REBE FERALDI: FBS PATH TEMPLATE: Tool for analyzing the way the natural model works

Natural model: *Mimosa pudica*, commonly referred to as the "Shy Plant," "Touch-me-not," or "Sensitivity Plant"

Function(s)

What effect do the behaviors create?

Leaf folding to ~ 90^{o} reduces leaf surface area

Leaf returned to initial 0^{o} - plane & maximum surface area

Seismonastic movement = bending of leaves from rectangular → fan-shaped via rapid (i.e., 1-2 s) folding and slow (1-2 min) return manages surface area of leaves after mechanical stimulation

Image Source: *Mimosa pudica* at: Reddit/gifs,

Behavior(s)

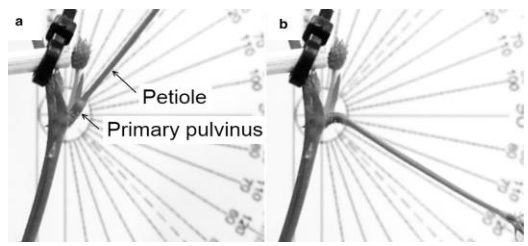
What action does the structure facilitate?

Decreasing petiole weight support → <100% → Leaf folding to ~ 90^{o} reduces leaf surface area

Decreasing petiole weight support → =100% → Leaf returned to initial 0^{o} - plane & maximum surface area

Decreasing petiole weight support (+ / -) Pulvinus turgor decreases

Pulvinus turgor decreases (+ / -) Pulvinus membrane Ion-channels opening



Primary pulvinus deformation from a) original to b) final position.

Image from Kwan et al. 2013

Pulvinar cell water redistribution theorized mechanism:

- Mechanically stimulated actuation triggers streaming potential & electrical current induced by electrolytic solution flow under capillary pressure differential; activates fast water transport across membrane through aquaporins
- Volumetric strain inside motor cells a function of [K+] and [Cl-] ion and water fluxes; diffusive coefficient for ion flows increases by < 15 times
- Pulvini swell on flexor side by ~ 7-17% as water enters and shrink by 20-38% on extensor side as water leaves

Structure(s)

What are the relevant components or physical elements that make up your natural model?

Pulvini

Primary, secondary, & tertiary **pulvini** connections at the stem-petiole, petiole-pinna, and pinna-pinnule, respectively

- Cellular-level sized motor organs
- Approximately spherical with isotropic elastic wall, membrane, and intracellular space
- Elastic modulus of the cell wall E[Pa] is 1^4 to 1^8
- Membrane has corrugations on surface to allow for expansion/contraction and water channels (aquaporins) for hydraulic conductivity
- Intracellular fluid has [K+] and [Cl-] ion and water
- Before stimulation, [K+] and [Cl-] are largely extracellular by an order of magnitude, i.e., salt gradient potential

Petiole — Leaf

Petiole — Pulvini

Pulvini — Stem

Pulvini — Pulvinus Membrane Ion-Channel Activation Structure (?)

Pulvinus Membrane Ion-Channel Activation Structure (?) → Pulvinus membrane Ion-channels opening

- Electrical double layer at boundary between cell wall and electrolytic liquid
- K+ and Cl- voltage-gated ion channels act as electrical starter of osmotic motor in pulvinus

TEMPLATE TO PROGRESS FROM BIOLOGY TO DESIGN WITH FBS PATH OUTCOMES

Biology

Strategy

A high level description of how the natural model is achieving the desired function/effect. Generally follows the formula: (Natural model name) uses (structure) in order to (behavior) resulting in (function). It is critical that it follows the logic of structure leading to behaviour which leads to function.

The *Mimosa pudica* has pulvini motor cell junctures between stem and leaf plant sections that swell and shrink osmotically on their flexor and extensor sides in response to mechanical stimulation in order to bend its leaves from and to their original plane to manage leaf surface area as a protective mechanism.

Mechanism

A detailed description of how the natural model is achieving the desired function/effect. Follows same general formula as above, but also includes critical descriptors, such as scale and time. As such, may include two or more sentences in order to generate a cohesive description.

The *Mimosa pudica* uses pulvini, cellular-level sized motor organs, at junctures between the stem-petiole, petiole-pinna, and pinna-pinnule to decrease or increase weight support of the plant section at the juncture and bend 90 degrees from and back to the initial leaf plane after mechanical stimulation. The pulvini are approximately spherical and have isotropic elastic walls; a bi-layer membrane with an elastic modulus between 1x104 and 1x108 and water channels, i.e., aquaporins; corrugations on the membrane surface to allow for expansion and contraction; and intracellular space with a potassium saltwater fluid. It is theorized that mechanical stimulation of the plant activates a bidirectional electrical potential difference both laterally and vertically (i.e., perpendicular to the stem's vascular bundles), which causes a redistribution of water and ions resulting in the opening of the pulvinus membrane ion-channels and volumetric strain inside the motor cells as a function of the [K+] and [Cl-] ion and water fluxes. The pulvinus flexor side swells by approximately 7 to 17 percent and shrinks on the extensor side by approximately 20 to 38 percent resulting in a loss of turgor that decreases the support of the adjacent plant section. This seismonastic movement is a bending of the leaves from rectangular to fan-shaped that is rapid (i.e., one to two seconds) and passively return to the original position in one to two minutes.

Translation from biology to design

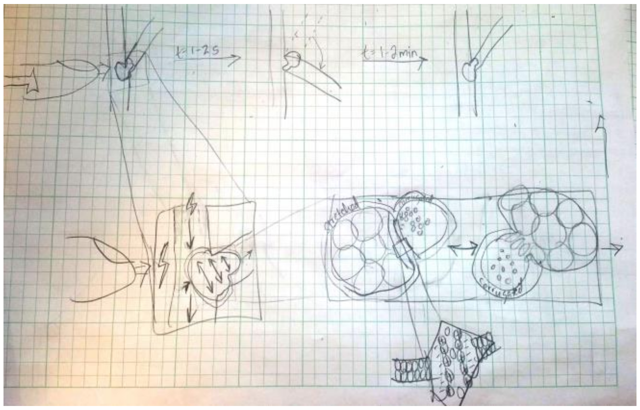
Design

Abstracted Design Principle

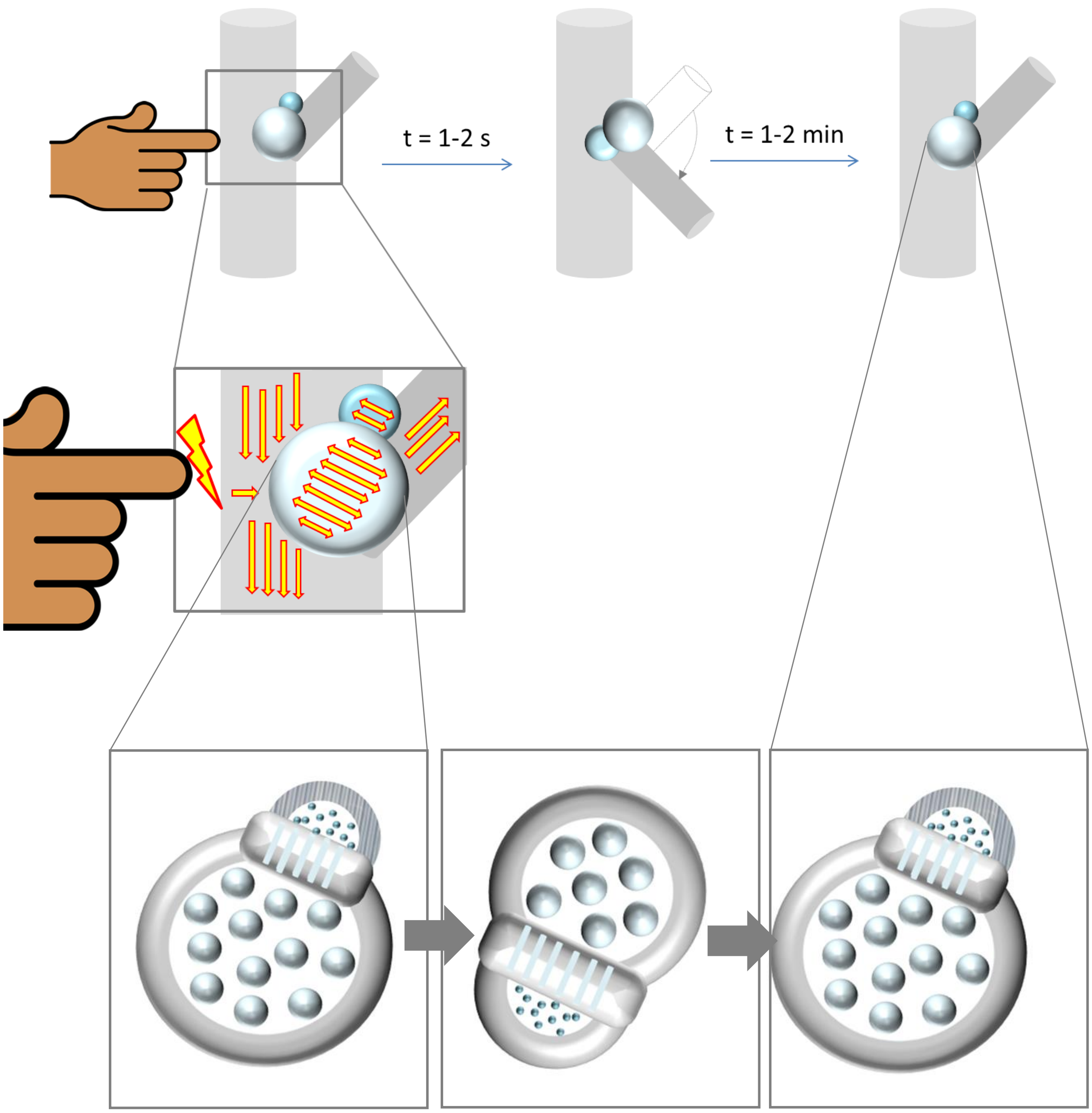
Mimics the mechanism in formula, but using analogous terminology to biology-specific terms, such as "cell." The analogous terminology should be domain-independent for this exercise, however could be domain-specific in practice if the desired application is known.

A strong but lightweight apparatus has long, flexible hinges each with corresponding fan-shaped modules that become facially appressed upon mechanical stimulation. At each link connecting a module to a hinge, there is a small pouch system having a flexible, impermeable outer layer with a corrugated surface (to allow expansion and contraction) that protects two inner compartments, i.e., with solutes of disparate salt concentrations separated by a thin (i.e., nano-meter scale), double-layered film partition that is interspersed with hydraulically conductive conduits, which open upon stimulation causing the pouch solvent to redistribute across the concentration gradient such that one side of the pouch system quickly (i.e., within 1 -2 seconds) swells under volumetric strain while the other shrinks and causes a temporary (several minutes), reversible one-directional bending/folding of each module longitudinally (~ 90 degrees from original orientation).

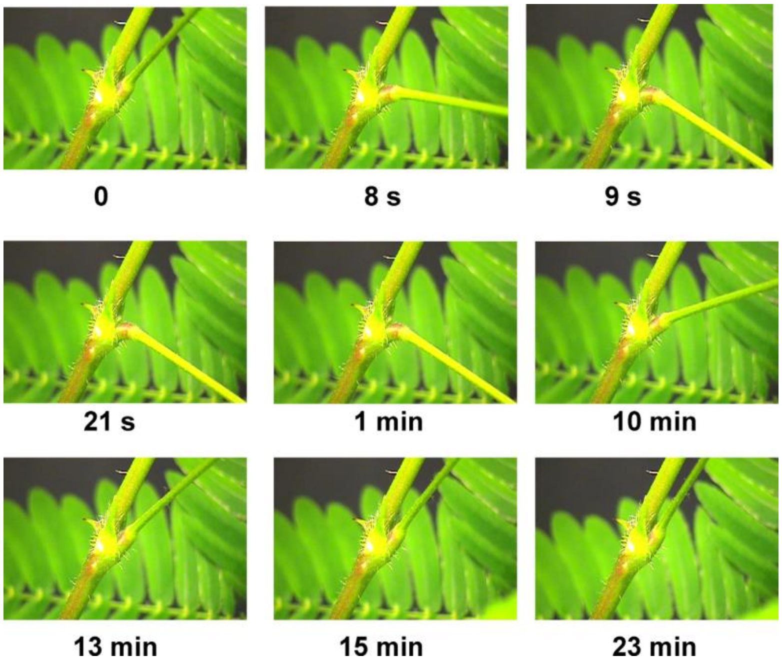
Biological Design Principle Illustration



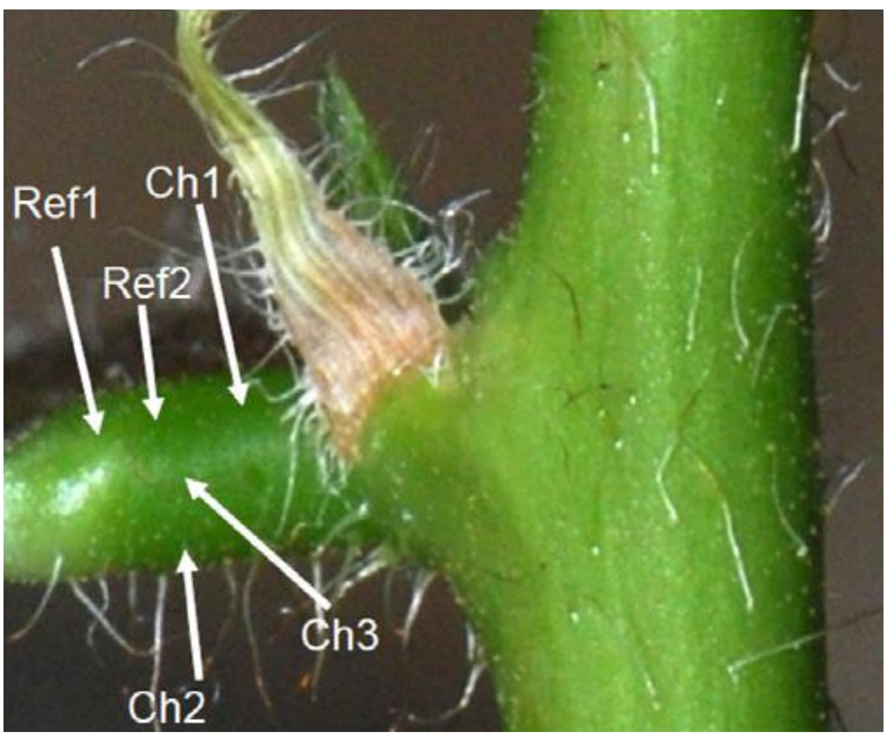
Abstracted Design Principle (ADP) Illustration



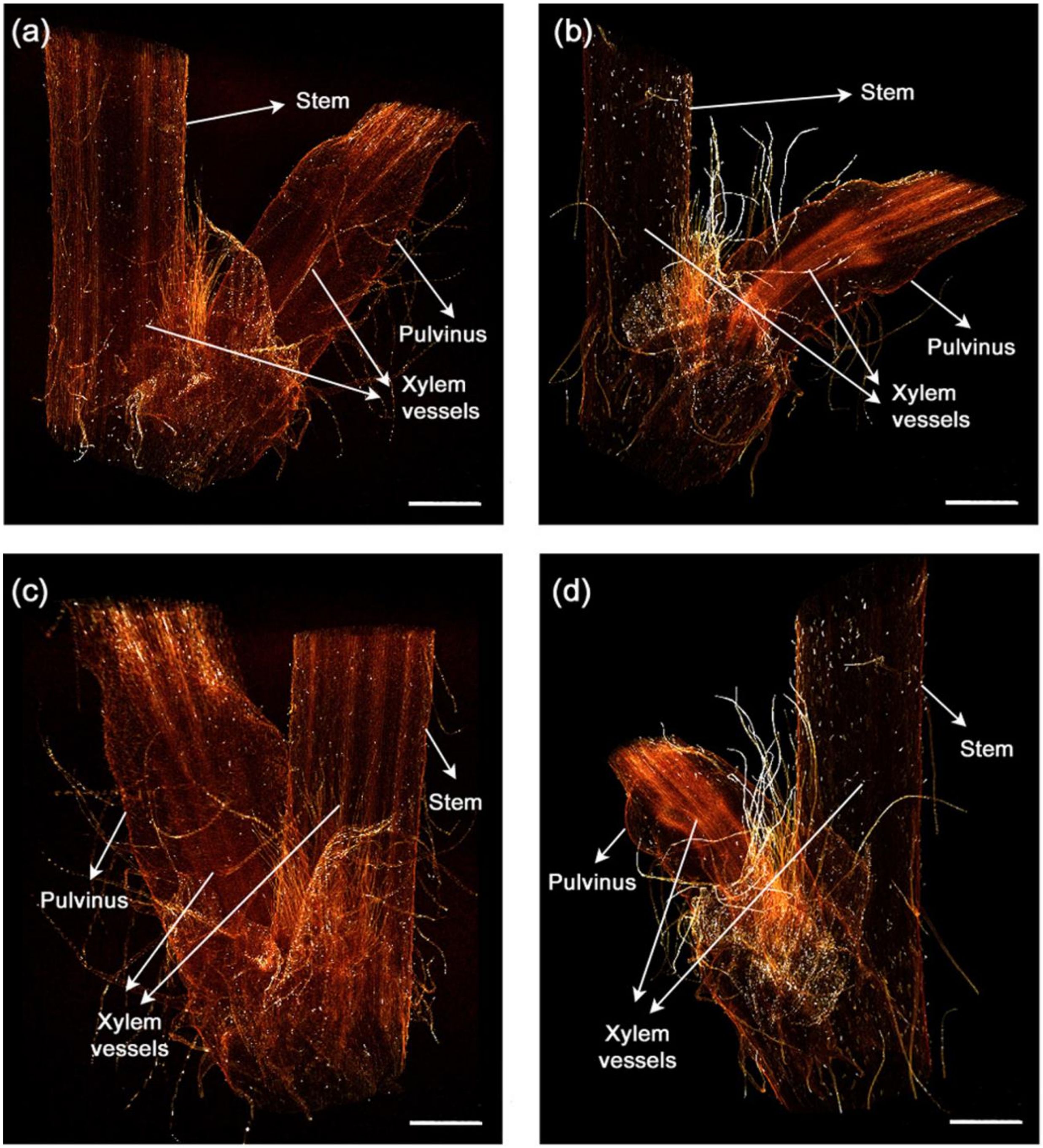
Additional Images of *Mimosa pudica*



1. Morphing Mimosa pudica structures at pulvinus and petiole after stimulation (Volkov et al. 2013)



2. Joint between stem & pinnules where pulvinus is located (Volkov et al. 2013)



3. 3D images of the xylem vessels inside the pulvinus and the morphological structure of the pulvini (Song et al. 2014).

REFERENCES:

Kwan KW, Ye ZW, Chye ML, Ngan AHW (2013). A mathematical model on water redistribution mechanism of the seismonastic movement of *Mimosa Pudica*, Biophysical Journal 105(1): 266-275.

Song K, Yeom E, Lee SJ (2014). Real-time imaging of pulvinus bending in Mimosa pudica, Scientific Reports 4(6466): 1-8.

Volkov AG, O'Neal L, Volkova MI, Markin VS (2013). Morphing structures and signal transduction in *Mimosa pudica* L. induced by localized thermal stress, Journal of Plant Physiology 170: 1317-1327.