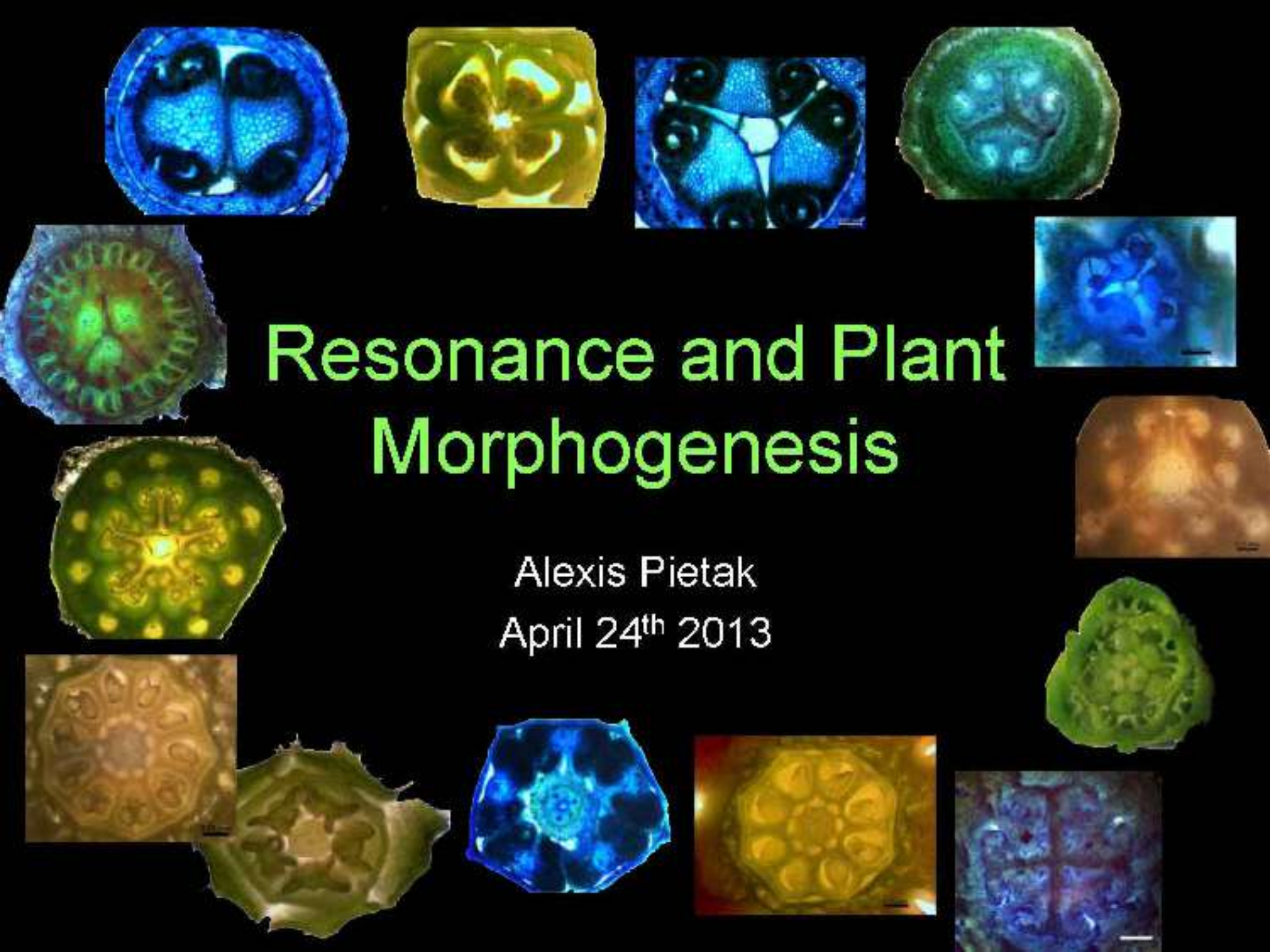


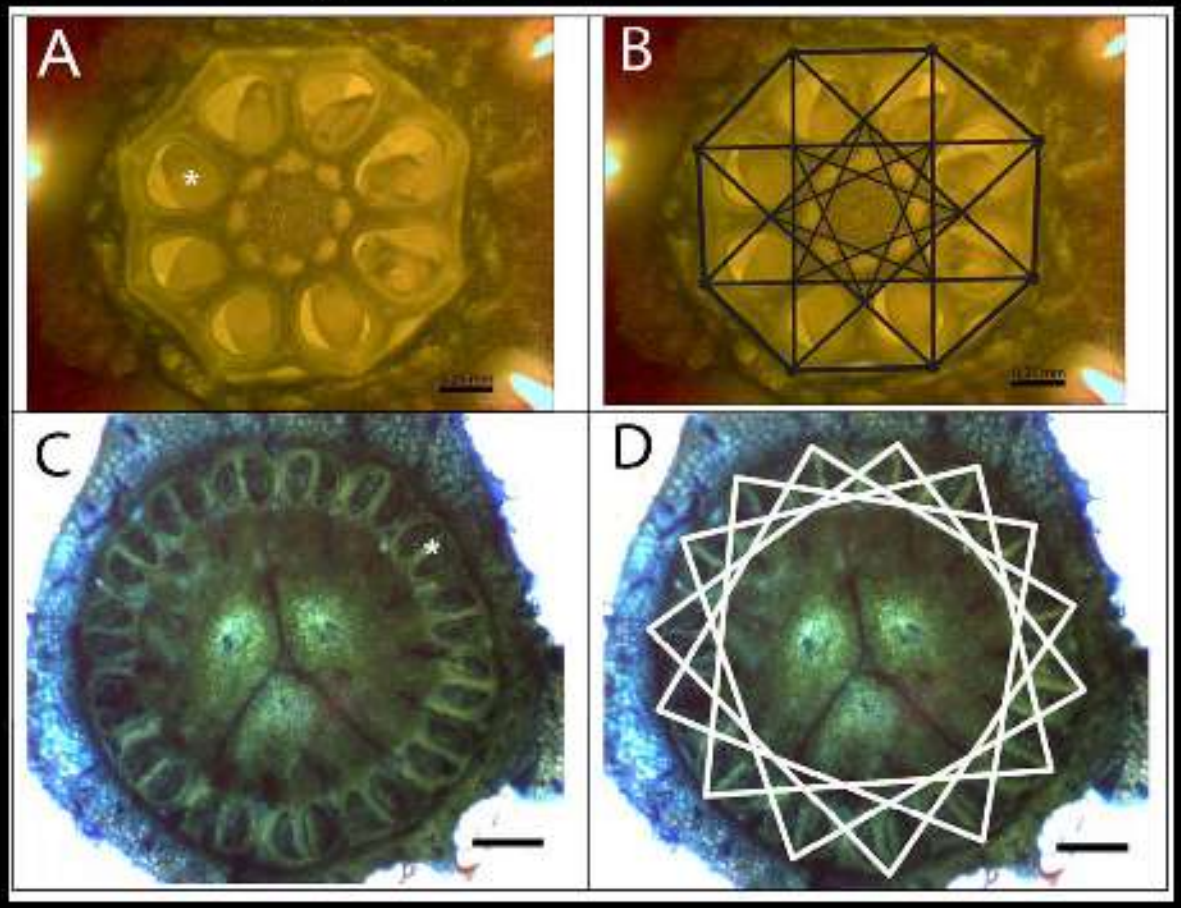
Resonance and Plant Morphogenesis

Alexis Pietak

April 24th 2013

Morphogenetic Mysteries

Interesting and intriguing patterns exist in flower primordia

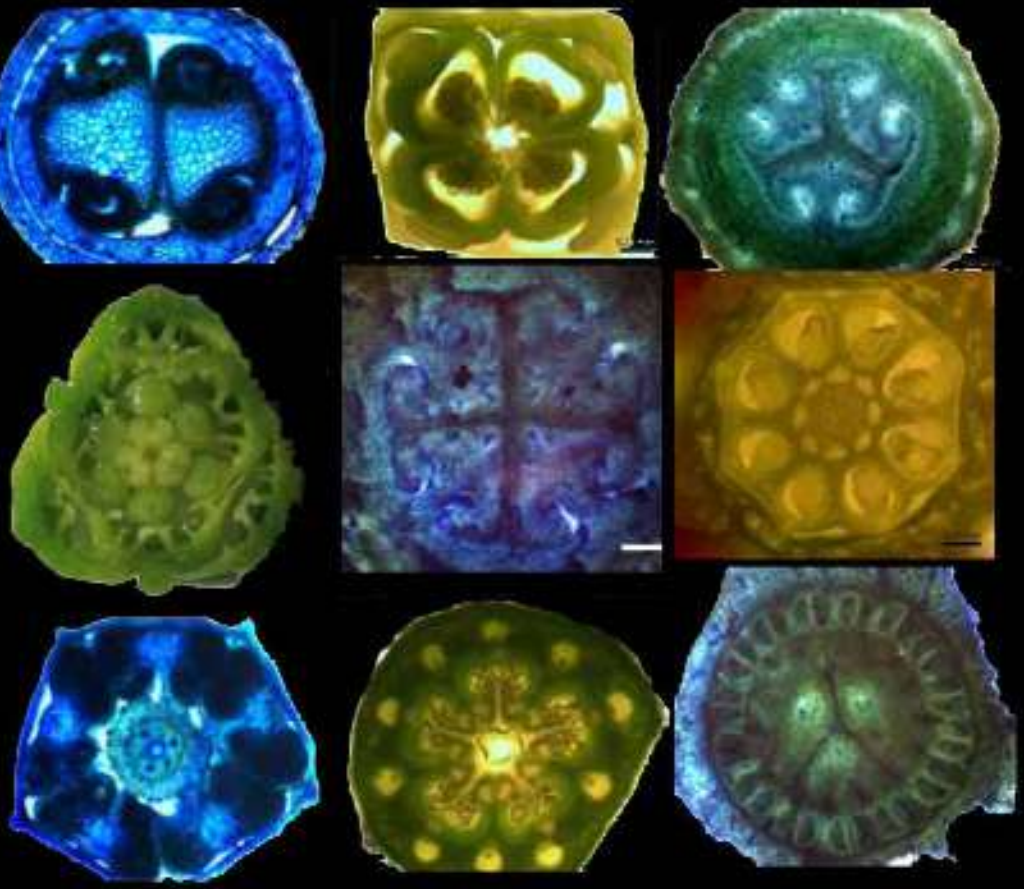


Top: Abutilon primordia and star polygon (8/3)

Bottom: Male squash primordium and star polygon (9/4)

Morphogenetic Mysteries

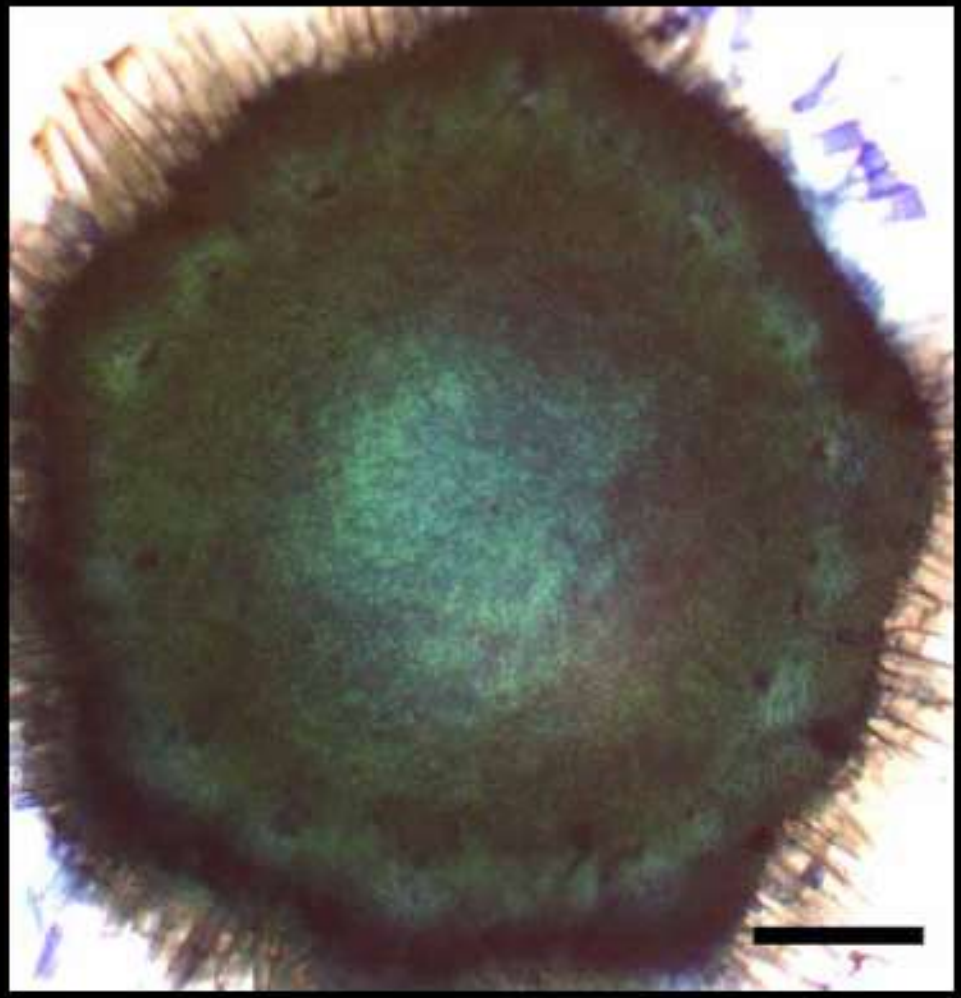
And it seems there is an endless amount of variety to be witnessed.



From top: crocus, kalanchoe, female squash, day lily, zucchini, abutilion, bellflower, apple blossom, and male squash primordia cross-sections.

Morphogenetic Mysteries

Primordia tend to begin as globular clumps of cells with a high degree of symmetry and no discernable patterning…



Squash flower primordium: d ~ 300 μm

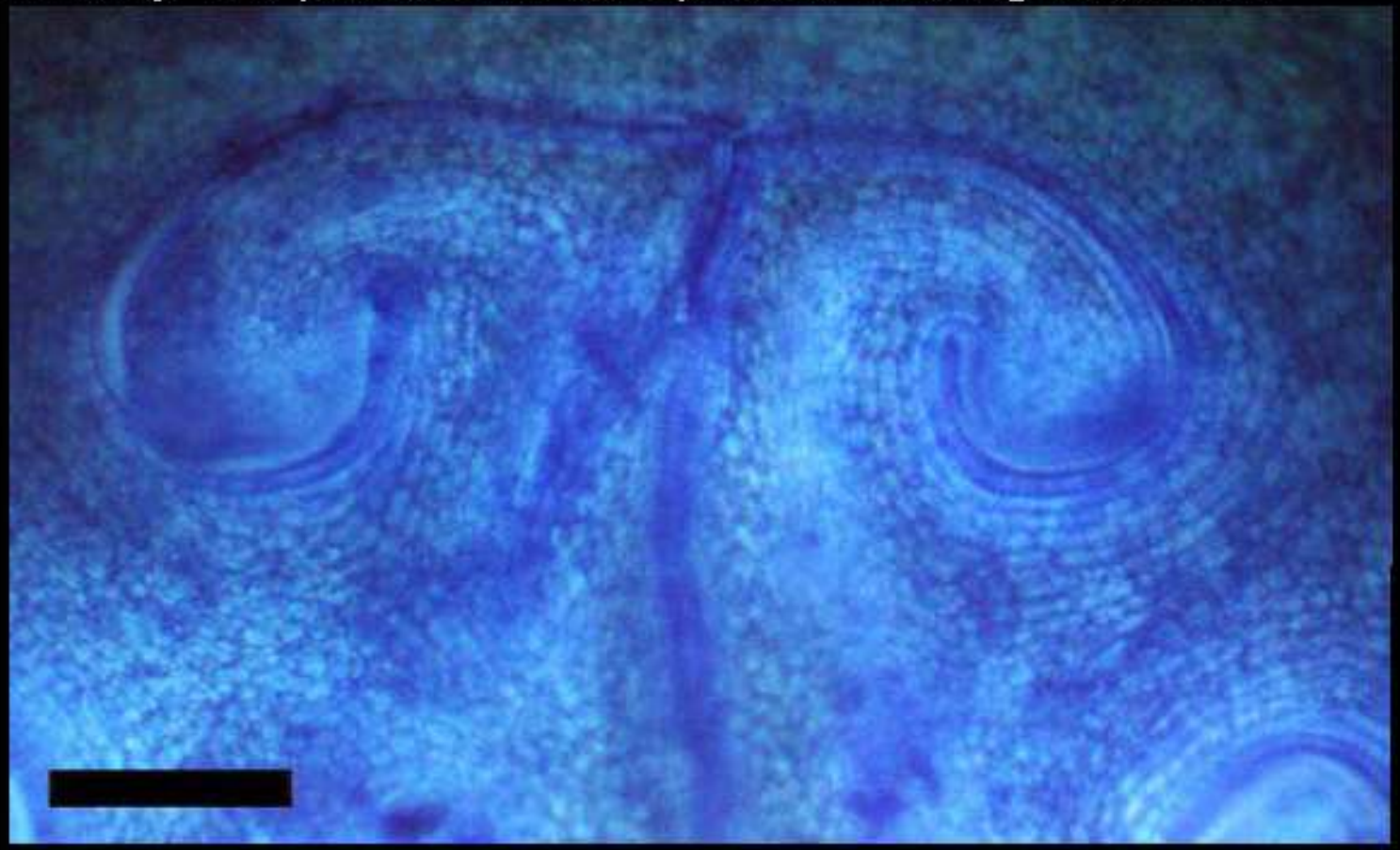
Morphogenetic Mysteries

With the first symmetry breaking, a characteristic pattern emerges…

Squash flower primordium: d ~ 350 μm

Morphogenetic Mysteries

Initially the pattern is comprised of single cells…



Squash flower primordium

Morphogenetic Mysteries

With growth and development more cells are involved but the overall patterning remains distinct…

Squash primordium: d ~ 450 μm

Morphogenetic Mysteries

The pattern remains distinct even with maturation of the organ and a size increase by a factor of ~1000 times.

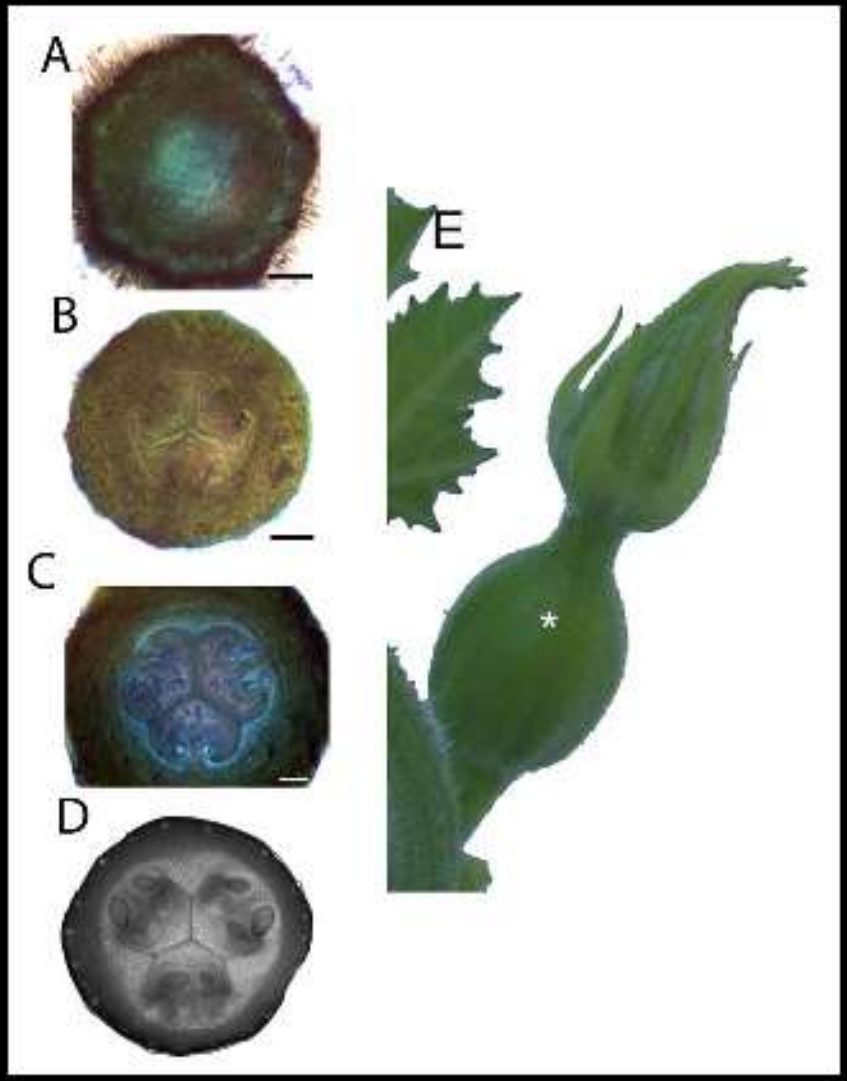
This is called morphostasis.

Mature squash fruit: d ~ 50,000 μm

Morphogenetic Mysteries

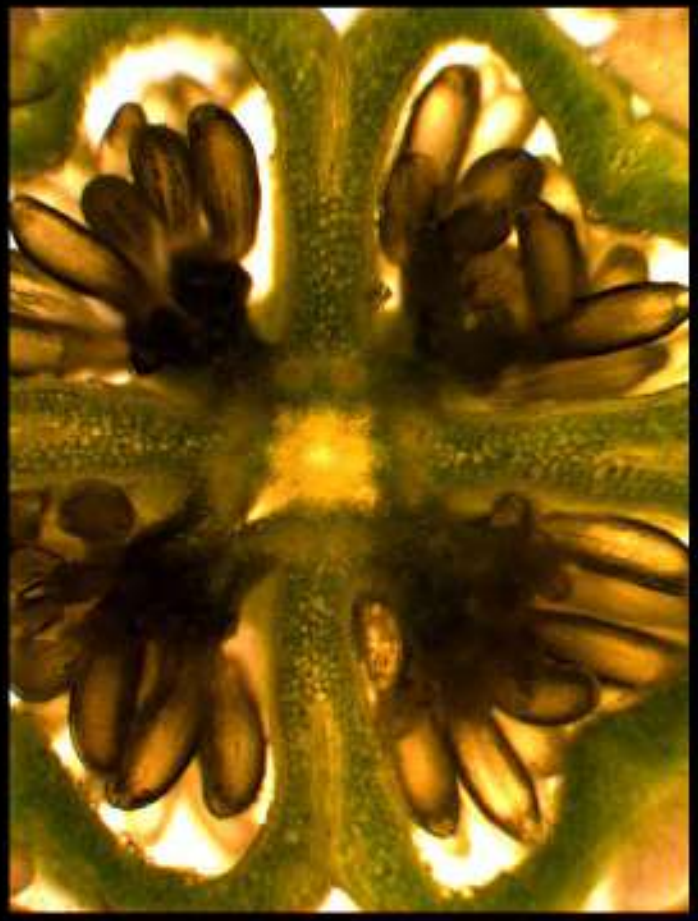
Typical features of plant flower development:

- Initial symmetrical ellipsoidal geometry
- Spontaneous symmetry breaking
- Morphostasis



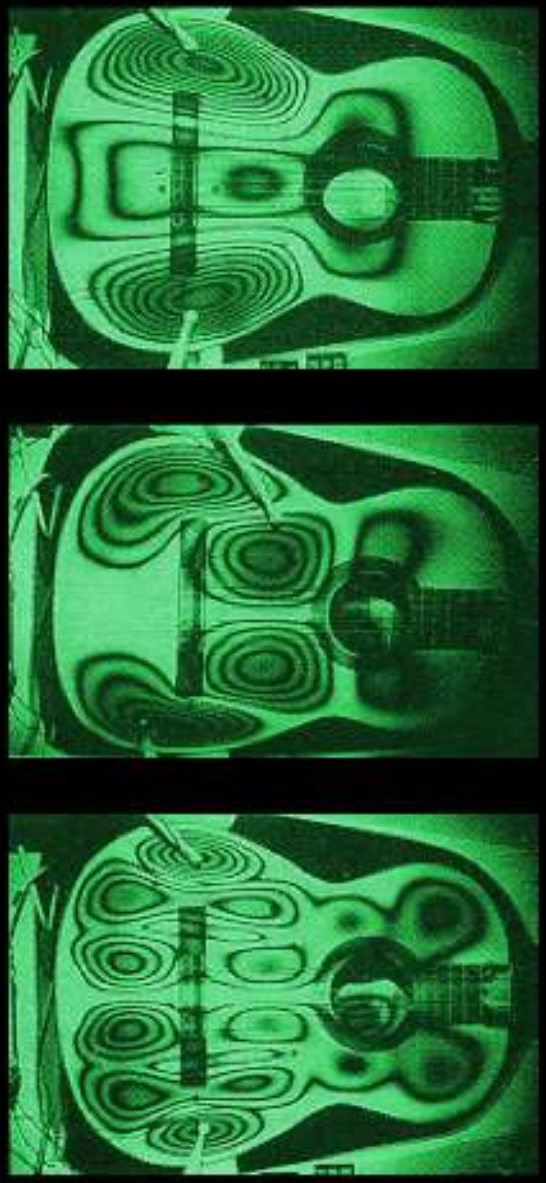
Morphogenetic Mysteries

- Genes associated with flower development have been determined (ABC + DE gene family).
- Mechanisms generating spatial variation in gene expression to form tissue patterns remain largely unknown.
- **Physical resonance** is a plausible mechanism capable of generating a positional information field.



Resonance

- Resonance is a ubiquitous occurrence in our everyday lives:
  - Sound: air pressure resonance
  - Structural vibration: mechanical resonance
  - Optical/electromagnetic fields: EM resonance (lasers)
- Resonance creates macroscopic pattern without individualized control of microscopic elements.



Structural resonances of a guitar

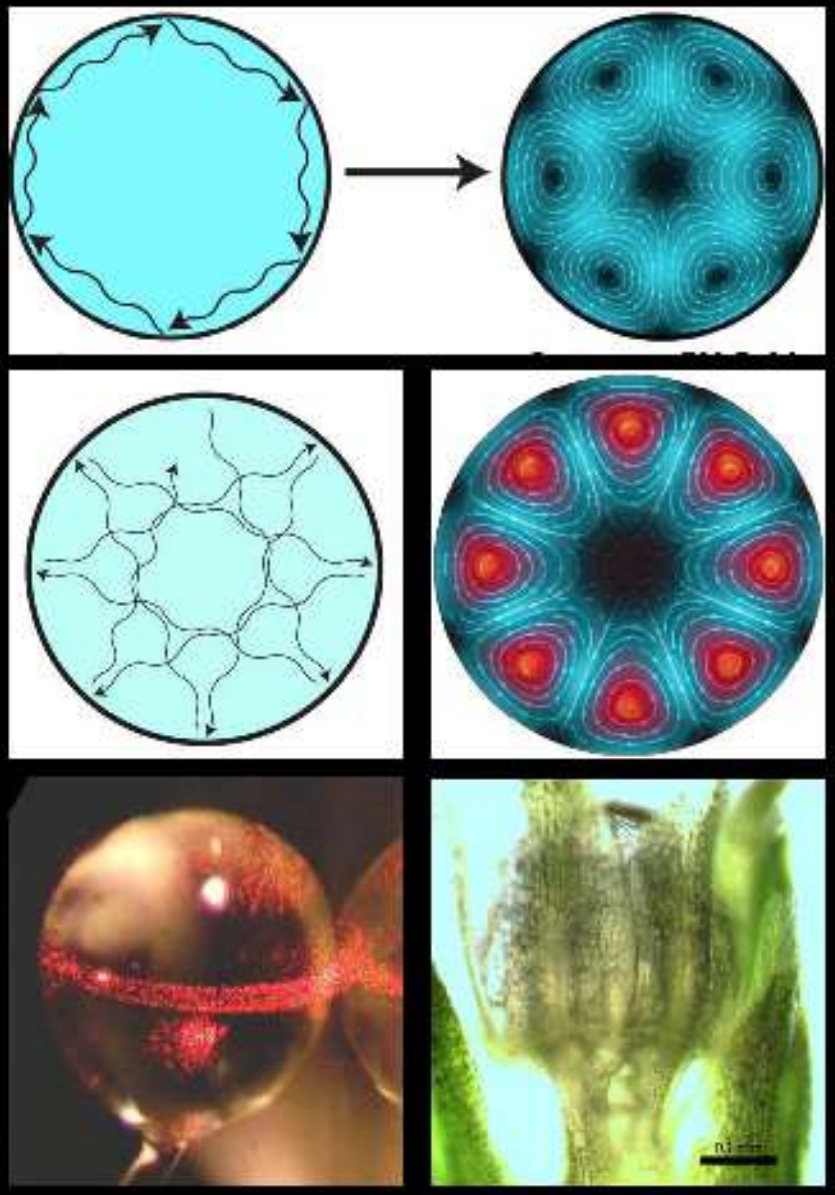
Ingredients for Resonance

Resonance occurs when three ingredients coincide:

1. **WAVES**: A phenomenon capable of existing as a wave (pressure, vibration, light, …)
2. **CONTAINER**: A container to support the wave phenomenon with minimal energy loss and boundaries that internally reflect the wave
3. **ENERGY**: An energy source to initiate and maintain the wave phenomenon.

Resonance in Action

- Waves in container are reflected back at the boundary.
- Reflected and incident waves interfere to form the resonant mode pattern.
- Mode pattern form changes with wave frequency and container size.
- Mode can be excited by broadband or noisy spectrum of wave energy.
- Example: Waterdrop laser cavity



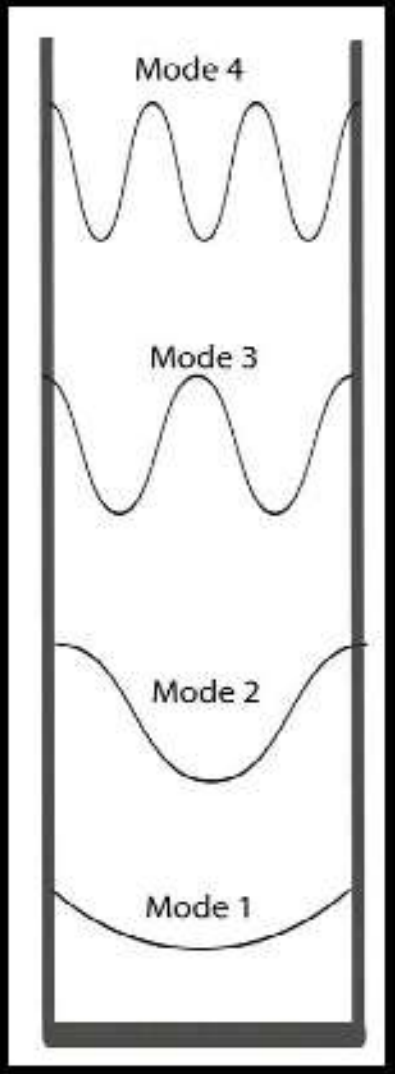
Whispering gallery mode resonators

Resonant Mode Patterns

Resonant mode patterns depend on the physics and the container geometry. Mathematically described.

Sinusoidal Resonances:

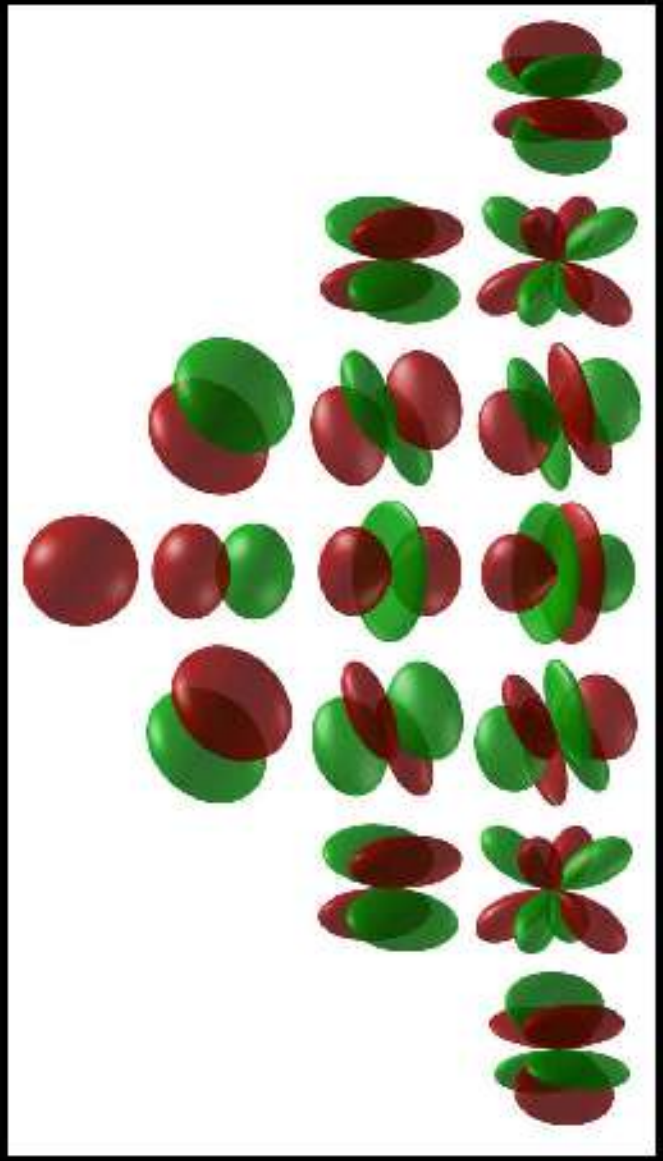
- The quintessential idea of a waveform with amplitude variations in space and time.
- Example: Plucked string tethered between two walls.



Resonant Modes

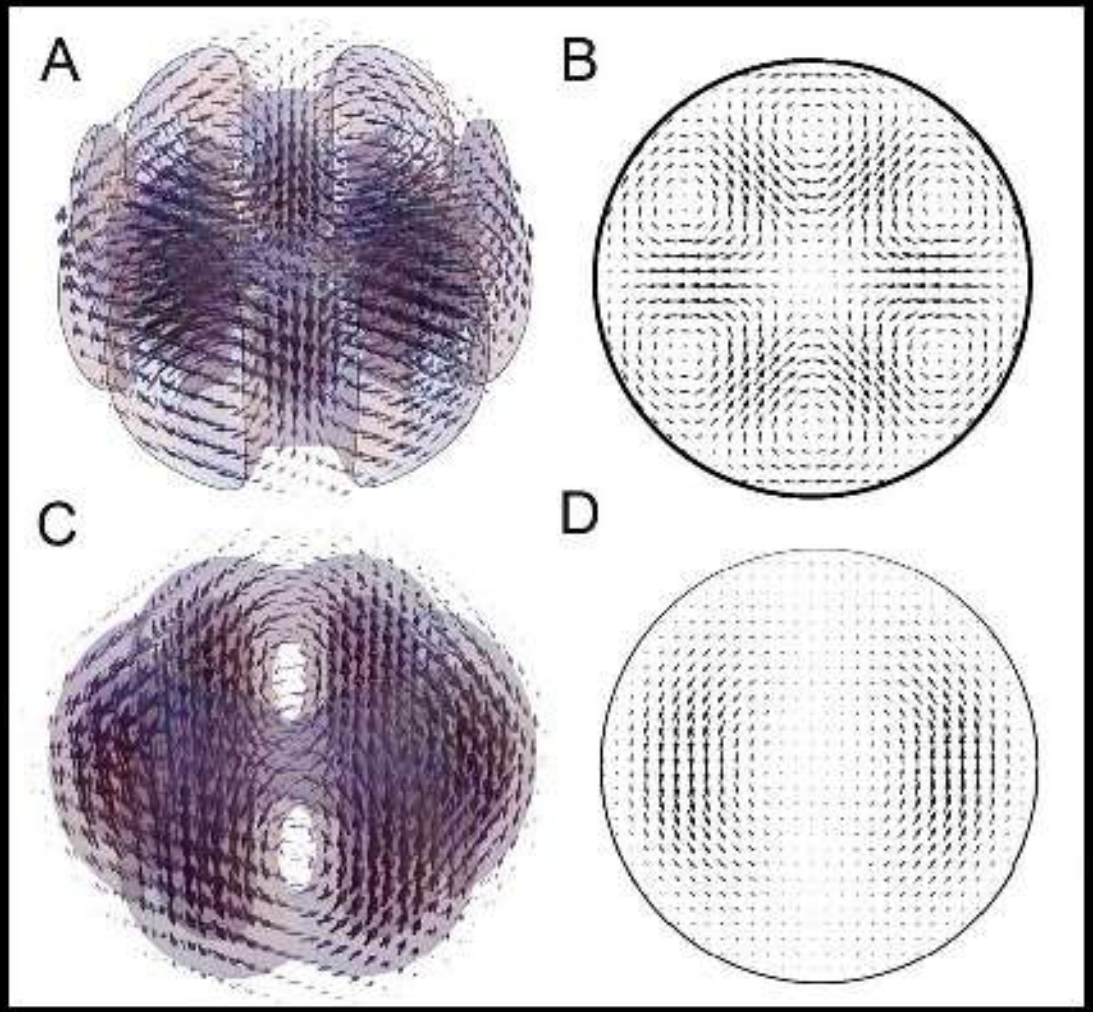
Spherical Harmonics:

- The classic wave extended to a spherical container.
- No longer appears anything like a “wave”.
- Amplitude variations in space and time.
- Example: Sound resonance.



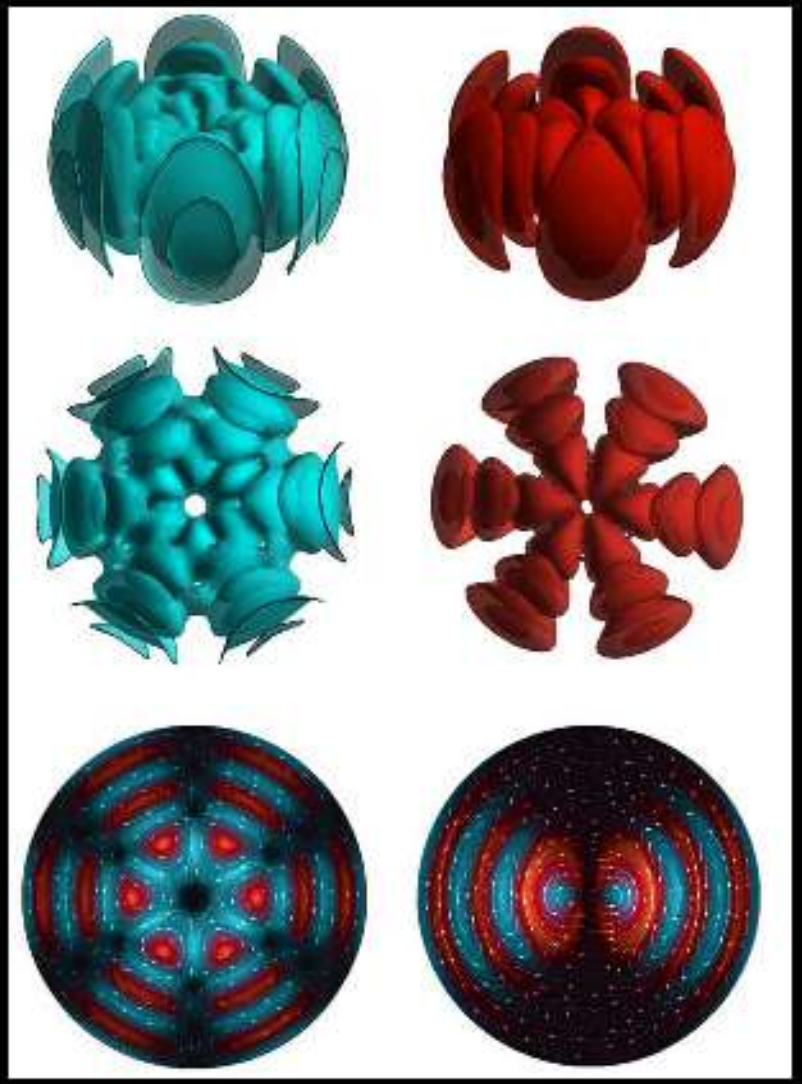
Vector Harmonics

VSH are terrifically intricate 3D patterns with variable intensity and direction at each point in space.



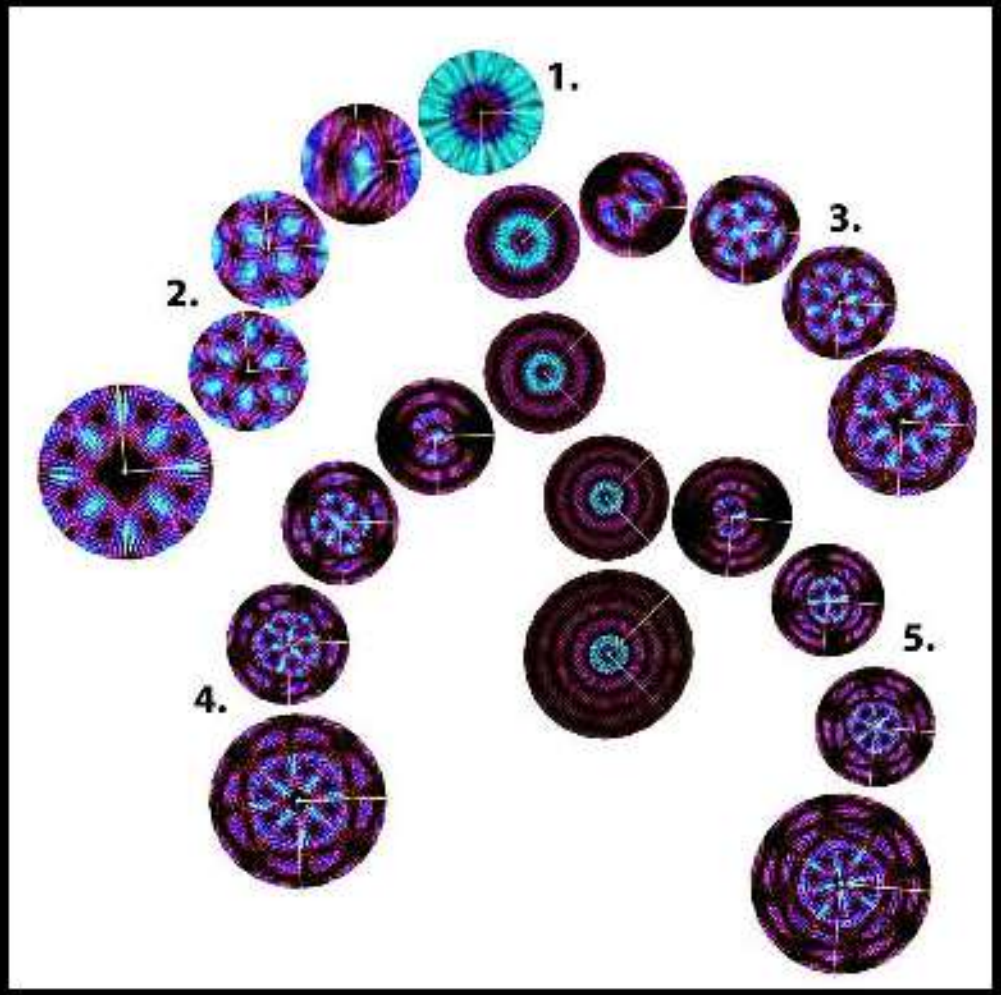
Vector Harmonics

- Each VSH comes with the possibility of two complementary field patterns (F-fields and G-fields)
- Occur via two known physical mechanisms:
  - Electromagnetic resonances (both F- and G-fields simultaneously)
  - Elastic wave resonances



Vector Harmonics

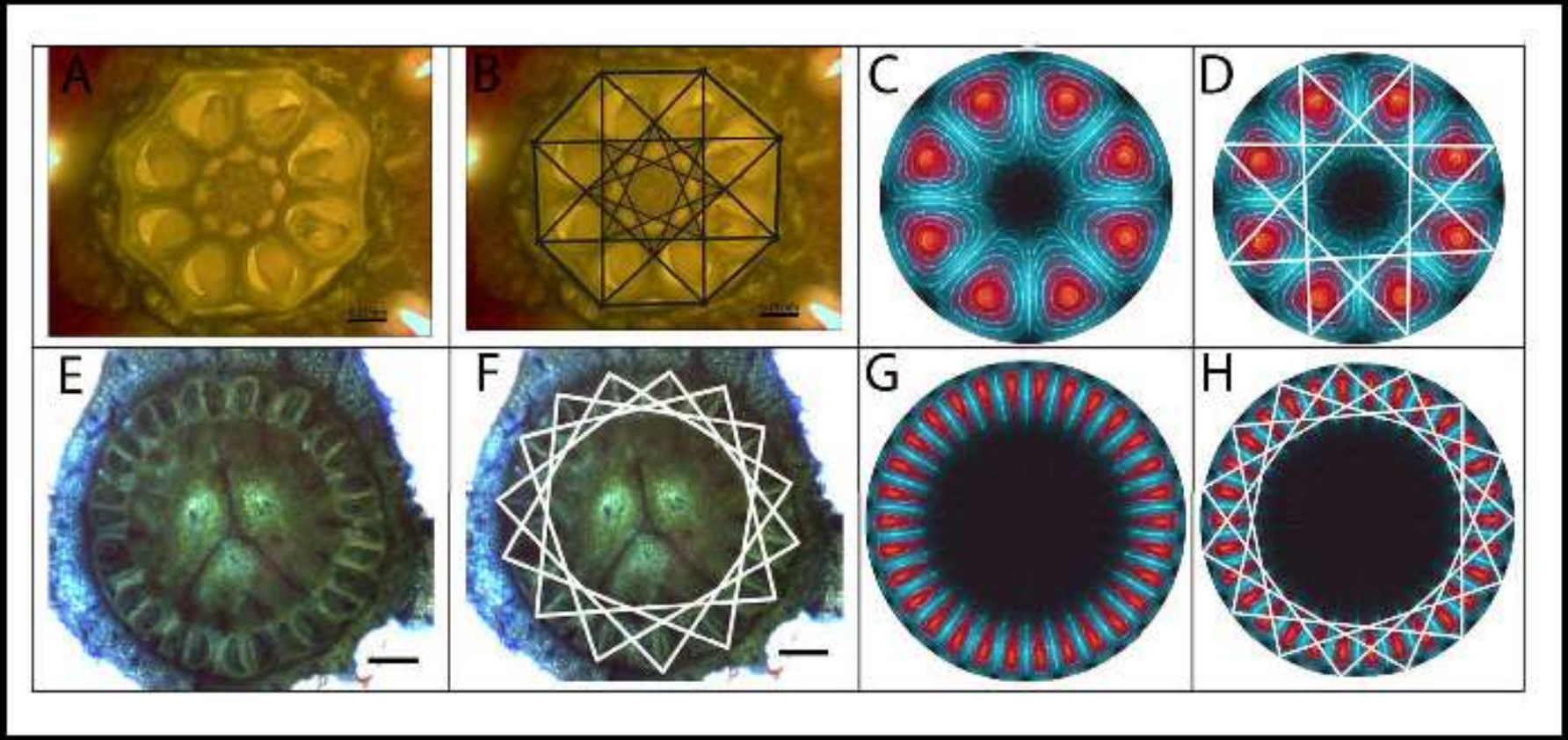
As resonance frequency increases, patterns follow relational lineages similar to an evolutionary tree.



Cross-sections of F-field resonances showing relational lineages

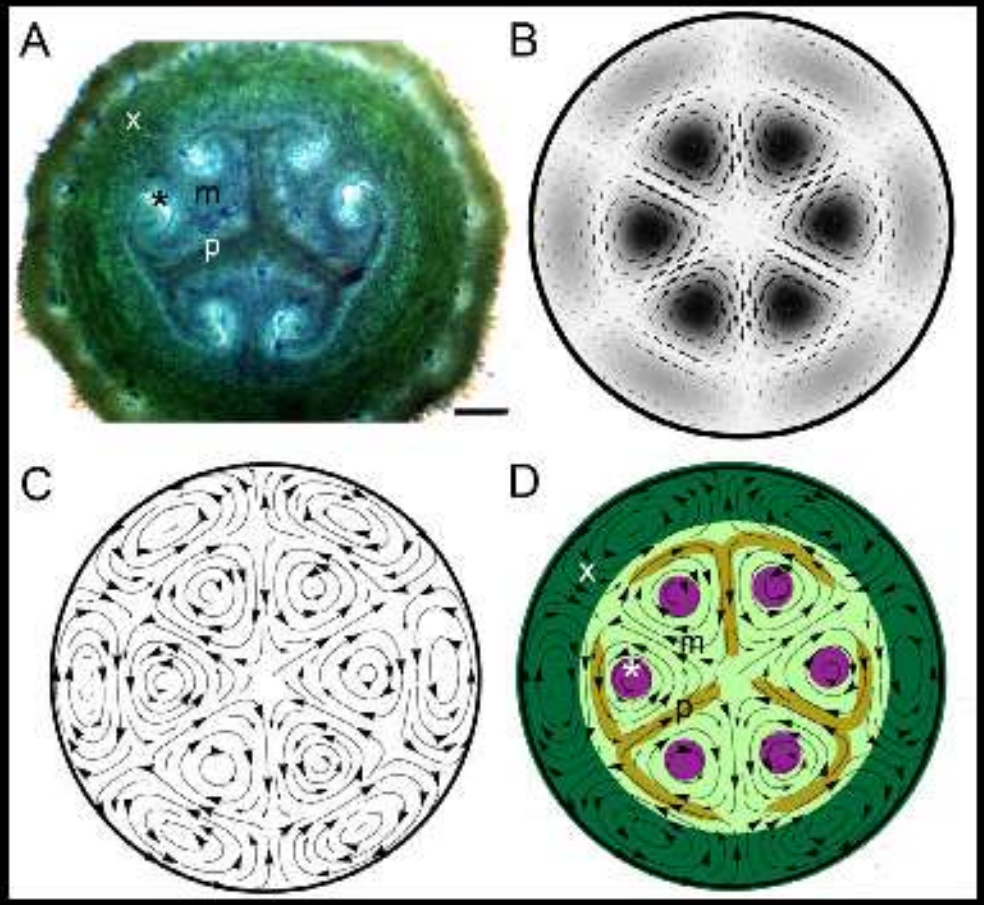
Vector Spherical Harmonics

There is a remarkable correspondence between VSHs and developmental plant patterns.



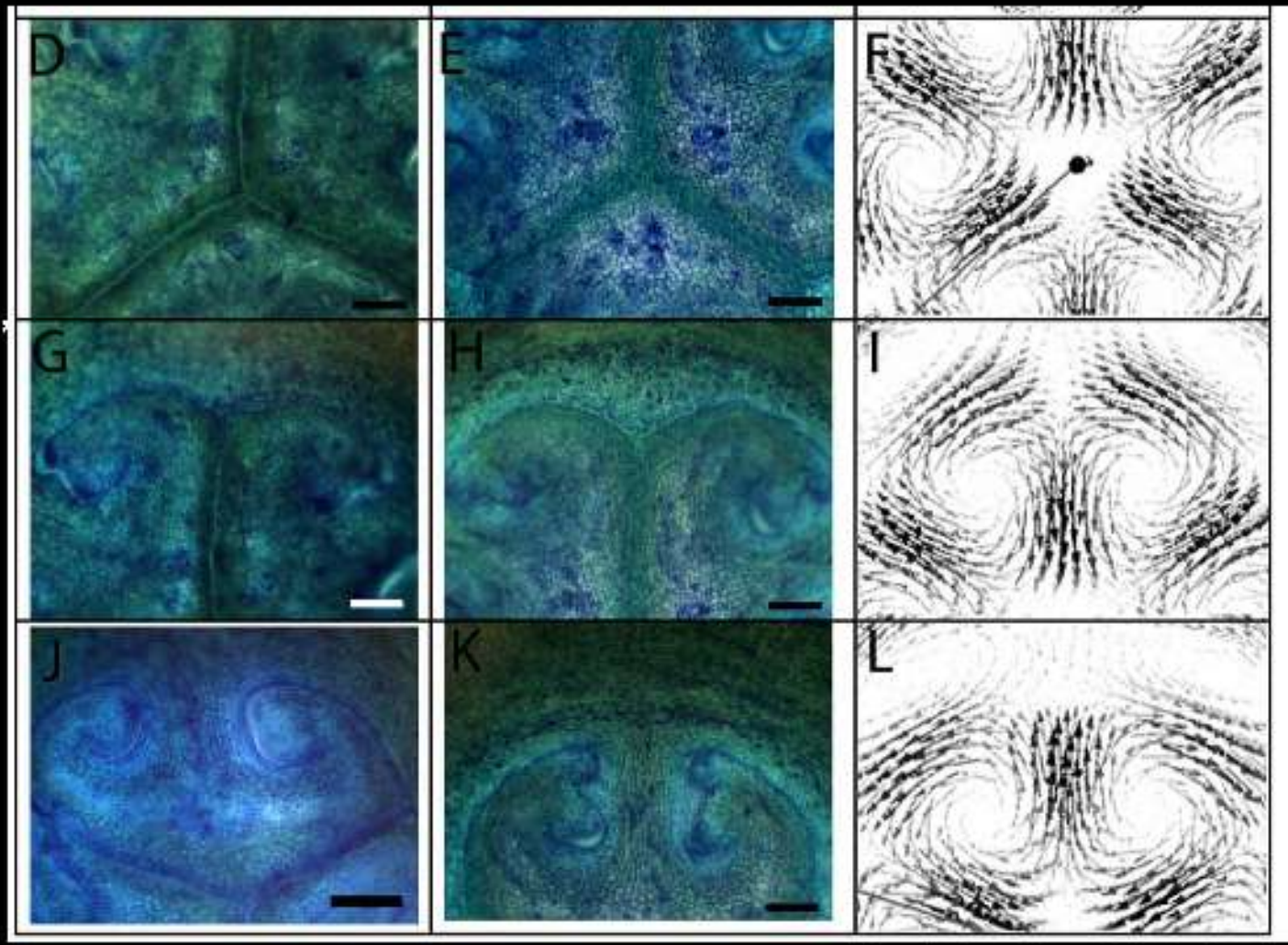
Consistent Observations

- Plant ova or pollen tube location coinciding with G-field maxima.
- Placental line or septa coinciding with complementary F-field maxima.
- Pattern relationship to a defining spherical geometry



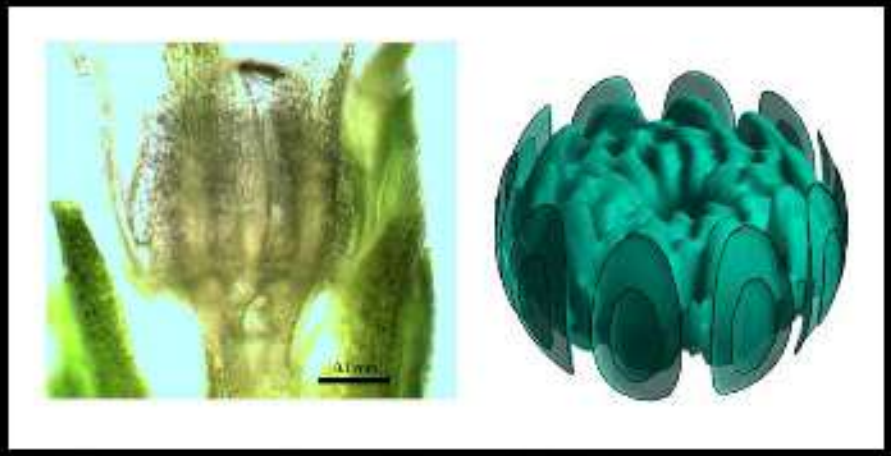
Consistently Observed

Shape, orientation, and location of differentiated tissue coinciding with magnitude and direction of VSH field lines.



Consistently Observed

A core central pattern with angular symmetry surrounded by a "whorl" or "shell" of additional features.

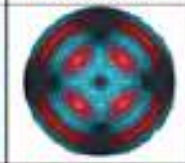
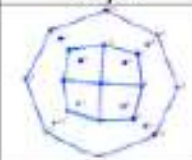
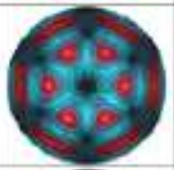
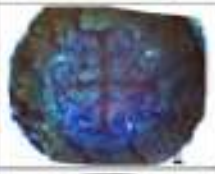
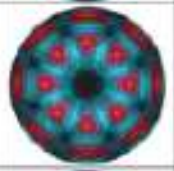
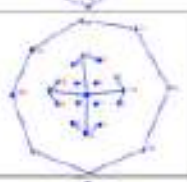
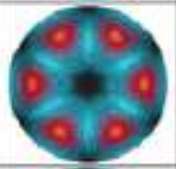
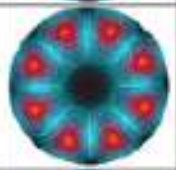
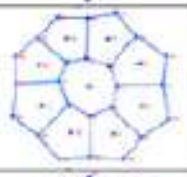
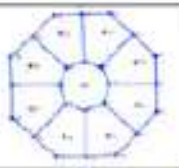
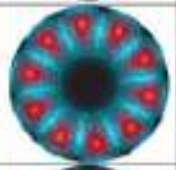
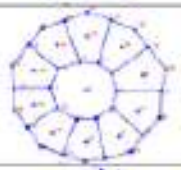
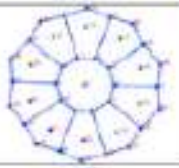
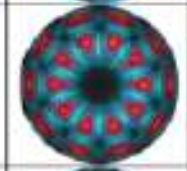
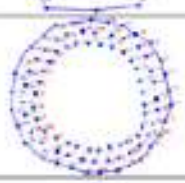


Bellflower primordia and 3D iso-surfaces of companion resonance mode.

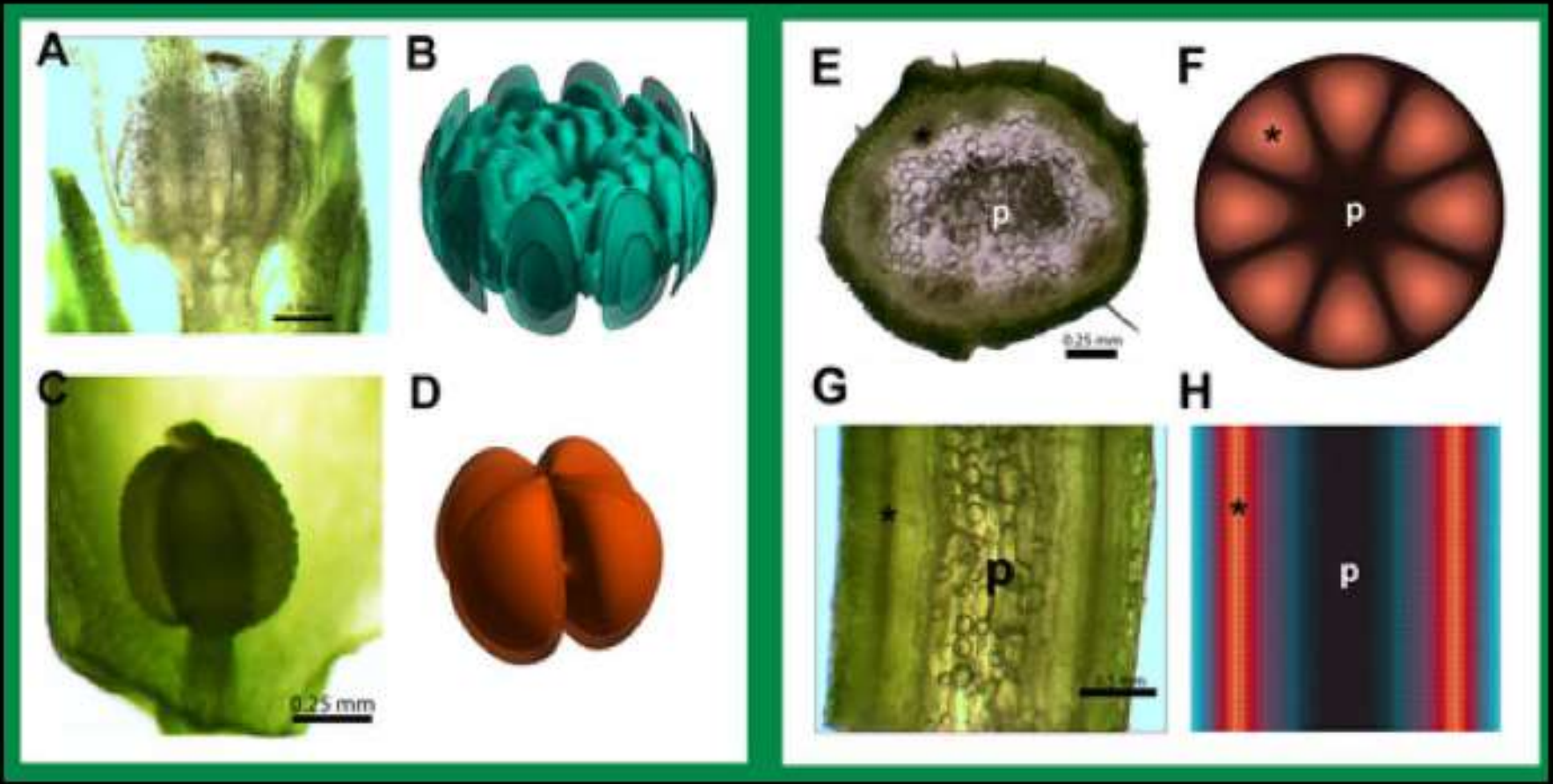
Kalanchoe primordia and 3D iso-surfaces of companion resonance mode.

Consistently Observed

A matching vector harmonic for every flower primordia investigated (8 unique species).

Plant Sample	Plant Example	Vector Harmonic	Plant Shape	Average Mode Shape
Kalanchoe Ovary 93%				
Squash Ovary (s3) 98%				
Squash Ovary (s4) 92%				
Watermelon 93%				
Abutilon Ovary (s4) 95%				
Abutilon Ovary (s5) 96%				
Apple Ovary 95%				
Male Squash Flower Bud 97%				

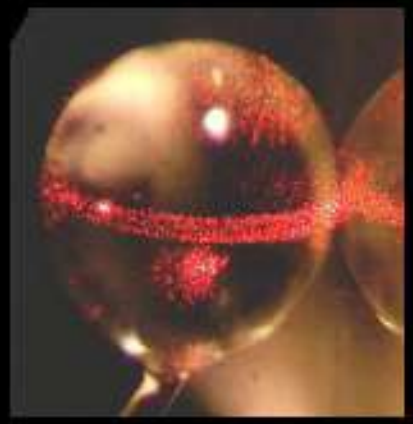
Additional Similarities



Bellflower primordia and VSH (A and B), kalanchoe anther and VSH (C and D), bellflower stem and VCH in cross-section (E & F) and long section (G &H)

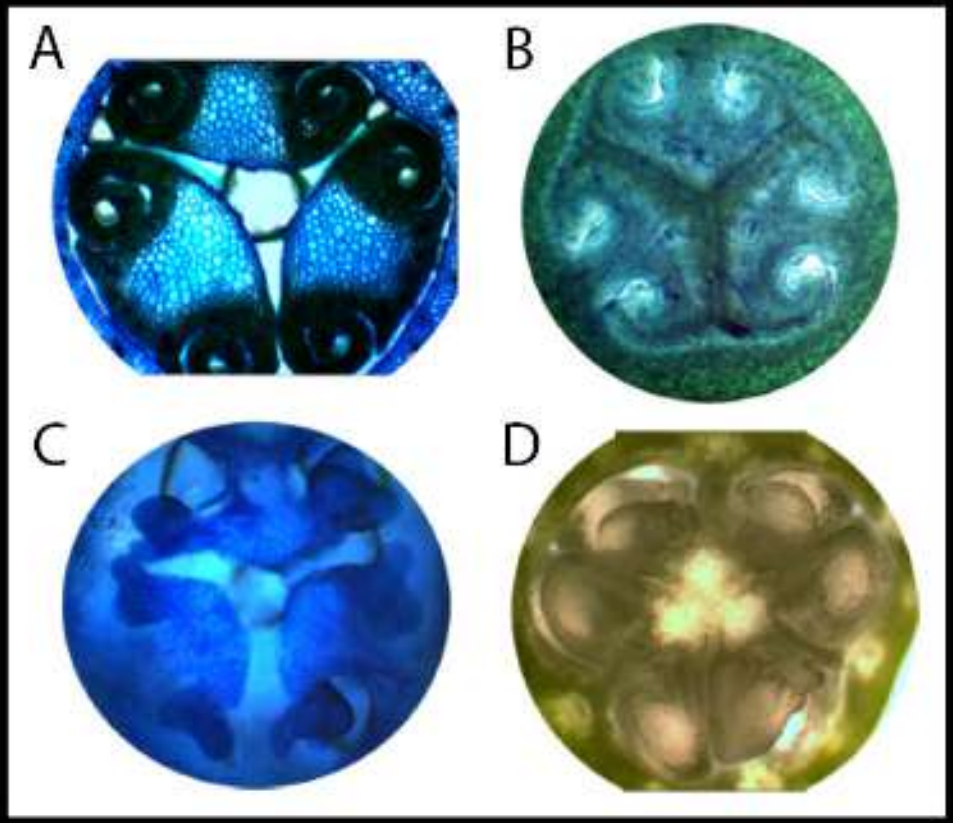
Mechanisms for Vector Harmonics

- Electromagnetic wave resonance via endogenous electromagnetism (0.150 to 2 THz)
- Structural elastic wave resonances via endogenous ultrasound (20 to 1000 kHz)
- Either case: resonant mode is a physical property with a precise spatial variation exerting a local influence on cellular activity.
- Both models have been theoretically evaluated and are indicated to be possible.



Implications of Biological Resonance

- A physical basis and mechanism for the morphogenetic field.
- The existence of an infinite number of phenotypic archetypes, as harmonics of a physical resonance.
- The identification of an emergent, coherent physical energy in the biological system, with physiological impacts.



Archetypes: Crocus leaf primordia (A), and squash (B), bellflower (C), and tulip (D) ovary primordia embodying the same VH resonance mode.

Summary

- Remarkable parallels observed between developing plant structure and vector harmonic resonances.
- The resonant mode supplies positional information to a receptive cellular collective.
- Endogenous electromagnetism or structural vibrations are two possible physical mechanisms.

Photo Credit: assiegal/flicker

Thank you for your attention!