Internship offer : Modeling Emergence of Oscillating Motions during Plant Growth

Context: Nutation is the phenomenon that causes the orientation of the long axis of an elongated growing plant to vary over time in a pseudo-periodical way. It was already observed for climbing plants by British botanists of the 17th century [1] and began to be studied by Hugo von Mohl and Ludwig Palm in the first part of the 19th century [2]. To the best of our knowledge, the term "nutation" was first mentioned by Charles Bonnet [3] although he acknowledges that this term had been named before him, by physicists who knew the phenomenon. They probably saw this motion as a botanical analog to the astronomical nutation. Darwin later introduced the idea that nutation had an endogenous origin and many plant motions were actually modified nutations [4]. The very origin of nutation was a source of debate at the time nonetheless [2], and it remains so up to this date [5, 6, 7].

Recently, Mathieu Rivière and collaborators [8] extensively studied the nutation in the plant *Averrhoa carambola*, which is a good model to study nutation because the leaves display very ample oscillations. See for example figure 1 or online supplemental videos (on a raw plant or on a fluorescent painted plant). They showed that the nutation motion originates from curvature changes in a small region, located at the basis of the growing zone. Interestingly, significant differences of elastic Young's modulus between the inner and outer faces were measured, leading to the hypothesis that the curvature changes are associated with differential growth rates between the two faces.

Objective: The goal of this internship is to propose a mechanistic model of the leaf where the growth is triggered by a decrease of the Young's modulus value, and where this decrease is itself triggered by the presence of auxin, an important morphogen in plants, above a threshold value. As auxin diffuses from the apex and decreases along the leaf, this would define the end of the growing region. Then, the oscillations would emerge from an inhomogeneous distribution of auxin in the end of the growing region.

Project: A possible outline of the work will be:

1. Integrate the biological ingredients described above into a 1D model (Fig. 1c): The geometry (curvature) influences the auxin distribution between concave and convex side because auxin is assumed to be transported from apex. Auxin changes imply (possibly dynamical) changes of elastic behaviour. Changes of elasticity affect growth via the Lockhart equation[9]. Finally, growth will change geometry and this will create the oscillation.
2. Derive a clean formalism: the phenomenon is happening in the eulerian frame related to the base, but it will be convenient to rewrite everything in the moving frame at constant distance from apex.
3. Analyse the limit cases of the analytical model.
4. Explore numerically the model and compare with experiments.

Skills: We are looking for a highly motivated student looking forward to manipulate equations and perform simple numerical simulations.

Environment: The successful applicant will be supervised by Ibrahim Cheddadi and Julien Derr, both members of the Mosaic group (RDP lab at ENS de Lyon). The RDP lab is internationnaly reknown for plant science. The student will benefit from the very inter-disciplinary athmosphere in the Mosaic group.

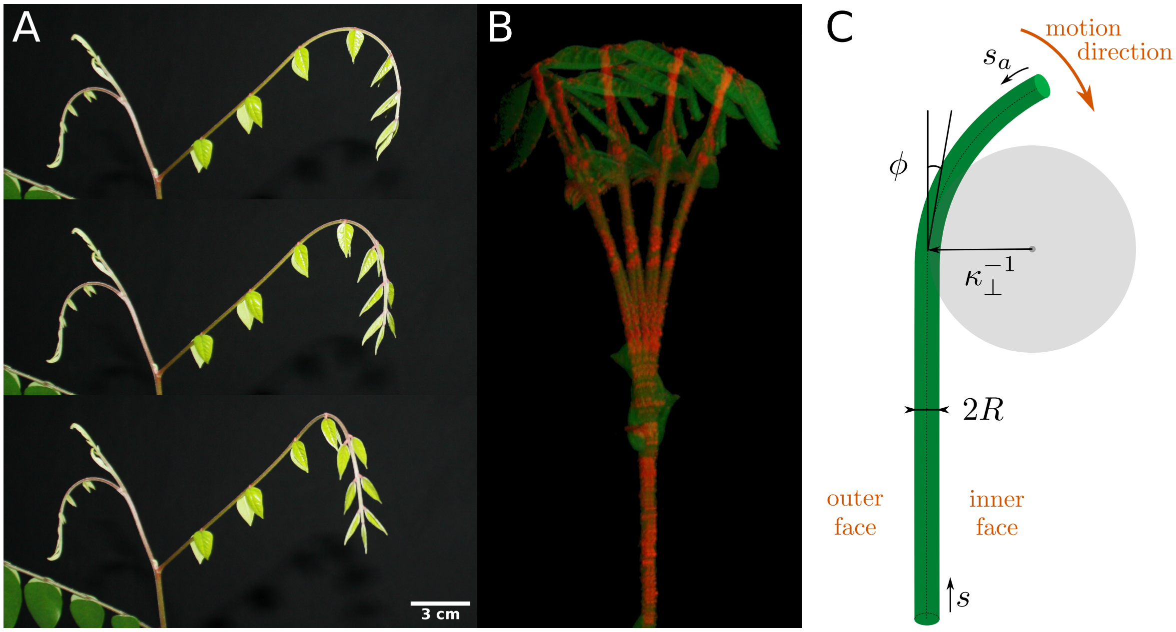

Figure 1: Time-lapse image of the nutation of a *Averrhoa carambola* leaf. **(A)** (side view). 30 minutes lapsed between each picture. One can see, from top to bottom, the hook coming out of the plane towards the observer **(B)** (top view). Eight superposed pictures taken every 15 min (the period of the motion is generally comprised between 1.5 and 4 hours). The leaf oscillates in a pendulum-like fashion, orthogonal to its growth axis, and superposing itself along the oscillation. At the end of one period the extension of the leaf is visible **(C)** Geometrical parameters describing the rachis and nutation.

Starting date: (Flexible)

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References

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[3] Charles Bonnet. *Recherches sur l'usage des feuilles dans les plantes: et sur quelques autres sujets relatifs à l'histoire de la vegetation.* chez Elie Luzac, fils, 1754.

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[5] Allan H Brown. "Circumnutations: from Darwin to space flights." In: *Plant Physiology* 101.2 (1993), p. 345.

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[9] James A Lockhart. "An analysis of irreversible plant cell elongation". In: *Journal of theoretical biology* 8.2 (1965), pp. 264–275.