

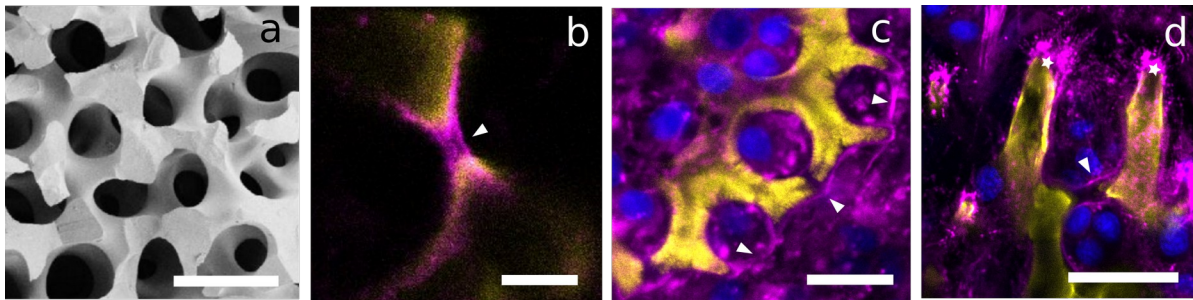
Morphogenesis of the sea urchin skeleton microstructure: the role of the cytoskeleton – *Numerical modelling*

Location: Laboratoire Matière et Systèmes Complexes (MSC), UMR 7057, 75013 Paris

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Context: Echinoderms, like sea urchins and sea stars, build a calcite endoskeleton whose porous microstructure, called **stereom**, bears a characteristic saddle-shaped curvature signature^{1,2} (Fig. **a**), which displays optimal mechanical properties³. Stereom growth has been addressed at different levels^{4–6} and was shown to rely on the progressive addition of small bids of mineral (~100 nm) at the tips of micro-spines, successively branching and looping to form a complex meshwork of much larger characteristic scale (10–50 μm). More recently, it was also proposed that the **cytoskeleton** may guide localized skeletal growth in sea urchin larvae⁷. In a very recent study on sea stars we confirmed that hypothesis and showed that stereom geometry, may be inherited from saddle-shaped **precursors** (Fig. **b**) made of actin fibers that attach to tips of the growing stereom and **self-organize** under tension⁸. Despite these findings, many fundamental questions remain: what is the dynamics of actin fibers? How they attach to the growing stereom? And above all, how pore-size precursors can explain such a strong and coherent curvature signature across the whole structure? We believe that surface curvature is not only an outcome, but also an actor of stereom growth, much like what I have shown for analogous saddle-shaped structures built by termites^{9,10} and coherently with many recent discoveries pointing to surface curvature as a strong biological morphogenetic cue¹¹.



Caption: **a:** sea urchin spine electron micrograph (Yang et al. 2020); **b-d:** Stereom confocal micrographs - freshly added mineral in yellow, actin in magenta, nuclei in blue. White symbols denote actin structures. **b:** close-up on a sea star arm plate (Humanski et al. 2026). **c:** close-up on a sea urchin juvenile shell. **d:** close-up on a regenerating sea urchin adult spine. Scale bars are 50 μm (a) and 10 μm (b,c,d).

Goal of the internship: We will model the stereom growth as a *moving boundary problem* involving two, **coupled**, continuous phases: a mineral hard phase that corresponds to the stereom, and a soft phase that corresponds to actin fibers. The base idea is that the growth of the hard phase is enhanced by the density of the soft phase close to the boundary, while the organization of the soft phase is affected by the geometry of that boundary, for example promoting the nucleation of fiber assemblies.

Practically, actin fibers will be treated as a viscoelastic active gel of variable density starting from a simplified 2D model¹². In particular we will couple boundary conditions of the actin field with the stereom geometry, for example enforcing higher actin density in region of higher curvature (Fig.d, stars). Complementarily, stereom growth will obey a modified DLA particle attaching algorithm¹³ where attaching probability is proportional to the local actin density which will promote stereom bridging within actin templates (Fig.b-d, triangles). Model predictions will be compared with experimental observations of stereom growth in sea urchins (Fig. c,d) performed by the same research team. This project is highly **interdisciplinary** and the candidate will interact with different scientific profiles spanning from Physics to Biology.

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