How-To-Do-It

Simple Lessons in Biomechanics & Biological Materials Using Everyday Objects

Alexander Werth

Learning begins by making observations and then asking questions. Primitive humans must have marveled at solar eclipses and pondered the causes of thunder and lightning, tides and earthquakes. So too children begin life by wondering about everything they encounter, particularly phenomena of nature. Biologists retain this curiosity about the natural world and never stop making observations and asking questions. This is nowhere more evident than in the field of morphology, the study of form. This term was coined in the 18th century by the German naturalist/poet Goethe (1749–1832), who believed every organic design concealed an underlying meaning or intention (Kardong 1998). Morphologists no longer presume that such forms imply a divine plan or purpose, so while they still seek to explain the design and construction of plants, animals, and other organisms, they now place such explanations in an evolutionary context. In fact, the very reason morphological explanations are often sought in the first place—aside from the need to satisfy curiosity—is to provide just such a context. Morphology has always supplied some of the best evidence for evolution.

Even if you don't teach a class in biomechanics and biological materials, odds are you will at some point (and at some level) wish to explain organismal design and construction. Why does that leaf, horn or snail shell look the way it does, and is there a reason for its shape, size and texture? What makes this fossil so dense and asymmetrical; why does it have these bumps and ridges? Why is this cactus short and round, and that one tall and slender? Why is this bone present at all: what does it do? Why are these spines hollow? Why is this stem circular in cross section and that one square? Why does this fish have a short, broad tail, and that fish a high, narrow one? How can one explain all the different types of bird wings and feet? Why do mammals from different continents have similar skulls but entirely dissimilar teeth? In essence, why do things look or act the way they do?

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You might feel an immediate urge to explain these observations—to yourself or to your students—by recalling surface to volume constraints limiting diffusion, buoyancy and thermoregulation, or (if you really remember your physics) by appealing to laws of Newton, Hooke and Bernoulli. Yet while reduction to first principles offers a solid basis for study, the combined influence of many contributing factors becomes apparent only after looking at the proverbial "big picture," relying on an emergent rather than a reductionist perspective.

There are several classes of explanation of form, and thus several fields (notably anatomy, physiology, evolutionary biology, and developmental biology) which address questions of form, both on a proximate (mechanistic) and ultimate (evolutionary) basis. Biomechanics and biomaterials science also deal with structure and function but at a narrower level, and as such they are often overlooked by biology teachers. While biophysics generally describes such things as the transfer of energy in heat exchange, the role of optics in vision, and the partial pressures of gases involved in respiration, biomechanics relates the cell and tissue-level structure of histology to the larger scale of gross anatomy and relates mechanical aspects of structures to their component materials. These fields apply physical laws to organismal design and operation, often relying on experimental analysis and analogy from engineering. What are the mechanical advantages of different types of connective tissues? How do bones respond to stress? What did the three little pigs learn about houses built of straw? Or, as Kardong (1998) asks, "Why are there no flying elephants?" and "Why do no vertebrates have wheels?"

In my experience the best way to explain design and construction is to use a common analogue drawn not from engineering but from everyday life. The best way to illustrate is with an example; the best example is the simple and familiar. Just as I use pairs of colored socks to elucidate meiosis and juggle tennis balls as symbolic "electrons" in redox reactions, I use other common household items to explore morphology.

My goals are 1) to engage students and 2) to encourage them to analyze how organisms work (i.e. how their operation relates to their construction). Students find answers the way we do: by posing simple questions based on observations, as in the list above. These questions stimulate thought and provoke discussion. They also make the study of structure and function interesting, innovative and multidisciplinary. This is especially important for students who tend to avoid mathematics, physical sciences, or any quantification in biology. This game works well with extinct organisms and imaginary ones—even if a 10 m ant could survive myriad physiological hurdles, would its exoskeleton be strong enough?—though it is best played with macroscopic rather than microscopic organisms, since relevant physical laws (of momentum, inertia, etc.) are applied quite differently.

Materials & Methods

My rules are 1) keep it simple and 2) make it fun. The easiest and perhaps the best way to follow both directives is to seek convenient objects to use as analogues for biological materials or systems. These range from mundane articles at hand in your desk drawer or on your pantry shelf (balloons, drinking straws, toothpicks, corks and stoppers, thread, dental floss, rubber bands, popsicle sticks, fiberglass strapping tape) to slightly more exotic or esoteric items readily obtainable on short notice (foam balls, suction cups, Jello™, yo-yos, Slinky® springs, and other toys or novelty items). Nothing beats Silly Putty® for showing the properties of viscoelastic solids (rapid failure and fracture under high tensile stress but slow yield in low-load conditions). Use the everyday object to demonstrate your point. Don't avoid technical terminology and formulae, but don't begin with profound, confusing abstractions. Play to your strength: choose materials from your own research (mine exposes me to whale blubber and baleen, enamel, tendons, and permineralized fossils). Or work with coral, chitin, cuticle, cotton or coconuts. The only limits are your ingenuity and imagination. Here are examples of various materials and methods with which to teach several simple concepts:

Body Mechanics

- Use a ruffled potato chip or corrugated cardboard to explain why ridges prevent deformation (compare chips of different shape and thickness in dips of varying viscosity—have a party!). Why is the narwhal's tusk spiraled?
- Use drinking straws, cardboard tubes, or other cylinders to show why a circular cross-section provides strength with economy of material for long bones and other hollow structures, like onion and dandelion stems.
- Use a crumbling sidewalk to explain isotropic (homogeneous) compounds like cement and anisotropic conglomerations like concrete and mineralized connective tissues; show how the latter affords strength while minimizing crack propagation.
- Use a pliant piece of foam to show how stresses (forces such as compression, tension and shear) cause strain (deformation).
- Study tension-resistant fibers in collenchyma strands of celery stalks or petioles.
- Bend or twist meter sticks to demonstrate how different axes resist deformation.
- Use different kinds of paper and cloth (view at 10 to 50X) to contrast loose (reticular, areolar) and dense (tendon, ligament) connective tissues as, respectively, a random feltwork versus a highly organized array of collagen and elastin fibers.
- Use a sponge to demonstrate absorbance of proteoglycans in articular cartilage, releasing water when compressed and soaking it up again as pressure is removed.
- Use a water balloon to demonstrate a hydrostat such as a tongue, trunk, tentacle, or tube foot or other highly mobile, constant-volume organ, or an entirely hydrostatic organism such as an earthworm or caterpillar. Water balloons can model a wide range of fluid compression element support systems (as in the stems of wilted and hydrated plants, or the notochord of chordates).
- Use familiar analogies of man-made structures (cranes, bridges, arches, columns, spokes, etc.) to explain osteological microstructure. Architectural analogues of bones can be found in many anatomy texts. Students can learn a great deal from a bone that has been broken or (better yet) sawed open to reveal internal architecture.
- Rely on woodworking principles to describe skeletons as beam and lever systems attached by joints (hinge, saddle, ball-and-socket); bony sutures may also be likened to woodworking joints (lap, butt, scarf, dovetail; see Hildebrand 1995). Plywood and veneer effects are found in such materials as plant and insect cuticle.
- Plastic models of dinosaurs (or other creatures) can teach lessons about isometric and allometric scaling and about estimation of body mass or volume.

Feeding

- Build on the ubiquitous example of Darwin's finches' diverse beaks as pliers of varying size and shape (e.g. gripping, needle-nose, wire-cutting). Have students find analogues of appendages, mouthparts, and other notable structures (e.g. of arthropods) in tools (saw, pick, hammer), instruments (scalpel, scissors, forceps, probe), or other devices such as straws, shovels and nutcrackers (Figure 1).
- Construct a bar-linkage chain from cardboard strips and mobile pin fasteners to demonstrate cranial/mandibular kinesis in, for example, snakes and fishes.
- Capture floating oatmeal particles with forceps, pipets, and sieves to illustrate aquatic foraging methods employed by raptorial (seizing), suction feeding and suspension (filter) feeding animals.

Locomotion

- Draw or construct a seesaw to demonstrate various orders of levers in a skeleton (Figure 2), with differing mechanical advantages depending on the placement of load and applied force relative to the fulcrum. Pry open a paint can with a screwdriver to explain lever systems and torque to reluctant students. Compare lever arms and in-forces and out-forces of cursorial and digging mammals (like deer and armadillos).
- Make paper airplanes or, better, use models (or photographs) to explore how airfoils create lift and drag (as in the classical comparison of bird and aircraft wings). Find other man-made analogues of aquatic, aerial and terrestrial locomotion (rowing, paddling, lateral/vertical undulation; gliding, flapping; crawling, rolling, burrowing) in vehicles, robots, and machines.
- Springs and rubber bands of diverse size and stiffness can stand in for elastic storage structures, such as the Achilles tendon and avian furcula ("wishbone").
- Have students run barefoot through mud to explore the intricacies of dinosaur trackways.
- Use archery bows or violin bows as analogues of the ligaments, tendons, and other musculoskeletal features of the mammalian trunk, or use suspension bridges, columns and cantilevers to explain body support and locomotion.

Respiration

- Inflate a balloon to show the relationship between lung compliance and volume. Soap bubbles easily demonstrate the role of surfactants in lowering surface tension.
- Construct a standard bell jar model of the lung (with rubber diaphragm) to show how lung inflation depends on enlargement of the less-than-ambient-pressure pleural space, and how a breach of the thoracic wall (pneumothorax) impairs normal ventilation (flow of air into the lung).
- I am sure you can think of many more examples. Please share them with me!

Conclusions

The analogies I present here are not so far-fetched as they seem; after all,

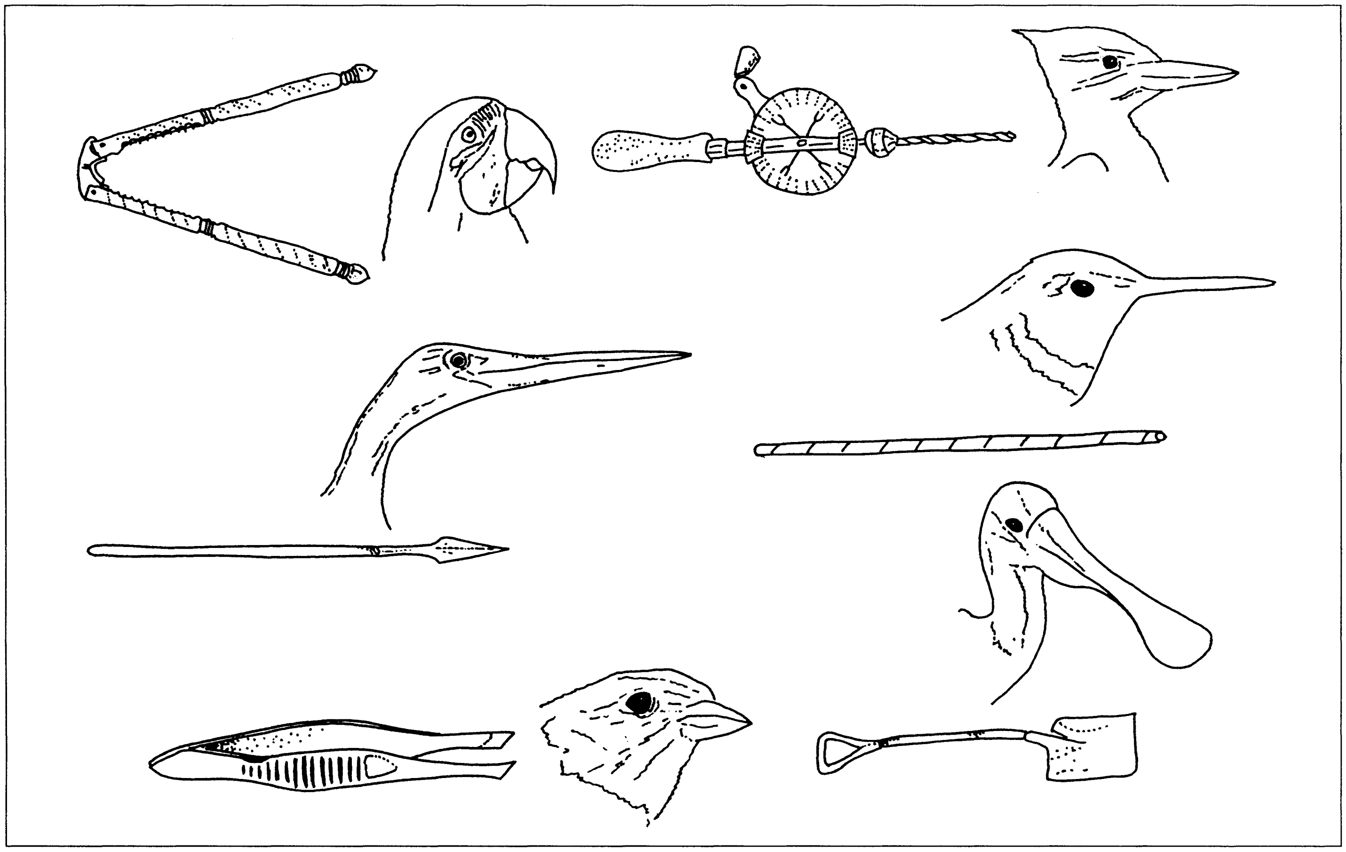

Figure 1. Bird beaks as mechanical analogues of everyday objects (left to right, top to bottom): nutcracker and macaw, drill and woodpecker, spear and heron, straw and hummingbird, forceps and sparrow, shovel and spoonbill.

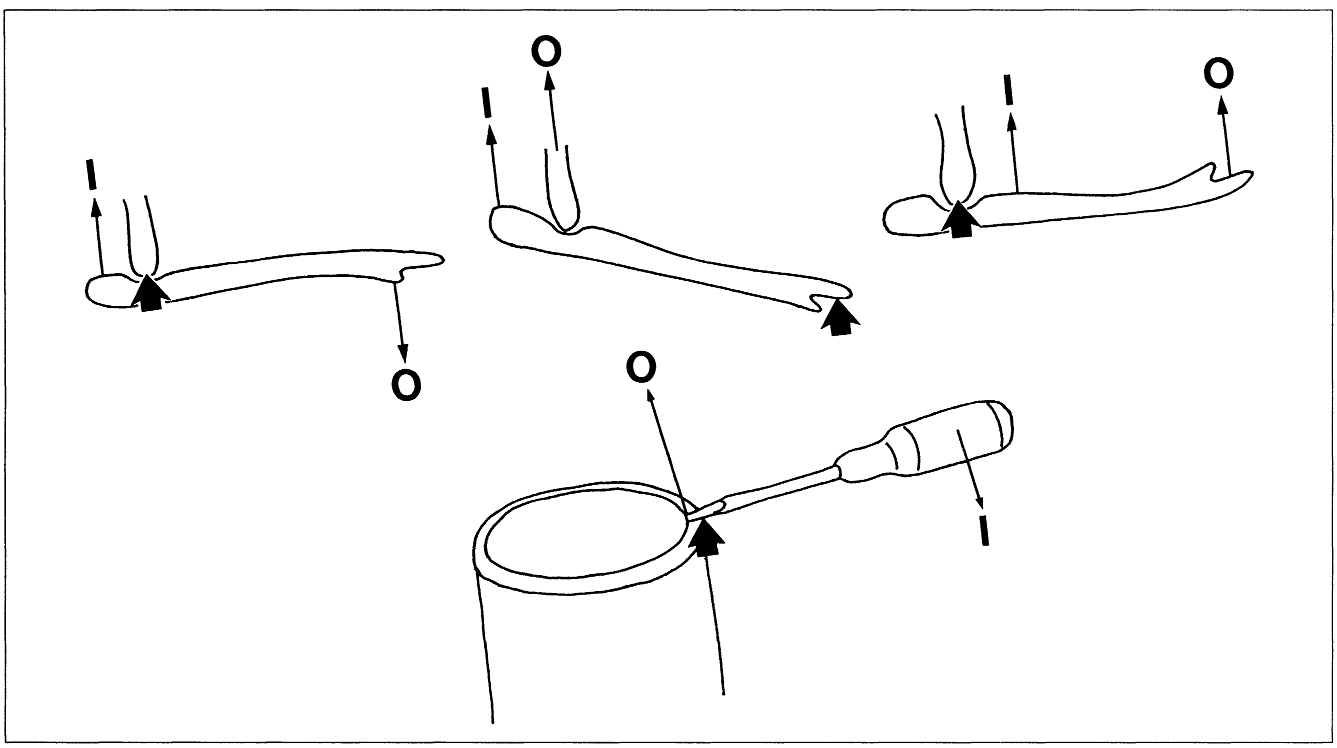

Figure 2. Three orders of levers as demonstrated by a forelimb, showing fulcrum and in-forces (I) and out-forces (O). A screwdriver acts like a first order lever when used to pry a can open, but has great mechanical advantage since the applied force (I) has a much longer lever arm than that of the output force (O).

many inventions are mere elaborations or variations on nature's devices (Alexander 1992; Vogel 1989, 1998; Wainwright et al. 1982). I frequently use these and other examples of biomechanics and material design in advanced courses on vertebrate anatomy, physiology, paleontology, and evolution. I have found them equally suitable for laboratory exercises and demonstrations in introductory biology, botany, and zoology. There is something richly satisfying in a clear, concise explanation, just as there is comfort in a familiar or intuitive example. Students gain an appreciation for the diversity and complexity of evolution and an understanding of the patterns and processes underlying form and function.

Structure is important for obvious reasons, not least of which is the fact that it is the principal manifestation of phenotype, and as such it forms the underlying basis for evolution, ecology, behavior and other fields beyond morphology. The environment (in the form of gravity, wind, currents and so on) interacts with and selects forms to create the astonishing convergence seen, for example, in feet and beaks of waterbirds, skulls and shoulders of ant-eating mammals, and spines and flowers of desert plants. Structural and functional influences emerge, of course, at many levels ranging from molecular and cellular to tissue and organismal.

While students should keep in mind that every tree and turtle is shaped by a balance of intrinsic (genetic) and extrinsic (environmental and epigenetic) influences, they must understand that organisms are seldom optimally designed. Employ "reverse engineering" strategies to discern "utility functions," remembering that teleological explanations, while intuitive, are unsatisfactory in that they wrongly ascribe a purpose or goal to evolution, unlike mechanistic explanations that rely on simple chains of cause and effect. Recall that many structures and systems are non-functional historic holdovers, atavistic quirks like the whale's pelvis or QWERTY keyboard. Others are makeshift solutions usurped from other functional complexes, like the panda's non-opposable "thumb," actually a carpal (wrist) bone used to snag bamboo branches since, as in all bears, digits are fused into a paw (Gould 1980). Morphology is just as much a cause as an effect of design.

In this regard the distinction between proximate (mechanistic) and ultimate (evolutionary) causes must always be borne in mind. The teaching examples cited here involve physical "rules" according to which organisms are constructed. However, these cannot substitute for evolutionary explanations. As mentioned in the introduction, no animals have wheels, but this is due to physical limitations. If it were possible for animals to evolve wheels and some did, certainly these would afford a tremendous competitive advantage, such that wheels might soon be ubiquitous. But organisms need only to do well enough to survive and reproduce, not be the best they can possibly be. Remind students that evolution can only work in the here and now; it has no way to plan ahead or foresee the future.

Remember too that when biologists speak of organisms being "designed" in a certain way, they are merely using a manner of accepted (if unfortunate) shorthand language. We know that the forms resulting from evolutionary processes arise from mutations that are tested in a competitive "battleground" that often unfolds over numerous generations. In addition, while biologists often speak of the evolution of hands or of wings, we recognize that nature actually "selects" whole organisms. Organisms are complex assemblages, and it is the sum of these parts, not the parts themselves, that survive and reproduce.

Observation is a critical step in any morphology exercise. Careful examination (and artistic rendering in a notebook) helps students gain appreciation for the complexity of evolution and understanding of the patterns and processes underlying form and function. Moreover, sculpting with clay or other basic modeling materials often reveals strategic three-dimensional subtleties. Fine points of aero- and hydrodynamics can be investigated without a wind tunnel, flume, or flow chamber. At the same time, encourage students to create mathematical models and use real numbers; simulations can be quantitative as well as qualitative. Because my research involves whales, which present formidable legal and logistical problems, I have come to depend on creative and resourceful modeling solutions.

It should be emphasized again that the biomechanical analogies presented here work only when modeling organisms subject to the same physical forces that affect us—that is to say, organisms in our relative size range. The world of very small organisms (prokaryotes, plankton, and so on) is ruled by the physics of low Reynolds numbers, in which viscous rather than inertial forces predominate. The locomotion of elephants and whales is governed by gravity, while that of bacteria and protozoans is much more affected by friction and surface tension. This is of course the essence of capillary action and the reason water striders cannot be large or heavy. The result is that it is inherently difficult to model organisms (or cells or subcellular structures) which are not of the human scale of size, as even elephants and whales are when compared to bacteria. However, it is not impossible to demonstrate the effects of extremely low Reynolds numbers—a copepod swimming through water is analogous to a human swimming in molasses—and to the extent that such exercises reveal the limitations of the world of our experience, they may prove highly informative.

Finally, encourage students to analyze how organisms work—how their operation relates to their construction—by posing simple observation-based questions, as in the list at the beginning. Such questions stimulate thought and provoke discussion; they also make the study of form interesting, innovative and multidisciplinary. This not only leads one to appreciate the dazzling diversity of life, but spurs awareness of the physical constraints that shape the dazzling array of life forms real and imagined, past, present and future. There is much to learn, and the best way to find answers is to begin by asking questions.

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