The Other Design

My work on *Pink Noise* included much research, exposing me to some very interesting science, which I will attempt to summarize here. We live during exciting times, at the beginning of another major scientific revolution.

Not that long ago, if anyone had asked me what was the greatest scientific discovery of the 20th century, I would have been stumped, not knowing which scientific discipline to favor: physics, genetics, computer science? Now, I wouldn't hesitate a bit before naming Ilya Prigogine (1917–2003) and his discovery of spontaneous self-organization in systems far from equilibrium—because, among other things, it spares me from having to choose between so many worthy scientific disciplines: Prigogine's discovery concerns them all.

To most people, the term *evolution* is associated exclusively with Charles Darwin and biology. Prigogine extended the evolutionary approach to many other fields of science.

He had forerunners. Ludwig Boltzmann (1844–1906) is well known as the father of thermodynamics. But few know that his intent was to do in physics what Darwin did in biology, to explain the formation and development of complex systems. Boltzmann began by studying not individual particles but large populations of them—statistically.

He formulated the concept of *entropy,* a measure of disorder in a system, and discovered the second law of thermodynamics, by which entropy in a closed (that is, not interacting with anything else) system grows with time. For example, if hot water is mixed with cold water in an isolated vessel, the system (not far from being closed) eventually reaches an internal equilibrium, a uniform state with the same temperature everywhere.

This, however, led to a rather pessimistic scenario for the eventual fate of the universe: the "heat death," a completely uniform state everywhere. No difference, no distinction. No life. This was completely opposite to what Boltzmann wanted to achieve, which led him into deep depression. He had failed. Where Darwin showed how a new species could appear, evolving from the simple to the more complex, Boltzmann only showed development from the complex back to the simple.

But, in a sense, he had succeeded. However pessimistic the results, he demonstrated the *irreversibility* of time. After all, all modern physics, classical and quantum alike, describe the trajectories of particles (classical) or wave functions (quantum) as reversible in time. The equations, both Newton's and Schrödinger's, are time-symmetric. The wave function collapse, widely cited to demonstrate the irreversibility of quantum systems, does not truly explain anything, because it is found outside the formalism of quantum mechanics, in interaction between a quantum system and a classical observer: the quantum system changes irreversibly once it's observed. One can say that the wave function collapse is just another formulation of the paradox of time. The equations clearly say that time is reversible. Yet we know well from our life experience that an egg, once broken, never comes back whole.

Some scientists went so far as to claim that time actually *is* reversible, that we simply don't live long enough to notice this. Presumably, eventually, after some gazillions of years, somewhere in the universe an egg mysteriously comes back whole from some random motion of particles.

It took Ilya Prigogine to complete what Boltzmann had begun and show why the point of view expressed in the previous paragraph is wrong.

INSTEAD OF STUDYING SIMPLE SYSTEMS CLOSE TO EQUILIBrium, like everyone else did at the time, Prigogine chose as his subject complex nonlinear systems far from equilibrium.

Simple systems are a natural first step in scientific exploration. They can be exactly solved, expressed in formulas. Their solutions can be taken as an intuitive ballpark, something to expect from a more complex system, at least in a certain approximation. They are well defined, more readily reproduced and, therefore, are more amenable to controlled experiment. Moreover, this is how we tend to design. The vast majority of our technological devices, from antiquity to present day, are simple and as closed as possible, because this makes them manageable, more *debuggable*—in other words, predictable. For it is hard to troubleshoot unruly chaos!

The problem with simple systems is that they are already near equilibrium. No wonder Boltzmann had arrived at the "heat death" scenario.

But systems *far* from equilibrium behave quite differently. To be sure, the entropy of a closed system still grows. But an *open* system can theoretically decrease its entropy by passing some of it to the outside environment, so that the total entropy still obeys the second law of thermodynamics. The incredible thing is that, as discovered by Prigogine, open systems far from equilibrium exhibit a tendency completely opposite to the "heat death" scenario: on average, they tend to *decrease* their entropy, spontaneously self-organizing! Think of this as an unnumbered "fourth law of thermodynamics."

A mix of hot and cold water, when left alone in an isolated vessel, equalizes in temperature. But if the water is continually heated, when it boils, hexagonal convection cells spontaneously develop, the water moving up and down in hexagonal cylinders. Once the heat is removed, the water stops boiling and equalizes. In order to keep lowering its entropy and thus increasing order, a system must remain open, must remain in a constant energy exchange with the environment.

The water cannot boil forever. Nor can an even more complex system, much farther from equilibrium—such as a human body—function forever. Every individual system eventually succumbs to entropy. But statistically, in terms of populations, spontaneous self-organization keeps growing. And so must the energy exchange keep growing. Living systems, for example, exchange energy much faster and through many more channels than non-living matter.

But evolution, understood in the broadest sense as an ever-growing spiral of self-organization, is not limited to living systems. From the fractal large-scale structure of the universe to the formation and evolution of galaxies, to stars and planets, to the geological processes, to life—it's no fluke!—and to the brain and consciousness, to our society and culture and economy, the self-organization keeps growing. And in an *infinite* universe, which is the only truly closed system, this progression can keep going without limit.

Evolution must be God's design!

Who knows what comes next?

This is why Prigogine's discovery is so important. It is universal, encompassing everything. It gives us an entirely new scientific paradigm—a science of complexity—bringing the evolutionary principle into many diverse disciplines in its most general form. Prigogine will be remembered long after most of the scientific darlings of the 20th century have been forgotten.

Murray Gell-Mann (b. 1929) discovered quarks (the 1969 Nobel Prize in Physics). Later, he turned to the study of complexity.

THE SYSTEMS THAT DEVELOP BY THE EVOLUTIONARY PRINciple were called *complex adaptive systems* by Murray Gell-Mann. They, and the complex nonlinear systems far from equilibrium in general, have an important property. Any classical or quantum system can be described in terms of individual particles' trajectories (classical) or wave functions (quantum), and in terms of the statistical density distribution function (classical) or density matrix (quantum). For a simple system, these descriptions are equivalent; these systems are reversible. But complex systems far from equilibrium have statistical solutions not expressible in terms of individual particles at all (this is what it *means* to be far from equilibrium). The whole is more than the sum of its parts. And it is these solutions that are irreversible.

It is important to understand that the subject of science is the kind of knowledge that can be tested by experiment. Therefore, the goal of science is not to establish absolute truth—this is impossible in principle, since experiments cannot prove, but only can potentially disprove, a theory. The goal of science is to *approximate* reality, to construct a model that allows one to predict the experiment with reasonable accuracy. Science is not a monolith but a rather loosely coupled set of theories, each with its specific domain of applicability. Classical mechanics, for example, does not apply to very high velocities and very small sizes. Quantum mechanics, being linear, only applies to simple systems (as we'll see shortly), and so on. Theories tend to be replaced after a while with new ones. Much of scientific knowledge isn't absolute.

What cannot be experimentally tested must be believed in (including the *belief* that God does *not* exist). This kind of knowledge is the subject of religion and philosophy. If neither religion nor science intrudes on the other's territory — which has happened both ways and many times — then they are not in conflict.

In this light, the above-mentioned defining property of systems far from equilibrium means that many fields of science cannot be reduced to physics. Studying the behavior of dolphins can't be done by deconstructing them into elementary particles, even if one has an infinite processing power to solve the equations.

This is also why there can be no single Theory of Everything.

Complex nonlinear systems aren't solved exactly—not even numerically, in many cases. As described in [18], T. Petrosky, one of Prigogine's students, ran a computer simulation for a system with one star, a single planet, and a comet. He tried to predict the number of orbits the comet would make before being expelled from the system. If the initial coordinates and velocities were rounded to one part in a million, the answer was 757 orbits. If up to one part in ten million, it was 38 orbits; one part in a hundred million, 235 orbits; one part in 10^{16}, 17 orbits. Yet different results could be obtained by different ways of rounding the intermediate results of calculations. Without absolute knowledge and infinite precision in calculation, the comet's orbit was simply unpredictable. Yet no randomness was involved. The system operated under the deterministic laws of Newtonian mechanics.

This is an example of the *deterministic chaos* phenomenon, also known as the *butterfly effect.* As shown by Henri Poincaré (1854–1912), there always exist *chaotic* orbits in gravitational systems with more than two bodies. Chaotic orbits never pass the same location twice yet may approach it arbitrarily close. Therefore, even a slight deviation can make a huge difference later on.

The world may be deterministic, but it is not predictable.

DIGITAL SYSTEMS TOO CAN DEMONSTRATE VERY COMPLEX behavior (see [34], for example). Some are even *NP-hard,* which is a technical term meaning that there exists no better algorithm to predict the system's state other than simply running it through its paces. But a faster system can simulate it sooner, thus predicting it. With complex analog systems exhibiting the butterfly effect, this is impossible in principle.

For the mathematically advanced reader: The spectra of the Hermitian operators representing the physical observables in quantum mechanics are discrete only in certain cases.

One can argue that the universe is actually not continuous but discrete in space and time, according to quantum mechanics. But this is incorrect, for only simple quantum systems are discrete. And only simple quantum systems are reversible in time. What we call the wave function collapse is the result of interaction between a simple quantum system and a complex nonlinear system, the observer. Therefore, the quantum system ceases to be simple—and ceases to be reversible.

Ilya Prigogine, thus, restored the arrow of time. No, it's not true that time only appears to be irreversible, as some claim. It is just that our simple systems—our ideal, linear approximations to the much more complex, nonlinear reality—appear to be reversible. The real world is not.

By the very nature of complex adaptive systems, they experience events when a small quantitative change brings about qualitative changes of enormous magnitude. Moreover, this is bound to happen to any complex adaptive system, given time: the birth of a new species, cancer, epiphany, economic crisis, political revolution, and so on. In general, this is called a *singularity*.

Revolution is the singularity aspect of evolution.

The science of complexity is still in its infancy, developing a new scientific methodology. Ilya Prigogine was awarded the 1977 Nobel Prize in Chemistry for his discovery of spontaneous self-organization in systems far from equilibrium. Until his death, he was the President of the International Academy of Science. Despite that, his work is relatively unknown outside the scientific circles. Some of the related evolutionary paradigms are well accepted by mainstream science, like Neural Darwinism, for example. Some are still being ignored, like Plasma Universe. (Both are drawn upon in *Pink Noise*.)

The opposition to this view can be found in the stubborn hold on scientists that the universe must have the quality of elegant simplicity, that a beautiful theory just *must* be true. But the ancient Greeks too believed that the orbits of planets simply had to be perfect circles—ending with the devilishly, artificially complex system of Ptolemaic epicycles.

For a brief description of epicycles (and their modern counterparts), see *Galaxies in Plasma Lab* on pages 145–146.

There *is* a beauty in the universe, but not the beauty of a simple perfect form. The beauty of the *natural* complexity—the beauty of a tree, not of a polyhedron.