Shape-changing micromachines

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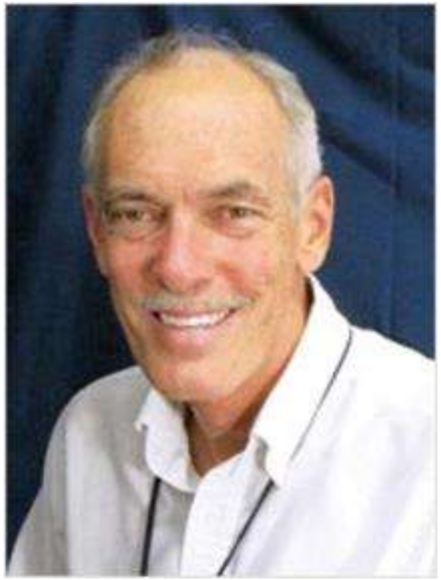

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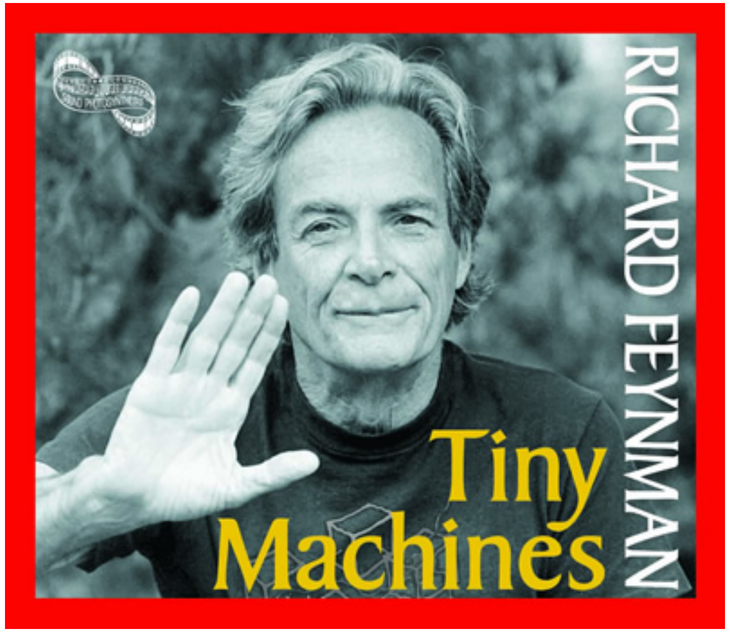
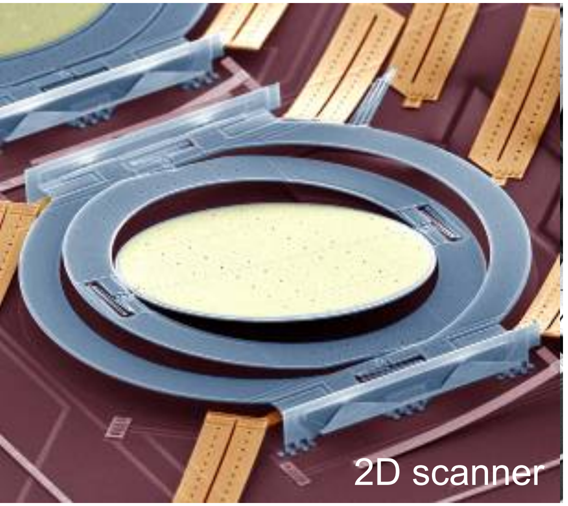
Miniaturized machines



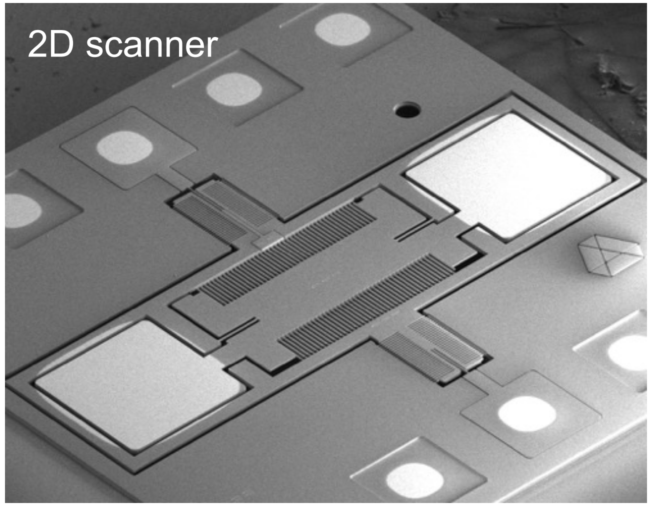
Miniaturize information ✓
Miniaturize computing ✓
Miniaturize machines ✗

Nanomachines: Nanoscale systems
Anything that can gather information and manipulate environment at the micro and nano world.

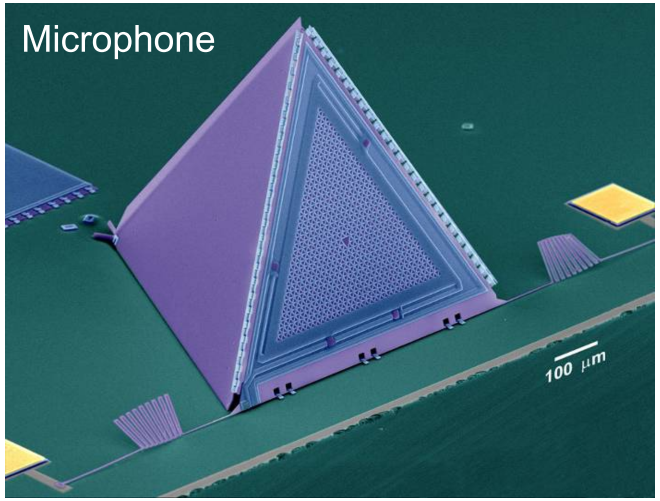
Micro Electro Mechanical Systems technology



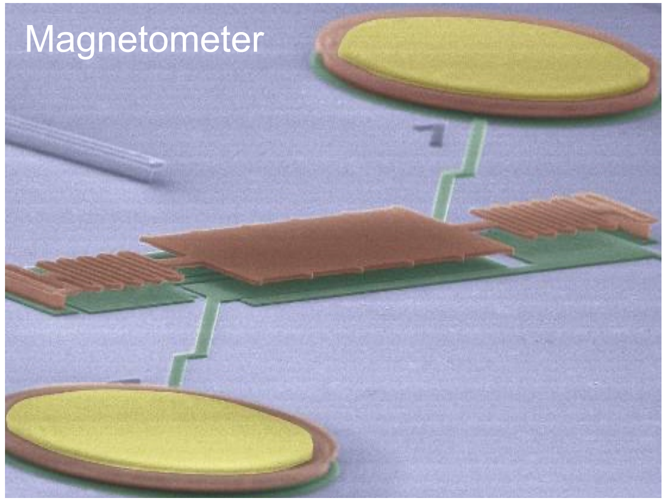
Bell Labs



ANL

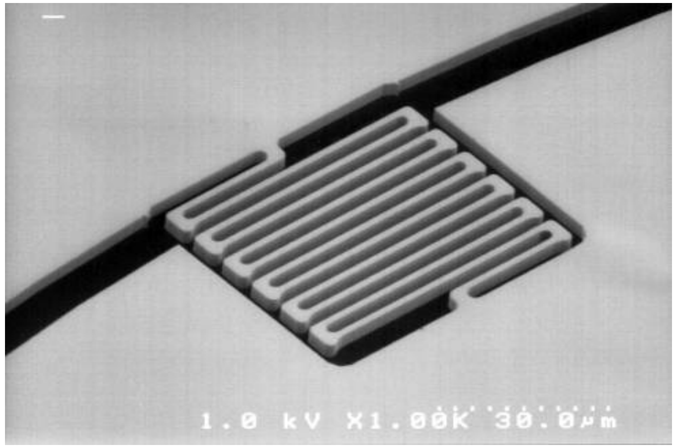


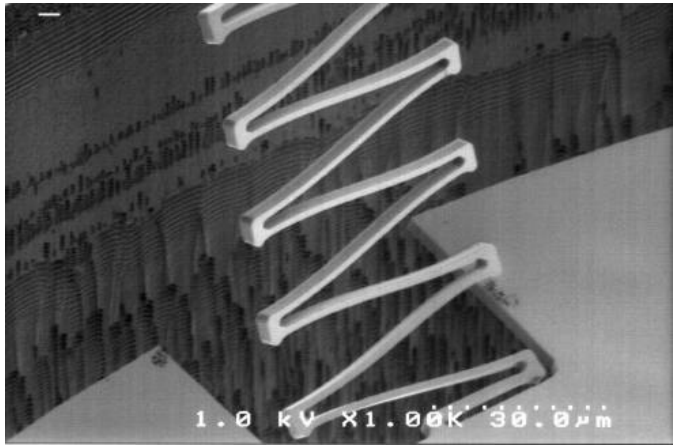
Bell Labs



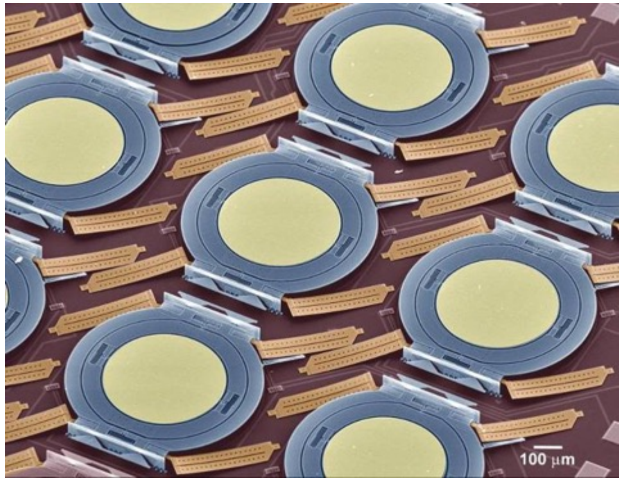
ANL

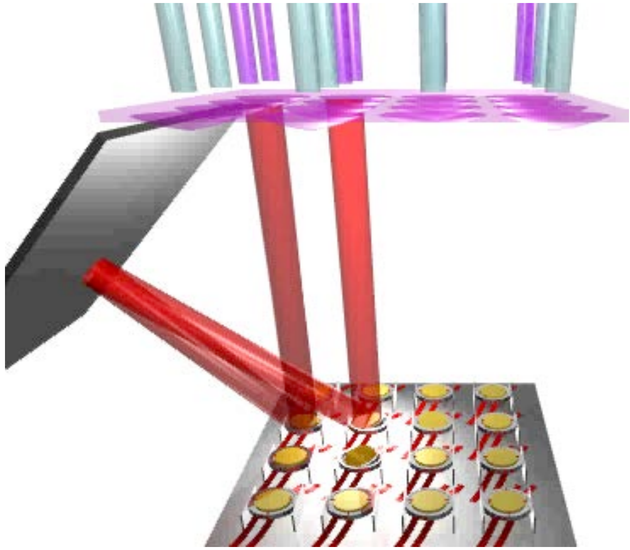
- Typical size: few µm to 100's µm
- Well known materials and fabrication processes
    - Si is a well understood material
    - Easy to design, control and manipulate
    - Elasticity theory works well (Hooke's law)
- Applications: basic science to high-end products
- Hard environments: X-rays, accelerations,…





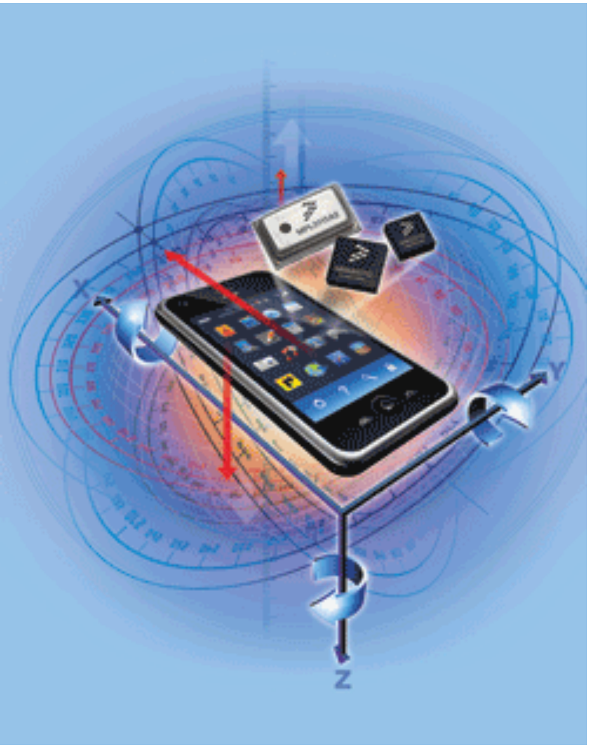
MEMS for communications

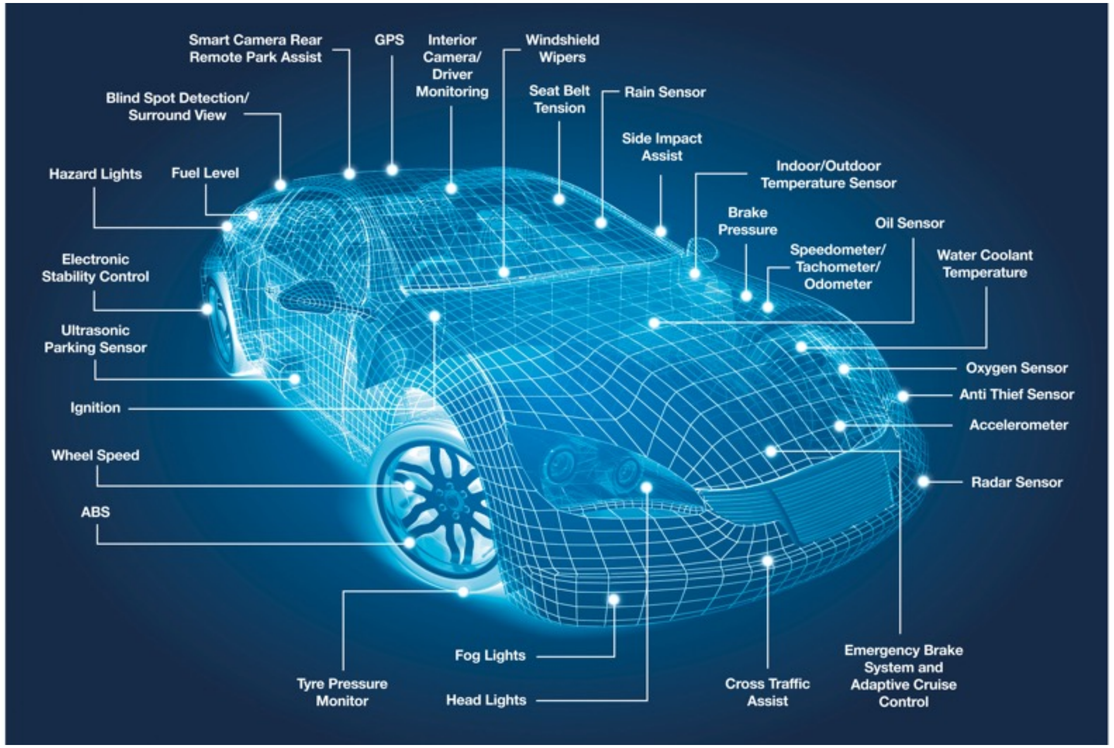




Handle large amount of information: Big Data

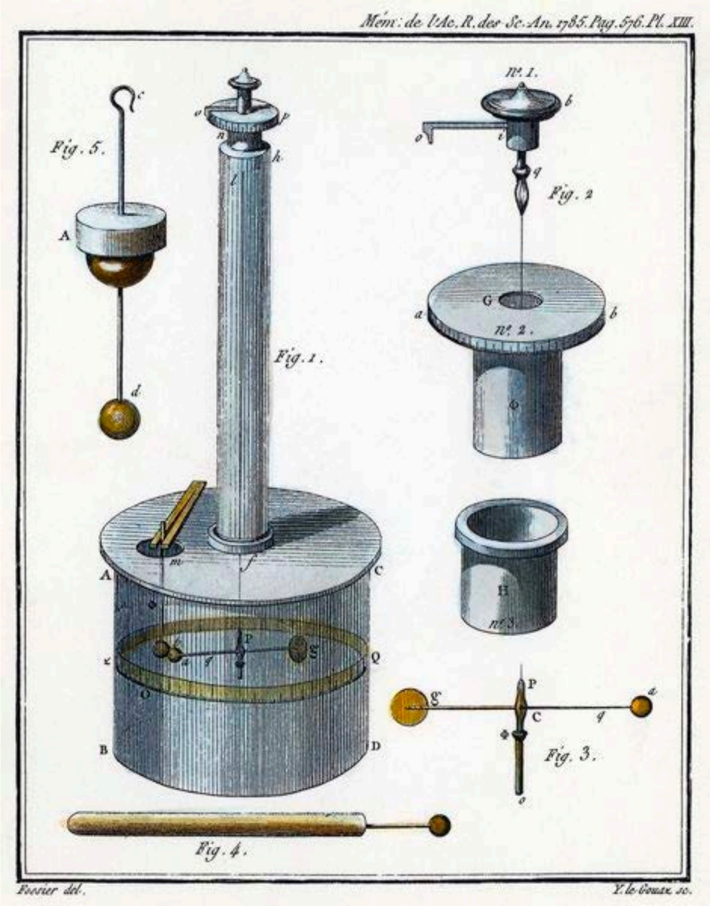
Micromachines today

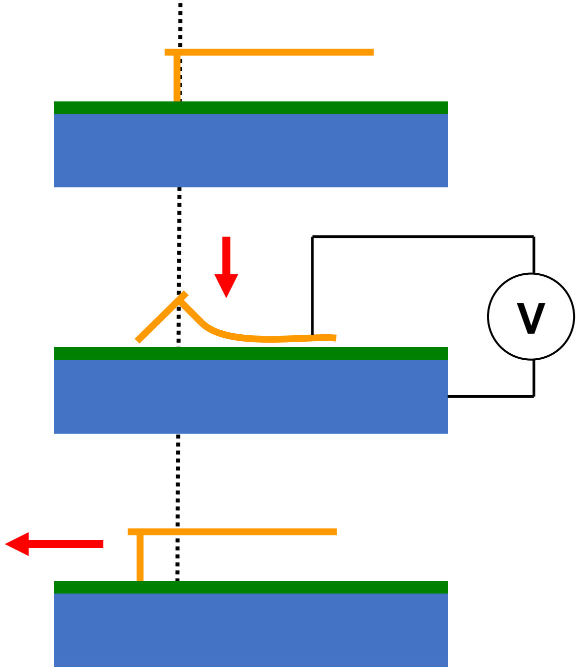


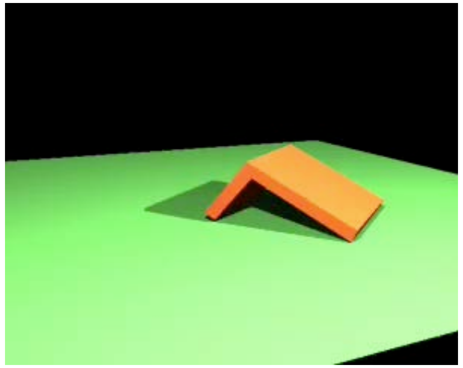


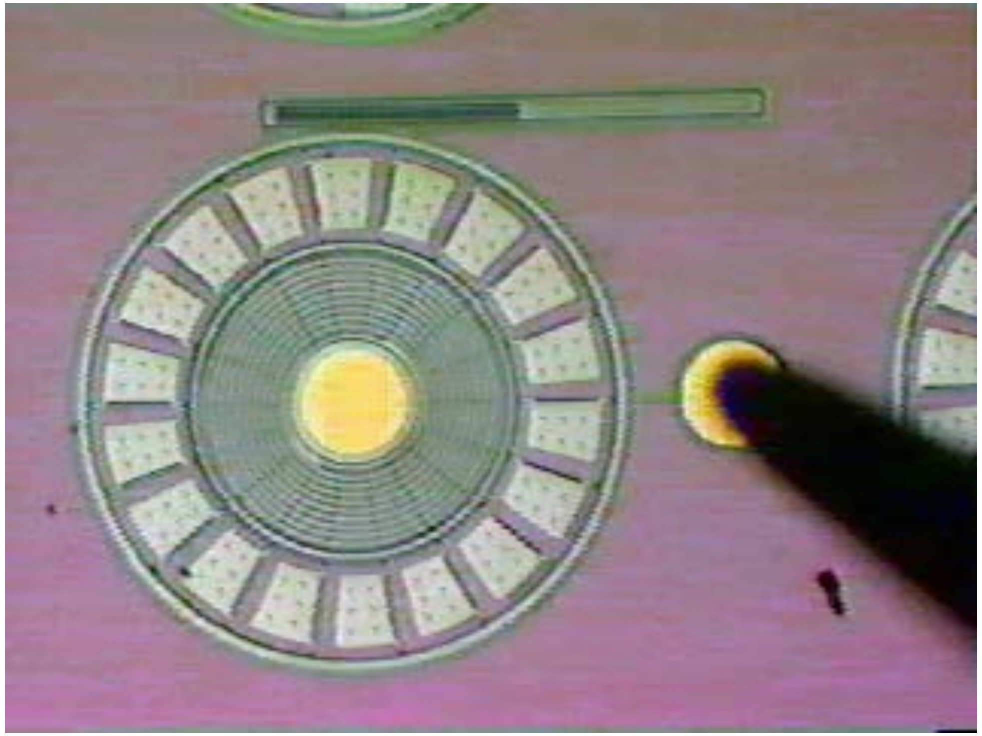
MEMS technology today: actuation forces

Coulomb balance - 1785



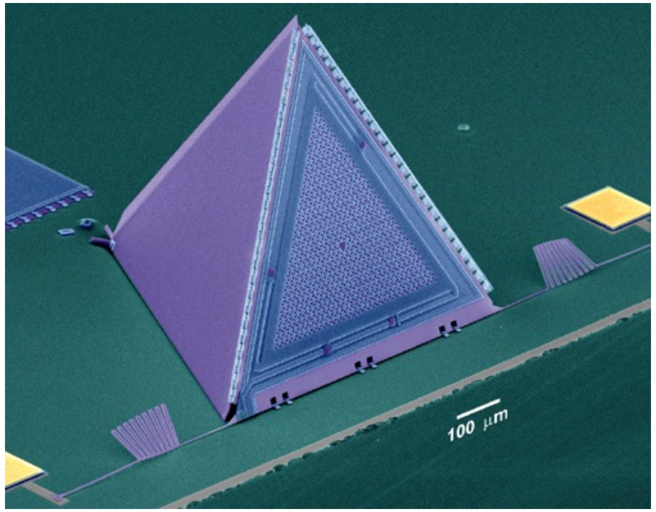


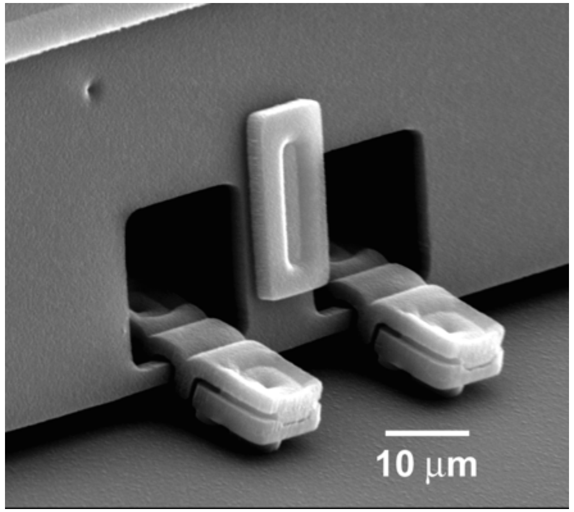


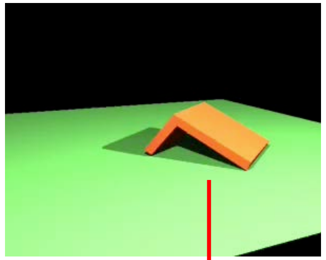


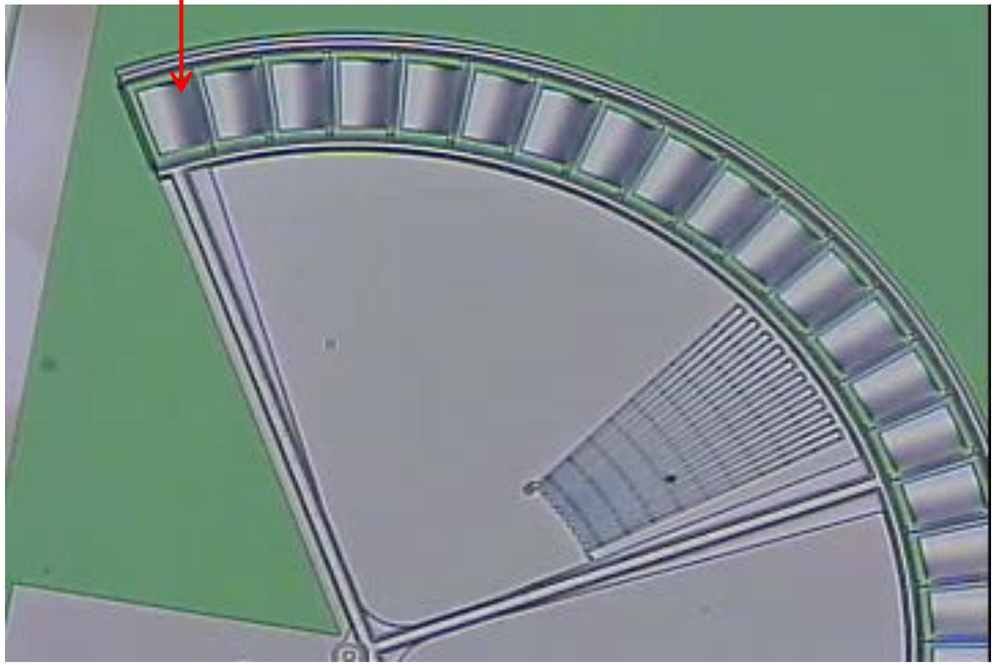
Electrostatic forces vs. Mechanical deformation

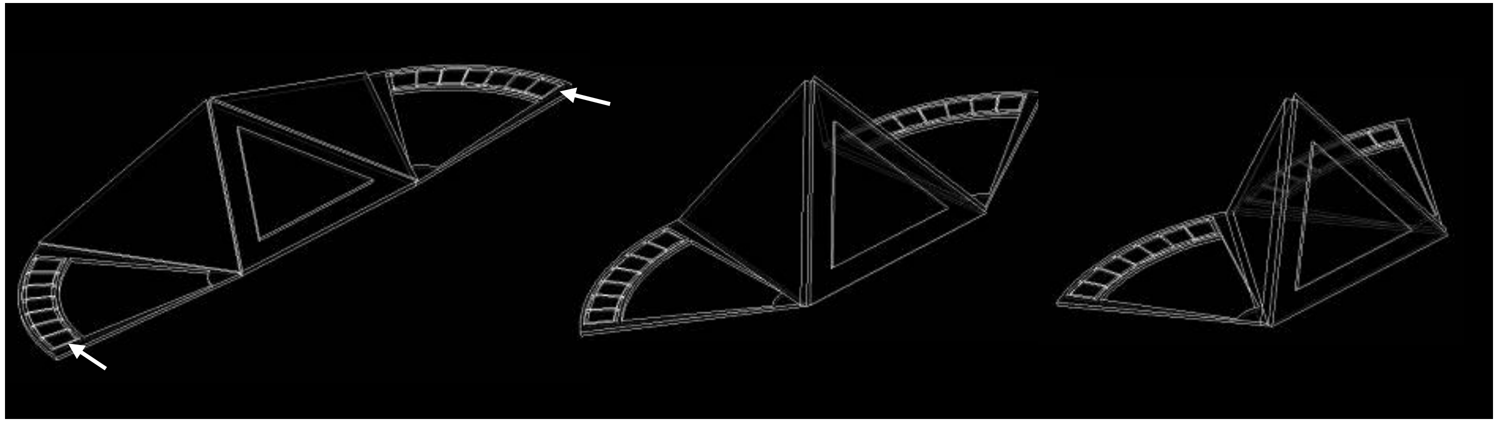
MEMS technology today: 3D structures











Micro-machines can be used to assemble and build micro-machines

Micromachines technology evolution

- Very large-scale integration of MEMS
- Intelligent micro-systems

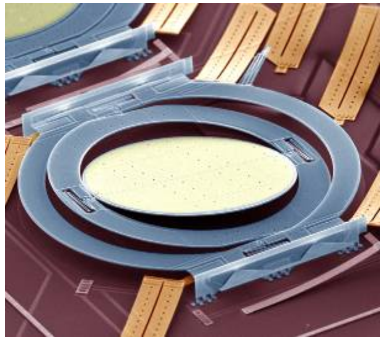
Very large-scale integration

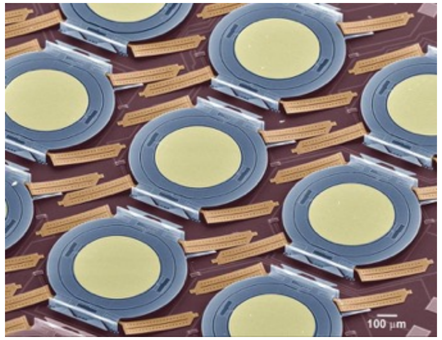
One transistor

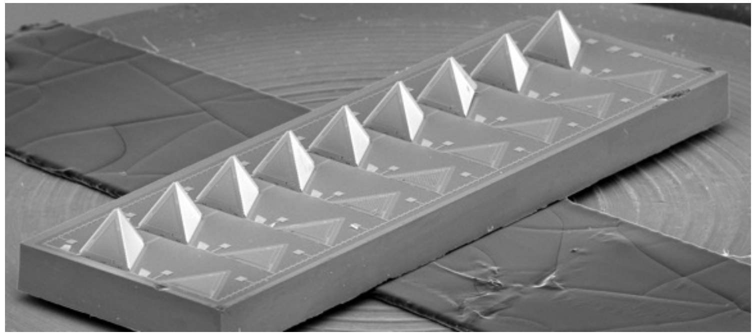
Few transistors

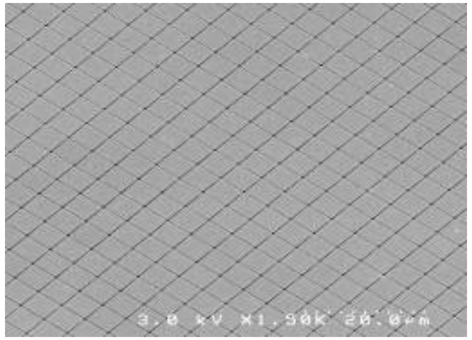
Few million transistors

High-end microprocessor (AMD "Epyc") contains 40 billion transistors in a chip about 3 cm on a side.





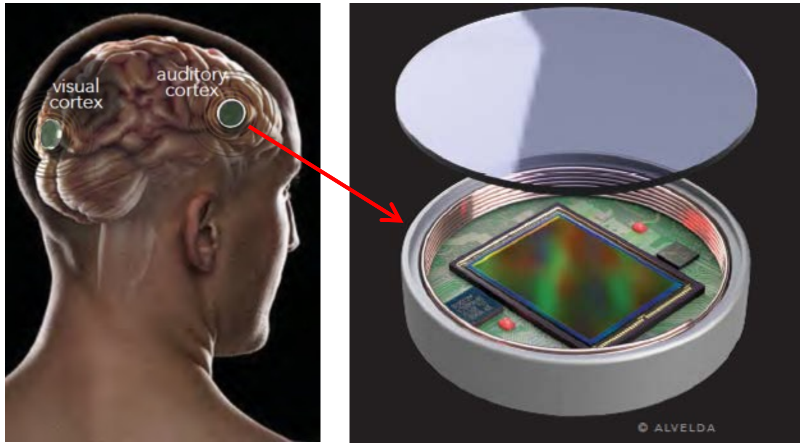




Building the mechanical equivalent of a Pentium chip:
giving arms to a microprocessor

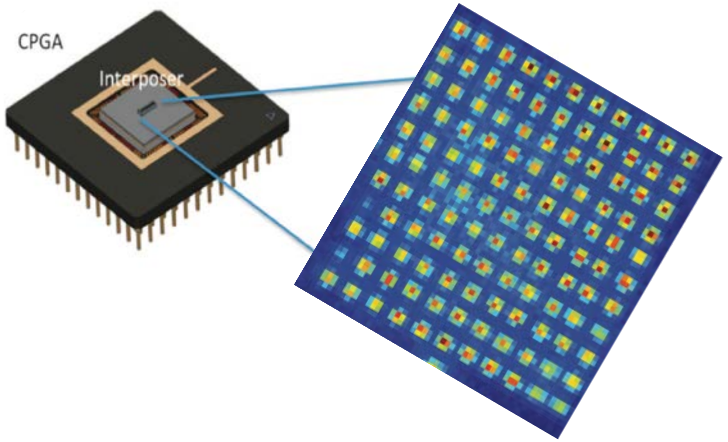
MEMS-based Spatial Light Modulators

Neural Engineering System Design (NESD)

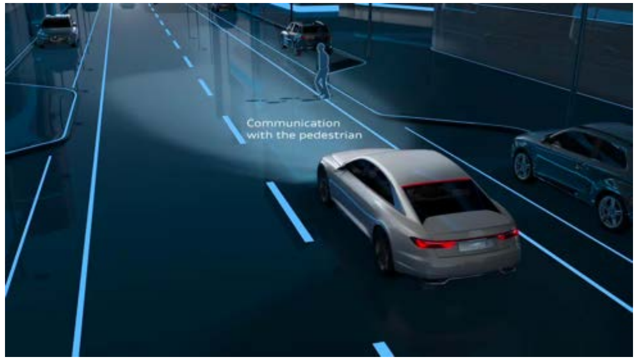


Device that can read 10^6 neurons and write to 10^5 neurons

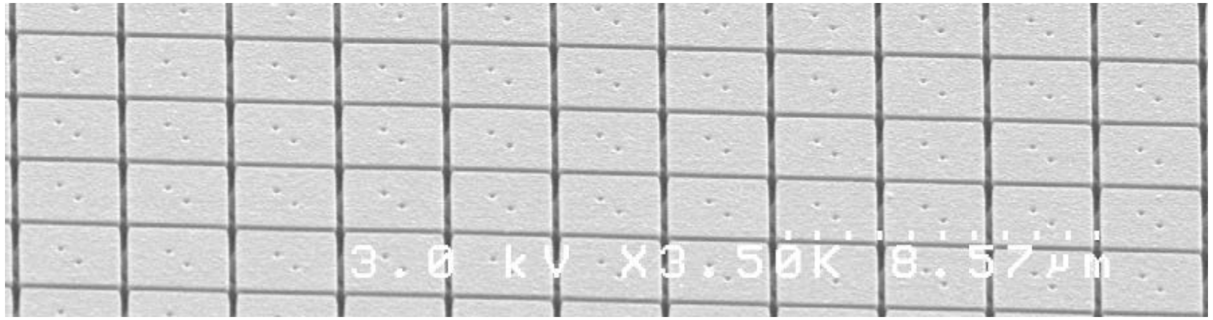
Optimization with Noisy Intermediate-Scale Quantum devices (ONISQ)

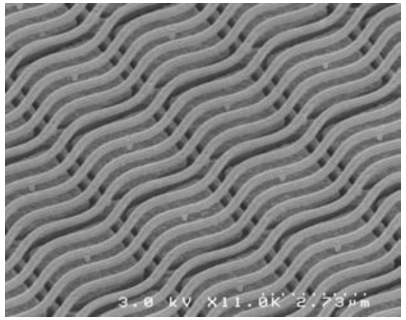


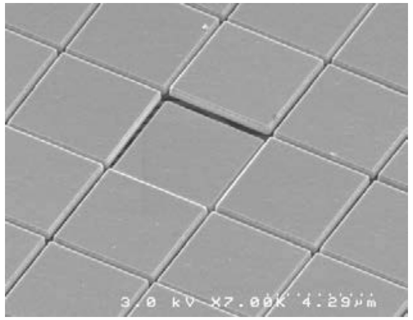
Trapping of neutral atom with parallel operation of gates and beam shaping at µsec speed



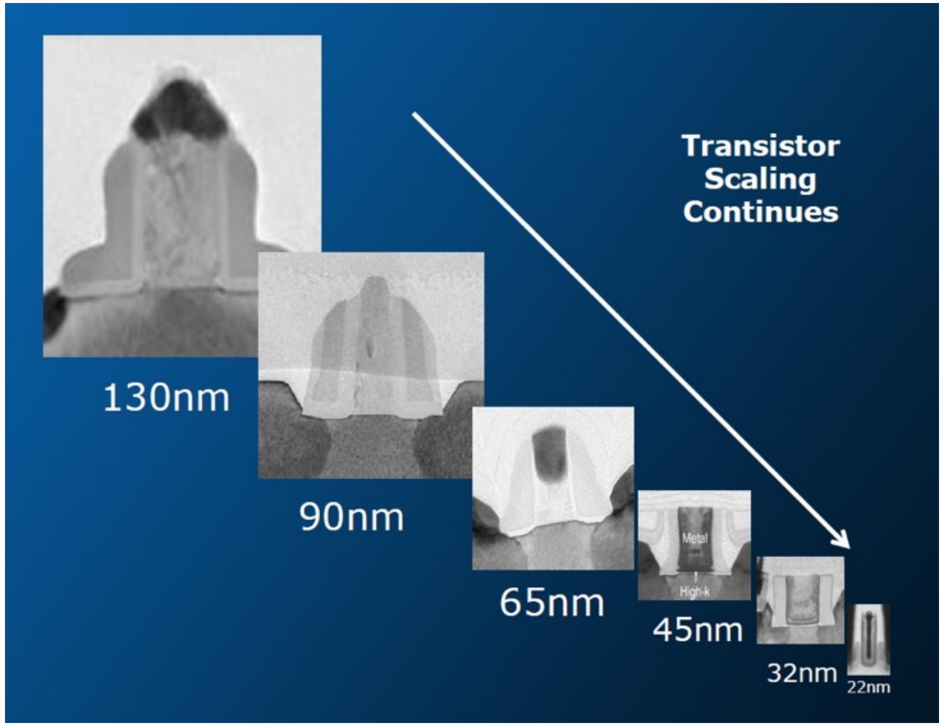
Active shaping of a vehicle's high beam



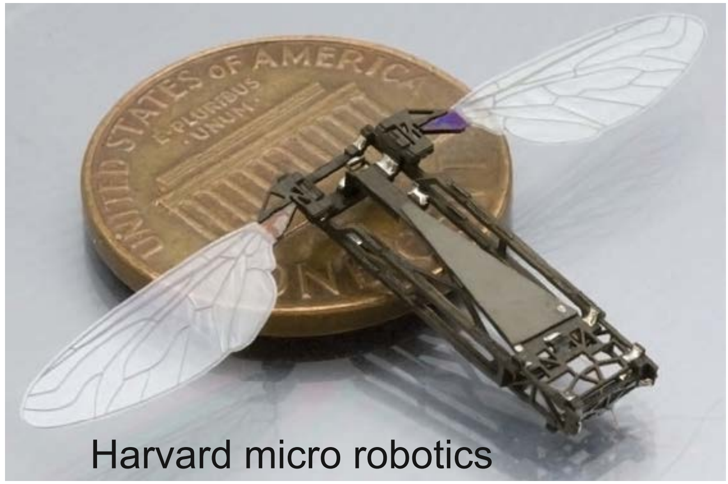


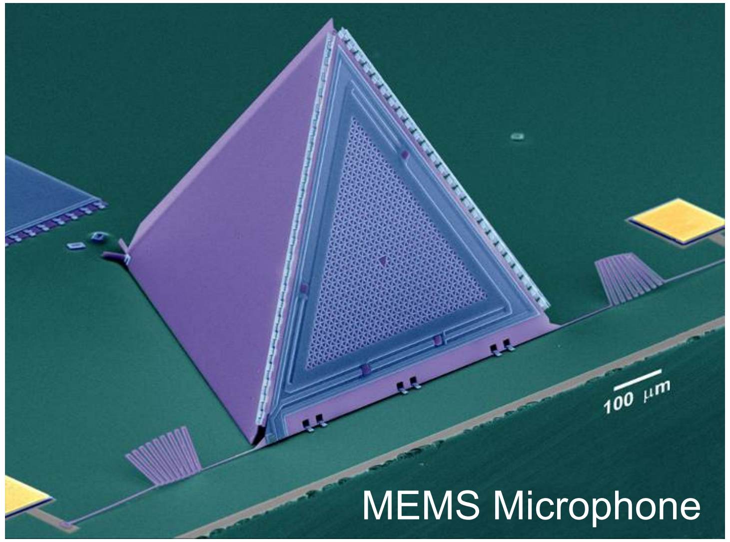


From MEMS to NEMS



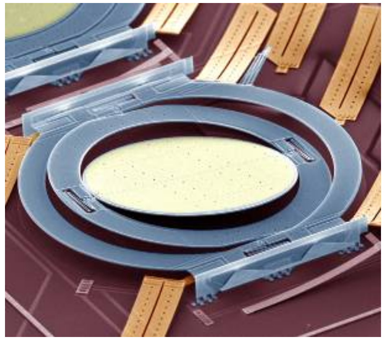
Scale invariant ➔ Moore's Law

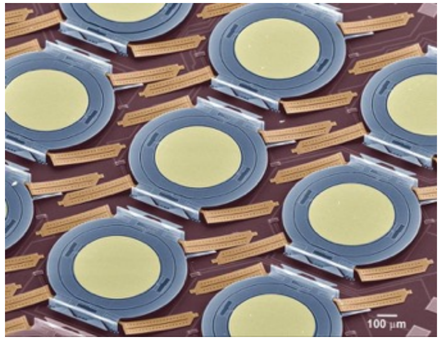


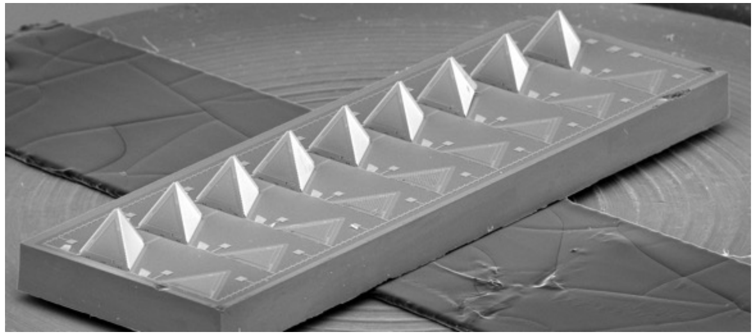


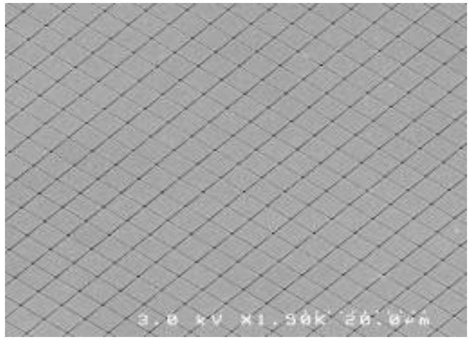
- NO Moore's law for nano-systems
- NOT scale invariant (physics is scale dependent)

Micromachines technology evolution





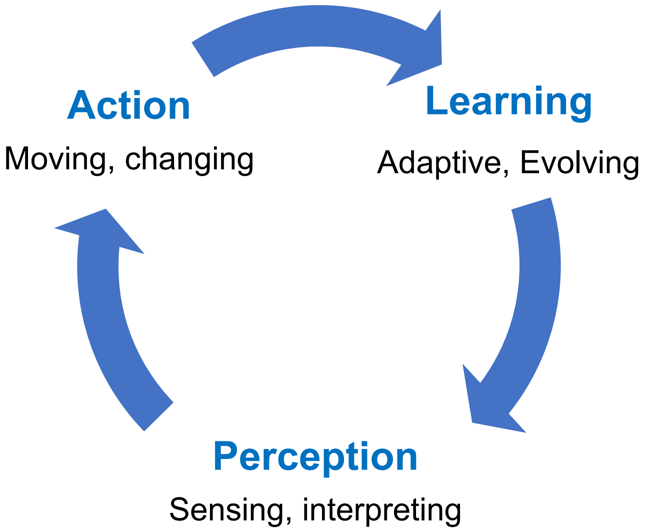




Intelligent micro-systems

Questions?

Intelligent micro-systems



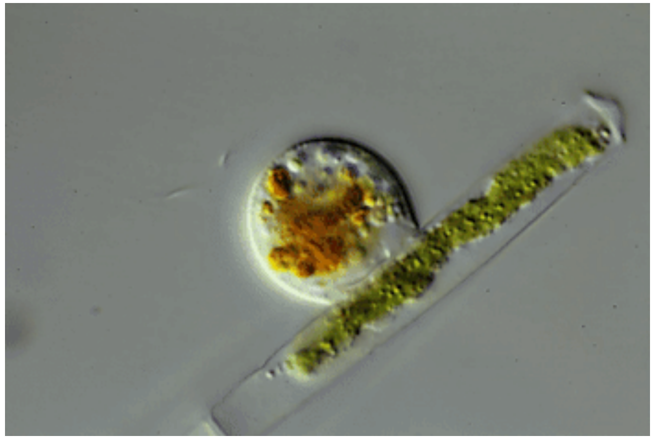
Physical Intelligence (PI)

Encoding intelligence (perception, action & adaptation/learning) inside the physical body of a physical agent (structure, machine, robot, etc.)

Physical intelligence versus neural Computational Intelligence

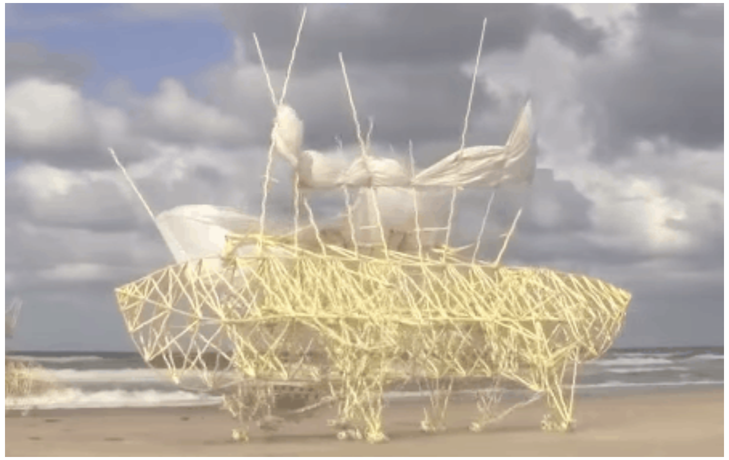
- Centimeter and larger scale: CI dominant
- Millimeter scale (limited on-board powering/actuation/computation): PI $\approx$ CI
- Microscale (no on-board powering/actuation/computation): PI only

Metin Sitti - Max Planck Institute for Intelligent Systems

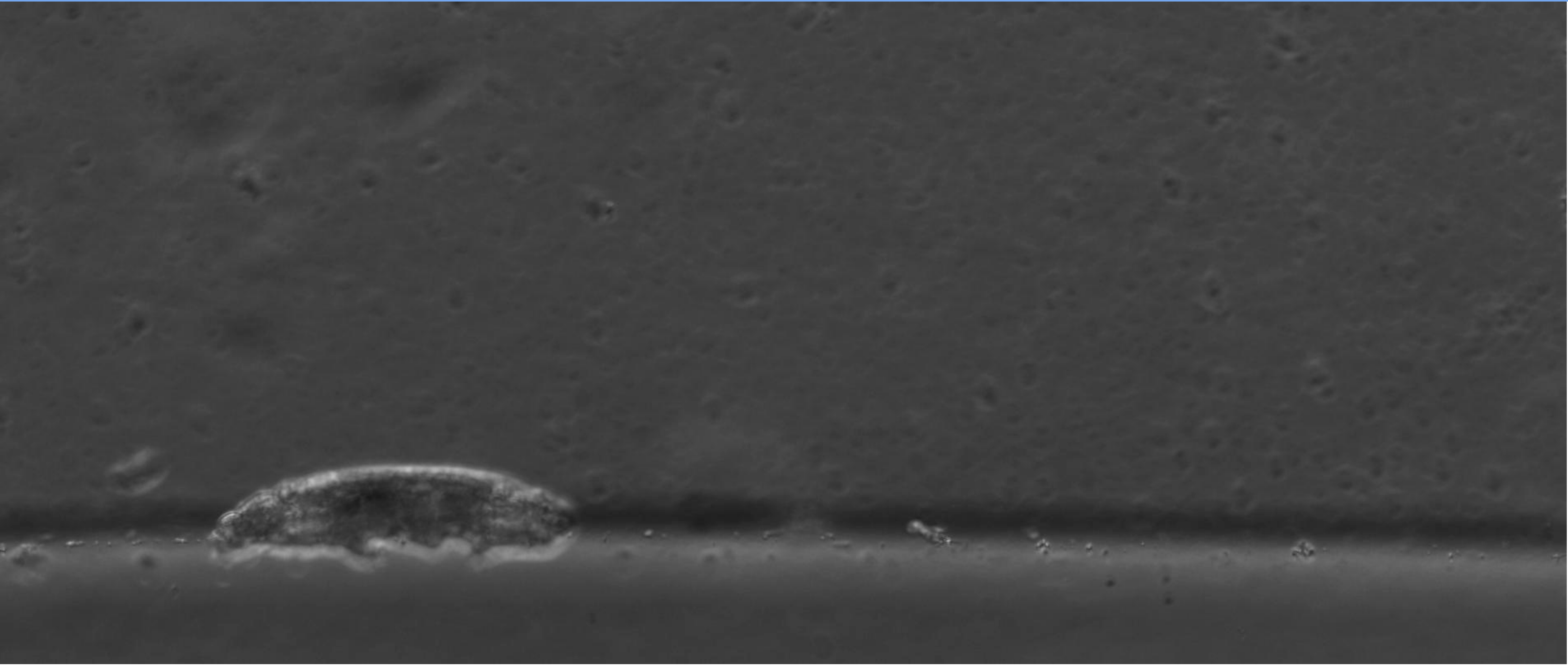


Cell-scale intelligence
(perception, action and learning/adaptation)

Theo Jansen

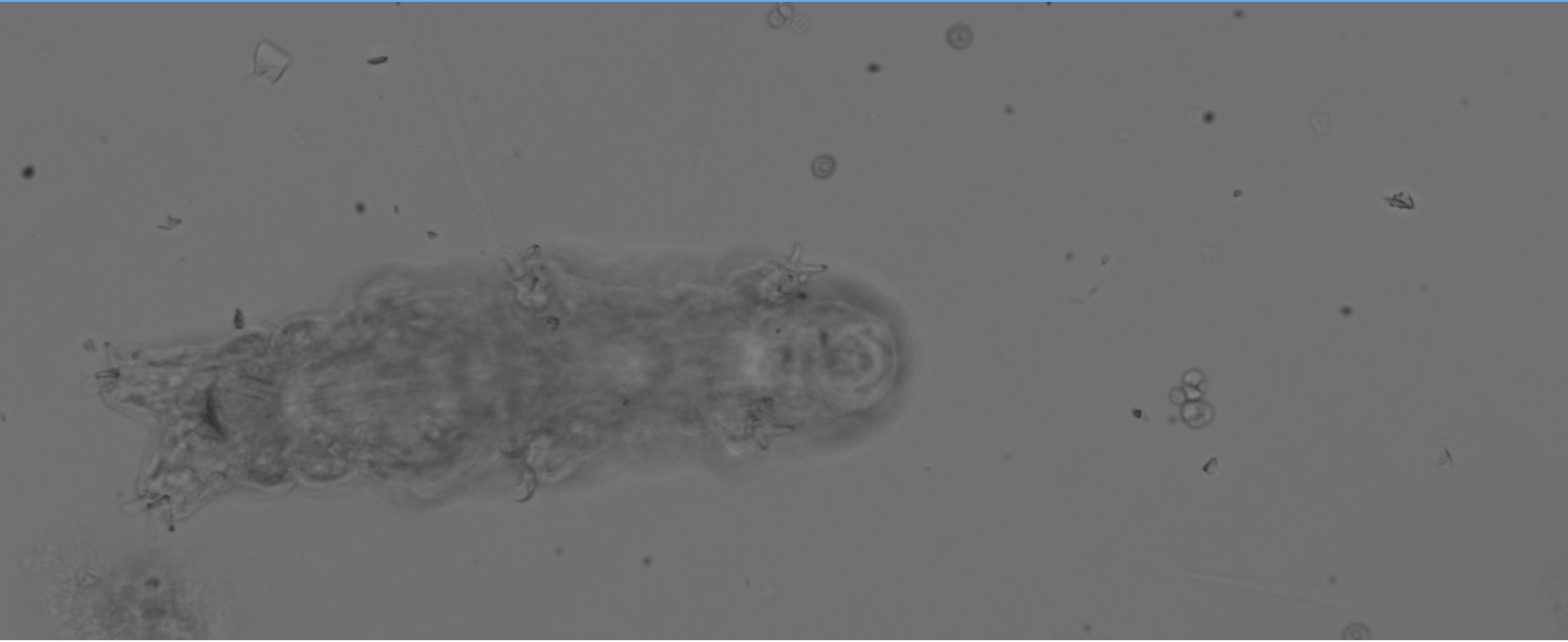


Intelligent micro-systems



Tardigrades exhibit robust inter-limb coordination across walking speeds (bioRXiv – 3/20/21)- Daniel Cohen's group

Intelligent micro-systems



Tardigrades exhibit robust inter-limb coordination across walking speeds (bioRXiv – 3/20/21)- Daniel Cohen’s group

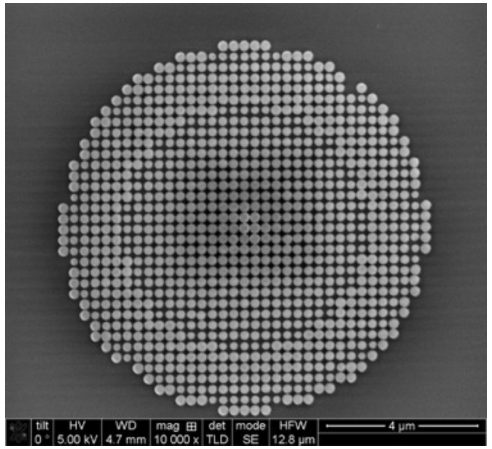
Physical Intelligence

How to create Physical Intelligence in Micro-systems?

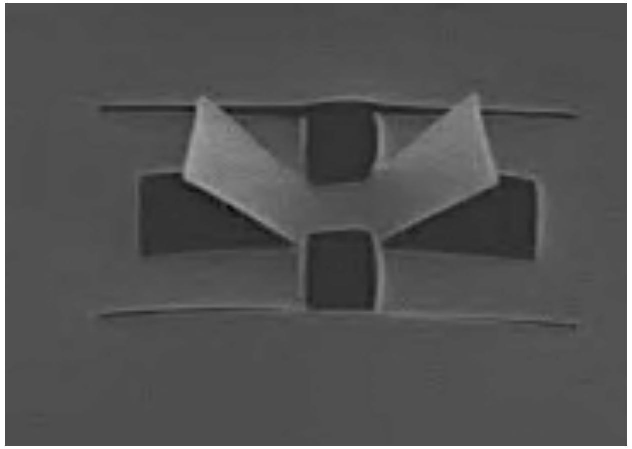
- Physical self-adaptation to changing conditions
  - Reconfigurable morphology, stiffness, damping, color
- Self-sensing & self-reacting to external stimuli or forces
  - Light, temperature, flow,
- Encoding autonomous behavior by smart materials & interactions
  - Mechanical memory
  - Self-propulsion
  - Self-organization

A vision for intelligent microsystems

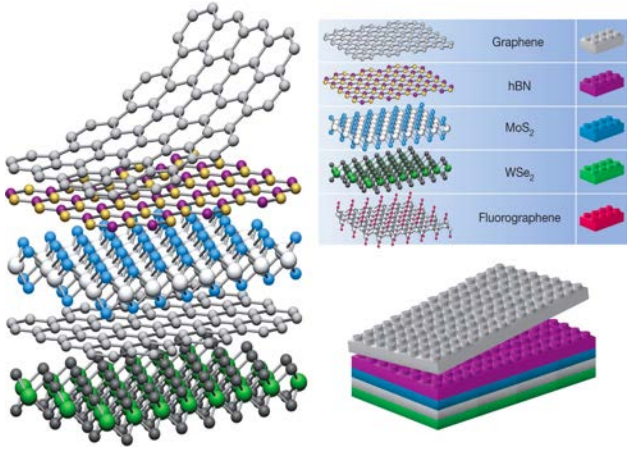
Flat optics



Kirigami nano-actuators

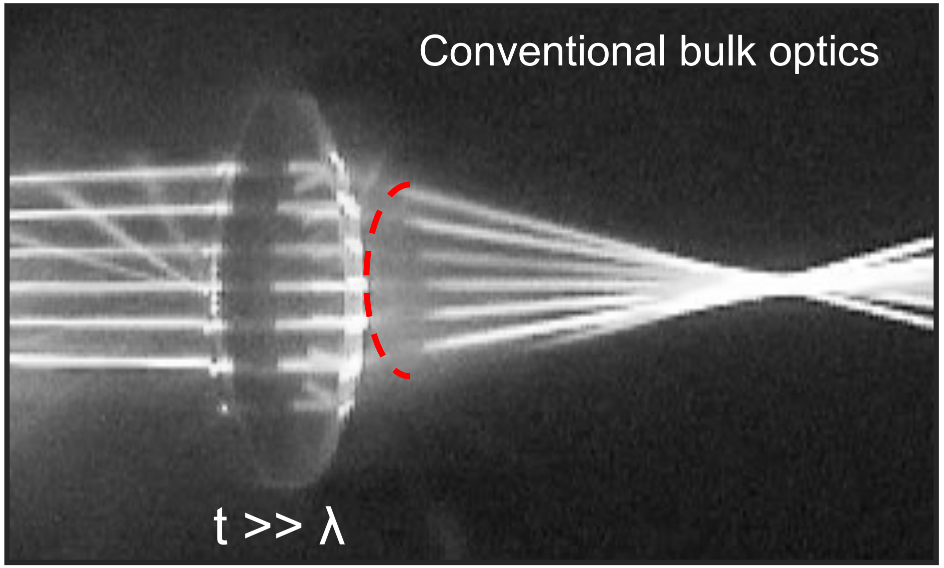


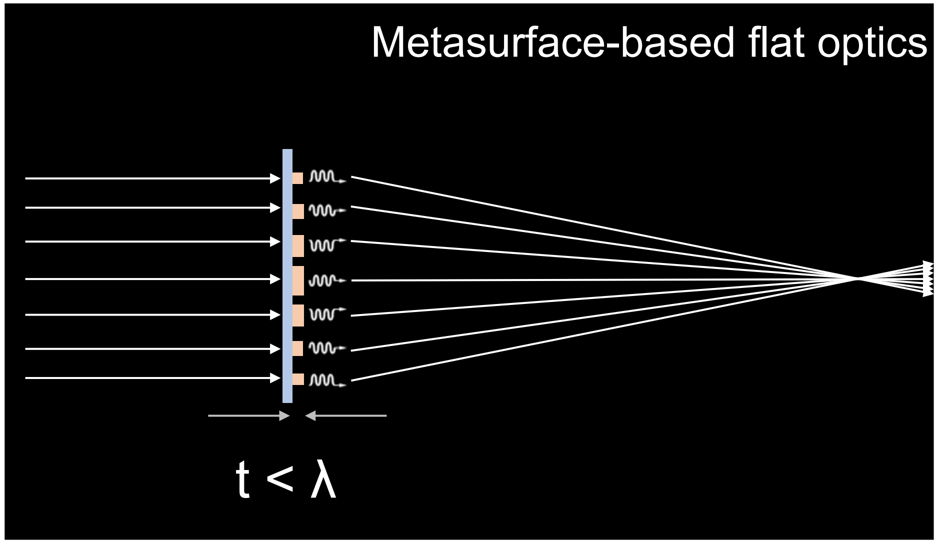
2D Electronics

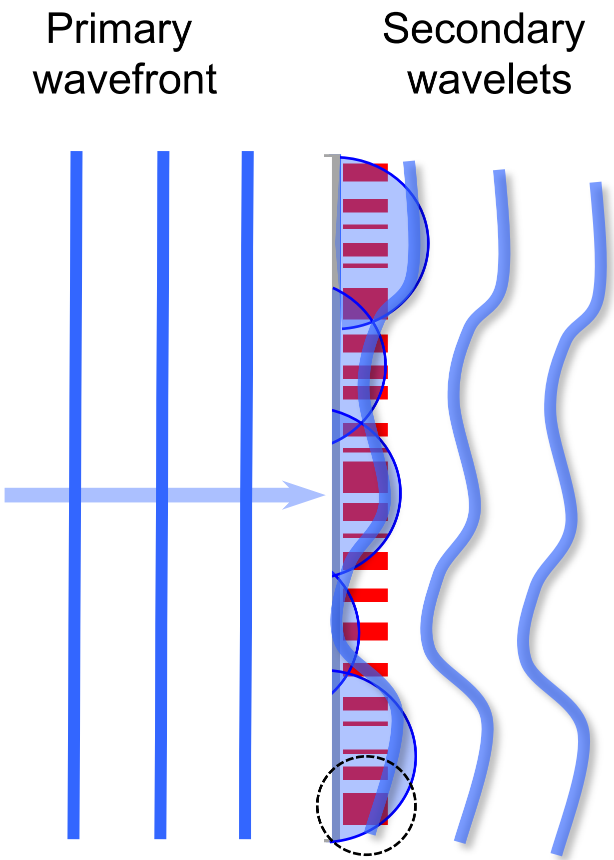


New paradigm for designing intelligent microsystems

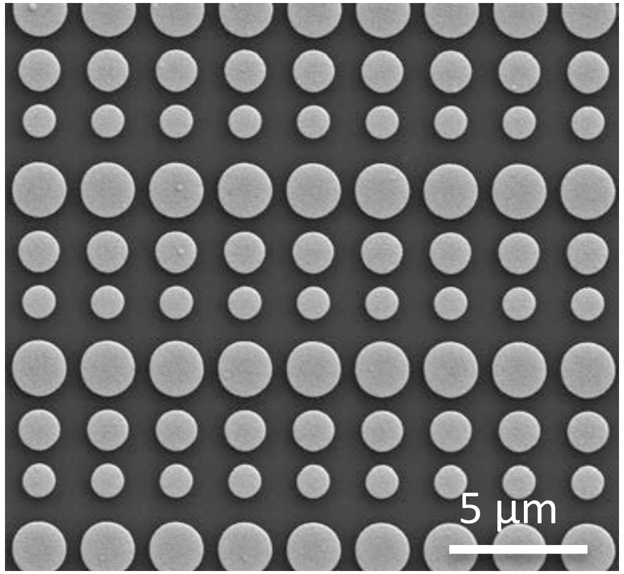
Metasurface-based flat optics





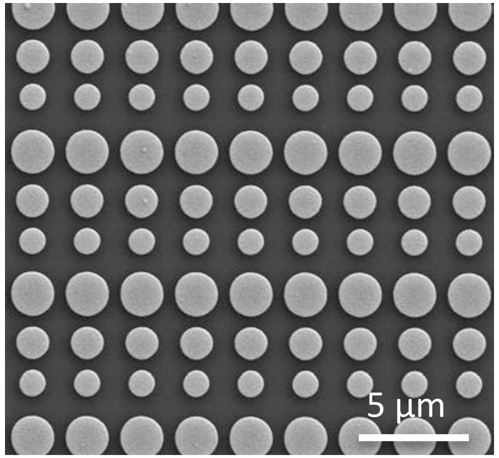


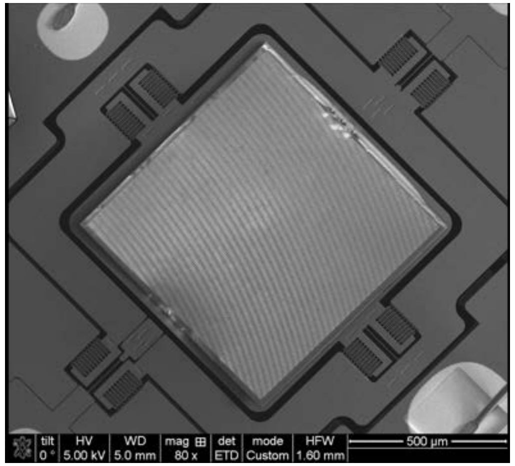
- **Straight-Forward Fabrication**
  - One mask level, cost effective
- **Compact**
  - Light weight
- **Unprecedented Control of Dispersion**
- **Overcome Limitations of Conventional Optics**
  - Aberrations, multifunctionality
- **CMOS compatible**

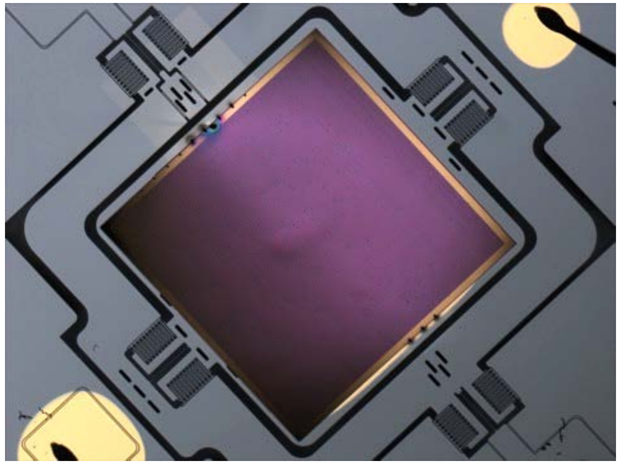


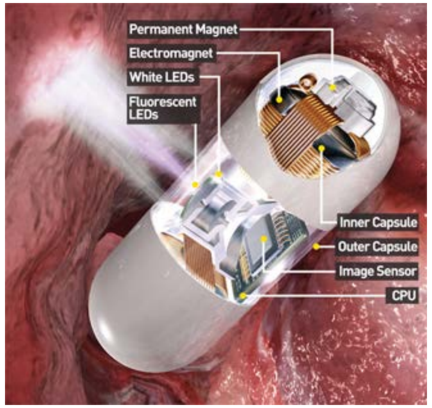
Metasurfaces and MEMS

Incorporation of flat-optics onto MEMS scanners → Flat optical systems









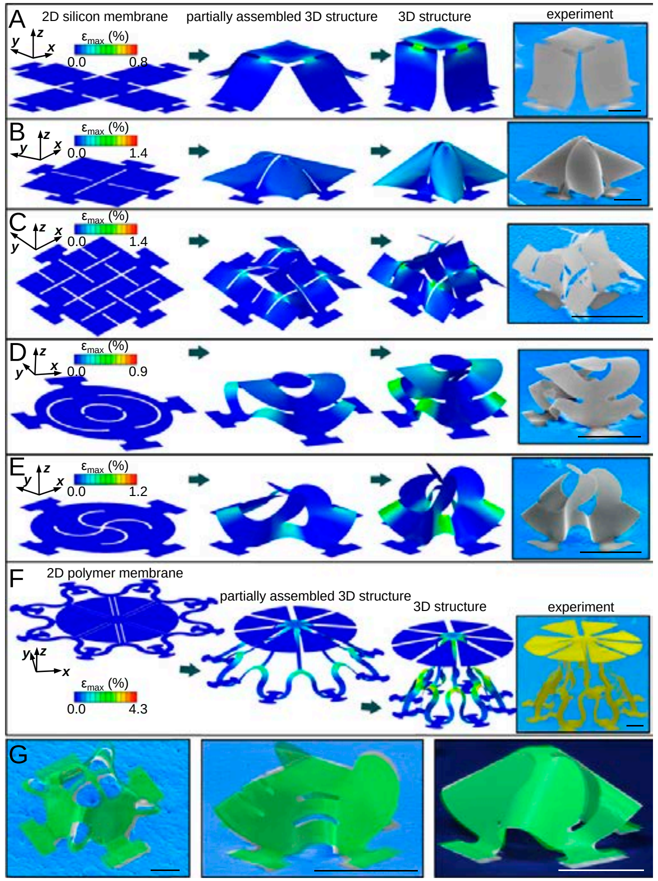
F. Capasso (Harvard)

Origami - Kirigami structures

Inspired by the ancient Japanese art of paper folding and cutting, and recent developments in modeling that allow inverse design of complex shapes from a single sheet of paper, Origami and Kirigami had emerged as a powerful strategy to transform 2D layouts into ***scale invariant*** 3D complex architectures that are difficult to achieve by conventional fabrication processes and additive manufacturing

A mechanically driven form of Kirigami as a route to 3D mesostructures in micro/nanomembranes

Yihui Zhang[a,1], Zheng Yan[b,1], Kewang Nan[c], Dongqing Xiao[d], Yuhao Liu[b], Haiwen Luan[e], Haoran Fu[e,f], Xizhu Wang[b], Qinglin Yang[b], Jiechen Wang[b], Wen Ren[g], Hongzhi Si[b], Fei Liu[a], Lihen Yang[b], Hejun Li[g], Juntong Wang[c], Xuelin Guo[b], Hongying Luo[e,h], Liang Wang[e,i], Yonggang Huang[e,2], and John A. Rogers[b,d,j,2]



John Rogers (NU)

nature materials
ARTICLES
https://doi.org/10.1038/s41563-019-0452-y

Programming shape using kirigami tessellations

Gary P. T. Choi[1], Levi H. Dudte[1] and L. Mahadevan[1,2,3*]

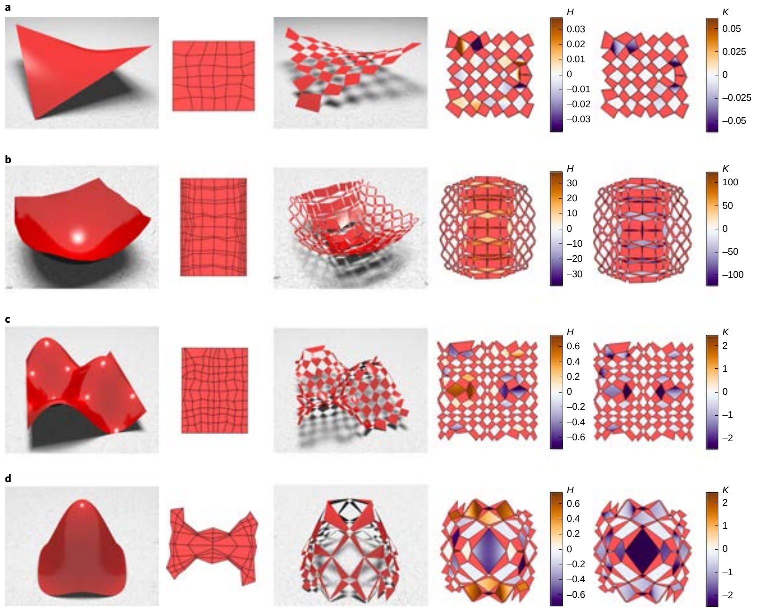


Fig. 4 | Generalized kirigami patterns for three-dimensional surface fitting. a–d, The target surfaces are a hyperbolic paraboloid (with negative curvature) (**a**), a paraboloid (with positive curvature) (**b**), a periodic patch of an egg-carton shape (**c**) and a bivariate Gaussian (**d**). Columns: the target surfaces (leftmost), the generalized kirigami patterns, the deployed configurations of the patterns that fit the target surfaces, the top views of the deployed patterns with the holes coloured with the approximated mean curvature *H* and the top views of the deployed patterns with the holes coloured with the approximated Gauss curvature *K* (rightmost).

L. Mahadevan (Harvard)
K. Bertoldi, D. Nelson

Origami - Kirigami structures

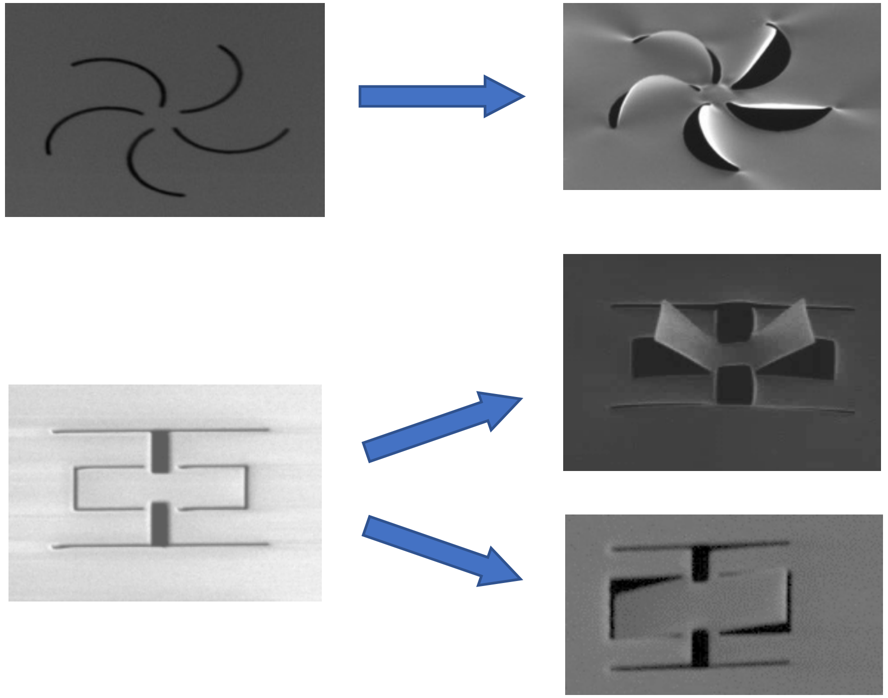
Japanese art of paper folding (Origami) and cutting (Kirigami)

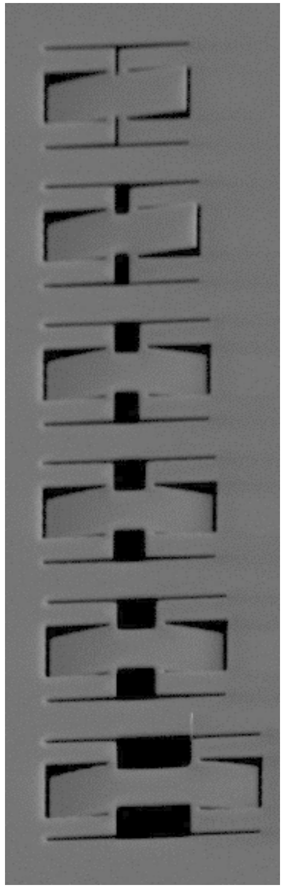
↓

Powerful strategy to transform 2D layouts

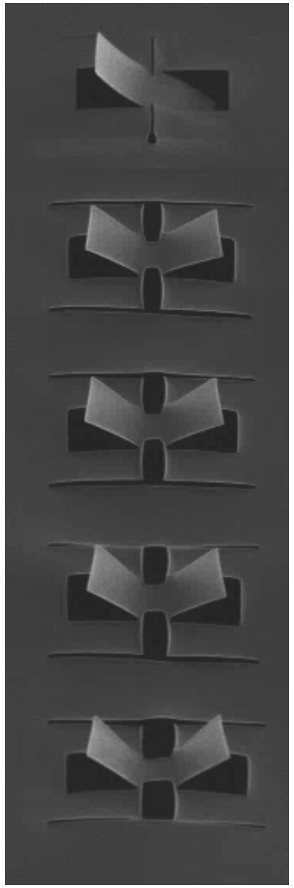
↓

Scale Invariant 3D complex architectures

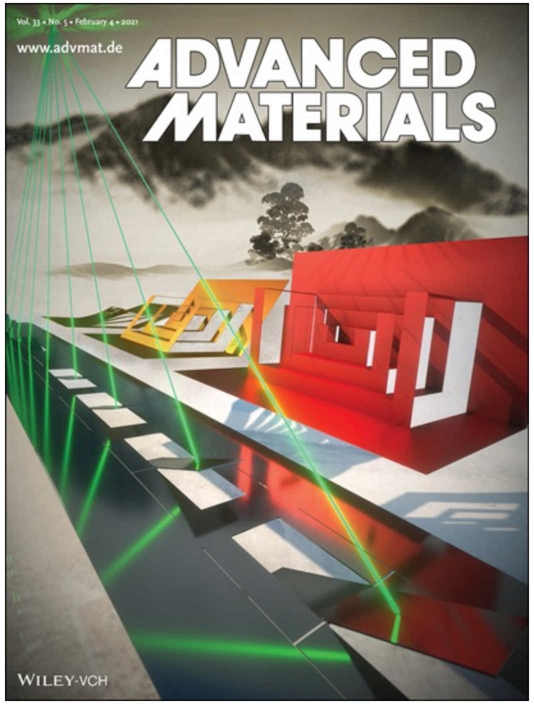




t = 100 nm



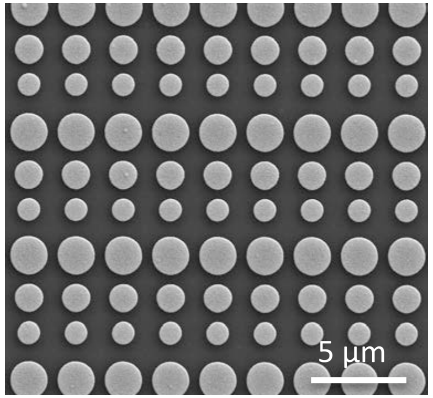
t = 50 nm

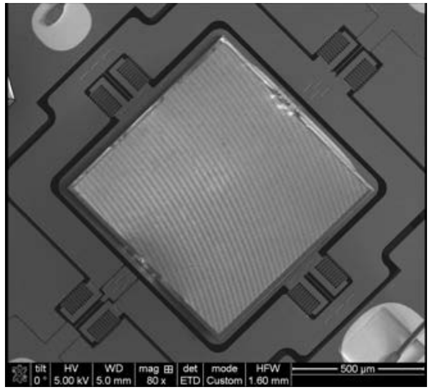


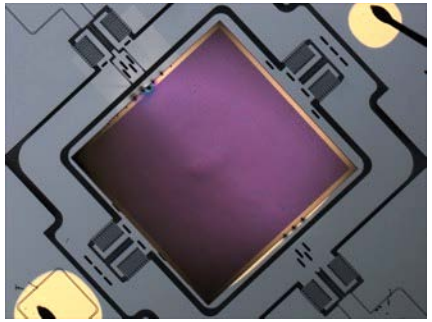
The most innovative applications of Origami/Kirigami engineering is the combination of structural and morphing capabilities that alters a device shape or enhances a material property.

Kirigami-based metasurfaces

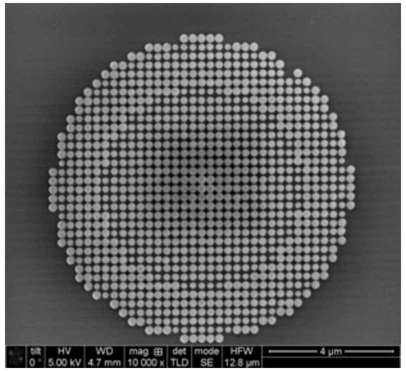
Incorporation of metasurfaces onto MEMS scanners

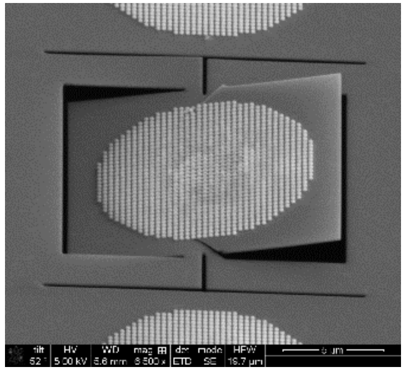


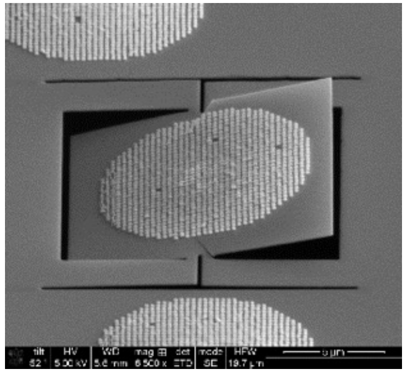


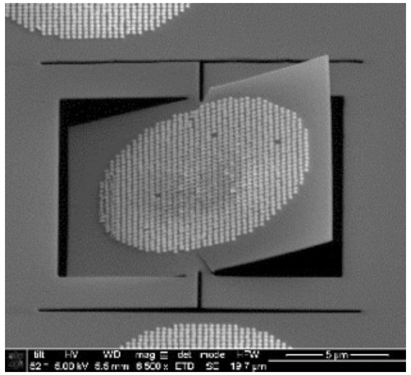


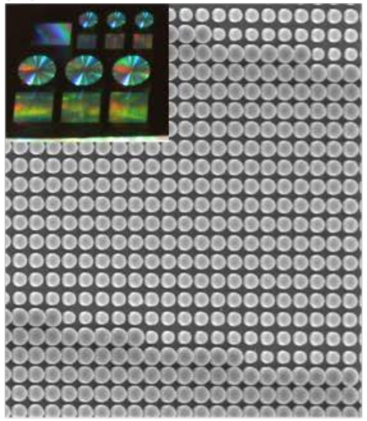
New methodology to fabricate complex 3D nanostructures: Reconfigurable Metasurfaces

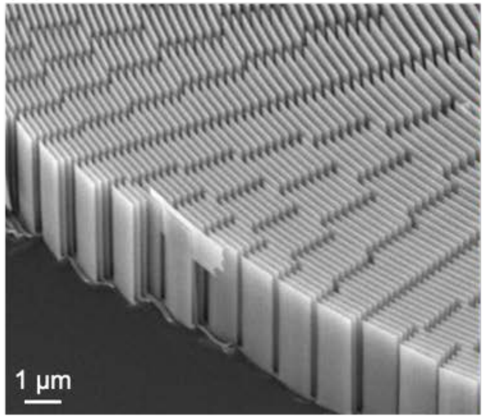


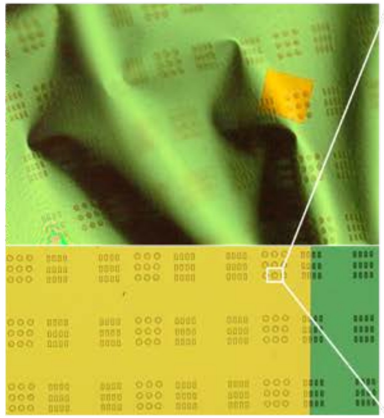


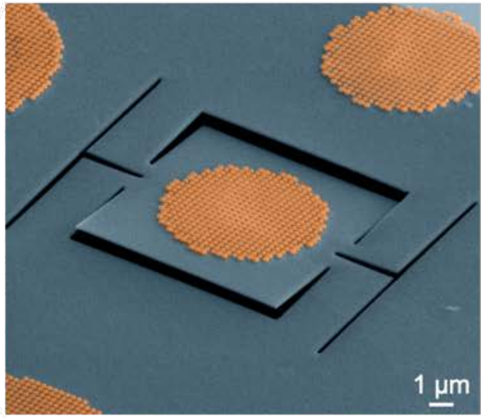












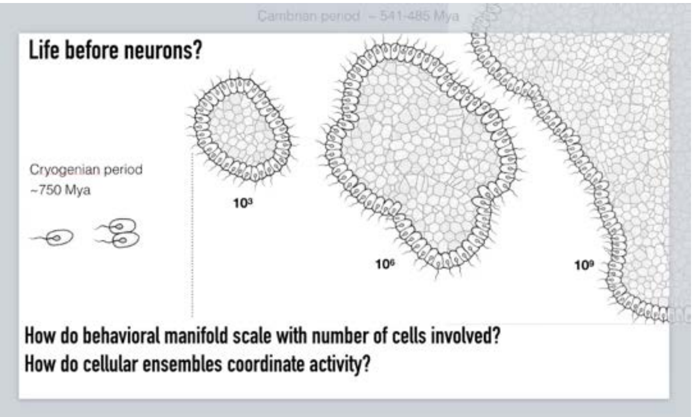
New fabrication of complex and tunable 3D nanostructures

- Monolithic integration
- Van der Waals techniques
  - hybrid integration of materials
  - piezoelectric, 2D, metals, metasurfaces

Xu Zhang (CMU)
Haogang Cai (NYU)

Intelligent microscale systems: what's next?

- Integrating sensing/learning functions
- Passive or active shape & dynamics
- Energetics of communications at small scale
    - High and expensive
    - how much communication you need
    - is local communication enough
- Swarms of autonomous micromachines
    - Coordination
    - Emergent behavior



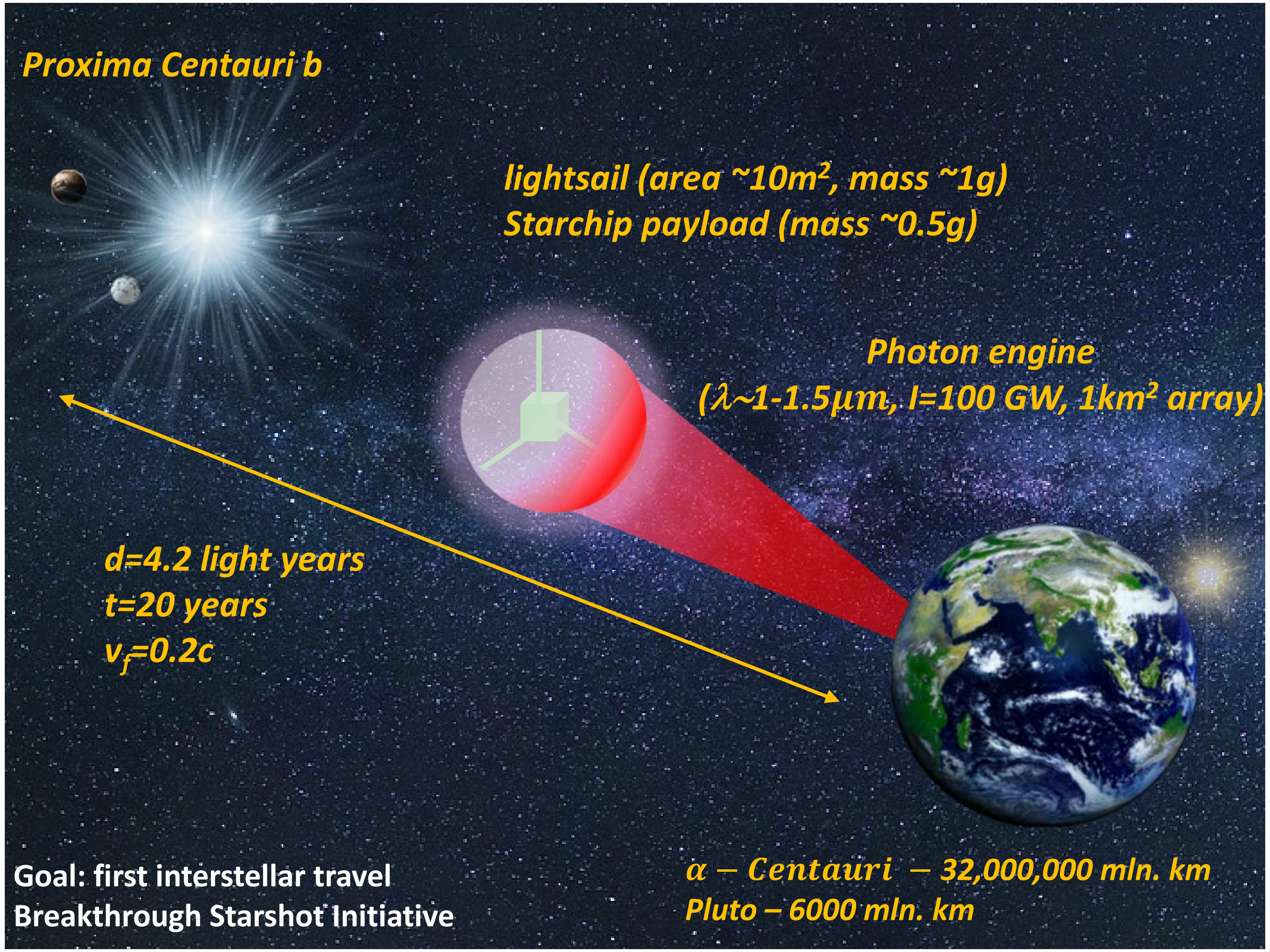
Manu Prakash (Stanford)

How does biological matter and body computation work?

Radhika Nagpal (Harvard)

The Next Big Thing (?)

Materials and structures for space exploration and settlement



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Materials challenges for the Starshot lightsail

Harry A. Atwater[1]*, Artur R. Davoyan[1], Ognjen Ilic[1], Deep Jariwala[1], Michelle C. Sherrott[1], Cora M. Went[2], William S. Whitney[2] and Joeson Wong[1]

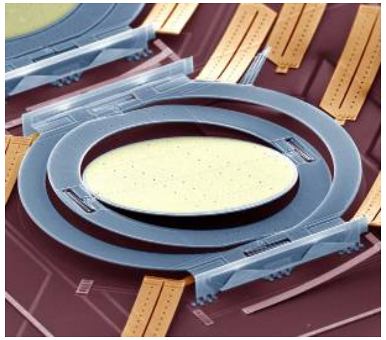
The Starshot Breakthrough Initiative established in 2016 sets an audacious goal of sending a spacecraft beyond our Solar System to a neighbouring star within the next half-century. Its vision for an ultralight spacecraft that can be accelerated by laser radiation pressure from an Earth-based source to ~20% of the speed of light demands the use of materials with extreme properties. Here we examine stringent criteria for the lightsail design and discuss fundamental materials challenges. We predict that major research advances in photonic design and materials science will enable us to define the pathways needed to realize laser-driven lightsails.

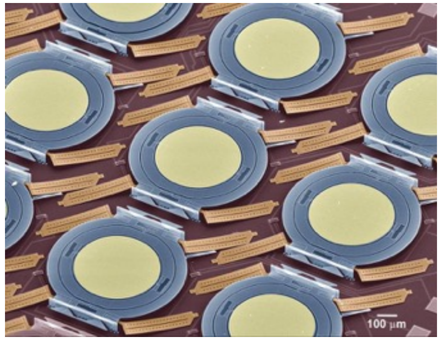
In order to reach relativistic speeds, the Starshot lightsail should have an area of ~10 m^2 and be kept to a mass of under ~1 gram, which translates into an equivalent thickness of approximately 100 atomic layers. The design of the lightsail will therefore need to push the boundaries of materials science, photonic design and structural engineering to enable high performance with minimal mass.

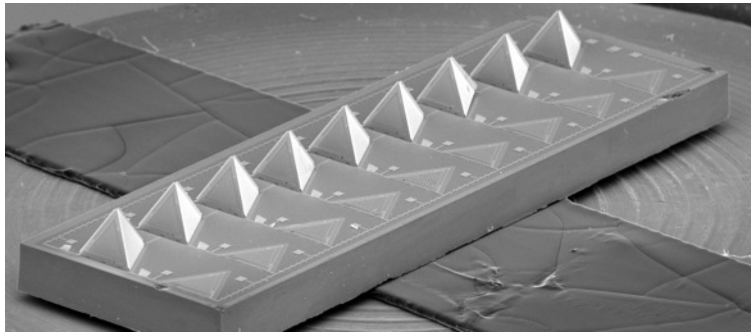
H. Atwater (Caltech)

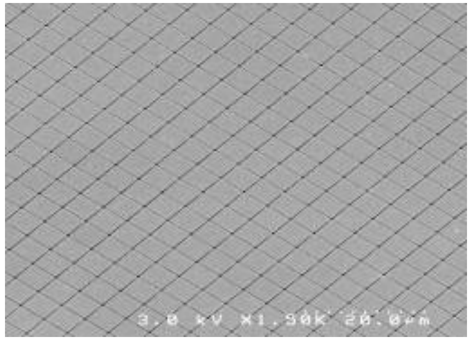
The most innovative applications of Origami/Kirigami engineering is the combination of structural and morphing capabilities that enhances or alters a material characteristic

Conclusions

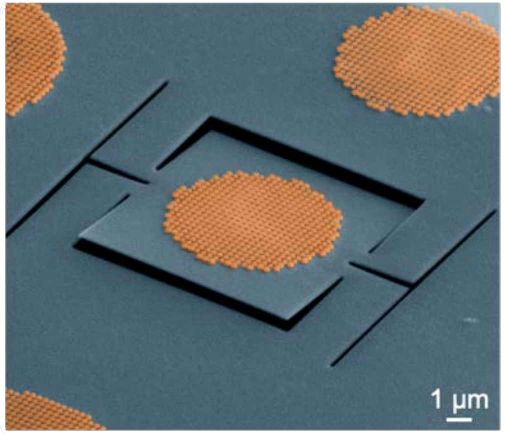








- Very large-scale integration of MEMS
- Intelligent micro-systems



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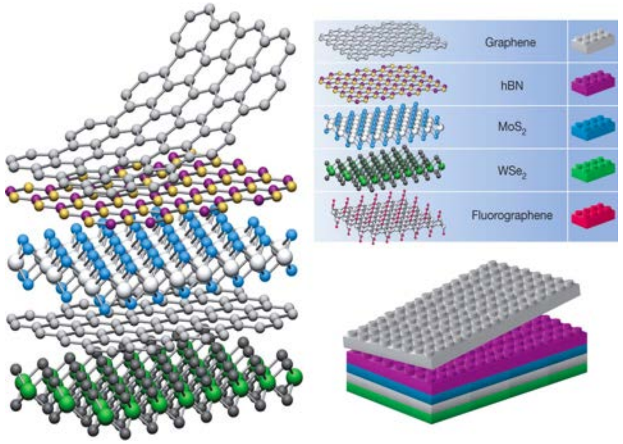

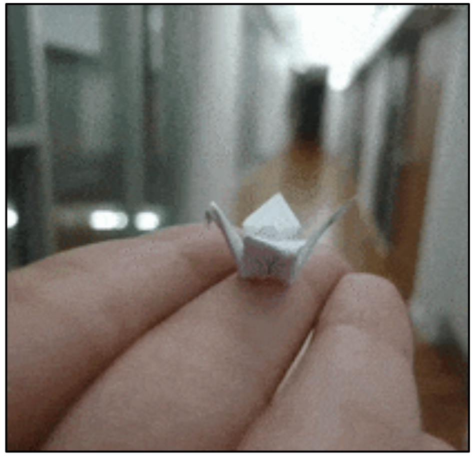

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