Windows in a clamshell: how natural fiber optic cables and condensing lenses transmit sunlight for photosynthesis

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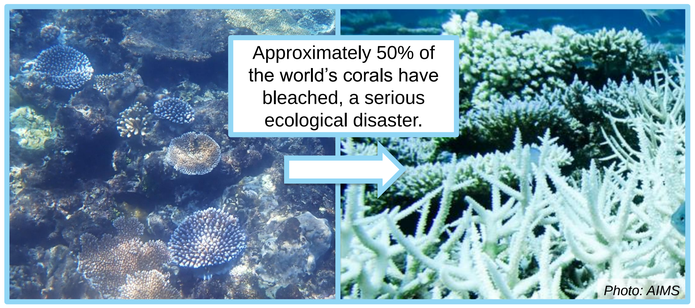
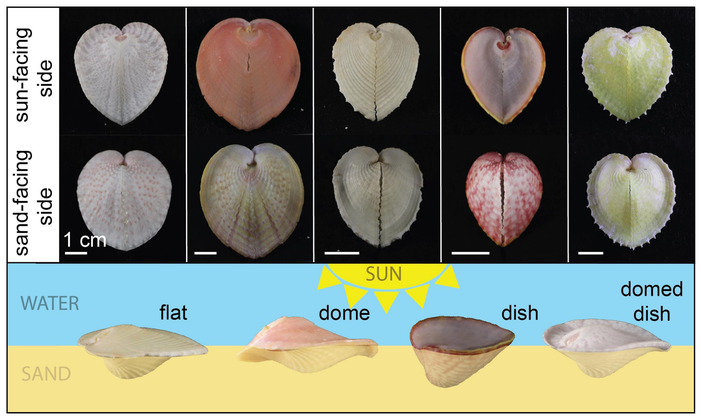
Motivation: explain paradoxical coral bleaching and explore the tree of life



- Coral reefs support about 25% of all marine life, provide food for millions of people, and stop coastal erosion.
- Global warming has caused widespread coral bleaching.
- This is an evolutionary paradox: why do corals bleach severely while other creatures (e.g., sponges and bivalves) are resistant?
- Hypothesis: corals have photonic structures that (i) make photosynthesis more efficient but (ii) cause light stress and bleaching in warming waters.
- By researching coral and other photosymbiotic creatures, we will:

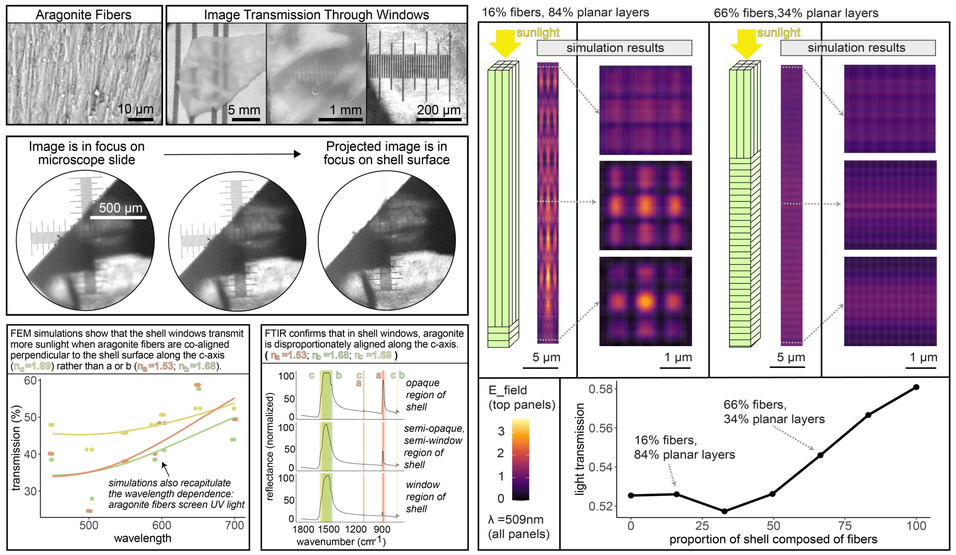
1. **Explore the marvelous, little-studied animals that convergently evolved photosymbiosis**
2. **Explain why corals bleach while other animals are resistant to global warming**
3. **Inspire new technologies based on nature's photonic innovations**

Strategy: apply photonic methods to illuminate shell windows in heart cockles

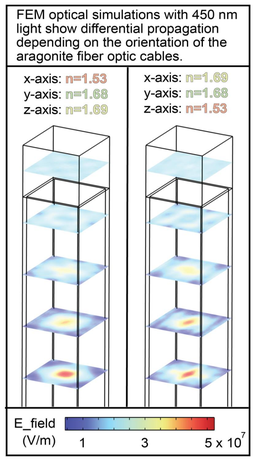


- Heart cockles (*Corculum cardissa*) are bivalves which live in the shallow oceans and have photosynthetic algal symbionts.
- To get sunlight to their symbionts without needing to open up, heart cockles have **transparent windows in their shell.**
- Here, we characterize the physical basis and evolutionary significance of shell windows in heart cockles
- We apply photonic tools, including UV-Vis spectroscopy, scanning electron microscopy, Fourier transform infrared spectroscopy (FTIR), optical modeling (FDTD- finite-difference time-domain; FEM-finite element), and more.

Shell windows have aragonite ($CaCO_3$) fiber optic cables, which transmit high-resolution images

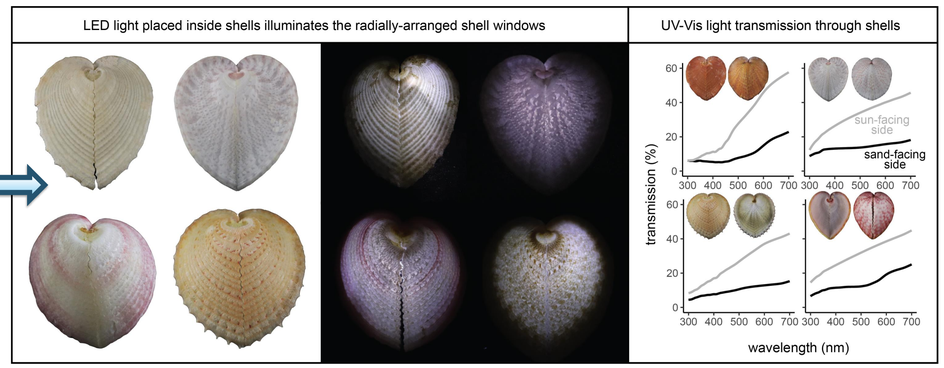


- Heart cockle shells are made of aragonite, the same material found in coral skeletons.
- Aragonite is an anisotropic crystal form of calcium carbonate ($CaCO_3$), with three refractive indexes corresponding to three axes (n_a=1.53, n_b=1.681, and n_c=1.686)
- In most marine animals, aragonite forms micro-scale plates.
- Surprisingly, in heart cockle shell windows aragonite forms fibrous prisms sized 1 x 1 x 200µm and aligned with incoming sunlight.
- These natural fiber optic cables project images at a high resolution (100 lines/mm) from one side of the shell to the other (akin to ulexite, the "TV rock.")
- The fibers are cladded by an organic matrix (n=1.435).
- Optical simulations show that the (i) fibrous prismatic shape and (ii) c-axis optical orientation may be adaptations to transmit more sunlight and screen out potentially harmful UV light.



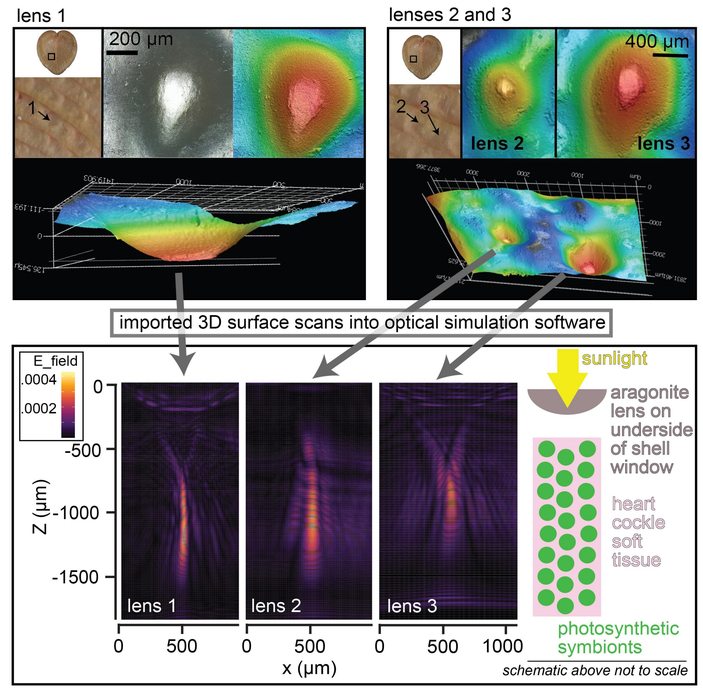
Shells in seawater transmit 30-50% of incident light and screen out potentially harmful UV light

- To illustrate the arrangement of shell windows, we placed an LED light inside the shells.
- To measure light transmission, we suspended fragments of shell in seawater in a cuvette.
- The sun-facing side of shells transmits ample light for photosynthesis but screens out potentially-harmful UV light due to the fiber optic structure (FEM simulations).



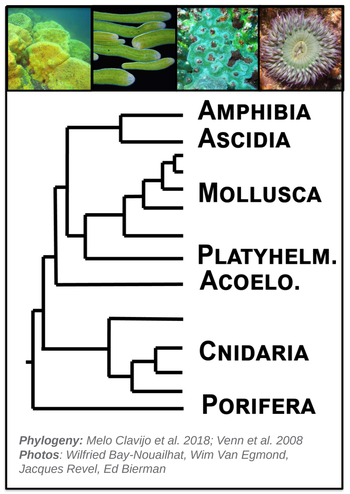
Condensing lenses focus sunlight into a beam to irradiate symbionts

- In some individuals, under each shell window lies an inward-facing bump with a truncated top that acts as a condensing lens.
- We obtained 3D surface scans (laser scanning microscopy) which we imported into optical simulation software (Lumerical FDTD).



Conclusions and Outlook

- Heart cockles evolved transparent shell windows with co-aligned aragonite fiber optic cables atop condensing lenses– a marvel of evolutionary innovation.
- UV light, which damages DNA and stresses algal symbionts *Symbiodinium*, is screened out in heart cockles– potentially protecting them from bleaching.
- In contrast, coral's symbionts are exposed directly to solar radiation *on top* of their aragonite skeleton.
- Unlike their giant clam relatives, heart cockles need not gape open to irradiate their symbionts (helping them avoid predation).
- What other photonic marvels lie hidden in photosymbiotic animals across the tree of life?



Phylogeny: *Melo Clavijo et al. 2018; Venn et al. 2008*
Photos*: Wilfried Bay-Nouailhat, Wim Van Egmond, Jacques Revel, Ed Bierman*

Acknowledgements

This work was funded by the Stanford Science Fellowship and the NSF Postdoctoral Research Fellowship in Biology. We are also grateful to Bio-X for their support.