Chapter 6
Quantum Gravity

The *Planck scale* has been mentioned many times already. It is the scale of time, lengths, masses, and energies, where three grand physical theories all play equally significant roles, being special relativity (where the speed of light c is essential), quantum mechanics (with Planck's constant $\hbar$) and Newton's theory of gravity (with Newton's constant G). Having

$$\begin{aligned} c &= 299\,792\,458 \text{ m/s}, \\ \hbar &= 1.05457 \times 10^{-34} \text{ kg m}^2/\text{s}, \\ G &= 6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}, \end{aligned} \tag{6.1}$$

one finds

$$\text{the Planck length,} \quad L_{\rm Pl} = \sqrt{\tfrac{G\hbar}{c^3}} = 1.616 \times 10^{-35} \text{ m}, \tag{6.2}$$

$$\text{the Planck time,} \quad T_{\rm Pl} = \sqrt{\tfrac{G\hbar}{c^5}} = 5.391 \times 10^{-44} \text{ s}, \tag{6.3}$$

$$\text{the Planck mass,} \quad M_{\rm Pl} = \sqrt{\tfrac{c\hbar}{G}} = 21.76 \text{ μg}, \tag{6.4}$$

$$\text{and the Planck energy,} \quad E_{\rm Pl} = \sqrt{\tfrac{c^5\hbar}{G}} = 1.956 \times 10^{9} \text{ J}. \tag{6.5}$$

In this domain of physics, one expects Special and General Relativity and Quantum Mechanics all to be relevant, but a complete synthesis of these three has not yet been achieved—in fact, our continued struggle towards finding such a synthesis was one of the main motivations for this work.

It is not unreasonable to suspect that the Planck length is the smallest significant length scale in physics, and the Planck time is the smallest time scale at which things can happen, but there is more. General Relativity is known to cause space and time to be curved, so, if one might talk of some "lattice" in space and time, curvature may be expected to cause defects in this lattice. Alternatively, one might suspect that lattice-like behaviour can also be realized by imposing a cutoff in local momentum and energy scales (a so-called bandwidth cut-off [57]); however, with such a cut-off, deterministic models are difficult to construct.

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It is also important to note that General Relativity is based on the local automorphism group. This means that time translations are locally defined, so that one may expect that gravity could be essential to realize locality requirements for the Hamiltonian. Mass, energy and momentum are local sources of gravitational fields, but there is more.

Gravitation is a destabilizing force. Causing masses to attract one another, it generates greater masses and thus even stronger attraction. This may lead to gravitational implosion. In contrast, electric as well as magnetic charges act repulsively (if they have equal signs), which makes electromagnetism a lot more stable than gravity as a force system.

When gravitational implosion takes place, black holes may form. *Microscopic black holes* must play an essential role at the Planck scale, as they may act as virtual particles, taking part in the vacuum fluctuations. When one tries to incorporate black holes in an all-embracing theory, difficulties arise. According to standard calculations, black holes emanate elementary particles, and this effect (Hawking effect [47, 48]) allows one to compute the density of quantum states associated to black holes. This density is very large, but as black holes increase in size, the number of states does not grow as fast as one might expect: it grows exponentially with the size of the surface, rather than the encapsulated volume. The quantum states that one might expect in the *bulk* of a black hole mysteriously disappear.

We expect all this to produce a profound effect on the putative deterministic models that could possibly lie at the basis of quantum theory. Discreteness of space and time comes for free, because one can also argue that the number of quantum states inside a volume V can never exceed that of a black hole occupying V, so that the surface at the border of V dictates how many independent ontological states are allowed inside V, an effect called the 'holographic principle' [81, 117]. Locality may come naturally because of the automorphism group as mentioned. Yet space–time curvature causes problems. Nature's book keeping system is still very ill-understood.