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Félix Hartmann, Mélanie Decourteix, Bruno Moulia. The role of curvature and (de)curving in plant acclimation and tropisms. CurvoBio 2024, EuroCurvoBioNet (COST action CA22153), Aug 2024, Warsaw, Poland. <hal-04782429>

HAL Id: hal-04782429

<https://hal.science/hal-04782429v1>

Submitted on 14 Nov 2024

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The role of curvature and (de)curving in plant acclimation and tropisms

Félix Hartmann, Mélanie Decourteix, Bruno Moulia

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28th August 2024
CurvoBio2024, Warsaw



initially straight horizontal stem



slight sagging under self weight



curving upward

uniformly curved zone

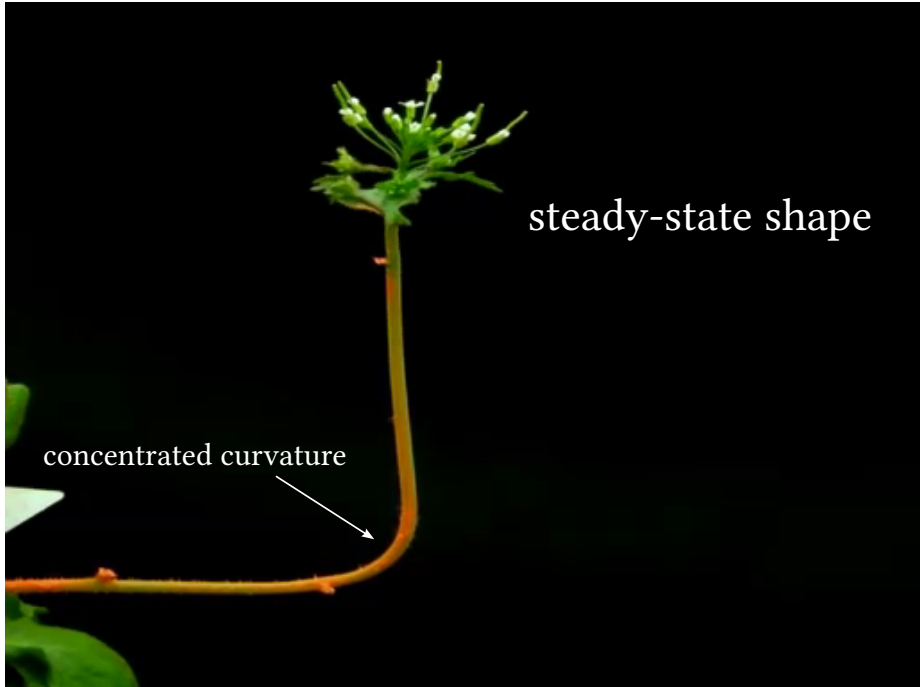


overshooting the vertical



decurving



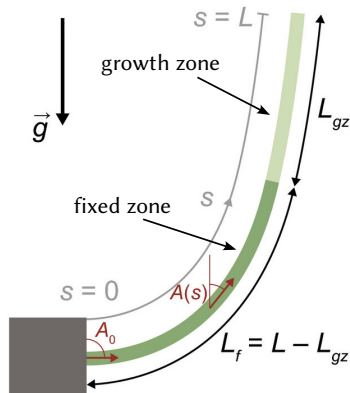


steady-state shape

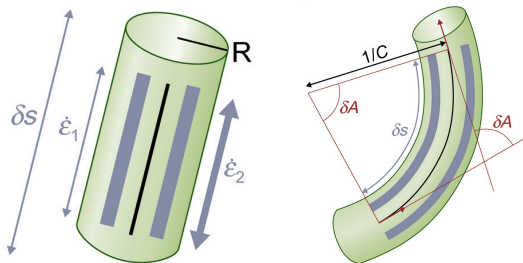
concentrated curvature

Growth and differential growth behind stem curving

s : spatial coordinate along the stem



Curving and decurving occur only in the growth zone of the stem.



Curvature changes when one side grows faster than the opposite one:

$$\dot{\epsilon}_2 > \dot{\epsilon}_1$$

$$\frac{dC(s, t)}{dt} = \frac{\dot{\epsilon}_2 - \dot{\epsilon}_1}{2R}$$

from Moulia et al. (2022) *New Phytol*

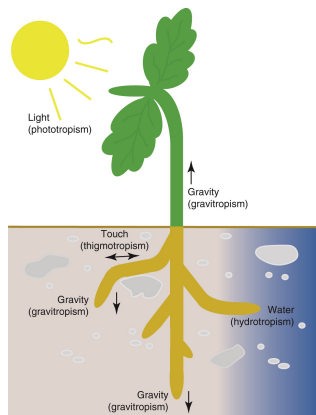
What is driving differential growth and, ultimately, curving?

Curving enables tropic movements in response to environmental stimuli.

Plant tropisms include

- gravitropism (positive in roots and negative in shoots);
- phototropism;
- hydrotropism (in roots);
- chemotropism (in roots);
- thigmotropism (response to touch);
- ...

from Gilroy (2008) *Curr Biol*



Current Biology

Stimuli are sensed and integrated into a unified tropic response:

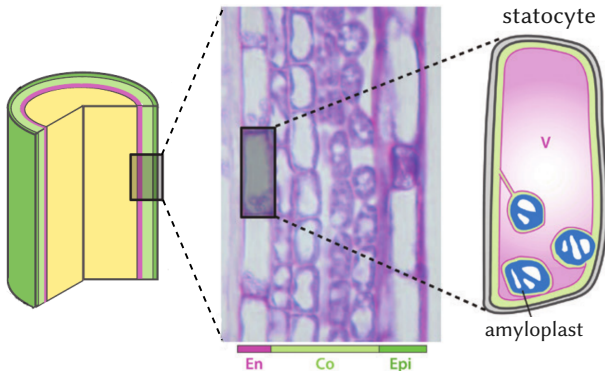
$$\frac{dC(s, t)}{dt} = f(\text{gravity, light, water gradient, chemical gradients, } \dots)$$

Sensing the orientation with respect to gravity

Statocytes and amyloplasts

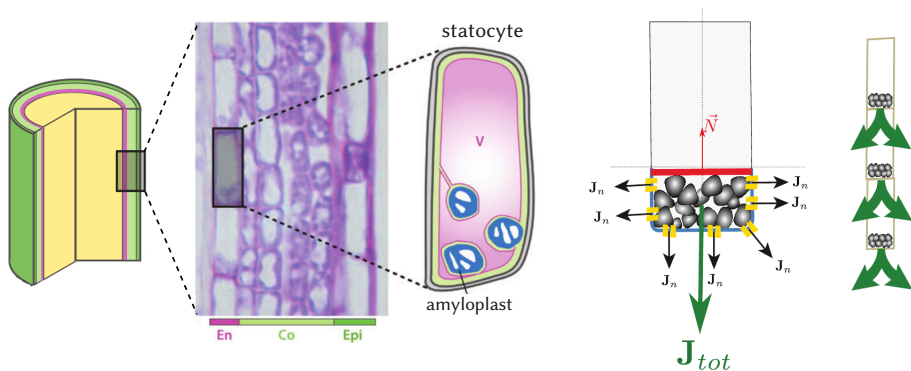
Statocytes are cells in the endodermis which contain starch-filled plastids called *amyloplasts*.

Amyloplasts tend to avalanche to the bottom of statocytes.



from Morita (2010) *Ann Rev Plant Biol*

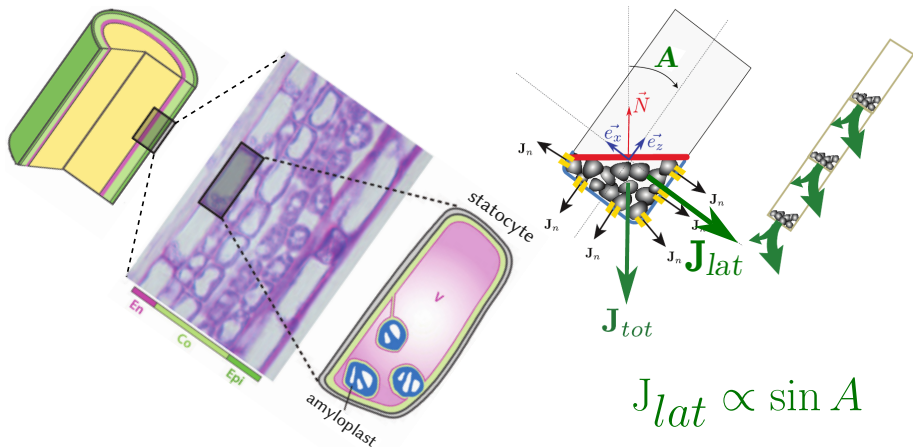
Amyloplasts direct the flux of the growth hormone auxin



The amyloplasts relocalize auxin transporters, which redirect the flux of auxin.

Amyloplasts direct the flux of the growth hormone auxin

When the stem is tilted, the amyloplasts flow to one side of the cell and induce a net lateral flux of auxin.



The lateral auxin gradient causes differential growth.

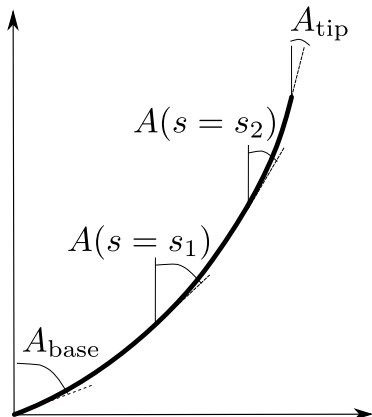
from Pouliquen et al. (2017) *Physical Biology*

Simple model of gravitropic response

The auxin gradient across the stem is assumed proportional to the sine of the inclination angle. This is matched by the curving rate:

$$\frac{dC(s, t)}{dt} = -\beta \sin A(s, t)$$

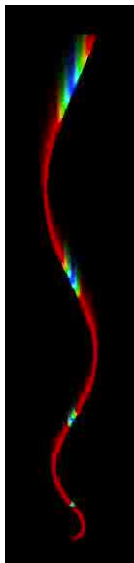
- β : gravitropic sensitivity (in $\text{m}^{-1} \text{s}^{-1}$)
- $A(s, t)$ inclination angle at position s and time t



s : position along the stem

Simulation of the simple gravitropic model

Simulation of the simple gravitropic model



The simulated stem oscillates indefinitely, never reaching a steady-state shape.

⇒ A **stabilizing feedback** is needed to converge toward a steady-state shape.

Proprioception as a stabilizing feedback

The plant proprioception hypothesis

Plants are endowed with the ability to sense their own local curvature, and to respond to it.

Gravi-proprioceptive model:

$$\frac{dC(s, t)}{dt} = - \underbrace{\beta \sin A(s, t)}_{\text{gravitropic drive}} - \underbrace{\gamma C(s, t)}_{\text{proprioceptive drive}}$$

γ : proprioceptive sensitivity (in s^{-1})

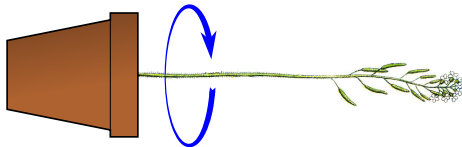
Bastien et al. (2013) *PNAS*, Moulia et al. (2021) *Science*

Simulation of the gravi-proprioceptive model

How can we demonstrate proprioception experimentally?

Clinostat

A clinostat is a device used to rotate a plant around an horizontal axis and suppress gravity sensing.

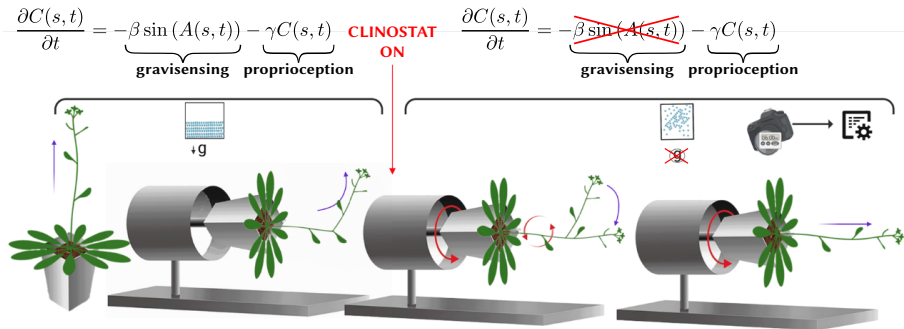


The rotation keeps the amyloplasts in suspension.

artificial system mimicking the motion of amyloplasts in a clinostat \implies

A clinostat in action

A typical proprioception experiment



TILT

bending up
under gravitropic drive

decurving / straightening
under pure proprioceptive drive

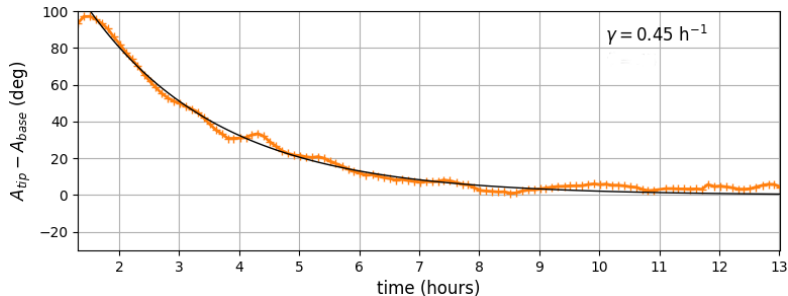
schematics by Kinza Khan

Timelapse imaging

Estimating γ during the decurving/straightening phase

$$\frac{dC(s, t)}{dt} = -\gamma C(s, t) \quad \Longrightarrow \quad A_{\text{tip}}(t) - A_{\text{base}} = A_0 e^{-\gamma t}$$

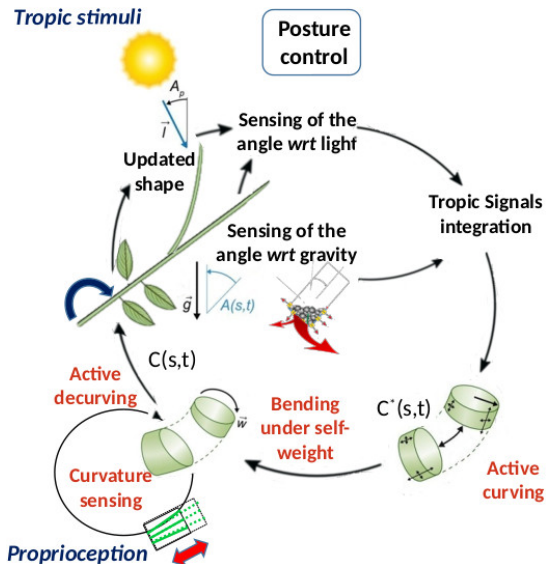
Exponential fit on $A_{\text{tip}} - A_{\text{base}}$:



Semi-automatic estimation with the Interekt software
(Hartmann et al., 2022).



Plant posture control as a curvature-based feedback loop



from Hartmann, Decourteix and Moulia (2024) *Current Biology*

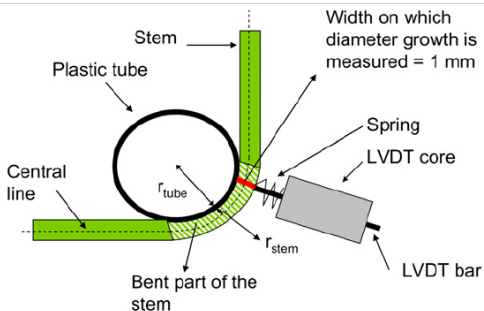
Transient curvature changes caused by external actions



Reed culms bending under the wind.

- Transient bending stimuli are filtered out from proprioception.
- They do not lead to tropic responses in terms of $\frac{dC}{dt}$.
- But they do elicit growth responses.

Controlled bending stimuli on plant stems

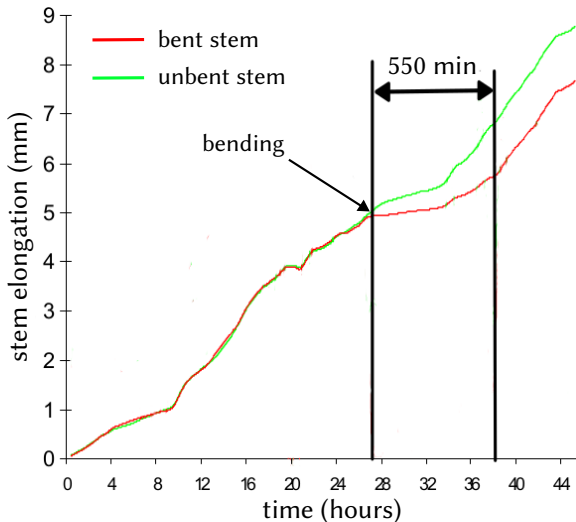


- A bending stimulus with a given curvature can be automatically applied during a few seconds.
- Stem growth is continuously measured.

from Coutand et al. (2009) *Plant Physiology*

Effect of bending treatment on stem elongation

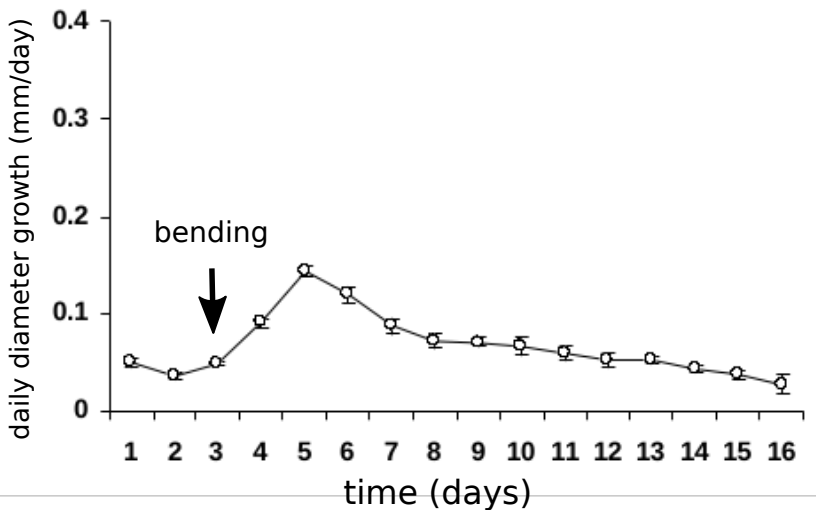
Stem bending transiently inhibits elongation in tomato.



from Coutand et al. (2000) *J Exp Bot*

Effect of bending treatment on stem diameter growth

Stem bending transiently promotes diameter growth in young poplars.



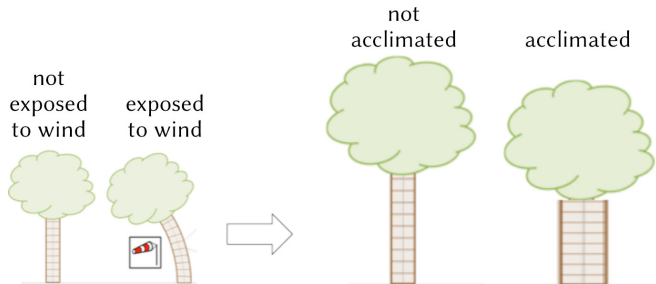
from Martin et al. (2010) *J Exp Bot*

Thigmomorphogenesis

A developmental process leading to acclimation

Definition

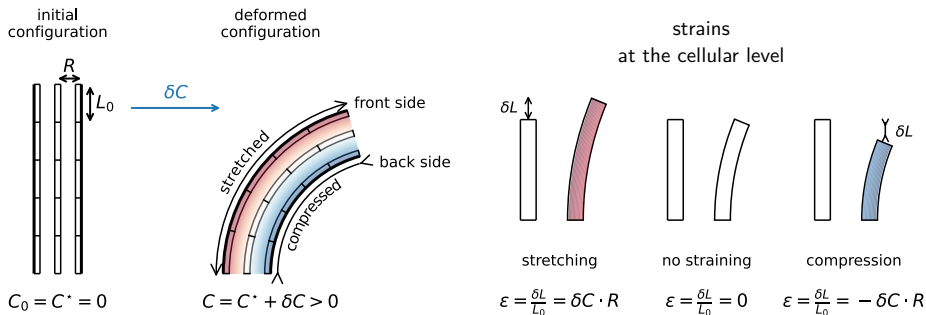
Thigmomorphogenesis refers to all the growth responses of a plant which has sensed transient mechanical stimuli (wind, weight of the snow, animals, ...).



As a result of thigmomorphogenesis, plants get acclimated to their mechanical environment, *i.e.* are more resistant to uprooting and stem breakage.

Stem bending and strains (mechanical deformations)

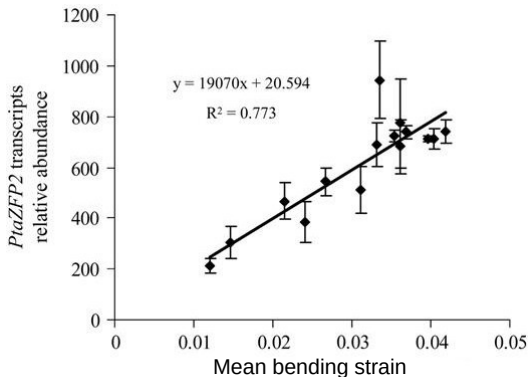
Bending a stem induces mechanical deformations (strains) in the tissues.
Some cells are stretched, others are compressed.



from Hartmann, Decourteix and Moulia (2024) *Current Biology*

Linear relationship between strain and gene expression

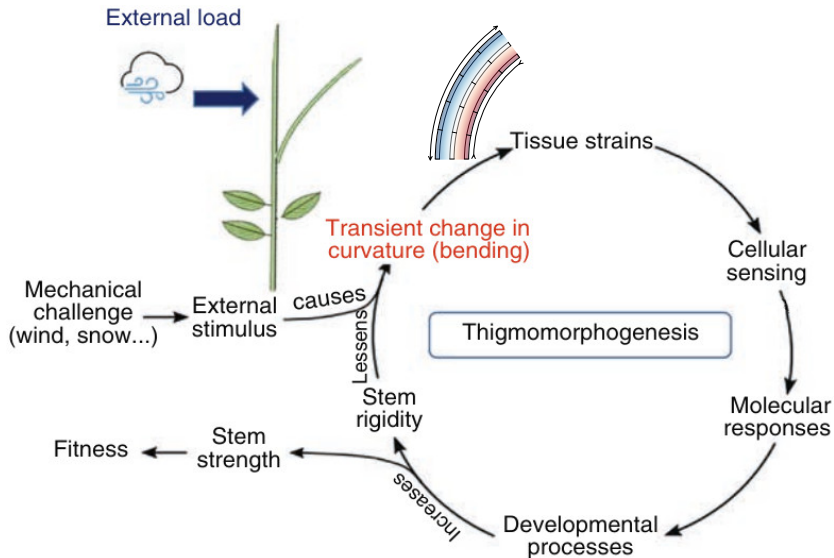
The expression level of the transcription factor *Zinc Finger Protein 2* (ZFP2) is proportional to the magnitude of tissue strains.



from Coutand et al. (2009) *Plant Physiology*

More than 2,000 genes are regulated in poplar after a bending stimulus (Pomiès et al., 2017, *BMC Genomics*).

Thigmomorphogenesis as a developmental feedback loop



from Hartmann, Decourteix and Moulia (2024) *Current Biology*

Two extras

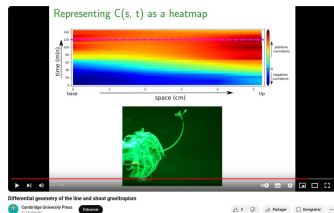
Interekt, a user-friendly software for tracking plant motions and measuring plant curvatures:



<https://forgemia.inra.fr/felix.hartmann/interekt>

<https://youtu.be/kIBaJqnDovE>

An educational Youtube video on plant curvatures and tropisms:



Thank you for your attention!

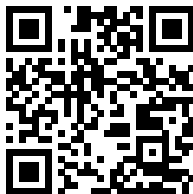
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- Nicole Brunel-Michac
- Valérie Legué
- Éric Badel
- Jérôme Franchel
- Kinza Khan (PhD student)
- Hugo Chauvet (former member)

External collaborators:

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- Julia Davies (Cambridge U.)
- Gary Stacey (Missouri U.)
- Jana Dlouhà and Thiéry Constant (INRAE, Nancy)
- Olivier Pouliquen, Yoël Forterre and Christophe Eloy (Aix-Marseille U.)

And don't miss our easy-to-read
Primer on *Curvatures in plants*:
<https://doi.org/10.1016/j.cub.2024.07.006>



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