LETTERS

Probing of Dimensional Analysis Reveals Scaling, Sapience and a Froudean Slip

I commend Steven Vogel for his essay entitled "Exposing Life's Limits with Dimensionless Numbers" (PHYSICS TODAY, November 1998, page 22), which elegantly relates biological limits to certain dimensionless numbers in physics. Relating physics to biological systems contributes to understanding in both fields.

One additional scaling relationship may help explain a matter that seems to have puzzled the author. The height to which an animal can jump is known to scale as the potential energy that can be achieved divided by the weight of the animal. The achievable potential energy scales as the maximum applied force times the leg length over which the force is applied. If L is a characteristic length of the animal's body, then the applied force scales as the strength, or cross-sectional area, of the leg muscles, which is proportional to L^2. The leg length is proportional to L, and the weight is proportional to L^3. Hence, the height to which an animal can jump is independent of L, or the size of the animal. This scaling explains why all jumping animals—whether a flea, grasshopper, frog, squirrel, house cat or lion, human or horse—can raise their center of gravity at most about 1 m, within a factor of two or so.

Vogel is puzzled as to why the trot-to-gallop transition for quadrupeds occurs at Froude numbers between 2 and 4, since neither gait involves gravitational energy storage (in the sense of the leg acting as a pendulum). The scaling relationship above suggests that gravity may reenter the picture for galloping animals, since their potential energy is changing periodically.

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I enjoyed Steven Vogel's excellent essay. This research field between biology and physics is both intriguing and very interesting. However, I find it difficult to understand Vogel's arguments (which I also have encountered previously among biologists) regarding the transport of sap in trees. In particular, I wonder whether the sap really is drawn upward by evaporative water loss from the leaves, and whether the large columns of water in the tree trunk's conduit system are actually kept together by the "internal cohesion of water."

With regard to sap flow, assuming that the pumping mechanism is evaporation from leaves, what happens in broad-leaved trees in the spring, given that they lost their leaves the previous autumn? Also consider that when grapevines are pruned in springtime, as they regularly are, sap oozes heavily from the stumps without any leaves being present. Further, when a colleague of mine chopped a branch off his walnut tree, the wound bled for a long time, and the sap pressure even pushed away a small board that had been nailed over the cut. Thus, there should be still another pumping mechanism at work besides suction from the leaves.

With regard to the water column in the tree trunk, assuming that leaf suction (if that were the only driving force) would create a vacuum above a height of 10 m, how exactly would the internal cohesion of water stop the sap from boiling in the conduits of trees that are, say, 50 m tall? Has this internal cohesion of water actually been verified by experiment? A simple check on this astounding assumption would be easy to carry out: Take a capillary plastic tube with an inner diameter of 80 μm, fill it with water and dangle it from a tall building.

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Steve Vogel's essay is fascinating. However, there appears to be a miscalculation on the ascent of sap in trees. Using the equation Vogel proposes for the Bond number for getting sap up a tree, I calculate that for water conduits of 0.05 mm radius, sap would rise less than 0.29 m, rather than the 3 m calculated by Vogel. Assuming the effective water-filled radius of capillaries in the trunk, branches and leaves to be 10^{-4} mm, then the maximum height of a tree that can sustain sap flow would be 146 m, rather than the 1500 m mentioned by Vogel. The world's tallest tree, according to the *Guinness Book of Records, 1998*, was a eucalyptus found at Watts River in Australia and estimated to have been over 500 ft (152 m) tall. The Bond number analysis suggests that the leaf pores and supporting capillary tissue in such a tree would have to have had radii of less than 10^{-4} mm. Water flow would be slow in such small pores. Flow resistance may be the reason for the ultimate limit on the height of trees.

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Vogel replies: I agree with both points made by Franklin Felber; I believe that his argument about heights of jumps was first made by Galileo. In reality, air resistance should reduce the flea's range by 80%, and only with a cunning trigger mechanism can the beast meet our crude expectations. As for the trot-to-gallop transition, I meant merely to imply that my reasoning was speculative, since we lack the experimental base that R. McNeill Alexander, C. Richard Taylor, Rodger Kram and others have given us for the onset of trotting.

Dietrich Bechert's uncertainties have largely been put to rest by the plant physiologists, whose textbooks give the details. A remarkable body of evidence supports the notion that water, under substantial tensile stress, is drawn up tree trunks by evaporation from the leaves. That water has sufficient cohesion was shown by Lawrence Briggs,[1] who (with admittedly heroic precautions against bubble nucleation) got tensions as high as 290 atmospheres! And we have good (if indirect) evidence for tensions of up to 120 atm in living plants. Bechert correctly notes that evaporation could not provide the positive pressures needed for the initial sap rise in the spring and observed at other times as well. Those pressures mainly come from pressure in the roots, generated osmotically and paid for metabolically. Incidentally, Bechert's proposed "simple check" wouldn't be so easy to do, in that a water column breaks from imperfect adhesion between the water and the tube's walls, or from bubble nucleation at that interface.

Glendon Gee points up an embarrassing error; in fact, I made two mutually offsetting errors. As he notes, capillary rise should be about 0.3 m, not 3.0 m. But the pore radius in the walls of the cells within the leaves is about 5 nm, not 100 nm.[2] So, drawing in air would require a sap column nearly 3000 m long, which doesn't constrain tree height. Since water leaves by evaporation rather than bulk flow, the small size of the pores shouldn't matter. In any case, the aggregate area of pores lining the internal air spaces of leaves exceeds their huge external surface area by more than tenfold, so no rapid movement need be assumed.

In closing, let me note that, based on what I've heard since my article was published, physicists may be assuming excessive originality on my part. In general, I have learned that they are surprised at how much decent physics can be found in the biological literature. As an ecologist, Joel Cohen, once remarked, "Physics envy is the curse of biology."

References

1. L. Briggs, J. Appl. Phys. **21**, 721 (1950).
2. See P. Nobel, *Physicochemical and Environmental Plant Physiology*, Academic, New York (1991), pp. 96–97.

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'First World' Journals Should Publish More 'Third World' Science

As both a physics professor at the University of Havana and a member of the American Physical Society, I write to express my concern that researchers in developing countries have too limited opportunities to have their work published in the scientific journals of the developed countries.

It is unquestionable that researchers in developing countries face more difficulties than those who work in developed countries, and that their results may not always contribute to the leading edge of research in the particular discipline. Nevertheless, the majority of researchers in developing countries take their work seriously, and when they obtain some noteworthy results, they attempt to share them with the scientific community through publication in journals that are read all over the world. In many cases, though, their manuscripts are summarily rejected by the