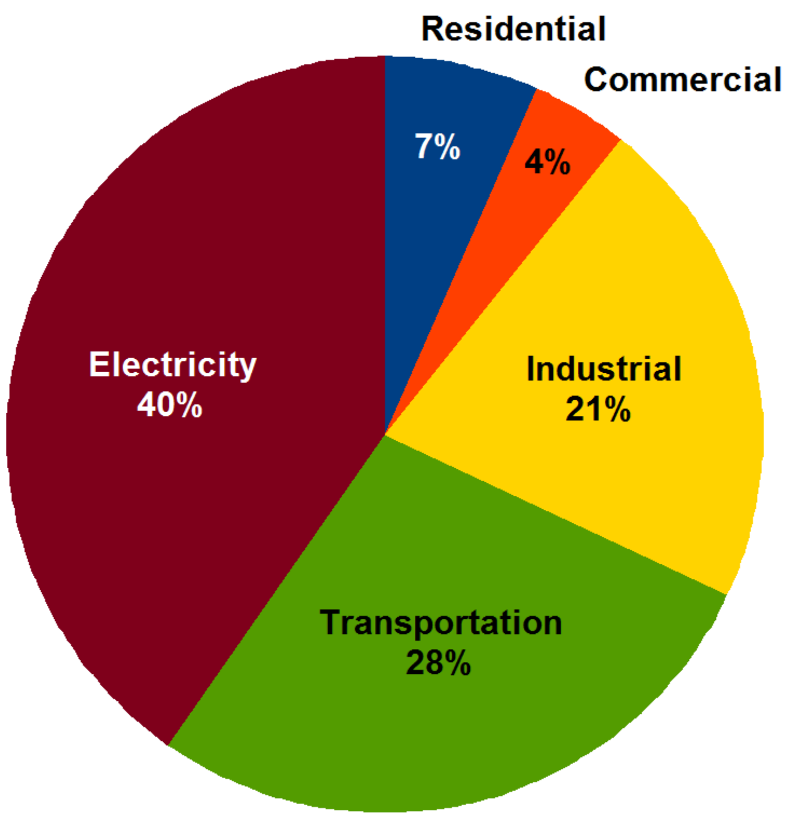
Bio-Inspired Design in Energy Applications

Anna Shneidman Harvard Energy Journal Club 10 Oct. 2018

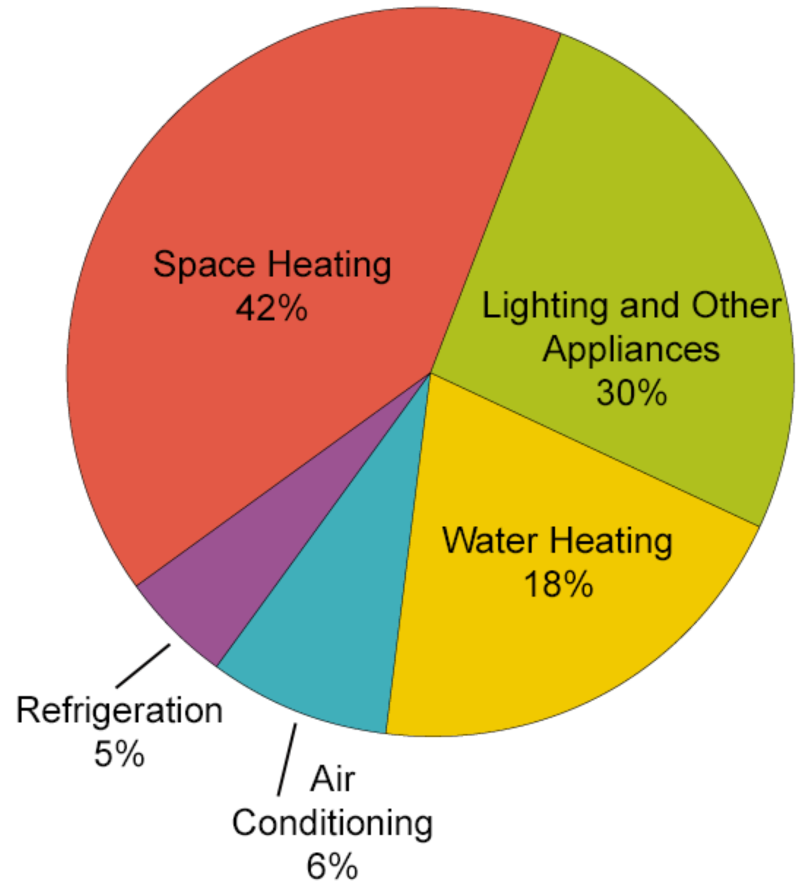
Background

US Energy Consumption by Sector



Data Source: US Energy Information Agency

How Energy Is Used in Homes (2009)*



* 2009 is the most recent year for which data are available.

Source: U.S. Energy Information Administration, *Residential Energy Consumption Survey (RECS) 2009*.

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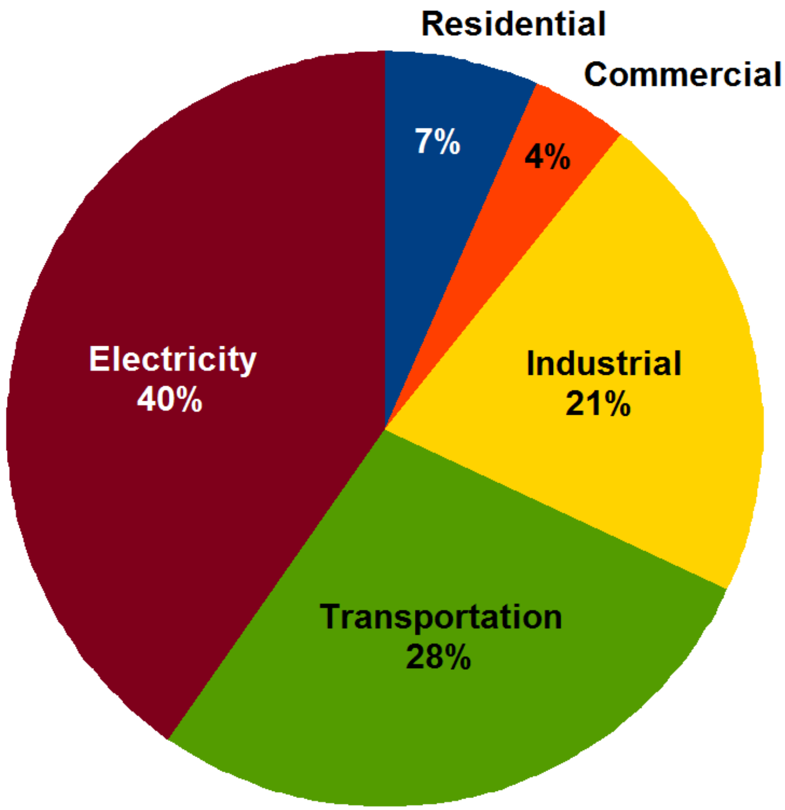

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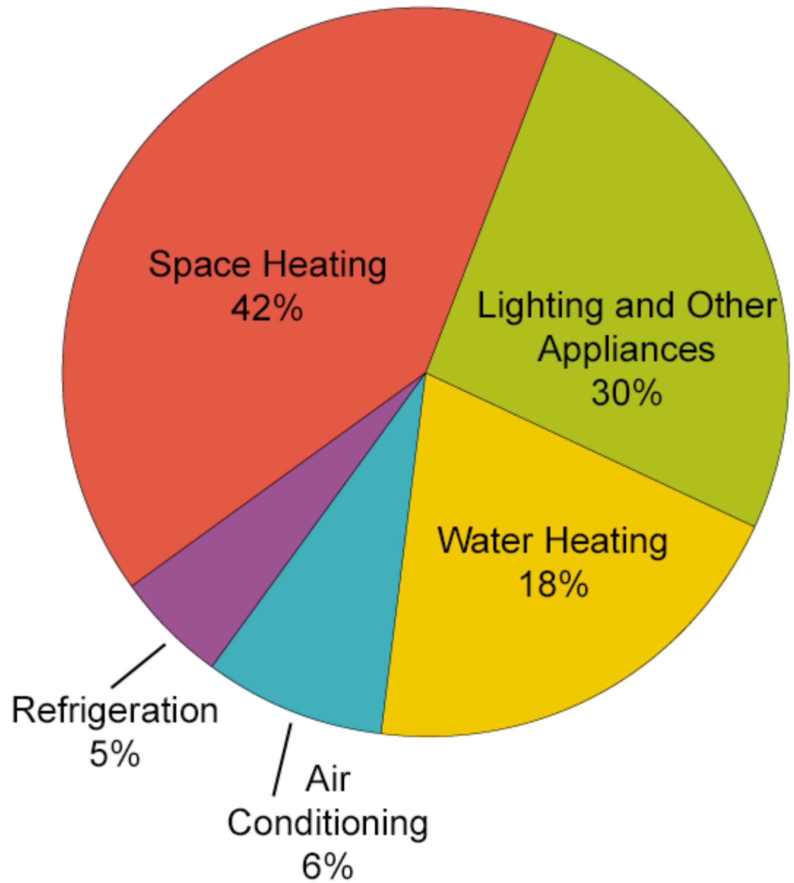


* 2009 is the most recent year for which data are available.

Source: U.S. Energy Information Administration, *Residential Energy Consumption Survey (RECS) 2009*.

<u>Key question</u>: how can we increase efficiency in all of these sectors?

Bio-inspiration

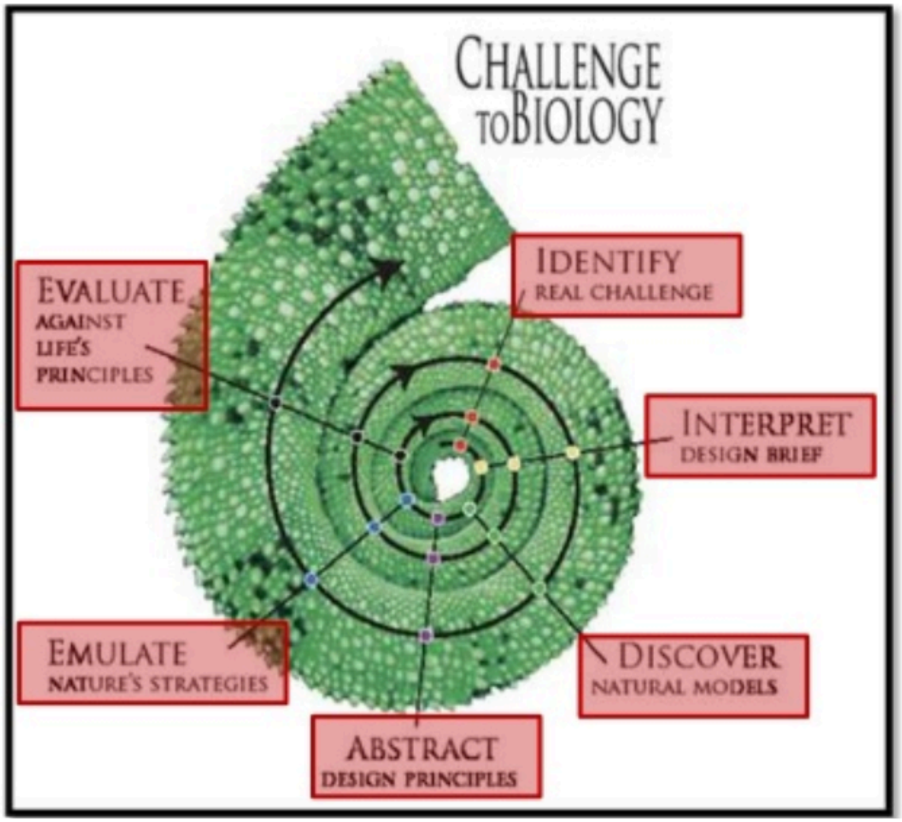
If we look into Nature, we see that organisms are remarkably well-adapted to their environments due to external and internal structures, as well as behavior (individual and collective).

- **They can swim or fly with minimal energy expenditure (transportation), keep warm/cool in cold/hot environments (thermal), and shine brightly (lighting).**
- **The ability of organisms to reduce drag and trap energy has implications for various applications (e.g. energy generation).**
- **The structures in organisms tend to be multi-functional. In some cases, this multi-functionality is critical to good function (e.g. self-cleaning surfaces).**
- **They are made through a careful balance of physical interactions between building blocks, meaning that expensive and energy-intensive equipment is not required (manufacturing).**

watch: https://www.youtube.com/watch?v=x2audOIniaQ&feature=youtu.be

Biomimicry and Bio-inspired Design

Once an organism which exhibits interesting phenomena is discovered, research typically involves detailed investigations to understand the design principles. When microstructures are involved, the following methods are often employed:



1) **Sectioning ("dissection") combined with optical and electron microscopies to identify and study structures responsible for certain effects.**
2) **Theoretical modeling (analytical and numerical simulations) of the structures obtained in #1 or a simplified analog to calculate the contribution of different parts to the effect.**
3) **Optimization algorithms using device-relevant materials to reach a target.**

By understanding Nature more deeply, humans can create new energy efficient solutions, or retrofit existing solutions.

Outline

Transportation

Thermal Management

Lighting

Energy Generation

Manufacturing

Transportation

Mission:

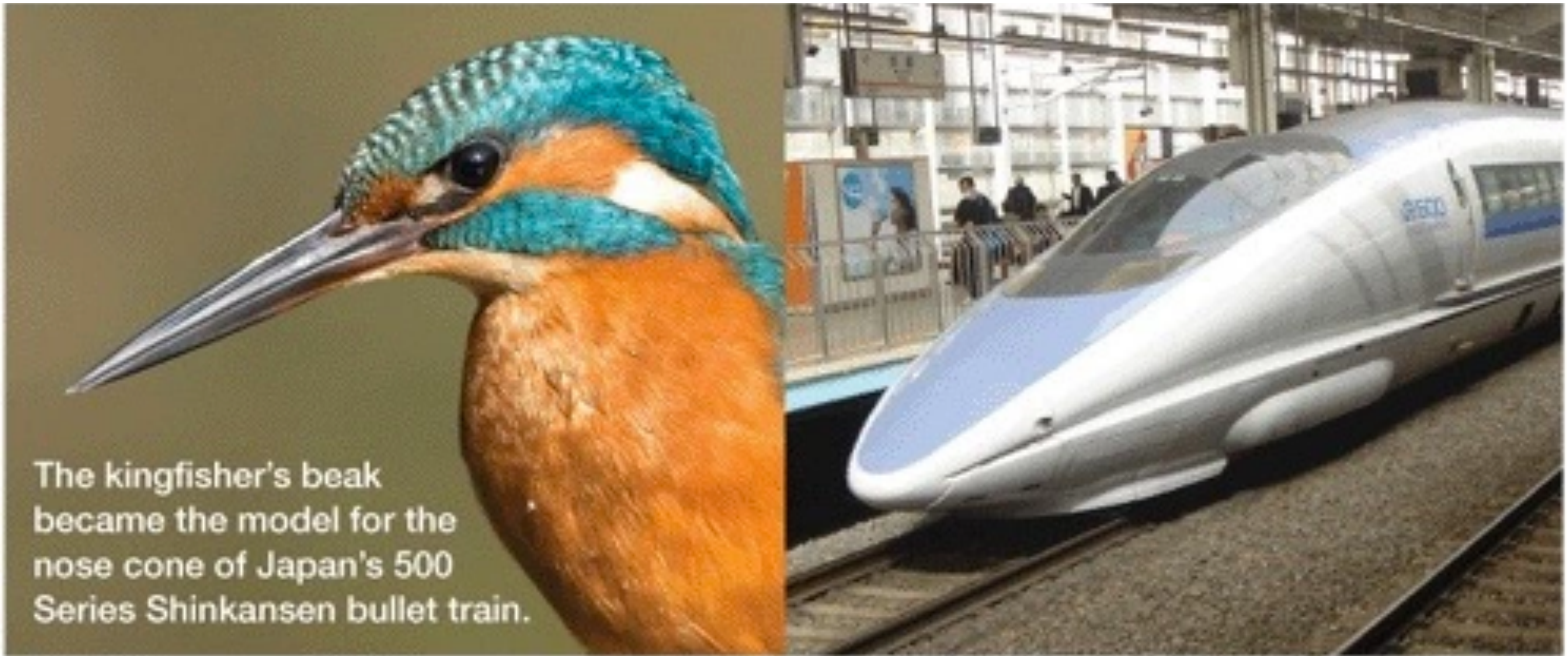
- Improve aerodynamics
- Reduce weight
- Increase fuel efficiency

While maintaining comfort, safety, crash-resistance.

In many cases, a “chimera” of organisms, combining various beneficial properties, can lead to the best technology.

Kingfisher-inspired Shinkansen Train

<u>Challenge</u> imposed by high speed trains: noise pollution.



<u>watch</u>: https://bit.ly/2jbTRnz
<u>recommended reading</u>: https://bit.ly/2epnsFx

200 mph, 10-15% more energy efficient than previous iteration due to enhanced aerodynamics

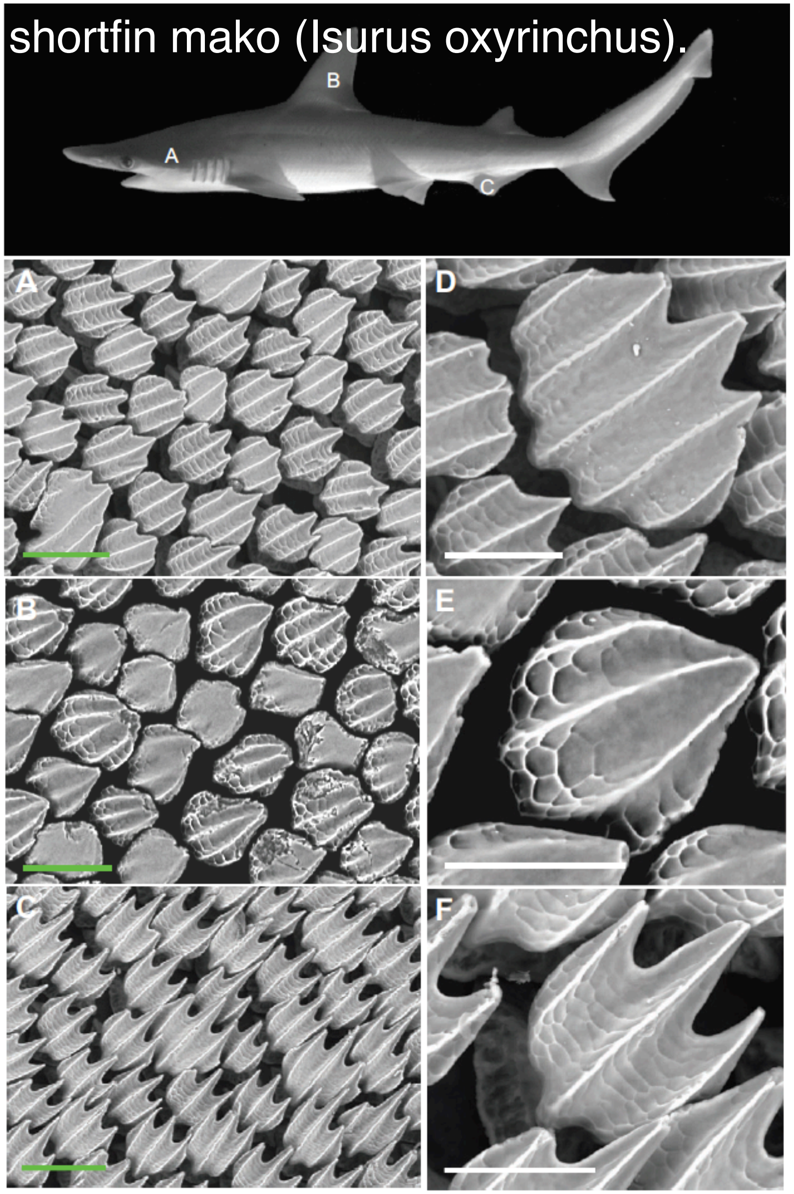
Yellow-boxfish-inspired Car

“Although the Bionic isn't coming to your local dealership, Mercedes does expect it to significantly influence the design language of its next generation of small cars.”

Source: https://web.archive.org/web/20131019205924/http://news.nationalgeographic.co.uk/news/2005/06/0615_050615_fishcar.html

- **Mimic the fish shape for the ease of maneuverability and speed: low drag coefficient, up to 118 mph.**
- **The rigid exoskeleton with honeycomb pattern for maximum strength for least weight: 30% weight reduction, 70 mi/gallon.**

Sharkskin-inspired Boats and Planes



<u>Challenges</u>:

- **Turbulent flows at the boat/water (plane/air) interface introduce drag.**
- **Biofouling increases mass and impairs the aerodynamic shape.**
- **Costs: for example, the Navy spends $550-600 million/ year on powering ships and submarines. At least $50 million is due to fouling-related increases in drag.**

<u>Shark-based solutions</u>:

- **Corrugated scales control water flow, including vortex formation**
- **Dynamic surface prevents fouling by barnacles and algae**

Sources: - http://research.ufl.edu/publications/explore/v10n1/extract6.html
- L. Wen, J.C. Weaver, G.V. Lauder "Biomimetic shark skin: design, fabrication and hydrodynamic function" The Journal of Experimental Biology (2014) 217, 1656-1666

Thermal Management

Mission:

- **Better thermal insulation**
- **Improved heat exchangers**

Thermal Insulation in Nature

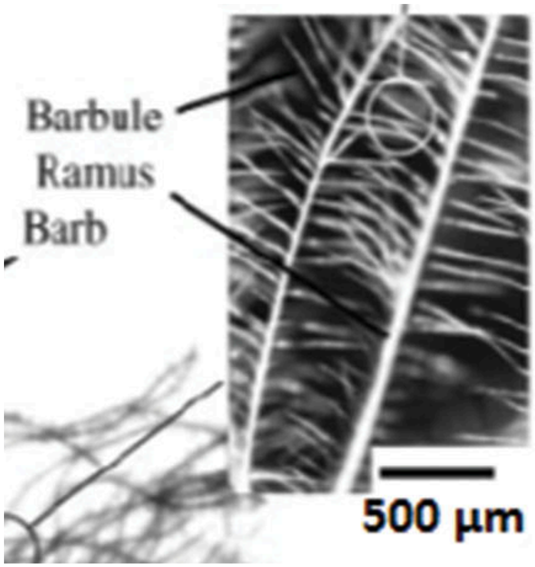
Organisms in various environments have developed methods to minimize heat loss.

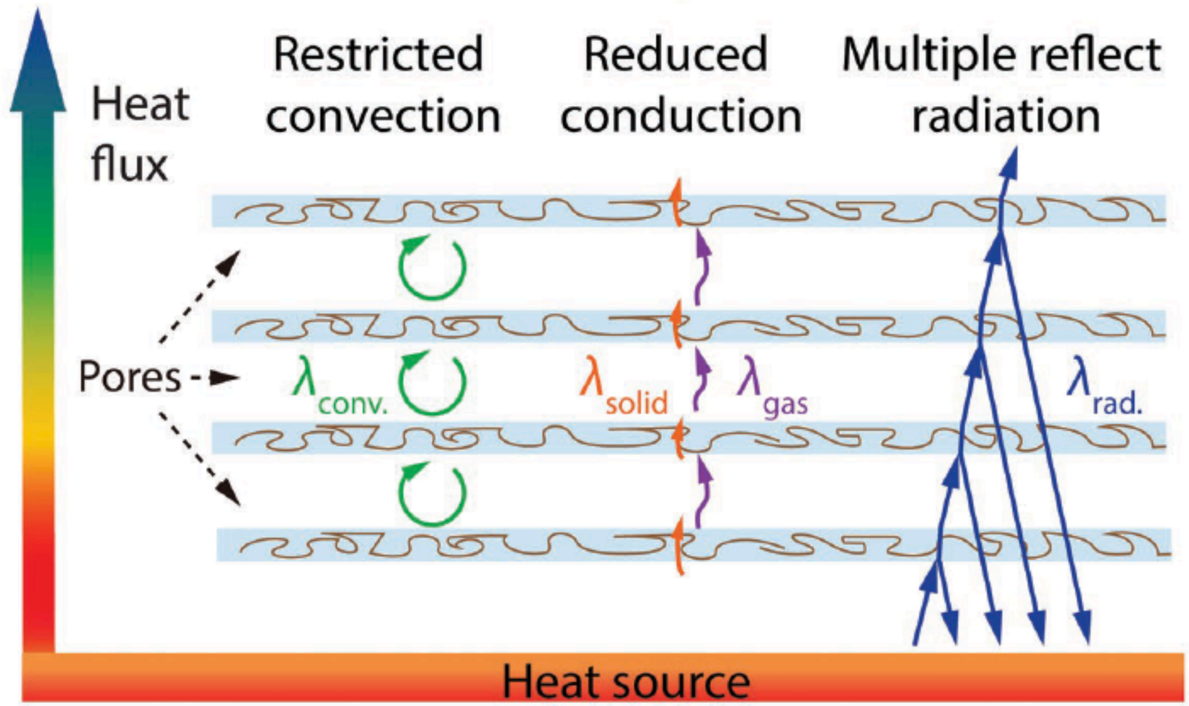



Penguins and polar bears have feathers and fur designed to trap their IR radiation. The silkworm cocoon has interwoven fibers for the same effect, as well as calcium oxalate crystals deposited on the outer walls for mechanical stability, protection against wind, and additional heat trapping.

Studies of Thermal Insulation Strategies

- **Experimental investigations include optical and electron microscopy and spectral measurements of reflection/ transmission.**
- **Theoretical modeling (analytical and numerical simulations) gives insight into the mechanisms.**



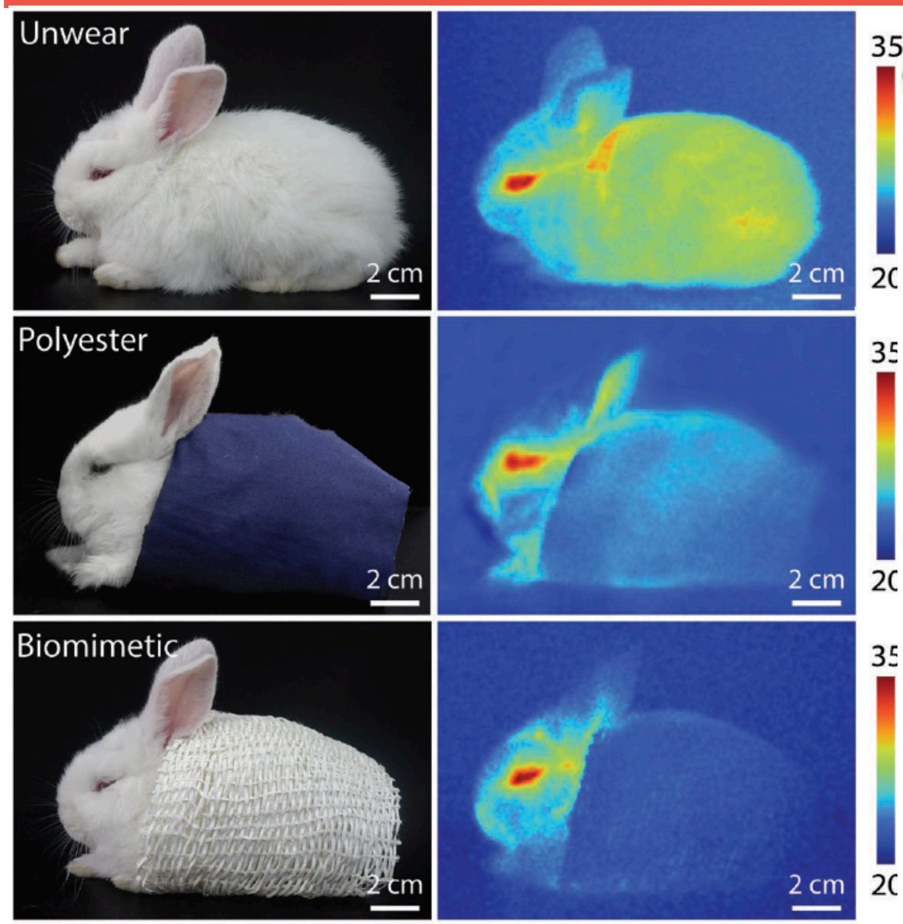


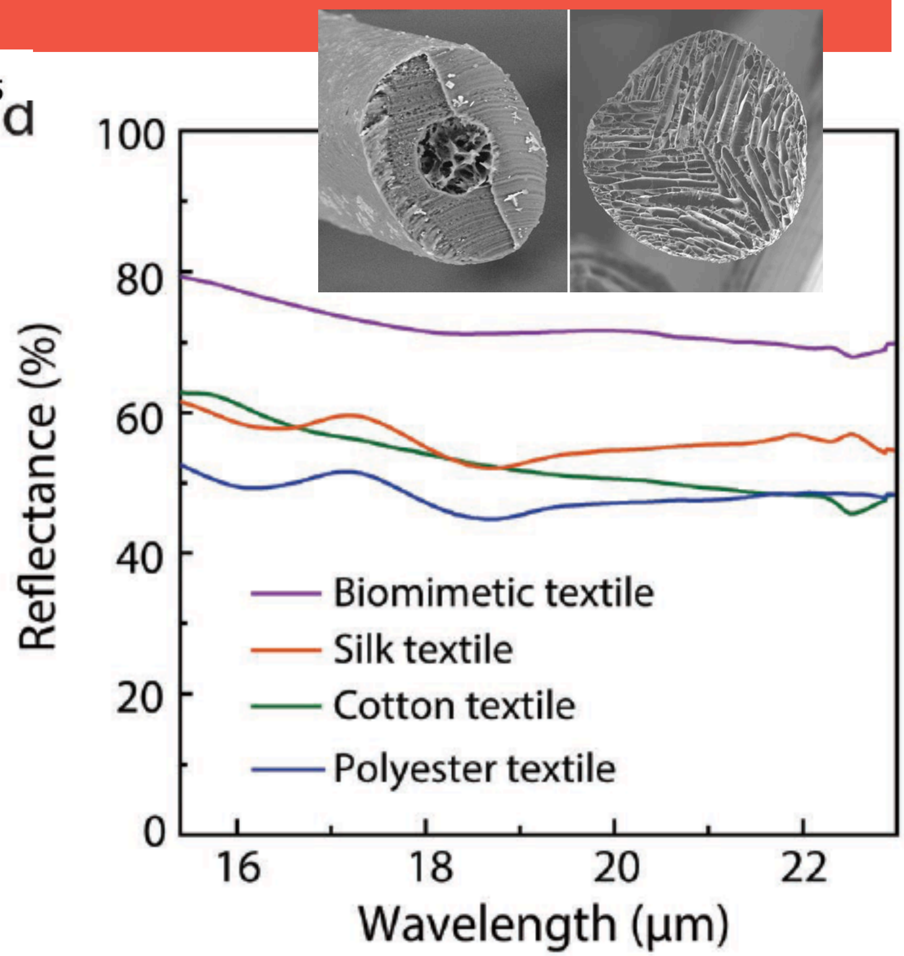
Sources: P. Tao et al. "Bioinspired Engineering of Thermal Materials" Adv. Mat. 2015; N. Du "An improved model of heat transfer through penguin feathers and down."J. Theor. Bio. 2007; Y. Cui et al. "A Thermally Insulating Textile Inspired by Polar Bear Hair." Adv. Mat. 2018.

In all cases, the porosity of the feathers, fur, or fibers results in a much lower thermal conductivity than in the unstructured case, due to the mechanisms shown above.

Polar-Bear-Inspired Blankets for Bunnies

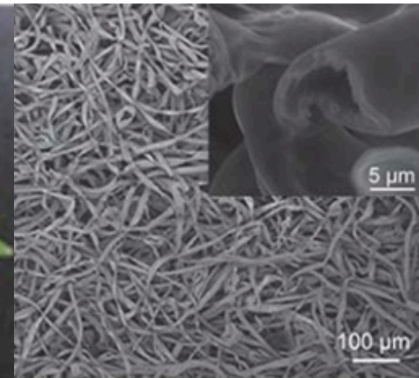
A new textile showing excellent thermal insulation properties was developed based on polar bear fur. It is produced using a “freeze-spinning” technique was for continuous and large-scale fabrication of fibers with aligned porous structure. The textile also displays good breathability and wearability.

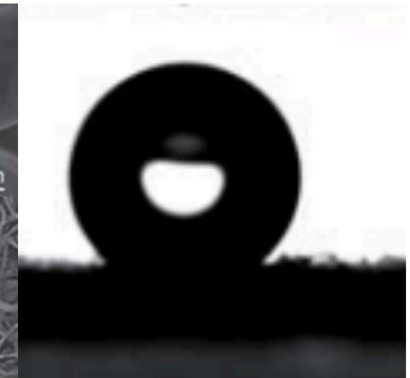


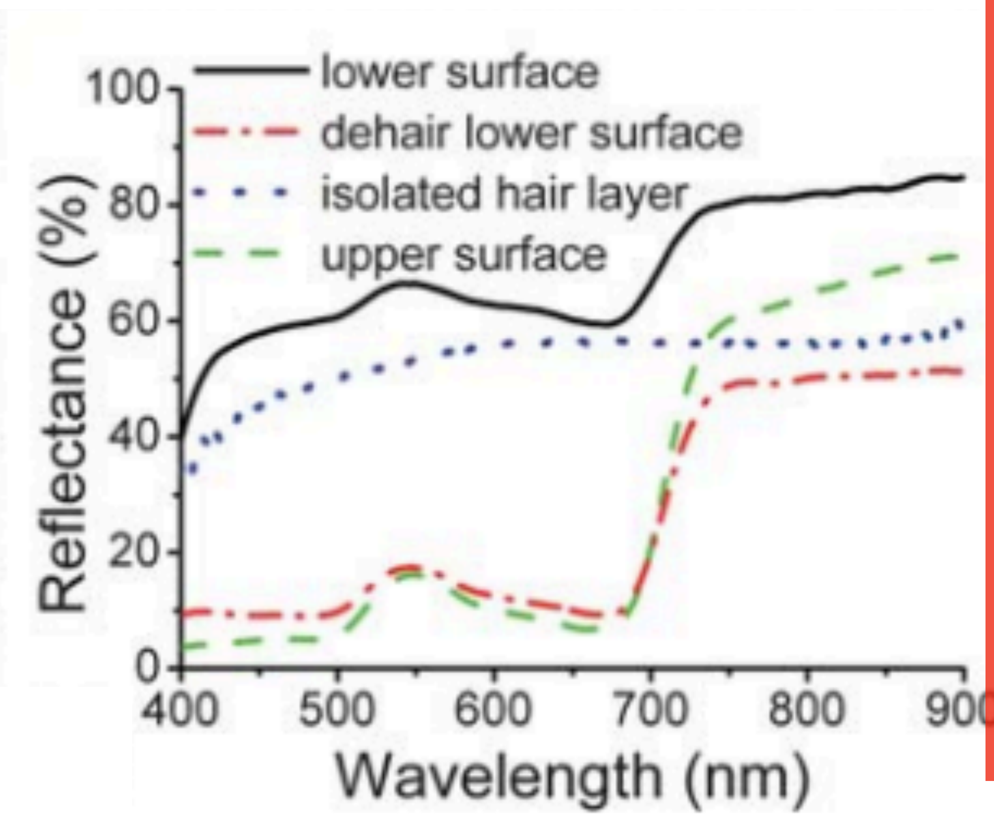


Source: Y. Cui, H. Gong, Y. Wang, D. Li, and H. Bai “A Thermally Insulating Textile Inspired by Polar Bear Hair” *Advanced Materials*. 2018.

Employing Microstructures to Keep Cool







Researchers used SEM to find that the lower surface of the leaves is covered by densely packed hollow fibers that behave similarly to polar bear fur and penguin feathers, only now reflecting IR from outside, thus preventing the plant from heating up.

An additional benefit is that the surface is superhydrophobic, leading water to bead up and slide off, rather than spreading.

Source: C. Ye at al. "Highly reflective superhydrophobic white coating inspired by poplar leaf hairs toward an effective "cool roof"" *Energy Environ. Sci.* 2011.

Poplar-Leaf-Inspired Cool Roofs

Broader context

The phenomenon of urban heat islands is becoming increasingly urgent. Increasing the urban albedo could result in reflecting more of the incoming global solar radiation, reducing cooling costs and electricity consumption of buildings. Highly reflective urban surfaces, or "cool roofs", could contribute to significant energy savings and hence a reduction in greenhouse gas emissions. Therefore the global warming effects could be slowed down to some extent. Studies have demonstrated that when the reflectivity of the roof rises to about 60%, the energy consumed for cooling the building cooling is reduced by more than 20%. In this paper, we investigated the role of the hairs on the poplar leaves' lower surface in scattering sunlight, and found that the hollow hairs provide the poplar leaves with an effective coating against the strong light. By learning and mimicking the natural phenomenon, we made a highly reflective and superhydrophobic white coating after the hair structure. The achieved bio-inspired fibrous films have high reflectance over a broad range of wavelengths, and will be of great potential for an effective "cool roof".

The researchers used the low-cost and "eco-friendly" technique of electro-spinning to mimic the hollow fibrous layer they found in their investigations of the poplar leaf. They demonstrated:

- **this can be accomplished with a wide range of polymer materials,**
- **high reflectance at visible and IR wavelengths,**
- **superhydrophobicity, which can help prevent water damage and erosion.**

Source: C. Ye at al. "Highly reflective superhydrophobic white coating inspired by poplar leaf hairs toward an effective ''cool roof''" *Energy Environ. Sci.* 2011.

Lighting

Mission:

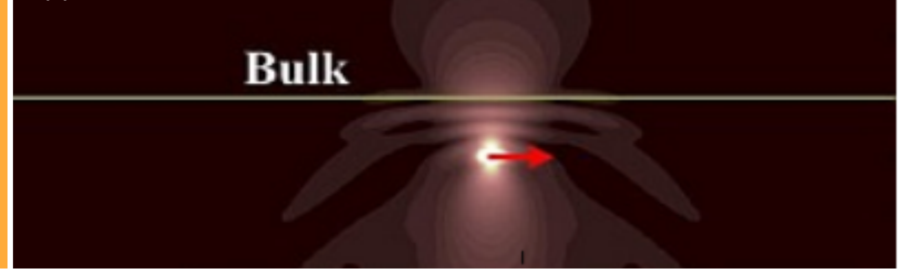
- Improve efficiency

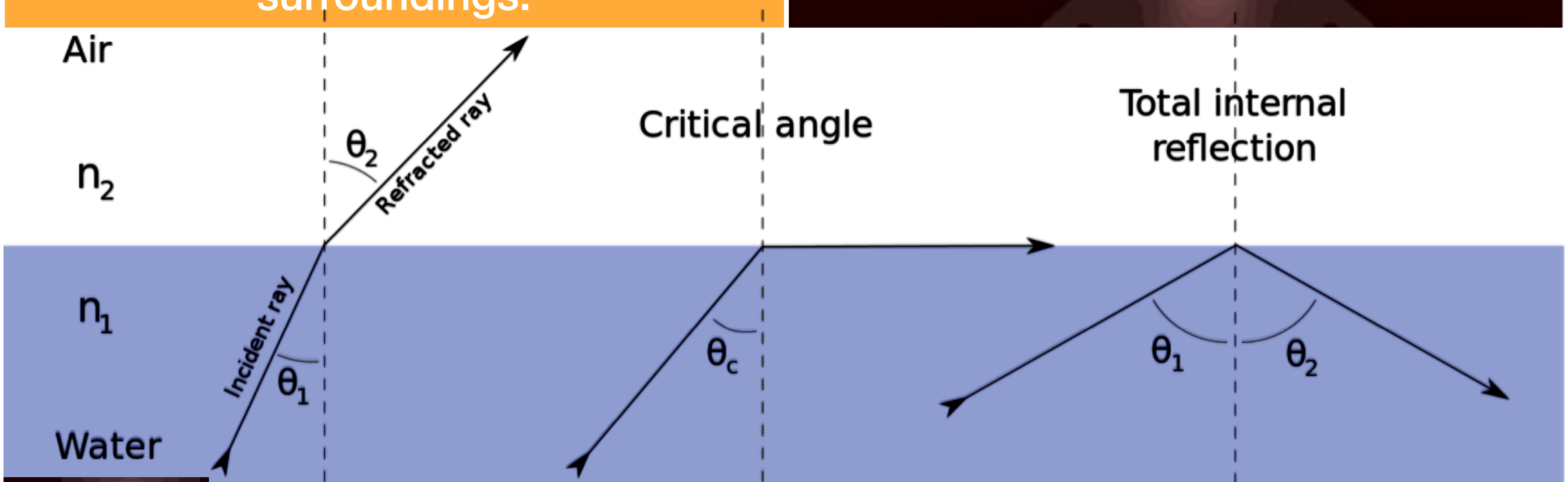
While maintaining visual comfort

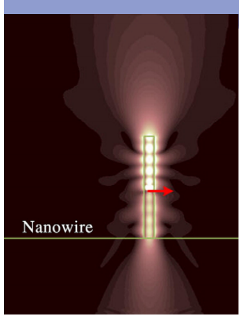
Surfaces for Better Light Extraction

Challenge:
Light gets trapped inside the material where it is created because of the mismatch of refractive indices between the material and its surroundings.

Source: B.J.M. Hausmann et al. "Fabrication of Diamond Nanowires for Quantum Information Processing Applications." Diamond and Related Materials. 2010







Source: https://en.wikipedia.org/wiki/Total_internal_reflection

Solution:
Structure the surface to frustrate total internal reflection.

Firefly-inspired LED Coatings

Bioinspiration:

- Fireflies are bioluminescent — they transform chemical energy into light. Like manmade devices, the light can be trapped inside their "lanterns."
- A 2013 study found that *Photorius sp.* fireflies have an enhanced light extraction efficiency (brighter for the same chemical energy) than would be expected for the lantern material.

https://www.mnn.com/earth-matters/animals/stories/why-do-fireflies-glow

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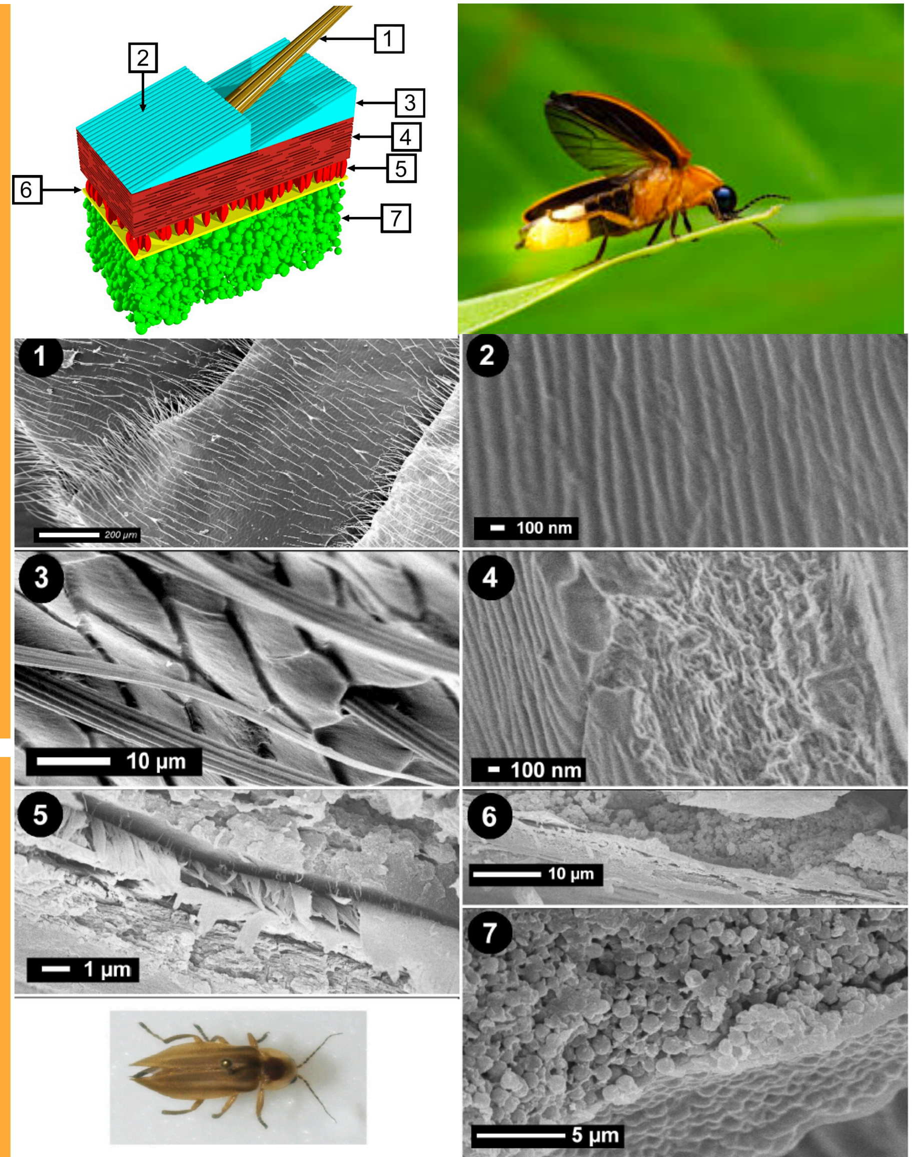
Analysis:

- Optical modeling and experimental measurements of the different layers were performed to identify the most important contributions to the enhanced performance.



Source: A. Bay et al. "Improved light extraction in the bioluminescent lantern of a *Photuris* firefly (Lampyridae)," *Optics Express,* 2012.

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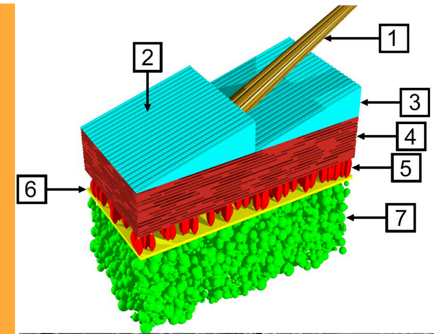
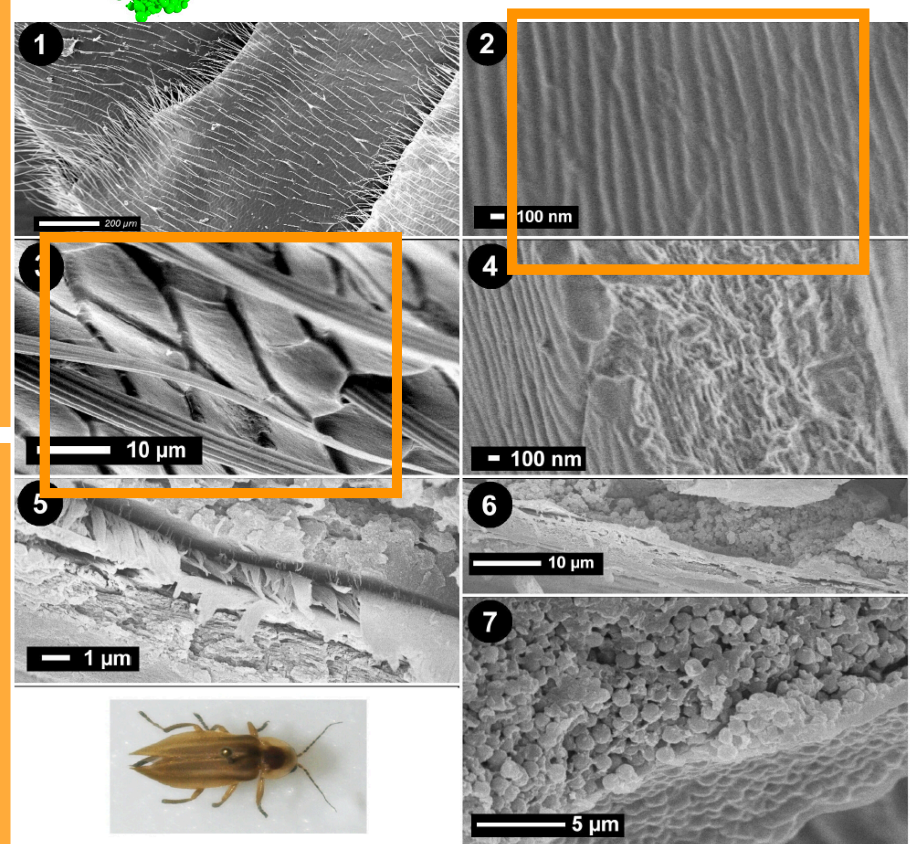


Conclusion:

- Surface corrugation is key!

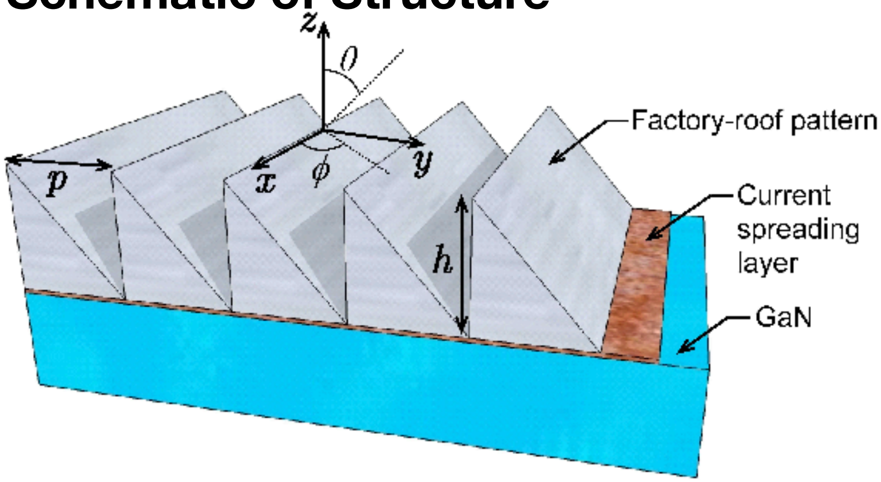


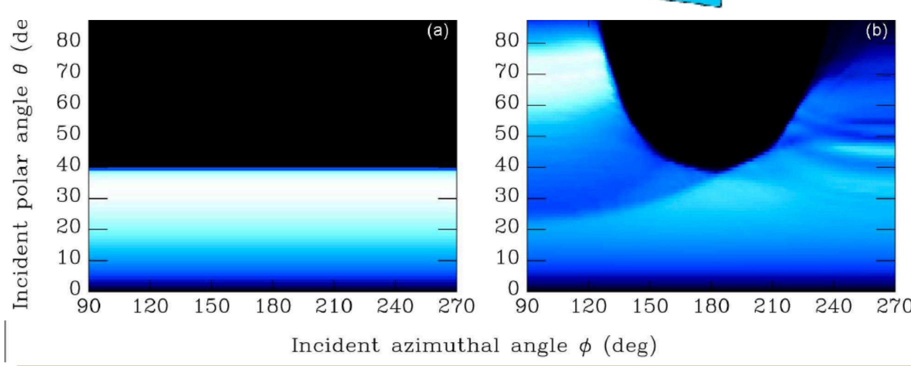
Source: A. Bay et al. "Improved light extraction in the bioluminescent lantern of a *Photuris* firefly (Lampyridae)," *Optics Express,* 2012.

Firefly-inspired LED Coatings

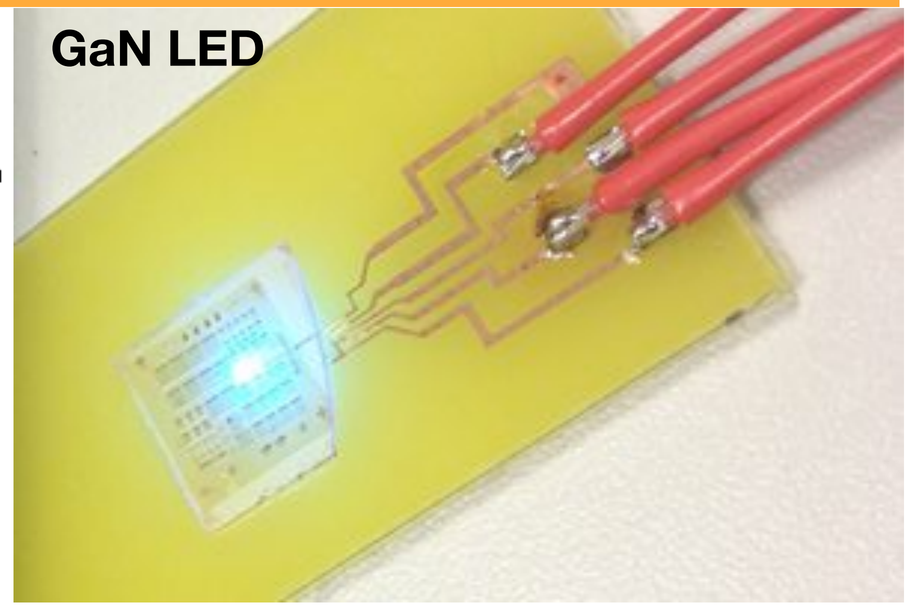
A supplementary “factory-roof-patterned” layer of polymer based on the firefly scale structure is added on top of an existing GaN (gallium nitride) LED to improve it’s output — this is advantageous from a. Fabrication standpoint since polymers are much easier to process than GaN.

Schematic of Structure





GaN LED



Left: Simulated light extraction for (left) planar surface (right) factory-roof-patterened surface.

Source: A. Bay et. al. "An optimal light-extracting overlayer, inspired by the lantern of a *Photuris* firefly, to improve the external efficiency of existing light-emitting diode,” *Optics Express,* 2013.

Up to 55% enhanced light extraction compared to an LED made of the same materials without the bio-inspired surface structure.

Energy Generation

Mission:

- **Improve efficiency of energy generation**

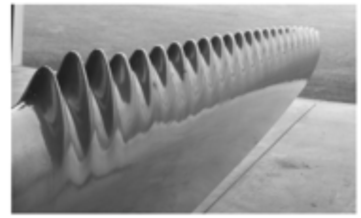
In particular, wind + solar energy will be discussed here

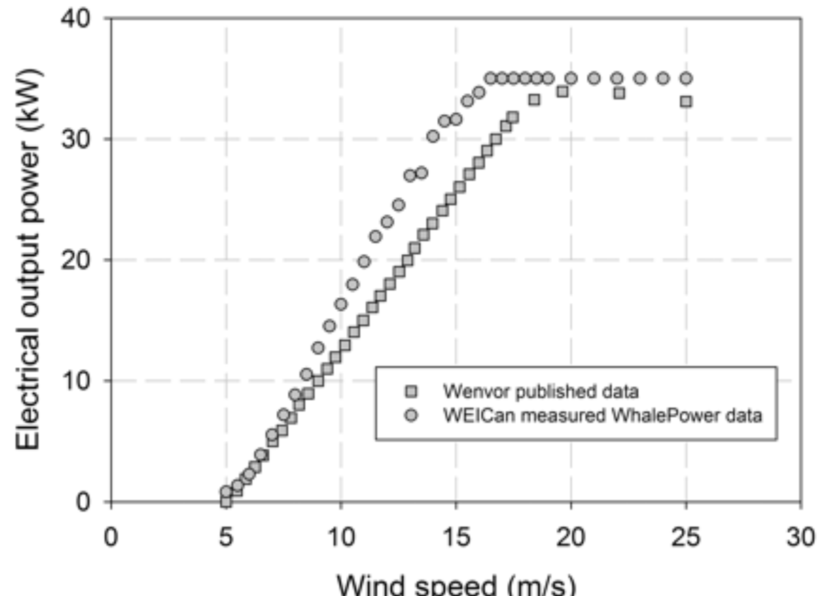
- **Improve turbine performance**
- **Improve light absorption (e.g. for solar cells)**

Biology can inspire improvements to the individual energy-converting device, as well as to a farm of devices (when collective behaviors of multiple organisms are studied).

Whale-fin-inspired Turbine Blades and Fans

Source: Frank E. Fish, Paul W. Weber, Mark M. Murray, Laurens E. Howle; The Tubercles on Humpback Whales' Flippers: Application of Bio-Inspired Technology, Integrative and Comparative Biology, Volume 51, Issue 1, 1 July 2011





Challenges:

- **Poor reliability when winds fall or fail.**
- **Noise — especially due to tip stalling**
- **Poor performance in unsteady or turbulent air.**

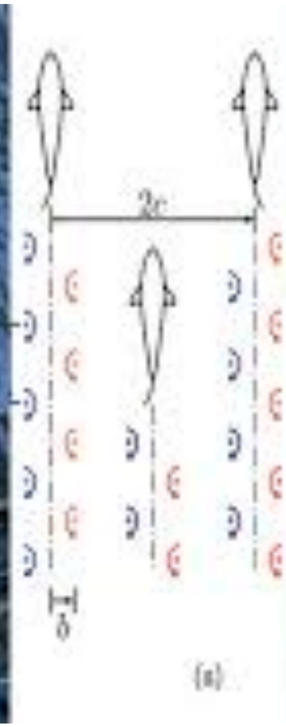
Source: https://whalepowercorp.wordpress.com/wind-turbines/

Whale-inspired solution:

- **Bumps on fin are used to reduce drag by controlling vortex formation and improving lift.**
- **WhalePower (Toronto, Ontario) tests such wind-turbine blades at wind-testing facilities in Prince Edward Island.**

Fish-School-Inspired Turbine Organization

<u>Challenge</u> imposed by grouping multiple turbines: interrupted air flow behind each turbine, leading to overall lower efficiency of the wind farm.



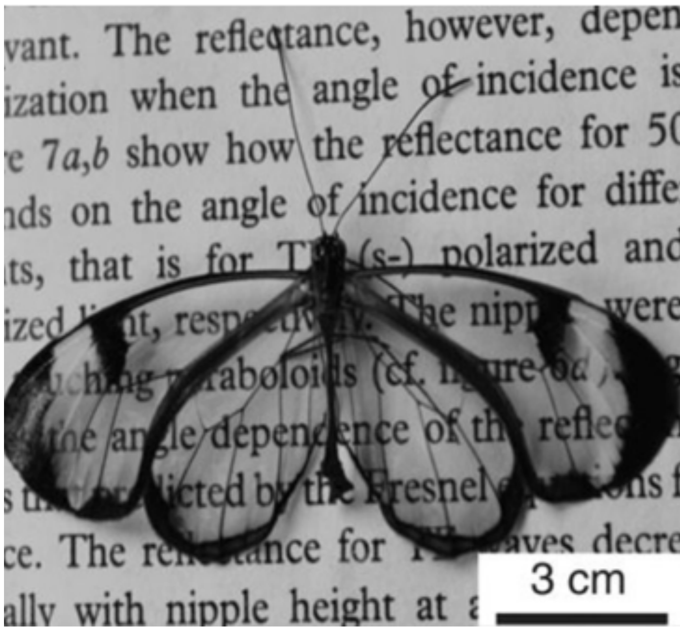
watch: https://www.youtube.com/watch?v=x2audOlniaQ&feature=youtu.be

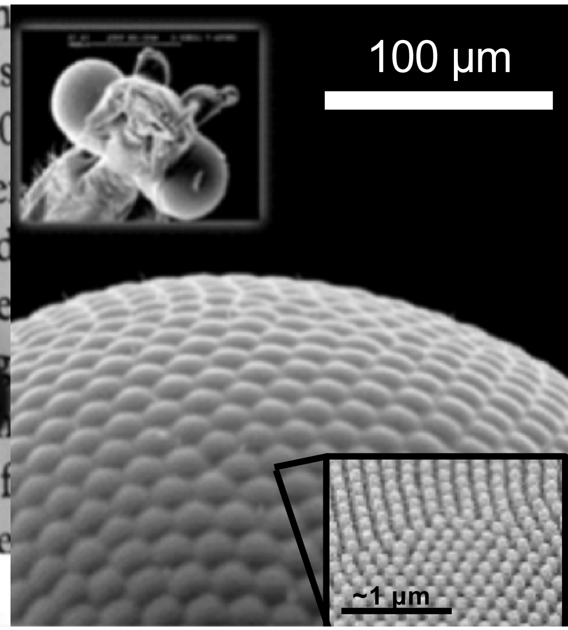
Source: <u>http://bioinspired.caltech.edu/windenergy/projects.html#fish</u>

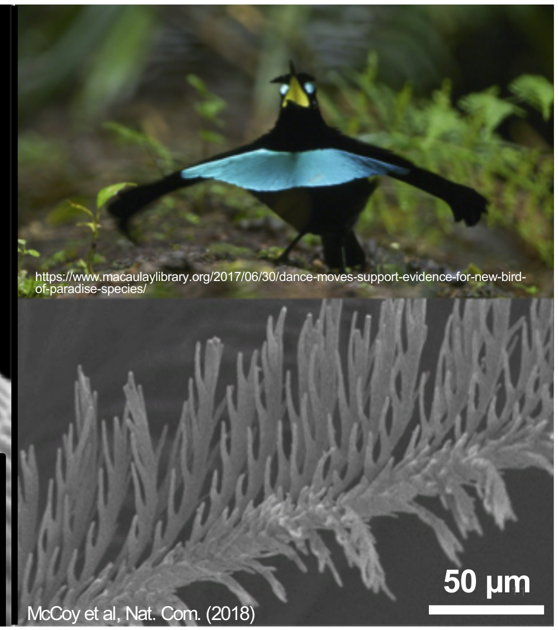
Observations that fish schools can take advantage of vortices produced by their neighbors, combined with fluid dynamics models and field tests have led to the understanding that this problem can be mitigated by constructive aerodynamic interference between adjacent group members leading to enhanced power density (i.e. power output per area of land) of wind farms based on these principles.

Surfaces for Better Light Collection

<u>Challenge:</u> refractive index contrast between material and air leads to reflections at the surface, thus reducing the amount of light that can be collected by an organism or a solar cell.





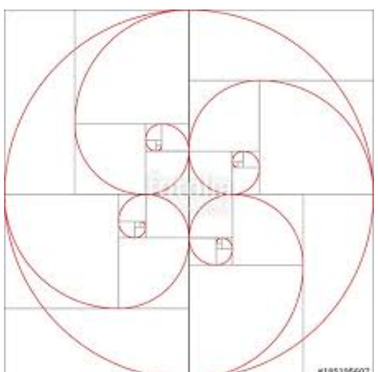


- **The butterfly wing and moth eye are coated with nanostructures to alleviate the abrupt change in refractive index between air and eye, thus minimizing reflections.**
- **The bird of paradise contains “super black” regions where the amount of light absorbed by melanin inside the feathers is enhanced by multiple scattering due to the shape of the feather barbules.**

Sunflower-Inspired Mirror Arrangement

Hunders of heliostats (mirrors) rotate with the sun and reflect concentrated sunlight towards a central tower, where water is heated to steam, driving a turbine to produce electricity.

Source: N. Collins "*Science*Shot: Sunflowers Do the Math" ScienceShots 2013



Source: https://asknature.org/idea/concentrated-solar-plant/#.W74M5RNKhsM

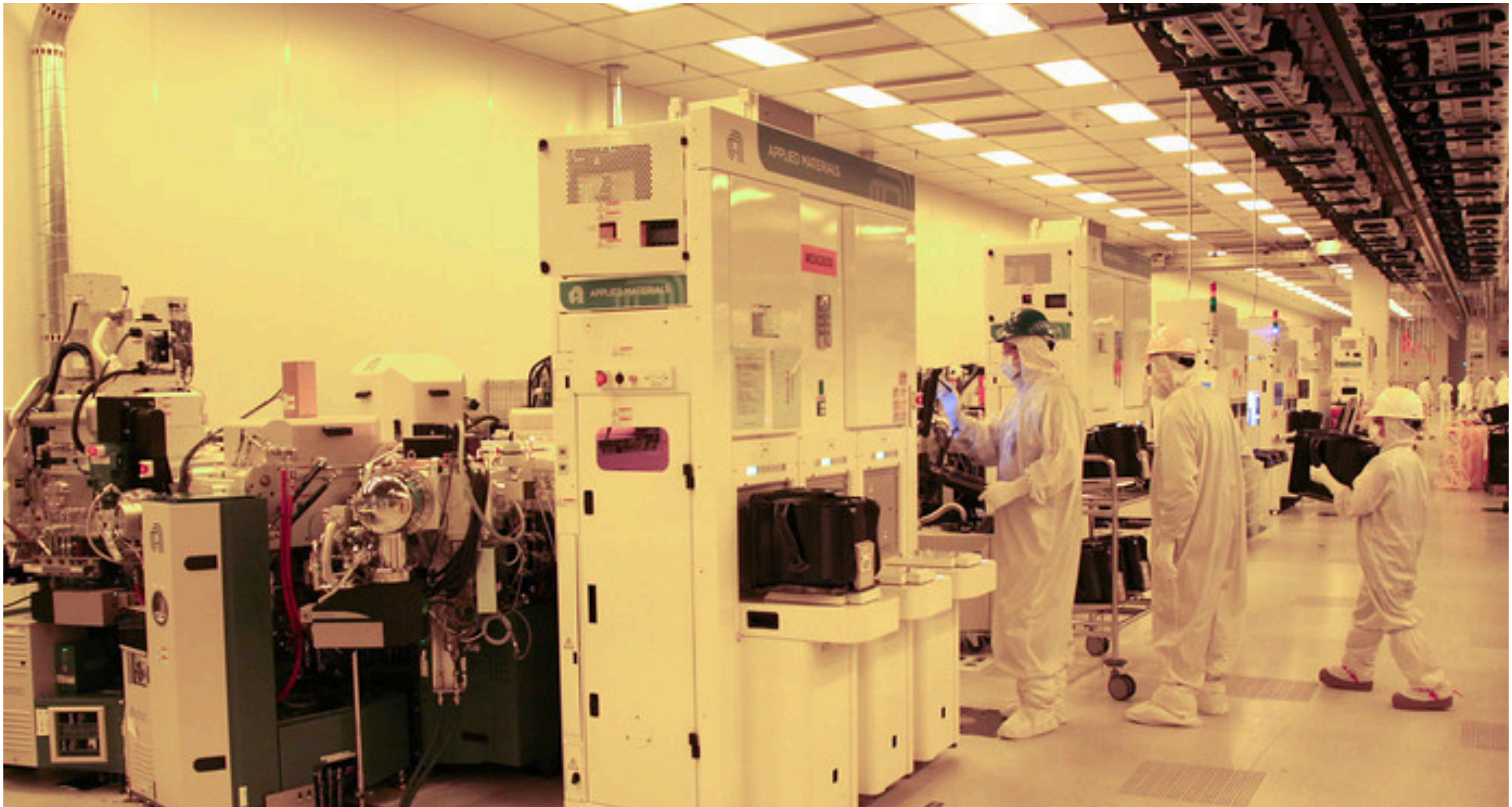
The arrangement of mirrors according to a Fibonacci spiral occupies up to 20% less land and exhibits higher efficiency than previously optimized designs.

Manufacturing

Mission:

- **Scalable fabrication**
- **Compatible with current industries**
- **Low toxicity**
- **Low energy inputs**

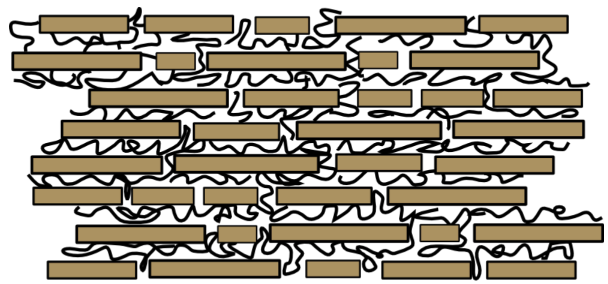
Nature's Fabrication Does Not Look Like This

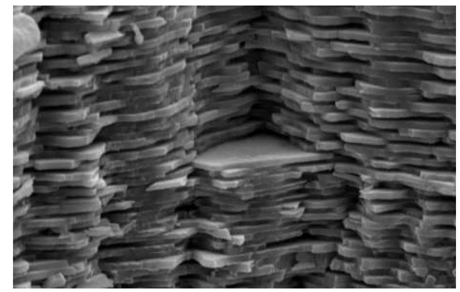


Without any sophisticated tools or equipment, Nature assembles complicated 3D hierarchical structures with precise arrangements from the nanoscale through the macroscale. This leads to subcellular structures with complex functions, to individual cells, and multicellular organisms.

Employing Nature's Design Strategies in the Lab

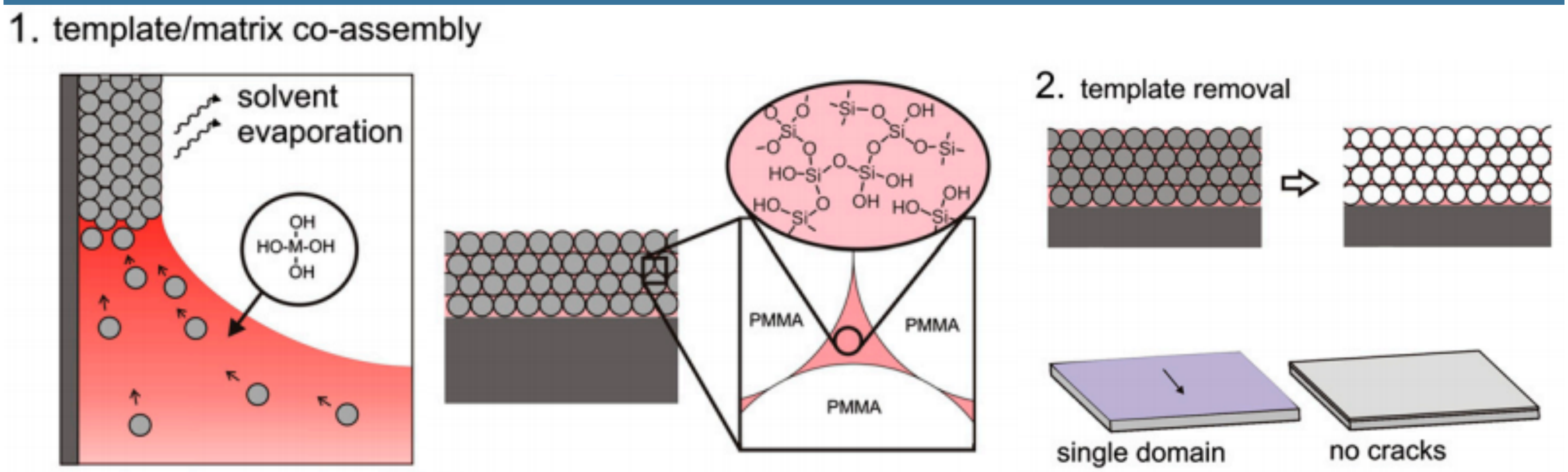
A common design strategy in Nature is to use an organic components to template the deposition of inorganic ones (biomineralization). For example, nacre growth is mediated by organics, controlling the onset, duration and form of crystal growth.





Source: https://en.wikipedia.org/wiki/Nacre

Inverse opals provide a low cost, "single-step", scalable fabrication.



Source: B. Hatton et al., *PNAS,* 2010.

Summary I



- **Natural systems have evolved numerous architectural and behavioral strategies to manage various forms of energy.**

- **The fabrication strategy does not require expensive equipment which itself is expensive and a huge energy cost.**

- **By understanding these systems more deeply, humans can create new energy efficient solutions, or retrofit existing solutions.**


Summary II

- **Transportation:**
  - **Aerodynamic shapes of sea creatures and birds as well as low-friction interfaces can reduce drag and noise pollution**
  - **Surface structures can control vortex formation.turbulence of medium through which they move, as well as prevent fouling.**

- **Thermal Management:**
  - **Many organisms use porosity to trap air, reducing convection, and to increase the reflection of IR radiation, either to stay warm (body warmth is trapped inside) or to cool down (external radiation, e.g. from the sun, is reflected away.**
  - **Numerous other strategies that were not discussed: vasculature-inspired heat exchangers, surfaces with optimized condensation and/or evaporation for latent-heat-based heat transfer, and perspiration-inspired cooling of electronic devices.**

Summary III

- **Lighting**:
  - **Organisms have developed microscopic surface structures to frustrate total internal reflection in order to maximize light emission. Such structures have been applied to LEDs to improve their efficiency.**

- **Energy Generation**:
  - **Wind turbines can benefit from structures that reduce drag, for example nodules on whale fins.**
  - **The light-collection ability of solar cells can be improved by employed nano- or micro-structured surfaces seen in nature.**
  - **Both wind farms and solar collection arrays can be optimized by learning from collective behaviors, e.g. fish schooling and spiral arrangements.**

- **Manufacturing**:
  - **Fabrication of complex 3D hierarchical structures in Nature does not require the enormous energy input and sophisticated equipment used by humans. Several assembly strategies have been developed based on studies of Nature's principles.**

Outlook

There are countless examples of concepts and strategies that can be learned from Nature beyond those discussed in this presentation. These include (but are not limited to):

- **Self-cleaning surfaces such as those inspired by the pitcher plant and lotus leaf are often essential to counter fouling the impedes almost all bio-inspired devices.**

- **Photosynthesis and strategies for efficient distribution of nutrients have inspired various solar-energy-harvesting technologies, catalytic converters, and fuel cells.**

- **Bio-inspired energy storage for batteries and capacitors: could we take lessons for charge transport/storage in capacitors and batteries from carbohydrates and ATP?**

•

…. and more!