GENERAL INTRODUCTION

The Mechanisms of Singularity

In theory, a number of different explanations could account for a singularity. Schematically, I distinguish seven different, not necessarily mutually exclusive kinds. Represented schematically in Figure I.1 (printed on the front endpaper of this book), these different kinds of singularities are, in the order of decreasing probability:

Mechanism 1. Deterministic Necessity. According to this interpretation, things could not have been otherwise, given the physical–chemical conditions that existed. Most physical and chemical phenomena belong to this category. They obey the laws of nature in a strictly reproducible fashion. Only at the subatomic level does quantum mechanics allow for some uncertainty. Life is not affected by events at that level, except, according to a theory proposed by some investigators but far from unanimously accepted, in the brain–mind connection.

Mechanism 2. Selective Bottleneck. This mechanism applies to any situation where different options are subject to an externally imposed selection process that allows only a single one to subsist. The most familiar such situation occurs in Darwinian natural selection, where different organisms compete for available resources within ecosystems and the organism most apt to survive and reproduce under prevailing environmental

Table I.1. *Converting chance to necessity*. A few examples illustrating the number n of opportunities required for an event of probability P to have a 99.9% chance of taking place. Calculations (see text) are based on the following formula (in which P_n is the probability of the event's occurring if n trials are made):

$P_n = 1 - (1 - P)^n$

Game	Probability P_n for $n = 1$	Value of n for $P_n = 99.9\%$
Toss of a coin	1/2	10
Toss of a die	1/6	38
Roulette (one zero)	1/37	252
Lottery (seven digits)	$1/10^7$	69×10^6
Point mutations (replication errors)	$1/(3 \times 10^9)$ per cell division	20×10^9 divisions

conditions ends up predominating. Many other instances of a basically similar process are encountered or can be created, depending on the nature of the competing entities and on that of the selection criteria. Thus, as is done in many bioengineering experiments, replicating molecules subject to mutations may be forced through a selective bottleneck rigged so as to let through only those molecules that exhibit a predetermined catalytic activity, eventually singling out the most efficient among the retained catalysts.

By definition, a selection process of this sort is restricted to the actual variants that are subjected to it. An organism or molecule fitter than the one selected may be possible. But if the required variant is not supplied in the first place, it obviously cannot be selected. When, as is often the case, variants arise by chance, the likelihood that a given variant will be offered for selection depends on the number of opportunities this variant is given to occur, relative to its probability.

This relationship is readily calculated (de Duve, 1995). Let P be the probability of the event; then the probability of its *not* occurring is $1 - P$ in a single trial and $(1 - P)^n$ in n trials. Thus, the probability P_n that the event will actually occur if it is given n opportunities to occur equals $1 - (1 - P)^n$. A few representative values calculated by this equation are shown in Table I.1.

What this calculation is meant to illustrate is that *chance does not exclude inevitability*. Even highly improbable events may be made to happen with near-certainty if enough opportunities are provided for them to happen. As a rough rule of thumb, multiply the reciprocal of the probability of the event by a little less than seven, and you have the number of opportunities needed to give the event a 99.9% likelihood of taking place. As indicated by Table I.1, even a seven-digit lottery number will come out in 999 cases out of 1000 if 69 million drawings are held. This fact is of little interest to buyers of lottery tickets but has deeply meaningful implications for the history of life. It allows for the possibility of *selective optimization* under given circumstances, if the situation is such that the range of possible variants can be explored exhaustively. We shall encounter a number of instances where this may indeed have happened.

Mechanism 3. Restrictive Bottleneck. This term refers to a situation in which internal constraints, imposed, for example, by the structures of genomes or by existing body plans, funnel evolution through an increasingly narrow pathway that ends in a singularity. Each step of an evolutionary process restricts the options open to the following step or, otherwise put, increases the degree of *commitment* in a given direction. The difference between this kind of bottleneck and the preceding one is that it is shaped by internal rather than external factors. These, of course, are theoretical extremes. In reality, the two kinds of factors are often involved simultaneously to varying degrees.

Mechanism 4. Pseudo-Bottleneck. This term is used to describe the case in which a single branch emerges, not through some sort of selective or restrictive process, but as a mere consequence of the progressive attrition of all the others. In this form of singularity, historical contingency plays a much more important role than it does in bottlenecks, whether externally or internally imposed. The two forms may, however, not be easily distinguishable from one another. There probably exists a continuous gradation between the chance survival of a given branch and its enforced emergence by a combination of selective and restrictive factors.

Mechanism 5. Frozen Accident. In this case, the singularity is due to pure chance deciding between two or more possibilities that happen to be such that a course can no longer be changed once it has been set. Imagine arriving at a road fork and flipping a coin to decide whether to turn left or right. Or make it a roundabout with six outlets and base your decision on the throw of a die. The main point is that all options are open until you have left it to chance to decide for you. After that, you are irrevocably committed; all other options are henceforth ruled out. Chance decides, but, once the decided direction has been taken, there is no going back and trying another one.

Mechanism 6. Fantastic Luck. In this mechanism, chance plays an even greater role than in the preceding one, in that the singularity is actually attributed to a highly improbable event, most unlikely to be repeated anywhere, any time. There is nothing untoward about such a possibility: Single events of extremely low probability take place all the time in nature and should not excite any wonder. An example I have cited before comes from the game of bridge. Each distribution of the 52 cards among the four players is one out of a total of 5×10^{28} possible distributions. This figure is truly immense. Even if the entire present population of the world had been playing bridge nonstop since the time of the Big Bang, only a small fraction of this number of distributions would have been dealt. Thus, the probability of any given card distribution is infinitesimally small. Yet no bridge player has ever exclaimed at being witness to a near-miracle. What would be a miracle, however, or, rather, unmistakable evidence of trickery, is if the same distribution should be dealt again, even once. The probability of such an occurrence is one in 2.5×10^{57} ($5 \times 10^{28} \times 5 \times 10^{28}$), that is, for all practical purposes, zero. Thus, in the realm of very low probabilities, chance and singularity go together, an argument often invoked in support of uniqueness in evolution.

Mechanism 7. Intelligent Design. This mechanism postulates the occurrence of evolutionary steps that could not possibly have taken place without the intervention of some kind of supernatural guiding entity. Strictly speaking, such a possibility hardly deserves mention in a scientific context, as it can come into account only after all natural explanations have been ruled out, and, obviously, they never can be. Intelligent design has, however, been advocated in recent years by a small minority of highly vocal scientists, who claim to have demonstrated that certain evolutionary steps cannot be explained in strictly natural terms. Loudly acclaimed in many fundamentalist and even more liberal religious circles, these arguments have failed to convince a significant number of scientists.

1 Building Blocks

All living organisms, from microbes to humans, are made of the same basic building blocks, consisting mainly of sugars, amino acids, fatty acids, and nitrogenous bases, altogether little more than fifty distinct, small chemical species, of molecular weights rarely exceeding 200. What largely differentiates organisms chemically is the manner in which these building blocks join into larger assemblages, mostly polysaccharides, proteins, lipids, and nucleic acids. A number of additional compounds peculiar to certain sets of organisms exist – chlorophyll in plants is an example – but these are most likely products of later evolution. In its earliest forms, life probably was made of little more than the universal building blocks found in all living organisms today.

Prebiotic Chemistry

This remarkable singularity goes back to the very beginnings of life, conveying a central message whose meaning did not catch the attention of biologists until 1953, when Stanley Miller observed the spontaneous formation of a number of amino acids and other typical biological constituents in a laboratory situation he and his mentor, the celebrated chemist Harold Urey, believed to be representative of the conditions that prevailed on the primitive Earth at the time life first appeared (Miller, 1953). Even though serious doubts have since been voiced about its underlying assumption, Miller's achievement remains a major landmark in the history of biology. It opened the new field of prebiotic chemistry and sparked a large number of interesting experiments.

Perhaps even more importantly, Miller's findings highlighted the possibility that the building blocks of life could have been the products of natural chemical phenomena, mandated by local physical–chemical conditions. This possibility should not have come as a surprise, for it was consistent with the view, already solidly established at that time, that living processes take place naturally, without the intervention of some special "vital force." But, with rare exceptions, biochemists in those days hardly bothered with the origin of life, which they relegated to the realm of the unknowable, not worth experimenting on or even thinking about.

Cosmic Chemistry

Surprisingly, nothing like the sensation created by Miller's experiments greeted the later, much more startling discoveries showing the presence of a variety of organic molecules in extraterrestrial sites never visited by any living organism. Detected by radioastronomical spectroscopy, by spacecraft-borne instruments sent to passing comets and other parts of the solar system, and by detailed analyses of meteorites that have fallen on Earth, these organic substances now number in the hundreds, creating a host of fascinating problems for the scientists who attempt to explain their formation (for two comprehensive reviews, see Botta and Bada, 2002; Ehrenfreund et al., 2002).

From the ultra-rarefied interstellar spaces, where hours may go by before an atom encounters another atom, to the tiny dust particles that float in space, to the material that makes up protoplanetary disks around new-forming stars, to the comets and asteroids that condense from this material, to the surfaces of planets and their moons orbiting around a star, there exists a gradation of complexity, ranging from small assemblages of a few atoms – such as the hydroxyl, methyl, and methylene radicals, water, methane, carbon monoxide, methanol, formaldehyde, cyanide, cyanate, isocyanate, and thiocyanate, to mention only a few – to a wide variety of larger molecules, including, in addition to a considerable amount of "junk" (as judged by a biochemist), amino acids, sugars, purines, pyrimidines, fatty acids, and other typical biological constituents, some engaged in more complex associations.

These observations have now reached the stage of laboratory experimentation. In France, the group of Guy Ourisson has obtained a wide variety of biological building blocks by high-energy bombardment of graphite targets with molecular beams of the desired atoms, simulating plausible interstellar events (Devienne et al., 1998, 2002). In another approach, two groups, one American (Bernstein et al., 2002) and the other European (Munoz Caro et al., 2002), have found that a number of amino acids arise spontaneously in simulated interstellar ice analogues containing water, methanol, and ammonia as main components, with, in addition, hydrogen cyanide in one case (Bernstein et al., 2002), and carbon monoxide and carbon dioxide in the other (Munoz Caro et al., 2002), exposed to UV irradiation at very low temperature and under very high vacuum.

There has been much discussion concerning the possible destruction of extraterrestrial organic molecules upon entry into the atmosphere, and later impact, of their carrying body, whether comet or meteorite (Botta and Bada, 2002; Ehrenfreund et al., 2002). It is generally believed that, even though such destruction may have been important, a sufficient proportion of the incoming material would have been spared, providing abundant building blocks for the origin of life on our planet. A partial contribution by terrestrial chemistry is, however, not excluded.

The general conclusion that emerges from all these findings is that *the building blocks of life form naturally* in our galaxy and, most likely, also elsewhere in the cosmos. The chemical seeds of life are universal. The first singularity that we detect is thus the consequence of the basic laws that govern the transformations of matter in the universe; it is clearly of *deterministic* origin (mechanism 1).

This conclusion presupposes that the products of cosmic chemistry (and of terrestrial prebiotic chemistry) did indeed serve to initiate the development of life on Earth. The remarkable similarities between these products and the building blocks of life would seem strongly to support this assumption. Nevertheless, as will be mentioned in Chapter 5, a theory vigorously advocated by some investigators holds that life started from scratch, so to speak, that is, from carbon dioxide and other simple materials developing into increasingly complex compounds by pathways that prefigured in some respects the reactions of present-day metabolism. As we shall see, these are very interesting proposals, which include a number of valuable aspects. But the assumption that the products of prebiotic chemistry may have had nothing to do with the initiation of life on Earth – and, therefore, that their similarities with the building blocks of life are a meaningless coincidence – does seem difficult to accept.

Note, however, that not all the products of cosmic chemistry are used for the construction of life. For example, α-aminobutyric acid and α-aminoisobutyric acid, which are present in fair abundance in the Murchison meteorite and in Miller's experimental flasks, are not found in living organisms. On the other hand, ubiquitous compounds, such as the amino acids tryptophan and histidine, have not so far been identified among products of cosmic chemistry and may never be, having appeared later in the development of life. Thus, selection and innovation are two key notions that have to be added to determinism at an early stage in our appreciation of life's building blocks. A remarkable singularity, in this connection, is the fact that life often uses only one of the two possible isomers whenever molecules exhibiting the phenomenon of chirality are employed. Known as homochirality (Greek for "same-handedness"), this trait, which is considered by many as one of the most mysterious properties of life, deserves to be examined in some detail.

2 Homochirality

It has been known since the days of Pasteur (famous, notably, for the separation of two forms of tartaric acid) that molecules containing an asymmetric carbon atom, that is, a carbon atom bearing four different groups, can exist in two forms that are to each other like one hand to the other (*cheir* means hand in Greek) or like an object to its image in a mirror. When aqueous solutions of such molecules are traversed by a beam of polarized light, the polarization plane of the light is rotated by a certain angle. The value of this angle, adjusted to the concentration of the solution and to the thickness of the liquid layer traversed, is known as the specific rotatory power, or optical activity, of the substance; it is the same in absolute value, but of opposite sign, for the two forms. By definition, the optical activity is said to be positive when the polarization plane of the light is rotated to the right, and negative in the opposite case. The two forms, known as enantiomers (*enantios* means opposite in Greek), are designated *d*, for dextrorotatory (*dexter* means right in Latin), and *l*, for levorotatory (*laevus* means left in Latin).

Following a proposal made at the beginning of the last century by the German chemist Emil Fischer, the nomenclature based on optical activity was replaced by one based on structure. Stereoisomers (*stereos* means solid in Greek) replaced optical isomers. Fischer based his classification on the two forms of glyceraldehyde, designating by D the *d* form of this