Mother Nature Knows Best

Design issues solved by nature

A kingfisher on the hunt [1]

Word count: 2697

<David Attenborough voice>

INTRODUCTION

Nature has been interacting with water, air, light and matter since its existence. We came to the party many years later and have had less practice at making the most out of the resources available to us. We are continuing to be baffled by parts of the natural world and inspired by others. We have gone beyond our own habitat and are exploring every inch of the planet as best we can. What we find, however, is that everything in the natural world that wasn't made by us seems to be better than us. Particularly exciting is the phenomenal evolution of species to adapt into perfect inhabitants of their environment. Even small and harmless creatures are way out of our league. Bees and termites are better architects than us [2] and ants never stand in traffic despite the huge numbers of commuters on the same route. Naturally, we have been inspired by nature. Leonardo Da Vinci's flying machines were often based on observations of birds [3]. In fact, the successful flying machine made by the Wright brothers was based on observations of pigeons [4].

Copying nature to overcome our design hurdles is known today as biomimicry, defined by the Biomimicry Institute [5] as "an approach to innovation that seeks sustainable solutions to human challenges by emulating nature's time-tested patterns and strategies." The term was not popularised until a book was published in 1997, in which Janine Benyus [6] suggests we should use nature as "A model, measure and mentor." I wholeheartedly agree. A key element of biomimicry is the sustainability of the design, which is extremely important as while we are taking inspiration from nature, we can't be simultaneously working to destroy it.

The challenges met in designs are often those studied in physics. Issues such as poor energy efficiency, friction and air resistance slowing our inventions down. In this article, some of these issues will be discussed, as well as the inspiration of the natural world that solved them, mainly focusing at interaction with various aspects of the natural world: water, air, matter and light.

THE DEEP BLUE: WATER

Most of the planet is covered by water and we use it for convenient transportation, we explore its depths and marvel at the weird and wonderful creatures it hides. However, those who have lived in it for over 400 000 000 years [7] are far more accustomed to the tricks of the habitat. As we travel through and over the seas, we require materials for boats, submarines and swimmers that experience minimal drag and don't get covered in algae, in order to reduce energy consumption and allow for easier maintenance of our machines.

When an object moves through water completely submerged, it experiences two main types of drag: pressure drag and viscous drag. There are further forms of drag associated with an object moving on the surface of the water, but these are not considered in this discussion. Pressure drag occurs due to the pressure exerted by the object moving relative to the fluid. It is essentially related to the energy needed to transfer the fluid from in front of the objet to behind it. It is the same pressure dogs feel when they stick their heads out of car windows. Pressure drag is also called form drag, as it essentially depends on the form of the object. A reduced cross sectional area and a more streamlines shape will of course reduce the contribution of this type of drag. Viscous drag occurs due to the interactions between the fluid molecules. It is the force due to the viscosity of the liquid. The fluid will form layers around the object with the nearest one moving with the object and the subsequent layers being dragged along until the layers which are still and unaffected by the motion. This is used to describe the motion of objects in laminar flow, which is generally rare but can be used as an approximation. Within the very first layer of fluid, small vortices are formed, which eject into the next layers. This means that although the first layer is fairly coherent, the subsequent ones exhibit randomness and turbulence, slowing the object down. Turbulent flow is thus developed. [8] Submarines, boats and swimming people experience these types of drag and their reduction could greatly aid us in our ventures.

Fast swimming sharks manage to create incredibly little turbulent flow as they move, allowing them to be silent and undetected. They have pointy heads. This reduces pressure drag and is a technique humans worked out fairly easily. The phenomenal properties of viscous drag reduction are however the more interesting ones. Shark skin contains dermal denticles, which are essentially little pointed teeth attached to the surface of the skin, usually a few hundred

µm across, shown in Figure 1. These stop the fast moving water from breaking up into vortices within the first viscous layer, as they essentially trap the vortices to within the denticle layer. In turbulent flow, drag correlates with surface area, as it depends on the area of the object with which to interact. Although the denticles actually increase the surface area of the shark, by "trapping" the vortices, only the very tips of the denticles are left exposed to interact with the fast moving water. [8] The entire mechanism of this drag reduction is as of yet unclear, but it is definitely effective. The wonder of denticles doesn't stop there. They also exhibit antibacterial properties, as well as making it difficult for barnacles and algae to latch on, making the shark one of the cleanest dwellers of the deep blue, despite putting minimal effort into its hygiene. This evolution of a predator to move as smoothly as possible is simply JAWSdropping.

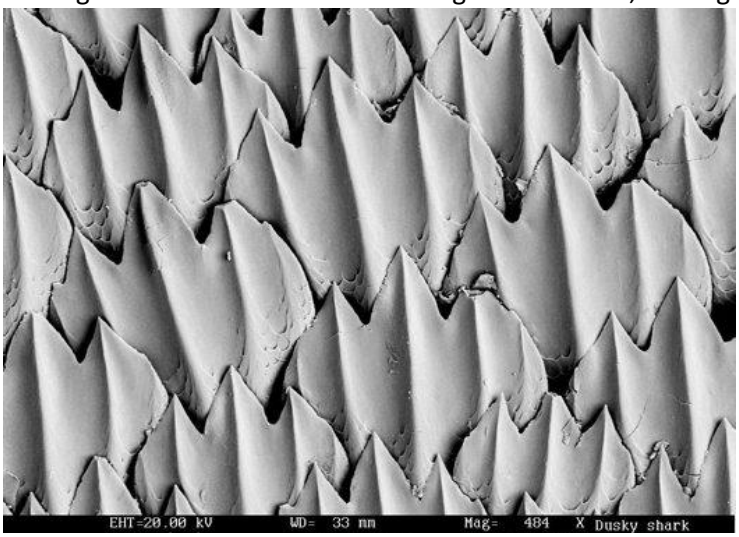

Figure 1: Shark denticles viewed by a microscope [9]

We have managed to mimic this type of patterned surface and manufacture artificial denticles for swimming costumes, wetsuits and boat surfacing. This has allowed us to move faster and keep surfaces travelling through water cleaner. Experiments testing micro-patterned surfaces have found energy dissipated due to turbulence to be reduced by ~25% compared to a smooth surface [10] and a speed increase of 25.2% [11] in swimming tests with the material. There may even be an application in hospitals to use micro-patterned surfaces, as they reduce bacterial attachment by up to ~98% [12]

DRAG IS IN THE AIR

The shark is not the only animal with the right idea. Owls use a similar principle to produce minimal disturbances in the air as they fly, making them close to silent in flight. This was used to solve a noise pollution issue caused by the Shinkansen bullet train, along with another bird inspiration – the kingfisher. The unique beak shape of the kingfisher produces very little rippling on diving into water. Together, these birds inspired solutions to two different parts of the same problem.

The Shinkansen bullet trains in Japan service a total of 2388km of railway and transport 820,000 people to and from work each day [13]. These trains also travel at speeds of up to 89 m/s and such fast movement is unfortunately very loud and comes with issues of noise pollution. The tracks run through many populated areas along the way, which led to a noise restriction of 75 decibels in order to protect the health of the habitats and residents, both human and animal, along the way [14]

There are two main causes of excess noise. Firstly, Karmen vortices are created by air flow past the pantographs, the features at the top of the train which link to the cables overhead, as well as past the body of the train and various other mechanisms mounted on top of the train. Karmen vortices are repeated swirling patterns of turbulence which alternate in direction and have been the cause for swaying and destruction of cooling towers or high levels of noise in the case of the bullet train. This is aerodynamic noise pollution, prominent at higher speeds, and scales as 6^{th} power of velocity [13].

Secondly, the piston effect caused sonic booms when travelling through tunnels. The piston effect describes motion of an object through a tunnel, as it can be modelled as a piston, assuming the cross sectional area of the object is close to that of the tunnel. As a train, for example, speeds through a narrow tunnel, the air in front of it experiences a great amount of pressure whereas the air behind experiences lower pressure. This causes a compression wave which builds up as the train travels along [15]. As the compression wave exits the tunnel, some of it is propagated out away from the tunnel and some is reflected back in. The expelled wave causes a loud bang called a tunnel boom, whereas the reflected wave causes pressure fluctuations which lead to discomfort for the passengers. The more pressing issue, the tunnel boom, can be around 149 decibels loud just 50m from the tunnel. [16] The contributions of these factors to noise had to be greatly reduced to fit within the pollution limit. Luckily, some of the design engineers working on this challenge were bird watchers.

Figure 2: Tawny owl serrations on the leading edge of the feather [18]

The owl has evolved to stalk its prey and land silently and undetected. There are numerous features of the wings and feathers which work towards this effect. One of these is small comb-like serrations at the leading edge of the wing, shown in Figure 2. When an object moves through a fluid, it can cause Karmen vortices. The serrations break up the vortices caused by flight into smaller ones, reducing turbulence.[17] Based on this idea, a cover was designed for the pantographs on the bullet train using small serrations and this was found to greatly reduce noise [19].

The kingfisher's beak is key in its ability to dive into water producing minimal ripples, as seen in Figure 3, important for its ability to hunt undetected. As the bird enters the higher drag environment of the water, it causes a minimal pressure to be exerted ahead of it, hence producing no ripples. This led to the perfect solutions: the beak was used as the shape for the front of the bullet train. In addition to reducing the width and height of the train to increase space around the train as it travels through a tunnel, this brought huge improvements. The train could now travel faster, stick to the 75 decibel limit and air resistance was decreased by 30%. In addition, the power consumption of the new and improved train was reduced by 13% compared to the previous model. [13]

Who knew kingfishers and owls could work together so beautifully? What a HOOT.

Figure 3: Kingfisher diving seamlessly into water, causing no visible ripples [1]

LET'S SHED SOME LIGHT

The kingfisher appears to be a simply universally magnificent bird. Its feathers are such a brilliant blue that they have inspired people to study them. Interestingly the bright orange feathers of the breast are coloured chemically; they contain a pigment, whereas the tail feathers are not blue because of their chemical composition, but because of the structure of the feathers. The different feathers are shown in Figure 4. The nanostructures within the feather barbs reflect and absorb various wavelengths, producing only one visible shade. Within kingfisher tail feathers, the barbs contain a spongy nanostructure which allows only dark blue light to reflect [20]. Such structural colours occur in many species in the natural world, for example through thin films causing light to interfere as it's reflected [21], and were the inspiration for a new type of e-reader display.

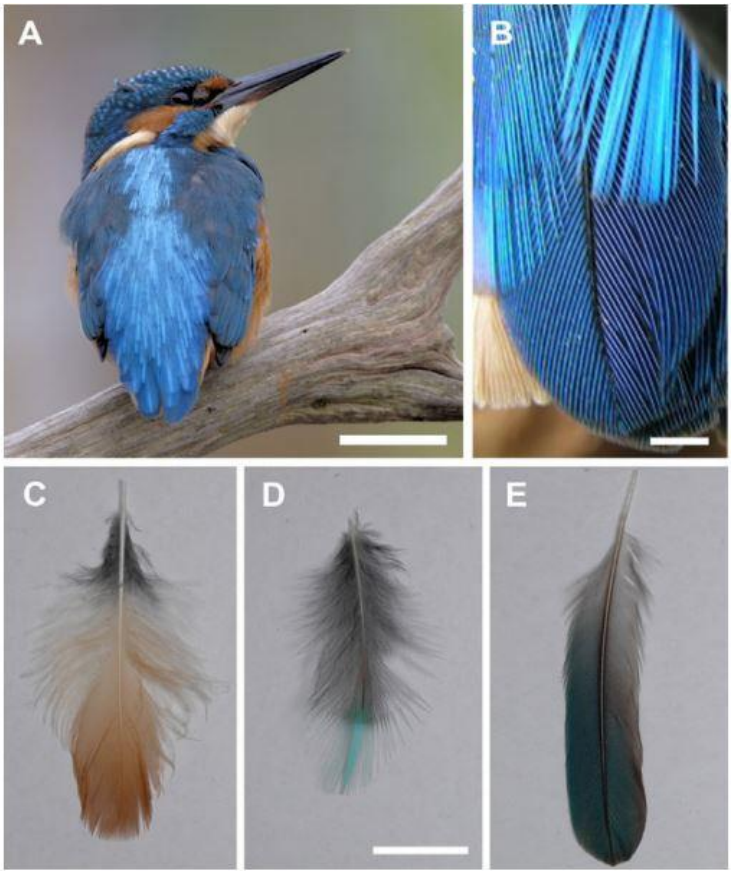

Figure 4: A Kingfisher (A), with orange breast feathers (C), cyan back feathers (D) and blue tail feathers (E). [20]

E-readers and tablets are wildly popular, but a perfect balance of readability, low power usage, speed, clarity and colour hasn't been found yet. The structural colour in animals inspired the idea to use reflection of natural light as opposed to a backlight in a way not yet done before, in interference modulator displays. In such a display, each pixel is a array of tiny imperfect mirrors, each reflecting light of a specific wavelength. Each pixel can be tuned to only reflect a single colour. This new design also came with hidden advantages. The new display has lower power consumption than previous models and can display clear colours not only in ambient light, but even in bright direct sunlight. The mirrors can also be tuned extremely quickly, allowing for good video refresh rates [22], wildly important for the modern user.

MATTER MATTERS

Finally we come to the final major component of our world – matter. Again, we have had practice with it, but those who must interact with it in weird and wonderful ways to survive serve as inspiration for us. Geckos have the remarkable ability to stick to almost any surface, at almost at any angle. They can freely run around on an inverted wall upside down. This is due to the tiny hairs on their feet called setae. Each squared mm of gecko foot contains approximately 14400 setae [23], each one then branches into structures called spatulae, on the nanometer scale, as seen in Figure 5. These structures can get so close to the surface of materials that Van der Waals forces kick in, creating an attractive force large enough to support the gecko. This mechanism comes with even more interesting properties. In order to stay attached to the surface, geckos do not need to apply a large preload, such as with regular tape. Geckos can also detach from a material in only 15 ns [23] simply by slightly changing the angle of contact between the setae and material. Gecko feet also exhibit self-cleaning properties which is surprising for an adhesive surface. After just a few steps with dirty feet, they are cleaned and the gecko can continue to move free of dust. This property comes from dirt particles being more strongly attracted to the material beneath the gecko's foot than to just a few setae [24]. These properties inspired a new form of adhesive.

Pressure sensitive adhesives, which are the most common type, degrade, adhere to themselves and random items, can't handle vertical or inverted surfaces well, require a preload to adhere and become increasingly dirty and unusable the more times they are used. Geckos do not have any of these issues, so inspired the production of synthetic setae tape, which is a manufactured tape covered in setae just like gecko feet. As a dry adhesive, it could mimic the properties of gecko feet: attach strongly in any direction, to nearly any material, with minimal preload, detach and reattach quickly and not stay dirty or stick to itself. A version made out of carbon nanotubes has been shown to perform better than natural gecko feet. A patch of adhesive just 500 µm across can support a shear stress of 3.7N which is three times higher than that of a gecko [26].

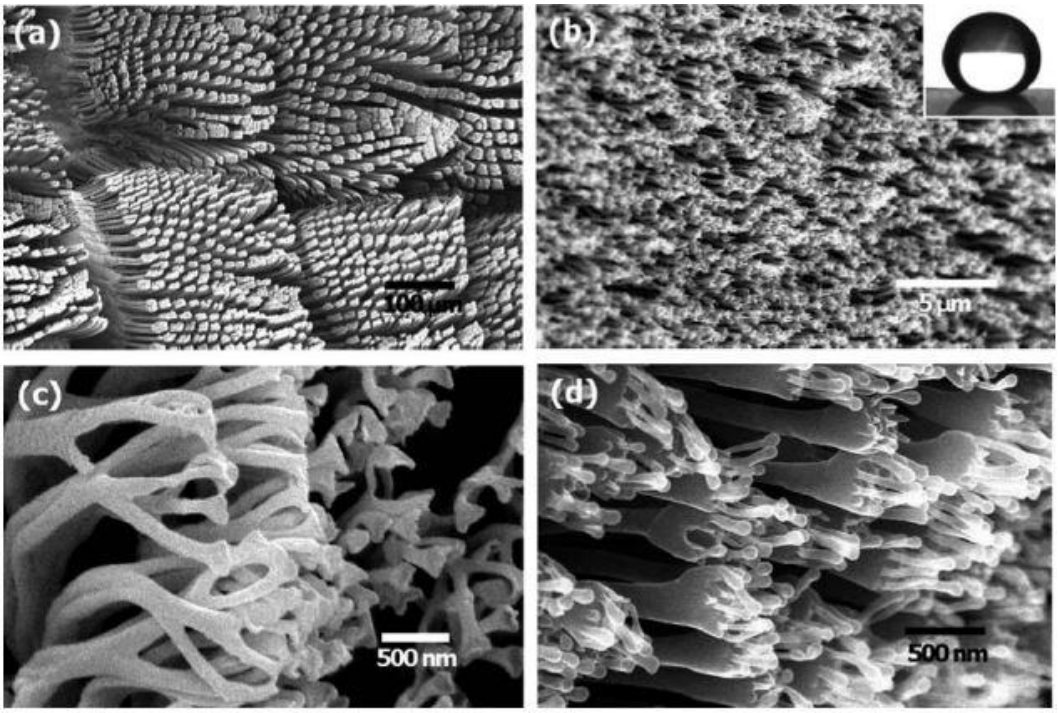

Figure 5: A gecko foot close up showing the setae (B) and the spatulae (D) responsible for its easy adhesion [25]

The applications of such a material are vast. A tape which can handle being dusty and reused many times means a smaller supply of it is necessary. Most interestingly it can be used as a resilient medical suture replacement that will not lose adhesion through various deformations or contaminations [27], which could be useful in some sticky situations.

CONCLUSION

Every time we discover a new animal, bacterium or survival mechanism in nature, we take inspiration from it. All the issues that we face can be mirrored in models in the natural world where they have already been solved. Even general technological issues such as the evermore complex communication methods that we use have been inspired by dolphins and bats. We may even venture to say that while we search for reliable, sustainable fuel sources, the naturally occurring stars have already got that sorted. Even the quantum effects which fry the brain of any physics student are happily whirring away inside the sun. It is baffling to think how much can be going on without us noticing due to a lack of correct perception techniques. I don't believe we will ever overtake nature in the race to have all the answers.

</David Attenborough voice>

<Scenic pan out>

ACKNOWLEDGEMENTS

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IMAGE page 2 : kingfisher image

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ARTICLE PLAN

Main aim of the article: to illustrate that nature has all the answers, look fairly deeply into the physics of some examples, leave people thinking 'that's pretty cool' and wondering about the boundaries of nature's guiding hand

Introduction – "Nature has been interacting with water, air, light and matter since its existence. We came along a lot later and have had less practice…" "We are continuing to be baffled by parts of it and inspired by others…". I will include a description of what I mean by nature: anything that wasn't made by humans on earth and mainly evolution i.e. adaption of species to be close to perfect in their environment. I will introduce trivial examples of nature winning that people are aware of to set the scene, like bees being better architects than us, ants having a more effective society etc. I will bring in the word 'biomimicry' – design and production based on biological structures.

Examples - (problem, nature's solution, our solution based on nature). The examples have been vaguely grouped into which element we interact with for cohesion

Water - We want materials (for boats, submarines, swimmers) that experience minimal drag and don't get covered in algae. Shark skin has denticles, which look like little pointed teeth and these stop the fast moving water from breaking up into vortices, as it would with a smooth surface, and stops algae, barnacles or even bacteria from latching on. We mimic this in: swimming costumes, wetsuits, boat surfacing, surfaces less prone to bacterial attachment, potentially to be used in hospitals. **Science:** vortex shredding, flow separation, micropatterned surfaces, antifouling, drag

Air – High speed trains, like the Shinkansen bullet train in japan, which travels at speeds up to 89 m/s, caused sonic booms when exiting tunnels, due to a build-up of pressure, which is a noise pollution issue. The kingfisher makes hardly any ripples when entering water, which is also quick motion from a low drag to a high drag environment. Owls are the most silent fliers, due to small feathers amongst the larger ones, which break up the large and loud air vortices. These effects were used in combination to produce the shape of the bullet train and small features of the surface to reduce noise, also making the train more energy efficient.

Science: tunnel boom (piston effect), serration feathers, vortex shredding, drag

Matter – Regular adhesives (pressure sensitive adhesives) degrade, adhere to themselves and random items, can't handle vertical or inverted surfaces well, and become increasingly dirty and unusable the more times they are used. Geckos seem to not have any of these issues due to the different type of adhesion the setae on their feet provide. Synthetic setae tape, as a dry adhesive, could mimic the properties of gecko feet: attach strongly in any direction, with little preload, to nearly any material, can detach and reattach quickly and won't stay dirty or stick to itself. It can also be used with a coating to adhere to wet surfaces, useful for resilient medical sutures. **Science:** pressure sensitive adhesion, Van der Waals forces…lots of Van der Waals forces!

Light - E-readers and tablets are wildly popular, but a perfect balance of readability, low power usage, speed, clarity and colour hasn't been found yet. A potential solution comes from butterfly wings: instead of the chemical composition of the wing, natural iridescence, caused by layers of crystals, gives them their colour. This has been mimicked to create e-readers which reflect light using an array of tiny mirrors. This topic is lacking good sources, may focus a lot more on the theory than the screen mechanism. **Science:** iridescence, interference modulator displays, structural colour

Conclusion – All human issues have already been solved by nature, maybe with some adaptations, but the answers are all there. I may briefly mention some extensions, such as quantum effects naturally occurring in space, while we work hard to find useful energy sources, but I don't believe there is space to go into detail about this.

What the article is <u>not</u> about: examples where we exploit the animal rather than just copying it, the fact that humans are ultimately destroying the natural world like a disease (it would set a sour tone to the article), the companies making the products, as I want to avoid bias, marketing and stick to the physics behind the examples

Bibliography notes- I have two types of references:

1. Popular/ simpler explanations for a brief overview and an idea of how to explain the concepts accessibly.
2. Scientific articles for my own deeper understanding – the sources for the information I condense.

FEEDBACK RECEIVED

Ok sounds good, but make sure you can put everything together in a coherent storyline rather than a random assembly of designs in nature. You have thought about a clear structure and also lots of science to discuss, which I like! The only danger might be that you run out of space to explain everything properly. Another issue would be to ensure that there is an interesting storyline. Lots of sources, great! Make sure to number them and refer to the numbers in the main text. Also, if possible, try to avoid webpages as much as you can and quote papers/articles/textbooks instead. Good article plan!

RESPONSE TO FEEDBACK

I have tried to produce a storyline by grouping the examples very obviously by the element of nature they are describing interactions with. I have tried to highlight this with separate headings to make it clearer.

The sources have been properly formatted for the article and filtered down to the truly necessary, helpful and reliable ones.

I believe that I didn't encounter the issue of having not enough space for the science, but rather than I couldn't explain a concept well without going too in depth and therefore have a lack of deeply interesting science, as all of the explanations have remained too basic for my liking.

CHANGES TO PLAN

I changed the order of the examples to suit areas where I found a link. I also found that the owl played a great role in the bullet train improvements, as well as the kingfisher, so I have added owls to the section.