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Self-assembly: Biology ⟷ Physics

Biology & physics interacting can illuminate fundamental questions

Biology may not be destiny, but when biology and physics feed back on each other a number of fateful happenings may be understood. In a review talk at the recent meeting of the American Physical Society in Dallas, E. A. Dimarzio of the National Bureau of Standards in Gaithersburg, Md., showed how certain critical principles of the physics of polymers could be used to model the processes involved in the self-assembly of biological systems and how the existence of such biological systems may help answer some of the mysterious questions about the fundamental constants of physics.

Self-assembly can be demonstrated in many biological structures: If an experimenter takes them apart, they will reassemble themselves. Many membranes have this capacity; and membranes, both at the boundaries and within the cell, play vital parts in the cell's function. "If we understand membranes, we understand a lot about the cell," Dimarzio says.

He proposes that the circumstances of this biological self-assembling characteristic are similar to phase transitions in physical systems, particularly polymers, and that the physical phenomenon can be used as a model to understand the biological one. The most familiar example of a phase transition in physics, cited by Dimarzio, concerns water: Take the disorder of liquid water. Depress the temperature and you get a beautiful structure that is ice. Phase transitions are changes in the physical state of some system, in its order or structure, as a result of some stimulus from its environment.

The similarity is that under some stimulus basic biologic elements order themselves into larger structures — as water molecules order themselves into ice crystals or as atomic magnetic moments in a metal order themselves from the random orientation characteristic of paramagnetism to the parallel orientation that makes ferromagnetism. As a classic example—it has been studied for decades — Dimarzio cites the assembly of a virus out of globular proteins.

Globular proteins are so called because they are molecules shaped like peas or peanuts. Isolated molecules of this kind will build themselves up into a spiral cylinder. "If you put an RNA molecule in with this," says Dimarzio, "you can reassemble a tobacco mosaic virus." Furthermore, this virus is potent. "You can put it in tobacco plants and kill them," he says.

Other biological entities can reassemble themselves out of constituents in similar ways. What Dimarzio would *like* to do, he says, is build up an "enormous catalog" of self-assembly processes in biology and of phase transitions in polymer physics that are analogous to them. But he says he can't—it would take generations of scientists working for lifetimes to assemble it.

Liquid crystals, which Dimarzio considers polymers, have a structure almost as orderly as solid crystals, but nevertheless have most of the physical characteristics of liquids. "Liquid crystals occur often in biology," Dimarzio says. He cites brain cells, myelin sheaths and bilipid membranes as examples.

Brain cells are particularly interesting. From the point of view of energy, the most efficient shape for a brain cell and its axon would be a spheroid. Actually, many such cells come in extended stringy shapes. These shapes are maintained for them by microtubules, stiff structures that give not only brain cells but other kinds of cells the shapes they need.

A prime example of the physical theories developed by polymer scientists and applied to biology is one for calculating the reaction rates for assembling the structure of microtubules from fundamental physical constants. Microtubules are built from globular proteins about 50 angstroms in diameter and weighing 40,000 to 60,000 daltons. Slight changes in temperature or chemistry induce these globules to assemble in chains. The chains spiral in such a way as to build hollow cylinders that resemble brick silos. Dimarzio refers to it as "a bricklayer's problem."

Growth (or shrinkage) tends to take place at the ends of these chains. Adding or subtracting a globule at the end requires establishing (or breaking) fewer chemical bonds than breaking the chain somewhere in the middle, so change at the ends is energetically favored. The models yield equations that predict rates of growth for these chains. They are even capable of distinguishing between structures that are one "brick" thick and those that are two "bricks" thick. It's a real physical theory that can take account of such a small shift, says Dimarzio.

These models can be extended to allow several different "colors" of "bricks," that is, different kinds of proteins in the same structure, the process known as copolymerization. A biological example is the formation of f-actin, an important constituent of muscle from the basic elements known as g-actin. The method can be extended to various polypeptide structures, including those that biologists call alpha helix (hair is one such), beta helix (horn and nail are examples) or the triple stranded structure of collagen (a constituent of skin, bone and tendon).

There are even possible medical extensions. At least two diseases, sickle cell anemia and Alzheimer's disease, are thought to have to do with deficiencies of self-assembly.

Dimarzio's survey leads him to conclude that self-assembly exists and is widespread in biology and that phase transitions in polymers are essential to it. Thus physics has a good deal to say about the structures of biology. There is also a converse.

The fundamental constants of physics, which play a crucial role in the basic equations of all branches of physics, determining the relative strengths of forces, measuring the basic properties of elementary particles, etc., are generally determined empirically. Philosophical or theoretical principles do not prescribe what their values should be. Physicists have long wondered why the fundamental constants should have exactly the values they do and not others.

These constants appear in the equations relating to biological structures and the complexity of biology often relates constants to one another that come from different parts of physics. The same complexity often indicates also that if certain physical constants were slightly more or less than what they are, the biological structures would not be able to form. So circumstances that seem to have no explanation in physics alone get an explanation from biological considerations, and they get it in a way that leads some people to wonder if there may be some purpose behind it all. Dimarzio ended his talk with one such example of his own.

Water molecules pervade the earth's atmosphere. They absorb electromagnetic radiation very efficiently except in a narrow range of wavelengths, the so-called water window. It happens that the response of the human eye peaks in this water window. This much can be explained as environmental selection acting on evolution: An animal that happened to see in the infrared and not in the water window would have poor survival probabilities because the earth's surface is not illuminated by infrared. However, it happens that the sun's emission also peaks in the water window, and that cannot be explained on such a ground.

The peak range of the sun's emission is determined by its temperature. The most basic controlling factor for the sun's temperature is its density. Its density depends on the strength of its self-gravitation, which is governed by the universal gravitational constant (G). A water molecule's absorption, on the other hand, is governed by its molecular structure, which is determined by two fundamental constants, the charge of the electron (e) and Planck's constant (h). So here the structure of the eye seems to be showing a relationship between two constants from microscopic physics, e and h, and one from macroscopic, even cosmological, physics, G. It seems biology does have something to tell us about physics. ☐