

ductors called topological superconductors as either quasiparticles localized at certain types of defects, such as vortices, or as delocalized quasiparticles propagating along the boundaries or the walls between different domains of superconductivity (see the figure). In condensed-matter physics, the Majorana quasiparticles are predicted to obey fundamentally new particle statistics that generalize from the Fermi-Dirac statistics governing identical particles with half-integer spin. Experimental observations of sharp tunneling conductance peaks that are consistent with the presence of Majorana quasiparticles in semiconductor-superconductor heterostructures (3–5) and ferromagnetic atomic chains deposited on superconductors (6) have been reported in the past few years, although definitive evidence is still lacking (7). These observations have only been on static quasiparticles, otherwise called localized or bound states. By contrast, evidence for Majorana quasiparticles that propagate along the boundaries or walls between different domains in superconductors has not been observed.

The challenge associated with the experimental demonstration of Majorana quasiparticles stems, essentially, from the complexity of the proposed host systems. These systems are multicomponent heterostructures (3–6) predicted to behave as topological superconductors under controlled external conditions. By contrast, Wang *et al.* exploit a key advantage of the iron-based superconductor  $\text{FeSe}_x\text{Te}_{1-x}$  in that it consists of a single material that supports all the key ingredients necessary for Majorana physics. This requires a nontrivial electronic band structure, superconductivity, and special types of domain walls that can support propagating Majorana quasiparticles. The surface of this system is a topological superconductor with a special band structure, based on an argument put forward by Fu and Kane (8). A domain wall separating regions of the crystalline lattice shifted by half a unit-cell should support a pair of counterpropagating Majorana quasiparticles identifiable with a linear energy-momentum dispersion relation (8).

Wang *et al.* used a combination of previous studies and experimental and theoretical evidence to show that this scenario exists for  $\text{FeSe}_x\text{Te}_{1-x}$ . Previous studies iden-

**“Experimental observations... are consistent with the presence of Majorana quasiparticles...”**

tified topological superconducting surface states with high-resolution angle-resolved photoemission spectroscopy (9) and observed sharp zero-bias peaks inside vortex cores (10). The authors’ scanning tunneling microscopy studies show a flat (bias-independent) differential conductance along the domain wall. This signature is the hallmark of the linearly dispersing Majorana quasiparticles propagating along a one-dimensional defect. The spatial distribution of domain wall states as a function of energy is also consistent with the evolution expected from the Majorana quasiparticle being localized along the domain wall at zero energy to become delocalized as its energy approaches the gap edge. The authors also show a robust zero bias anomaly observed in vortex cores below the superconducting transition temperature  $T_c$ , which is a signature of companion Majorana quasiparticles localized at vortex cores consistent with previous studies (10).

The experiments from Wang *et al.* provide a compelling case for topological superconductivity and propagating Majorana quasiparticles in a class of iron-based superconductors. This system is attractive because the observations and theory suggest Majorana behavior occur in a single material, without a heterostructure. The findings open a new chapter in the field of iron-based superconductors and represent a large step in the quest for Majorana fermions in condensed-matter systems. For practical applications, Majorana systems in condensed-matter physics are attractive for quantum computing because their fundamentally new particle statistics may be useful for the development of fault-tolerant topological quantum computation (11, 12). This makes these iron-based systems important both for fundamental science and quantum technology. ■

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#### DEVELOPMENTAL BIOLOGY

## Building a carnivorous trap

Experiments and computations reveal developmental origins of cup-shaped leaves

By Derek E. Moulton and Alain Goriely

Variation, according to evolutionary biologist Stephen Jay Gould, is “nature’s only irreducible essence” (1). The variation and diversity of shapes in nature is a central focus of both evolutionary and developmental biologists. Unified under the unlikely roof of “evolutionary developmental biology,” the ultimate goal of these scientists is to understand how variation arises both through natural selection (on geological time scales) and during development (on embryological time scales). On page 91 of this issue, Whitewoods *et al.* (2) present a fascinating example of evolutionary developmental biology in a carnivorous plant.

The herbarium of our early school years taught us that leaves come in many different sizes, shapes, and textures that have evolved by subtle gene rearrangements to solve various packing and arrangement problems (3). Whereas many leaves are nearly flat, so as to present their best face to the Sun, others have been sculpted by evolution to function as mechanical devices; ropes, springs, spikes, claws, spears, hooks, catapults, and traps are the medieval weapons that plants use in their daily struggle with the environment. Perhaps most intriguing are carnivorous traps, the revenge of the plant kingdom and one of the lesser-known interests of Darwin (4).

The humped bladderwort (*Utricularia gibba*), is an inconspicuous, easy-to-grow aquatic plant found on all inhabited continents. Yet, it has developed a nearly spherical cage and a sophisticated release mechanism that can swallow an unsuspecting crustacean in a few milliseconds (5). How can a leaf develop into such an elegant and complicated structure?

With its small genome, the bladderwort turns out to be an excellent model system. In these plants, the same branch supports both needle-like leaves and bladder-shaped traps

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(see the figure). Both structures develop from the same initial dome-shaped organ primordia. The selection of one shape or the other occurs through the physical translation of a delicate variation in differential gene expression and morphogen production, which can be probed experimentally and theoretically through computational modeling.

During its development, the leaf must solve a problem in geometry. There is a fundamental difference between a flat sheet and a sphere, a fact that can be appreciated by trying to flatten an orange peel. The two states are geometrically incompatible, so transforming one into the other involves either stretching or cutting. Because the in-

by inducing expression of one of the genes in an abnormal position on a leaflet.

Having established relevant gene expression profiles, Whitewoods *et al.* turned to a computational model for leaf morphogenesis. Most computational work in plant biology tends to model morphology by tracking cell growth and division (7). One of the singular features of the authors' research was their study of growth deformations at the tissue level. In their model, each point in the budding organ—treated as a three-dimensional continuum—was given differential growth rates in each of three selected directions. These directions are linked to a polarity field obtained by the diffusion of a

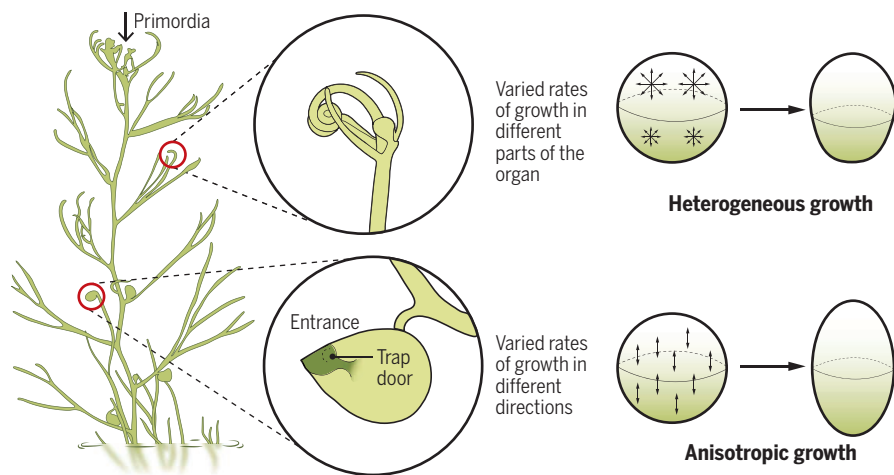
tion of cell division? The new model demonstrates a logical sequence of differential gene expression preceding growth polarity, which precedes cell-division orientation.

By showing that spherical traps, conical needles, and flat leaves all can be generated from the same initial tissue shape through small shifts in gene expression and growth differentials inspired by morphogen distribution, the new study opens exciting lines of research. For example, can these polarity fields be explicitly identified by measurements of gene expression at the cellular level? How are the polarity fields influenced by chemical and mechanical stimuli (12)? And how exactly does the developmental process form a functioning trap? The trap mechanism involves the slow build-up and rapid release of mechanical energy (13), which is intimately linked to morphological changes during development (14), but the connection has not yet been explored.

More broadly, Whitewoods *et al.* offer key insights into the competing pressures that ultimately shape every living thing. Development is inherently a physical process and is thus the end result of physical forces subtly manipulated by genetic clues. To understand such a process requires analysis across multiple scales as well as the integrated tools of mechanics, mathematics, and biology (15). However, this multidisciplinary approach tells only half the story of evolutionary developmental biology. On the species scale, evolution is driven by forces that enable one organism to successfully reproduce while another dies out. To properly connect evolutionary and embryonic forces across vastly different scales is to understand the very nature of variation: “the hard reality” (1). ■

## Bladderwort beginnings

During development of the humped bladderwort, the same initial primordia (arrow) on a single branch can be transformed into either needle-like leaves (left, top circle) or carnivorous traps (left, bottom circle). The key to shaping an organ is differential gene expression, which creates differential growth that is either heterogeneous or anisotropic.



tegrity of the leaf is preserved through development, the incompatible morphological change from dome to needle or trap can occur only through differential growth that can be either anisotropic (varied rates of growth in different directions) or heterogeneous (varied rates of growth in different parts of the organ). For example, a small sphere of material may be deformed into an ellipsoid or with a bulge on one side (see the figure).

The challenge, then, is to decipher the genetic underpinnings of the necessary growth differentials. Much is known about the effects of particular genes on the shape of leaves (6). In developing leaves, key genes are expressed differentially in zones on the adaxial (upper) versus abaxial (lower) surfaces. Whitewoods *et al.* revealed that these same genes are expressed differently in leaflets that form traps versus ones that form needle-like leaves. This crucial observation was confirmed by showing that trap development can be inhibited

morphogen. Their model is an adaptation of the theory of morphoelasticity (8), which allows for continuous changes resulting from both mechanics and growth. This theory has been used successfully in animal morphogenesis to describe the formation of a wide range of structures, from folds in the brain to seashell architecture (9, 10).

Notably, by simply varying the growth rates, the computational model showed how the same dome can develop into either a needle-like cone or a planar leaf shape. By making these growth rates nonuniform in space, Whitewoods *et al.* further demonstrated a simple mechanism for generating cup-shaped traps and other features, such as the ridges found in a related cousin, *Sarracenia purpurea* (11). The model also provided some insight into a chicken-and-egg problem in development: Does the orientation of cell division generate growth anisotropy, or does growth anisotropy generate the orienta-

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