Family 1		Family 2		Family 3	
Particle	***Mass***	***Particle***	***Mass***	***Particle***	***Mass***
Electron	.00054	Muon	.11	Tau	1.9
Electron-neutrino	$< 10^{-8}$	Muon-neutrino	< .0003	Tau-neutrino	< .033
Up-quark	.0047	Charm Quark	1.6	Top Quark	189
Down-quark	.0074	Strange Quark	.16	Bottom Quark	5.2

Table 1.1 The three families of fundamental particles and their masses (in multiples of the proton mass). The values of the neutrino masses have so far eluded experimental determination.

Force	*Force particle*	*Mass*
Strong	Gluon	0
Electromagnetic	Photon	0
Weak	Weak gauge bosons	86, 97
Gravity	Graviton	0

Table 1.2 The four forces of nature, together with their associated force particles and their masses in multiples of the proton mass. (The weak force particles come in varieties with the two possible masses listed. Theoretical studies show that the graviton should be massless.)

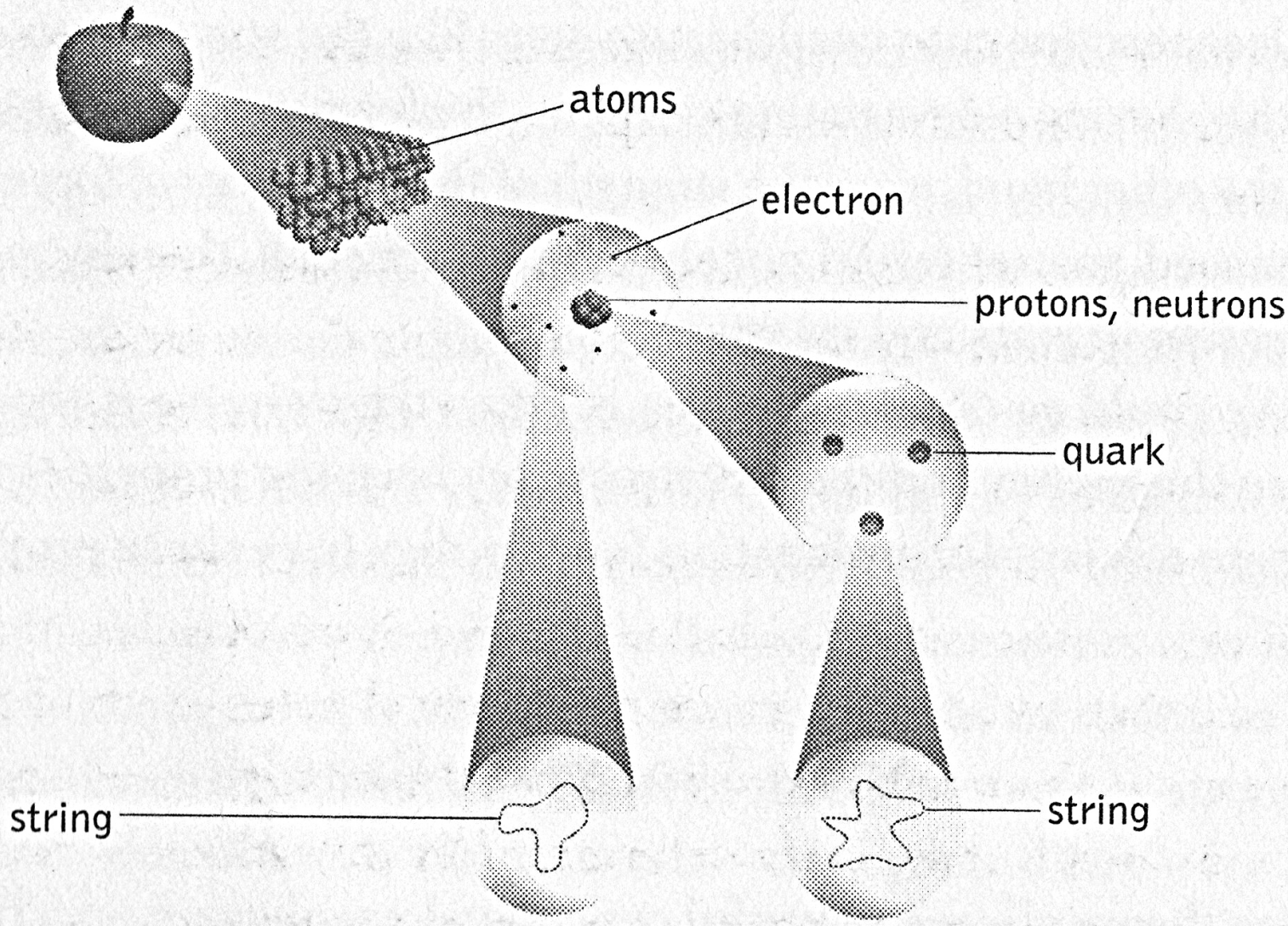

Figure 1.1 Matter is composed of atoms, which in turn are made from quarks and electrons. According to string theory, all such particles are actually tiny loops of vibrating string.

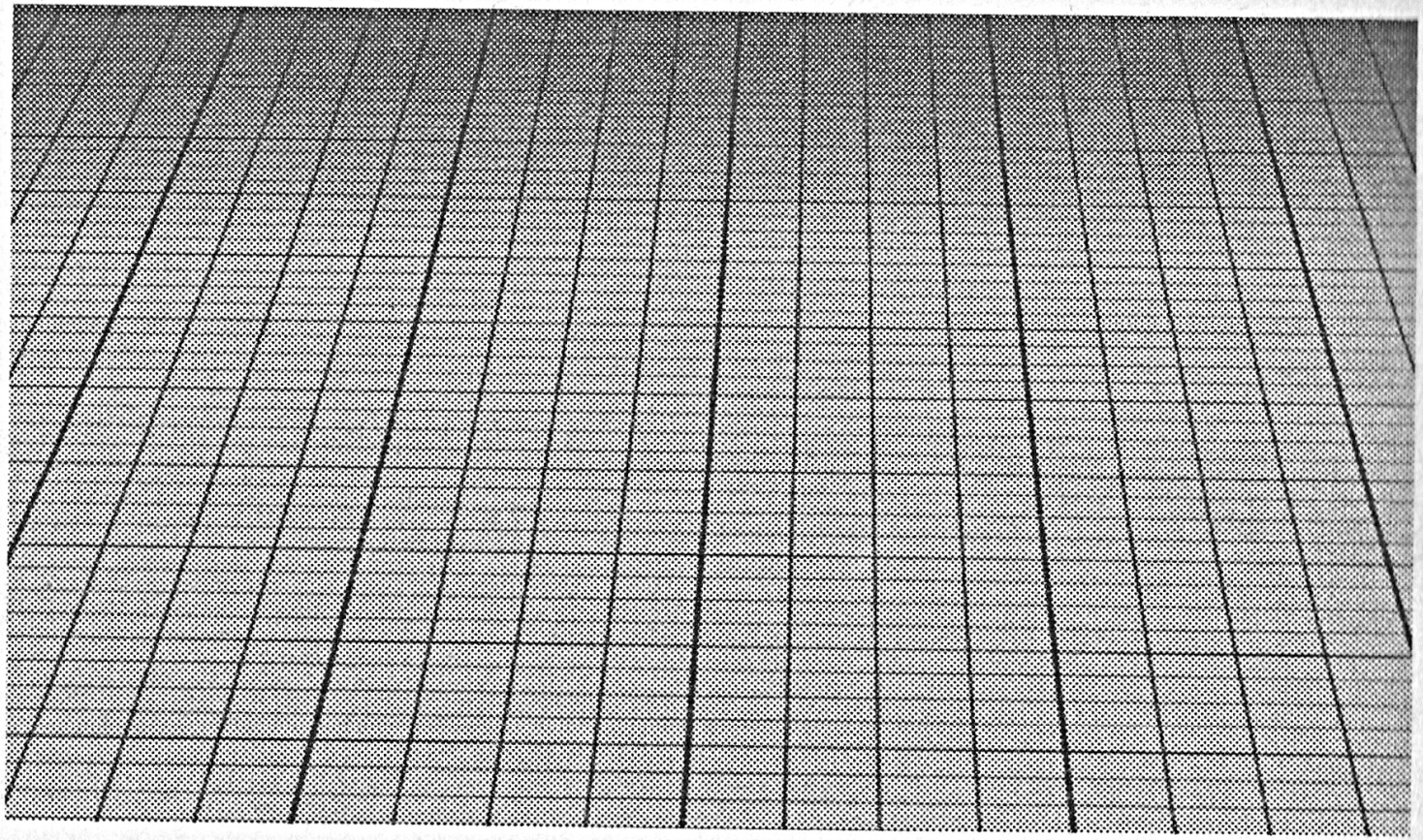

Figure 3.3 A schematic representation of flat space.

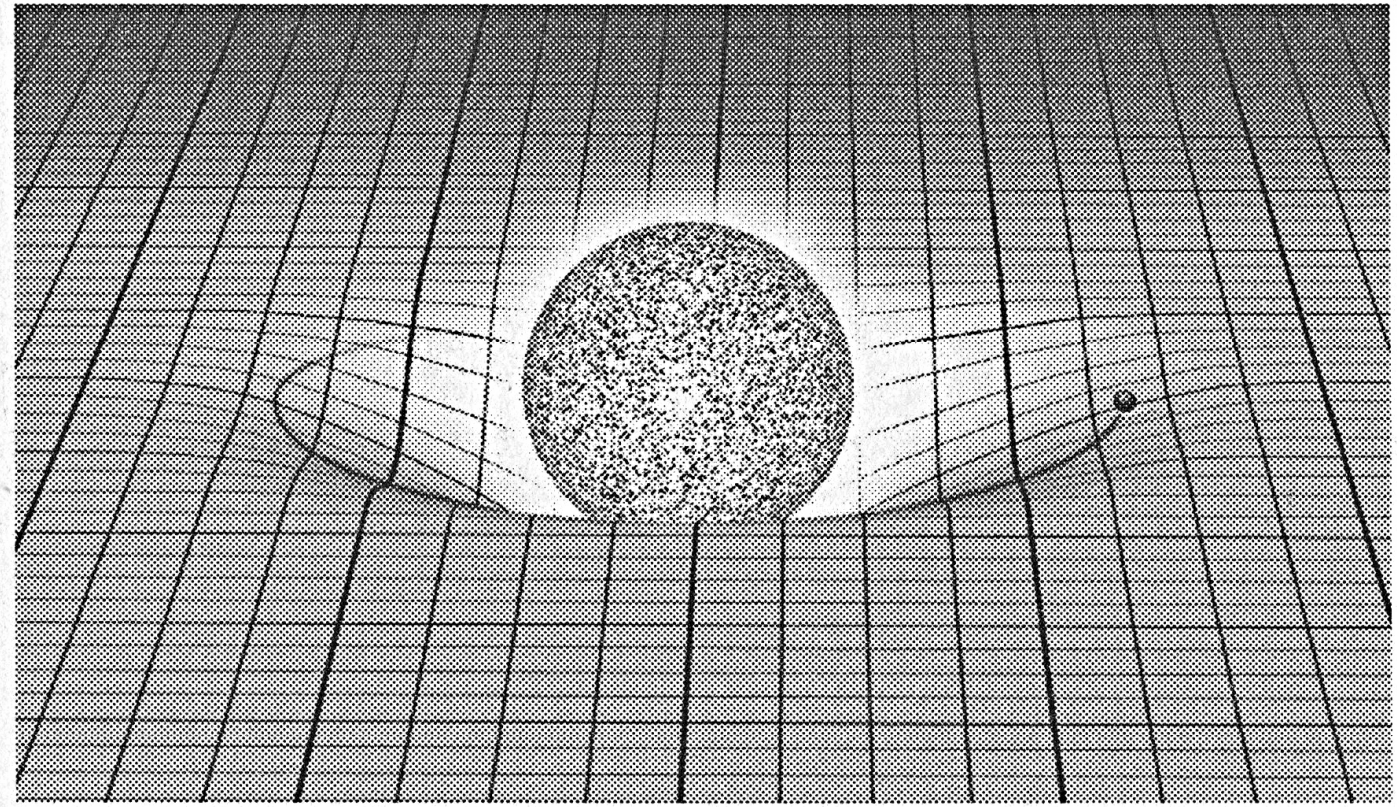

Figure 3.5 The earth is kept in orbit around the sun because it rolls along a valley in the warped spatial fabric. In more precise language, it follows a "path of least resistance" in the distorted region around the sun.

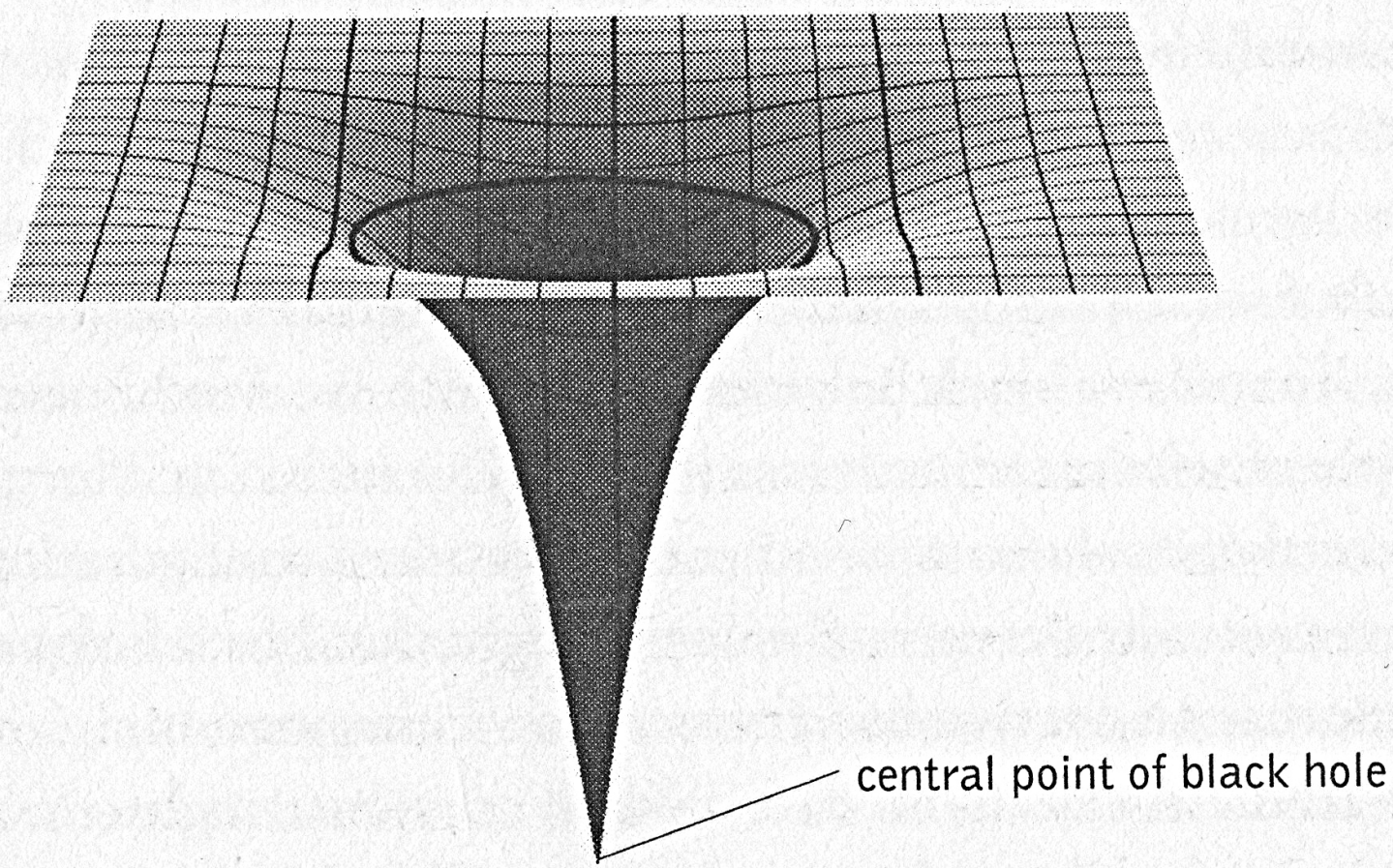

Figure 3.7 A black hole warps the surrounding spacetime fabric so severely that anything that comes within its "event horizon"—illustrated by the dark circle—can't escape from its gravitational grip. No one knows exactly what happens at the deepest interior point of a black hole.

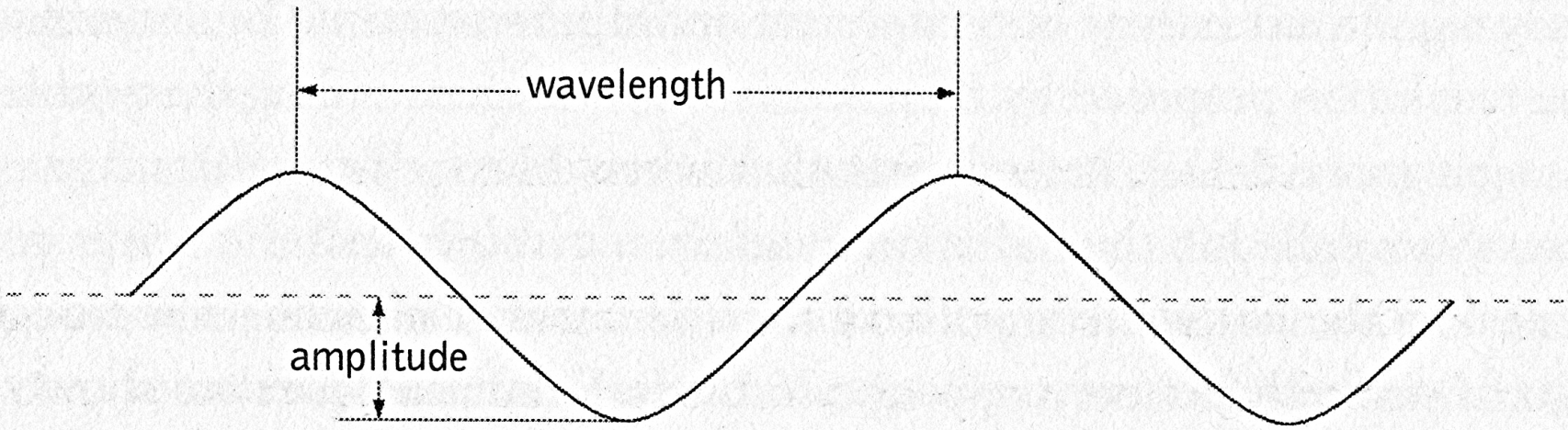

Figure 4.2 The wavelength is the distance between successive peaks or troughs of a wave. The amplitude is the maximal height or depth of the wave.

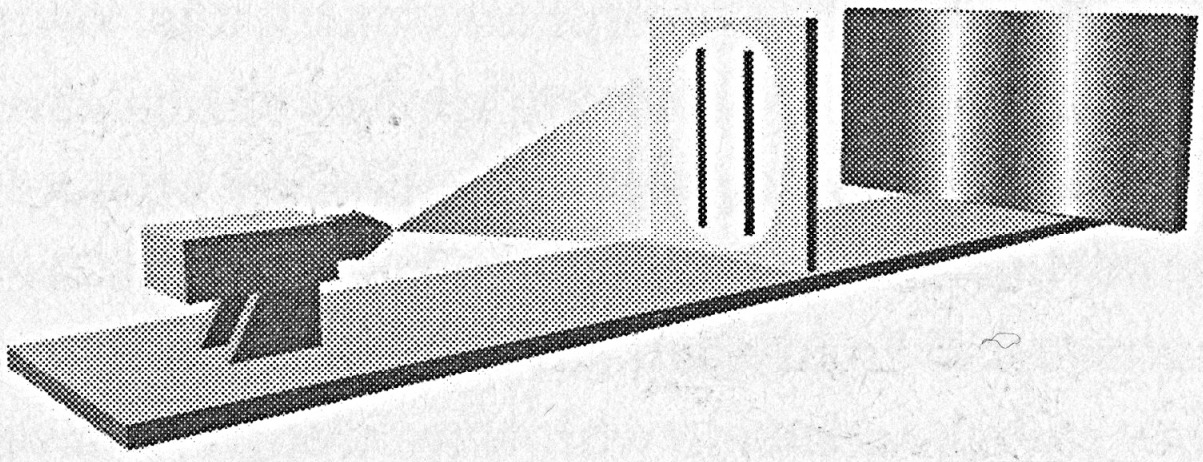

Figure 4.6 Newton's particle view of light predicts that when both slits are open, the photographic plate will be a merger of the images in Figures 4.4 and 4.5.

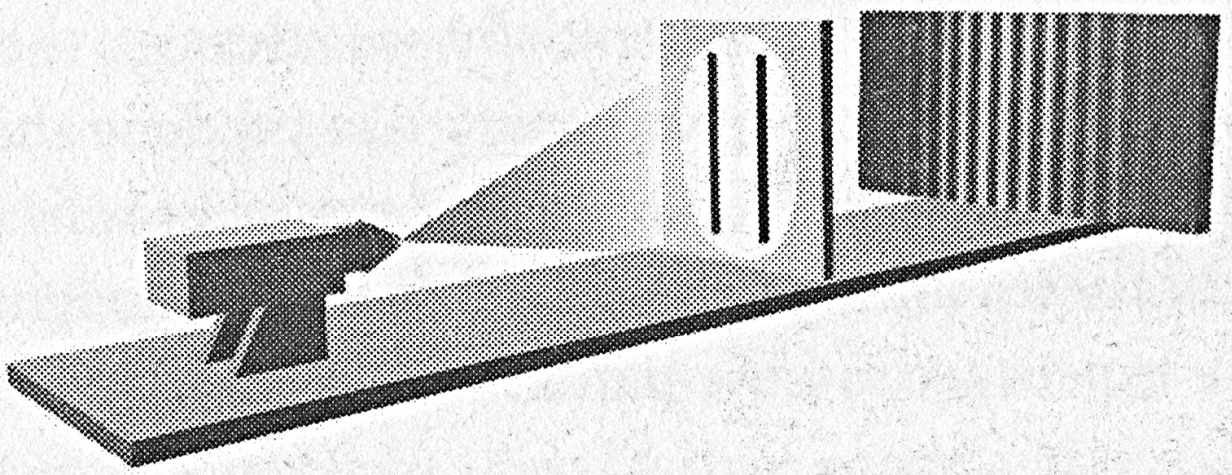

Figure 4.8 If light is a wave, then when both slits are open there will be interference between the portions of the wave emerging from each slit.

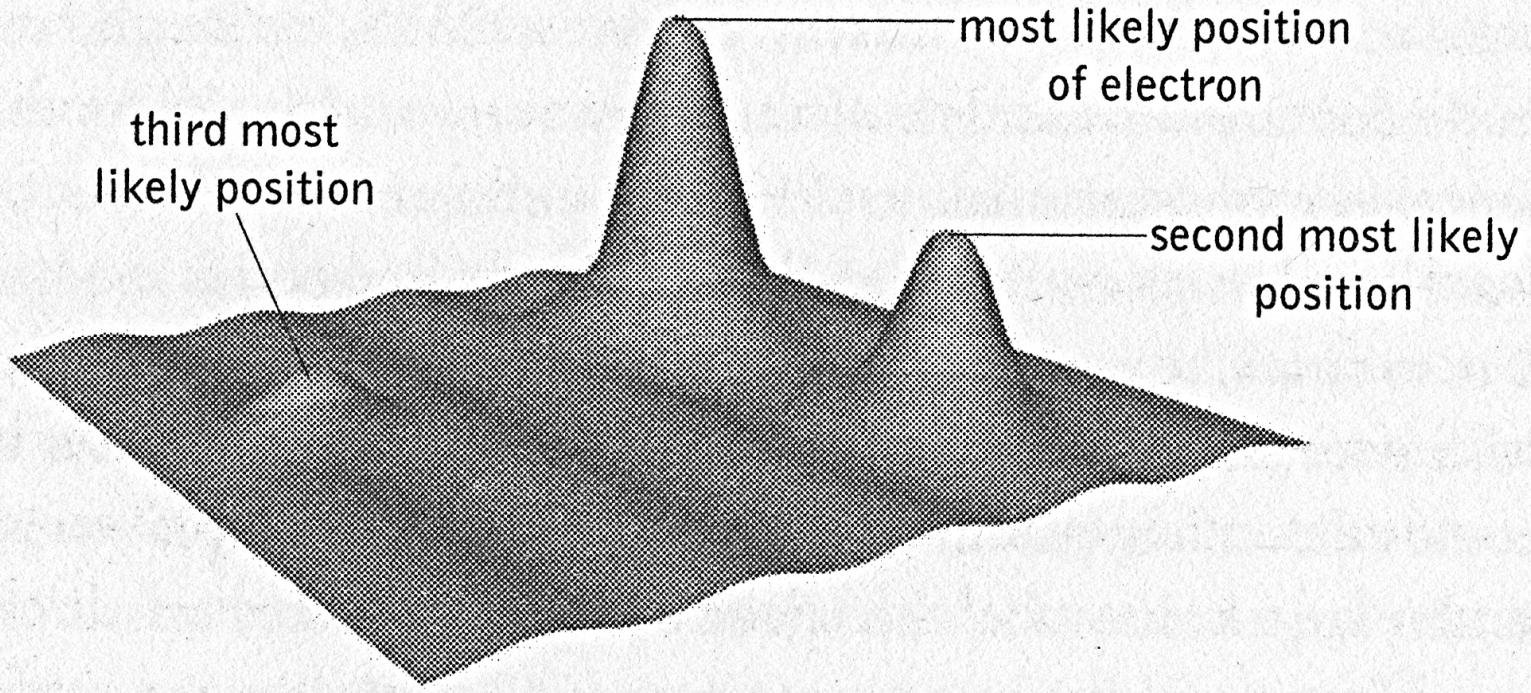

Figure 4.9 The wave associated with an electron is largest where the electron is most likely to be found, and progressively smaller at locations where it is less likely to be found.

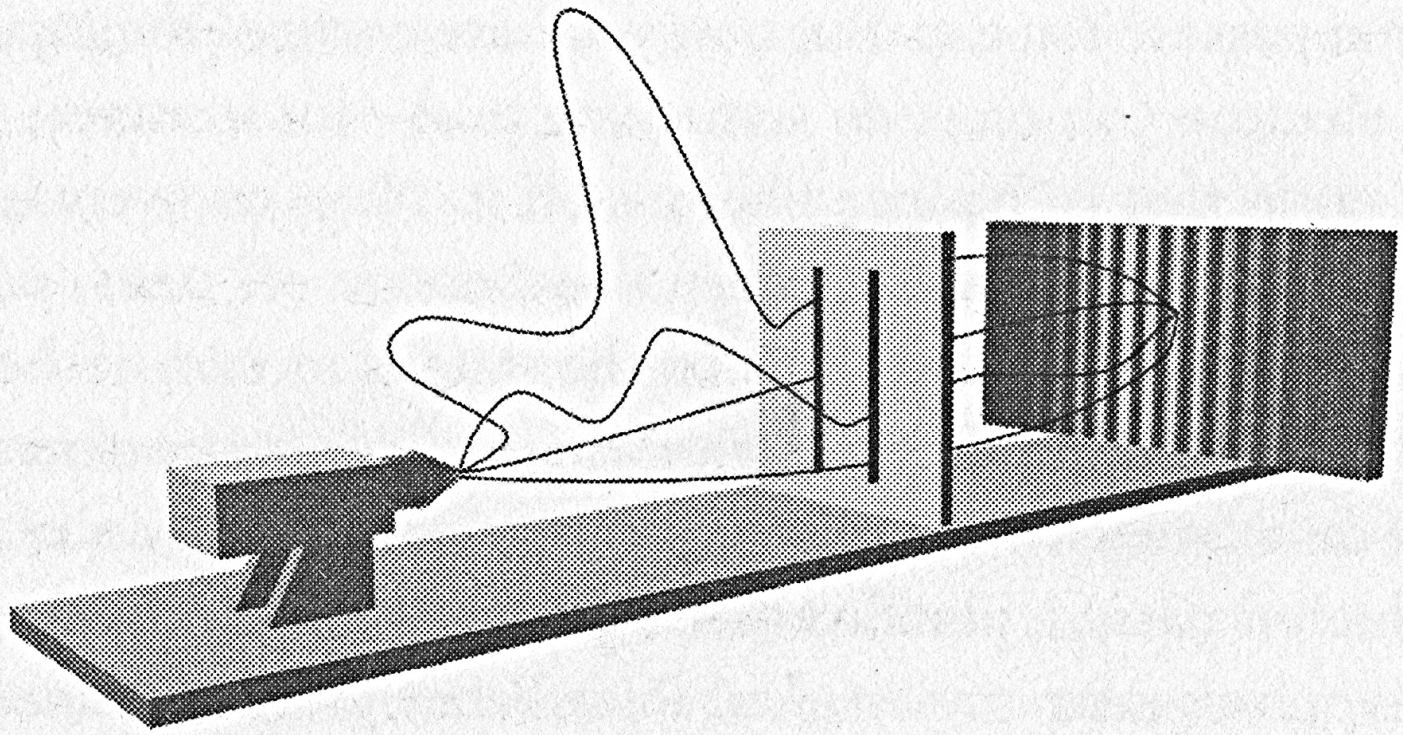

Figure 4.10 According to Feynman's formulation of quantum mechanics, particles must be viewed as travelling from one location to another along every possible path. Here, a few of the infinity of trajectories for a single electron travelling from the source to the phosphorescent screen are shown. Notice that this one electron actually goes through both slits.

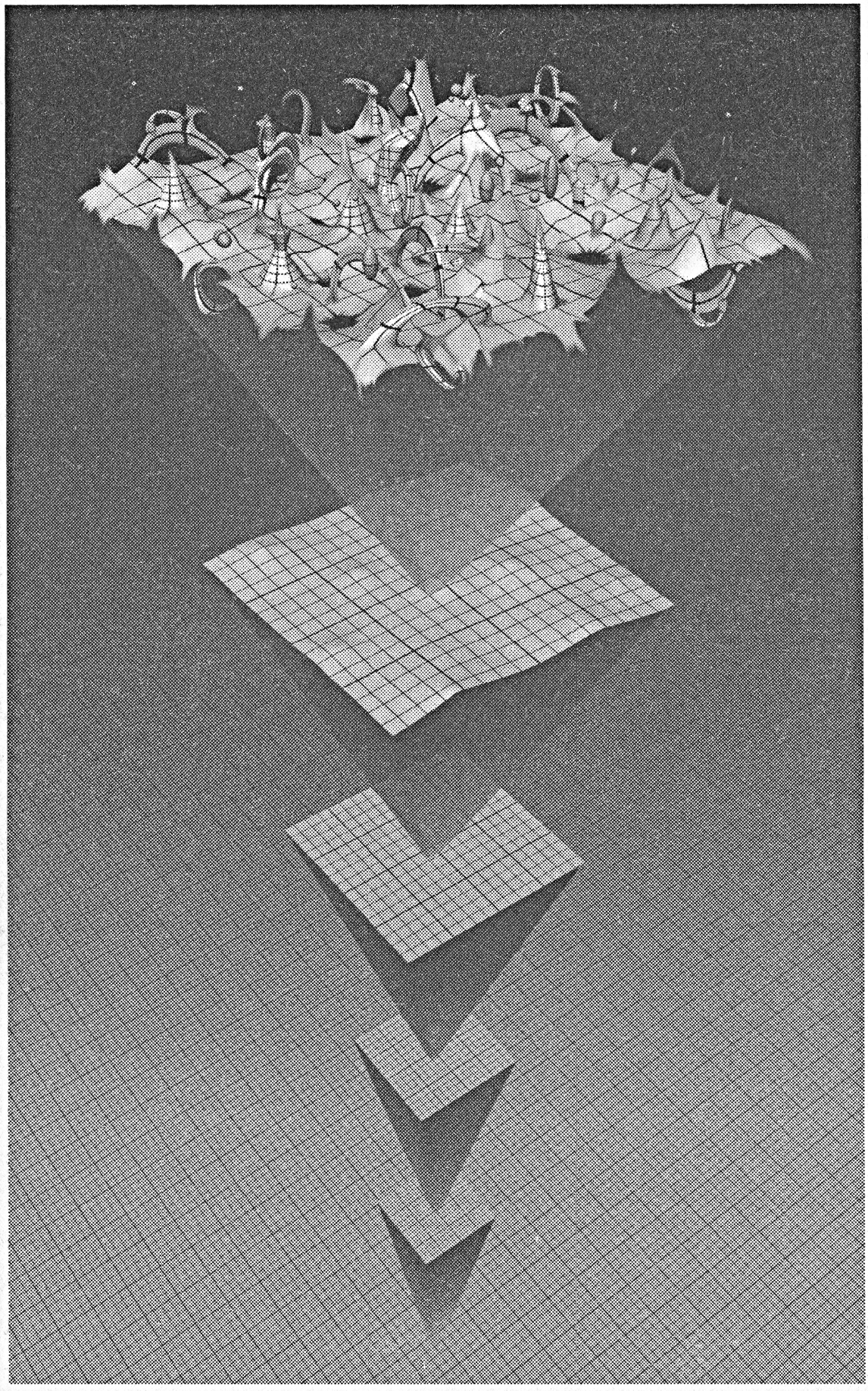

Figure 5.1 By sequentially magnifying a region of space, its ultramicroscopic properties can be probed. Attempts to merge general relativity and quantum mechanics run up against the violent quantum foam emerging at the highest level of magnification.

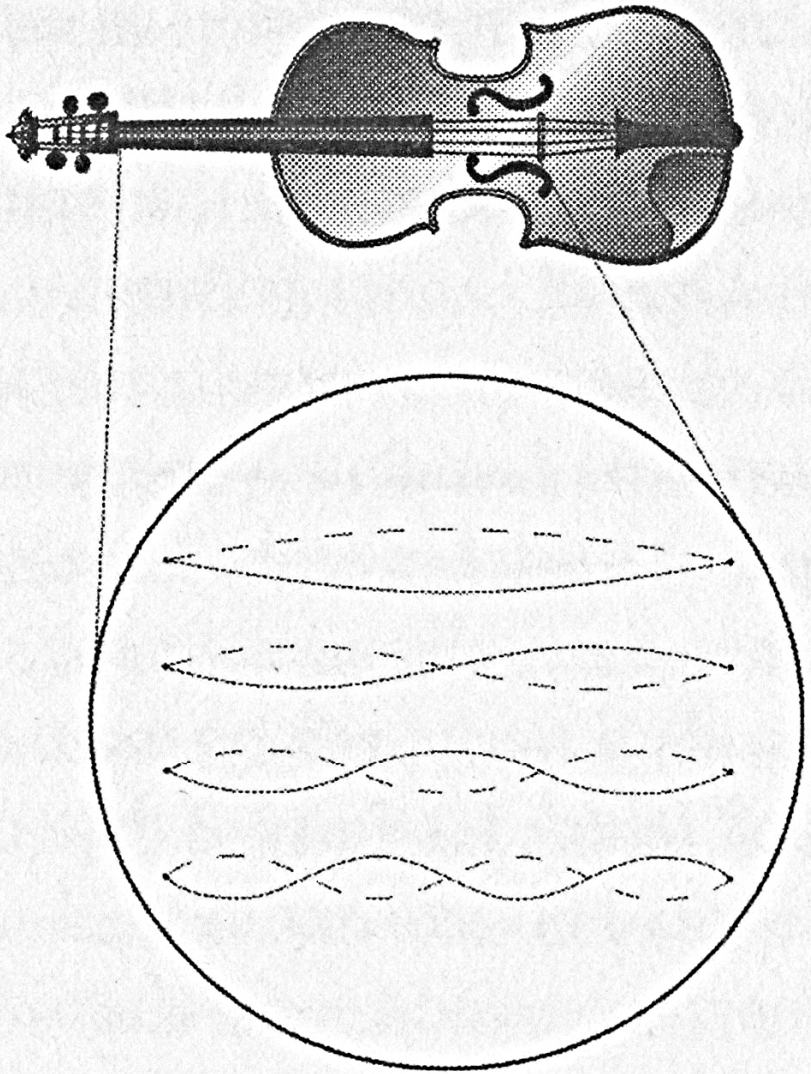

Figure 6.1 Strings on a violin can vibrate in resonant patterns in which a whole number of peaks and troughs exactly fit between the two ends.

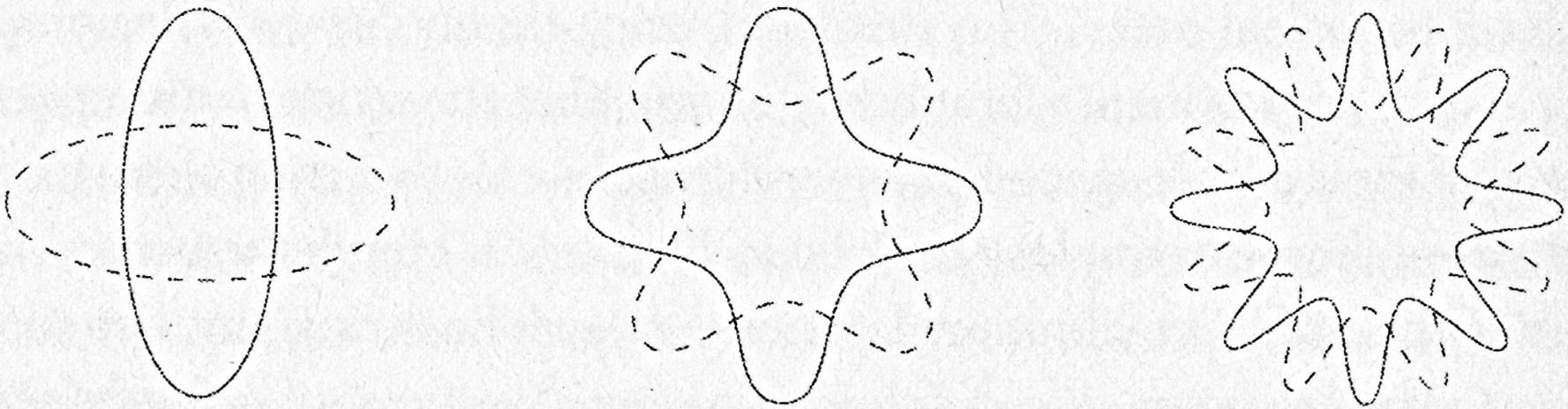

Figure 6.2 The loops in string theory can vibrate in resonance patterns—similar to those of violin strings—in which a whole number of peaks and troughs fit along their spatial extent.

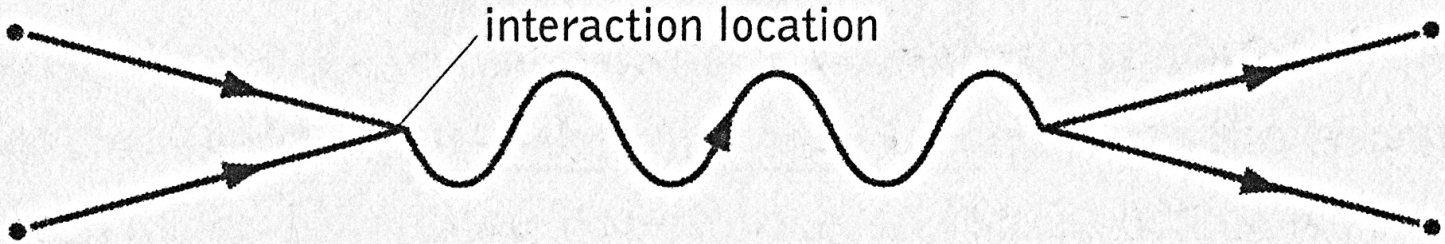

Figure 6.6 In quantum field theory, a particle and its antiparticle can momentarily annihilate one another, producing a photon. Subsequently, this photon can give rise to another particle and antiparticle traveling along different trajectories.

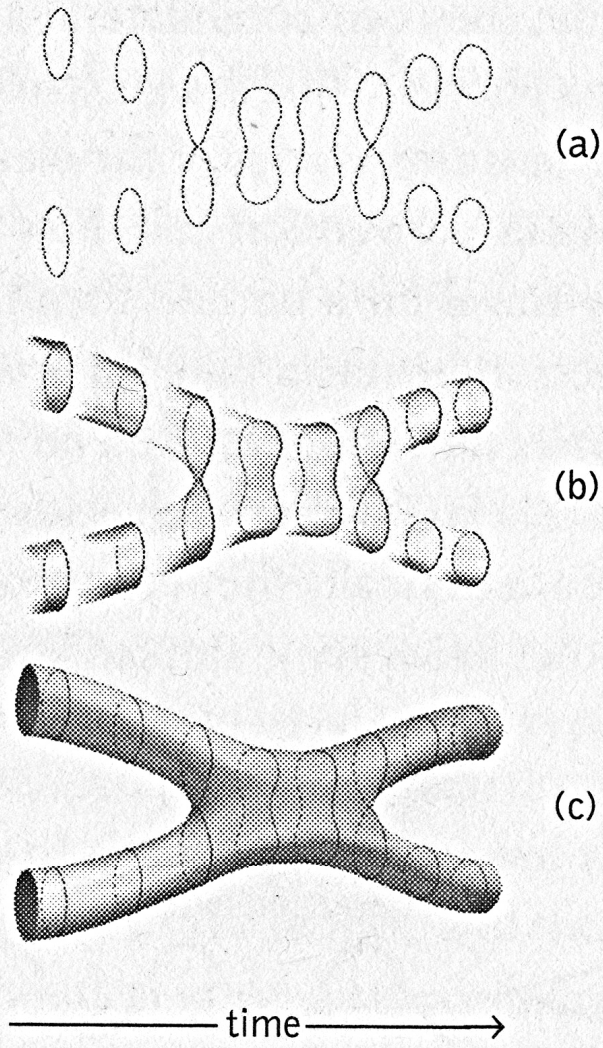

Figure 6.7 (a) Two strings on a collision course can merge into a third string, which subsequently can split apart into two strings travelling along deflected trajectories. (b) The same process as shown in (a), emphasizing string motion. (c) A "time-lapse photograph" of two interacting strings sweeping out a "world-sheet."

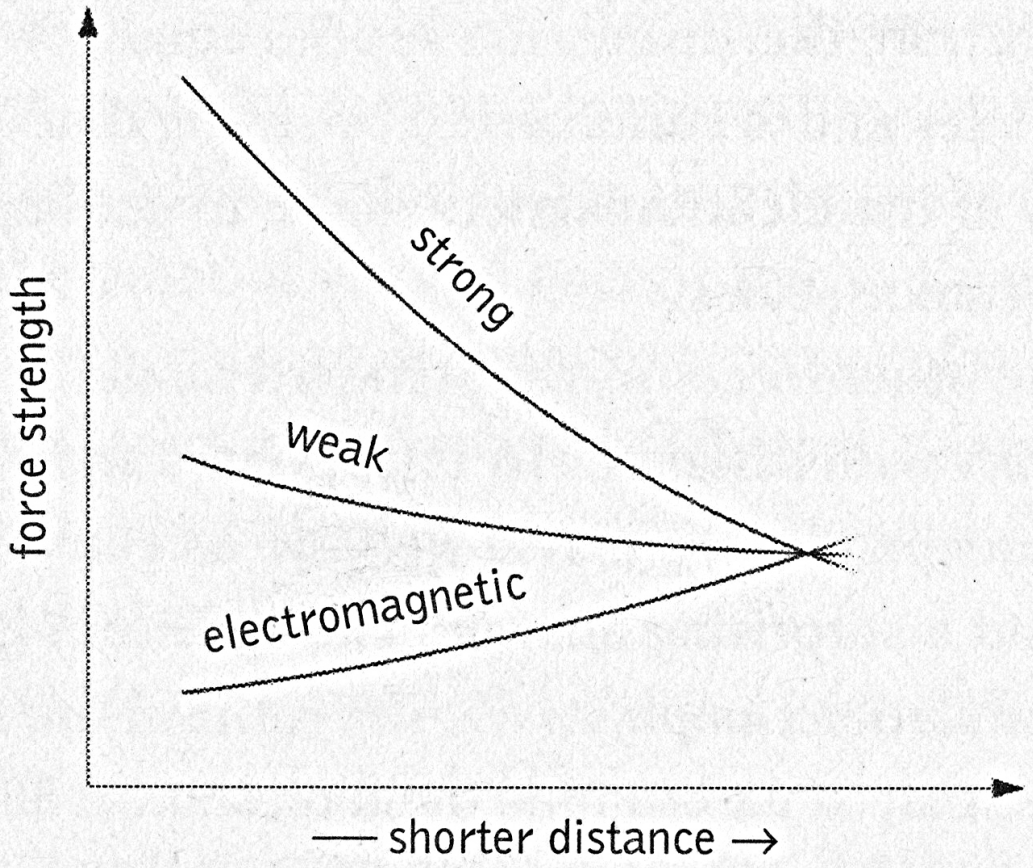

Figure 7.1 The strengths of the three nongravitational forces as they operate on ever shorter distance scales—equivalently, as they act on ever higher energy processes.

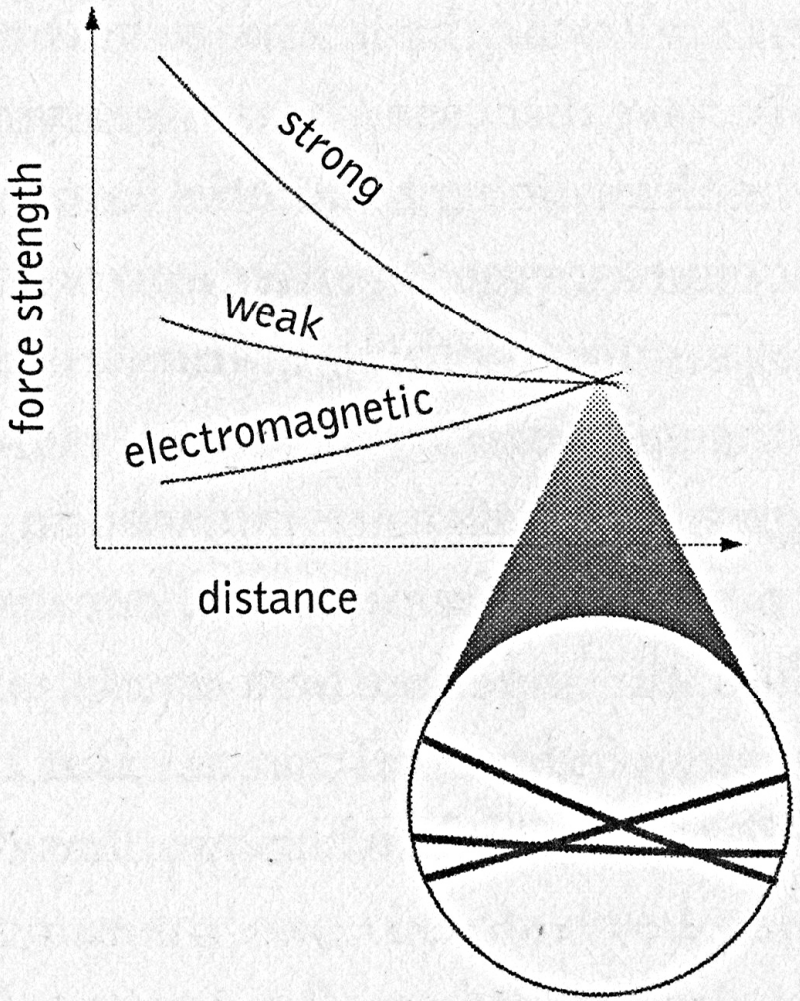

Figure 7.2 A refinement of the calculation of force strengths reveals that without supersymmetry they almost, but not quite, meet.

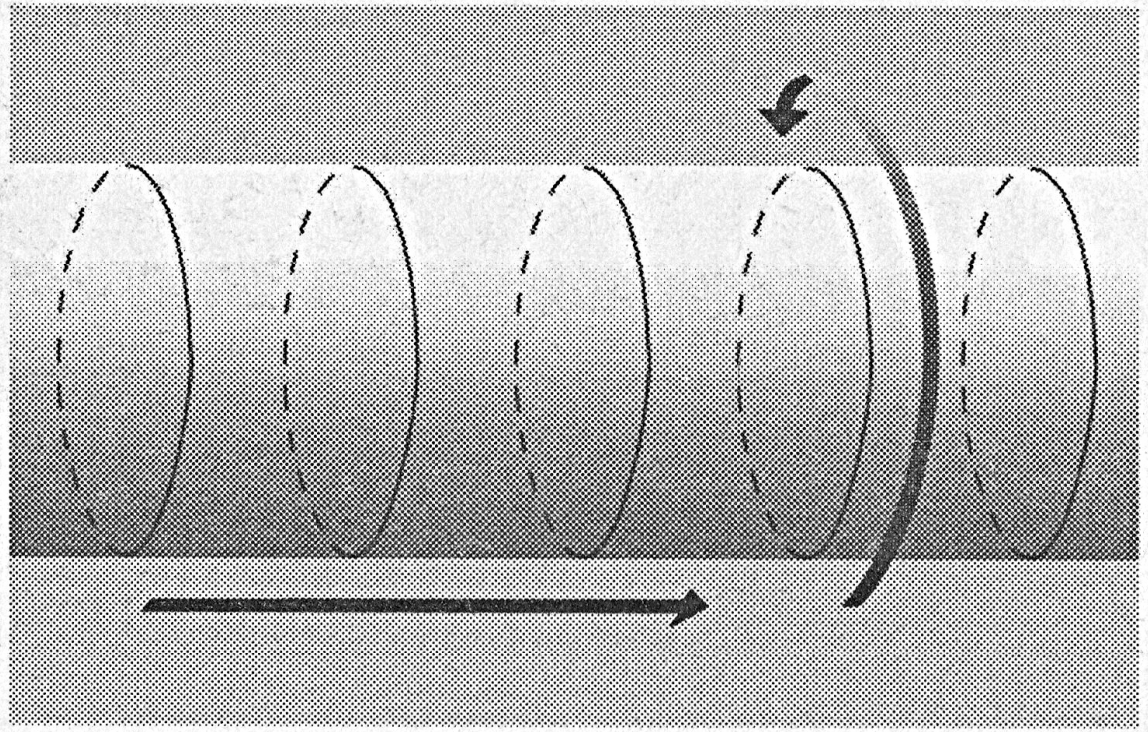

Figure 8.2 The surface of the garden hose is two-dimensional: one dimension (its horizontal extent), emphasized by the straight arrow, is long and extended; the other dimension (its circular girth), emphasized by the circular arrow, is short and curled up.

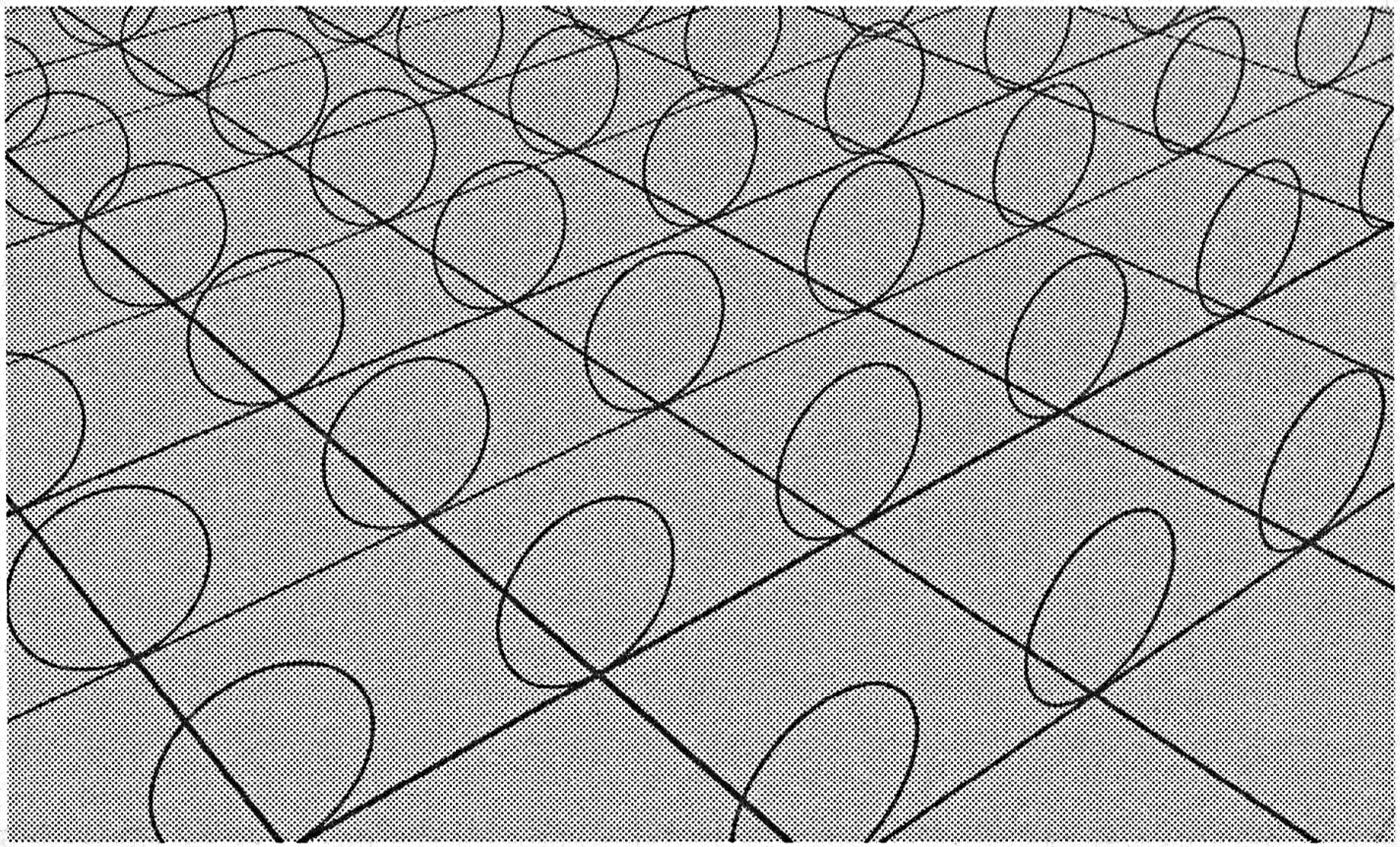

Figure 8.4 The grid lines represent the extended dimensions of common experience, whereas the circles are a new, tiny, curled-up dimension. Like the circular loops of thread making up the pile of a carpet, the circles exist at every point in the familiar extended dimensions—but for visual clarity we draw them as spread out on intersecting grid lines.

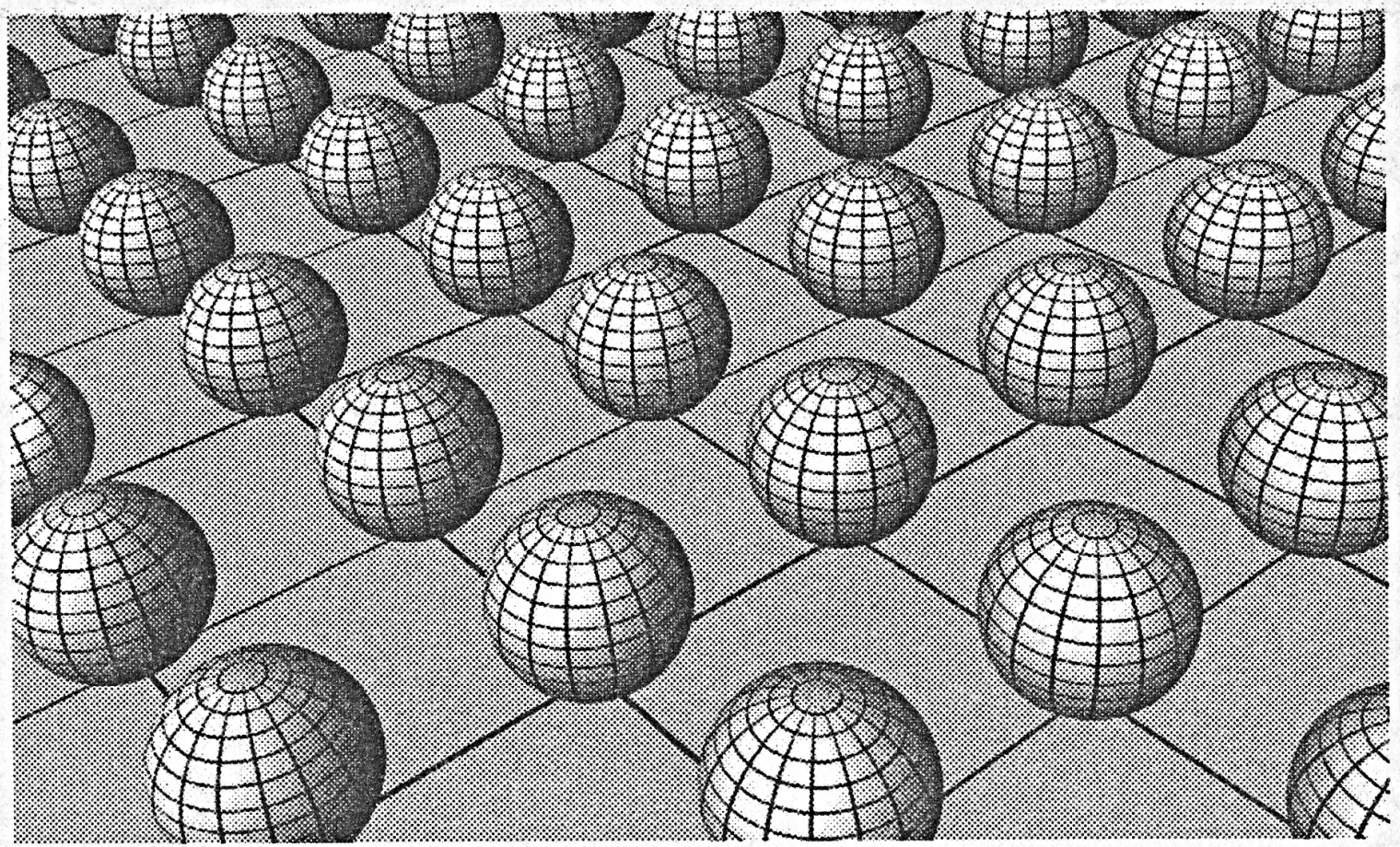

Figure 8.7 Two extra dimensions curled up into the shape of a sphere.

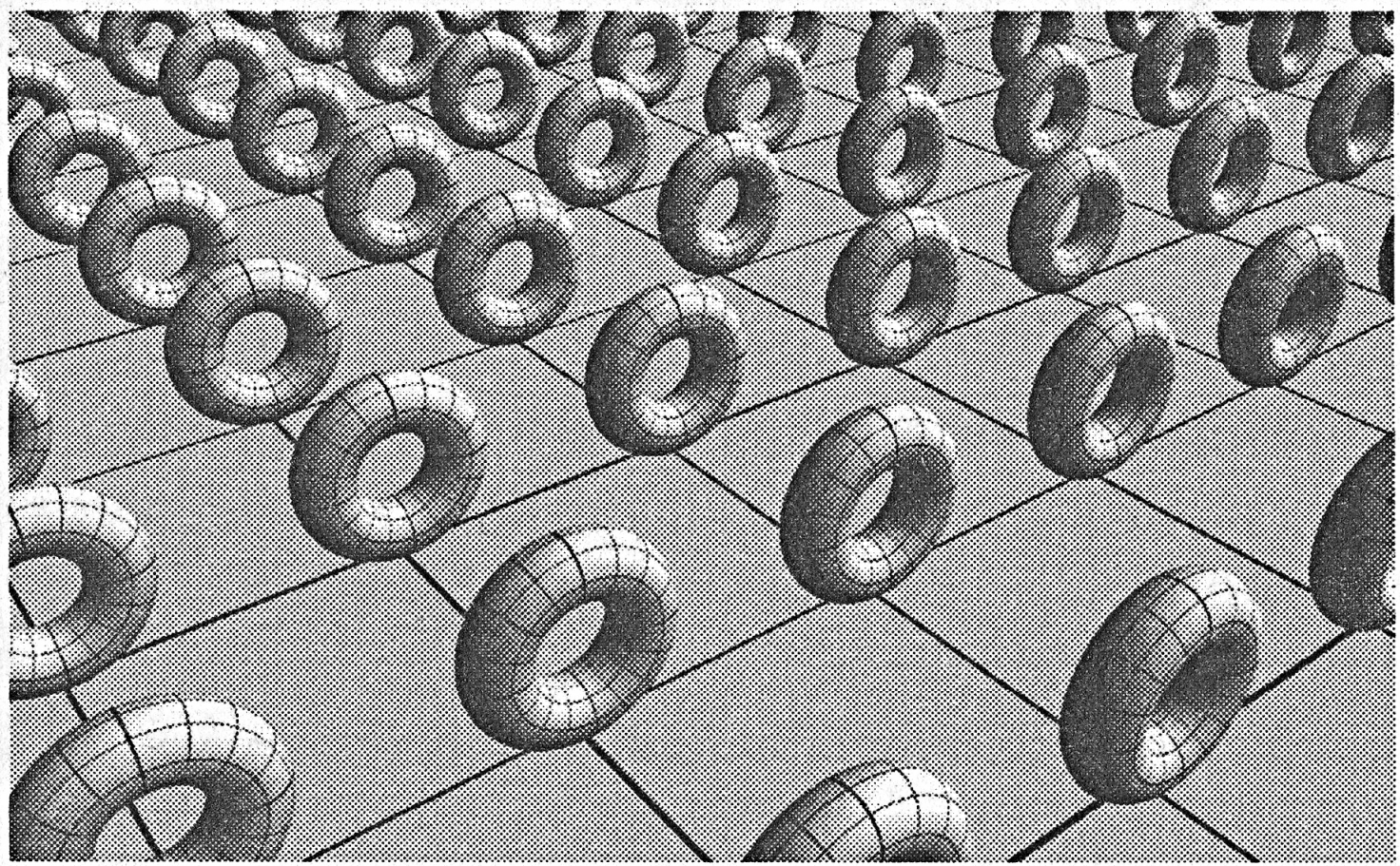

Figure 8.8 Two extra dimensions curled up in the shape of a hollow doughnut, or torus.

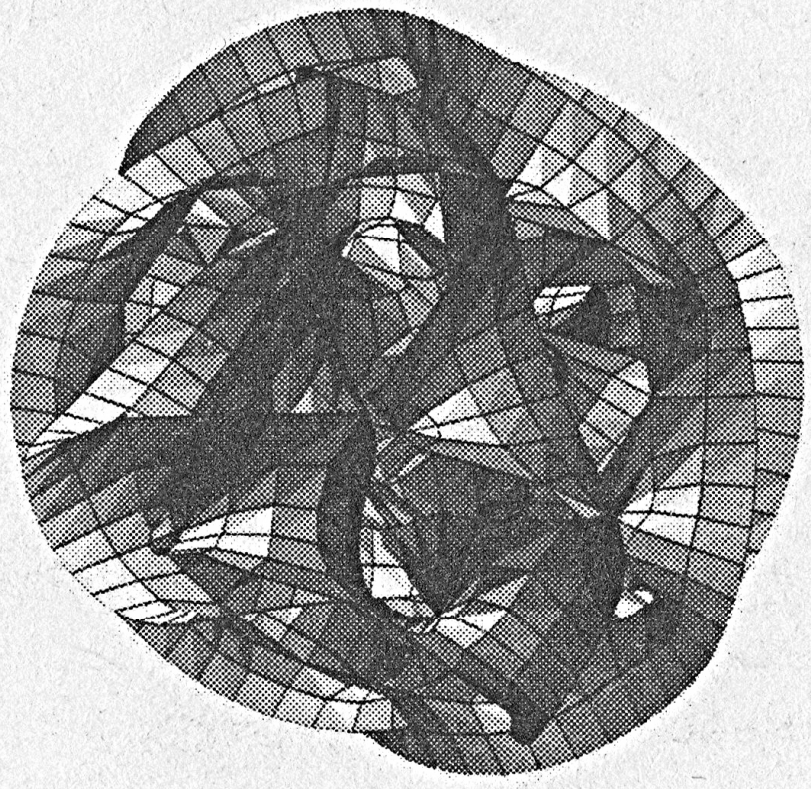

Figure 8.9 One example of a Calabi-Yau space.

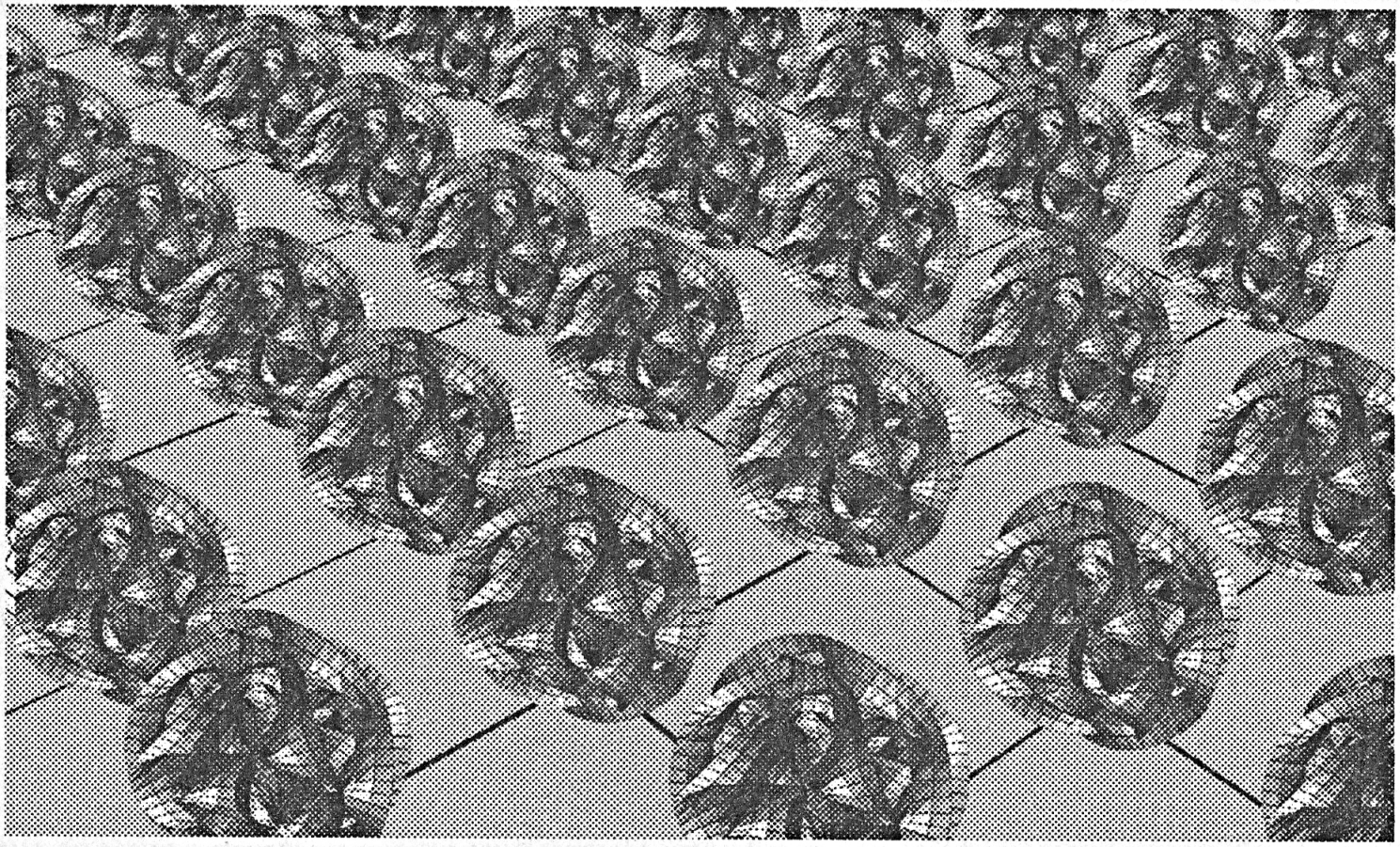

Figure 8.10 According to string theory, the universe has extra dimensions curled up into a Calabi-Yau shape.

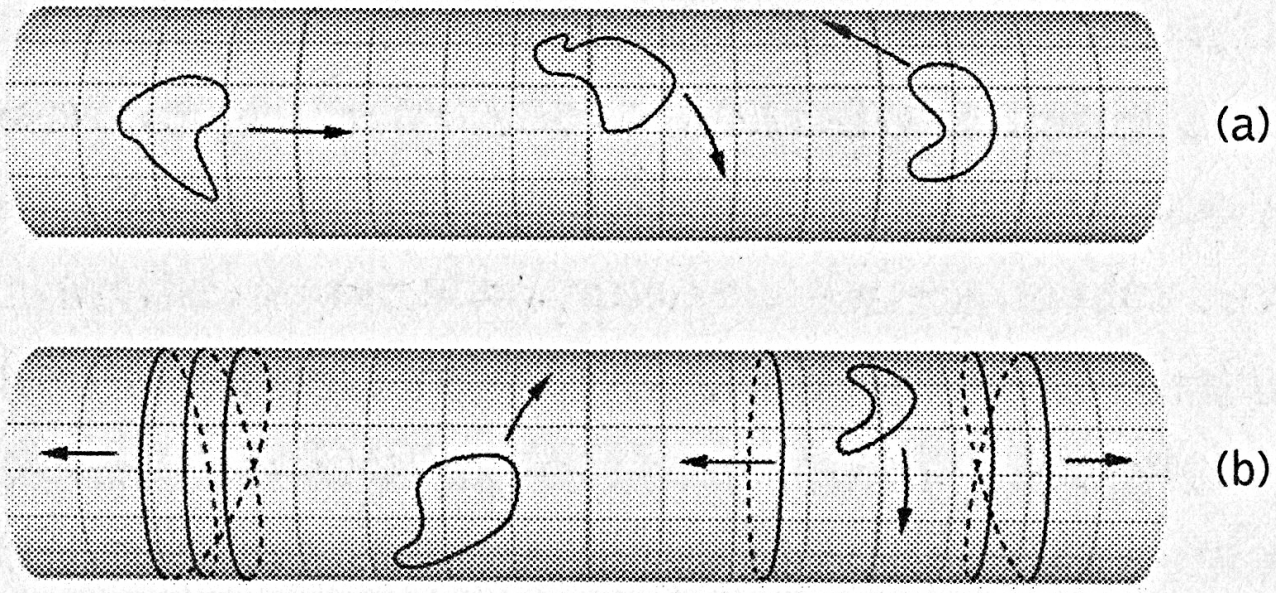

Figure 10.3 Strings can move on a cylinder in two different ways—in "unwrapped" or "wrapped" configurations.

Vibration number	*Winding number*	*Total energy*
1	1	1/10 + 10 = 10.1
1	2	1/10 + 20 = 20.1
1	3	1/10 + 30 = 30.1
1	4	1/10 + 40 = 40.1
2	1	2/10 + 10 = 10.2
2	2	2/10 + 20 = 20.2
2	3	2/10 + 30 = 30.2
2	4	2/10 + 40 = 40.2
3	1	3/10 + 10 = 10.3
3	2	3/10 + 20 = 20.3
3	3	3/10 + 30 = 30.3
3	4	3/10 + 40 = 40.3
4	1	4/10 + 10 = 10.4
4	2	4/10 + 20 = 20.4
4	3	4/10 + 30 = 30.4
4	4	4/10 + 40 = 40.4

Table 10.1 Sample vibration and winding configurations of a string moving in a universe shown in Figure 10.3, with radius $R = 10$. The vibration energies contribute in multiples of 1/10 and the winding energies contribute in multiples of 10, yielding the total energies listed. The energy unit is the Planck energy, so for example, 10.1 in the last column means 10.1 times the Planck energy.

Vibration number	*Winding number*	*Total energy*
1	1	10 + 1/10 = 10.1
1	2	10 + 2/10 = 10.2
1	3	10 + 3/10 = 10.3
1	4	10 + 4/10 = 10.4
2	1	20 + 1/10 = 20.1
2	2	20 + 2/10 = 20.2
2	3	20 + 3/10 = 20.3
2	4	20 + 4/10 = 20.4
3	1	30 + 1/10 = 30.1
3	2	30 + 2/10 = 30.2
3	3	30 + 3/10 = 30.3
3	4	30 + 4/10 = 30.4
4	1	40 + 1/10 = 40.1
4	2	40 + 2/10 = 40.2
4	3	40 + 3/10 = 40.3
4	4	40 + 4/10 = 40.4

Table 10.2 As in Table 10.1, except that the radius is now taken to be 1/10.

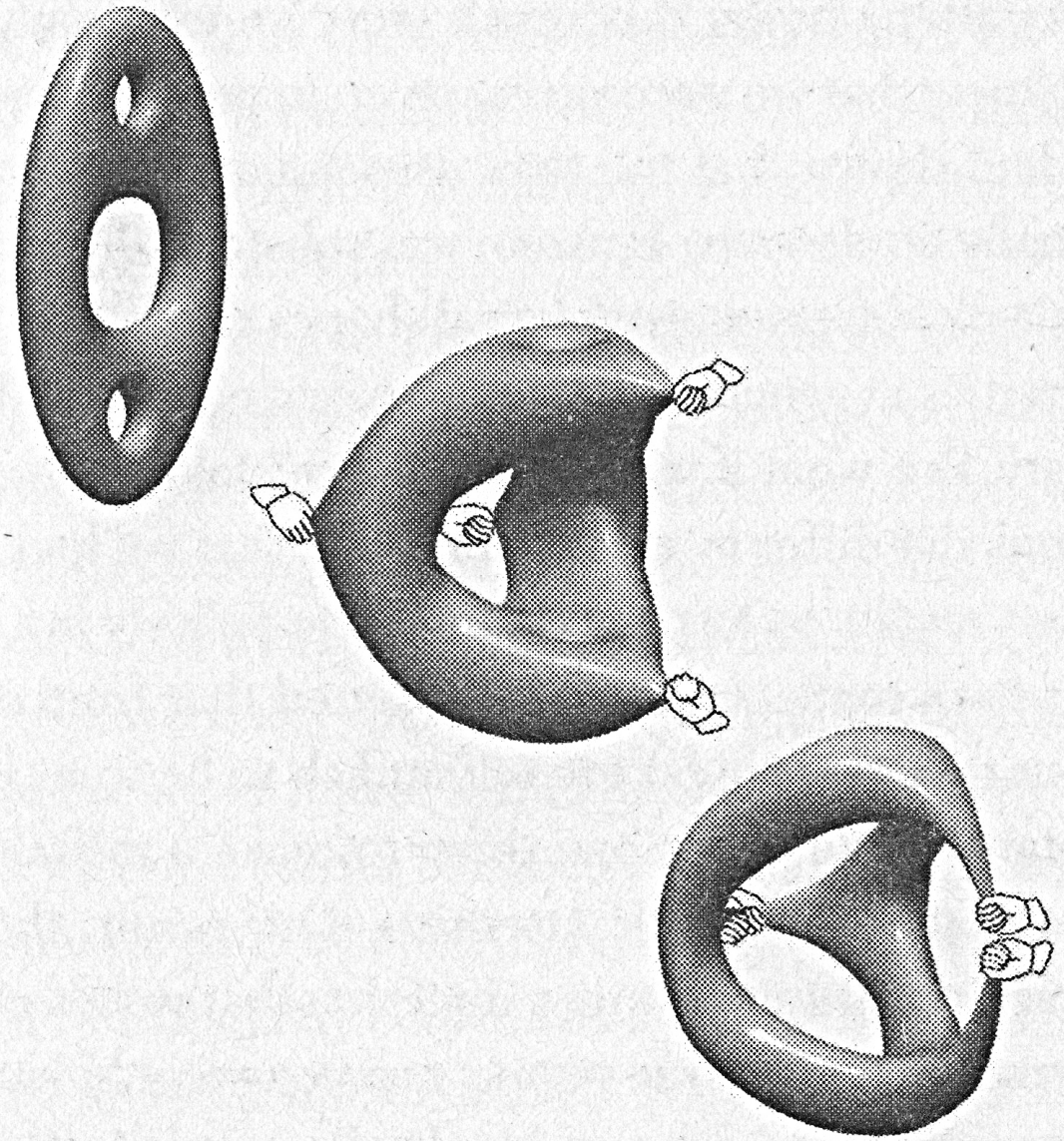

Figure 10.4 Orbifolding is a procedure in which a new Calabi-Yau shape is produced by gluing together various points on an initial Calabi-Yau shape.

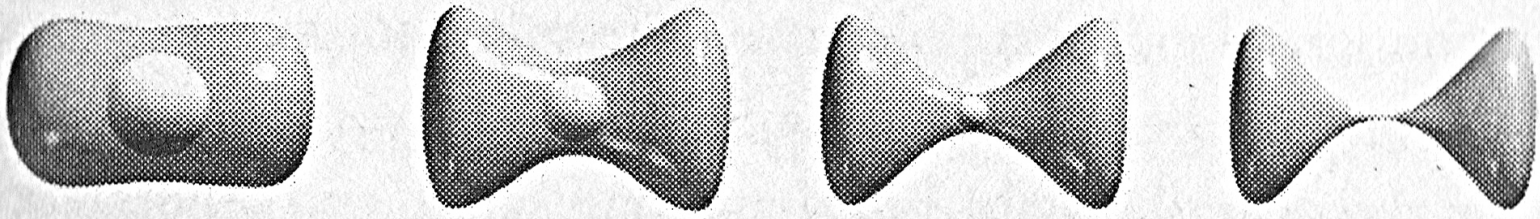

Figure 11.3 A sphere inside a Calabi-Yau space shrinks down to a point, pinching the fabric of space. We simplify this and subsequent figures by showing only part of the full Calabi-Yau shape.

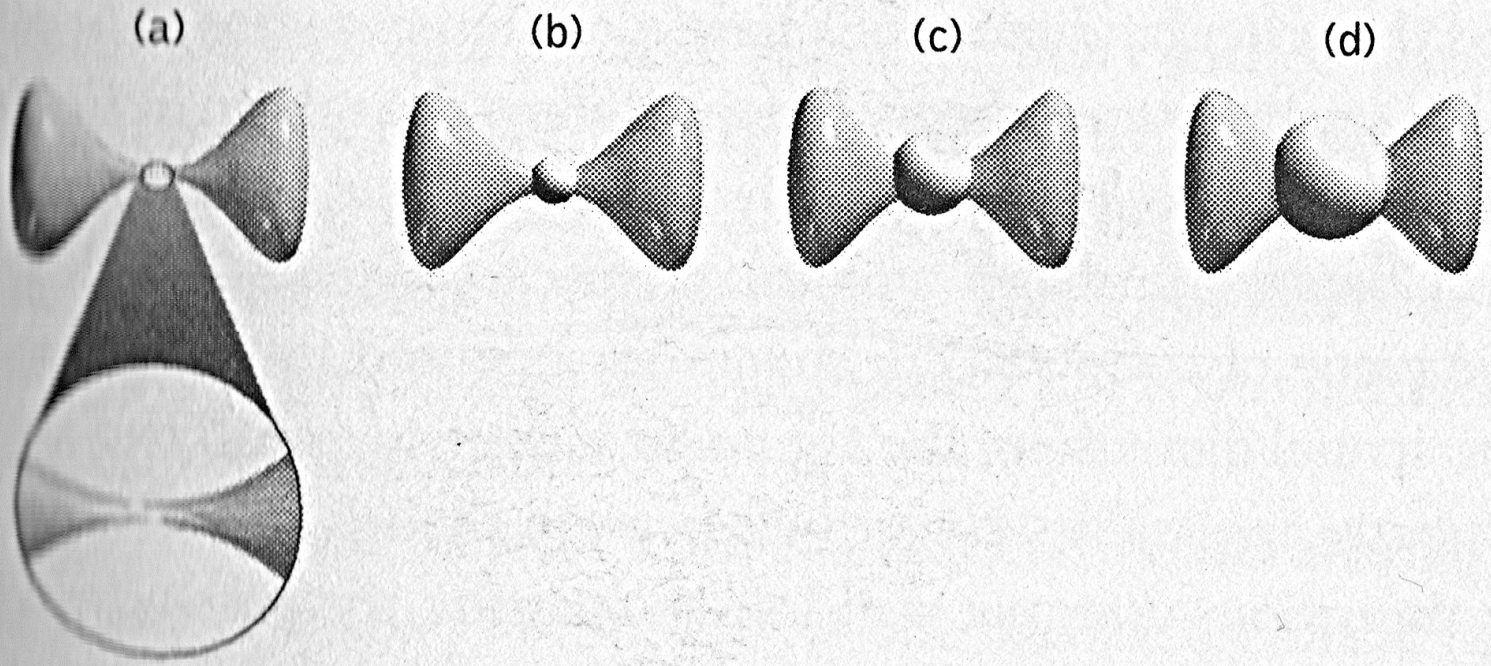

Figure 11.4 A pinched Calabi-Yau space tears open and grows a sphere that smoothes out its surface. The original sphere of Figure 11.3 is "flopped."

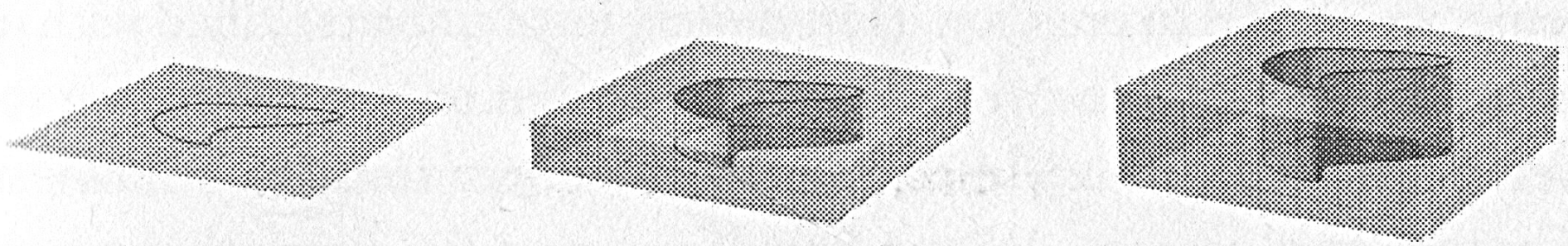

Figure 12.7 As the Heterotic-E string coupling constant is increased, a new space dimension appears and the string itself gets stretched into a cylindrical membrane shape.

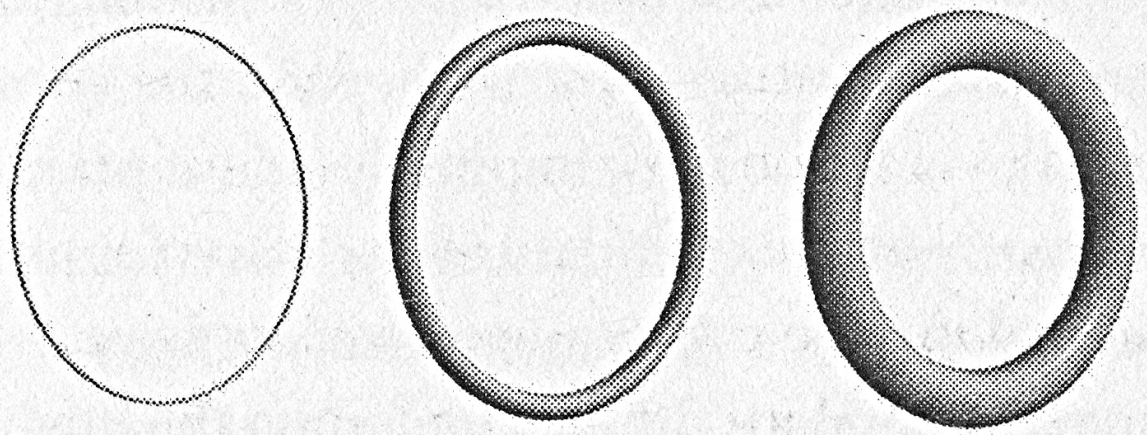

Figure 12.8 As the Type IIA string coupling constant is increased, strings expand from one-dimensional loops to two-dimensional objects that look like the surface of a bicycle-tire inner tube.

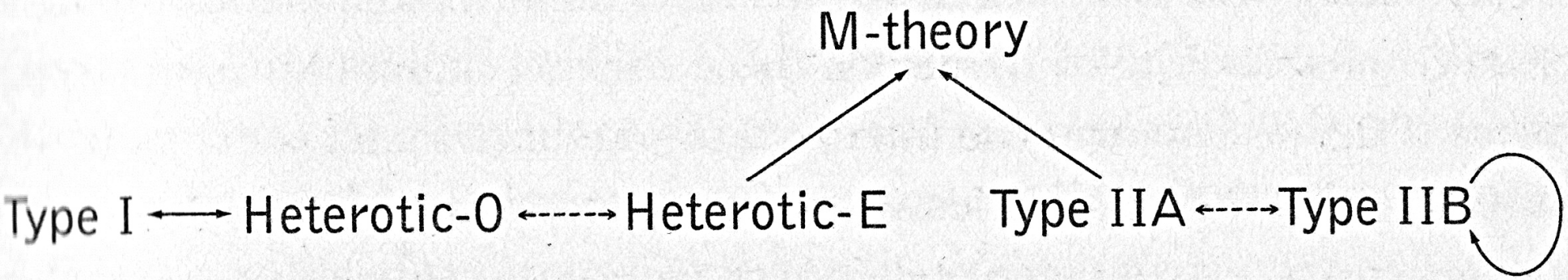

Figure 12.10 By including the dualities involving the geometrical form of spacetime (as in Chapter 10), all five of the string theories and M-Theory are joined together in a web of dualities.

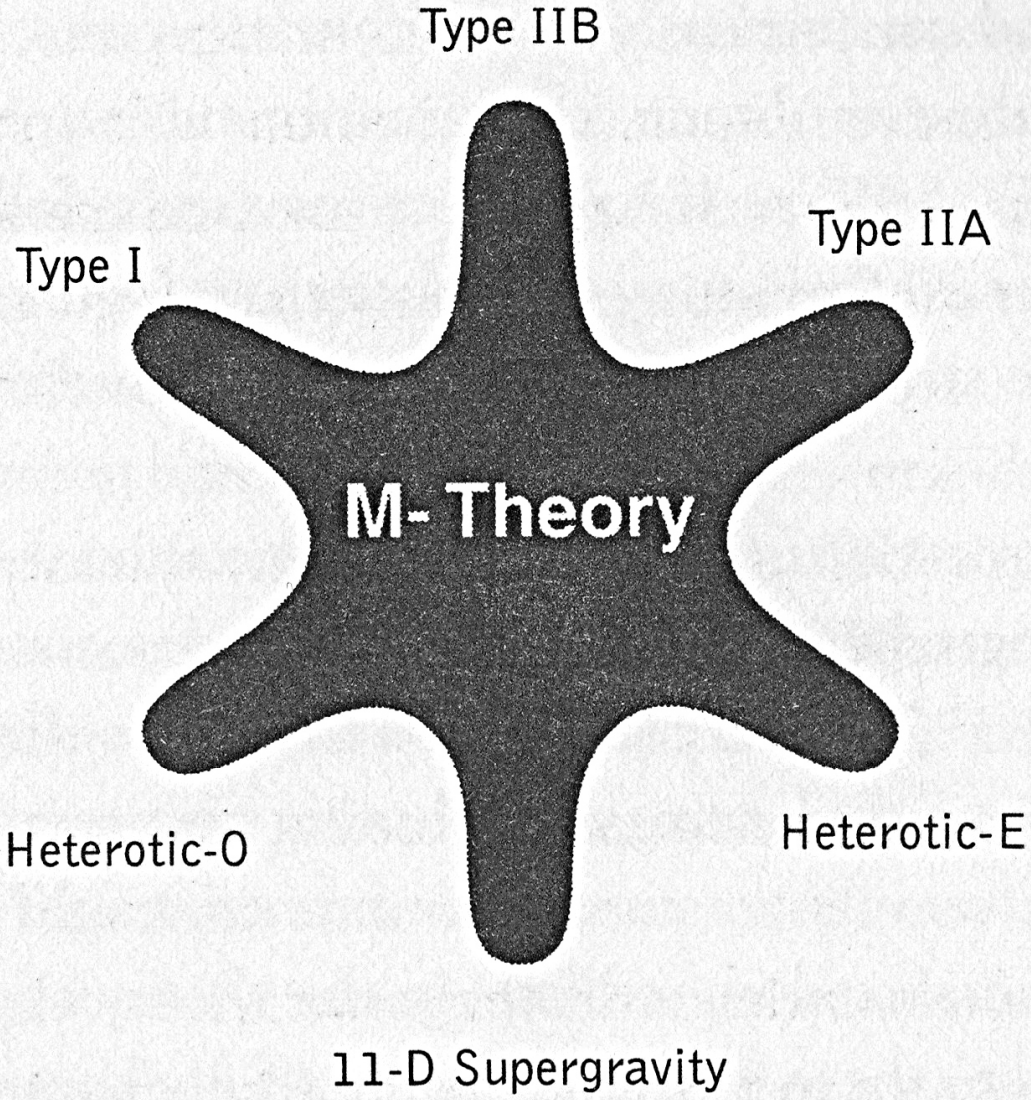

Figure 12.11 By incorporating the dualities, all five string theories, eleven-dimensional supergravity, and M-theory are merged together into a unified framework.

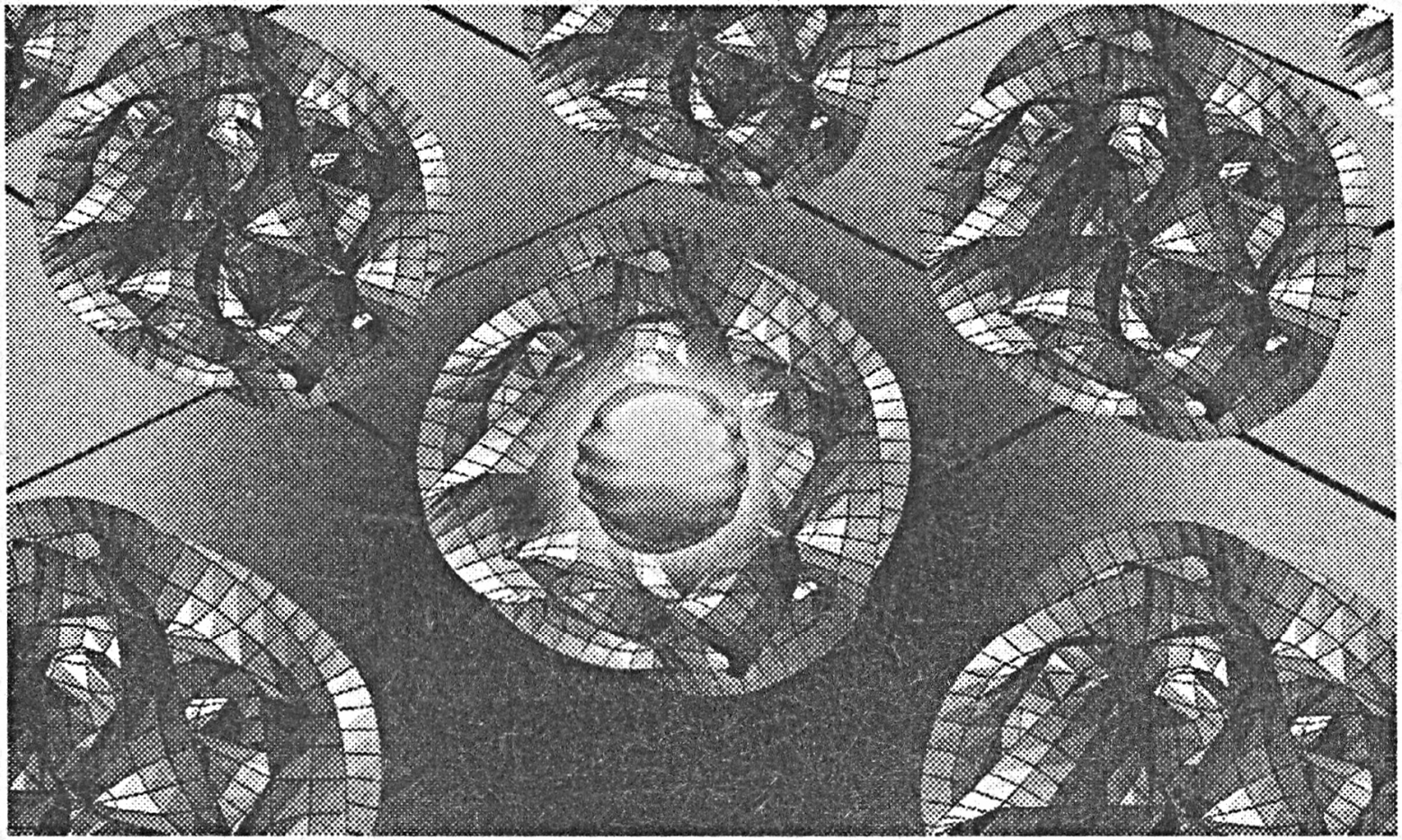

Figure 13.4 When a brane wraps around a sphere that is within the curled-up dimensions, it appears as a black hole in the familiar extended dimensions.

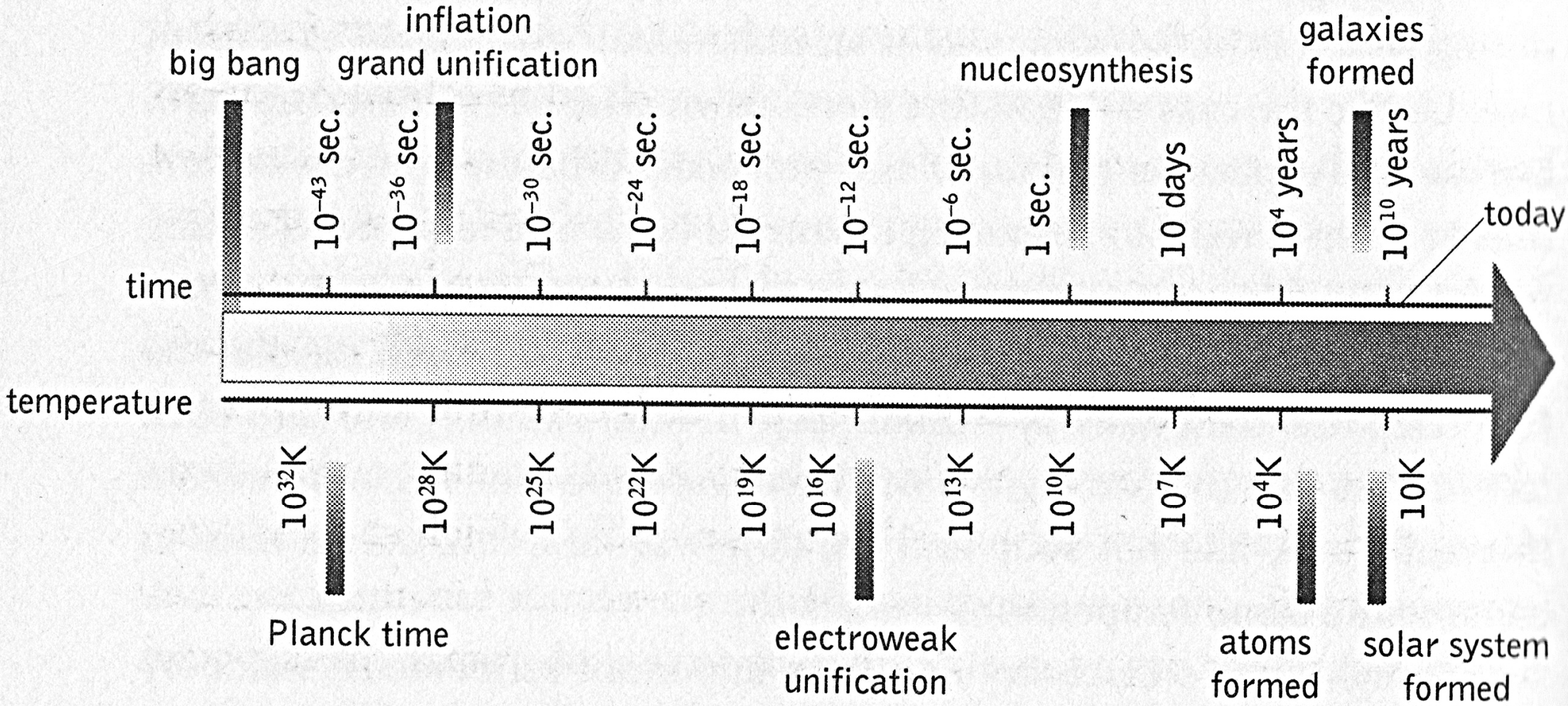

Figure 14.1 A time line denoting a few key moments in the history of the universe.

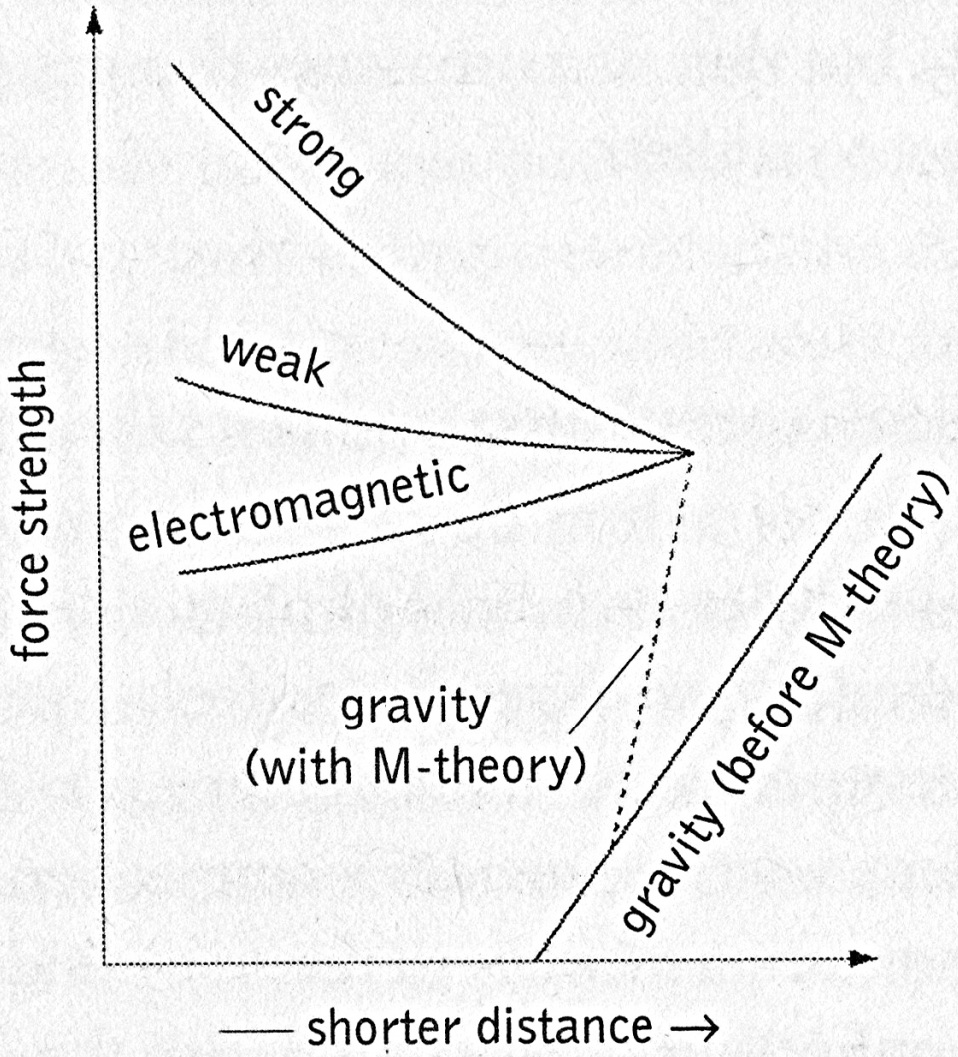

Figure 14.2 Within M-theory, the strengths of all four forces can naturally merge.