creates new bits of information, bits which previously did not exist. In other words, quantum mechanics, via decoherence, is constantly injecting new bits of information into the world. Every detail that we see around us, every vein on a leaf, every whorl on a fingerprint, every star in the sky, can be traced back to some bit that quantum mechanics created. Quantum bits program the universe.

Now, however, there seems to be a problem. The laws of quantum mechanics imply that the new bits that decoherence injects into the universe are essentially random, like the tosses of a fair coin: God plays dice. Surely, the universe did not arise completely at random! The patterns that we see when we look out the window are far from random. On the contrary, although detailed and complex, the information that we see around us is highly ordered. How can highly random bits give rise to a detailed, complex, but orderly universe?

5.4 TYPING MONKEYS

The computational ability of the universe supplies the answer to how random bits necessarily give rise to order and complexity. To understand how the combination of randomness together with computation automatically gives rise to complexity, first look at an old and incorrect explanation of the origin of order and complexity. Could the universe have originated from randomness alone? No! Randomness, taken on its own, gives rise only to gibberish, not to structure. Random information, such as that created by the repeated flipping of a coin, is highly unlikely to exhibit order and complexity.

The failure of randomness to exhibit order is embodied in the well-known image of monkeys typing on typewriters, created by the French mathematician Emile Borel in the first decade of the twentieth century (Borel, 1909). Imagine a million typing monkeys (*singes dactylographiques*), each typing characters at random on a typewriter. Borel noted that these monkeys had a finite probability of producing all the texts in all the richest libraries of the world. He then pointed out that the chance of them doing so was infinitesimally small. (This image has appeared again and again in popular literature, as in the story that the monkeys immediately begin to type out Shakespeare's *Hamlet*.)

To see how small a chance the monkeys have of producing any text of interest, imagine that every elementary particle in the universe is a "monkey," and that each particle has been flipping bits or "typing," since the beginning of the universe. Elsewhere, I have shown that the number of elementary events or bit flips that have occurred since the beginning of the universe is no greater than $10^{120} \approx 2^{400}$. If one searches within this huge, random bit string for a specific substring (for example, Hamlet's soliloquy), one can show that the longest bit string that one can reasonably expect to find is no longer than the logarithm of the length of the long, random string. In the case of the universe, the longest piece of Hamlet's soliloquy one can expect to find is 400 bits long. To encode a typewriter character such as a letter takes seven bits. In other words, if we ask the longest fraction of Hamlet's soliloquy that monkeys could have produced since the beginning of the universe, it is, "To be, or not to be – that is the question: Whether 'tis nobler ... " Monkeys, typing at random into typewriters, would not produce Hamlet, let alone the complex world we see around us.

Now suppose that, instead of typing on typewriters, the monkeys type their random strings of bits into computers. The computers interpret each string as a program, a set of instructions to perform a particular computation. What then? At first it might seem that random programs should give rise to random outputs: garbage in, garbage out, as computer scientists say. At second glance, however, one finds that there are short, seemingly random programs that instruct the computer to do all kinds of interesting things. (The probability that monkeys typing into a computer produce a given output is the subject of the branch of mathematics called algorithmic information theory.) For example, there is a short program that instructs the computer to calculate the digits of π, and a second program that instructs the computer to construct intricate fractal patterns. One of the shortest programs instructs the computer to compute all possible mathematical theorems and patterns, including every pattern ever generated by the laws of physics! One might say that the difference between monkeys typing into typewriters and monkeys typing into computers is all the difference in the world.

To apply this purely mathematical construct of algorithmic information theory to our universe, we need two ingredients: a computer, and monkeys. But we have a computer – the universe itself, which at its most microscopic level is busily processing information. Where are the monkeys? As noted above, quantum mechanics provides the universe with a constant supply of fresh, random bits, generated by the process of decoherence. Quantum fluctuations are the "monkeys" that program the universe (Lloyd, 2006).

To recapitulate:

(1) The mathematical theory of algorithmic information implies that a computer that is supplied with a random program has a good chance of producing all the order and complexity that we see. This is simply a mathematical fact: to apply it to our universe we need to identify the computing mechanism of the universe, together with its source of randomness.
(2) It has been known since the end of the nineteenth century that if the universe can be regarded as a machine (the mechanistic paradigm), it is a machine that processes information. In the 1990s, I and other researchers in quantum computation showed that the universe was capable of full-blown digital computation at its most microscopic levels: the universe is, technically, a giant quantum computer.
(3) Quantum mechanics possesses intrinsic sources of randomness (God plays dice) that program this computer. As noted in the discussion of the history of information-processing revolutions above, the injection of a few random bits, as in the case of genetic mutation or recombination, can give rise to a radically new paradigm of information processing.

5.5 DISCUSSION

The computational paradigm for the universe supplements the ordinary mechanistic paradigm: the universe is not just a machine, it is a machine that processes information. The universe computes. The computing universe is not a metaphor, but a mathematical fact: the universe is a physical system that can be programmed at its most microscopic level to perform universal digital computation. Moreover, the universe is not just a computer: it is a quantum computer. Quantum mechanics is constantly injecting fresh, random bits into the universe. Because of its computational nature, the universe processes and *interprets* those bits, naturally giving rise to all sorts of complex order and structure (Lloyd, 2006).

The results of the previous paragraphs are scientific results: they stem from the mathematics and physics of information processing. Aristotle, when he had finished writing his *Physics*, wrote his *Metaphysics*: literally "the book after physics." This chapter has discussed briefly the physics of the computing universe and its implications for the origins of complexity and order. Let us use the physics of the computing universe as a basis for its metaphysics.

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