6. Forays into uncharted landscapes

Is the world built out of information? Is everything software?

Now for some even weirder stuff! Let's return to *The Thirteenth Floor* and to the ideas that we briefly referred to in the introductory section of this chapter.

Let's now turn to ontology: What is the world built out of, made out of?

Fundamental physics is currently in the doldrums. There is no pressing unexpected, new experimental data — or if there is, we can't see that it is! So we are witnessing a return to pre-Socratic philosophy with its emphasis on ontology rather than epistemology. We are witnessing a return to metaphysics. Metaphysics may be dead in contemporary philosophy, but amazingly enough it is alive and well in contemporary fundamental physics and cosmology.

There are serious problems with the traditional view that the world is a space-time continuum. Quantum field theory and general relativity contradict each other. The notion of space-time breaks down at very small distances, because extremely massive quantum fluctuations (virtual particle/antiparticle pairs) should provoke black holes and space-time should be torn apart, which doesn't actually happen.

Here are two other examples of problems with the continuum, with very small distances:

- *the infinite self-energy of a point electron in classical Maxwell electrodynamics,*
- *and in quantum field theory, renormalization, which Dirac never accepted.*

And here is an example of renormalization: the infinite bare charge of the electron which is shielded by vacuum polarization via virtual pair formation and annihilation, so that far from an electron it only seems to have finite charge. This is analogous to the behavior of water, which is a highly polarized molecule forming micro-clusters that shield charge, with many of the highly positive hydrogen-ends of H_2O near the highly negative oxygen-ends of these water molecules.

In response to these problems with the continuum, some of us feel that the traditional

Pythagorian ontology:
God is a mathematician,
the world is built out of mathematics,

should be changed to this more modern

→ **Neo-Pythagorian ontology**:
God is a programmer,
the world is built out of software.

In other words, all is algorithm!

There is an emerging school, a new viewpoint named **digital philosophy.** Here are some key people and key works in this new school of thought: Edward Fredkin, http://www.digitalphilosophy.org, Stephen Wolfram, *A New Kind of Science*, Konrad Zuse, *Rechnender Raum* (Calculating Space), John von Neumann, *Theory of Self-Reproducing Automata*, and Chaitin, *Meta Math!*.[1]

These may be regarded as works on metaphysics, on possible digital worlds. However there have in fact been parallel developments in the world of physics itself.

Quantum information theory builds the world out of qubits, not matter. And phenomenological quantum gravity and the theory of the entropy of black holes suggests that any physical system contains only a finite number of bits of information that grows, amazingly enough, as the surface area of the physical system, not as its volume — hence the name *holographic principle*. For more on the entropy of black holes, the Bekenstein bound, and the holographic principle, see Lee Smolin, *Three Roads to Quantum Gravity*.

One of the key ideas that has emerged from this research on possible digital worlds is to transform the **universal Turing machine**, a machine capable of running any algorithm, into the **universal constructor**, a machine capable of building anything:

Universal Turing Machine → **Universal Constructor**.

And this leads to the idea of an *information economy*: worlds in which everything is software, worlds in which everything is information and you can construct anything if you have a program to calculate it. This is like magic in the Middle Ages. You can bring something into being by invoking its true name. Nothing is hardware, everything is software![2]

A more modern version of this everything-is-information view is presented in two green-technology books by Freeman Dyson: *The Sun, the Genome and the Internet*, and *A Many-Colored Glass.* He envisions seeds to grow houses, seeds to grow airplanes, seeds to grow factories, and imagines children using genetic engineering to design and grow new kinds of flowers! All you need is water, sun and soil, plus the right seeds!

From an abstract, theoretical mathematical point of view, the key concept here is an old friend from Chapter 2:

$$H(x) = \text{the size in bits of the smallest program to compute } x.$$

[1] Lesser known but important works on digital philosophy: Arthur Burks, *Essays on Cellular Automata*, Edgar Codd, *Cellular Automata.*

[2] On magic in the Middle Ages, see Umberto Eco, *The Search for the Perfect Language*, and Allison Coudert, *Leibniz and the Kabbalah.*

$H(x)$ is also = to the minimum amount of algorithmic information needed to build/construct x, = in Medieval language the number of yes/no decisions God had to make to create x, = in biological terms, roughly the amount of DNA needed for growing x.

It requires the *self-delimiting programs* of Chapter 2 for the following intuitively necessary condition to hold:

$$H(x, y) \leq H(x) + H(y) + c.$$

This says that algorithmic information is sub-additive: If it takes $H(x)$ bits of information to build x and $H(y)$ bits of information to build y, then the sum of that suffices to build both x and y. Furthermore, the mutual information, the information in common, has this important property:

$$H(x) + H(y) - H(x, y) = \begin{cases} H(x) - H(x|y^*) + O(1), \\ H(y) - H(y|x^*) + O(1). \end{cases}$$

Here

$H(x|y)$ = the size in bits of the smallest program to compute x from y.

This triple equality tells us that the extent to which it is better to build x and y together rather than separately (the bits of subroutines that are shared, the amount of software that is shared) is also equal to the extent that knowing a minimum-size program $y^\star$ for y helps us to know x and to the extent to which knowing a minimum-size program $x^\star$ for x helps us to know y. (This triple equality is an idealization; it holds only in the limit of extremely large compute times for x and y.)

These results about algorithmic information/complexity H are a kind of economic meta-theory for the information economy, which is the asymptotic limit, perhaps, of our current economy in which material resources (petroleum, uranium, gold) are still important, not just technological and scientific know-how.

But as astrophysicist Fred Hoyle points out in his science fiction novel *Ossian's Ride*, the availability of unlimited amounts of energy, say from nuclear fusion reactors, would make it possible to use giant mass spectrometers to extract gold and other chemical elements directly from sea water and soil. Material resources would no longer be that important.

If we had unlimited energy, all that would matter would be know-how, information, knowing how to build things. And so we finally end up with the idea of *a printer for objects*, a more plebeian term for *a universal constructor.* There are already commercial versions of such devices. They are called 3D printers and are used for rapid prototyping and digital fabrication. They are not yet universal constructors, but the trend is clear...[3]

In Medieval terms, results about $H(x)$ are properties of the size of spells, they are about the complexity of magic incantations! The idea that everything is software is not as new as it may seem.

[3] One current project is to build a 3D printer that can print a copy of itself. See http://reprap.org.

Wiener integrals, Feynman integrals and the Multiverse

In Chapter 2, we considered sums over all programs like the summation that is used to define the halting probability Ω. Now we'd like to go from sums over all paths (Wiener) to sums over all histories (Feynman) to sums over all geometries (Wheeler) to sums over all universes (Tegmark)!

The Wiener measure is a probability on the space of all continuous functions and is basically just brownian motion. Here is a beautiful application of Wiener measure and the corresponding Wiener integral: We will use the Wiener integral to solve an important partial differential equation. Given boundary conditions, we get the solution to Laplace's equation (value at point x = average of value on infinitesimal sphere centered on x) by taking the average value at the point on the boundary that you eventually hit by taking a random walk starting at the point x. For more on this, see Mark Kac, *Probability and Related Topics in Physical Sciences.*

Now let's turn to the Feynman path integral = path democracy = sum over all histories = sum over all trajectories. There is

$$\exp\left[\frac{i}{\hbar}\int \mathcal{L}\, dt\right]$$

weight on each path. Here $\mathcal{L} =$ the Lagrangian and is the difference between the kinetic and the potential energy at each point on the path. The actual classical path minimizes the integral of the Lagrangian $\mathcal{L}$ over the entire path; this is the famous *principle of least action.*[4] In quantum mechanics you do not have a single trajectory; many paths may contribute to the final answer, to what you get by performing a measurement on the system.

Feynman's basic idea is that a physical system simultaneously performs a time evolution over all possible histories, which interfere constructively and destructively according to the quantum amplitude (complex-valued probability) $e^{iS/\hbar}$ associated with each path, which depends on the action $S = \int \mathcal{L}\, dt$. In the classical world, all but one of these paths cancel out due to quantum interference; but in the quantum world this fails to occur.

This also explains the basic idea of *quantum computation*, which is to exploit the *quantum parallelism* revealed by the Feynman path integral. A quantum computer will simultaneously perform a great many, ideally exponentially many, computations in parallel.[5]

For more on the Feynman integral and the principle of least action, see Feynman, *QED: The Strange Theory of Light and Matter*, *The Feynman Lectures on Physics*, and Feynman and Hibbs, *Quantum Mechanics and Path Integrals.*

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[4]The principle of least action is often attributed to Maupertuis but is in fact actually due to Leibniz.

[5]Nobody knows yet if such computers will actually work, but there are already useful technologies emerging from the attempt to build quantum computers. As Raymond Laflamme, the head of the Waterloo, Canada, Institute for Quantum Computing explains, this is a win-win situation. For if quantum computers are so sensitive to perturbations and noise that they decohere and fail to work, then instead of getting working quantum computers what you get is extremely sensitive new measurement technology. Either way you win.

The Wiener integral is mathematically rigorous. Physicists love the Feynman path integral formulation of quantum field theory and Feynman integrals are tremendously useful, but it has not yet been possible to formulate Feynman integrals in a mathematically rigorous fashion. Now let's look at some stuff that is even more weird.

Inspired by the Feynman path integral formulation of quantum mechanics, the huge book Wheeler et al., *Gravitation*, has a chapter on sums over all space-time geometries and on quantum fluctuations in gravitational fields. By analogy with classical electrodynamics, Wheeler et al. propose calling this new field *geometrodynamics.* Unfortunately, although the physical intuition is compelling, the field of quantum gravity remains largely *terra incognita*, in spite of decades of work on quantum gravity since *Gravitation* was published.

Now let's go from geometrodynamics, to Susskind's cosmic landscape, to the multiverse celebrated by Deutsch, Tegmark, Vilenkin and others. First see Leonard Susskind, *The Cosmic Landscape*, for the "landscape" of all possible string theories, a relatively down-to-earth kind of multiverse.[6] And for much more extreme multiverses, see David Deutsch, *The Fabric of Reality*, and the Max Tegmark article in the big John Barrow et al., John Wheeler festschrift published by Cambridge University Press.

According to Tegmark and others, the laws of this particular universe are of no fundamental interest; they are just our postal address in the multiverse, in the space of all possible universes! And who cares about a postal address?! What is fundamental is the multiverse, the ensemble of all possible universes. That is a conceptual structure worthy of study, not the particular laws of this particular, uninteresting universe!

Here is another way that Tegmark explains this: The infinite set $\{1, 2, 3, \ldots\}$ of all positive integers is very simple to calculate, but some positive integers, e.g., 935394237634876237638476 73, are very complicated, they require arbitrarily large programs. Similarly, according to Tegmark the space, the ensemble, of *all possible* physical universes is simpler than having to specify *individual* universes.

When considering the multiverse of all possible universes, we encounter this fundamental

Measure problem: *What weight should we put on each possible universe?*[7]

If following Tegmark the multiverse consists of all possible mathematical structures, then the measure problem is an extremely difficult problem, like attempting to rigorously define Borel's know-it-all oracle number. But if each universe = software, then there is no problem, none at all! Following Chapter 2, the weight of the universe defined by the program p is just $2^{-|p|}$, 1 over 2 raised to the size in bits of p. This is what we get by replacing God the mathematician

[6]String theory is an attempt to construct a theory of quantum gravity by replacing point particles by strings in order to avoid all the divergencies, all the calculations that give infinite answers. Basically there is a minimum distance scale given by the width of a string.

[7]We thank Alexander Vilenkin, author of *Many Worlds in One*, for telling us about the measure problem.

with God the computer programmer: an easy solution to the problem of what measure, what *a priori* probability, to associate with a given universe p.

In spite of these suggestions to give up on our own universe and instead consider the multiverse of all possible universes, Stephen Wolfram is actually conducting a systematic computer search for the laws of this universe, along the lines described in Chapter 9 of *A New Kind of Science.*

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