Excerpt from *The Nature of Technology*,

by W. Brian Arthur

An Experiment in Evolution

Here is a thought experiment. Could technologies be combined in the lab or in a computer to create new technologies, as argued in this book? That would be difficult. Technologies differ greatly in type, and it would be hard for a computer to figure out whether some combination of, say, papermaking and the Haber process would make sense and do something useful. But we might be able to confine ourselves to some restricted world of technologies, some world that would evolve on a computer that we could study.

In 2005 my colleague Wolfgang Polak and I set up an artificial world (one represented within the computer) to do just that. In our model world the technologies were logic circuits. For readers not familiar with these, let me say a word about them.

Think of logic circuits as miniature electronic chips with input and output pins. Inputs to a given circuit might be numbers, in the binary form of 1s and 0s. Or they might be some combination of *true* and *false* representing some set of circumstances that are currently fulfilled. Thus the inputs to a logic circuit in an aircraft might check which of engine conditions *A, C, D, H, K,* are *true* or *false*, representing the status say of fuel conditions, or temperatures, or pressures; and the output pins might signal whether certain switches *Z*, *T, W,* and *R* should be “on” (true) or “off” (false) to control the engine accordingly. Circuits differ in what they do, but for each set of input values a given circuit arranges that a particular set of output ones appears on the output pins. The interesting circuits for computation correspond to operations in arithmetic: addition say, where the output values are the correct summations of the inputted ones. Or they correspond to operations in logic, such as 3-bit AND (if input pins *1*, *2*, and *3*, all show *true*, the output pin signals *true*; otherwise it signals *false*).

Working with logic circuits gave Polak and me two advantages. The precise function of a logic circuit is always known; if we know how a logic circuit is wired together, we can figure (or the computer can) exactly what it does. And if the computer combines two logic circuits—wires them together so that the outputs of one become the inputs of the other—this gives us another logic circuit whose precise function we also know. So we always know how combinations perform, and whether they do something useful.

Polak and I imagined our artificial world within the computer to be peopled by little logicians and accountants, anxious to tally and compare things within this logic-world. At the beginning they have no means to do this, but they have a lengthy wish-list of needs for particular logical functionalities. They would like to have circuits that could perform AND operations, Exclusive-ORs, 3-bit addition, 4-bit EQUALS, and the like. (To keep things simple we imagined this long need list or opportunity-niche list to be unchanging.) The purpose of our computer experiment was to see if the system could evolve technologies—logic circuits—by combination from existing ones to fulfill niches on the list, and to study this evolution as it happens.

At the start of our experiment, as I said, none of these opportunity niches was satisfied. All that was available by the way of technology was a NAND circuit (think of this as a primitive circuit element, a computer chip not much more complicated than a few transistors). And at each step in the experiment, new circuits could be created by combining existing ones—wiring them together randomly in different configurations. (At the start these were simply the NAND ones.) Most new random combinations of course would fail to meet any needs, but once in a long while a combination might result by chance that matched one of the listed needs. The computer was instructed then to encapsulate this as a new technology itself, a new building block element. It then became available as a building-block element for further wiring and combination.

This experiment in technology evolution ran by itself within Polak's computer; there was no human intervention once we pushed the return button to start it. And of course it could be repeated again and again to compare what happened in different runs.

What did we find? In the beginning there was only the NAND technology. But after a few tens and hundreds of combination steps, logic circuits that fulfilled simple needs started to appear. These became building block elements for further combination, and using these, technologies that met more complicated needs began to appear. After about a quarter of a million steps (or 20 hours of machine time) we stopped the evolution and examined the results.

We found that after sufficient time, the system evolved quite complicated circuits: an 8-way-Exclusive-OR, 8-way-AND, 4-bit-Equals, among other logic functions. In several of the runs the system evolved an 8-bit adder, the basis of a simple calculator. This may seem not particularly remarkable, but actually it is striking. An 8-bit adder has sixteen input pins (eight each for the two numbers being added) and 9 outputs (eight for the result and one extra for the carry digit). If again you do some simple combinatorics, it turns out there are over $10^{177,554}$ possible circuits that have 16 inputs and 9 outputs, and only one of these adds correctly. $10^{177,554}$ is a very large number. It is far far larger than the number of elementary particles in the universe. In fact, if I were to write it down as a number, it would take up nearly half the pages of this book. So the chances of such a circuit being discovered by random combination in 250,000 steps is negligible. If you did not know the process by which this evolution worked, and opened up the computer at the end of the experiment to find it had evolved a correctly functioning 8-bit adder against such extremely long odds, you would be rightly surprised that anything so complicated had appeared. You might have to assume an intelligent designer within the machine.

The reason our process could arrive at complicated circuits like this is because it created a series of stepping-stone technologies first. It could create circuits to satisfy simpler needs and use them as building blocks to create circuits of intermediate complexity. It could then use these to create more complicated circuits, bootstrapping its way forward toward satisfying complex needs. The more complicated circuits can only be constructed once the simpler ones are in place. We found that when we took away the intermediate needs that called for these stepping stone technologies, complex needs went unfulfilled.

This suggests that in the real world radar might not have developed without radio—and without the need for radio communication. There is a parallel observation in biology. Complex organismal features such as the human eye cannot appear without intermediate structures (say the ability to distinguish light from dark) and the "needs" or uses for these intermediate structures (a usefulness to distinguishing light from dark).

We found other things too. When we examined the detailed history of the evolution, we found large gaps of time in which little happened at all. Then we saw the sudden appearance of a key circuit (an enabling technology) and quick use of this for further technologies. A full adder circuit might appear after say 32,000 steps; and 2-, 3-, and 4-bit adders fairly quickly after that. In other words, we found periods of quiescence, followed by miniature "Cambrian explosions" of rapid evolution.

We also found, not surprisingly, that the evolution was history dependent. In different runs of the experiment the same simple technologies would emerge, but in a different sequence. Because more complicated technologies are constructed from simpler ones, they would often be put together from different building blocks. (If bronze appears before iron in the real world, many artifacts are made of bronze; if iron appears before bronze, the same artifacts would be made of iron.) We also found that some complex needs for circuits such as adders or comparators with many inputs—different ones each time—would not be fulfilled at all.

And we found avalanches of destruction. Superior technologies replaced previously functioning ones. And this meant that circuits used only for these now obsolete technologies were themselves no longer needed, so these in turn were replaced. This yielded avalanches we could study and measure.

In these ways we were able to examine the evolution of technology in action, and it bore out the story I gave earlier in this chapter.