fied as an environmental payment or credit. It may be possible to extend this and include other environmental impact parameters, such as water demand, environmental toxicity, and pollutants.

Categories of material rather than individual ones could also be the focus. For example, if we are interested in polymer fibers for clothing, then all of the materials capable of forming fibers could be compared in terms of their potential for closed-loop processing, to allow us either to select between them or to look for improvements on the current material.

A further interpretation of materials ecology puts emphasis on avoiding end-of-life situations where a material cannot be reused or recycled, or the energy required to do so is prohibitively high. Are there ways to validate this concept? Perhaps one way is to view the amount of energy required to place a material in a closed loop and consume it as a starting material for another industrial process. This could be in terms of the energy required for a conversion. For example, carbon dioxide's Gibbs free energy of formation is very high. This means that a lot of energy input is required to convert $CO_2$ into a useful product in a closed-loop system. In a materials ecology network analysis diagram, $CO_2$ will appear as an island with a relative high cost of closed-loop processing.

In the worst cases, products are treated as dead-ends, because complex products, particularly with many constituent materials, are not really designed for reuse. Materials ecology is about the evolution of a new generation of products that can easily be reused elsewhere at the end of their lives. For example, a modern automobile is a very complex product requiring many thousands of parts. At the end of its life, the car is dismantled and much of it is recycled, especially the metals. Some components are less effectively recycled and go to landfill. However, there is a growing trend in some industries to reuse polymer waste rather than landfill it, and materials ecology embraces this potentially lower-energy option. The modern term "upcycling" is actually an old tradition: In rural communities, objects are endlessly reused and adapted for new uses as they age. This was actually practiced by the father of mass production, Henry Ford. Almost 100 years ago, Ford shipped model "A" trucks in wooden crates from the Ford factory; the crates were then used as the floorboards for the vehicle when sold.

The current obsession with "elementalism," that is, striving to return all objects as close to the pure element state as possible, regardless of the environmental cost, is going to look rather odd in the future. New industrial processes will be required to take in objects and "reshape" them for new uses rather than crush and melt them down into pure elemental streams

The key success parameters of the new industrial landscape are no longer based solely on profit margin, but now include environmental, social, and ethical measures. This will only increase in the future, and the most successful materials will be the ones that thrive in this more complex framework of materials ecology.

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CELL BIOLOGY

# Irremediable Complexity?

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Complex cellular machines may have evolved through a ratchet-like process called constructive neutral evolution.

Many of the cell's macromolecular machines appear gratuitously complex, comprising more components than their basic functions seem to demand. How can we make sense of this complexity in the light of evolution? One possibility is a neutral ratchet-like process described more than a decade ago (*1*), subsequently called constructive neutral evolution (*2*). This model provides an explanatory counterpoint to the selectionist or adaptationist views that pervade molecular biology (*3*).

Seemingly gratuitous complexity is illustrated by RNA processing systems such as splicing and editing. The most complicated macromolecular machine in the cell may be the eukaryotic spliceosome (*4*), which removes noncoding regions (introns) from precursor messenger RNA (mRNA) in a process called splicing. The spliceosome uses five small nuclear RNAs and hundreds of proteins to do the same job that some catalytic introns (called ribozymes) can do alone. The mitochondrial RNA editing system of trypanosomes, in which hundreds of guide RNAs and several large protein complexes insert and delete uridine residues to restore mRNAs to their "ancestral" state, is similarly complex (*5*). Even the multicomponent contemporary ribosome, which translates mRNA into protein, boasts far more constituent parts than most imagine its purely ribozymatic ancestor would have required.

When faced with such complexity, the favored (adaptationist) explanation would surely be selection for improved basic function. For example, ribosomal complexity is not generally regarded as gratuitous, but rather the result of evolutionary accretion of proteins that made this machine progressively faster, more stable, and more efficient at translation (*6*). For the addition of some of these proteins, selection probably did drive increased complexity, but there is no basis to assume that this explains all, or even most, of the increased complexity of these machines.

As an alternative to such adaptationist thinking, Lynch invoked fixation of neutral or slightly deleterious features as a general and unavoidable source of complexity in

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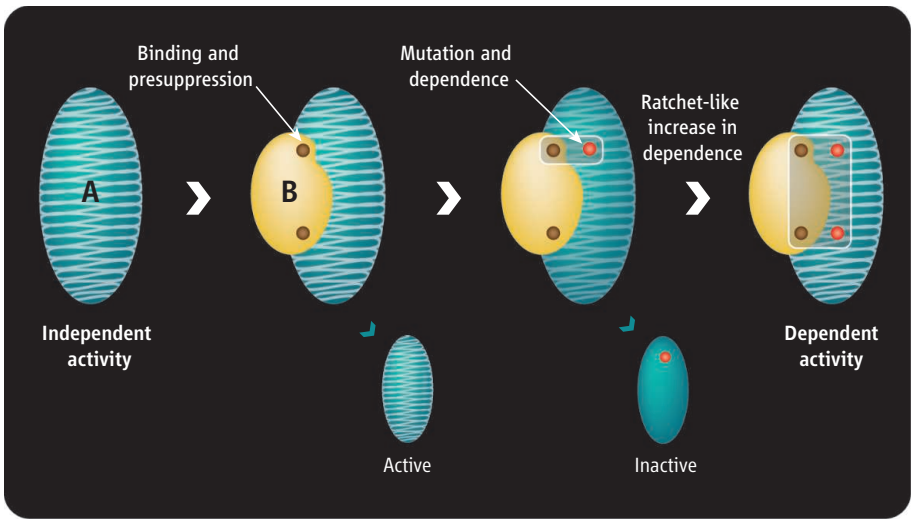


**Becoming interdependent.** Cellular component A fortuitously interacts with B, which allows (presuppresses) mutations that would otherwise inactivate A. Subsequent mutations render reversion to independence unlikely.

taxa with small populations (*3*, *7*). Such nonselective processes could account for the origins and spread of transposons (mobile DNA elements), introns, and other contributors to the high DNA content of many eukaryotes, which typically have small populations relative to prokaryotes. Neutrally fixed complexity could be neutrally "unfixed" (through random reversion), but ratchet-like (one-directional) tendencies might prevent this. For example, a genome once infected with an active but harmless transposon will not likely regain its simpler, pristine condition without selection for reduced element number. At the organismal level, Maynard Smith and Szathmary proposed that a ratchet mechanism called contingent irreversibility might render previously independent evolutionary units interdependent for "accidental reasons that have little to do with the selective forces that led to the evolution of the higher entity in the first place" (*8*). An example is the mutual loss of autonomy by the symbionts that became mitochondria or plastids and the cells that harbored them.

At the subcellular level, similar forces may also be at work, a simple example of which is found in the *Neurospora* mitochondrion (*9*). The *Neurospora* mitochondrial genome encodes several introns, some of which can self-splice, but others require a tyrosyl tRNA synthetase (TyrRS) to splice. This interaction is typically interpreted as having arisen "to compensate for structural defects acquired" by the intron sequences (*10*). But this order of events puts the cart before the horse: Introns bearing such defects would be at an immediate selective disadvantage and would not likely be fixed in populations before the TyrRS binding evolved to suppress their deleterious effects. If the order of events is reversed, then there would be no deleterious intermediate. Specifically, if the binding interaction arose first—fortuitously or for some reason unrelated to splicing—its existence could allow the accumulation of mutations in the intron that would have inactivated splicing, were the protein not bound. Because the compensatory or suppressive activity of the protein is imagined to exist fortuitously before any intron mutation, this might be called "presuppression," and the acquisition of protein dependence by the intron could be selectively neutral (or even slightly disadvantageous), and yet also inevitable, in finite populations.

An idealized general model of such a chain of events (see the figure) illustrates how the two components (such as an intron and TyrRS) might revert to independence, but are more likely to "ratchet" toward greater dependency over time. An initial mutation creates a dependent state, and only reversion at this site is likely to break the dependency. By contrast, mutations at any other site have the potential to create further dependencies. Random mutations are therefore unlikely to restore one component to its original state of independence from the other. If there are more ways for dependence to increase than decrease, an increase is unavoidable. Thus, constructive neutral evolution is a directional force that drives increasing complexity without positive (and in small populations, against mildly negative) selection. Negative selection is involved, but only as the stabilizing force that keeps this directionality from reversing.

Both the order of events and the potential for a ratchet-like increase in complexity are often overlooked when explaining complex systems, in particular when intricate features are interpreted as having arisen as corrections or countermeasures. RNA editing has been rationalized as a form of repair (*11*), whereas the nuclear-cytosolic compartmentalization that defines eukaryotes has been hypothesized to have arisen to compensate for the baleful effect of introns on translation (*12*). Although compensation for defects caused by "selfish" (self-propagating) DNA elements may seem intuitive, it is problematic to propose that, on the way to evolving compensatory machinery, an intermediate state had to exist that was less fit than its ancestors and sisters. Why would such an intermediate not just die out in competition before its rescue by compensatory complexity yet to be invented? A more workable model is that the compensating mechanism was already present (possibly serving unrelated functions).

Although this model is easiest to illustrate using molecular systems of peripheral importance or limited distribution (such as splicing or RNA editing), there is no reason why it might not contribute to the generation of any cellular complexity (the ribosome; mitochondrial respiratory complexes; light-harvesting antennae in photosynthetic organisms; RNA and DNA polymerases and their initiation, elongation, and termination complexes; protein import, folding, and degradation apparatuses; the cytoskeleton and its motors). Much of the bewildering intricacy of cells could consist of originally fortuitous molecular interactions that have become more or less fixed by constructive neutral evolution. Indeed, although complexity in biology is generally regarded as evidence of "fine tuning" or "sophistication," large biological conglomerates might be better interpreted as the consequences of runaway bureaucracy—as biological parallels of nonsensically complex Rube Goldberg machines that are overengineered to perform a single task (*13*).

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