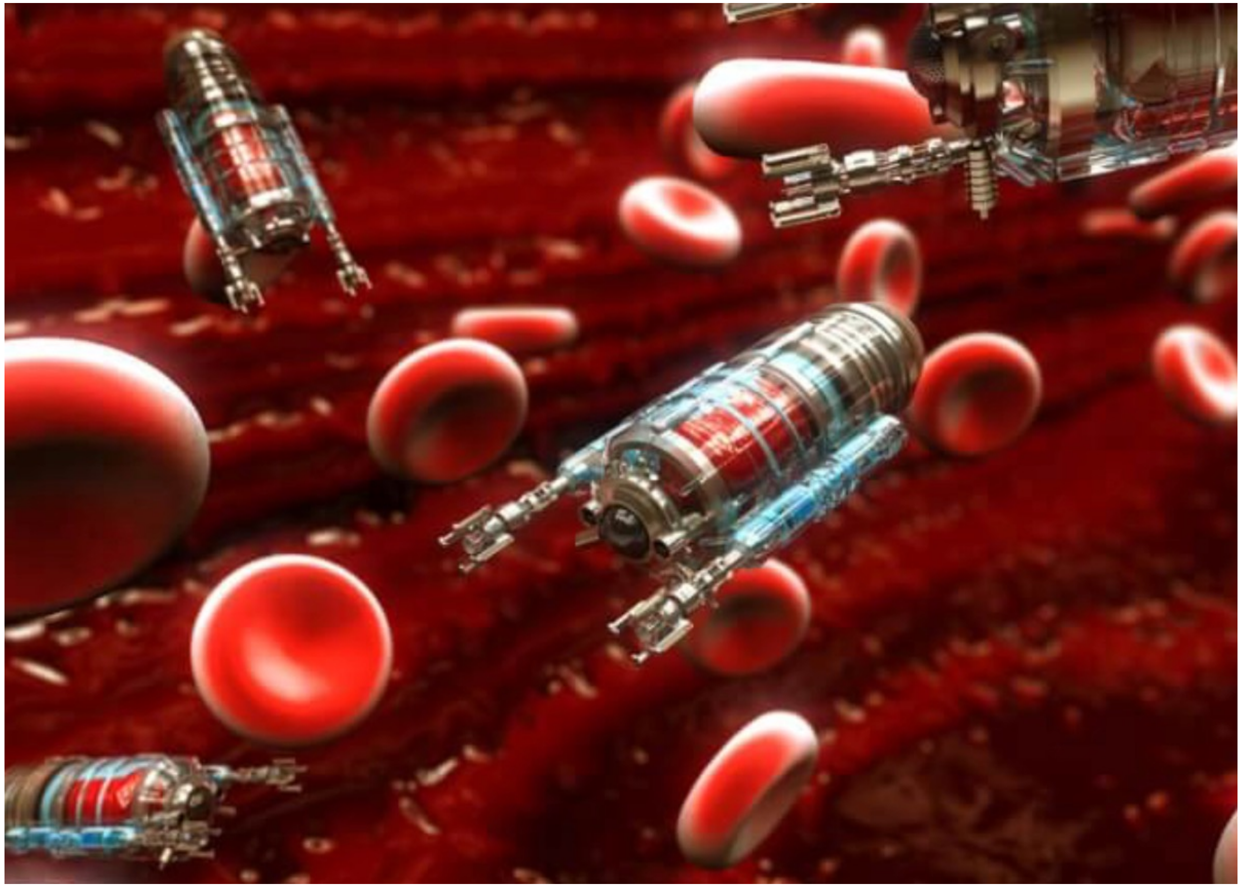
Time :14:57:48

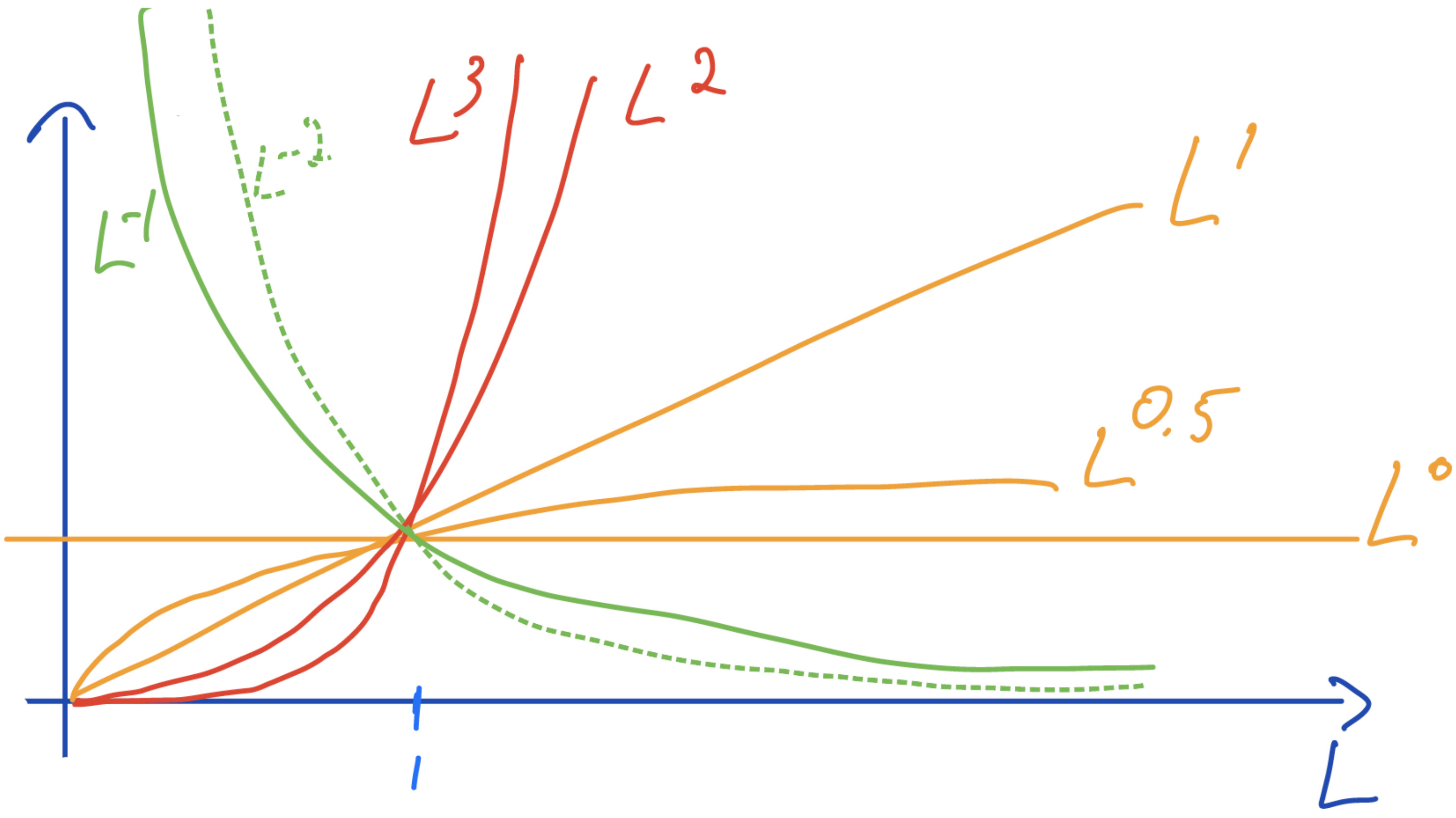




FOUR MEN AND ONE WOMAN ON
THE MOST FANTASTIC, SPECTACULAR
AND TERRIFYING JOURNEY
OF THEIR LIVES...
FANTASTIC VOYAGE
RAQUEL WELCH
DONALD PLEASENCE
WILLIAM REDFIELD
ARTHUR KENNEDY

20th CENTURY STUDIOS

Scaling with L



Simplified overview of mechanical scaling laws. 1 of 3

Parameter	Scaling Law	comment
Mass	$M \propto L^3$	
Area	$A \propto L^2$	
Surface-to-volume ratio	$\gamma \propto L^{-1}$	=> good for chemical reactions
Inertial forces	$F_{inertial} \propto M \propto L^3$	
Contact forces	$F_{contact} \propto A \propto L^2$	
Contact/inertial forces ratio	$\propto L^{-1}$	=> bad for manipulation
Van der Waals forces	$F_{VdW} \propto d^{-7}$	very short range!

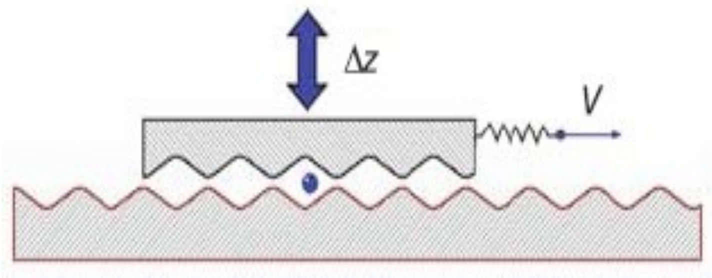
Simplified overview of mechanical scaling laws: Friction

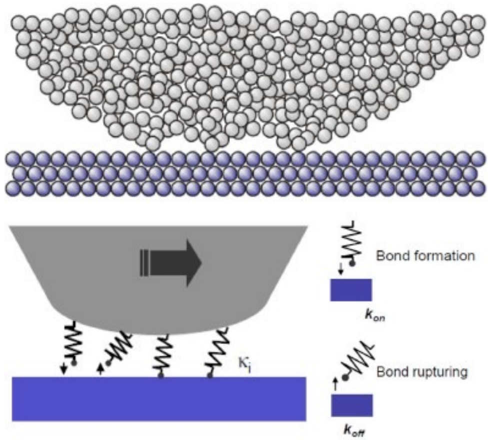
$F_{friction} = \mu\, F_{normal}$ (Coulomb friction)

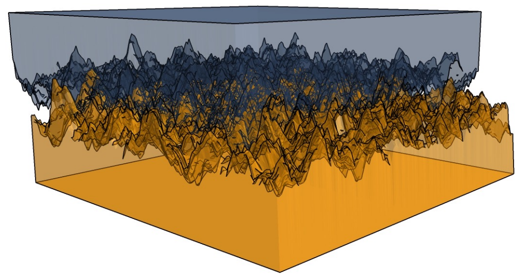
$$F_n = F_{gr} \quad \propto L^3$$
$$F_n = F_{surf} \quad \propto L^2$$

- At macro scale, friction is dominated by the weight of object: $F_{normal} \propto L^3$
- At the micro scale, contact forces dominate $F_{normal} \propto L^2$

In reality, friction forces are a combination of many phenomena, at micro and atomic scale.
There is no simple scaling law.







https://en.wikipedia.org/wiki/Friction

- *"The nonlinear nature of friction", Nature 430, 525-528 (29 July 2004)* | doi:10.1038/nature02750
- *"Modeling friction: From nanoscale to mesoscale", Rev. Mod. Phys. 85, 529 (2013)*

Simplified overview of mechanical scaling laws: 2 of 3

Parameter	Scaling Law	comment
Spring Constant	$k \propto L$	calculated using Hook's law on a bar of cross-section A and length l: $k = \frac{AE}{l}$ (E: Young's modulus)
=> Spring (restoring) Force	$F \propto kx \propto L^2$	
Acceleration (intrinsic)	$a = \frac{F}{M} \propto L^{-1}$	
Natural frequency	$\omega_0 = \sqrt{\frac{k}{M}} \propto L^{-1}$	
"switching" time	$t_s = 1/\omega_0 \propto L$	
Viscous drag forces	$F_{vd} \propto \eta L v \propto L$	
Quality factor (=energy stored/energy loss per cycle)	$Q_f \propto \frac{kx^2}{F_f x_0} \propto L$	reality is more complicated…

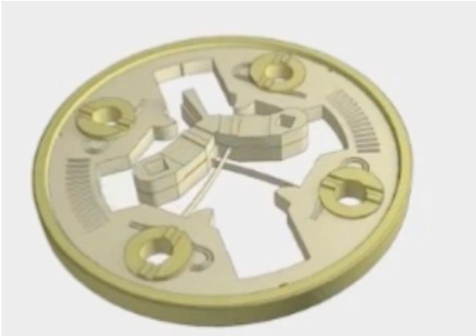
Simplified overview of mechanical scaling laws: 3 of 3: energy

Parameter	Scaling Law	comment
Kinetic Energy	$E_{kin} = \frac{mv^2}{2} \propto L^3$	assuming v is constant. If $v \propto L$, then $E_{kin} \propto L^5$
Potential energy of a spring	$E_{pot,spring} = \frac{1}{2}kx^2 \propto L^3$	
Mechanical power	$P_{mec} = Fv \propto L^2$	
Mechanical energy density	$\frac{E_{pot,spring}}{m} = \frac{1}{2}\frac{\sigma^2}{E} \propto L^0$	scale invariant

Simplified overview of fluidic scaling laws

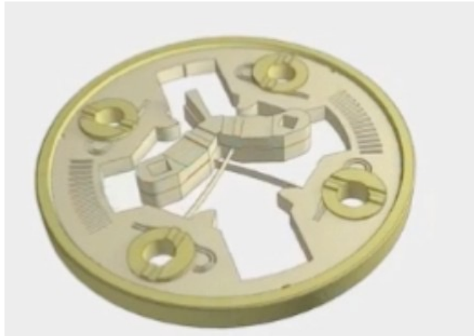
Cartoon "Antz"

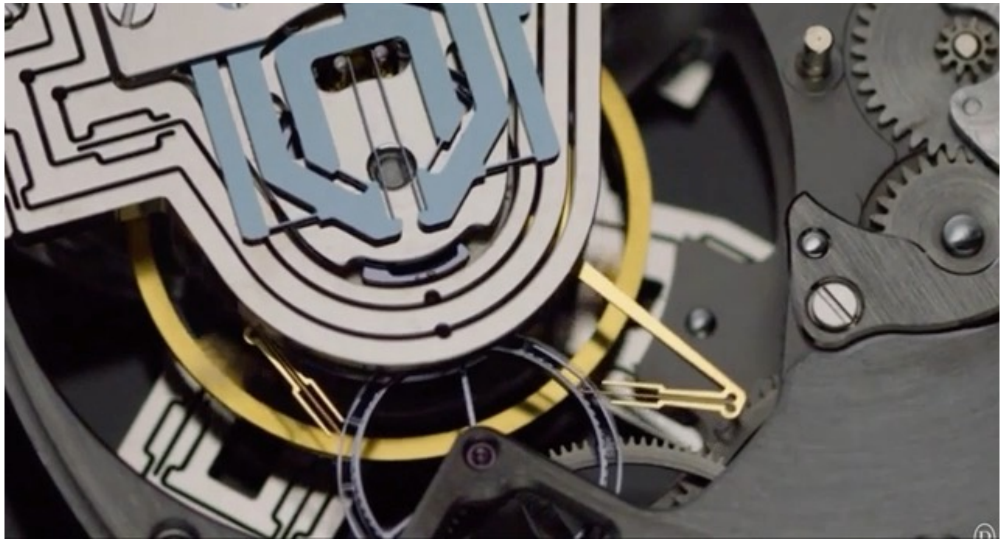
Reality…



Friction-less spring-mass CSEM "Genequand" movement

Parameter	Scaling Law	comment
Fluidic impedance	$R_{fluidic} = \frac{8\eta L}{\pi r^4} \propto L^{-3}$	
Surface Tension	L^{-1}	
Force to move a plate at speed v against viscous forces	$F_{shearplate} = \frac{\eta v A}{h} \propto L^{-1}$	- assumes speed v is scale independent - bad for lubricating small parts





Simplified overview of <u>electrical</u> scaling laws

Parameter	Scaling Law	comment
Resistance	$R \propto L^{-1}$	
Voltage (at constant E field)	$V \propto L$	
Current (at constant current density)	$I \propto L^2$	
Joule Power dissipation	$P_{diss} = RI^2 \propto L^3$	
Capacitance	$C \propto L$	
Charge on capacitor	$Q = CV \propto L^2$	bad for RAM
RC time constant	$\tau = RC \propto L^0$	

Simplified overview of electrical scaling laws: energy

Parameter	Scaling Law	comment
Electrostatic energy density	$w_{ES} = \frac{1}{2}\varepsilon E^2 \propto L^0$	assuming constant E field
Electrostatic forces	$F_{ES} = A.w_{ES} \propto L^2$	
Magnetic field (from a coil)	$B = \frac{NI}{l} \propto L$	
Magnetic energy density	$w_{em} = \frac{1}{2}\frac{B^2}{\mu_0} \propto L^2$	magnetic energy $\propto L^5$
Magnetic forces	$F_{em} \propto L^4$	
Magnetic power	$P_{em} \propto F_{em} v \propto L^4$	bad for small actuators
Power/losses ratio (magnetic)	$\frac{P_{em}}{P_{joule}} \propto \frac{L^4}{L^3} \propto L$	

Continuum breakdown in down-scaling

Some examples:

"Grain size" effects:

- Electrical conductivity (ex: Cr thin film)
- Strength and elastic modulus (ex. whiskers)
- Fatigue (ex. DMD)

Rarefied gas properties:

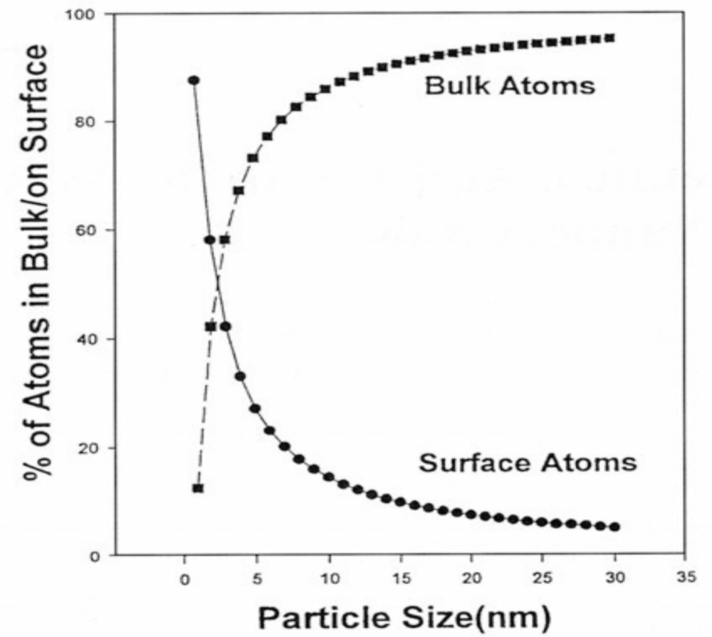
- Flow in capillaries ("slip flow")
- Fluid to molecular flow
- Mechanical damping
- Heat conduction
- Electrical breakdown (Paschen curve) - *important*

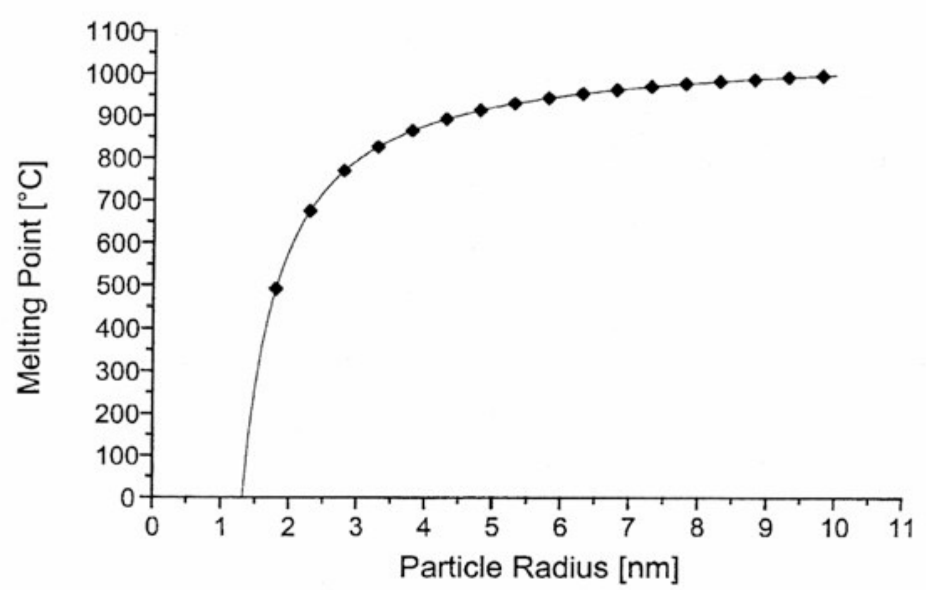
Downscaling particles

Full-shell Clusters		Total Number of Atoms	Surface Atoms (%)
7 Shells		1415	35
4 Shells		309	52
1 Shell		13	92

Nanoscale Materials in Chemistry, Wiley, 2001

Downscaling particles





for spherical iron nanocrystals : J. Phys. Chem. 1996, 100, 12142

This leads to size dependent physical and chemical properties:

- Optical properties, magnetic properties
- Bandgap
- Melting point
- Specific heat
- Surface reactivity

Quantum-like breakdown (we will ignore this in this class)

The non-classical effects start to dominate when the feature size of the devices are in the order of magnitude of the associated "wavelength" of the energy carriers (photons, phonons and electrons).

For visible photons, the wavelength is below 1 micron.
For electrons and phonons (at room temperature), this is below 1 nm.

	Electrons in metals	Phonons in Insulators and Semiconductors
Wavelength [nm]	0.1 -1	1-5
Mean free path [nm]	10	10-100

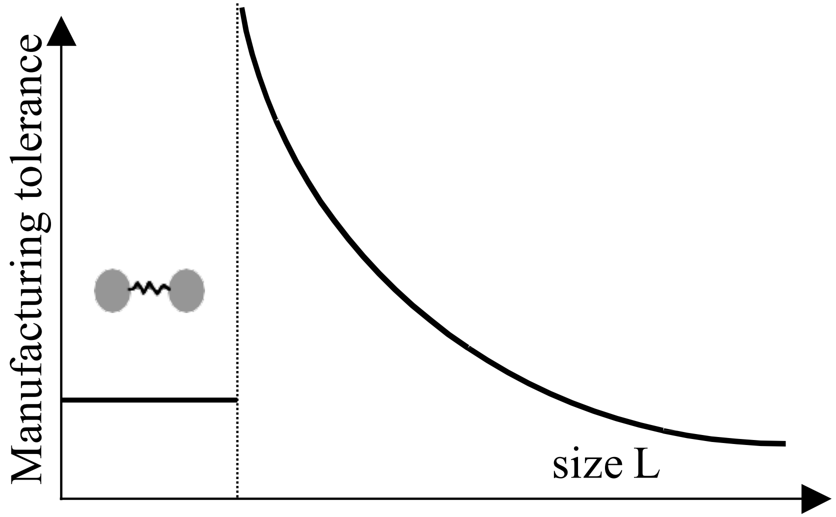
When using microtechnologies (feature size above 100 nm) the quantum confinement is not effective for electrons and phonons. But for optics (photons) diffractive models must be used.

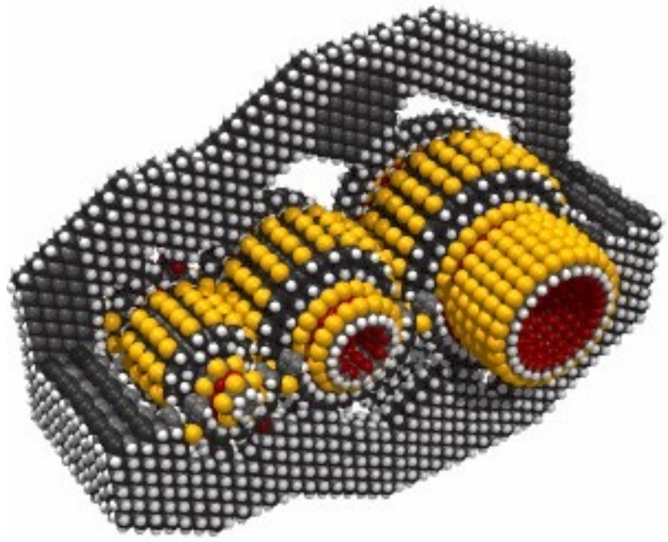
Examples:

- Surface roughness (atoms at the surface).
- Super-paramagnetic limit in magnetic recording
- Electrical conduction in nanowires
- Quantum wells and quantum dots
- Depletion in ultra-small MOS channels (no depl. <20 nm)
- Heat conduction in nanostructures

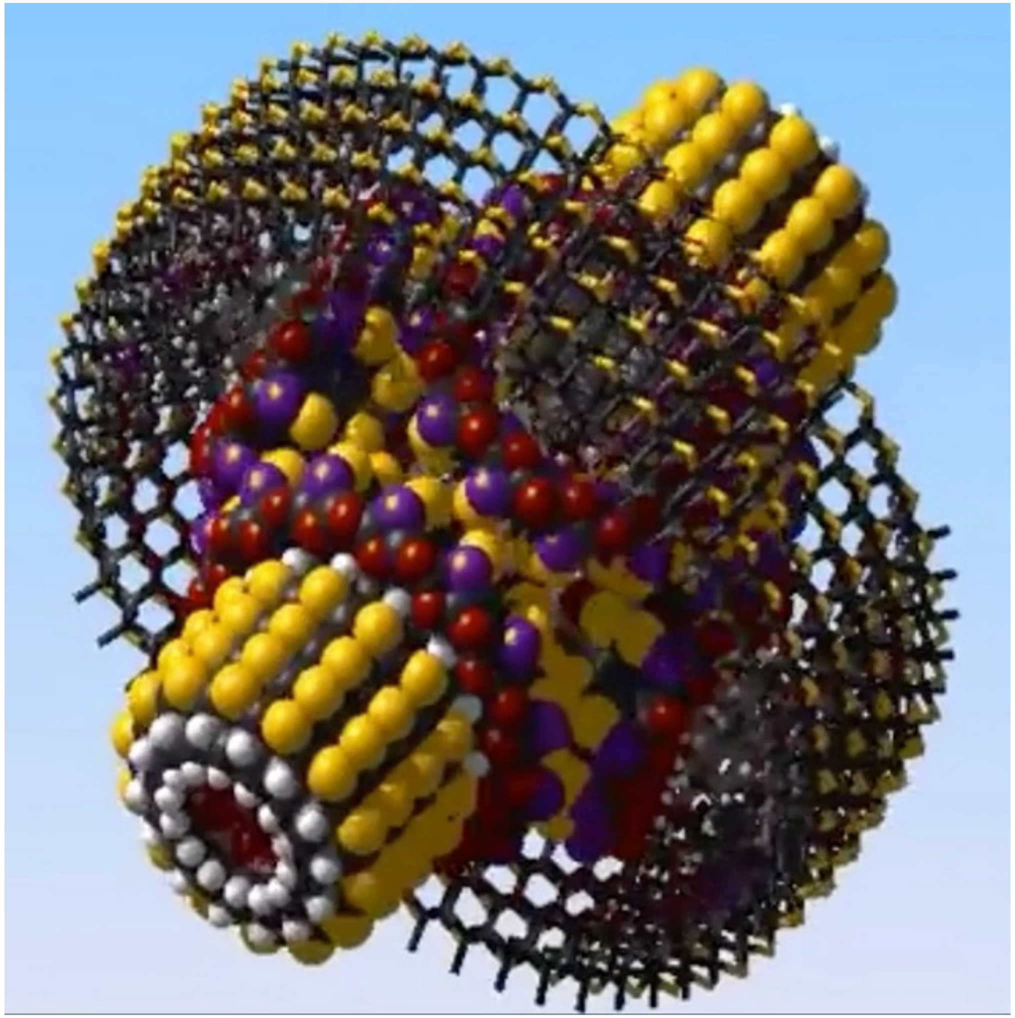
Molecular manufacturing accuracy

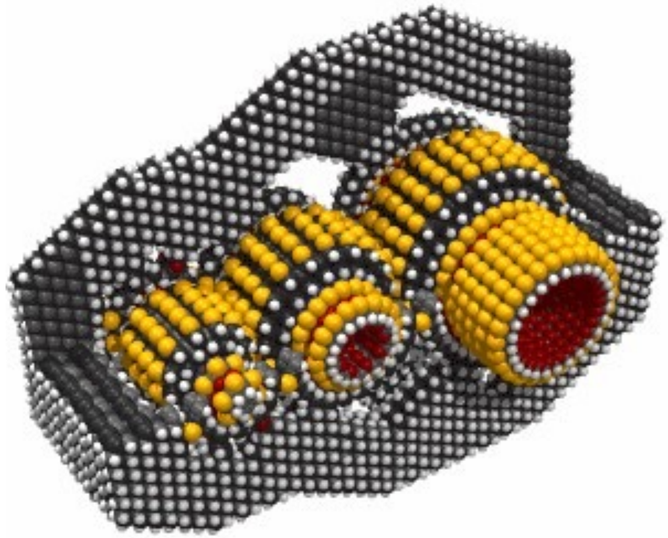
- Positioning within 0.1 nm precision
- Parallel synthesis at 10^6 op./device/sec
- Natural frequencies of 10^9 Hz
- "gate" switch in 0.1 ns and 10^{-21} J/op.





- R. Feynman, "There is plenty of room at the bottom", 1959 talk, reprinted in J. MEMS 1 (1992) 60
- R. Feynman, "Infinitesimal machinery", 1983 talk, reprinted in J. MEMS 2 (1993) 4
- K.E. Drexler « Engines of Creation, The Coming Era of Nanotechnology », Anchor Books, 1986



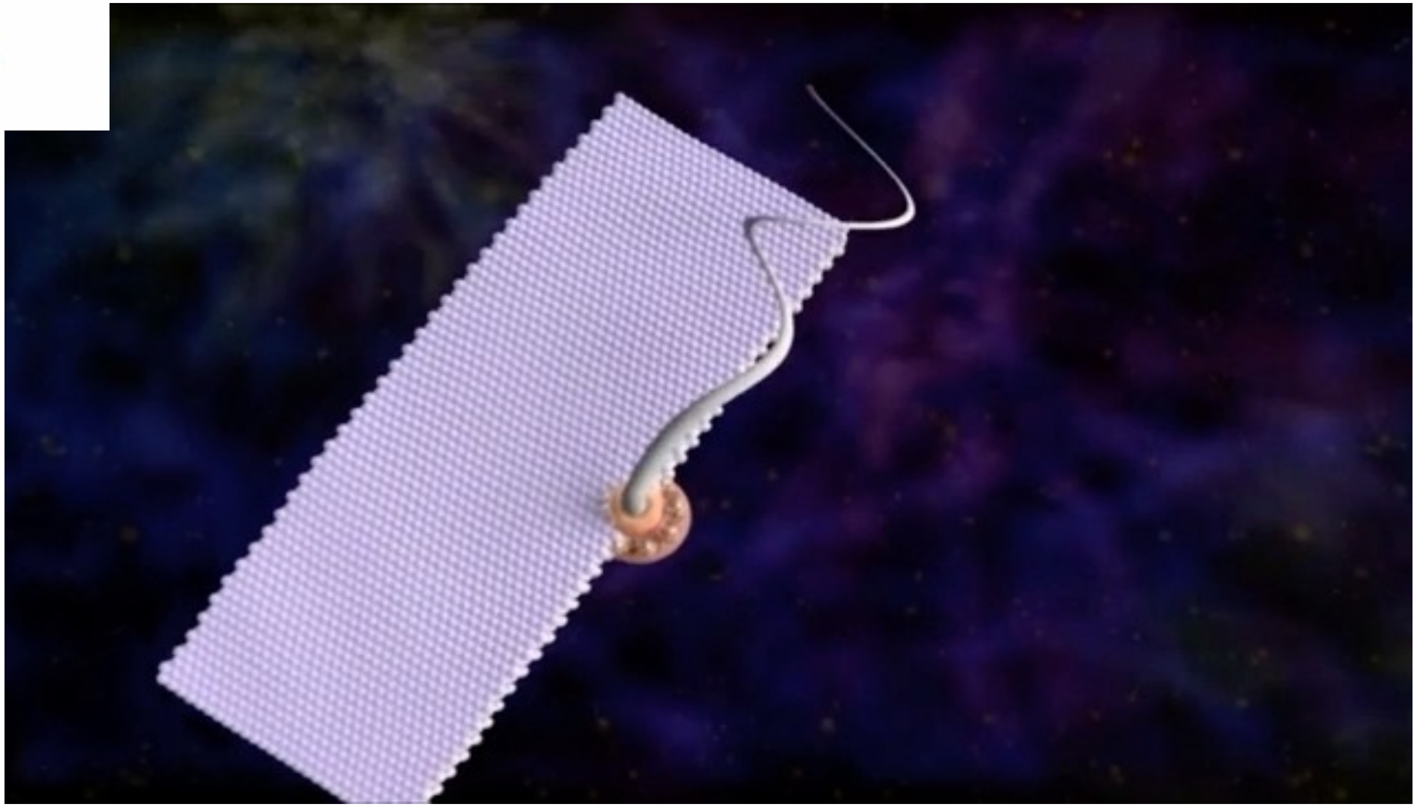


Molecular dynamics simulation of Drexler molecular machine

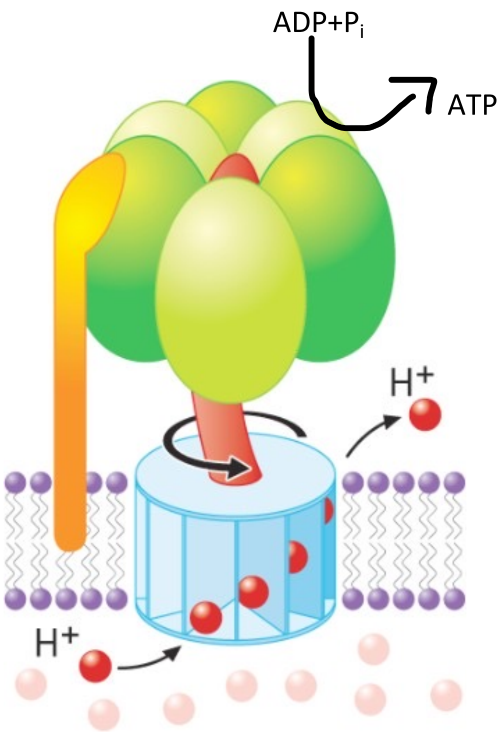
Molecular machines in nature: Rotation Motor for flagella

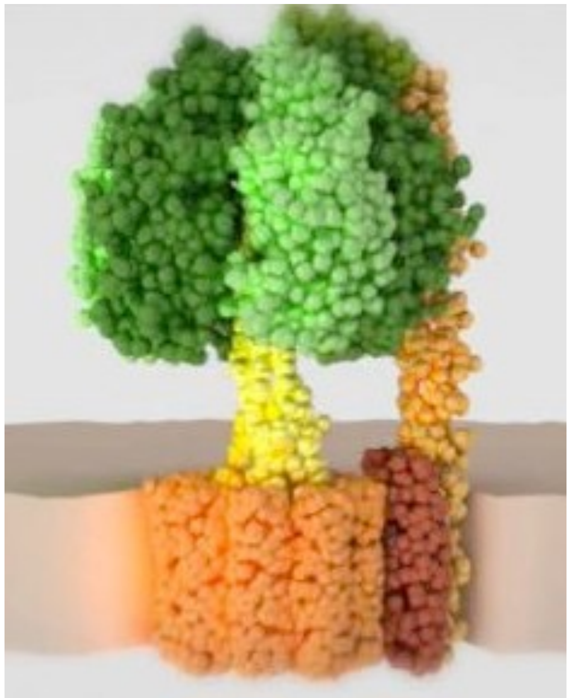
Flagellar Motor - Mechanism

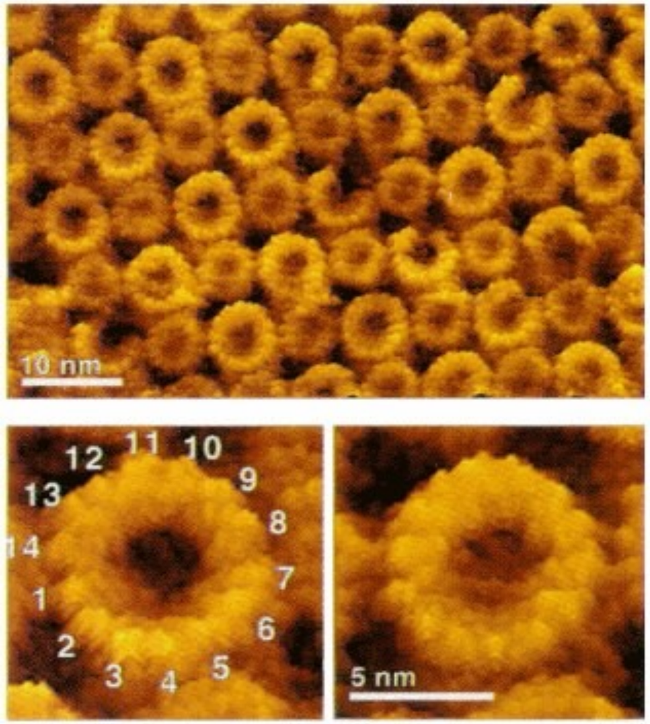
- Motor generates ~10^{-15} W, propelling cells at 100 $\mu m \cdot s^{-1}$
- Maximum torque ~1260 pN·nm
- Maximum speed ~400 Hz
- Motor is self-assembling and self-repairing



Molecular machines in nature ATP synthase



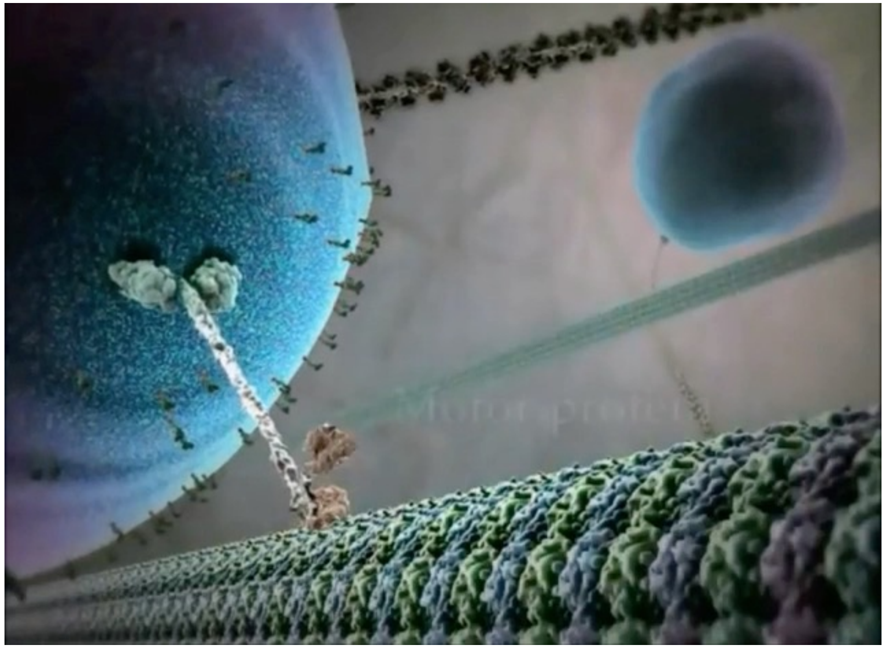


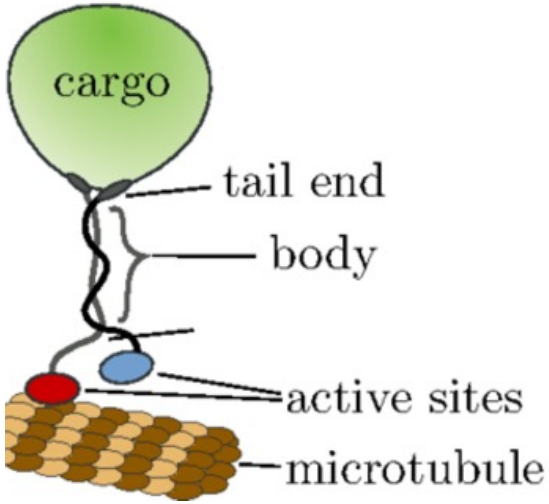


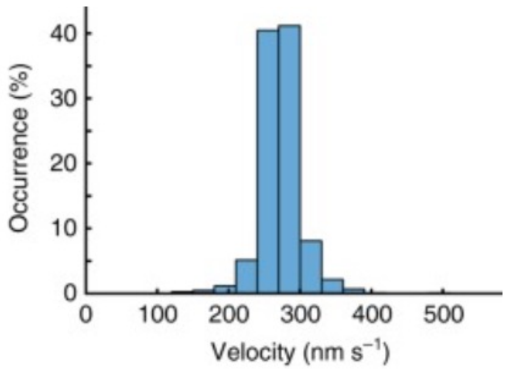
AFM images

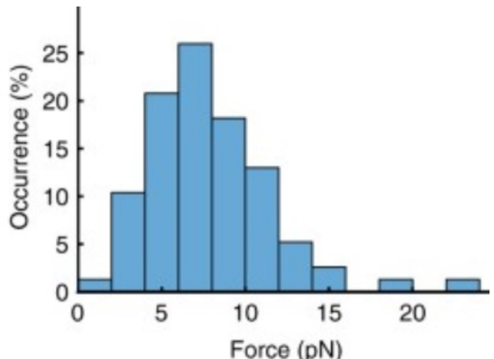
- Stahlberg, H et al., (2001) Bacterial Na+-ATP synthase has an undecameric rotor. *EMBO Reports* 2, 229-233
- Yoshida, M., Muneyuki, E. & Hisabori, T. ATP synthase — a marvellous rotary engine of the cell. Nat Rev Mol Cell Biol 2, 669–677 (2001). https://doi.org/10.1038/35089509

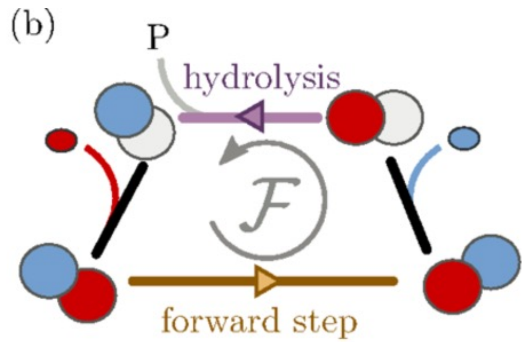
Molecular machines in nature: Kinesin motor











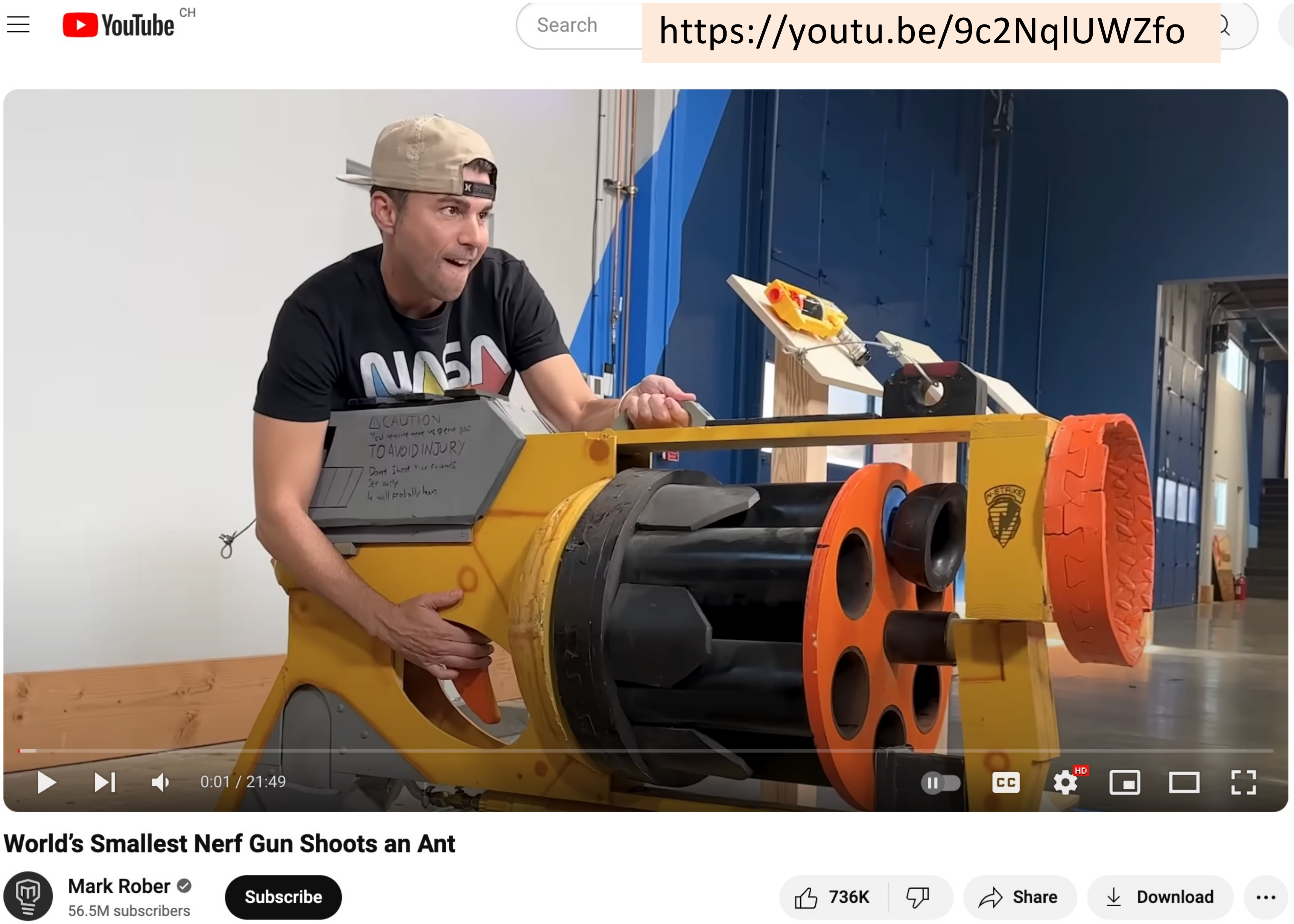
one ATP molecule is hydrolyzed for each 8-nm step

At maximum load of 6 pN = efficiency ~**60%**

T. Ariga, Phys. Rev. Lett. 121, 218101 (2018).

http://dx.doi.org/10.1103/PhysRevLett.121.218101

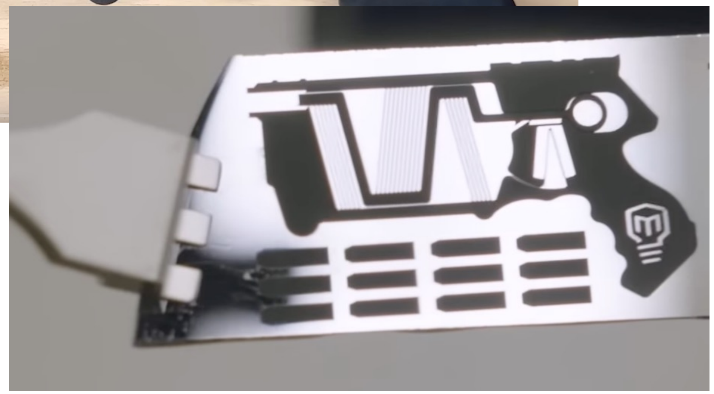
https://youtu.be/9c2NqlUWZfo

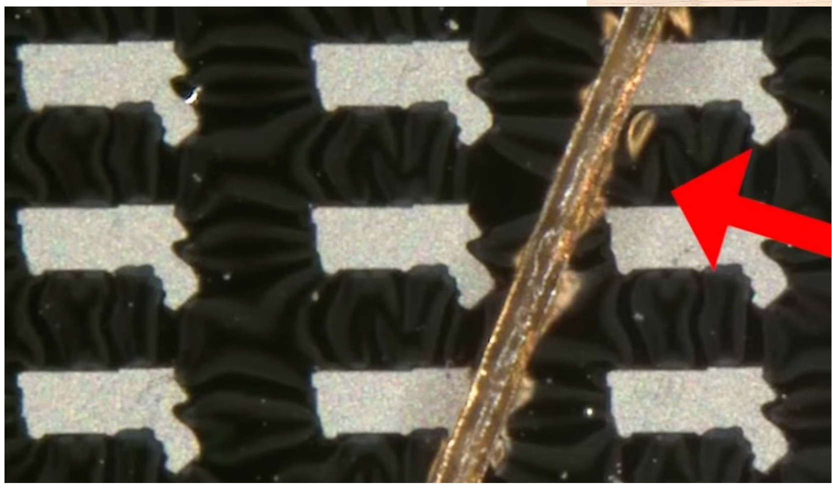


https://youtu.be/9c2NqlUWZfo

Making Nerf guns on many size scales

- Commercial: assembled
- Use compliant mechanisms
    - 3D print
    - Microfab (litho)
    - DNA



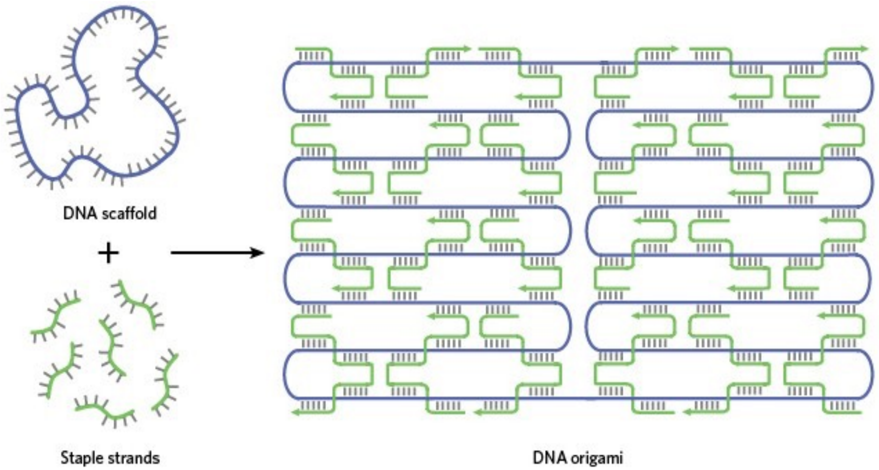


https://youtu.be/9c2NqlUWZfo

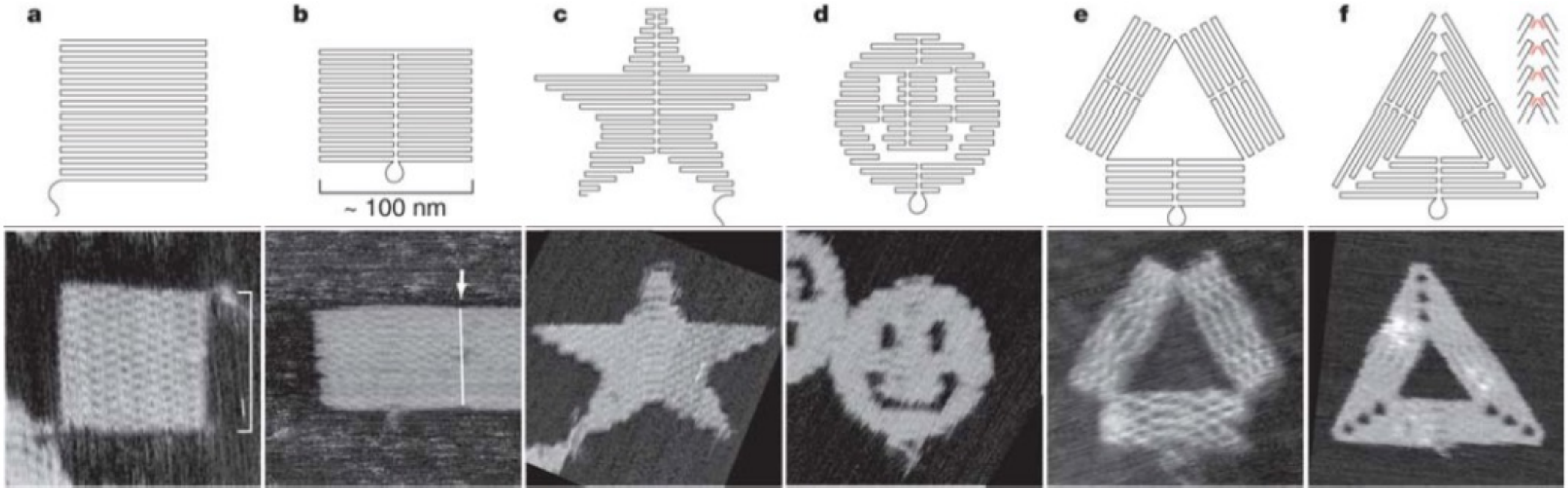
DNA origami

DNA origami

Employs a virus-based DNA single strand (e.g 7 kb long) as a scaffold which is brought into shape by hundreds of short oligonucleotides (“staples”)

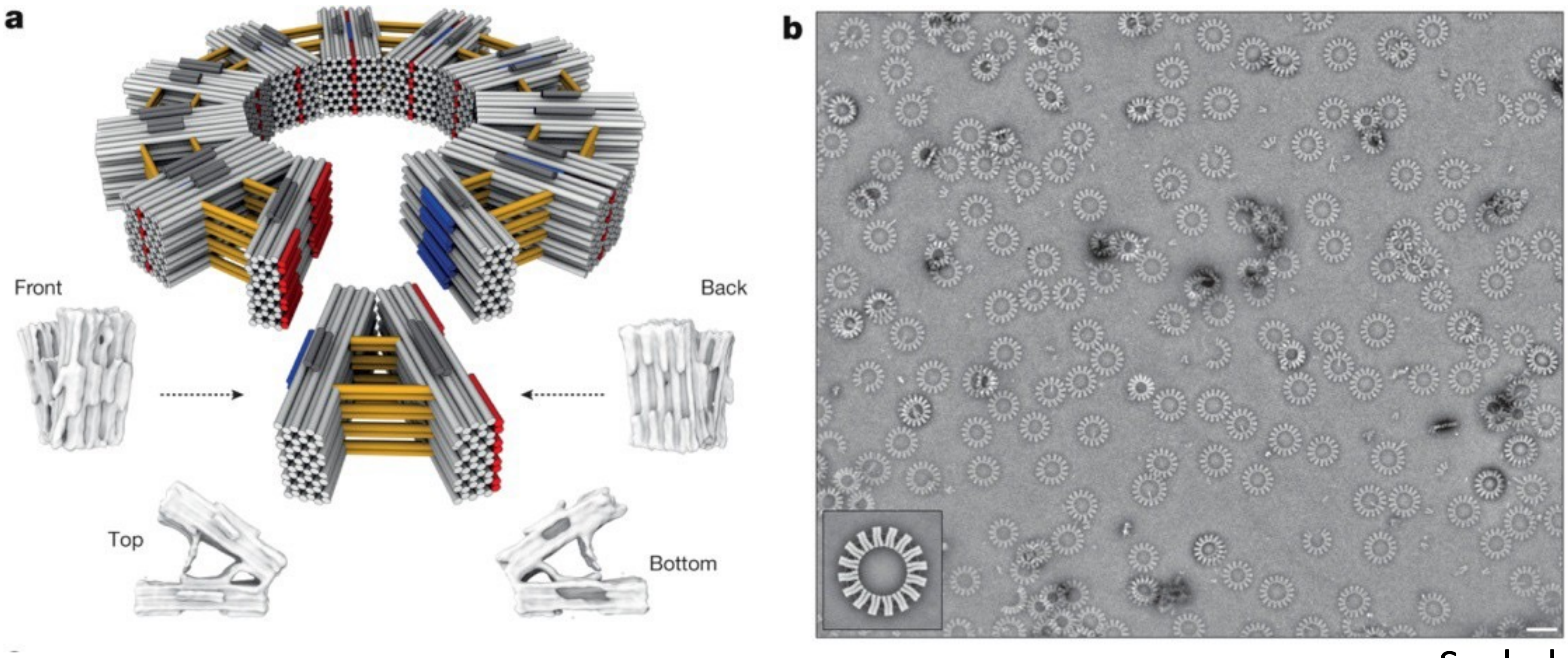


https://www.softmatter.physik.uni-muenchen.de/liedl_group/index.html



P. Rothemund, *Nature, vol 440, pages 297–302 (2006)*

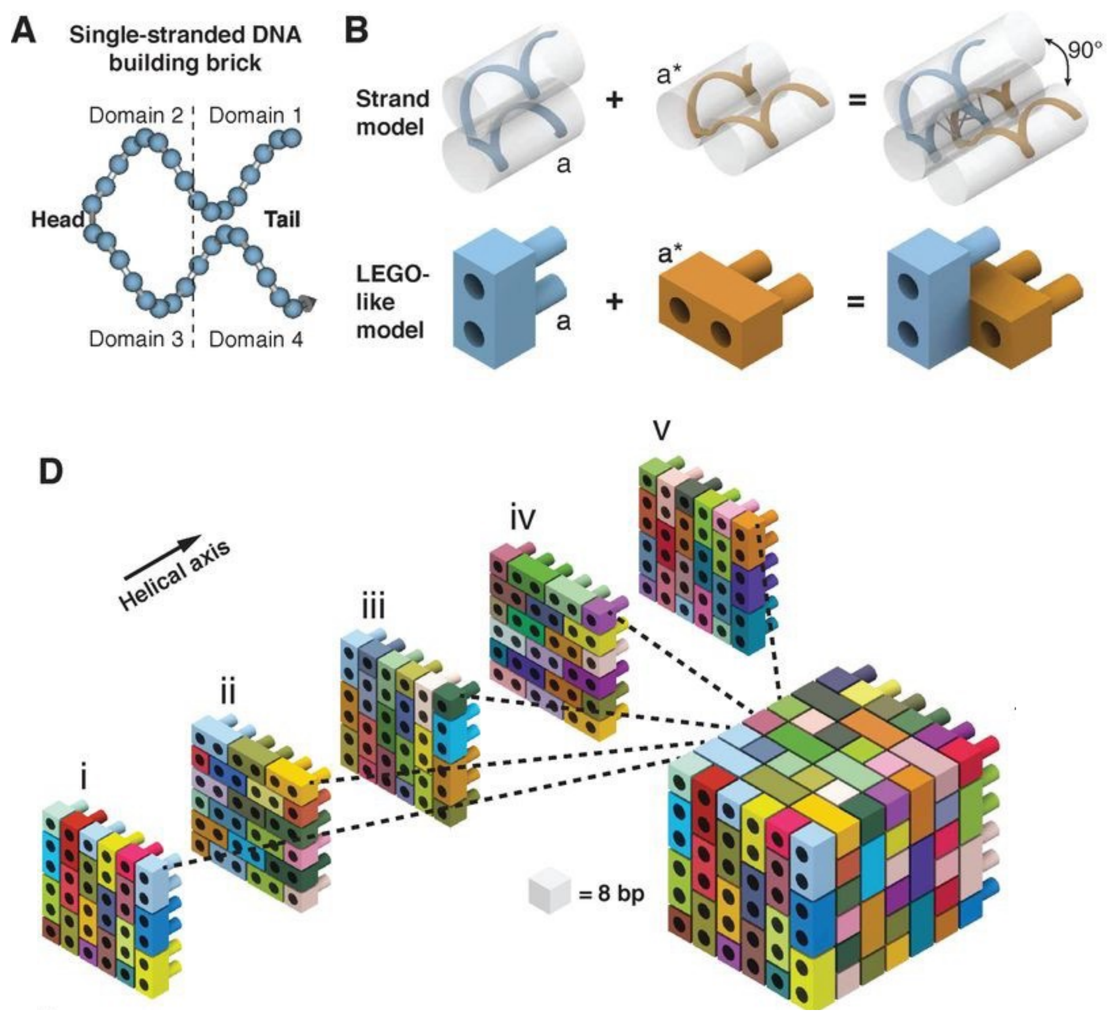
DNA origami: in 3D

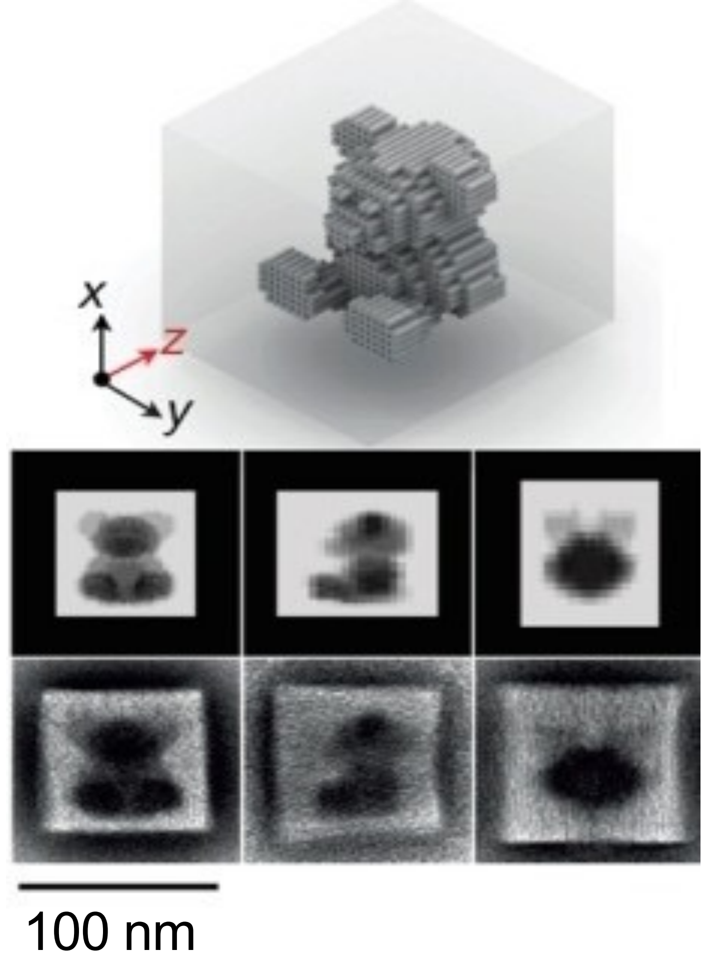


Scale bar, 300 nm

K F Wagenbauer et al. Nature 552, 78–83 (2017)
doi:10.1038/nature24651

DNA origami: Universal bricks





L L Ong et al. Nature 552, 72–77 (2017) doi:10.1038/nature24648

CADNANO cadnano.org

"**Cadnano** simplifies and enhances the process of designing three-dimensional DNA origami nanostructures. Through its user-friendly 2D and 3D interfaces it accelerates the creation of arbitrary designs. The embedded rules within cadnano paired with the finite element analysis performed by cando, provide relative certainty of the stability of the structures."

DOWNLOAD CADNANO
It's free and open source.