Curvature-growth interplay in the Morphogenesis of skeleton microstructures: Diatoms, sea Urchins & Butterflies

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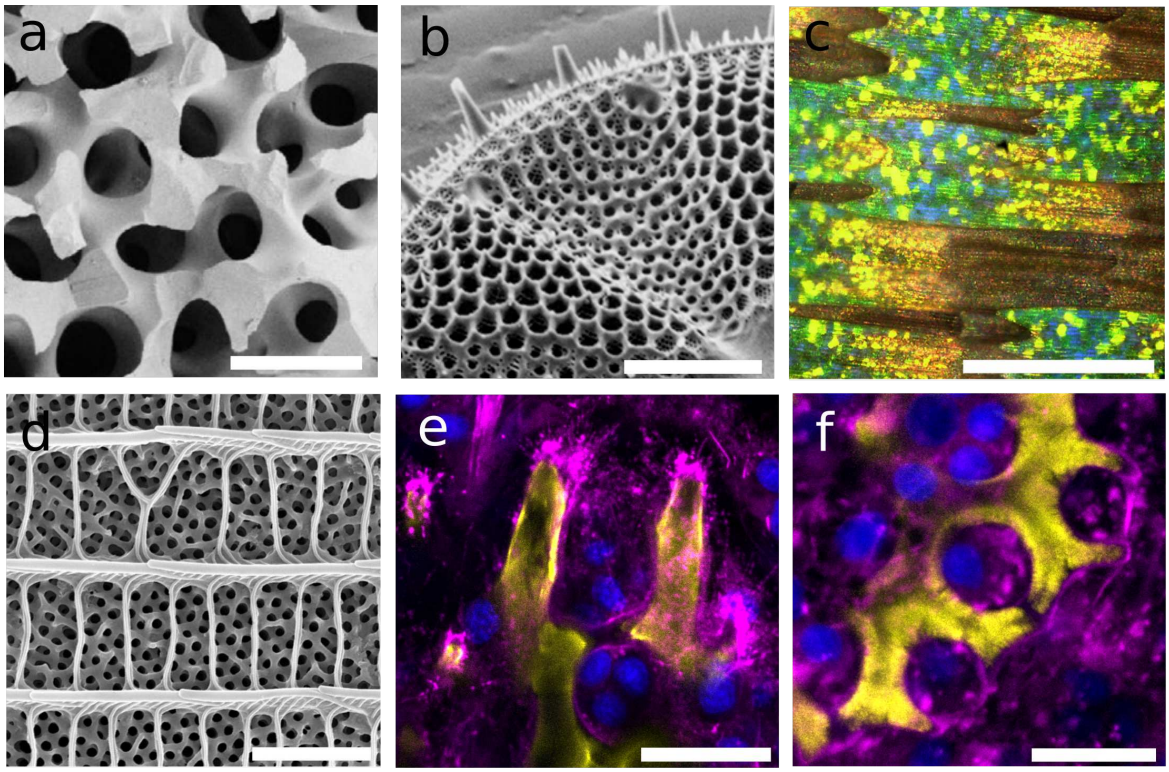
The context: Echinoderms, like sea urchins and sea stars, and sea cucumbers build a calcite skeleton whose porous microstructure, called *stereom*, bears a characteristic saddle-shaped curvature signature[1] (Fig. **a**), close to a gyroid minimal surface. At a much smaller scale, diatoms also produce silica shells (frustules), species-specific saddle-shaped porous architectures, while being in detail very variable (Fig. **b**). Around the same scale, butterfly scales made of chitin can show iridescent colours, and some iridescent spots, each spot corresponding to a local gyroid like structure[2] (fig. **c**, **d**).
Stereom growth has been addressed at different levels[3,4]and was shown to rely on the addition of small bids of mineral (~100 nm) at the tips of micro-spines, successively branching and looping to form a complex Nevertheless, the question of how preferential bio-mineral deposition is organised to produce such a coherent, peculiar geometry remains unsolved since solid deposition models would create only trees without reconnections. Frustule growth remains mysterious, even if a handful of models were proposed. Formation of gyroids as in the butterfly scales may be guided by membrane structures[5] following the minimization of interface energy, but the experimental evidence of such a growth is scarce. Interestingly, recent studies point to a role played by the cytoskeleton in templating and guiding the formation of these hard structures, respectively in echinodemr stereom[6–8], diatoms frustules[9] and butterflies scales[10]. Despite these findings, **many fundamental questions remain**: how and when does branching and looping events take place? Why the final structure bears such a peculiar saddle-shaped geometry? Do stereom, frustule and scale growth rely on a simple and robust self-organized mechanism?



a *: sea urchin spine electron micrograph (Yang et al. 2020);* **b** **:** *electron micrograph of Actinoptychus senarius* ***c,d:*** *Scales of Callophrys rubi.* ***c :*** *Light micrographs reflecting the poly-crystalline nature of the crystallites with different orientation of the Gyroid structure.* ***d :*** *Electron micrograph of the gyroid structure under the scale grid (B, scale bar 2 µm) (Saba et al. 2014)* ***e,f*** *: confocal micrograph of sea urchin stereom in a regenerating adult spine (**e**) and a juvenile shell (**f**) : nuclei in blue, freshly grown stereom in yellow, actin in magenta; Scale bars are 100 µm (a,c), 10 µm (b,e,f), and 2 µm. (MSC lab)*

The internship: We will study the emergence of peculiar geometries in frustules, sea urchin stereom and butterfly scales and model their growth, taking inspiration in our previous work on termite nests[11], and coherently with many recent discoveries pointing to curvature as a strong biological morphogenetic cue[12] The biological cues are not repatterning, but the intervention of another group of biological molecules that can self-organize and direct the growth of the skeleton. In particular we will investigate the role of the actin cytoskeleton, and test the hypothesis that its spatial self-organisation (i) depends on the shape of the pre-existing skeleton and (ii) determine the shape of the skeleton that is built.

To this aim the candidate will **build a minimal numerical model** able to imitate the saddle-shaped geometry of frustules (Fig. **b**) stereom (Fig. **a**) butterfly scales (fig. **d**) starting from very simple interaction rules. As a first model, we will use a mean field approach where a continuous field that mimic the transport and organization of the organic fibres interacts with a growing hard boundary. The model can then be adapted to the specific case of sea urchin stereom comparing the model predictions with the experimental observations performed in our lab (Fig. **e** and **f**) both in wild types and specimen where the cytoskeleton has been perturbed with pharmacological treatments.

This is a **highly interdisciplinary** project and the candidate will interact with different scientific profiles spanning from Physics to Biology. This is a **theoretical/numerical internship** but according to the skills, curiosity, and motivations of the candidate, the internship may be also oriented toward data analysis or experiments (see also, related experimental internship on sea urchins).

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