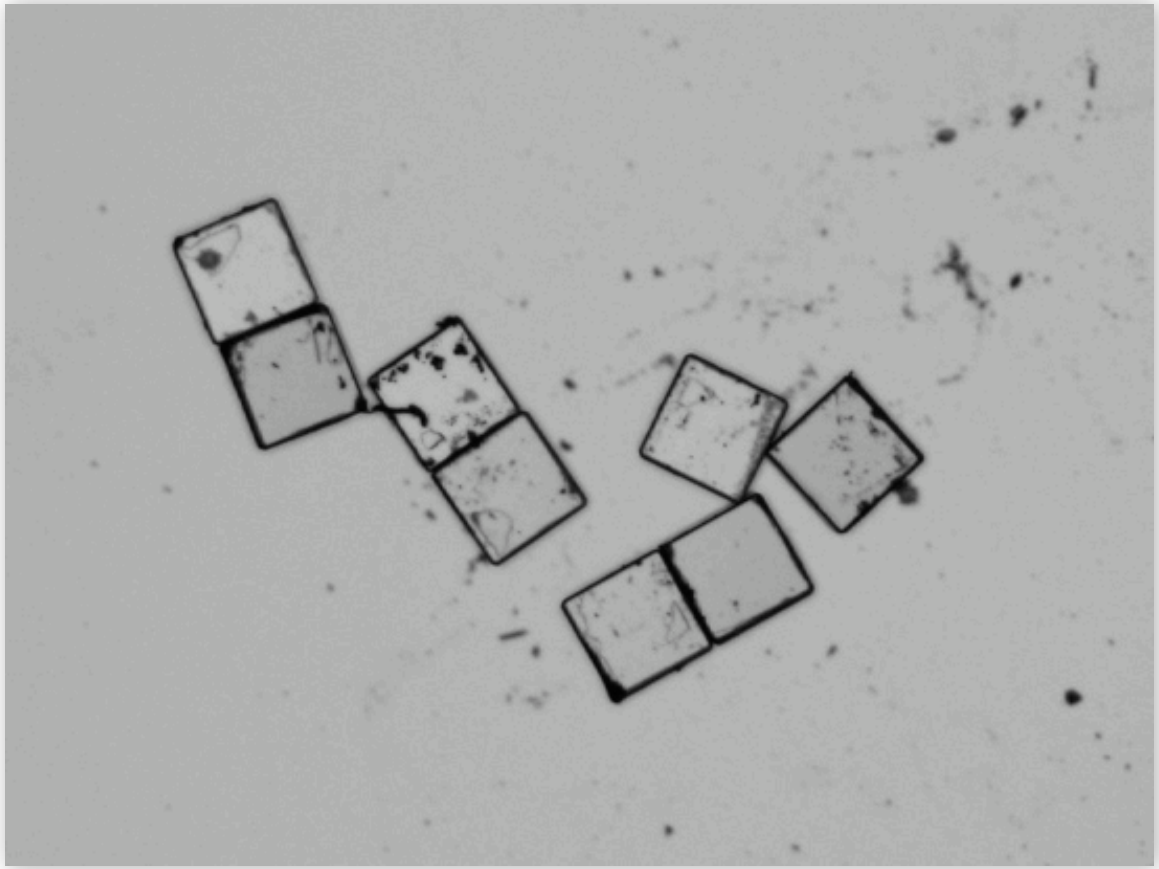
Controlling and Exploiting Self-Assembly of MEMS



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A lot of bricks, but where is the plan?

Today

An avalanche of beautiful micro/ nanobricks: nanowires, nanorods, nanotubes, DNA strands, nanoparticles, microspheres, nanocrystals, cells, etc.

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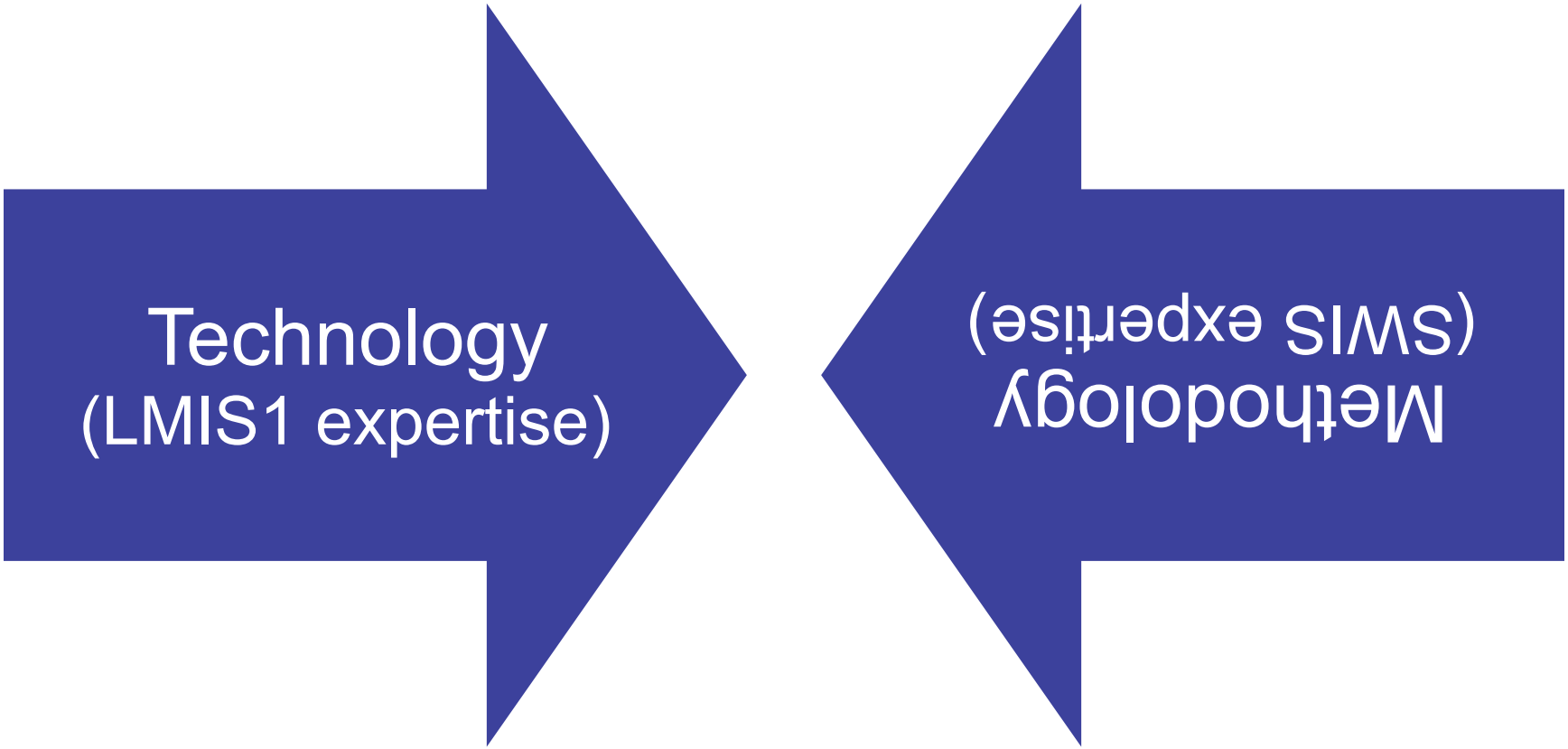
The challenge of tomorrow

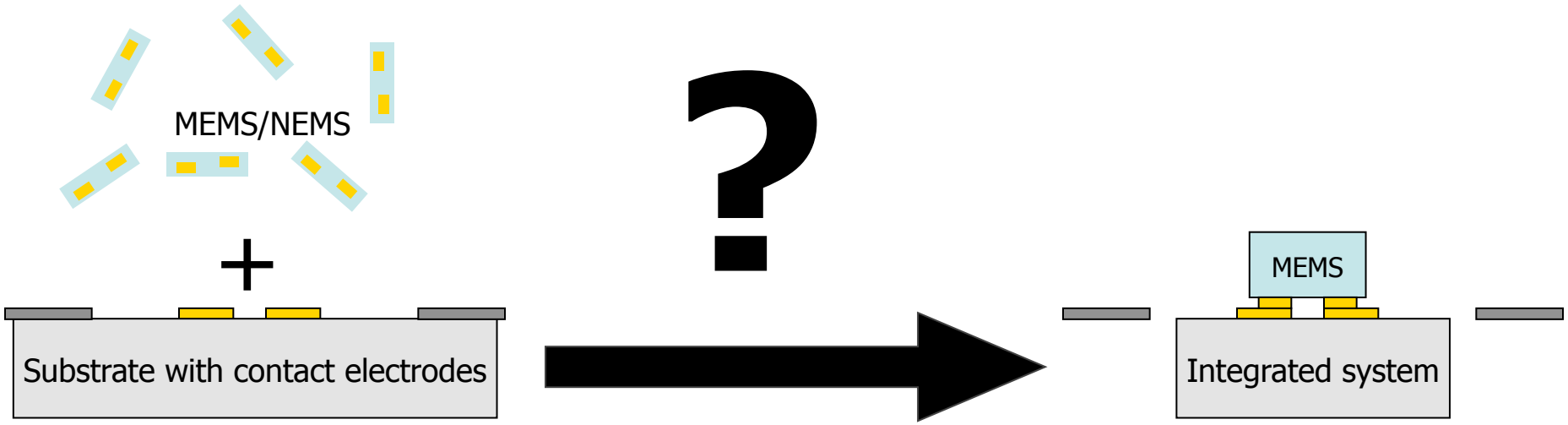
Finding a way to (self-)assemble these bricks into functional micro/nano-systems

2 fields + 2 motivations + 2 frameworks = 1 challenge



Motivation: technology

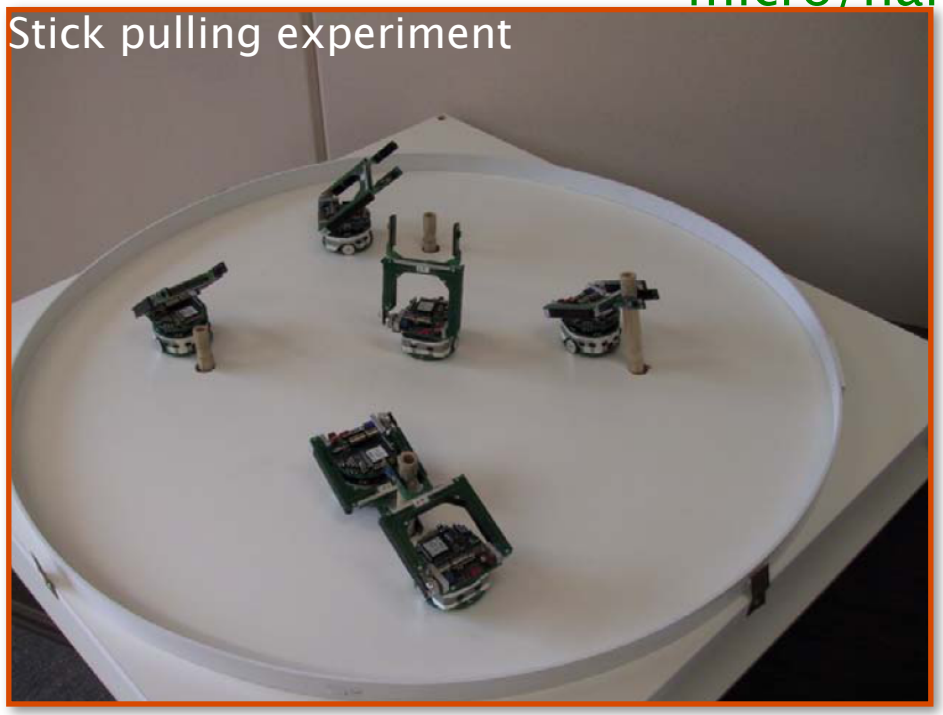
- Lithography: great advances in engineering of devices in the size range of 0.1–100 µm, **but**…
- How to build non-monolithic, hybrid systems assembled from a set of components which are coming from different fabrication processes?

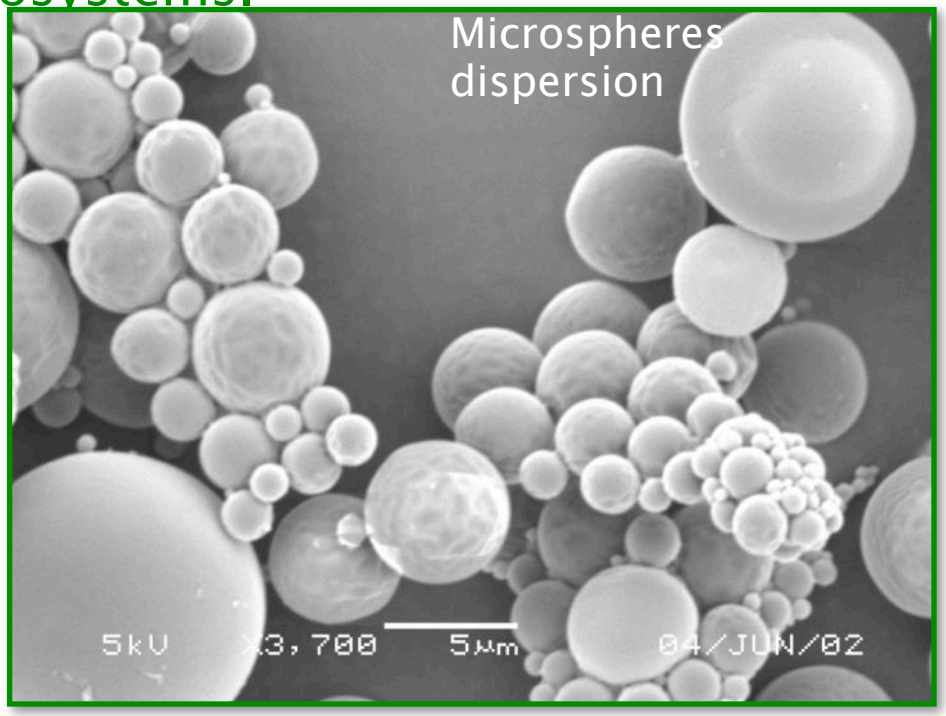


Manipulation?
Alignment?
Assembly?

Motivation: methodology

We aim at applying our expertise in model-based design and optimization of swarm robotics system to the design of self-assembling micro/nanosystems.





- Typical length scale: a few centimeters
- Typical swarm size: tenth to hundreds
- Sensing, computation, communication

- Typical length scale: 1 nm to 500 µm
- Typical swarm size: 10^3 to 10^6 units
- No sensing, no computation, no communication, but **local interactions**

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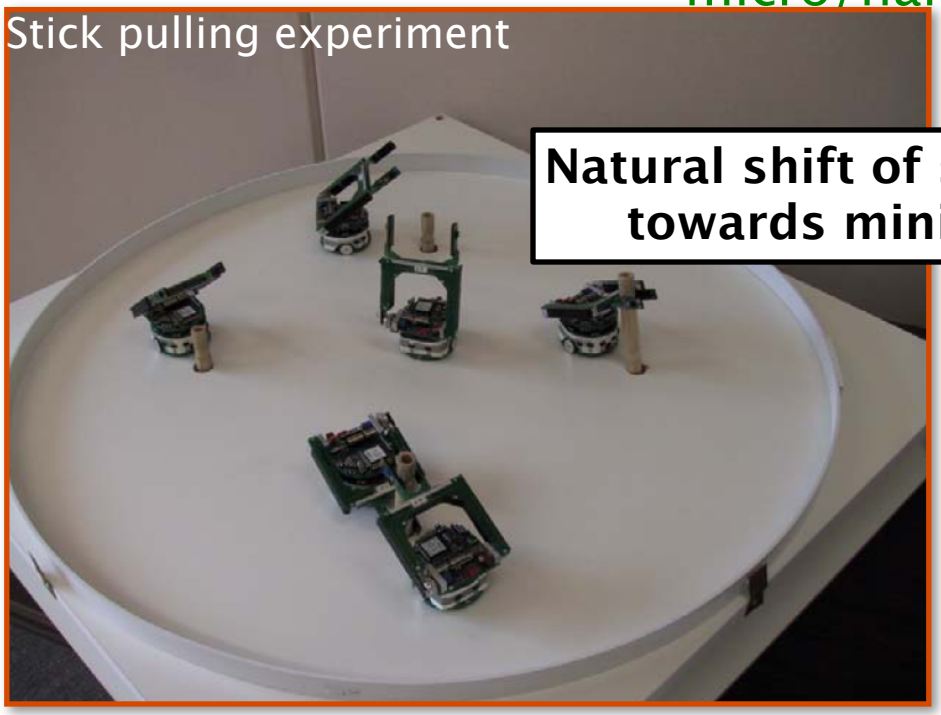
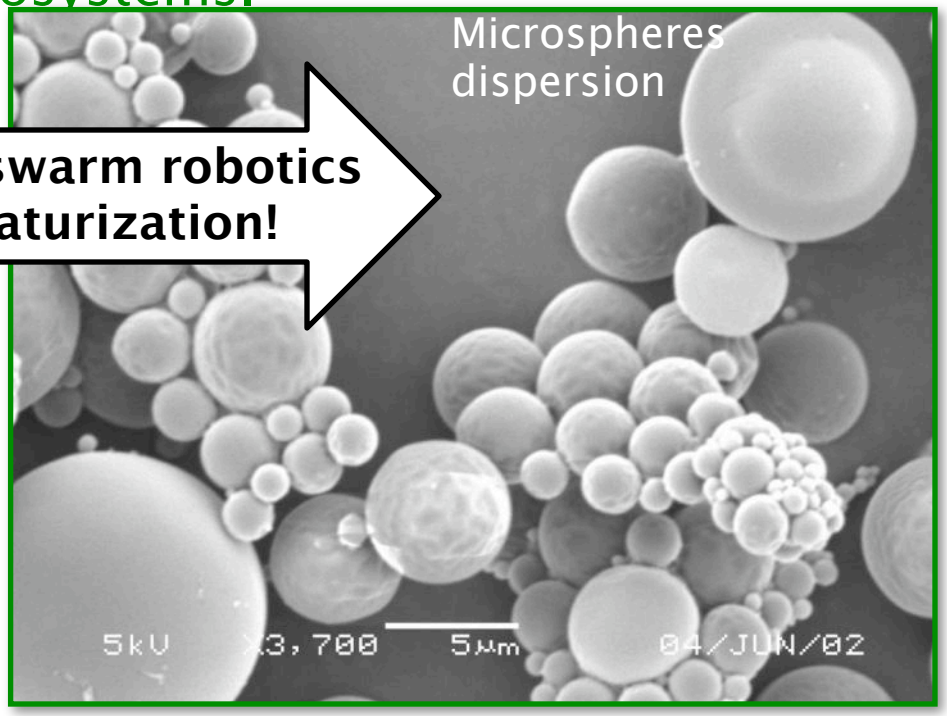


Natural shift of swarm robotics towards miniaturization!



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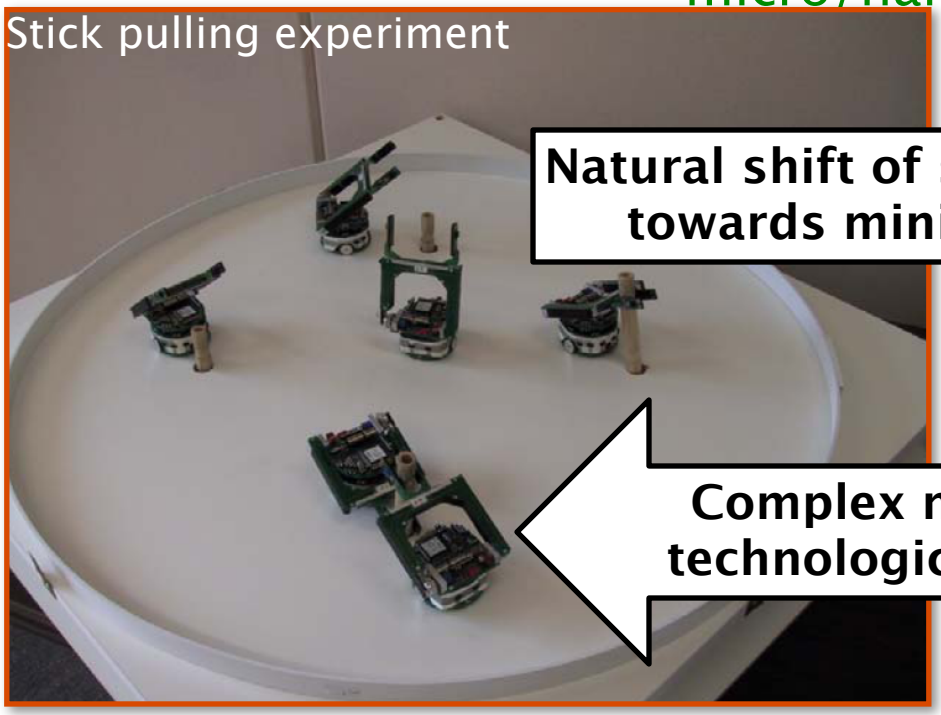

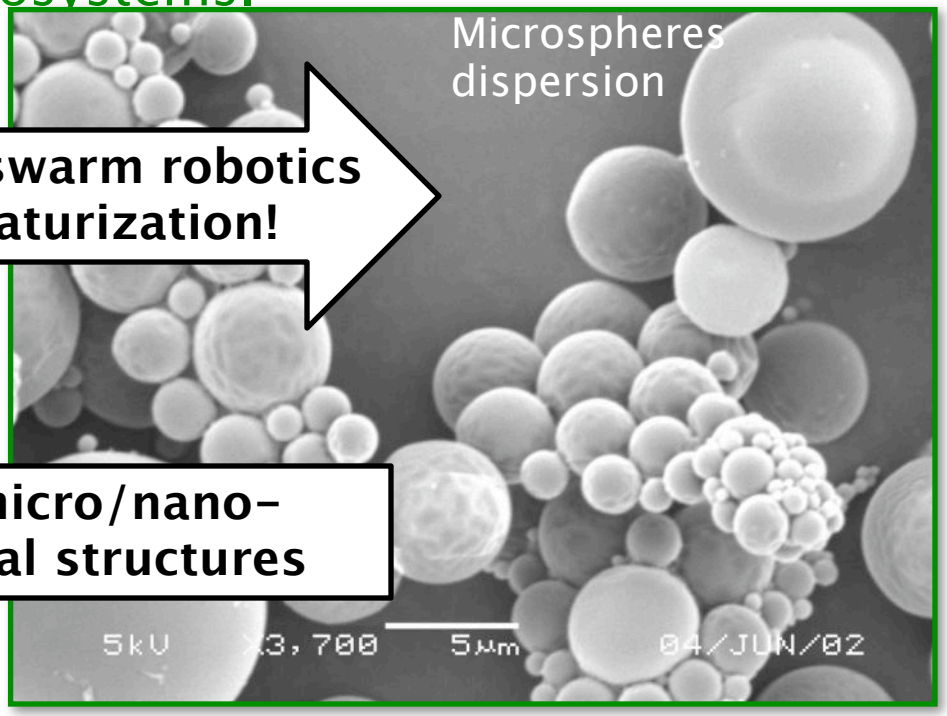

Natural shift of swarm robotics towards miniaturization!

Complex micro/nano-technological structures

- Typical length scale: a few centimeters
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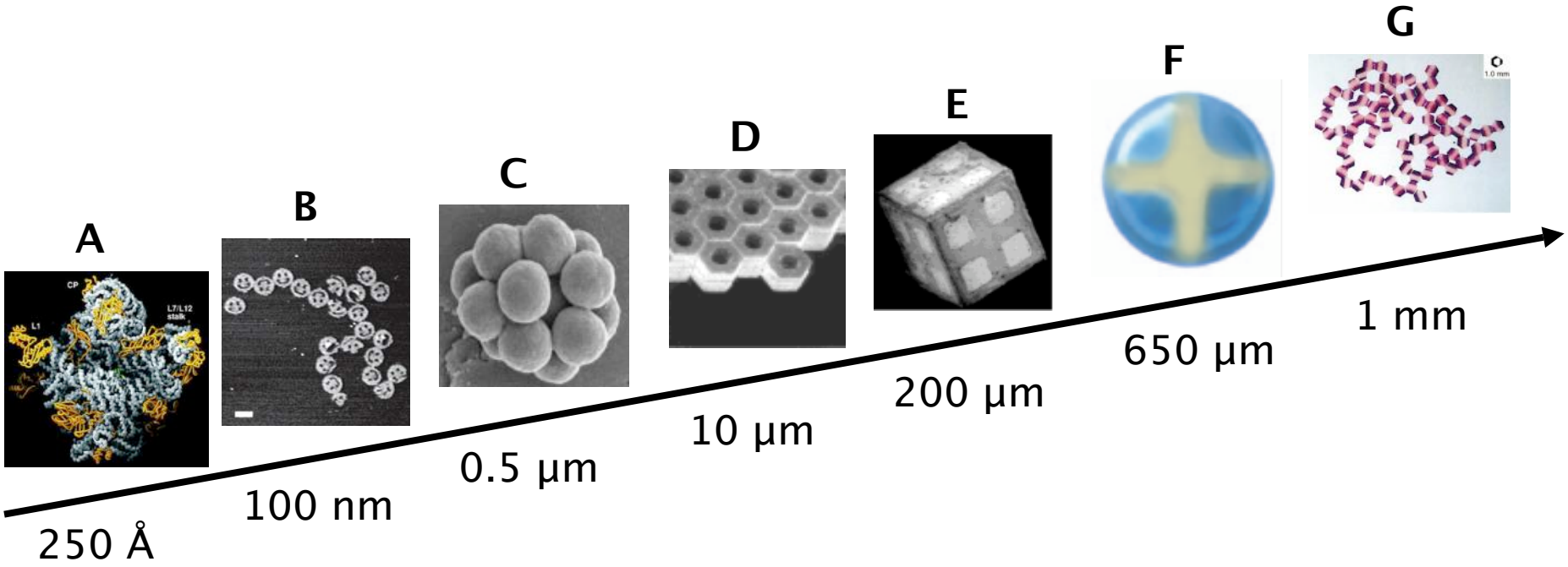
Self-assembly at all scales



A. Crystal structure of a ribosome [Yusupov et al., 2001]
B. Scaffolded DNA origami of 100 nm in diameter [Rothemund et al., 2006]
C. Clusters of 0.5-μm-sized spheres packed by surface tension [Manoharan, 2003]
D. Capillary SA of 10-μm-sized hexagonal plates into crystal structures [Clark, 2001]
E. Capillary SA of 200-μm-sized polyhedra [Gracias et al., 2002]
F. Capillary SA of polymeric spheres of complex internal structures from pipetted droplets [Fialkowsi et al., 2005]
G. SA of 1-mm-sized hexagonal plates using “capillary bond” [Bowden et al., 2001]

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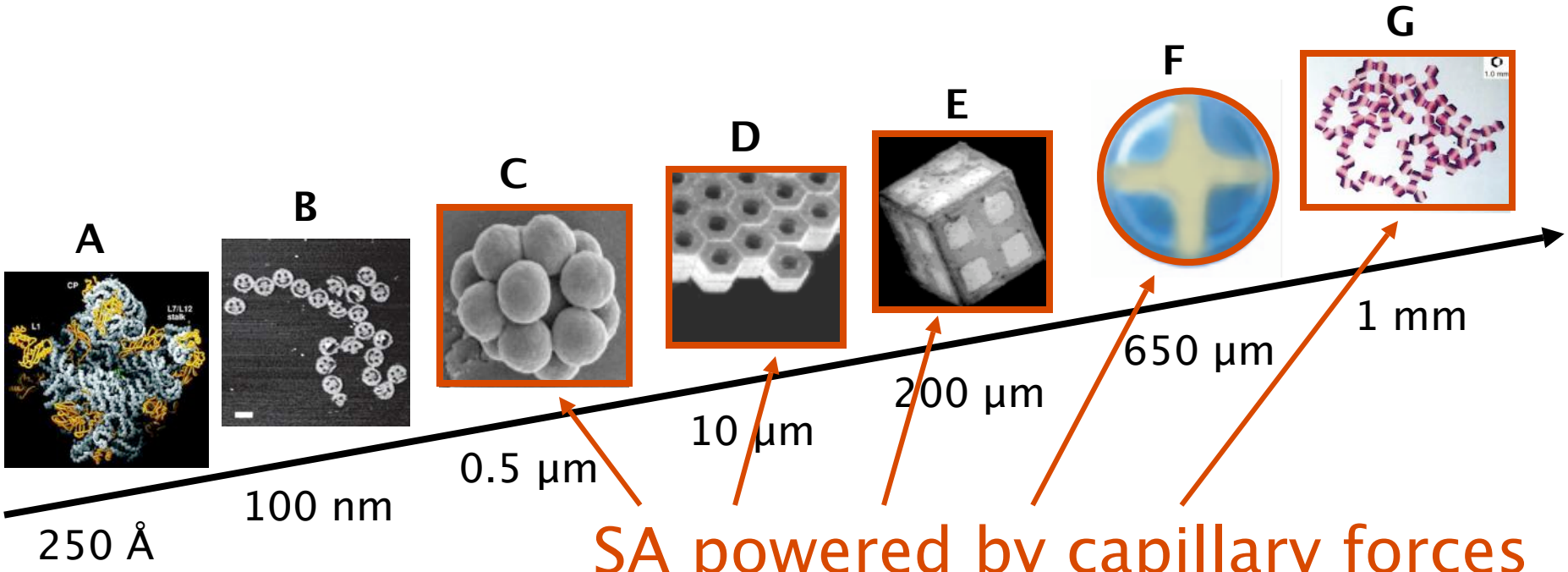

SA powered by capillary forces

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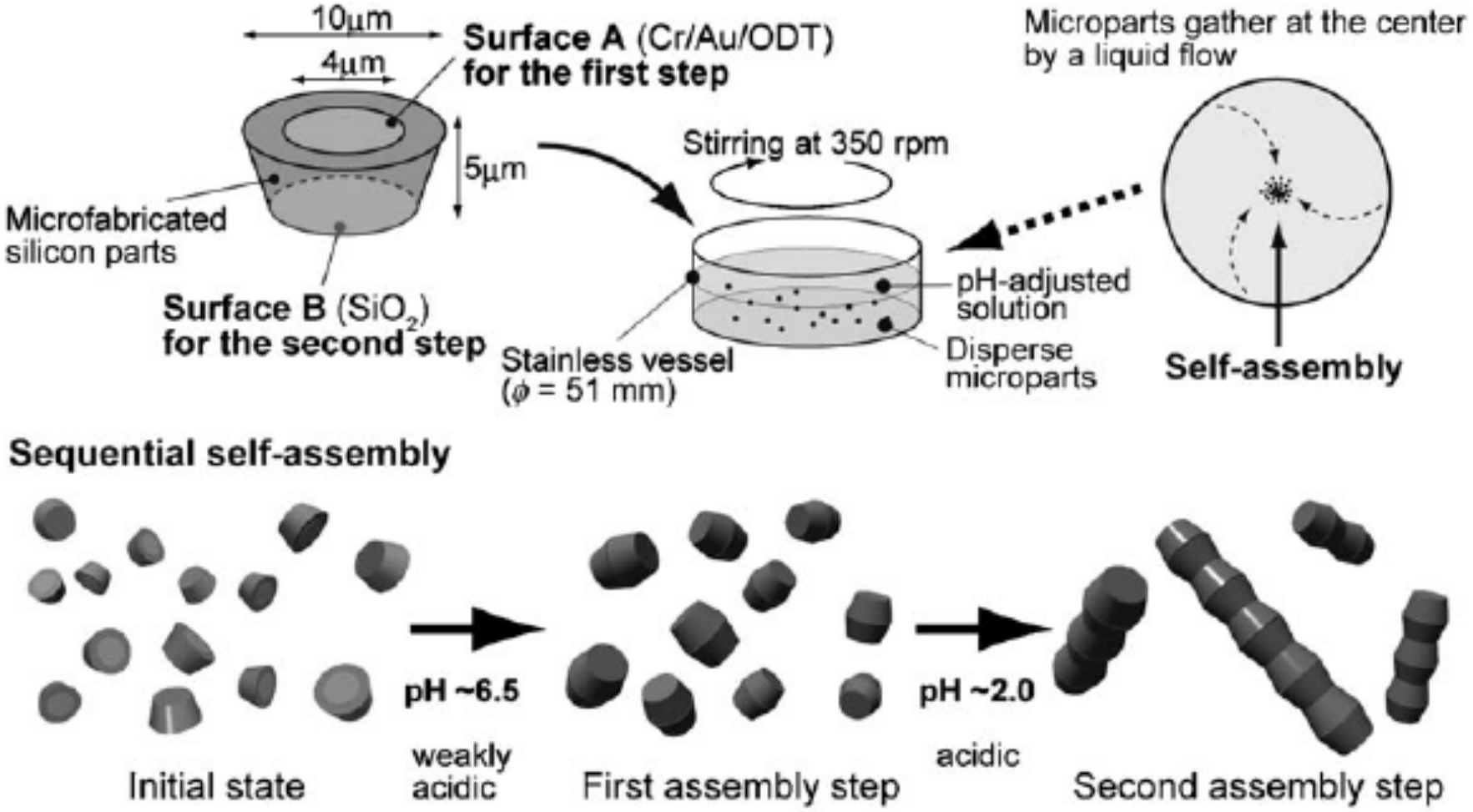
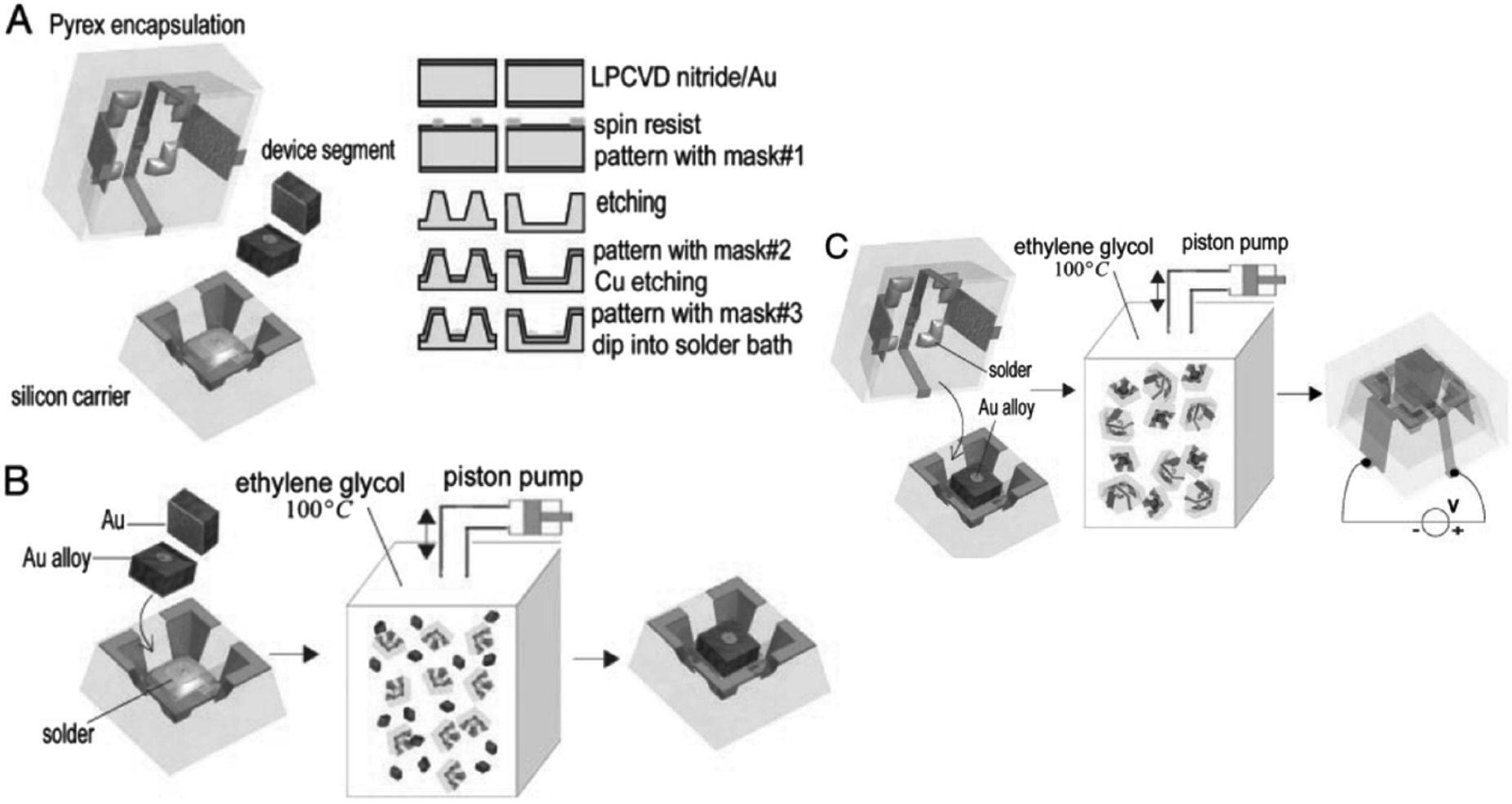
Hydrophobic interaction (part-to-part)



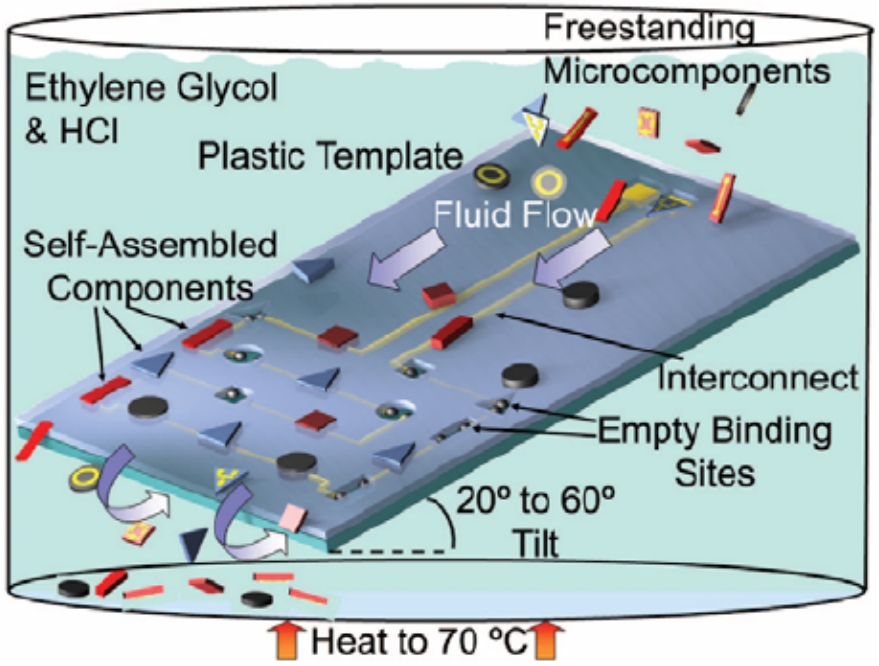
[Onoe et al., 2007]

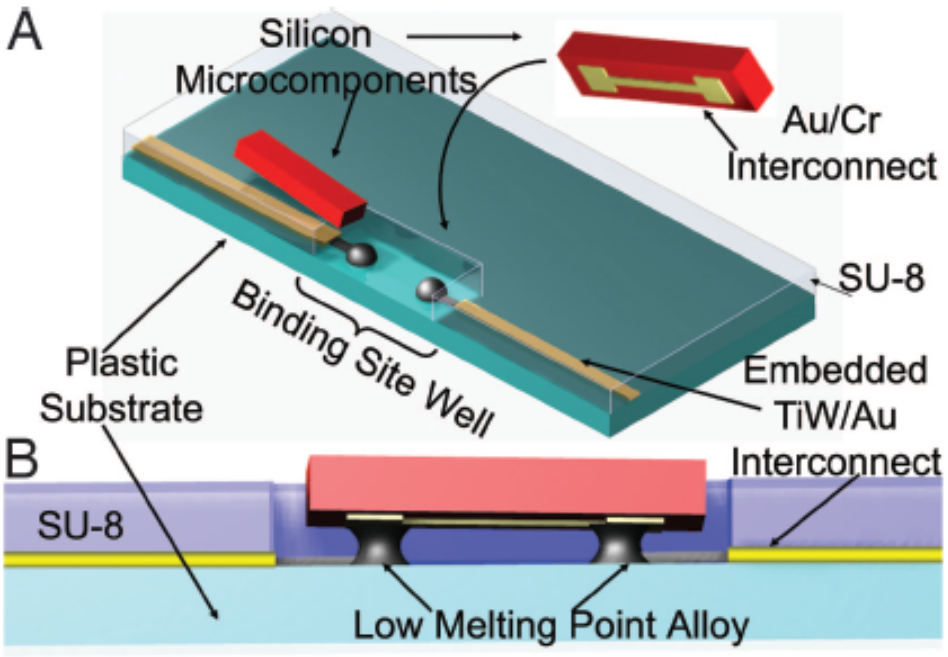
Capillary interaction (part-to-part)



[Zhengh et al., 2004]

Capillary interaction (part-to-





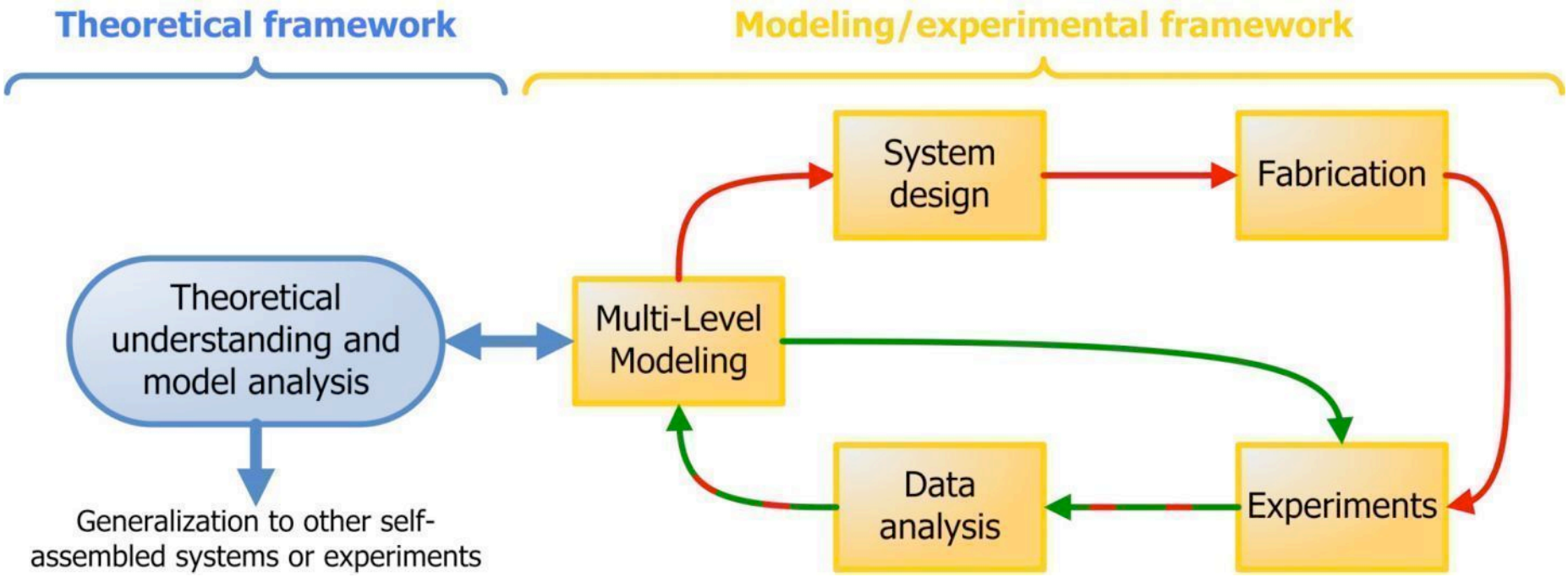
[Stauth and Parviz,

Putting several mechanisms together:

- A dramatic increase in interaction variety (in magnitude, length- and time-scales)
- The apparition of competing interactions (attractive vs repulsive)
- Dynamical steady states resulting from a balance between competing interactions
- Non-linear positive or negative feedbacks resulting from the intricacy of the interaction scheme

These features motivate an efficient and appropriate methodological framework

Methodological framework



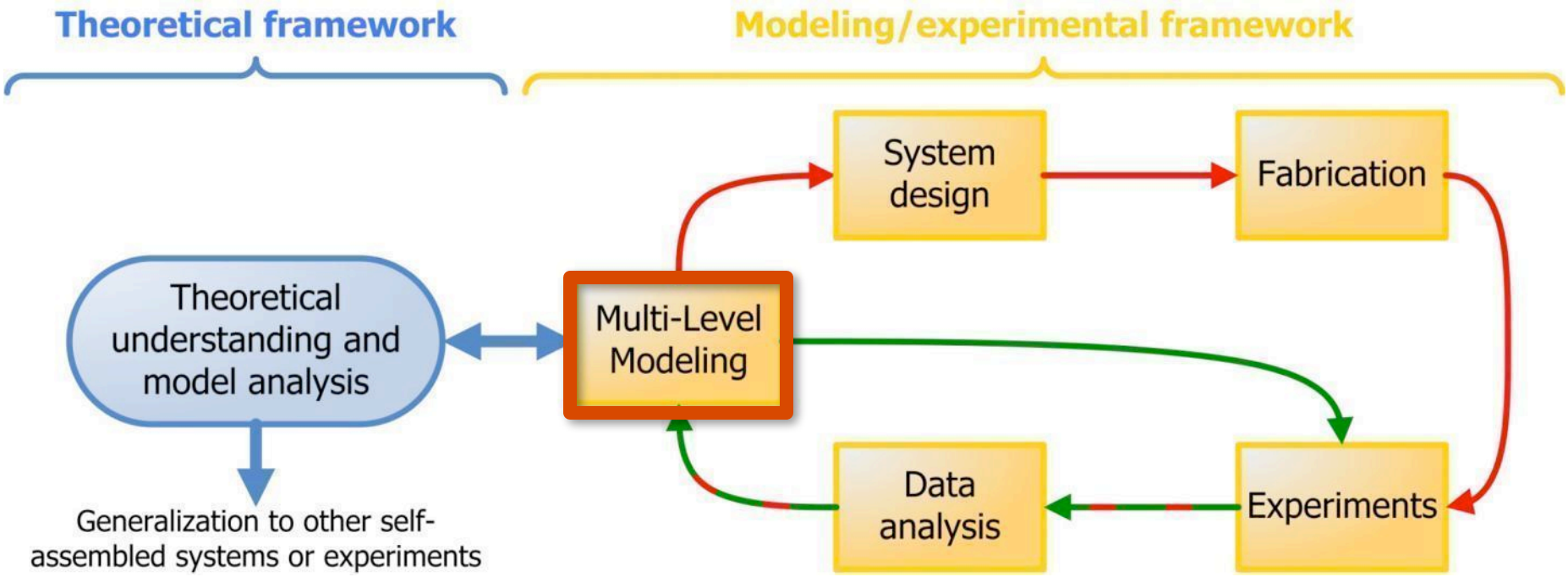
Two ingredients:

- Multi-level modeling
- Experimental work

Two experimental loops:

- Fabrication (slow)
- Modeling (fast)

Methodological framework



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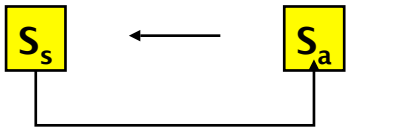
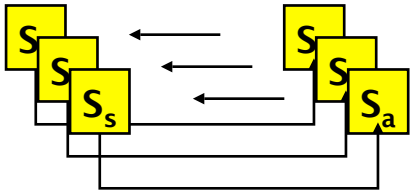
Multi-Level Modeling Methodology

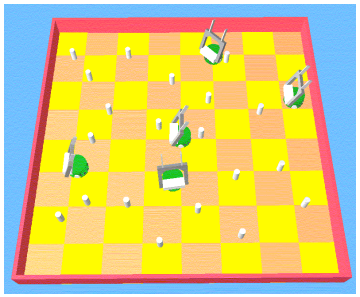
$$\frac{dN_n(t)}{dt} = \sum_{n'} W(n \mid n', t) N'_n(t) - \sum_{n'} W(n' \mid n, t) N_n(t)$$



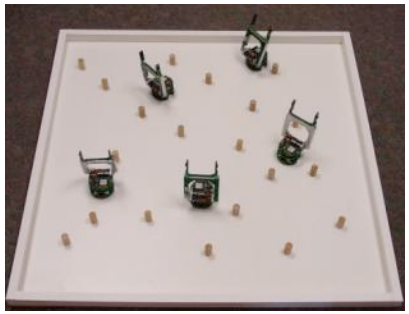
→ Macroscopic: rate equations, mean field approach, whole swarm



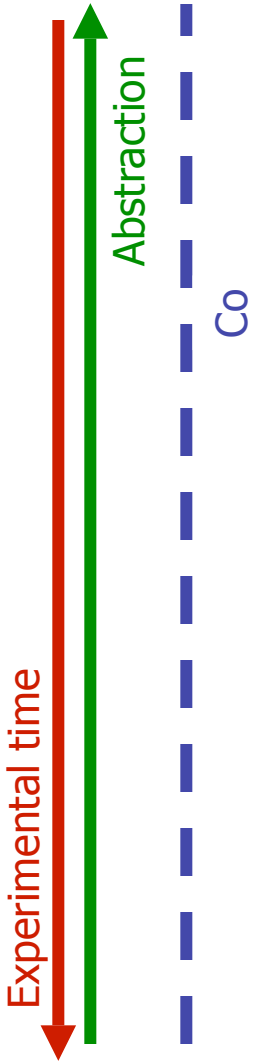
→ Microscopic: multi-agent models, only relevant robot feature captured, 1 agent = 1 robot



→ Realistic: intra-robot (e.g., S&A) and environment (e.g., physics) details reproduced faithfully



→ Physical reality: Info on controller, S&A, morphology and environmental features

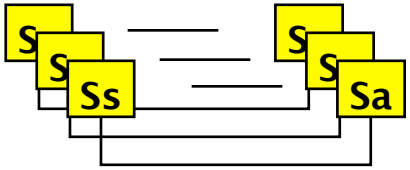


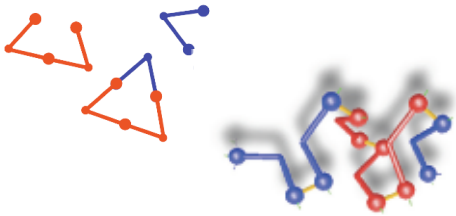
MLMM applied to Supramolecular SA

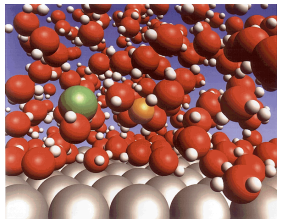
$$AB + A \rightleftharpoons AAB$$

$$K_5 = 3\,K_{AA}K_{AB}^2 = \frac{[AAB]}{[A][A][B]}$$

$$\frac{d[AAA]}{dt} = [AA][A]\,k_{fAA}^2 - [AAA]\,k_{rAA}^2$$







Macroscopic 1: Chemical equilibrium is completely defined by equilibrium constants K of each reaction (law of mass action)

Macroscopic 2: Reactions kinetics describes how a reaction occurs and at which speed (differential equations)

Microscopic 1: Agent-Based model, molecules geometry abstracted, 1 agent = 1 aggregate

Microscopic 2: Agent-Based model, molecules
2D- and 3D geometry captured, 1 agent = 1 aggregate

Physical reality: microscopic (e.g., crystallography) and macroscopic measurements (chemical reaction)

Experimental time

Abstraction

Common metrics

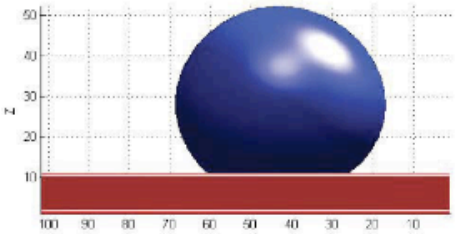
[Mermoud et al., 2007, in preparati

MLMM applied to Droplet Motion

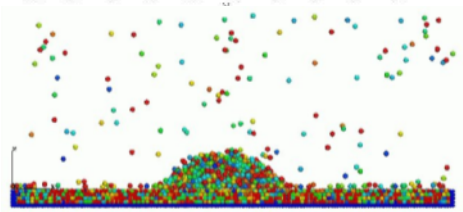
Macroscopic 1: Surface evolver, surface energy minimization by gradient descent, no dynamics

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbb{T} + \mathbf{f}$$

Macroscopic 2: Navier–Stokes equations



Mesoscopic: Lattice Boltzmann Method, particle distribution, discrete velocities and directions



Microscopic: Molecular dynamics, 1 agent = 1 molecule

Physical reality: contact angles measurements, dynamics imaging with high speed camera

Experimental time

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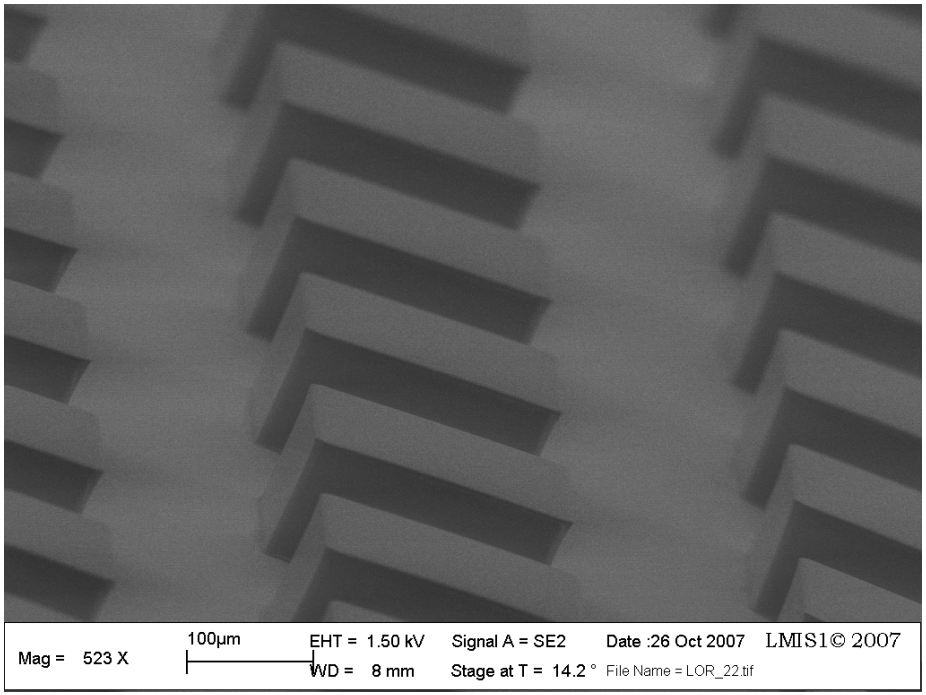
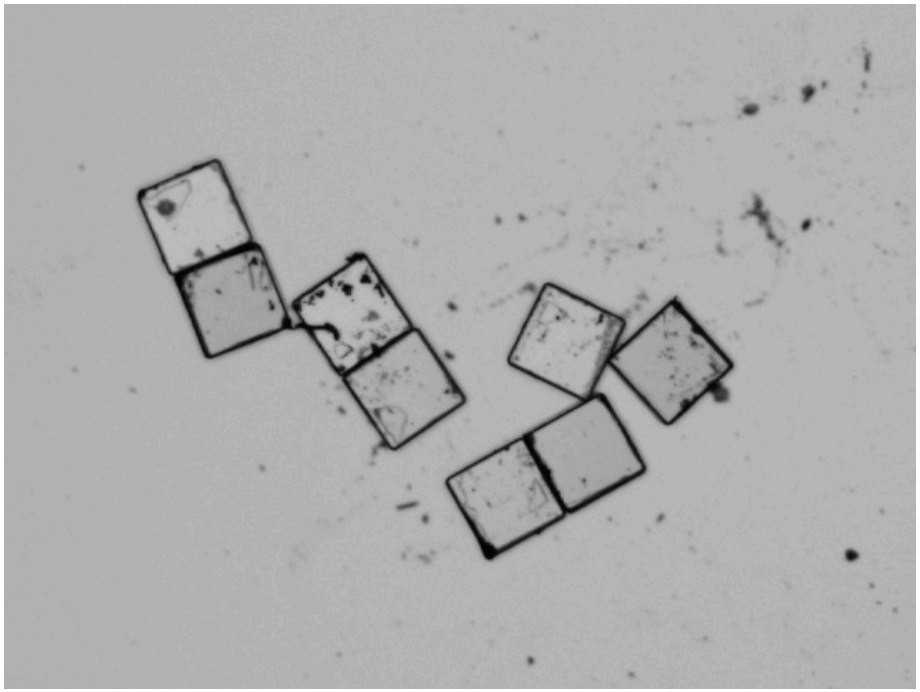
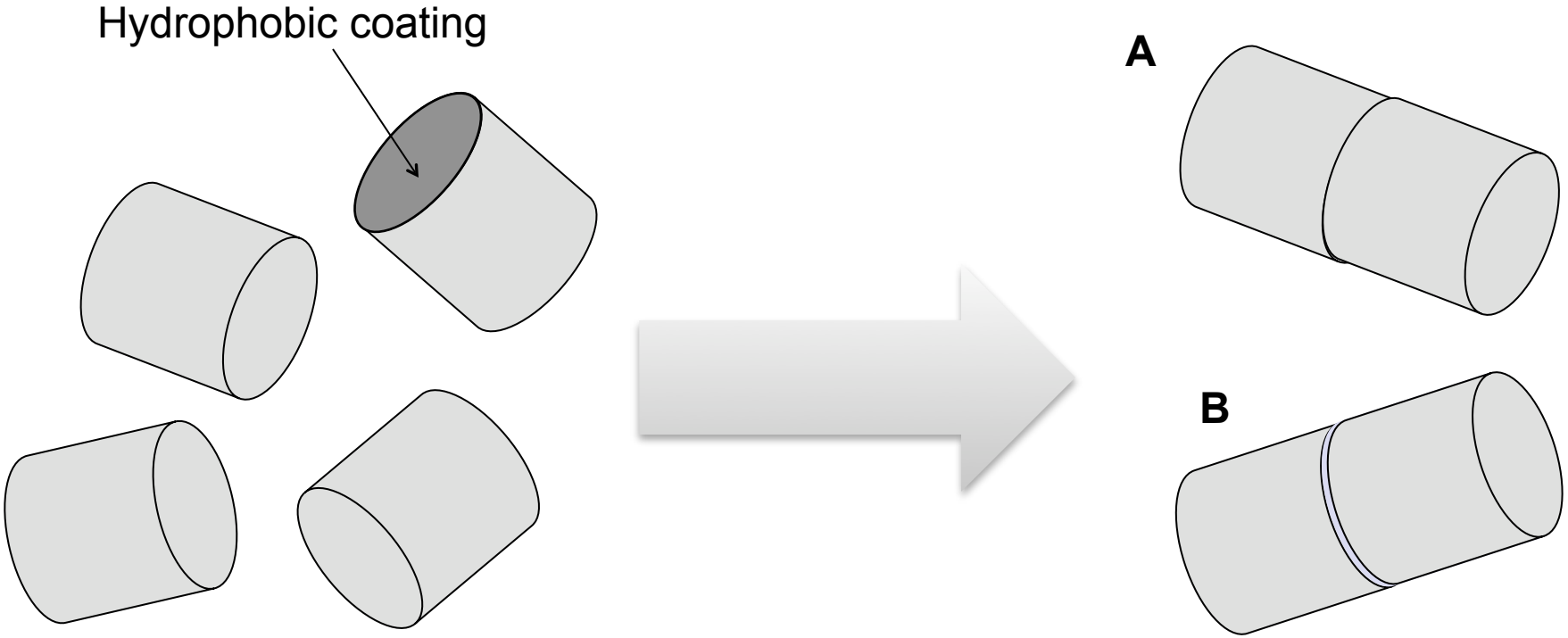
Our preliminary case study





- 200µm-sized SU-8 building blocks
- Fabrication and release is under control
- Next batch: smaller, barrel-shaped building blocks to be assembled into pairs

Our preliminary case study



- Hydrophobic interaction (A) or capillary interaction mediated by an hydrophobic solder (B)
- Same methodology as in robotics: multi-level modeling, imaging (including tracking)