So What Would Nature Do?

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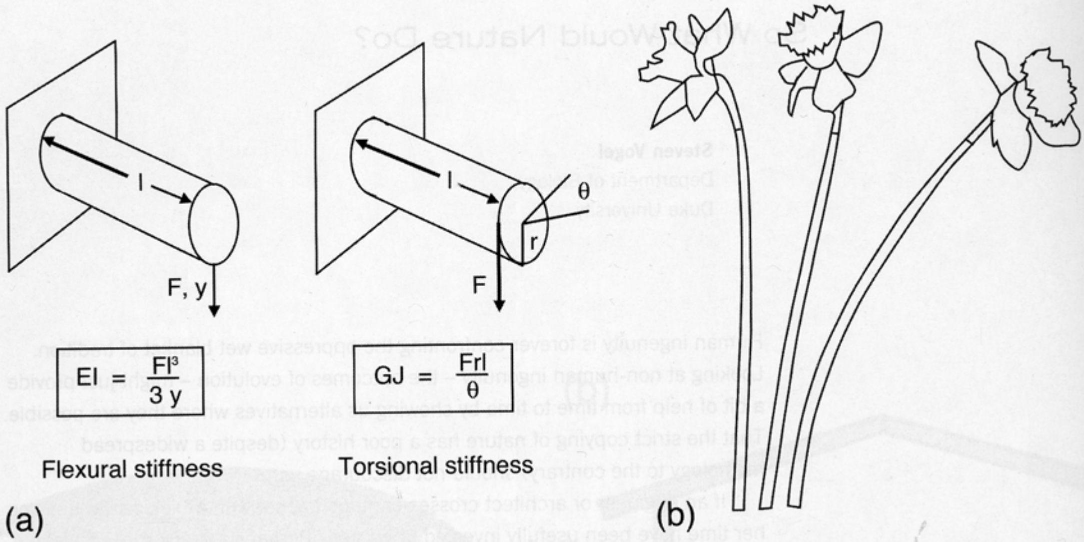
Human ingenuity is forever confronting the oppressive wet blanket of tradition. Looking at non-human ingenuity – the outcomes of evolution – might just provide a bit of help from time to time by showing us alternatives where they are possible. That the strict copying of nature has a poor history (despite a widespread mythology to the contrary) should not discourage us.

If an engineer or architect crosses campus to chat with a biologist, will his or her time have been usefully invested or wasted? Perhaps a quick trip will yield nothing, but I want to argue that larger investments in bridging the considerable cultural divide can pay substantial dividends. We biologists will not have heard of or thought about damping, convection, elastic moduli, or drag coefficients – our required courses in physics steered clear of much that matters in the real world – but we catch on quickly enough if one perseveres and explains.

Consider, then, a series of technological challenges – from small-scale, minor, and specific, to more general and pervasive – examples rather than admonitions… The first challenge is to ventilate a sealed house in a cold climate with a minimal loss of expensive heat. Insulation works wonderfully well, but both our bodies and our appliances produce noxious emanations; the classic solution in nature is a counter-current (or counterflow) heat exchanger. These allow, for instance, warm-blooded birds to keep blood flowing to feet that wade in ice water without expending energy in a futile attempt to heat the ocean. While counterflow exchangers receive proper attention in engineering textbooks, they are awkward to contrive, with two opposing flows in intimate thermal contact, pipes that are necessarily minute, and intricate manifolds.

However, one variant version in nature holds some promise. A small bird or desert rodent pulls cold, dry air into warm moist lungs. But from those lungs it exhales air that is almost as cold as what came in. Its trick depends on brief heat storage in and on the walls of its respiratory passages – complex channels close to the wall, channels that are anything but circular in section. *(image 1a)* Inhaled air is warmed before getting to the lungs; exhaled air is cooled before leaving the body.[1]

Now imagine a sealed house with two such exchangers far from one another, one equipped with a reversing fan. *(image 1b)* The exchangers now need only a single set of pipes and no manifold at all, nothing more complex than parallel plates or the 'honeycomb' material used to reinforce flat surfaces in aircraft and spacecraft. In a constant-volume sealed house, only a single, periodically reversing fan is needed to make the exchange work. Note that we have deviated



2 (a) Two structural properties, flexural stiffness and torsional stiffness – how they might be measured and expressed.
(b) A daffodil twisting and turning in an increasing wind, traced from the author's photographs.

considerably from what nature does. No animal bothers with such paired exchangers since breathing animals are not constant volume systems. Nor do we expect to use anything close to nature's muscle-powered, positive displacement pumps – rotating fans, with no macroscopic living analogue, would be more appropriate.

Another challenge is how to build tall, light-weight, wind-resistant structures with small footprints. Trees, flower stems, and feathers all extend outward from fixed bases, bending like ordinary wind-loaded cantilever beams. We have long experience and reliable rules for minimising the bending of such a structure. But nature may have a trick we commonly overlook. As the late James Gordon used to point out,[2] we most often build to a criterion of adequate stiffness (elastic moduli) while nature worries less about stiffness and focuses on getting adequate strength (breaking stress). If we can wean ourselves from the biases of our current tradition and accept greater mechanical flexibility (we currently refer to this as 'deformation'), we might economise on material.

Flexibility, though, has multiple dimensions, both spatial and temporal – complexity beyond the capacity of single-valued elastic moduli. While the bane of the analyst (read, perhaps, scientist), complexity affords opportunity for the designer. Consider just one element of mechanical flexibility, the interplay of resistance to bending and resistance to twisting. In formal terms, this can be expressed as the ratio of flexural to torsional stiffness. *(image 2a)* One can adjust that ratio either (as we occasionally do) by changing the cross-sectional shape of a structure or (as nature more often does) by manipulating the anisotropic character of the material of which the structure is made. An ordinary circular cylinder of common engineering materials resists both bending and twisting – in formal terms, the ratio will be between 1.2 and 1.5. An I-beam twists readily and therefore will have a vastly higher ratio, but we regard that torsional flexibility as pathological and make multiple I-beams offset each other's lack of torsional stiffness. Once in a while we allow simple things like poles for road signs to have great torsional flexibility, but use them solely for applications with negligible torsional loading.

By contrast, the stem of a daffodil flower has a ratio of flexural to torsional stiffness of about 13,[3] some reeds of about 25,[4] and the petioles (leaf stems) of banana plants of 50 or more.[5] All twist with remarkably little resistance but do not readily bend. In each case, twisting in the wind permits the structure to reduce effective wind exposure (drag). As several poets remind us, daffodils 'dance' in the puffy breezes near the ground – reorienting to face downwind drops the drag of the flower about 30 per cent. *(image 2b)* Reeds do much the same thing. Banana petioles twist enough so the whole top of the plant can collapse (again our prejudicial term) into a tight bundle with (presumably) very low drag. Thus nature capitalises on weakness in one dimension to reduce the amount of strength needed in another.

Only very rarely do we deliberately make structures that twist with little provocation but strongly resist bending. The Wright brothers did just that in order to control their early fliers through span-wise wing torsion, but one early monoplane simply shed its wings when torsionally loaded.[2] At least one tall thin building turned out to be so torsionally flexible that the top floor had to be relegated to a chamber for a pair of 300-tonne damping masses. Worse than not capitalising on torsional flexibility, the design of both monoplane and tower reprehensibly ignored it.

Perhaps we ought to think of applications where we go beyond just remembering to account for twistiness and do what nature does in the daffodil, reed, and palm frond and deliberately employ relatively high torsional flexibility to achieve some technical virtue. Drive shafts must take torsion, but a shaft that retains some torsional flexibility might damp transmission of torsional impulse and thus permit either smoother operation of some intermittent device or reduction in the necessary strength of other components in a drive chain. Or we might build lighter, cheaper, and less obtrusive transmission towers by designing them to do the banana petiole's trick in especially severe storms, accepting of course temporary loss of function. Whether we increase the flexural to torsional stiffness ratio by adjusting cross section or using anisotropic material is, one might say, immaterial, but we should recognise that both routes are available.

While nature does make stiff materials they are not her default. Bones are stiff, which is necessary for muscles to act on them; wood is stiff, but it faces an extreme form of gravitational loading. Tensile construction economises on material and thus weight relative to compressive construction, but it rarely produces particularly stiff products – though the longer the structural element, the greater the advantage of tensile loading. Our favourite materials, however, take compressive stresses best – bricks, cement, etc – or withstand compressive and tensile stresses about equally well – metals, dry and sliced wood, plastics, etc. We avoid pure tensile loading and use the tension-resisting character of materials such as metals to help structures bear bending and torsional loads.

Loading in tension has at least two disadvantages. First is a lack of stiffness for equally strong designs. Second, connections between elements are harder to arrange – bricks may be held in place by mortar, but the stays of a sailboat's mast or the suspenders of pants or suspension bridge need fancy attachments.

Nature, though, seems to have little trouble attaching a tendon to a bone or a muscle to a mollusk shell. And, especially where locomotion costs significant energy, weight economy seems to be a matter of high priority. Sometimes she makes only tension-resisting components, using that ubiquitous liquid, water, packaging it in tensile membranes to take compression. 'Hydroskeletons' are strong, versatile, and cheap in materials though not very stiff. Examples are earthworms, which can penetrate soil; roundworms, which can penetrate flesh; the tube feet of echinoderms; and the penises of most mammals.[6]

Might we get some useful ideas by looking at nature and then considering something even more foreign to contemporary human practice? Imagine a most peculiar technology. It has no solid compression-resisting material – it cannot make or obtain any solid material that can withstand being pushed against – so compression can be taken only by liquids or gases. It has fluids that won't freeze at any temperature, so freeze-thaw damage is of no concern. Imagine a world of ropes, sheets, and tubes together with a culture of creatures that have created its devices, creatures themselves built and living within its constraints. They need not be not primitive – they might have buildings, engines, vehicles, sports, and even weapons. They can use fibers and membranes that stretch to many times resting length and others that are nearly inextensible. They may have some materials of high resilience and others in which the work of extension heats them. But they know nothing of bricks and mortar, of I-beams and ordinary columns, nor of wooden studs and nails.

So I leave you with an assignment. Imagine such a world as an intellectual exercise, one intended to distance you from the weight of tradition. So that this imagined world has some terrestrial equivalency, assume gravitational acceleration, ambient temperatures, and the properties of air, water, and materials exist as we know them. Assume also that the physical environment is similar to the one we have now – flat and hilly land, still and moving water. But use no clay, stone, and so forth as building materials. What artefacts would characterise this civilisation? What kinds of structures, passive devices, engines?

References

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