Where Darwin doesn't fit...

We've struggled for 150 years to devise a theory of evolution for technology. Now complexity guru **W. Brian Arthur** believes he has cracked it

BARELY four years after the publication of Darwin's *On the Origin of Species*, the Victorian novelist Samuel Butler was calling for a theory of evolution for machines. Since then, a few hardy souls have attempted to oblige him, but none have quite hit the mark. Their reasoning, very much à la Darwin, is that any given technology has many designers with different ideas – which produces many variations. Of these variations, some are selected for their superior performance and pass on their small differences to future designs. The steady accumulation of such differences gives rise to novel technologies, and the result is evolution.

This sounds plausible, and it works for already existing technologies – certainly the helicopter and the cellphone progress by variation and selection of better designs. But it doesn't explain the origin of radically novel technologies, the equivalent of novel species in biology. The jet engine, for example, does not arise from the steady accumulation of changes in the air piston engine, nor does the computer emerge from accumulated changes in electromechanical calculators. Darwin's mechanism does not apply to technology.

So what would a theory of evolution for technology look like? Do technologies descend by some unambiguous process from the collective of earlier technologies? In my new book, *The Nature of Technology*, I argue that they do. But to see how, we need to tailor our thinking directly to technology, not borrow from biology.

PROFILE

W. Brian Arthur is External Professor at the Santa Fe Institute in New Mexico. He has won both the Schumpeter prize for economics and the Lagrange prize for complexity science. His new book is *The Nature of Technology: What it is and how it evolves* (Penguin/The Free Press)

To start with, we can observe that all technologies have a purpose; all solve some problem. Yet they can only do this by making use of what already exists in the world. That is, they put together existing operations, means, and methods – in other words, existing technologies – to do the job.

Take a Global Positioning System. This measures the time that signals take to travel from a location in question to four or more satellites. Knowing these timings and the satellites' positions, the system can calculate the location's exact coordinates. To do this, GPS combines the existing technologies of satellites, computing chips, radio receivers, transmitters and atomic clocks.

So novel technologies are constructed from combinations of existing technologies. While this moves us forward, it is not yet the full story. Novel technologies (think of radar) are also sometimes created by capturing and harnessing novel phenomena (radio waves are reflected by metal objects). But again, if we look closely, we see that phenomena are always captured by existing technologies – radar used high-frequency radio transmitters, circuits, and receivers to harness its effect. So we are back at the same mechanism: novel technologies are made possible by - are created from - combinations of the old.

In a nutshell, then, evolution in technology works this way: novel technologies form from combinations of existing ones, and in turn they become potential components for the construction of further technologies. Some of these in turn become building blocks for the construction of yet further technologies.

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Feeding this is the harnessing of novel phenomena, which is made possible by combinations of existing technologies.

This mechanism, which I call combinatorial evolution, has an interesting consequence. Because new technologies arise from existing ones, we can say the collective of technology creates itself out of itself. In systems language, technology is autopoietic (from the Greek for "self-creating"). Of course, technology doesn't create itself from itself all on its own. It creates itself with the agency of human beings, much as a coral reef creates itself from itself with the assistance of small organisms.

Autopoiesis tells us several things: that every technology stands atop a pyramid of ancestral ones that eventually made it possible; that all future technologies will derive from those now existing (though we cannot say exactly how); and that a novel technology's value lies not just in what it does,

In biology, change is mostly about variation and selection: in technology, combination is king

but also in what further technologies it will lead to.

It also tells us that the history of technology is not one of more-or-less independent discoveries, but an evolutionary story of related devices, methods, and capturings of phenomena. In the time of the earliest humans, we picked up phenomena lying around on nature's floor. Certain fibres possess strength and flexibility? Binding materials. Friction creates heat? Fire. Fire allows the smelting of metals? Metal tools. Combinations of braided fibres and metal cutting-heads make axes. Combinations of levers, ropes and toothed gears make possible grain milling, irrigation, and building construction.

"Darwinian variation and selection kick in only once a technology exists"

In more modern times, chemical, and electrical phenomena yield myriads of technology elements, and combinations of these have given us industrial chemistry, the telephone, radio, the computer, the internet. In just a few millennia, with repeated capturings and repeated combinations, the few have become many and the simple have become complex. We have progressed from grinding stones to iPhones.

So is it possible to see combinatorial evolution at work not just in history but somehow in the lab, or on a computer? Recently my colleague at Santa Fe Wolfgang Polak and I set up an artificial world within a computer to see if we could reproduce such evolution and study it. In our virtual world the "technologies" were logic circuits. We started with a single primitive technology element, a simple NAND circuit, and allowed the computer at each step to wire copies of these together, to combine them randomly in different configurations to see if we got anything useful.

We also gave the computer a wish-list of desired functions we hoped to see circuits created for: AND functions, Exclusive-ORs, *N*-bit adders and the like. If any one of these "needs" could be met, the circuit that fulfilled it would automatically be declared a new technology, and would become a building block for further random combinations.

Once we launched the experiment we found, unsurprisingly, that most new random combinations failed to meet any needs. But after a few hundred steps, circuits started to appear that matched some elementary needs, and could be used as further building blocks. From these, more sophisticated technologies evolved. After about a quarter of a million steps, we found that the system had evolved quite complicated circuits: an 8-way-exclusive-OR, 8-way-AND, 4-bit-Equals – even an 8-bit adder, the basis of a simple calculator.

Our evolutionary process could arrive at complex circuits like this by itself because it first created circuits to satisfy simpler needs and used these as building blocks to create circuits of ever-increasing complexity. When we took away these simpler needs, these stepping-stone technologies did not emerge, and complex needs went unfulfilled. I believe that the real world works this way, too. Radar needed the stepping stone of radio to come into existence.

To return to our initial question, a theory of evolution can indeed be constructed for technology. But its central mechanism, things creating novel things by combinations of themselves, differs from Darwin's. Combinatorial evolution is not absent in biology. Certain primitive bacteria share genes and combine them, and larger structures, the eukaryotic cell, for example, occasionally emerge as combinations of simpler structures. Overall, however, incremental change through variation and selection rules in biology, with combination present but rare.

In technology, the opposite is true. Darwinian variation and selection kick in only once a technology exists. For what really counts, the formation of new "species" in technology, combinatorial evolution holds sway. ■

doesn't fit...

For 150 years, we've struggled to devise a theory of evolution for technology. Have we finally cracked the problem?

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