Rhino horns and paper cups: Deceptive similarities between natural and human designs

STEVEN VOGEL

Department of Zoology, Duke University, Durham, NC 27708-0325, USA

(Fax, 919-684-6168; Email, svogel@duke.edu)

One cannot assume that resemblances between the mechanical devices of human technology and those produced by the evolutionary process reflect either specific copying of nature by people or some particular point of functional superiority. A third alternative is that the two mechanical contexts derive quite different advantages from a given arrangement. While this latter might appear unlikely, one can argue that it underlies such things as the use of conical shapes, helical tensile structures, spheres and cylinders, beams and columns of relatively low torsional stiffness, and geodesic shells.

1. Introduction

Despite profound differences in scale, in materials, in manufacturing methods, and in the basic design process, the mechanical devices we humans build quite commonly resemble those we find in nature. We stiffen structures by corrugating them just as does a scallop's shell. We inject and extrude through tubes that resemble the fangs of many venomous snakes and spiders. Our hollow columns follow the same logic as those of many plant stems, arthropod legs, and vertebrate long bones. One can continue a list of mechanical similarities almost indefinitely. How can we explain them?

Two rationales come immediately to mind. The first, that we humans have deliberately copied, using nature as model for our technology, turns out – as I have argued elsewhere (Vogel 1998) – to be less important than ordinarily believed. Some devices are indeed bioemulatory;, decent evidence for copying exists for such disparate items as barbed wire, streamlined bodies, earphones, and rayon. But their diversity is more impressive than their number. The second, that the common context of the two mechanical worlds implies similar solutions to analogous problems, certainly underlies most of the resemblances between them. After all, things made by both nature and people must work under the gravitational force of the same planet, in ways determined by the same rules of physics and mathematics, and constrained by the same properties of ubiquitous substances such as air and water.

A third possible rationale for resemblance has received much less attention than these previous two. Similarity may be essentially fortuitous; that is, the two systems might find a given design or device attractive for entirely different reasons. An aspect of its behaviour may recommend it to one; another aspect of its behaviour may press it on the other. While the matter might initially seem to be no more than something needed to fill out a set of logical alternatives, I would argue that it is far from trivial in practice, and that its examination exposes with especial clarity key differences between how we make things and how nature does so.

2. Cones

Consider the conical objects found among both human and natural designs. Some are immediately obvious –teepees, dunce caps, ice cream cones, paper cups, limpet shells, rhinoceros horns. Some are hidden – the wheel bearings of our cars, the tool-holding holes of metal lathes, the compression fittings between pipes. Some aren't obviously conical – the horns of sheep and goats, the shells of snails and nautili, the screw-in couplings of drain pipes and garden hoses. Conical shapes unquestionably appeal both to nature and to human designers. What underlies that appeal?

Cones turn out to have two splendid features for mechanical

Keywords. Biomimetics; biomechanics; functional morphology

applications. For one thing, identical cones nest within each other to form mutually reinforcing stacks. The way we ship and store edible cones for icecream and paper cones for drinking water makes fine use of this tidy stacking. For another, either extending the edge or thickening the wall of a cone increases its size without changing its shape – a cone that grows by these schemes retains the same taper, the same ratio between its height and the width of its base. A snail grows by such edge extension, and Egyptian pyramids (really just squared-off cones) or a Babylonian ziggurat can be enlarged by such simple incremental addition.

Nesting in stacks isn't just a convenience for transporting identical items. Something with a conical outside will fit snugly into something with a conical inside, as long as their cones have the sametaper. Press them together harder and the connection gets tighter.That adjustable snugness underlies the use of conical rollers as bearings for the wheels of our cars – as opposed to ball bearings or cylindrical rollers. It's also why we give a slight taper to the threads used to screw pipes into their fittings – opposite diameters converge at a barely-noticeable 3· 6° (Oberg *et al* 1984). By contrast, ordinary screws and nuts are cylindrically-grooved. Thus the connection gradually tightens as a pipe and coupling are forcibly screwed together. As long as the threading tool has the right taper, pipes can be cut off and rethreaded quite casually.

Lathes, familiar to every machinist if not to most of us, make fine use of a similar device. Both their large drills and their chucks for small drills have conical back ends. These fit into the hole in the tailstock (the opposite end from the motorized headstock) as the male halves of a pair of nesting cones. Three degrees (across their diameters) is typical of these conical tapers; because of this slight taper, when the drill pushes back against the tailstock it tightens the fit – they're said to be "self holding". But if the drill suddenly jams in the work, it can spin non-destructively in the tailstock. Not only are such nesting cones relatively easy to machine, but the angle of taper isn't sensitive to the changes in size that accompany heating and cooling.

Cylinders, by contrast, behave quite differently. Manufacturing tolerance determines how tightly the pieces of a telescoping radio antenna will fit together, and wear makes them loosen. Nor will identical cylinders nest together. Corks for one-time use, as in wine bottles, are cylindrical. Corks for repetitive use, as in chemistry laboratories and in an earlier generation of Thermos bottles, are conical. Conical corks will do almost as well after long use as when new,and stoppers in a dozen sizes suffice to fit every flask. Conical ground glass stoppers are almost completely interchangeable, but we often number the ground glass cylinders and pistons of hypodermic syringes to facilitate non-promiscuous remating after they get a communal washing. So there's no great mystery about why modern mass-production technology often selects cones where cylinders look at first glance like the more obvious choice.

Organisms occasionally take advantage of the way identical cones nest together. One kind of mollusc, a slipper limpet aptly named *Crepidula fornicata*, lives in a nested stack. A limpet arrives (as a swimming larva) at a rock, settles down, and grows into a juvenile with a low, conical shell. But larval limpets prefer limpet shells, when available, to rocks as surfaces for attachment. So a second limpet commonly settles on the first and grows into a juvenile, while the first grows into a mature male. A third limpet then lands on the second, the second matures as a male, and the first metamorphoses into a female. And so on, with the lowest shells becoming just passive supports that no longer house living animals. The fit of male upon female provides proper reproductive proximity, new space on a rock need only rarely be won, and the stack grows up and away from any other creatures that crowd its periphery and protrude into the flows that provide it with food. But the case is unusual.

The other advantage of cones, to remind ourselves, is growth by incremental addition without change of shape. Adding to the end of a cylinder or a rectangular solid makes it relatively skinnier while a cone suffers no such alteration. That seems to be the key feature that makes cones attractive to nature. Most conspicuously, it facilitates the growth of almost all shelled molluscs. Most may not look quite conical, but that's only because besides strict cones, a more general cone-like form retains its shape as it grows. Thus if one adds material preferentially to one side of the free edge of a hollow cone, one gradually transforms it into a spiral. It may be a flat, two-dimensional spiral, as is a *Nautilus* shell; or it can be a spiral with a little helical extension to one side, as are the shells of snails, whelks, and periwinkles; or it can form a very low spiral, as are the half-shells of clams.

All these are spirals of the particular kind – so-called logarithmic or equiangular spirals. A logarithmic spiral gets wider exactly in proportion to how far it has lengthened – just like a cone except that the thing now wraps around itself. The general equation for such a spiral is

$$r = e^{a\theta}$$

– the radius, r, of the spiral increases at a rate determined by a as it swings around through an ever-increasing angle θ. (Positive a's produce left-hand spirals, increasing in diameter with counter-clockwise turning; negative a's produce right-hand spirals.) The larger the cone that's enlarged by edge and surface addition, the more material it takes to do the enlargement, since the larger cone has more edge. But the requirement for material scales conveniently, retaining its proportionality with the volume already present. Cones and spirals interconvert easily –thus pastry chefs often take high, narrow cones and wrap them into spirals. Note, though, that spirals don't so inevitably nest together.

Why this great elaboration of cones and logarithmic spirals among the molluscs? Most likely that great phylum can't do much better when it comes to growing its hard parts. Molluscs can't molt periodically like arthropods or take advantage of that splendid vertebrate invention, a living skeletal system that can grow internally. But molluscs aren't the only creatures that use this basic shape. Cones and spirals turn up in the minute shells of many protozoa, in flowers and other parts of plants, and in tusks and horns. The paired half-shells of brachiopods, a group that figured large during the Palaeozoic but now persist as just a few species of tinyanimals, closely resemble the half-shells of bivalve molluscs – both live within the geometrical constraints on growth by edge and surface addition without change in shape. No common ancestor shared the design; in fact the half-shells of a brachiopod are morphologically top and bottom rather than the left and right sides of a mollusc.

Mammalian horns are logarithmic spirals, while antlers are not. Horns, which grow outward from the skull, enlarge by addition at their bases, just as do mollusc shells; and they form either simple cones or flat or helical spirals. An antler forms beneath a thin layer of skin, is shed annually, and gets replaced by a larger one. Growing this way imposes no such geometric constraint, and very few antlers are cones or spirals. On the other hand, periodic shedding can't be cheap. Among the artiodactyls, cows, sheep, and goats have horns; deer, elk, and moose have antlers.

Nature's inordinate fondness for logarithmic spirals – often looking persuasively conical – caught the eye of three different biologists in the early 1900's. James Bell Pettigrew (1908) saw in them some evidence of a divine designer, Theodore Andrea Cook (1914) envisioned a general principle of design, and the better remembered D'Arcy Thompson (1917) viewed them as part of a kind of mathematical perfection in nature. We treat them as something less grand if no less interesting – the morphogenetic convenience of a system that doesn't have unlimited information for specifying form.

Once in a while we humans take advantage of this characteristic of cones, enlarging our conical structures by incremental addition to edges and walls. The ziggurat towers of the Babylonians and Assyrians were conical, with stepped terraces or with pathways spiralling up to the top. One could gradually enlarge one's ziggurat without scaffolding or functional alteration. But we build most of our conical dwellings – teepees, for instance – once and for all. When we do enlarge our houses, we don't care much about maintaining their original shapes. In one case, at least, we reverse the process, incrementally subtracting from the walls and thus ungrowing a cone. That happens every time we sharpen a pencil – can you imagine a sharpenable pencil with a non-conical end?

Have the separate worlds of human and natural design hit on the same shape for the same reason? While at first glance that might appear to be the case, reality is more subtle and instructive. As noted, almost all the common cases of nesting cones involve items of human design – *Crepidula* provides a nice tale, but it represents no widely used scheme in nature. Nesting is mostly our game. By contrast, almost all growing cones occur in nature's designs – ziggurats have never been in the architectural mainstream, and wooden pencils are an isolated instance. Growing by edge addition is mainly nature's ploy.

Each world of design finds one advantage compelling while remaining largely indifferent to the other. And the two worlds have contrasting preferences. For human technology, that ability to nest proves enormously valuable; since we don't grow our artifacts, incremental addition rarely matters. In nature, most things get big by growing, most materials are soft, and even the hard parts are rarely press-fit together. If the contrast carries a lesson it is that recognition of nature's affection for cones should not in and of itself induce us to design conical objects. Motivation is what matters, and we can't assume that what's good for nature will fit our needs as well. Nor should we allow ourselves to be misled by any notion of nature's greater sophistication or longer experience.

3. Helices, spheres and cylinders, non-cylindrical columns, geodesic shells

This lesson extends beyond cones and spirals. Nature's goals aren't our goals, nor are her means our means. A good design in her mechanical world – not even a "technology" in a strictly literal sense since it does nothing intentionally – may hold no advantage in ours. Or, as here, a shape that works well for both may do so for quite different reasons. Nor does the point rest entirely on this one example. Cones aren't the only instances where coincidence between nature's designs and our own proves purely coincidental.

Both systems use helices. The most common human-made ones are twisted ropes. If the strands of a rope are twisted, then pulling on the rope as a whole causes the individual strands to press together more tightly and therefore to slip against one another less. In that way short fibres can be made – spun – into long, strong, ropes. No second material need stick the fibres together; indeed binding them may render a rope abnormally susceptible to transverse cracking and other modes of failure. Humans have been doing this rope trick for many thousands of years and probably discovered it on more than one occasion. Cordage immediately suitable for human use is rare in nature, but short fibres suitable for twisting into ropes abound. We don't just make ropes this way – the scheme underlies all the short-fibre threads from which we weave cloth. Making practical thread of even the long strands produced by silkworms involves some spinning.

Nature, by contrast, doesn't make ropes or threads this way. Hers either use fibres long enough to run the full length of the tensile structure, as in silk cocoons and webs, or else shorter fibres get joined to form a long structure with a second component, a glue. The molecules of one of her most common tensile materials, collagen, turn out to be long, triple helices. So our tendons and the walls of our arteries do use helical material to withstand tension. But the strength of collagen depends in no way on the same kind of resistance to mechanical shearing between strands; any special significance attaching to the helical form of collagen needs another explanation.

And nature's fondness for helices does have another explanation, one first proposed by a physicist, Horace Crane, back in 1950. Instructing a system to make a helix, he noted, requires very little information. In a helically-twisted stack, each component fits into place exactly the same way as does every other one. And one can argue that development is, in a sense, an information-starved process, making complex three-dimensional structure from a simple linear code. Indeed, many important intracellular structures turn out to be just such simple helices built of monotonous repeats of some basic monomeric units in equivalent positions –

microtubules, microfilaments, some muscle proteins, and others. Some can be made to self-assemble *in vitro* from a solution of their monomers in the right chemical environment – the desired way is simply the only way they can go together. None uses shear between fibres to resist being pulled upon in the manner of our threads and ropes.

Our ball bearings, wheels, and rotating shafts take advantage of the smooth and steady way spheres and cylinders roll, behaviour that depends on their specific and constant radii. Gears, pulleys, flywheels, and capstans form no minor collection of cylindrical rolling devices, and they just begin the list of our hard rollers. Spheres may be slightly less ubiquitous, but they're far from rare. Complex mechanical devices seem almost unimaginable without spheres and cylinders rolling around.

While spheres and cylinders are common enough in nature, only rarely do they roll. They're typically used for pressurized vessels – tanks and conduits. Such vessels are cheapest to make if they have the same curvature everywhere, which spheres and cylinders do. "Cheapest" here applies equally to informational economy and material economy relative to volume. Pressurize an enclosed volume with a membrane of uniform thickness without further instructions and one gets (depending on the conditions) a sphere, ellipsoid, or cylinder. Deviating from these basic shapes costs – any place where the radius of curvature is greater will feel a greater tension tending to cause further bulging (an aneurysm) or to split the wall; so the greater radius of curvature will demand a proportionately thicker wall. For thin-walled cylinders, the rule, often called "Laplace's law", is that transmural pressure equals wall tension divided by radius of curvature. For spheres, that pressure is twice the wall tension divided by the radius.

Nature's water-filled balloons, organisms or their parts that use hydrostatic stiffening in what are called "hydroskeletons", include many unicells, lots of worms, the tiny feet of starfish, the bodies of squid, and most mammalian penises. Beyond these, virtually all blood vessels and other internal fluid conduits are cylinders with pressure differences across their walls; usually but not universally, pressures are greater inside. Our technology likes the rolling behaviour of spheres and cylinders with their constant radii, nature likes the wall-tension equalizing behaviour of these shapes of constant curvature. Both, though, recognize that cylinders make good shafts and struts when these are subjected to torsion, face failure by buckling, or have to withstand flexural loads from any direction. Thus bicycle frames, architectural columns, tree trunks, and long bones share both their cylindrical cross sections and the rationale for adopting them.

We commonly use struts and beams in shapes that resist bending quite well but that are much less effective at resisting twisting. An I-beam, for instance, resists twisting only about half as well as does a cylinder, relative to their respective resistances to bending. And our various U- and L-channeled struts share that lack of torsional stiffness. We ordinarily circumvent it by using such beams in pairs or groups so their communal action resists torsional loads. Thus the deck of a bridge may be supported by two or more I-beams but never by a single one. Occasionally we simply tolerate some torsional flexibility. Thus when we mount street signs atop channeled poles, we make them protrude equally to the right and left; winds thereby impose no torsional loading that might make the signs oscillate about their vertical axes.

Nature also uses structures that resist bending more than twisting. Hers more often take the form of cylinders with lengthwise grooves instead of I-beams, although some of the neural and hemal spines ("ribs") extending above and below fish backbones come close in cross section to I-beams. But she most often uses such structures individually for applications where some specific virtue emerges from their relatively greater torsional flexibility. Thus each of the feathers that form the tips of the wings of birds has a groove along its shaft, a groove that allows it to twist more easily. That means it can twist one way when the wing moves upward and the other way when the wing moves downward again, as the aerodynamics of flapping flight demands. At the same time, the feather resists bending, as it must. After all, in flight a bird (or airplane) quite literally hangs its body from its wings. Insect wings do much the same thing, passively twisting one way on the upstroke and the other on the downstroke. In this way they may avoid what might be difficult problems of coordinating phasic muscles where wingbeat frequencies run into the hundreds per second. Tree trunks, leaf petioles, and daffodil stems also have high twistiness to bendiness ratios. For these, twisting in the wind appears to be a device to achieve orientations that incur lower drag – flexibility under torsional loading reduces the bending loads they must sustain (Etnier and Vogel 2000).

One other difference distinguishes the way nature's structures and ours respond to flexural and torsional loads. How something bends and twists depends on the material of which it is made as well as on how that material is arranged. So using a non-circular cross section isn't the only way to decrease a structure's resistance to twisting. We ordinarily use materials that, however diverse in other ways, provide little room for adjustment of relative resistance to bending and twisting – we depend almost entirely on cross-sectional geometry. While nature does tinker with cross sections – lengthwise grooves are common among both animals and plants – she does much more with materials. Using both material and geometric factors permits the ratio of torsional to flexural stiffness to vary by more than an order of magnitude, considerably wider than the roughly three-fold variation among our structures. So in practice a lengthwise groove both raises the ratio somewhat and alerts us to the high likelihood that specialized material arrangements are at work raising it considerably further.

When we build geodesic domes we take advantage of the efficient way they allow a large, stiff, and strong structure to be built with short, light, struts. We don't make great use of them, perhaps on account of some basic incompatibility with our predominantly rectilinear designs. One might expect geodesic structures to occur widely among organisms, between their material efficiency and the fact that nature need not escape any preexisting bias toward rectilinear forms. But they're rare, even among such obvious candidates such as the spicular skeletons of sponges. Perhaps getting high stiffness at low cost matters less among natural designs, which seem to place a lower premium on stiffness, as opposed to strength. Sponges, for instance, have adequate strength to withstand typhoons, but they're notably low in stiffness.

Nature does build domes – egg shells, nut shells, cranial cases, and so forth – but they're not geodesically strutted. The crucial feature of most of her domes is their uniform resistance to impact or puncture, as when hit or bitten, something a strutted membrane fails to achieve. Where she does use geodesic assemblies is in viral shells, and here what matters is much more likely to be the same kind of informational economy we noted for helices. Multiples of a single basic component can be designed to self-assemble into standard shells. Once again, the same device reflects different imperatives.

Yes, nature's designs often resemble ours on account of similar underlying constraints or functional imperatives. Yes, we can learn useful lessons about design from analyzing her designs. And, yes, we can sometimes even make useful devices that copy hers. But nature speaks an unfamiliar language, and a literal translation – simple, slavish copying with its tacit assumption of similar imperatives – is all too likely to misinterpret her messages and all too unlikely to produce practical products. The utility of a design has meaning only in the context in which it lies, and the mechanical technology created by us humans differs profoundly from the mechanical world of the rest of nature.

Acknowledgements

The author thanks the Raman Research Institute, Bangalore, at which most of this article was written, for both gracious hospitality and intellectual stimulation.

References

Cook T A 1914 *The Curves of Life* (London: Constable)

Crane H R 1950 Principles and problems of biological growth; *Sci. Mon.* **70** 376–379

Etnier S A and S Vogel 2000 Reorientation of daffodil (*Narcissus*: Amaryllidaceae) flowers in wind: drag reduction and torsional flexibility; *Am. J. Bot.* **87** 29–32

Oberg E, Jones F D and Horton H L 1984 *Machinery s Handbook* 22nd edition (New York: Industrial Press)

Pettigrew J B 1908 *Design in Nature* (London: Longmans)

Thompson D'Arcy W 1917 *On Growth and Form* (Cambridge: Cambridge University Press)

Vogel S 1998 *Cats Paws and Catapults: Mechanical Worlds of Nature and People* (New York: W W Norton)

MS received 4 January 2000; accepted 5 May 2000

Corresponding editor: RENEE M BORGES