INFORMATION AND THE NATURE OF REALITY

From Physics to Metaphysics

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include *A Legacy of Living Systems: Gregory Bateson as Precursor to Biosemiotics* (2008) (as editor) and his major work *Biosemiotics: An Examination into the Signs of Life and the Life of Signs* (2008).

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5 The computational universe

Seth Lloyd

It is no secret that we are in the midst of an information-processing revolution based on electronic computers and optical communication systems. This revolution has transformed work, education, and thought, and has affected the life of every person on Earth.

5.1 THE INFORMATION-PROCESSING REVOLUTIONS

The effect of the digital revolution on humanity as a whole, however, pales when compared with the effect of the previous information-processing revolution: the invention of moveable type. The invention of the printing press was an information-processing revolution of the first magnitude. Moveable type allowed the information in each book, once accessible only to the few people who possessed the book's hand-copied text, to be accessible to thousands or millions of people. The resulting widespread literacy and dissemination of information completely transformed society. Access to the written word empowered individuals not only in their intellectual lives, but in their economic, legal, and religious lives as well.

Similarly, the effect of the printed word is small when compared with the effect of the written word. Writing – the discovery that spoken sounds could be put into correspondence with marks on clay, stone, or paper – was a huge information-processing revolution. The existence of complicated, hierarchical societies with extended division of labor depends crucially on writing. Tax records figure heavily in the earliest cuneiform tablets.

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Just as printing is based on writing, writing stems from one of the greatest information-processing revolutions in the history of our planet: the development of the spoken word. Human language is a remarkable form of information processing, capable of expressing, well, anything that can be put into words. Human language includes within it the capacity to perform sophisticated analysis, such as mathematics and logic, as well as the personal calculations ("if she does this, I'll do that") that underlie the complexity of human society.

Although other animals have utterance, it is not clear that any of them possess the same capacity for universal language that humans do. Ironically, the entities that possess the closest approximation to human language are our own creations: digital computers, whose computer languages possess a form of universality bequeathed to them by human language. It is the social organization stemming from human language (together with written language, the printed word, computers, etc.) that have made human beings so successful as a species, to the extent that the majority of the planet's resources are now organized by humans for humans. If other species could speak, they would probably say, "Who ordered *that*?".

Before turning to even earlier information-processing revolutions, it is worth saying a few words about how human language came about. Who "discovered" human language? The fossil record, combined with recently revealed genetic evidence, suggests that human language may have arisen between 50 and 100 000 years ago, in Africa. Fossil skulls suggest that human brains underwent significant change over that time period, with the size of the cortex expanding tenfold. The result was our species, *Homo sapiens*: "man with knowledge" (literally, "man with taste"). Genetic evidence suggests that all women living today share mitochondrial DNA (passed from mother to daughter) with a single woman who lived in Africa around 70 000 years ago. Similarly, all men share a Y chromosome with one man who lived at roughly the same time.

What evolutionary advantage did this Adam and Eve possess over other hominids that allowed them to populate the world with their offspring? It is plausible that they possessed a single mutation or chance combination of DNA that allowed their offspring to think and reason in a new and more powerful way (Chomsky *et al.*, 2002). Noam Chomsky has suggested that this way of reasoning should be identified with recursion, the ability to construct hierarchies of hierarchies, which lies at the root both of human language and of mathematical analysis. Once the ability to reason had appeared in the species, the theory goes, individuals who possessed this ability were better adapted to their immediate surroundings, and indeed, to all other surroundings on the planet. We are the offspring of those individuals.

Once you can reason, there is great pressure to develop a form of utterance that embodies that reason. Groups of *Homo sapiens* who could elaborate their way of speaking to reflect their reasoning would have had substantial evolutionary advantage over other groups who were incapable of complex communication and who were therefore unable to turn their thoughts into concerted action.

I present this plausible theory on the origin of language and of our species to show that information-processing revolutions need not be initiated by human beings. The "discovery" of a new way of processing information can arise organically out of an older way. Apparently, once the mammalian brain had evolved, then a few mutations gave rise to the ability to reason recursively. Once the powerful information-processing machinery of the brain was present, language could evolve by accident, coupled with natural selection.

Now let us return to the history of information-processing revolutions. One of the most revolutionary forms of information processing is *sex*. The original sexual revolution (not the one of the 1960s) occurred some billion years ago when organisms learned to share and exchange DNA. At first, sex might look like a bad idea: when you reproduce sexually, you never pass on your genome intact. Half of your DNA comes from your mother, and half from your father, all scrambled up in the process called recombination. By contrast, an asexually reproducing organism passes on its complete genome, modulo a few mutations. So even if you possess a truly fantastic combination of DNA, when you reproduce sexually, your offspring may not possess that combination. Sex messes with success.

So why is sex a good idea? Exactly because it scrambles up parents' DNA, sexual reproduction dramatically increases the potential rate of evolution. Because of the scrambling involved in recombination, sexual reproduction opens up a huge variety of genetic combinations for your offspring, combinations that are not available to organisms that rely on mutation alone to generate genetic variation. (In addition, whereas most mutations are harmful, recombination assures that viable genes are recombined with other viable genes.) To compare the two forms of reproduction, sexual and asexual, consider the following example: by calculating the number of genetic combinations that can be generated, it is not hard to show that a small town of 1000 people, reproducing sexually with a generation time of 30 years, produces the same amount of genetic variation as a culture of one trillion bacteria, reproducing asexually every 30 minutes.

Sex brings us back to the mother of all information-processing revolutions: life itself. However it came about, the mechanism of storing genetic information in DNA, and reproducing with variation, is a truly remarkable "invention" that gave rise to the beautiful and rich world around us. What could be more majestic and wonderful? Surely, life is the original information-processing revolution.

Or is it? Life arose on Earth some time in the last five billion years (for the simple reason that the Earth itself has only been around for that long). Meanwhile, the universe itself is a little less than fourteen billion years old. Were the intervening nine billion years completely devoid of information-processing revolutions?

The answer to this question is "No." Life is not the original information-processing revolution. The very first information-processing revolution, from which all other revolutions stem, began with the beginning of the universe itself. The big bang at the beginning of time consisted of huge numbers of elementary particles, colliding at temperatures of billions of degrees. Each of these particles carried with it bits of information, and every time two particles bounced off each other, those bits were transformed and processed. The big bang was a bit bang. Starting from its very earliest moments, every piece of the universe was processing information. The universe computes. It is this ongoing computation of the universe itself that gave rise naturally to subsequent information-processing revolutions such as life, sex, brains, language, and electronic computers.

5.2 THE COMPUTATIONAL UNIVERSE

The idea that the universe is a computer might at first seem to be only a metaphor. We build computers. Computers are the defining machines of our era. Consequently, we declare the universe to be a computer, in the same way that the thinkers of the Enlightenment declared the universe to be a clockwork one. There are two responses to this assertion that the computational universe is a metaphor. The first response is that, even taken as a metaphor, the mechanistic paradigm for the universe has proved to be incredibly successful. From its origins almost half a millennium ago, the mechanistic paradigm has given rise to physics, chemistry, and biology. All of contemporary science and engineering comes out of the mechanistic paradigm. To think of the universe not just as a machine, but also as a machine that computes, is a potentially powerful extension of the mechanistic paradigm.

The second response is that the claim that the universe computes is literally true. In fact, the scientific demonstration that all atoms and elementary particles register bits of information, and that every time two particles collide those bits are transformed and processed, was given at the end of the nineteenth century, long before computers occupied people's minds. Beginning in the 1850s, the great statistical mechanicians James Clerk Maxwell in Cambridge and Edinburgh, Ludwig Boltzmann in Vienna, and Josiah Willard Gibbs at Yale, derived the mathematical formulae that characterized the physical quantity known as entropy (Ehrenfest and Ehrenfest, 2002). Prior to their work, entropy was known as a somewhat mysterious thermodynamic quantity that gummed up the works of steam engines, preventing them from doing as much work as they otherwise might do. Maxwell, Boltzmann, and Gibbs wanted to find a definition of entropy in terms of the microscopic motions of atoms. The formulae that they derived showed that entropy was proportional to the number of bits of information registered by those atoms in their motions. Boltzmann then derived his eponymous equation to describe how those bits were transformed and flipped when atoms collide. At bottom, the universe is processing information.

The scientific discovery that the universe computes long preceded the formal and practical idea of a digital computer. It was not until the mid twentieth century, however, with the work of Claude Shannon and others, that the interpretation of entropy as information became clear (Shannon and Weaver, 1963). More recently, in the 1990s, researchers showed just how atoms and elementary particles compute at the most fundamental level (Chuang and Nielsen, 2000). In particular, these researchers showed how elementary particles could be programmed to perform conventional digital computations (and, as will be discussed below, to perform highly unconventional computations as well). That is, not only does the universe register and process information at its most fundamental level, as was discovered in the nineteenth century, it is literally a computer: a system that can be programmed to perform arbitrary digital computations.

You may ask, So what? After all, the known laws of physics describe the results of experiments to exquisite accuracy. What does the fact that the universe computes buy us that we did not already know?

The laws of physics are elegant and accurate, and we should not discard them. Nonetheless, they are limited in what they explain. In particular, when you look out your window you see plants and animals and people; buildings, cars, and banks. Turning your telescope to the sky you see planets and stars, galaxies and clusters of galaxies. Everywhere you look, you see immense variation and complexity. Why? How did the universe get this way? We know from astronomical observation that the initial state of the universe, fourteen billion years ago, was extremely flat, regular, and simple. Similarly, the laws of physics are simple: the known laws of physics could fit on the back of a T-shirt. Simple laws, simple initial state. So where did all of this complexity come from? The laws of physics are silent on this subject.

By contrast, the computational theory of the universe has a simple and direct explanation for how and why the universe became complex. The history of the universe in terms of information-processing revolutions, each arising naturally from the previous one, already hints at why a computing universe necessarily gives rise to complexity. In fact, we can prove mathematically that a universe that computes must, with high probability, give rise to a stream of ever-more-complex structures.

5.3 QUANTUM COMPUTATION

In order to understand how and why complexity arises in a computing universe, we must understand more about how the universe processes information at its most fundamental scales. The way in which the universe computes is governed by the laws of physics. Quantum mechanics is the branch of physical law that tells us how atoms and elementary particles behave, and how they process information.

The most important thing to remember about quantum mechanics is that it is strange and counterintuitive. Quantum mechanics is weird. Particles correspond to waves; waves are made up of particles; electrons and basketballs can be in two places at once; elementary particles exhibit what Einstein called "spooky action at a distance." Niels Bohr, one of the founders of quantum mechanics, once said that anyone who can contemplate quantum mechanics without getting dizzy has not properly understood it.

This intrinsically counterintuitive nature of quantum mechanics explains why many brilliant scientists, notably Einstein (who received his Nobel prize for his work in quantum mechanics), have distrusted the field. More than others, Einstein had the right to trust his intuition. Quantum mechanics contradicted his intuition, just as it contradicts everyone's intuition. So Einstein thought quantum mechanics could not be right: "God doesn't play dice," he declared. Einstein was wrong. God, or whoever it is who is doing the playing, plays dice.

It is this intrinsically chancy nature of quantum mechanics that is the key to understanding the computing universe. The laws of physics clearly support computation: I am writing these words on a computer. Moreover, physical law supports computation at the most fundamental levels: Maxwell, Boltzmann, and Gibbs show that all atoms register and process information. My colleagues and I exploit this information-processing ability of the universe to build quantum computers that store and process information at the level of individual atoms. But who – or what – is programming this computing computer? Where do the bits of information come from that tell the universe what to do? What is the source of all the variation and complexity that you see when you look out your window? The answer lies in the throws of the quantum dice.

Let us look more closely at how quantum mechanics injects information into the universe. The laws of quantum mechanics are largely deterministic: most of the time, each state gives rise to one, and only one, state at a later time. It is this deterministic feature of quantum mechanics that allows the universe to behave like an ordinary digital computer, which processes information in a deterministic fashion. Every now and then, however, an element of chance is injected into quantum evolution: when this happens, a state can give rise probabilistically to several different possible states at a later time. The ability to give rise to several different possible states allows the universe to behave like a quantum computer, which, unlike a conventional digital computer, can follow several different computations simultaneously.

The mechanism by which quantum mechanics injects an element of chance into the operation of the universe is called "decoherence" (Gell-Mann and Hartle, 1994). Decoherence effectively