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Form in nature

La forme dans la nature

Formen in der Natur

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SUMMARY
Bodies in nature are built only from appropriate materials: mistakes are extinct. Biological materials are composite: crystalline polymeric fibers in hydrated polymer gel matrix; some have calcium salts or silica included. Hydrated materials confer low shear modulus on the more flexible bodies and joints. Orientation of fibrous polymers allows appropriate reinforcement of pressurized bodies. Rigid materials allow for systems of levers and their attendant mechanical or speed and displacement advantages.

RESUME
Les corps dans la nature ne sont construits qu'à partir de matériaux appropriés: les erreurs sont éliminées. Les matériaux biologiques sont composites: fibres cristallines polymérisées dans une matrice gelée de polymères hydratés; certains ont des sels de calcium ou de silicium à l'intérieur. Les matrices hydratées confèrent, aux corps les plus flexibles et aux joints, un faible module de cisaillement. L'orientation des fibres des polymères permet un renforcement approprié des corps pressurisés. Les matériaux rigides permettent de réaliser des systèmes de leviers présentant des avantages d'ordre mécanique ou de vitesse et de déplacement.

ZUSAMMENFASSUNG
Natürliche Körper bestehen immer aus geeigneten Materialien, Fehler sind ausgeschlossen. Biologische Materialien können zusammengesetzt sein aus kristallartigen polymeren Fasern in hydratisiertem Polymer-Gel; einige enthalten auch Kalziumsalze oder Silikate. Hydratisierte Materialien übertragen kleine Schubmoduli auf flexible Körper und Verbindungen. Die Beeinflussung der polymeren Fasern ermöglicht eine zweckmässige Bewehrung beanspruchter Körper Steife Materialien bringen Systemen von Hebeln mechanische oder Geschwindigkeits- und Verschiebungs-Vorteile.

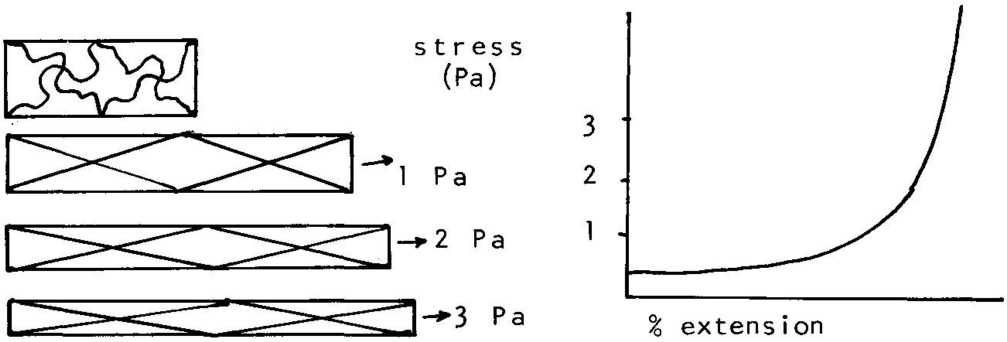
The predominant form of bodies in nature is the cylinder. The bodies of plants and animals are either simple cylinders or branched cylinders. The cylindrical form of organisms arose from the action of environmental selective forces on a set of materials that have been organized into bodies. The materials were and still are produced at climatic temperatures and pressures from carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorous in compounds that are dissolved in water surrounding the organism. Some natural cylindrical bodies are stiff and some are limber. An important observation is that all of them bend - some more than others, some actively, some passively, but they all bend.

The materials

Basically the materials of which organisms are made are of three general kinds. They are polymers, water and calcium salts. The polymers are polyanionic proteoglycans whose configuration and mechanical properties depend on their thermal energy, on the ionic environment surrounding them, on their crosslinking and on the included calcium salts between them. These polymer molecules are usually very long, straight-chained proteins or polysaccharides and since they are highly hydrated and polyanionic, they are, in fact, fibers in an aqueous matrix. These polymeric materials are composite from the very beginning. They are indeed soft and flexible and such stiffening devices as calcium salts are present in only a few of the many materials that occur in organisms.

Let us look at more complicated soft connective tissues in animals, materials such as skin or the mesenteries that hold our intestines together. These are flimsy, stretchy, flexible materials. They are made up of many cells, of course, but outside the cells there is a voluminous fiber and gel matrix composite. These are not all alike, but a predominant polymer acting as a fiber in such composites is the macromolecular protein, collagen. Now collagen is the material of which tendons and ligaments are made, and tendons and ligaments are not stretchy and cannot be deformed in the tensile mode very much at all, and yet the soft connective tissues in animals can be deformed by hundreds of percent. This means that the collagen molecules in the soft connective tissues are not connected one to the other by short crosslinks in a network as they are in tendons and ligaments.

When one pulls on a piece of skin one finds that the first few millimeters of deformation come very easily: very small forces are necessary to make this deformation. But as one continues to pull, one notices that within a few more millimeters of stretch the material becomes very stiff indeed. We reckon this interesting increase in stiffness with strain is caused by the collagen and other fibrous polymers in the skin becoming progressively oriented in the direction of the force and that in fact they are linked together in a network which ultimately comes to be pulled on and responds by pulling back with the stiffness of collagen, even as it is known in tendons and ligaments. This means in engineering terms that skin has a stress-strain curve shaped much like the letter J



and Professor Gordon has brought this phenomenon to the attention of biologists and he has told us what it is about. One thing we can add further to his discussion is that it is quite clear that the increased stiffness of such materials acts as a safety factor in organism design. It says to the organism, "Stop pulling!" and it even pulls back at the organism, further preventing rupture. It tells you when to stop stretching your skin, but at the same time it has allowed you to stretch your skin by 50 to 100 percent. So we have stiffness ultimately, but we have permission for a great range of changes of shape on the way to that great stiffness. This strain-dependent stiffness and the viscoelastic nature of the polymeric connective tissues of animals make them unique in the world and make them of unusual interest to engineering material scientists.

Stiffer animal tissues such as cartilage are similar to the soft connective tissues just described but they simply represent the stage where much of the water has been taken out and there is a greater degree of crosslinking among the polymer molecules in the hydrated polymeric composites. Cartilage at the end of our long bones is not very flexible, extensible or compressible and when force is applied to it, as when we stand up and put our entire weight on the ends of our leg bones, this material is squashed and is deformed slightly because water is actually squeezed out of the pores of the material. As soon as we take the weight off our legs this water is actually sucked back into the cartilage by combination of the ionic strength of the molecules in the cartilage and the actual stiffness of the material itself.

One of the stiffest of all the natural composite materials is the crisp outer covering of insects and shrimps and some crabs. This exoskeletal cuticle is almost entirely dehydrated. In fact the current theory of Dr. Vincent of Reading University says that the reason that cuticle is such a remarkable material is that when it is formed it is in a highly hydrated state and it is soft and flexible and then, by mechanisms as yet unknown, the water is drawn out of it leaving a very rigid material indeed. The most famous component of this material is a polysaccharide named chitin but there are equal parts of large molecular weight proteins that are tightly linked to the chitin and to each other. One of the major differences between a caterpillar and a butterfly is that the caterpillar has a soft, more highly hydrated cuticle and the butterfly, especially in its wing membranes, has a dehydrated, rigid material for its flapping airfoils.

Looking at plants for a moment, the floppy seaweeds have given rise over evolutionary time to much stiffer land plants. If you are going to be a successful plant out on land and you are going to compete with your fellow plants for the sunlight, you're going to have to be rigid, and in the extracellular materials in land plants the same thing has happened that has happened in the animals, namely a progressive loss of hydration. The water goes and the agar is replaced with a particular material called lignin that polymerizes and forms a rigid glue. Perhaps we can say that the major difference between a seaweed and an oak tree is that the shear modulus of the polymeric material between cells in the seaweed is low whereas that in the oak tree is very high. Another major difference consistent with this is that the volume percent of fibrous material, namely cellulose, is far greater in the wood of trees than it is in seaweed.

And finally we come to the very rigid calcareous materials of animals and plants. In our own bodies, bone is simply a calcified polymer and, as a matter of fact, less than half of the material of bone is calcium salt: most of it is polymeric. This means that although a bone is a rigid object and we depend on its rigidity as we walk and run and ski and fall down, the actual viscoelastic properties of the polymeric matrix material in the bones allow a bone to absorb far more energy in its breaking than it would be if it were made only of calcium salts.

Bone must be made at great cost by sequestering calcium from the foods we eat and then putting it through complex physiological processes to form salts in our bones. Crabs and corals and sea urchins would seem to have an easier task because the sea water around them is rich in both calcium and the other elements necessary to make calcium salts.

The body

Now a body that is a random aggregate of polymers is just a blob. In order to create a cylindrical body, a certain property of the polymers in such a blob is necessary and this is the ability of these polymer molecules to become preferentially oriented. When this happens then long cords of molecules lying parallel to one another can exist and give elongated form to the body. Materials made of highly oriented polymer molecules are anisotropic in many kinds of properties: mechanical, optical, electrical and so on. The ability of similar molecules to achieve any degree of preferred orientation is one of the bases of diversity in biological systems and I maintain it is one of the bases for the formation of the first cylindrical body. There are species of lower plants and animals that are only just plate-shaped or cylindrical in their form and that can be easily described as a system of cells in a gel matrix reinforced with oriented polymers.

Structural types of bodies

The three familiar body types that we see in natural forms are the branched solid cylinders of corals, seaweeds, bushes and trees, the stretched membrane hydrostats of worms, sea anemon es, sea cucumbers and caterpillars and the braced jointed frameworks that are familiar to us in insects, crabs, shrimps as well as fishes, frogs, birds and mammals. First we will look at the branched solid cylinders. Here we will see a continuum from the floppy seaweed to the flexible soft coral, the flexible palm tree, to the much more rigid oak and maple trees and the very rigid, brittle, stony coral. The plants are aggregates of cylindrical cells held together by tensile forces in a continuous network of cellulose filaments. In the floppy seaweed, cellulose is wound in tight helical array around columns of cells that are dispersed in a highly hydrated gel-like matrix. Because these cellulose columns are central in the stem of the plant and because the matrix has a very low sheer modulus, the seaweed body bends readily with the flow and in so bending it becomes streamlined and avoids the high drag forces associated with high rates of flow that come with wave action. As they flop down into the boundary layer they further avoid the higher rates of flow. So the seaweed plant has an integrity that is due to the tensile strength and stiffness of cellulose as it reinforces a gel-like matrix of intercellular agar and it depends on extreme flexibility for survival.

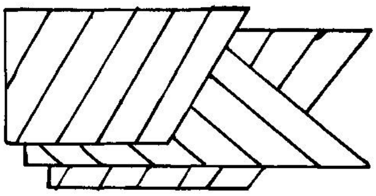
Next we come to the oak tree or the maple tree. In wood the matrix is reduced to submicroscopic layers of very rigid glue material called lignin that cross-links the cellulose. These thin layers of rigid glue confer a very high shear modulus to the material and make the tree and its parts very rigid in torsion. When the wind blows, oak and pine trees do bend especially at the branch tips and their leaves flow out in streamlines with the wind thus reducing the drag on the entire tree. The entire tree and especially the trunk does not bend nearly as much as the palm trees and seaweed.

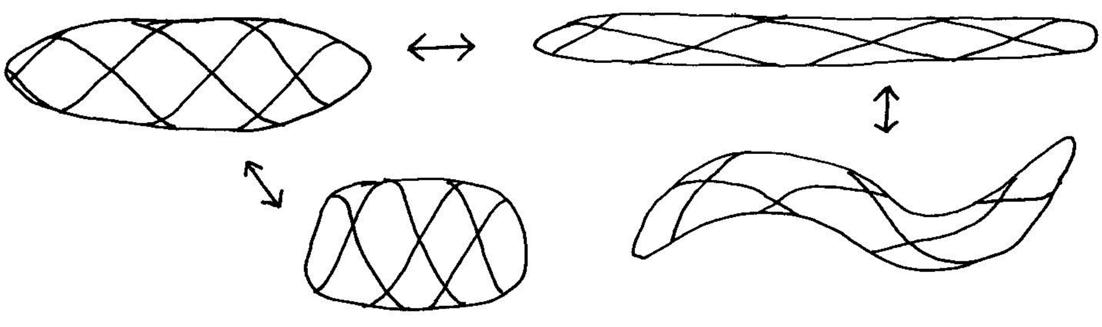
The seaweed and the palm tree and the oak tree all have a tensile integrity of cellulose throughout their entire plant body. This tensile integrity is especially important at the branch points where the design is clearly suited for the stable and smooth transmission of stresses from the limbs to the trunk as the limbs are effected either by gravity or by wind forces. To build a body form with branches that transmit forces as smoothly as do those of branches of trees must be a marvel indeed in the engineer's eyes. There are no new and different materials put at these branch points, there are no new aspects of design, but the fibers of the trunk and the fibers of the branch interdigitate perfectly in complete compatibility of materials for the smooth transmission of forces across the joint.

Also in the branched solid cylinder category we have the coral. Coral shapes are made up of skeletal material that is entirely extracellular. They are not made up of columns of fiber wound cells as the seaweed and the various trees we have just discussed. The stony corals are made of solid, polycrystalline calcium carbonate. The crystals are for the most part submicroscopic but there is mass continuity of mineral throughout the skeleton. The material is extremely brittle. The branching pattern is similar to that in plants and the smooth transmission of forces across joints is characteristic of corals.

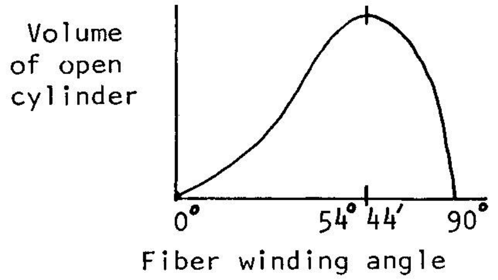
The stretched membrane hydrostat shows the influence of preferred orientation of polymer fibers in the gel matrix on the behavioral properties and capabilities of the fully formed body.

Soft tissues in animals have interesting J-shaped stress-strain curves that arise as described above. Now collagen, a macromolecular protein, is the predominant polymer in these soft tissues. The J-shaped stress-strain curve occurs in material where in the polymers may be initially randomly oriented or in a polymeric material whose polymers are in parallel array in layers that alternate their orientation. In the case of the sheets of oriented polymers, if such a material is wrapped into a cylinder, we have a model for all cylindrical plant cells, all bodies of polyps and worm-like animals as well as the guts and arteries of some of us less worm-like creatures. As a direct result of being thus crossed helically wound, these bodies and tubelike organs can lengthen and shorten but, most important of all, they can bend without kinking. I cannot stress enough the importance of this simple observation that bodies in nature can bend without kinking and that this behavior is due to the fact that they are cylindrical shapes reinforced by a helical array of fibrous polymers.





Cylinders can have quite directional mechanical properties. The winding angle of their reinforcing fibers combined with that unique animal invention, the muscle, give us the most interestingly diverse systems ever to have evolved. Most worms have a sheet of muscle oriented longitudinally and another sheet oriented circumferentially and can perform many contortions, but one very large and successful group, the nematodes, lack the circumferential set of muscles and yet these animals still wiggle because the fiber winding angle is about 75 degrees. The figure shows that contraction of any longitudinal muscle in such a cylinder will tend to decrease the volume of the cylinder. Since the volume cannot decrease, the internal pressure rises and this stretches the body wall with the crossed helical array of fibers in it. These fibers then become stretched and they store elastic energy. When the longitudinal muscle relaxes, the internal pressure falls and elastic recoil causes the animal to return to its resting shape. Thus the animal has made a compensatory movement without having a set of antagonistic muscles to do so. It is simply using elastic recoil that resides in a material due to its particular array of polymer molecules.



The stretched membrane hydrostat must be powered by sheets of muscle that apply distributed loads to the membrane. They must not leak or be liable to be punctured, therefore these are hard to maintain on land away from easy access to bulk water and they are obviously too bulky and heavy for flying organisms. They are however, excellent body forms for locomotion in low Reynold's number situations: small animals in water, larger animals burrowing in soft soil such as mud and sand and the leaf litter of the forest floor. And it is in these habitats that animals with the stretched membrane hydrostat have their greatest diversity and success.

The braced jointed framework is really just a stretched membrane hydrostat in which the compression resistance of the fluid is replaced by that of rigid solid materials. These rigid solid materials will either be polymeric as in the insect cuticle or they may be calcareous as in crabs, snails, fishes, frogs, dinosaurs and people. Fluids resist only changes in volume and the hydrostatic skeleton resists changes in shape because many constraints upon its design arise from this particular design problem. Since rigid solid materials can resist changes in shape directly, bodies made from them can have long, stiff limbs supported by long, thin rigid elements and these limbs can be powered by spindle-shaped muscles that apply point loads to rigid elements in the system. This becomes then a system of levers that can have either mechanical advantage or displacement and speed advantage. This adaptable system produces fast running and that most extreme form of locomotion, powered flight. It is characteristic of these braced jointed frameworks to be branched: have arms and legs. The joint in this case is much more flexible than those in plants and involves a change in materials at the point where it joins the body. Here we have the problem of maintaining compatibility of materials across the joint for the smooth transmission of forces and it may be here in the design of joints that the great groups of animals including the insects and the mammals and birds have attained their greatest degree of engineering sophistication. Stiffness in bending is a matter of both the material modulus of the material and the shape or the second moment of area of the cross section. Both of these tactics have been involved in the design of animal skeletons in the evolution of braced jointed frameworks: both the material modulus and the second moment of area have been varied in the evolution of the wide variety of point, hinge and sliding joints that exist.

SUMMARY

We have seen three quite distinct ways to make cylindrical bodies. Cylindrical bodies confer on organisms, the ability to orient to environmental stimuli, the ability to locomote effectively with sense organs at the leading end. Locomotion is accomplished either by undulating the cylindrical body itself or by the action of cylindrical branches. Such branched cylindrical bodies demand cleverly built, cleverly designed joints where forces can be transmitted across the joints smoothly without interruption in function or disruption of structure. In all the three types of bodies we have met, the integrity of the body is effected by tensile stresses in long straight chained polymers of either polysaccharides such as cellulose in plants or the great macromolecular protein known as collagen in various kinds of animals. In all forms these polymers are distributed throughout a gel-like matrix and according to how stretchy or flexible the cylinder is, the gel-like matrix will be more hydrated. In the more rigid ones such as the design of trees, the gel-like matrix is reduced to an exceedingly thin layer of rigid glue.

If you are going to be a stretched membrane hydrostat, it is pretty clear you must be made of a polymeric material. If you wish to run about on land or to fly you must have rigid materials so that you can have a lever system that will confer upon you the mechanical and particularly the displacement and speed advantages that lever systems can give. We do not see seaweeds or trees that can crawl or swim, we do not see animals with stretched membrane hydrostats running or flying and we don't find animals with braced jointed frameworks wasting their time being attached to the surface of the earth like a plant waiting for the environment to bring them food. So in this sense the materials that constitute each part of natural forms are precisely those that are most appropriate.

It is amusing to a biologist to think of this particular set of ideas that we are thinking about in this session, namely the influence of materials on the selection of form, because if you start where evolution started with polymers in water, outside of cells, and you try to build bodies with the materials at hand, you simply would not build bodies that are inappropriate for the materials at hand. In evolutionary language, inappropriate designs are eaten by better ones. You would not think of trying to build a house or a car without rigid material. Houses and cars certainly did not come first as far as evolving organisms are concerned, they had to work with what they had and they did so. They first built blobs and then they built small, simple, soft, cylindrical worms or simple plants. The plant forms became larger and more complex and then branched and became more rigid as they came out on land and withstood gravity and could bear heavy fruits high in the air. Animal bodies also became more complex and used the rigid materials in jointed frameworks in combination with the actively contractile material, muscle, to produce the most remarkable living machines of all, flying insects, birds and bats.

Further reading

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Wainwright, S. A., W. D. Biggs, J. D. Currey and J. M. Gosline. 1976. Mechanical Design in Organisms. Edward Arnold, London.

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