Part I

Historic, philosophic and metaphysical foundations

Foreword to Part I

> "It is my contention that mathematics took a disastrous wrong turn some time in the sixth century B.C. ... The impact... has entangled itself into our most basic notions of what science is. ... From this common concern with measurement, concepts pertaining to mathematics have seeped into epistemology, becoming so basic a part of the adjective scientific that most people are quite unaware they are even there." (Rosen, [3])

From a resonant perspective, Part I is a discourse that considers how the prevailing views in modern physics came to be, and what this revealed and contributed to the development of *Process Physics*. This part is organized as follows:

- **Chapter 1** addresses paradigms in physics in the ancient and pre-modern eras.
- **Chapter 2** deals with the modern era, including recent ideas on discrete physics, stochasticity, and concepts of pregeometric approaches to physics.
- **Chapter 3** responds to the insights gained from the previous chapters and reports on relevant aspects from complexity science.
- **Chapter 4** considers the limitations of logic revealed first by Gödel.
- **Chapter 5** states the philosophical underpinning for *Process Physics* and provides a prescription for the new theory constructed in Part II.

Chapter 1

Paradigms in physics I – the ancient and pre-modern eras

Do not seek to follow in the footsteps of the
men of old; seek what they sought.

– Basho

1.1 Introduction

Now, as always, the pursuit of science is a journey of discovery, yet with ill-defined destination but for the intuitive, perhaps wishful notion that a destination exists. It is a journey marked by waypoints, those hiatal episodes of crisis and emergence of scientific theories that Kuhn labelled *paradigm shift* [4] (a term now so horribly over-employed that a change in preference of breakfast cereal might qualify).

This chapter provides a sketch of the larger paradigms in physics from ancient days until the start of the modern era to underscore the prevailing climate of physics as it entered the 20th Century.

1.2 Ancient models

Modern science, particularly physics, dates from the 16th and 17th Centuries, with the names Galileo and Newton usually associated with its origin. Yet a study of Ancient Greek science reveals a strong connection with its contemporary counterpart. Although Galileo confronted Aristotelian dynamics, the pioneers of modern science revived the Greek legacy in a renaissance that embraced systematic experimentation in contrast to the blind acceptance of medieval teachings that had increasingly separated science from nature and phenomenology. Ancient Greek science was itself heir to knowledge from yet earlier times – principally the wealth of two thousand years of Babylonian and Egyptian science with their empirical successes in astronomy and mathematics. But these civilizations, though they developed impressive engineering technologies, failed to unify their knowledge and no single uniform body of scientific thought emerged. The attempt to systematically rationalize phenomena and explain them in terms of general hypotheses in a scientific approach to the study of nature was the invention of early Greek philosophy.

So modern physics owes much to the rich legacy of the Ancient Greeks of Asia Minor. Aristotle (384-322 BCE) has it that systematic scientific reasoning dawned at the start of the 6th Century BCE at Miletus on the west coast of Asia Minor. In particular, the pre-socratics (Socrates, 470-399 BCE) of Ionia, working in the 6th and 5th Centuries BCE, were the first physicists. They attempted to explain physical existence and the natural phenomena they observed by the application of reason and logic rather than the theocentric and anthropomorphic mythologies that preceded them. The Milesians - principally, Thales (624-546 BCE), Anaximander (610-545 BCE), and Anaximenes (died c.525 BCE) – saw order in physical processes, which seemed to be governed by natural laws, and each sought to identify some single substance as the 'stuff' from which all things are formed.

Thales is credited with the invention of a key scientific principle – namely that a maximum of phenomena should be explained by a minimum of hypotheses. The Platonic ideal is to derive the sum total of phenomenological observation from a single root.[1]

Anaximenes supported the concept of 'conservation laws' that are now so vital to science that it is inconceivable that new science could ever develop in a direction that would not allow the formulation of such laws. He proposed two guiding principles that remain relevant to modern science:

- priority of observation (do not postulate that which cannot be observed); and
- ontological simplicity (the principle of economy of hypothesis)

The peak of the Milesian School was achieved in the realization of the principle that quality can be reduced to quantity – this is the essence of science, proceeding from the time of Anaximenes to the present where it is embodied in the mathematization that extracts all phenomenological qualities of observation and enumerates them in the abstract calculations of the mathematician and physicist.

The discovery of Pythagoras' Theorem was profoundly disturbing since it led to the inescapable consequence of the irrationality of the square root of two ($\sqrt{2}$) and so

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[1] This process of simplification is seen in the modern era in Newton's demonstration that his law of gravitation included Kepler's laws; the proof that light, radio waves and X-rays are all electromagnetic radiation; the inclusion of heat in the concept of energy; the generalization of Newtonian physics by Einstein's relativity (in particular the embodiment of time as a geometrical construct inherently linked with spatial geometry and gravitation); and the unification of the electromagnetic and weak nuclear forces being but a few examples.

to irrational numbers generally, with the realization that some distances in the (Euclidean) plane can be specified completely only by an infinite amount of information. This is the problem of the continuum and it so challenged the rational perfection of the Pythagorean world view that the discovery was long kept a closely guarded secret.

The Milesians and Pythagoreans viewed the world as a collection of stable 'things' subject to orderly laws of behaviour and sought to explain change and physical processes. In contrast, to Heraclitus (540-480 BCE) it was not change or process that required explanation but the *appearance of stability* and the philosophy of *becoming* rather than the continuity of past-present-future. Challenging the common sense view of reality, he postulated 'cosmic fire' as the essence of the Universe, with the world always in a state of flux with balancing opposing changes producing the appearance of stability and the apparent existence of 'things' – not only is everything changing but everything is one. In many respects Heraclitus' insight anticipated the concepts of quantum fluctuations and decoherence – but modern physics omits his view of time.

Parmenides (515-430 BCE) and his student, Zeno (490-440 BCE), lived in Elea, Southern Italy. The Eleatic School of Thought produced the philosophy of being (*cf* Heraclitus) whereby all existence is one - uncreated, unchangeable, complete, and timeless – and perceptions of change are illusionary.

Empedocles of Akragas (490-435 BCE), much like Heraclitus, saw the existence of the cosmos as a kind of dynamic equilibrium between attractive and repulsive non-material forces that exist simultaneously. By extension his arguments yield the principle that two bodies cannot be in the same place, which holds good in one form or another for all circumstances and in all dimensions.[2]

Anaxagoras (500-428 BCE) had been an adherent of Anaximines. If the world was to be explained at all, an original plurality must be admitted. He therefore substituted for the primary 'air' a state of the world in which 'all things were together, infinite both in quantity and in smallness', meaning that the original mass was infinitely divisible but, however far division was carried, every part of it would still contain all 'things', and would in that respect be just like the whole.

The Atomists devised a model of stable, indivisible atoms moving according to orderly and rational laws within a continuous container (the void), which was given an absolute, primary, and material existence, identical to the notion of absolute space adopted by Newton some two thousand years later. Believing that a designing intelligence was unnecessary, they also argued that given enough time and space and matter, organization must ultimately be inevitable (although there would be no preferred tendency for this to occur)[5] – a prophetic idea that has resurfaced in the modern sciences of complexity and synergetics.

Perhaps the greatest achievement of the Atomists was the introduction into scientific reasoning of the method of inference that remains so important in explaining phenomena and interpreting experiments.

From the beginning of the 3rd Century BCE emerged the original concept of the Stoics – the continuum of space and matter with continuity in the propagation and sequencing of phenomena. The Stoic continuum model opposed and rivalled the atomic model of Epicurean philosophy and also was fundamentally different from

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[2] The Pauli Exclusion Principle would seem to be the most fundamental expression of this principle – later it will be postulated that the Pauli principle precedes geometry and hence the space-time continuum.

Aristotle's passive continuum. For the Stoics, the continuum was an active quality seen as a governing principle in all phenomenology. They called the active substance of the cosmos '*pneuma*' (spirit, breath) and in later Stoic teaching it became a mixture of fire and air, where the aspect of fire added a dynamic life force so that one of the basic properties of the pneuma was its rôle in uniting the whole of nature which it permeates.

The Stoics used the analogy of water waves saying that the air is a continuum containing no empty spaces which, when struck by impulse, rises in circular waves propagating out to infinity. This wave expansion within a continuous medium was taken to be connected to the tensional quality of the pneuma and was considered to be the mechanism responsible for the propagation of light and sound. It seems certain that the Stoics observed standing waves as a special form of vibration symbolising the coexistence of motion and rest in the same system. They called this 'tensional motion' (*toniké kinesis*) and the concept was extended to describe the propagation of 'state' in its broadest context. It is a striking observation that the definition of the structure of matter, and the forms it may take, by the vibrations of the pneuma is remarkably similar in scientific conception to the wave mechanics of contemporary quantum theory.

A significant problem for the early Greek continuum model was that of 'mixture': the pneuma was certainly material in substance (being a composite of elemental fire and air) so how could it permeate other substances? The mixing problem extended to the classification of materials comprising more than one component. The debate over the nature of mixing reveals that the problem of continuity is intimately tied to problems of infinite divisibility and *discreteness*. Zeno of Elea (c.460 BCE) devised four paradoxes that illustrate the fundamental dilemma: one paradox posits the seeming non-existence of motion, since a moving body has, *ad infinitum*, to reach the halfway point before it attains its goal; another supposes that an arrow in flight is at rest, which arises from the assumption that time is composed of points of the present. The solution of Zeno's paradoxes could be achieved in a *continuum* only by the application of mathematics that would not be developed for another thousand years – the infinitesimal calculus, attributed by most writers to Newton, with its definitions of limit and convergence that allow the transition from finite interval to the limit that reduces to zero the distance between intermediate points and the end of the line.

It is illuminating to consider Aristotle's analysis of these problems. He observed that distance and time (and everything continuous) are called 'infinite' in two senses: either as capable of division, or as regards to the distance between extrema. In this, Aristotle treats distance and time[3] in a similar manner, intuitively linking time and distance together by the parameter of velocity to solve the problem of motion. In so doing, Zeno's paradoxes of motion are seen to be equivalent - each paradox relies essentially on the restriction of the respective debates to the distance or time domains in isolation whereas, in speaking of velocity today, both domains are invoked in addressing the problem so that *two* points in space and *two* points in time are required - thus the kinetic concept applied to a given point-like object makes sense only in terms of interval. Modern infinitesimal calculus makes it possible to define to zero the convergence of the interval between the space and time points by which the kinetic behaviour of the point-like object is defined. The calculus is so successful

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[3] Formulating his general theory of dynamics, Aristotle said of time: "... we wish to know what time is – what exactly it has to do with movement." He concludes that "Time is just this – number of motion in respect of 'before' and 'after'... Time then is a kind of number" (*"Physics"* 219a,b), a view of time that persists into the modern era.

in resolving this fundamental problem that the continuum model now is accepted generally almost without question. But the reduction of the 'here and now' to a dimensionless mathematical point is no less a construct than Zeno's paradoxes, which may be resolved by another hypothesis advanced by Xenocrates (a pupil of Plato in the latter part of the 4^{th} Century BCE) who introduced an atomic (minimum) length together with 'atoms of time', both inaccessible to further division. Today, one might call Xenocrates' invention a cosmological lattice model or discrete theory – forms that receive increasing attention from high-energy physics where it is shown that the continuum fails at sufficiently high energy (equivalently, short distances – the Planck scale, say). The Stoics vigorously rejected Xenocretes discretized universe in favour of a dynamic continuum capable of infinite division whose dynamic character is embodied in the Stoic definition from Plutarch (c.46-120 CE): "There is no extreme body in nature, neither first nor last, with which the size of a body comes to an end. But every given body contains something beyond itself and the substratum is inserted infinitely and without end."[4] It is particularly notable that the Stoics should have included the principle of convergence (know only to a few privileged mathematicians of the time) in their doctrine, expressing it with greater generality. When their originality in defining the infinite set is joined with the intuitive appeal of the continuum and the formalism and efficacy of Newton's calculus, it is little wonder that the space-time container model figures so prominently in modern physics.

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[4] Plutarch: *"de Comm. not."* 1078E

1.3 Physics in the Middle Ages

Although the Roman Empire preserved much of the scientific legacy of Ancient Greece, the dark ages following the collapse of the Western Empire led to a major decline in intellectual pursuits but Greek texts translated into Arabic were safeguarded by Syriac science for a thousand years. In particular, the Arab thinker Averoes (Ibn Rud, 1126-1198 CE) was to exert considerable influence as The Commentator on Aristotle, surrounding him with an aura of reverence that accompanied the transmission of Greek philosophy to the western world. In Europe, the ancient teachings were entrusted to the secular tradition of scientific study by monks prepared in a method of instruction that was maintained throughout the Middle Ages. Notably, two great intellectual factors survived to fuel the revival of physics: the first, Aristotelian philosophy and science, came to be most influential in the 13th Century while the second, Greek mathematics, had to wait another three hundred years.

The 13th Century can be characterized by the radical renewal of interest in pure thought. It is probable that the metaphysical and philosophical content of Aristotelian teachings ensured their influence on the emerging western culture and Aristotle's influence in philosophical and scientific matters became as great as that of the Church leaders in theological issues. Unity of religious and intellectual thought was achieved to an unprecedented degree but eventually the revival of scientific pursuits led to discoveries of errors in Aristotle's arguments.

In the period between the revival of Aristotelian science and philosophy and the 16th Century development of Galilean mechanics, physics was enriched in several ways and the 14th Century doctrine of the *Calculationes* (a branch of Scholasticism particularly practiced at Merton College, Oxford) arose in an attempt to apply arithmetical and algebraic arguments to general scientific and philosophical problems. The language and thus science was enriched by the introduction to the *calculationes*, by French Schoolman, Oresme (died 1382), of the graphical representation of variations in intensity of a quality, a method still generally in use (the *Mertonian Rule*, equating graphical areas of acceleration to areas of constant velocity, is a prime example). The introduction of such graphical representation and the general expedience of *geometrical* illustration had outstanding practical significance for mechanics when the instantaneous velocity $\frac{ds}{dt}$ gained the geometrical interpretation of the slope of the tangent to the distance and time curve. The ease of visualizing the tangent and its direction provided an intuitive insight into kinematics that was unparalleled by analytical methods of the day.

1.4 The beginnings of classical physics

Kepler's discovery at the end of the 16th Century of his first two laws of planetary motion marked a turning point in the methods of scientific inquiry that is significant in the present context. Dijksterhuis [6] writes of this:

> The principle features of this (Kepler's) method are:
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> 1. Rejection of all arguments which are solely based on tradition and authority.
> 2. Independence of scientific inquiry of all philosophical and theological tenets.
> 3. Constant application of the mathematical mode of thought in the

formulation and elaboration of hypotheses.

4. Rigorous verification of the results deduced from the latter by an empiricism raised to the highest degree of accuracy.

Increasingly, Aristotelian thought in matters of physics was distilled from the metaphysical components of his teachings, tested empirically, and found wanting. The direct influence of Aristotelian theory diminished but the continuum model was firmly embedded in the roots of developing classical science, with no indication of inquiry akin to Xenocrates' hypothesis of discretised space and time.

The appeal of mathematics turned Galileo Galilei (1564-1642) toward the Platonic school, which regarded mathematics as essential to scientific pursuits, and the influence of Archimedes rather than the qualitative doctrines of the Aristotelian school. A passage from the *Dialogo* (1632) is illustrative: Simplicio (representing Aristotelian thinking) asks Salviati (Galileo's alter-ego) to indicate whether the motion of the earth is to be ascribed to an internal or external principle. Salviati says he is prepared to answer but first Simplicio must state by what cause heavy bodies are conducted downwards. "That is quite familiar, anyone knows that it is gravity." replies Simplicio and Salviati responds "You are mistaken, Signor Simplicio, you ought to have said: anyone knows it is **called** gravity."

Here Galileo reveals a major weakness in Aristotelian philosophy - that by giving a name to an essentially unknown identity, one's understanding is somehow extended. It is a simple yet remarkably profound insight; when Chrysippus [7] defined time as "the interval of movement with reference to which the measure of speed or slowness is always reckoned" he gave a name to the 'interval of movement' yet revealed nothing whatsoever of the origin of the time phenomenon. Contemporary physics is no less inclined to substitute nomenclature for knowledge – true, it is necessary to give names in order to form concepts and the appropriate choice of name may facilitate clear thinking; on the other hand if the name, a mere device, is taken to *be* the concept, the possibility of understanding is strictly limited[5]. With this recognition, Galileo confined himself to the mathematical definition of observations from which a more profound insight into causes then might be achieved. In this he firmly established the scientific method of the experimental physicist.

Galileo's contributions to classical mechanics are legendary. Dijksterhuis observes that the Galilean principle of inertia - along with a new way of regarding the effect of a constant force acting upon a particle of matter – "probably constitutes the most important element of all in the transition from ancient and mediaeval to classical science... Moreover, the law of inertia is not just a detail but one of the (underlying) foundations" [6]. Galileo's exposition on inertia reveals the natural progression to the Galilean principle of relativity. He staunchly refuted arguments against the Copernican doctrine of rotation of the earth, all of which were due to a lack of understanding of inertia. Consequently one of the general principles explained by Galileo is the principle of superposition of motions – he showed that various motions take place independently but an observer sees only the resultant.

The second revolutionary aspect of Galileo's work was in his treatment of time as a mathematical quantity and graphs showing time as line segments accompany proofs. In his theorems time was calculated just like length or any other linear geometric quantity so that the metric property of the line was used to quantify time intervals:

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[5] Richard Feynman said, "You can know the name of a bird in all the languages of the world, but when you're finished, you'll know absolutely nothing whatever about the bird... So let's look at the bird and see what it's doing that's what counts. I learned very early the difference between knowing the name of something and knowing something." [8]

as shown in Figure 1.1, with a line segment to represent the time variable t, time-separated events a, b are assigned positions t_a, t_b on that line; the *distance* interval $d(a,b)$ between t_a and t_b then is associated with the *time* interval, or duration, $t(a,b)$. The efficacy of this device became apparent when Galileo demonstrated that such quantification of time intervals was useful in kinematic observations of experimental phenomena, and that regular oscillations of a pendulum, for example, could be used to measure $t(a,b)$.

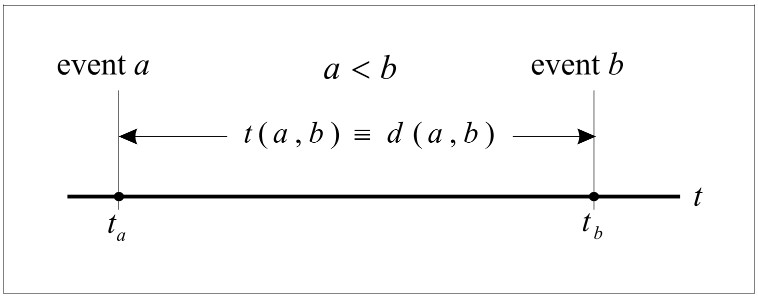

Figure 1.1: Galilean geometrical time representation where temporal ordering of events (here, event a precedes event b, denoted $a < b$) is represented by the ordering of points on a line segment.

What was not appreciated then (and now, to possibly as great an extent) was the exclusion of the 'present moment' – by employing this method, the observer stands outside of, and apart from, time. When considered at all, the present moment is imagined by the meta-rule of a point in motion along the line. Galileo's linearization of time as a continuous geometrical entity was a superb abstraction that led the way to the complete mathematization of physics and totally stifled serious conjecture as to the actual nature of the time phenomenon. His work provided the foundation of theoretical mechanics but once the axioms had been established the topic turned from the study of phenomena in the domain of physical science to the idealization of mathematics where it developed autonomously, cocooned from physical reality.

Dijksterhuis cautions that this happened in the 17th Century and it is still happening today [6].

René Descartes (1596-1650) vigorously pursued the identification of mathematics with natural science. By introducing the still new algebraic methods into geometry he brought about a fundamental reform of mathematics and became the author of analytical geometry. It is a typically Cartesian construct that nature is ultimately material and defined by geometrical extension – the geometric characterization of bodies and their kinematic behaviour. In as much as physics is the science of moving forms of and in space it follows (in the Cartesian view) that it can be deduced axiomatically *a priori*. Particularly effective in light of the dominant rôle played by mechanics in the physics of the day, Descartes' influence served to ensure that the geometric continuum model of the Ancients became enshrined in physics, yet there was no more justification to support this *philosophy* than had existed in Aristotle's day. The ideas of Galileo and Descartes are indicative of the mechanistic character developed by 17th Century natural philosophy. Whether all natural phenomena could be explained mechanistically was no longer considered a problem but the question of how to achieve such explanations assumed great importance.

1.5 Classical physics

Classical science took on an independent existence, separating from philosophy and theology with the work of Isaac Newton (1642-1727). He can be seen both as a staring point and an end – the various lines of development that preceded him converged and from this nexus came the foundations of classical physics and the beginning of the modern scientific era, which saw Newton's æther theory, together with Aristotle's view of time, applied in the dynamic sense of the Stoic pneuma.

Newton systematically axiomatised the diverse bodies of knowledge that preceded him, establishing connections where none had existed before. But this axiomatisation was not undertaken in the sense understood by modern mathematicians, rather it took the form of a selection of statements that were considered, if not self-evident, at least plausible. These then provided a starting point, requiring no further explanation. Euclid's *Elements* apparently served as a model for Newton's *Philosophiae Naturalis Principia Mathematica* [9]. He assumed and believed in the existence of absolute and infinite space, mathematically identified with the infinite Euclidean space $\mathbf{R}^3$, providing room (position) for all bodies and in which the absolute motion of a body takes place so that the inertial motion of a point is absolutely uniform and rectilinear. This, however, was to give rise to paradoxes such as the darkness of the night sky (Olbers' Paradox, originally raised by Kepler) and to problems of boundary conditions.

In contrast, Leibniz (1646-1716), in many respects Newton's great rival, proposed another sort of space. It has no *a priori* status but arises out of the relationship of objects. "I have more than once stated that I hold space to be something merely relative, as time is"[10]. Space then becomes a secondary thing – it is not an arena in which the world plays out its drama but rather is generated out of *process* [11].

Newton assumed and believed, also, in absolute time. From the *Principia*:

> Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration... Absolute time, in astronomy, is distinguished from relative, by the equation or correction of the vulgar time... The duration

> or perseverance of the existence of things remains the same, whether the motions are swift or slow, or none at all: and therefore it ought to be distinguished from what are only sensible measures thereof; and out of which we deduce it, by means of the astronomical equation. The necessity of which equation, for determining the times of a phenomenon, is evinced as well from the experiments of the pendulum clock, as by eclipses of the satellites of Jupiter.

This idea of absolute time is indistinguishable from the Galilean geometrical concept: if a and b are two events, each of negligible duration, then one may assert that a is earlier than b, **or** that b is earlier than a, **or** that a and b occur simultaneously. The truth of any such assertion, say that "a is earlier than b", is then an absolute truth and does not depend upon anything else.

Leibniz, on the other hand, conceived time as merely the successive order of things, with instants defined by the successive relative configurations of the Universe [10].

The distinction between *absolute* time, which flows without reference to anything external, and *relative*, *apparent*, or *common* time, which is a measure of duration made by comparison of motions, indicates that Newton clearly distinguished between the concept of absolute time as an ideal and the practicality of measuring its passing, that *time* and *clock* are not synonymous. That he held these beliefs axiomatically is evident from the early pages of the *Principia*, where he wrote, "I do not define time, space, place and motion, as being well known to all. Only I must observe, that the common people conceive those quantities under no other notions but from the relation they bear to sensible objects." Although he formulated the principle of classical relativity in *Corollary V* of the *Axioms*, showing the existence of an infinite number of inertial reference frames, he did not consider them equivalent to absolute rest frames.

Newton adopted Galileo's model of time and developed it much further when he showed its utility in modelling his equations of motion, employing the equivalence of algebra and geometry demonstrated by Descartes. For example,

$$m\frac{d^2x(t)}{dt^2} = F(t) \tag{1.5.1}$$

where t represents the geometrical abstraction of time carried over into algebraic form in the use of the *calculus* developed independently by Newton and Leibniz. The great success of Newton's methods and the paradigm of reality evinced by equation 1.5.1 was utterly seductive in subsequently leading most physicists to accept, generally without question except as a philosophical curiosity, the concept of time as nothing more than geometry (just as space was taken to be a mere container, of no great interest but as an arena in which events are played out).

The first chapters of the *Principia* refer to the general operation of a force and Newton unmistakably ascribed to the æther the cohesive function – he wrote of "a certain subtle spirit which pervades and lies hid in all gross bodies; by the force and action of which spirit the particles of bodies attract one another at near distances, and cohere, if contiguous". He attributed the æther with properties other than that of cohesion: "And electric bodies operate to greater distances as well repelling as attracting... ; and light is emitted, reflected, refracted, inflected and heats bodies". The results were extended to arrive at the general principle of gravitation but the ontology put forward in the *Principia* has nothing to mediate the gravitational force. Newton recognized the problem, his assertion clearly expressed in a letter to Richard Bentley in 1691 [12]: "That one body can act upon another at a distance through the vacuum without the mediation of anything else… is to me so great an absurdity that I believe no man, who has in philosophical matters a competent faculty of thinking, can ever fall into it." He attempted to use the æther to explain the gravitational force and proposed variations to the rarity and density of the æther (according to whether it is within matter or outside it) to explain the universal and mutual attraction of substances. The theory seemed contrary to the new mechanistic view of nature since it implied 'action at a distance' – mechanics demanded that every motion must result from the direct contact of material bodies – and Newton was criticized by his contemporaries (notably, Huygens and Leibniz) for leading science back to metaphysics. His answer was to assert that the centre of a force was a mere mathematical device devoid of physical meaning. In the *Scholium Generale* (IV: 314) he wrote: "… I have not yet been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses [*hypothesis non fingo*]… it is enough that gravity does really exist".

Newton's 'universal' phenomenological inverse-square law of gravity,

$$F = \frac{Gm_1m_2}{r^2}, \tag{1.5.2}$$

where G is Newton's gravitational constant, was based on observations of planetary motion in the solar system, abstracted in Kepler's empirical laws, and describes the gravitational force between two masses. This in turn now explains Kepler's laws – for example, that the square of a planet's orbital velocity is inversely proportional to the radius of its orbit (for circular orbits) i.e. $v^2(r) \propto 1/r$ (the most famous of Kepler's laws), follows immediately when equation 1.5.2 is identified with Newton's Second Law (equation 1.5.1) expressed in the form for circular motion, $F = mv^2/r$. The gravitational force was taken to act instantaneously, whereas Newton wrote in the

Principia of light, “For it is now certain from the phenomena of Jupiter’s satellites, confirmed by the observations of different astronomers, that light is propagated in succession and requires about seven or eight minutes to travel from the sun to the earth.”

Originally established for weak gravity over the scale of the solar system, Newton’s Law of Gravity appeared universal by virtue both of its $1/r$ dependence on distance and its coupling strength: central to the law is the gravitational potential $V(r) = -MG/r$, which displays three key characteristics:

- the potential falls off as $1/r$ at large distances
- the potential is an extensive function that depends on the amount of matter in the gravitational source
- gravity is universally coupled through the fundamental constant, G

The gravitational constant, G, is the only ‘universal’ constant in Newtonian physics but in the standard theory it cannot be measured independently because it is always tied to the product MG, so the canonical value amounts to the choice of units for measuring mass, and G may not actually be fundamental [13]. The second aspect of universality is in the $1/r$ dependence for the gravitational potential yet there is scope, at least, to question whether the Newtonian potential is appropriate on all distance scales [13]. The claim to universality thus seems open to challenge on this aspect alone. Indeed, since Newtonian gravity is the principal foundation stone of the standard theory, one might legitimately begin to question whether the standard theory should continue to be regarded as the correct theory.

Although the rigorous mechanism of the 17th Century had reached its peak before him, Newton, clearly, must be regarded as the founder of classical physics and the features of Newtonian science – absolute time and space, local ontology, and fixed laws of motion – provide a description of the Universe called the *mechanical world-view*, according to which the Universe consists only of real (objective) particles moving through absolute space in the course of absolute time in a completely deterministic manner governed by God-given immutable laws. In this picture, the future has no existence or influence in the present and hence cannot enter into any event or choice, yet the future is utterly determined by present events. By extension, the logical consequence is the annihilation of free will, since everything must ultimately and necessarily proceed from initial conditions specified by a creative deity. The *appearance*, then, of free will is an illusion that stems merely from a lack of precise knowledge. Beyond the philosophical meta-language of the *Principia*, however, this picture of the world is mathematical: objects are described mathematically, enumerating the locations and velocities of all the particles, as are the laws governing those numbers. The propositions, theorems, and proofs in the *Principia* are dominated by geometrical arguments that embrace the spatial container of the Ancient Greeks and Galileo's linearized time.

Unquestionably, Newton's legacy was a remarkable conception and a superb abstraction, providing highly efficient and effective methods of empirical description and prediction yet, as physics approached the modern era, becoming increasingly problematic. Perhaps the most readily identified difficulty, for physicists, was that of 'action at a distance' but Newton at least declared honestly and openly, in his *hypothesis non fingo*, that his theory was to be taken as a systemization or codification of relations between measurements and observations rather than statements as to the nature of reality. Therein, however, lies the nub of a greater deficiency in terms of the ancient and original aims of natural philosophy – to understand Nature via a systematic and rational approach to its study. The ontological content of the *Principia* is decidedly non-mathematical. In the *Scholium Generale*, Newton writes:

> This most beautiful system of the sun, planets, and comets, could only proceed from the counsel and dominion of an intelligent and powerful Being [God]... This Being governs all things... All that diversity of natural things which we find suited to different times and places could arise from nothing but the ideas and will of a Being necessarily existing.

It is unclear whether such views stemmed purely from Newton's deep religious convictions, in which case they may be seen as obviating (from Newton's perspective) any need for ontological expression, or whether they represented an attempt to reconcile his faith with the logical consequence of the mechanistic world view – the clockwork Universe that appeared to render God obsolete beyond the act of Creation.

From the perspective of the present work, the most significant aspects of Newton's influence relevant to the development of *Process Physics* are: the mathematization of physics with its geometric model of time and lack of rational, scientific ontology (particularly with regard to motion and inertia) – notions that persisted to become firmly entrenched in the doctrines of modern physics; the supposed universality of Newtonian gravity; and determinism, which was to be challenged by quantum theory (in its 'proper' domain), only to reassert itself in the macroscopic classical limit of 'large' quantum systems.

1.6 Concluding remarks for paradigms in physics I

Physics of ancient times was concerned as much with the nature of existence as it was with formulating rules to describe and predict observations. The objectification of the world, contrasted with the process, relational, and holistic views of Heraclitus, Empedocles, and Anaxagoras (also, later, Leibniz), came to dominate classical thinking, particularly from the time of Galileo and Descartes and, beginning most notably with Newton's impressive formalization in the Principia, the mathematization of physics came to subsume natural philosophy as a means of coaxing Nature to divulge her secrets.

The ontological status of spacetime had been hotly debated by physicists and philosophers throughout the classical and pre-modern eras (and, of course, is no less heated today), centering about the conflicting juxtaposition of *absolutism*, which considers spacetime as much an object as rocks and atoms – a physical entity possessed of specific properties, and *relationalism*, which asserts that spacetime has no separate existence but for the complex of relations among physical things and ultimately, as Leibniz intuited, defined by the presence of everything 'else' [14].

At the close of the pre-modern era, the great majority of physicists were firmly in Newton's camp on this matter, as with the entire philosophy and methodology of practicing their science, a state nowhere more aptly encapsulated than in poet Alexander Pope's *Epitaph for Newton*:

> Nature and Nature's laws lay hid in night;
> God said, "Let Newton be!" and all was light.

Chapter 2

Paradigms in physics II – the modern era

Go - not knowing where. Bring - not knowing what.
The path is long, the way unknown.

– Russian Fairy Tale

2.1 Introduction

In this chapter, the status of modern physics is examined, together with its assumptions and limitations, past and present, consideration of which informed, motivated, and provided insight for the development of *Process Physics.* The intention is to place the latter in context with the former.

It might be argued that discussion of the modern era should start, say, with Maxwell's electromagnetism or perhaps Carnot and thermodynamics. Though momentous in their own right, nevertheless it was surely Einstein who captured the public imagination and signalled the birth of the modern era in physics, thus the discussion begins with Einstein's relativity, gravity, and the standard model. From there, quantum theory is examined before turning to *the* problem of the modern era:

the efforts to merge the two great paradigms of 20th Century physics in a unified theory of quantum gravity and quantum cosmology.

2.2 Einstein's relativity

Einstein, too, made assumptions about the nature of space and time, though acutely different from those of Newton. Maxwell's theory of electricity and magnetism had been published in *A Treatise on Electricity and Magnetism* (1873), which included the formulæ today known as the Maxwell equations. Maxwell showed that these equations necessitated the existence of electromagnetic waves propagating at the speed of light and, since the existence of waves seemed to demand the existence of an appropriate medium, he also proposed a physical theory of a luminiferous æther. Because of the appearance in the equations of a velocity, they were thought only to express electromagnetism in the rest frame of the æther, until the (incorrectly reported[1]) null result of the Michelson-Morley experiment required alternative explanations to be sought by Lorentz and others. Consequently, in respect of electromagnetism, Galilean invariance – the principle that the fundamental laws of physics are the same in all inertial frames of reference and under which, as applied to Newtonian mechanics, all lengths and times remain unaffected by a change of velocity – give way to the principle of Lorentz invariance under which lengths and times *are* affected by a change in velocity, which is then described mathematically by a Lorentz transformation.

Einstein's 1905 paper, "On the Electrodynamics of Moving Bodies", more commonly known as the special theory of relativity, stemmed from the Michelson-Morley 'failure' to observe the æther. He posited that the æther concept was redundant and

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[1] See [15]–[30], stemming from the further development of *Process Physics* beyond the foundations reported here, where this issue is dealt with extensively by Cahill.

proposed, via two postulates, a solution to the problem of the propagation of light. The first postulate is that the laws of physics are the same for all inertial observers, and the second postulate is that all inertial observers must agree on the speed of light, no matter how fast its source is moving. Implicitly, there could be no sensible meaning to the concept of simultaneity - two events observed to occur simultaneously from one frame of reference would not generally so appear when observed from a different frame. Galilean invariance was supplanted by Lorentz invariance for *all* physical observations, not just those pertaining to electromagnetic phenomena, and both time and length were required to be relative quantities. Thus, Einstein abandoned Newton's notion of an absolute or 'true' time flowing equably for all observers (and with it went absolute space), although he retained the relative or common time that can be measured and determined by means of actual clocks associated with *local* observers, that is: each observer has a unique frame of reference and, with respect to time, his time frame is his own clock; the universe as a whole has no frame of reference of its own. For Einstein, time is *always* connected to the actual clocks of observers and the rules by which the observer can measure the motion of the observed systems or bodies. It is never the "true time" and never can it be said to "flow equably" for all observers, no matter how they are situated each with respect to another.

The special theory had shown how to relate observations made in different frames of reference moving in uniform motion, one to the other. It holds only to the extent that the effects of gravity can be ignored. Over the next decade, Einstein worked to extend the theory to deal with reference frames moving in arbitrary ways, speeding up, slowing down, changing direction. That is, he wanted to extend to accelerating observers those relativistic invariance properties established by the special theory. He recognized, in the *Principle of Equivalence* (originally stated in 1907) a link between such accelerated motion and a gravitational field and postulated that no experiment can locally distinguish between a uniform gravitational field and a uniform acceleration, thus broadening the principle of relativity to the case of uniformly accelerated motion of the reference frame. The equivalence principle implies [31] that any reasonable description of gravity will have a geometrical structure and thus, by extension, the principle of equivalence developed to become the general theory of relativity (GR), in which the convenient device of Galilean geometrical time was married to Newton's absolute three-dimensional space to provide the four-dimensional geometrical construct called *spacetime*, where gravitational fields determine the causal structure of spacetime by affecting light signals and spacetime intervals (in particular, gravity is capable of generating regions of spacetime from which no information can reach the outside world through classical propagation of signals. This existence of 'trapped surfaces' has no parallel in any other interaction). By constructing a field theory of gravity, the hitherto unexplained gravitational force was thereby construed not as 'force' but as *geometry*, the curvature of spacetime, related by Einstein's field equations to the energy-momentum tensor determined by the matter-energy density [32, 33]. For velocities much less than the speed of light, the formalism of Einstein's model of gravitation was constrained so as to ensure agreement with Newtonian gravity while otherwise generalizing Newton's model.

The apparent successes of the postulates of special relativity and the curved spacetime model of GR, with achievements such as prediction of the perihelion precession of Mercury, gravitational red-shift, and the bending of light due to gravity, led to the development of the Minkowski-Einstein spacetime ontology that rapidly gained almost universal acceptance within the physics community.

Cosmology developed rapidly on the heels of general relativity, with the aim of relativistic cosmology being to deduce from the gravitational field equations physical models of the Universe. In 1929, Hubble observed the recession of galaxies, indicating that the Universe is expanding. The discovery led to Gamow's theory for the origin of the Universe, dubbed the 'Big Bang' by Hoyle, who never accepted the notion (Hoyle steadfastly maintained his own 'Steady State' theory – proposed in 1948 by Hoyle, Bondi, and Gold – that the Universe had, and always would, exist). Standard Big Bang cosmology relies on three constructs:

- the cosmological principle, that on large scales the Universe is homogeneous and isotropic, which implies a spacetime metric in Friedmann-Robertson-Walker (FRW) form:
$$ds^2 = a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2\left(\vartheta^2 + \sin^2\vartheta d\varphi^2\right)\right] \tag{2.2.1}$$
- a perfect fluid description of matter in the Universe, that is, matter can be described as an ideal gas with an equation of state, $p = w\rho$
- the integrity and principles of general relativity, where the dynamics of the expansion of the Universe is governed by the Einstein equations, which relate the expansion rate to the energy-density ρ and pressure p.

One of Einstein's strongest motivations [34] was to provide a model for a finite yet boundless space since, following Mach and Riemann, the closure of space was necessary to solve the problem of inertia and resolve (most of) the paradoxes found in Newtonian cosmology. It is well known [35] that in this Einstein was greatly influenced by Mach's ideas, which he called 'Mach's Principle', that assert (in essence) that the local properties of matter, such as motion, inertia, and centrifugal forces, must be determined fully by the distribution of other matter in space i.e. by the global structure of the Universe (although it has been said [36] that the Einstein theory does not, in fact, successfully embody that principle – in an ‘empty’ universe, a test particle should not know how to move; that is, empty space should be devoid of geometry, whereas the Einstein equations permit flat geometry in a space with no matter or radiation).

Ironically, having first dispensed with Newtonian absolutes to arrive at the special theory of relativity, Einstein then proceeded to imprint physics with the ultimate absolute: the static four-dimensional spacetime edifice “defined by idealized readings of clocks and rulers”[12] and endowed with the substantialism that spacetime points are genuine, basic objects of physical theory [37] – one indivisible and unchanging reality worthy of the Eleatics of Ancient Greece that, with its deep geometric formalism, completed the rigid mathematization of physics begun by Galileo. Barrow [38] commented that Einstein appears to have become increasingly convinced that by pursuing mathematical formalism alone, the compelling simplicity of a unified description of the world would become inescapable:

> I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena ... I hold it true that pure thought can grasp reality, as the ancients dreamed.

2.2.1 Problems with gravity and the standard model

Einstein's relativity is a highly sophisticated mathematization that makes *measurement* primary – it is a theoretical framework that informs as to measurements rather than a theory that "informs as to the true nature of reality" – and the standard model, deeply rooted in Einstein's work, has been besieged with a number of profound theoretical problems that remain unresolved after many decades of work. While clearly it does not follow that the mere existence of problems renders a theory invalid, equally clearly science advances at least as much through re-evaluation of accustomed modes of thought as it does by rare, pure inspiration and fortuitous discovery. If a theory is to be regarded as *the* correct theory it must, of course, survive all conceivable tests and, moreover, have no open theoretical loose ends [13]. Popular myths and daring claims propagated by proponents of psuedoscience aside, there are several genuine problems and open questions arising from the standard theory that are well-known to the physics community and a deal of effort has been expended towards their resolution. Some if these issues are identified here:

- **Dark matter**

  Perhaps the greatest current problem for astrophysics and cosmology is that of 'dark matter' – supposed baryonic and (perhaps) more exotic matter that cannot be detected by light emission – which, in modern astronomical theory, provides the gravitational 'seeds' onto which the visible parts of galaxies condense. Dutch astronomer Jan Oort [39] first discovered the 'presence' of dark matter in the 1930's when studying stellar motions in the local galactic neighborhood, finding that dynamical estimates of the local matter density differed by a factor of three from estimates obtained from luminosity observations.

While Oort was carrying out his observations of stellar motions, Fritz Zwicky of Caltech inferred, through his studies of galactic clusters, the presence of dark matter on a much larger scale. Measuring the radial velocities of galaxies in the Coma cluster, Zwicky observed the redshifts of individual galaxies and found mass discrepancies of one to two orders of magnitude in the mass-to-light (M/L) ratio, based on the Einstein/Newtonian theory of gravity [40, 41]. The M/L ratio can also be evaluated by studying galaxy pairs, groups, clusters, and superclusters. Observations of the Andromeda and Milky Way galaxies indicated an M/L ratio of about ten [42], and more recent measurements have found that certain galaxy clusters (and binary galaxies) have M/L ratios up to 300, over a length scale of about 1 Mpc.

The dark matter effect was discovered to influence the dynamics of spiral galaxies when it was realized that rotation velocities in the outer regions of spiral galaxies were again much greater than expected from their luminosity and almost flat rotation-velocity curves were observed [43, 44, 45, 46, 47]. On the other hand, dark matter effects do not appear to be the norm for elliptical galaxies. Although some astronomers claim to have observed dark matter effects in ellipticals, these were mostly very rare, bright examples that may not be representative of elliptical galaxies as a whole. In 2003, Romanowsky and his colleagues studied the kinematics of the outer parts of three intermediate-luminosity elliptical galaxies [48]. The galaxies' velocity-dispersion profiles were found to decline with the radius and there was little if any evidence of dark matter in these galaxies' halos. According to Romanowsky *et al*, "The unexpected result conflicts with findings in other galaxy types and poses a challenge to current galaxy formation theories.” [48]

There are two broad categories of dark matter candidates – baryonic and non-baryonic. The latter is further subdivided into hot dark matter – minute-mass, rapidly moving particles, and cold dark matter – particles with relatively large mass and moving at slow speeds. After decades of investigation, no trace of any such material has yet been found. Mannheim [49] remarks thus:

> Since there is not yet a single independent verification of standard gravity on these larger distance scales [from galaxies all the way up to cosmology] which does not involve an appeal to dark matter, we thus see the complete circularity of the reasoning which led to dark matter in the first place, with such dark matter potentially being nothing more than an artifact which serves to parameterize any detected departure from the luminous Newton-Einstein expectation.

The discrepancies in the dark matter hypothesis together with the assumptions of Einstein/Newtonian gravity theory appear to be strong indications that the classical theory of gravity may be fundamentally flawed.

- **Isotropy**

  The strongest evidence for the Big Bang is the existence of the ‘cosmic microwave background’ (CMB), an isotropic radiation bath that permeates the entire Universe. Standard cosmology cannot explain this observed isotropy [50], which holds to within about one part in a thousand.

- **The flatness problem and initial conditions**

  In standard cosmology and for an expanding Universe, the ratio of the observed density to the critical density $\Omega = 1$ is an unstable fixed point. In order to explain the present small value of $\Omega - 1 \sim \mathcal{O}(1)$, the initial energy density had to be extremely close to critical density. The flatness problem asks, "What is the origin of these fine tuned initial conditions?" [50]. Barrow highlights the importance of understanding initial conditions since they "play a decisive rôle in endowing the world with its sense of temporal direction" [38].

- **Structure formation**

  According to Big Bang theory, the Universe was initially dominated by radiation whereas now the energy density resides mostly in cold matter, with the transition occurring at time t_{eq}. There is no causal mechanism for non-randomly correlated perturbations in the energy density before that time but after t_{eq} perturbations can develop via the action of gravitational clustering. Observations show that galaxies and clusters have non-random correlations on scales greater than 50Mpc, however gravity is too weak, in general, to have produced these after t_{eq}. There is no answer within standard cosmology to explain either the primordial density perturbations or the observed non-random correlations [50].

- **Cosmic repulsion**

  Einstein introduced the cosmological constant Λ in his theory of general relativity, guided by the paradigm of the day that the Universe was static, neither contracting nor expanding. Following Hubble's discovery of the expanding Universe, Einstein's response was his famous declaration that the cosmological constant (Λ) was his "biggest blunder". In 1998, following observations of type Ia supernovae, compelling evidence of an apparent cosmic repulsion was reported [51], indicating that, not only is the Universe expanding, it is expanding at an accelerating rate due to Λ representing as much as 70% of the total mass-energy density of the Universe, and thus the expansion is likely to go on forever. This was contrary to previous expectations and assumptions that the expansion was slowing down, perhaps to the point of reversal so that the ultimate fate of the Universe would be its demise in a 'Big Crunch'.

One interpretation of this development is that first, ordinary visible matter was demoted in its contribution to the mass-energy density of the Universe by the supposed presence of non-baryonic dark matter and, now, with the discovery of cosmic repulsion, the elusive dark matter has itself been supplanted by "yet more exotic gravitational sources such as a cosmological constant or a possible quintessence (non-luminous matter with negative pressure) [or a so-called "dark energy" – residual energy in empty space that is causing the expansion of the Universe to accelerate] ... it is perplexing that the standard theory so often finds itself in need of remodeling." [49]

- **Dimensionality**

  Why does space-time have three plus one dimensions? The generally accepted theory of the structure of space-time, general relativity, cannot explain this simple observation (nor, in fact, does it even allow the question) [52].

- **Gravitational anomalies**

  1. ***Pendula***

     Over the last fifty years evidence has accumulated from diverse physics experiments that, in some situations, various dynamical systems behave in ways that are not predicted by the standard theory. In 1954, Maurice

Allais reported that a Foucault pendulum exhibited peculiar movements at the time of a solar eclipse. The Allais experiments, and variants thereof, have been repeated by numerous researchers (for example [53, 54, 55]) and the subject remains an active topic of investigation worldwide.

Saxl and Allen [56] in 1971 reported that “quantitative observations made with a precise torsion pendulum show, in agreement with many earlier, less precise, recordings made at Harvard since 1953, that the times required to traverse a fixed fraction of its total angular path vary markedly during the hours before the eclipse and during its first half...”. The observed effects were of such magnitude that they stated, “This leads to the same conclusion arrived at by Allais – that classical gravitational theory needs to be modified to interpret his (and our) experimental results.” [56].

2. ***Mines and boreholes***

Anomalous gravity gradients have been observed in measurements of gravity in mines and boreholes (including a 2-km-deep hole in the Greenland ice cap). Using the data to estimate the value of the Newtonian gravitational constant G, results have provided values for G that are higher than the laboratory value. Although researchers admit the possibility of systematic error due to density inhomogeneity in unexpected geological features, the evidence indicates that such error appears improbable. Rather, the anomalies are at least suggestive of violations of Newton's inverse-square law [57, 58, 59].

3. ***Pioneer, Galileo, and Ulysses spacecraft***

   Radio metric data from the Pioneer 10/11, Galileo, and Ulysses spacecraft, accumulated over 15 years, indicate an apparent anomalous constant acceleration acting on the spacecraft with a magnitude $\sim 8.5 \times 10^{-8}$ cm/s^2, directed towards the Sun [60, 61]. Researchers claim to have eliminated those explanations deemed most plausible and thus far no explanation based on conventional physics and understanding has been found. The European Space Agency was reported to be considering plans for a number of experiments and missions that will test gravity in new ways, one of which is designed to test the Pioneer anomaly directly [62].

- **Weak gravitational shielding effect**

  Under the conditions of Meissner-effect levitation in a high frequency magnetic field and rapid rotation, apparent anomalous forces have been detected in the vicinity of a disk of high-T_c superconducting material, producing a weak shielding of the gravitational field. Further work from the same researcher(s) describes a gravitational impulse effect. If independently verified, the existence of such phenomena cannot be explained by standard gravitational theory [63, 64, 65].

- **Origin of law**

  Einstein's general theory of relativity provides no ontological basis for the origin of the Universe. Of course, for a static Universe (as originally assumed in the formulation of GR) such ontology is, perhaps, not required of the physics and could be left for philosophers or theologians. Otherwise, if the Universe as a whole is described by a law of Nature such as that enshrined in GR, then there must exist a logical structure larger than the physical Universe, an implicit assumption in most cosmological studies [38].

- **Continuity**

  General relativity assumes the *continuity* of the four-dimensional spacetime manifold, which is one area of interaction between fundamental physics and questions regarding infinity. Most fundamental pictures of the physical world, and GR is the foremost of these, assume that the basic notions – fields, space, and time – are continuous entities [38]. Forbidden in the Standard Model, the question remains: whether or not a true continuum exists in reality.

- **Fundamental flaw**

  Quoting Padmanabhan [31]:

  > The truely [*sic*] remarkable feature of classical general relativity is that *this theory is fundamentally wrong.* This is most easily seen from the fact that one can ask questions — in the form of thought experiments — to which the theory cannot provide sensible answers. One such question could be the following: "A neutron star of mass $6M_\odot$ collapses to form a blackhole. How will the physical phenomena appear with respect to a hypothetical observer on the surface of the neutron star at arbitrarily late times as measured by the observer's clock?" Such questions cannot be answered in classical general relativity because the relevant equations lead to an infinte curvature singularity. Such a theory must clearly be wrong and has to be replaced by a better formulation at very strong curvatures.

2.3 Quantum physics

The history of quantum physics since its inception in the early 20th Century is full and complex, yet characterized by two remarkable features. First, the outstanding, even overwhelming, success of quantum mechanics in predicting and accounting for a great array of physical phenomena, in perfect agreement, it would seem, with experimental evidence – most strikingly in the domain of the very small [66, 67, 68, 69, 70]. The second feature is the decades of debate and controversy over the interpretation and ontology of quantum theory and there is extensive literature concerning the effectiveness of the theory contrasted with the obscurity of its meaning, *viz*

- "... this theory presents crucial conceptual difficulties, about which a lively scientific debate is still going on." [67]
- "According to widespread views, quantum mechanics (QM) is in perfect agreement with all definite physics experiments. None of them forces us either to correct or to complete the theory. On the other hand, it has been recognized since the earliest time of understanding [quantum mechanics] that it contradicts our general macroscopic world view." [68]
- "The current formulation of quantum mechanics is generally thought to be incomplete and unsatisfactory. Although quantum mechanics provides a precise and successful framework for describing microphysics, doubts and questions arise when it is extended to macrophysics. Prominent among these problems are those of the collapse of the wave packet and the transition to a classical description of large objects." [69]
- "The problem of how the classical macroscopic world emerges from the quantum

substrate is the main problem of the interpretation of quantum mechanics and it is still the subject of an intense debate." [71]

- "... quantum mechanics is much too simple a theory to adequately describe a complex world ... " [72]
- "Quantum theory is the 'hard core' of physics today ... [but] it suffers from an obstinate interpretation problem: what does the formalism really mean philosophically?" [73]
- "We want to believe that quantum theory is fundamental, but its interpretation is so arbitrary!" [74]
- "... we have many quantum theories or quantization methods. This means that the sixty-year history of quantum mechanics would not be enough to fix its theoretical formulations and to explore its physical implications, and that we are working in an era in which quantum mechanics itself is still being examined, reformulated, and extended over its present version." [75]
- "For Albert Einstein, John Bell and Abner Shimony a quantum theory which can be used to analyse experiments, but which does not present a consistent and complete representation of the world in which we live, is not enough ... Although the mathematical laws of probability in the usual Copenhagen theory are clear, the theory is no more clear than Darwin about the mechanism." [76]
- "Interpretation of quantum mechanics remains rooted in classical ideas about objective reality ... Use of a less correct theory as underpinning for a more correct theory has spawned the puzzle of measurement ..." [1]

To better appreciate the relevance to the development of *Process Physics* of comments such as these, it may be useful to first adumbrate from an historical perspective the advent of the 'quantum age' and the development of its interpretation during the 20th Century.[2]

2.3.1 Quantization and formalism

Fundamental work by Kirchhoff on blackbody radiation (a term he introduced in 1862) – a blackbody is an object that absorbs all incident energy; it is also a perfect emitter – showed that the emitted energy E depends only on the temperature T of the body and the frequency ν of the emitted energy, i.e. $E = J(T, \nu)$, and Kirchhoff challenged physicists to find the function J. In October of 1900, Planck guessed the correct formula and then tried to give its theoretical derivation, resulting in the unprecedented step of assuming that the total energy is the sum of discrete elements – *quanta* of energy – so that the energies of any harmonic oscillator, such as the atoms of a blackbody radiator, are restricted to values that are integer multiples of a minimum value. The energy E of this basic *quantum* is directly proportional to the frequency ν of the oscillator, or $E = h\nu$, where h is the number known now as Planck's constant. For his efforts, Planck received the 1908 Nobel Prize in Physics.

In 1905 Einstein came to examine the photoelectric effect because the electromagnetic theory of light, which treated light as a wave propagation phenomenon, gave results that were not in agreement with experimental evidence. To resolve the problem, he proposed a quantum theory of light in which light behaved, in certain

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[2] The use is acknowledged of an excellent essay, 'A history of Quantum Mechanics' [77], which may be found on the mathematics website at St Andrews University – http://www-history.mcs.stand.ac.uk/history/, and also the equally excellent essay 'Quantum mechanics' to be found on the Wikepedia website – http://en.wikipedia.org/wiki/Quantum_theory#History and related links.

situations, as a particle phenomenon (giving rise to the so-called wave-particle duality of light). He realized that Planck's theory implicitly employed the light quantum hypothesis and correctly guessed that energy changes in a quantum material oscillator occur in discontinuous increments that are multiples of $\hbar\nu$, where $\hbar$ is Planck's reduced constant (sometimes called Dirac's constant) and ν is the frequency. Einstein received the 1921 Nobel Prize in Physics for his work on the photoelectric effect. Reputedly, the derivation of Planck's formula had not been to Planck's satisfaction and Einstein, too, was unhappy with it. However, Bose's 1924 paper, "Planck's Law and the Hypothesis of Light Quanta", though just four pages long was highly significant since Bose derived Planck's formula from Boltzmann's statistics, thereby removing a major objection to light quanta. It was endorsed by Einstein, who arranged for its publication after previous rejection by referees.

Following Rutherford's 1911 discovery of the nuclear atom, in 1913 Bohr again used the quantum concept when he published a revolutionary paper on the hydrogen atom in which he conjectured that an atom could exist only in a discrete set of stable energy states, the differences of which amount to the observed energy quanta. This explained both atomic structure and atomic spectra, showing the connection between the electrons' energy levels and the physically observed spectral lines. The work earned Bohr the 1922 Nobel Prize. At around the same time as Bose's work, de Broglie, inspired by Einstein and Planck, extended the concept of wave-particle duality to all material particles, using the Hamilton-Jacobi theory that had been applied both to particles and waves; de Broglie was rewarded with the 1928 Nobel Prize.

These theories comprise what is today known as the 'old' quantum theory and, being purely phenomenological, they lacked rigorous theoretical justification for quantization.

Werner Heisenberg was awarded the 1932 Nobel Prize in Physics for the creation of 'modern' quantum mechanics and he is generally acknowledged as the principle author of its formalism, beginning with his 1925 invention of *matrix mechanics* (further developed jointly with Max Born and Pascual Jordan), which was the first version of quantum mechanics and emphasized the possibilities of quantum transitions, or jumps, between the stable energy states E_n of a bound electron, although no mechanism was suggested to explain the actualities of these spontaneous transitions in continuous time. In 1926, Erwin Schrödinger's paper, "Quantisierung als Eigenwertproblem" ["Quantization as an Eigenvalue Problem"] [78] appeared in Annalen der Physik. In a series of six papers, he introduced the formalism of *wave mechanics*[3] [80], which Dirac later showed to be precisely equivalent to Heisenberg's matrix mechanics formulation. The essential concept of quantum mechanics is captured by the notion that for each dynamical variable representing a physical quantity in classical mechanics there is a corresponding *operator* such that the numerical values that may be taken by physical quantities are the eigenvalues of their respective operators. Energy is represented by the *Hamiltonian* operator, with observable energy levels being identified with eigenvalues of the Hamiltonian. Schrödinger expressed this in his celebrated wave equation and suggested finding those wavefunctions $\psi(q)$ that satisfy the linear equation

$$H\psi = E\psi \tag{2.3.1}$$

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[3] The following year, Schrodinger was nominated for the Nobel Prize but failed to receive it in that and five further consecutive years, the reason behind the rejection being 'the highly mathematical character of his work'. He finally shared the Prize with Dirac in 1933. [79]

where the Hamiltonian operator $H \equiv H(q, \frac{\hbar}{i}, \frac{\partial}{\partial q})$. In the fourth paper, he suggested the non-stationary wave equation for the complex time-dependent wavefunction $\psi(q,t)$ simply as

$$i\hbar\frac{\partial}{\partial t} = H\psi(t). \tag{2.3.2}$$

Initially, Schrödinger thought that the wavefunction corresponded to a physical vibration in a real continuous spacetime because it was not stochastic, but he was puzzled by the failure to explain the black-body radiation and photoelectric effect from this wave perspective. However, after realizing that $\psi(t)$ in 2.3.2 must be a complex function, he acknowledged that it cannot be given a direct interpretation. Even before discovering wave mechanics, Schrödinger was an advocate of the idea that the most fundamental laws of the microscopic world are random, yet he failed to see the probabilistic nature of $|\psi|^2 = \psi\bar{\psi}$. Indeed, his equation was not stochastic and did not account for the individual random jumps $E_m \rightarrow E_n$ of the Bohr-Heisenberg theory. For the rest of his life Schrödinger apparently tried to find a more fundamental equation that would be responsible for the energy transitions in the process of measurement of the quanta $\hbar\omega_{mn}$ [79].

In 1926 Born set aside the causality of classical physics. Speaking of collisions, he wrote, “One does not get an answer to the question, What is the state after collision? but only to the question, How probable is a given effect of the collision? From the standpoint of our quantum mechanics, there is no quantity which causally fixes the effect of a collision in an individual event” [77].

Heisenberg stated in 1927 his *uncertainty principle*, which provides a theoretical bound over all measurements. As it was initially considered by Heisenberg, the uncertainty principle follows from wave-particle duality in cases where neither the classic 'point particle' description nor the 'wave' description is entirely appropriate to the exclusion of the other. Sometimes erroneously explained by claiming that the measurement of position necessarily disturbs a particle's momentum, the rôle of disturbance is not essential; rather, the uncertainty principle, in its general form, applies to every pair of *conjugate variables* (e.g. position and momentum, energy and duration, orthogonal components of total angular momentum) – indeed, most generally, for any pair of Hermitian operators – and follows as a consequence of conjugacy and non-commutativity of quantum observables. Again in 1927, de Broglie found an equation of particle motion equivalent to the guiding equation for a scalar wave function, which, as he explained at the 1927 Solvay Congress, could account for quantum interference phenomena [81]. However, he did not pursue this early 'pilot wave' approach, which was a hidden variable theory with underlying determinism.

Led by such researchers as Dirac, Pauli, Weisskopf, and Jordan, 1927 also saw the beginning of *quantum field theories* (QFT), in which quantum mechanics is applied to fields, rather than single particles, and Dirac (who pioneered the use of operator theory) achieved the unification of quantum mechanics with special relativity.

In 1932 von Neumann formulated the rigorous mathematical basis for quantum mechanics as operator theory [82] and during the 1940s, QFT was extended by Feynman, Dyson, Schwinger, and Tomonagato in the formulation of *quantum electrodynamics* (a quantum theory of electrons, positrons, and the electromagnetic field that is the basis of subsequent quantum field theories).

In the 1930s, Imre Fényes founded the stochastic interpretation of quantum mechanics [83, 84], which restores the original status of causality.

In 1952, de Broglie's pilot wave formulation was rediscovered by Bohm, who fully understood its significance and implications [85]–[89] (see §2.3.2 on page 57), developing the version known now as Bohmian mechanics, probably the best-known hidden-variable theory.

Beginning in the 1960s, quantum chromodynamics (QCD) was developed, with its present form due to Polizter, Gross and Wilzcek in 1975. From pioneering work by Schwinger, Higgs, Goldstone and others, Glashow, Weinberg and Salam independently showed how the weak nuclear force and quantum electrodynamics between elementary particles could be merged into a single electroweak force [82], for which they were awarded the 1979 Nobel Prize in Physics.

In 1966, Nelson followed Fényes, from a different point of view, to reintroduce the stochastic quantization approach [84, 90]. Modern stochastic quantization (SQM) was proposed by Parisi and Wu in 1981 [75, 91].

2.3.2 Interpretation and problems

The reasons for the interpretive difficulties that have beset quantum theory since its inception are manifold and a full discussion is beyond the scope of this work. However, Butterfield and Isham point out that quantum theory is not a theory *per se*; rather, it is a conceptual framework within which specific theories are constructed [92]. Moreover, postulates about measurements and probabilities in the 'standard' quantum formalism, though "repeated in all textbooks", lie outside that formalism and are never derived – they are neither derivable nor deducible from within the formalism [74].

According to 't Hooft, "Quantum mechanics is not a theory about reality, it is a prescription for making the best possible predictions about the future, if we have certain information about the past" [93]. As with relativity, quantum theory makes measurements primary – in keeping with the 'orthodox' view expressed by the Copenhagen interpretation, it must be regarded as the codification of connections between relatively measurable quantities; that is, the (given/assumed) underlying spacetime framework must be understood in terms of possible measurement results and the mathematical quantum formalism is just a *tool* for making statistical predictions about the results of such measurements [12]. Hence, ontological conclusions are confounded by a constant foundational shift to and fro between the phenomenological level of atoms to the level of macroscopic measuring devices and observers, so that one "cannot pass with certainty from knowledge about the structure of phenomena to knowledge about the structure of the underlying reality. Accordingly, the orthodox [Copenhagen] interpretation ... tries to separate 'science' from 'natural philosophy'." [12]

The Copenhagen interpretation was formulated by Bohr and Heisenberg circa 1927 (though neither used the term to refer to their ideas nor were they entirely in agreement) and is probably the most widely accepted view – certainly that has been so for most, if not all, of the history of quantum mechanics. As Bell pointed out, despite more than seventy years of interpreting quantum mechanics, the more pragmatic form of Bohr's interpretation remains the'working philosophy' for the average physicist [94]. Today it is mostly regarded as an amalgam of indeterminism, Born's statistical interpretation of the wave function, Bohr's correspondence principle and his complementarity interpretation of certain atomic phenomena.

Two processes are assumed to influence the wavefunction: unitary evolution in accordance with the Schrödinger equation; and the measurement process. It is the latter that spawned the controversy that continues to this day. Either the wavefunction is to be regarded as a real ‘entity’, in which case it undergoes ‘collapse’ at the instant of measurement, or it is to be regarded as an imaginary mathematical device the sole purpose of which is to yield probabilities for measurement outcomes. Whatever the case, Bohr stressed that only the *results* of quantum experiments are meaningful, since these are the only observables, and therefore additional questions about what is ‘really’ occurring are philosophical rather than scientific and thus outside the domain of physics. Hence, the Copenhagen interpretation forbids questions such as, “Where was the particle before its position was observed?”; no matter how ‘natural’ and reasonable a question may seem from the point of view of classical common-sense and intuition, if it cannot be answered by a measurement process then its subject can form no part of physical reality in so far as that reality belongs to the quantum domain. The Copenhagen interpretation also holds that the probability statements of quantum mechanics are irreducible; whereas classical probabilities are used to reflect incomplete knowledge of processes that are, in principle, totally deterministic, quantum measurement outcomes are *fundamentally* lacking in determinism.

The third and perhaps most problematic feature of the Copenhagen interpretation is the instantaneous collapse of the wavefunction occasioned by the act of measurement, whereby exactly one state is realized, at random, to the exclusion of all other possibilities and the wavefunction immediately is transformed so as to reflect that outcome. In this, it appears that conflict arises between certain principles of the theory; in particular, “the postulate of collapse seems to be right about what happens when we make measurements [while] the dynamics seems to be bizarrely wrong ... and yet the dynamics seems to be right about what happens whenever we aren’t making measurements.” [95] (citing [96]). This has become known as the *measurement* *problem*, the central difficulty of which is that the measurement process is afforded special status with no epistemological foundation, explanation, or justification other than ‘it works’.

Contention over the Copenhagen interpretation is multi-faceted, involving uncertainty and randomness, measurement and localization, causality, classicality, non-locality and completeness – as Etter and Noyes ask, “What about non-locality? The collapse of the wave front? Quantum measurement?” [97]. In the last thirty or so years, the appearance of existence in seemingly “classical” surroundings has come to be generally (though not unanimously) understood as arising dynamically through quantum decoherence as a result of interaction with the environment [98] so that *classicality* implies that non-local quantum states spontaneously evolve into localized ones [99]. But, since decoherence and localization are problematic, to say the least, *nothing* about classicality and classicalization can be said to be ‘understood’, which is why this is the outstanding problem of the interpretation of quantum mechanics.

Those who enter the interpretation debate tend to fall into one of two camps, reflecting opposing trends in modern quantum theory. The first and perhaps more usual of these is the pragmatic or empiricist’s view that demands only that a theory be useful in predicting or describing experimental results (in essence, the “Shut up and calculate!”[4] stance) – thereby answering “What?” questions. The second is the realist’s view that demands considerably more of a theory: it must satisfy not only the former dictum, but also justify its predictions and inform as to the nature of the physical reality it seeks to describe – thereby answering both “What?” and “Why?” This was Einstein’s position. Although widely acknowledged as one of

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[4] This presumably tongue-in-cheek ‘quote’ (if, indeed it is that) is generally attributed to Feynman.

the 'founding fathers' of quantum theory and initially enthusiastic, by 1935 that enthusiasm had turned to disappointment, leading him to oppose quantum mechanics principally on two counts – its lack of observer-independent 'reality' and silence as to the state of Nature in the absence of observation; and the loss of determinism due to the probabilistic interpretation arising from the uncertainty relations whereby the theory relies on intrinsic yet unexplained randomness. He began to question whether the theory was complete. Since loss of both realism and determinism were given strong support by Bohr's complementarity, this became Einstein's first target, resulting in the infamous Einstein-Podolski-Rosen (EPR) debate that framed the paradoxical situation that one must, as Einstein later put it ([100], p.682, cited in [101]), "relinquish one of the following two assertions:

(1) the description by means of the psi-function is complete

(2) the real states of spatially separate objects are independent of each other"

By (2), Einstein meant the concept of locality, which could not be given up without accepting what he termed "spooky action at a distance". The debate was essentially unresolved until 1964, when Bell showed that certain measurable correlations obtaining from a modified EPR experiment satisfy, under a given set of assumptions (notably including that of locality), a particular set of constraints now known as the Bell Inequalities. In such an experiment, however, the predictions of quantum theory violate, by an experimentally significant amount, those inequalities thus showing the theory to be inconsistent with the assumptions and hence permitting the inference that quantum theory is non-local [101]. 'Bell's Theorem' is the collective name given to a family of such results, all showing the impossibility of a *Local Realistic* interpretation of quantum mechanics [102]. Contemplation of the theoretical and experimental investigations concerning Bell's Theorem leads one to ask whether it is legitimate to infer from such investigations that quantum mechanics is, indeed, non-local – that is, do the experimental data provide proof positive that Bell's Inequalities are violated and, if so, what conclusions then can be drawn about the physical world and the nature of reality?

Thanks to the work of Bell and those who followed – most notably, the Aspect (*et al*) experiments [103, 104, 105] – and other Bell tests (including those more recently by Zeilinger in 1999 [106] and Go in 2003 [107]), the first part of the question is resolved: quantum non-locality is now well established [108]. In 1993, exploiting *entanglement* (Einstein's "spooky action at a distance"), a method was devised to instantaneously transfer quantum information about one object to another distant object [109] using pairs of 'EPR particles' in a process called *quantum teleportation*. Actual quantum teleportation was achieved in the laboratory in 1997 [110, 111] and long-distance teleportation has now been reported [112, 113] (most impressively, perhaps, the latter: 'Quantum teleportation across the Danube' in 2004).

What now of the second part of the question? Thus far, at least, the locality of Einstein's relativity has not been directly challenged – neither matter nor energy have been teleported, only (random) information – yet there is the perception, at least, of an uneasy tension between relativistic locality and the *prima facie* non-locality of quantum mechanics. *Some* unknown superluminal mechanism appears to be at work in the arbitrarily fast connection between the outcomes of correlated measurements and begs such questions as: why (and how) is the occurrence of a real event subjected to the probabilistic control of a quantum state? how are entangled states sustained? what happens when the entanglement is broken? how does the wavefunction collapse? Unwittingly, with the EPR paradox Einstein demolished the assumption that he sought to retain; yet, although this meant a failure to reject the completeness assertion, it is by no means clear that the corollary holds. The evidence for non-locality *also* (paradoxically) supports incompleteness, since it demonstrates the existence of a phenomenon that finds no explanation within quantum theory.

Consideration of non-locality, and all that it implies, was highly significant in the development of *Process Physics*, not least because of the sort of views reported, in response to the metaphysical aspects of the foregoing questions, by Shimony [102], *viz*:

> A radical idea concerning the structure and constitution of the physical world, which would throw new light upon quantum non-locality, is the conjecture of Heller and Sasin (1999) about the nature of space-time in the very small, specifically at distances below the Planck length (about 10^{-33} cm). Quantum uncertainties in this domain have the consequence of making ill-defined the metric structure of General Relativity Theory. As a result, according to them, basic geometric concepts like point and neighborhood are ill-defined, and non-locality is pervasive rather than exceptional as in atomic, nuclear, and elementary particle physics. Our ordinary physics, at the level of elementary particles and above, is (in principle, though the details are obscure) recoverable as the correspondence limit of the physics below the Planck length. What is most relevant to Bell's Theorem is that the non-locality which it makes explicit in Quantum Mechanics is a small indication of pervasive ultramicroscopic

> non-locality. If this conjecture is taken seriously, then the baffling tension between Quantum non-locality and Relativistic locality is a clue to physics in the small.

Efforts to overcome the various difficulties posed by quantum theory have resulted in several interpretations beyond the strict Copenhagen view with its wave-particle duality, mysterious spontaneous collapse of the wavefunction, and priority of measurement. Notable alternate formulations or extended interpretations include:

- the probability interpretation proposed by Schrödinger
- the statistical interpretation suggested by Born
- the pilot wave interpretation, originally conceived by de Broglie and rediscovered and developed by Bohm as *Bohmian mechanics*
- the stochastic quantization approach founded by Féynes, reintroduced by Nelson, and reformulated by Parisi and Wu, including alternate quantum theories of this general kind
- the many worlds interpretation of Everett's 'Relative State' formulation

The parsimonious descriptions that follow greatly over-simplify the conceptions of their authors, however the present intent is merely illustrative since *all* of the interpretations (or re-formulations) address only a part of the complete set of difficulties associated with quantum mechanics, sometimes replacing one troubling concept with another, with no full resolution achieved. Rather, they serve to add weight to the concerns to be addressed by *Process Physics*.

Schrödinger's probability interpretation

Schrödinger's probability interpretation [78, 80, 114] proposes that a physical system has no objective meaning prior to a measurement, the associated wavefunction ψ characterizes it completely, and the probability density, given by $|\psi|^2$, is fundamental and provides a complete description of an individual quantum entity.

Born's statistical interpretation

Born's statistical interpretation ([77, 115], and [116] citing [117, 118]) is essentially the same except that the individual entity is described entirely in statistical terms involving measurements or actual observations; there is no scope to attempt to ascribe any physical, objective meaning prior to measurement (or the issue is simply considered irrelevant). These are subtle metaphysical differences and both interpretations adhere to the concept that a probabilistic description is complete. They both retain discontinuous and instantaneous changes in the wavefunction at the moment of observation [116].

Bohmian mechanics

The pilot wave, or Bohmian, interpretation [85]–[89], is a non-local hidden-variable theory that is equivalent to Quantum Mechanics except for the introduction of trajectories – in Bohmian mechanics, the system is regarded as a (real) particle following a trajectory determined by the Bohmian field, which flows as a classical fluid. The Schrödinger equation is modified to provide a set of coupled equations, leading to a *deterministic* evolution of the particle's trajectory. For example, according to this view, in the famous double slit experiment the particle passes through one slit or the other while the wave passes through both, with the probability of the particle being found in a space-time region being then determined by the wave.

Stochastic quantization

The central idea of the stochastic interpretations is the view that the uncertainty in a particle's observable properties, such as position and momentum, is not due to its lack of a sharp trajectory, but rather that it follows a random trajectory that is not directly observable. Stochastic quantization recognizes that randomness and fluctuation are intrinsic to the quantum domain. Alternative quantum theories of this general kind are based on a diffusion of quantum states or on quantum jumps. A quantum state diffuses when it changes continuously, but stochastically, like a Brownian motion for quantum states. A quantum state jumps when it makes an instantaneous transition between two states without spending any time in intermediate states. These theories modify the Schrödinger equation, so in principle they are distinguishable from ordinary quantum theory by experiment.

The stochastic approach [83, 84, 90, 119, 120, 121, 122] first arose when certain similarities were discovered between the equations of classical statistical mechanics and the Schrödinger equation. In the introduction to his 1952 paper, Fényes stated "the deeper investigation shows us that there is not any difference between the statistical apparatus of classical physics and wave mechanics ... all of peculiarities [*sic*] distinguishing quantum mechanics from classical physics are the consequence of statistical method, and it can be traced all of differences between classical and quantum physics back to this method" [83]. Fényes presented the probability theory of Markov-processes, showed the generalized form of the Fokker equation, demonstrated that it becomes possible to use procedures analogous to quantum mechanics to derive the

Heisenberg uncertainty relations – showing that these are not connected with measurement, and restored the original status of causality.

Nelson went on to develop Fényes ideas theory from a different point of view by deriving the Schrödinger equation from Newtonian mechanics via the hypothesis that every particle of mass m is subject to a Brownian motion with diffusion coefficient $\hbar/2m$ and no friction. Nelson's stochastic quantization is formulated, like Bohm's theory, in terms of *real* time [75]. The physical interpretation is entirely classical, particles have continuous trajectories, and the wave function is not a complete description of the state. According to Nelson, "the departure from classical physics produced by the introduction of quantum mechanics forty years ago was unnecessary" [90].

Yasue reviewed the stochastic quantization procedure with an introduction to Markov processes, Martingales and Fokker-Planck equations, reporting that "the stochastic quantization procedure ... is found to possess remarkable features which can not be achieved within the conventional framework of quantum theory. This admits us to give systematic analyses of irreversible[5] quantum dynamics of dissipative systems and the vacuum tunneling phenomena in non-Abelian gauge theory" [119].

The Parisi-Wu stochastic quantization (SQM) [75, 91] was designed to produce quantum mechanics from the thermal equilibrium limit of a hypothetical stochastic process with respect to a new fictitious or imaginary time rather than the ordinary

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[5] Irreversibility and the restoration of causality as a feature of the stochastic quantization approach provide great insight to what is known as the 'problem of time' in quantum mechanics. Nothing thus far has been said of this because, while generally esoteric for most quantum theorists, the topic is enormously significant in quantum cosmology and for *Process Physics*, so that separate treatment is warranted. See §2.4.1 on page 68.

time, though this is not essential to SQM as some researchers have successfully formulated SQM in terms of Minkowski spacetime coordinates while keeping time real [75]. The procedure is based on a well-defined Markoffian process of the Wiener type with Gaussian white noise and the original idea is that a D-dimensional quantum system is equivalent to a $(D + 1)$-dimensional classical system with random fluctuations. Namiki reports that SQM is a "powerful quantization method for enlarging the territory of quantum mechanics beyond that of conventional theories" [75], adding the highly speculative suggestion that, in so far as the fictitious time is concerned, its use is viewed as a mathematical tool yet one might imagine the possibility of discovering its physical roots "in exotic space-time worlds surrounding ours"; that is, the source of quantum fluctuations might be regarded as classical trajectories in a many-dimensional curved space making a trace of random intersections with the present four-dimensional world.

At least in some of its versions, the stochastic quantization approach is able to avoid the standard objections to local hidden variable theories [123] (see [115, 121]; for a discussion of these objections, see [124]) . Many stochastic-dynamical approaches to quantum mechanics largely follow the 'state vector reduction' of Pearle [125, 126]: the 'primary state diffusion' of Gisin and Percival [76, 127, 122, 128, 129, 130], with generalization by Diósi [68, 131], whereby quantum measurement, quantum nonlocality, and classicalization problems are treated through the application of nonlinear stochastic dynamics. The first complete alternative quantum theory of this kind, developed by Ghiradi, Rimini and Weber (GRW) in 1986 and later with Grassi [132, 133], is based on quantum jumps. Bell improved it and it was reformulated as quantum state diffusion (QSD) by Diósi, Gisin and Pearle; the theory is now called ‘continuous spontaneous localization’ [122].

Stochastic interpretation is an increasingly popular approach. Sharlow [123] has indicated some of the many available examples in the literature, not already cited, including [134]–[143].

Many worlds

Everett’s ‘Relative State’ formulation [144, 145, 146], commonly known as the many worlds interpretation [147], was an attempt to solve the measurement problem by dropping the wavefunction collapse dynamics from the standard von Neumann-Dirac version of quantum mechanics and so eliminate the discontinuous change that results from an act of measurement. According to Everett, the collapse ‘mechanism’ (whatever that is) requires that observers be treated externally to the system being described (the exophysical standpoint) so that the orthodox interpretation could not be applied to the Universe as a whole, since the Universe contains observers. Simplistically stated, Everett’s view denies the existence of a separate classical domain and asserts that it makes sense to talk about a state vector for the whole Universe. This state vector never collapses and hence reality as a whole is rigorously deterministic [145]. That is, a physical system is composed of many states, each one in a ‘world’ of its own, and the state in which it is observed depends on the world the observer ‘enters’ – the collapse of the wavefunction is avoided by introducing many copies of the world. All of the other aspects of the quantum mechanical formulation are maintained.

There have been many attempts to explain what Everett actually had in mind, due to a gap in his exposition between what he sets out to explain and what he ultimately ends up saying [146]. Apparently second in number only to those favouring the orthodox approach, proponents of the many-worlds interpretations are attracted by the theories' avoidance of the collapse postulate and randomness in favour of determinism and the ability to view quantum mechanics as a complete and consistent physical theory which agrees with all experimental results obtained to date [147] and for much of the physics community Everett's thesis has been seen as a resolution of the measurement problem [148].

From the perspective of considerations motivating the development of *Process Physics*, on the one hand it is clear that the insights gained from the application of various 'flavours' of quantum physics have been of inestimable value in adding, in particular, to the description of objective reality via what has been learned of the atomic and sub-atomic world and the structure of matter; on the other hand, perhaps even greater value obtains from the flaws of quantum theory and the insights suggested thereby. The following words of F. David Peat seem appropriate to conclude this section:

> ... there is genuine confusion at the heart of physics and the ongoing debate about the interpretation of the quantum theory shows no signs of abating. Indeed, there are today many different interpretations of the quantum theory, each with its own adherents who claim to be the sole possessors of the truth ... Clearly, at the heart of physics, at this supposedly most fundamental level of reality, there is a total lack of clarity and agreement as what the theory actually means. [149]

2.4 Quantum gravity and quantum cosmology

"The feature of quantum gravity that challenges its very right to be considered as a genuine branch of theoretical physics is the singular absence of any observed property of the world that can be identified *unequivocally* as the result of some interplay between general relativity and quantum theory" [150], writes Isham in his very readable discourse of basic issues in quantum gravity, which nevertheless goes on to identify motivations for studying the subject. From the quantum point of view:

- elementary particles described quantum mechanically experience gravitational interactions
- short-distance divergences in relativistic quantum field theory seem to require a cut-off at Planck energy
- either a consistent quantum gravity theory will necessarily unify *all* fundamental forces, or any consistent unification of non-gravitational forces will necessarily require GR

While from the general relativists' perspective:

- predicted pathological spacetime singularities may yield to an appropriate quantum description
- blackhole evaporation is a quantum phenomenon; quantum gravity is needed to understand high energy phenomena generally and the fate of matter undergoing extreme gravitational collapse; similarly, quantum gravity is needed to understand the origin, early state, and possible ultimate fate of the Universe

- GR is mute to explain 3+1 macroscopic spacetime dimensionality and possible higher dimensions at the Planck scale

The era of classical Newtonian physics was founded on quite nâive conceptions of material objects and the dynamics of their interactions in a fixed, absolute, and passive arena. Those conceptual foundations were radically modified during the early 20th Century by Einstein's relativity and quantum theory – the two great pillars on which modern physics stands [151]. Despite their respective shortcomings and open problems, the theories have nevertheless obtained solid successes in their particular domains, gathering an impressive array of experimental corroboration. However, while each claims to be universal in that they both attempt to discover the deepest laws and to probe the most basic levels of reality [152], it has become increasingly apparent that such is not the case and, at best, they might be considered complementary descriptions. For several decades, the 'holy grail' of modern physics has been the successful integration of these two theories into a single all-embracing unified theory – to bring together the principles of quantum theory and gravity, in the first instance unifying gravity with the electro-weak and strong interactions, thereby to attain a theory of quantum cosmology (QC) with the hope of discovering the deepest laws and probing the most basic levels of matter [31, 152, 153, 154, 155].

According to Rovelli, the group of fundamental laws of GR and the standard model, while falling short of providing a satisfactory global picture of Nature, is "perhaps the best confirmed set of fundamental theories after Newton's universal gravitation and Maxwell's electromagnetism" [151]. That may well be so, but his next claim that "there aren't today experimental facts that openly challenge or escape this set of fundamental laws" [151] is more than extravagant – it is wrong, as evidenced by the various problems outlined previously in §2.2.1 and §2.3.2 beginning, respectively, on pages 34 and 49. In a not dissimilar vein, Sorkin [156] holds the view that

> "...both Quantum Theory and General Relativity are consistent with the facts they were created to explain, but they are not consistent with each other. That this contradiction is purely internal to theory has meant until very recently that only people with a philosophical bent have taken the quantum gravity (QG) problem very seriously ... Recently this neglect has given way to intense interest; but it still cannot be said that we have any direct conflict between experiment and accepted theory to guide us."

Regrettably, many physicists (fortunately, not all) exhibit this catechistic perspective on 20th Century physics, apparently with faithful conviction that there are no profound deficits, merely notional difficulties that, implicitly, must eventually yield to yet more intense mathematization in preference to a radical review of the basic theoretical tenets and conceptual underpinnings of extant methods.

Quantum theory, with its problems of interpretation, has challenged general relativity perhaps more so than vice-versa, eliciting – even demanding – the possibility of new meanings for such ideas as space, time, causality and matter, and presenting the physics community with the major difficulty of unifying this theory with that of relativity [149]. As a 'working definition', quantum gravity may be taken as a theory that describes the structure of spacetime and the effects of spacetime structure down to sub-Planckian scales for systems containing any number of occupied states [157]. Butterfield and Isham provide a comprehensive and eloquent exposition on quantum gravity [158] from which the following categorization of four major approaches (similarly to earlier presentations by Isham [150, 159]) is quoted:

1. ***Quantise general relativity*** ... usually taken to be quantisation of the metric tensor regarded as a special type of field. In practice, the techniques that have been adopted fall into two classes: (i) those based on a spacetime approach to quantum field theory – in which the operator fields are defined on a four-dimensional manifold representing spacetime; and (ii) those based on a canonical approach – in which the operator fields are defined on a three-dimensional manifold representing physical space. [This category includes the Loop Representation of Quantum Gravity [160, 161], where knot theory is central.]

2. ***General relativity as the low-energy limit of a quantization of a different classical theory*** ... general relativity might emerge as a low-energy (large-distance) classical limit of a quantum theory, that is given to us as a quantization of a different classical theory ... this type of approach is exemplified by the main current research programme: superstring theory, which quantizes a classical 'string theory' and yet has general relativity as a low-energy limit ... However, superstring theory is by no means the only example of this type of approach ... there have been more radical attempts to quantise aspects of space, or spacetime, itself. For example, there have been several attempts to construct a quantum theory of topology; and there have been attempts to quantize causal structures in which the underlying set is discrete.

3. ***General relativity as the low-energy limit of a quantum theory that is not a quantization of a classical theory*** ... it is certainly reasonable to consider the construction of a quantum theory *ab initio* with

no fundamental reference to an underlying classical theory [an example of this category is the concept of spacetime quantization, dating from the 1940s with Snyder's proposal to replace spacetime coordinates with non-commutative operators [162, 163] cited in [148]] – for example as a representation of some group or algebra [for example Quantum Groups, an example of what mathematicians call a deformation [148]] ... recent developments in understanding the non-perturbative aspects of superstring theory suggest that this type of approach may well come to the fore...

4. ***Start ab initio with a radically new theory***. The idea here is that both classical general relativity and standard quantum theory emerge from a theory that looks very different from both. Such a theory would indeed be radically new... presumably by not being a quantum theory, even in a broad sense – for example, in the sense of states giving amplitudes to the values of quantities, whose norms squared give probabilities. ... [This approach] is often motivated by the view that the basic ideas behind general relativity and quantum theory are so fundamentally incompatible that any complete reconciliation will necessitate a total rethinking of the central categories of space, time and matter. [Topological Quantum Field Theories, introduced by Witten [164], various lattice models of gravity, 'It from Bit' information and cellular automata theories, and *pregeometric* theories tend to belong to this category, though some are more properly to be associated with the second category.]

The conception of *Process Physics* belongs to the last category, not merely because GR and the quantum theory are "fundamentally incompatible" [150, 159] but more so because of the essential and unresolved problems intrinsic to each. In *Process Physics*, as will ultimately be shown in Chapter 8, general relativity (or, rather, an equivalent description modulo the gravitation flaws) and quantum theory emerge as higher level measurement theories without the necessity of a forced marriage of the two, this last being an endeavour that, from the perspective of *Process Physics*, is an ill-fated, though understandably motivated, contrivance.

2.4.1 The problem of time

Carnap wrote of Einstein [165],

> Once Einstein said that the problem of the Now worried him seriously. He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics. That this experience cannot be grasped by science seems to him a matter of painful but inevitable resignation. I remarked that all that occurs objectively can be described in science: on the one hand the temporal sequence of events is described in physics; and, on the other hand, the peculiarities of man's experiences with respect to time, including his different attitude toward past, present and future, can be described and (in principle) explained in psychology. But Einstein thought that scientific descriptions cannot possibly satisfy our human needs; that there is something essential about the Now which is just outside of the realm of science.

One of the key conceptual problems for theoretical physics is the problem of time in quantum cosmology. First recognized in the 1950s, it has continued to resist solution, despite numerous and varied attempts [166, 167, 168] and the "embarrassing situation of not knowing 'what is time' in the context of quantum gravity" [169] has given rise to much debate. Time is treated disparately in quantum theory and GR. Standard quantum theory is constructed on an assumed fixed causal structure where time is treated as part of a fixed theoretical background structure in the sense of classicality, in the sense of non-dynamicism, and in the sense that it is treated in the same way in all quantum models; in GR time is fixed only in the sense of classicality: it is not the same in all models, and it is dynamic, since the model-dependent and dynamic spacetime geometry dictates time-like vectors [92].

In GR-motivated approaches to quantum theory, the metric tensor establishes the causal structure of spacetime so quantum fluctuations of the latter cannot be escaped by the former. So, too, if the metric turns out to be but a coarse-grained idealization then likewise the causal structure. The rôle of measurements made by an observer is central to both classical and quantum physics but in GR an observer is synonymous with a time-like curve and the meaning of 'time-like' depends on the metric of spacetime, so that an attempt to quantize gravity serves also to quantize observers, rendering the standard interpretation problematic [150].

This is the 'problem of time' and causality, already discussed by philosophers (see, for example, [170]). Whether time is 'real' or merely a means to perceive reality might be regarded as a question of viewpoint: from an internal perspective, time is a local and "inexorable primary precept" that carries both observer and observed from present moment to present moment, lacking both velocity and direction but for a (possibly remembered) history, whereas for an external observer time becomes global and contextual [171]. According to Wheeler[6], 'time' is in trouble because "no difficulties are more central than those associated with the concept of 'time' " [172] – on the cosmological scale, time appears to be bounded by the inevitability of Big Bang and Big Crunch singularities whereas quantum theory, as it is presently understood, abandons causality and denies meaning to the concept of 'before' and 'after' on the microscopic scale. One propounded resolution of the former problem is the Hartle and Hawking 'no-boundary' proposal in the Euclidean approach to quantum gravity, based on imaginary time (which behaves like another direction in space), to model quantum cosmogenesis [173]. Here 'real' time is emergent; at the extremum points where singularities are encountered, 'real' time devolves into the Euclidean imaginary time domain where there is no singularity. However, the no-boundary proposal remains problematic because it avoids the 'problem of time', to the solution of which it makes no contribution [92].

Kauffman and Smolin [168] presented an argument against the notion that time is fundamental that proceeds along the following lines. Classically, the object of one's interest is a system that is a sub-system of the Universe; an inertial observer standing outside the system uses a clock to mark and label the trajectory of the system in some configuration space, so that classical trajectories are extrema of some action principle and each possible trajectory exists in its entirety as a curve on the configuration space. Intrinsically, there is nothing about the specification of those trajectories that corresponds to a 'flow' of time (there is no flowing time in Newton's equations of motion, for instance – the t refers to the observer's clock as a parameter of the description of the observation, not some inherent property of the system being

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[6] "Time is what prevents everything from happening at once. Space is what prevents everything from happening to me." - attributed to John Archibald Wheeler

modelled).

The situation in quantum mechanics is similar. The time-dependent Schrödinger equation is always separable and the t assigned to a quantum state is again merely a label that obtains from an external clock. In an essential sense, then, the responsibility for giving a real, physical representation to time is abrogated in classical and quantum physics in favour of a simple labelling device; the device works well enough for practical purposes, since one set of consistent labels is as good as any other and there is no need to be concerned about time in any absolute sense. However, when it comes to cosmological considerations, there is no external clock to which one can appeal. Any cosmological theory then is required to find expression without reference to any particular parameterization of trajectories, no parameterization has any physical meaning, and 'time' disappears from the formalism. This leads to a re-statement of the 'problem of time' [168], either

- find an interpretation of the standard theory that restores a rôle for time; or
- find an interpretation whereby time appears in the classical limit but is absent from a fundamental description of the world.

These objectives are problematic in and of themselves: (a) one cannot restore that which was never present: the requirement really speaks to labelling; and (b) why aspire to obtain in the classical limit that which is absent from the classical formalism? The latter point highlights an important consideration – there are *two* problems for time: one is the problem *of* time, thus far discussed; the other is the problem of the *emergence* of time. In quantum gravity research, it is an implicit assumption that 'time' is an emergent feature (indeed, as revealed in Chapter 6, that view initially prevailed in the early development of *Process Physics*) but, like any assumption, it is open to challenge.

The *real* problem of time is thus exemplified – 'time' is a slippery and ill-defined concept, no less so in physics than in philosophy and metaphysics ("What is time? I know what it is, but when you ask me I don't." – Augustine of Hippo). A central goal for physics surely must be to afford 'time' a sensible and consistent definition: an aspiration that is surely inseparable from the task of achieving a truly fundamental description of reality, whereby the proper culprit, spacetime, is revealed as a phenomenological construct.

2.4.2 Quantum gravity and quantum cosmology in crisis?

The following quoted extracts (obviously, not an exhaustive list) pertaining to quantum gravity speak for themselves:

- "... there are fundamental contradictions between the formulation of quantum field theory and that of general relativity" [31].
- "General relativity and quantum mechanics are the two most important and comprehensive theories of contemporary physics. ... [but] these two comprehensive theoretical structures appear to be mutually incompatible, that they seem to involve different – and contradictory – assumptions about the nature of space, time and causality" [174].
- "[there is] profound tension between the foundational principles of our two most fundamental physical theories – general relativity and quantum mechanics ... [the] incompatibility ... is so severe that the unflinching orthodox view maintaining a status quo for quantum superpositions – including at such a special

scale as the Planck scale – is truly baffling. ... The orthodox response to the conflict is to hold the fundamental principles of quantum mechanics absolutely sacrosanct at the price of severe compromises with those of Einstein's theory of gravity" [175].

- "Matter and space-time are the fundamental entities of our description of nature. Why do particles have the masses they have? The quantum theory of the electromagnetic, weak and strong nuclear forces cannot answer the question. Why does space-time have three plus one dimensions? ... One concludes that the description of nature by these theories is still incomplete" [52].
- "... there is arguably still no definitive proof that general relativity has to be quantized in some way" [150].
- "Some deep questions
    - What is the rôle of time in quantum gravity?
    - What is the rôle of a fundamental constants in the physics of the microscale?
    - Why do the fundamental constants have the relative values we observe?
    - Is there a structural breakdown of manifolds at the extreme microscale? Do topological fluctuations and/or manifold fluctuations and/or dimensionality fluctuations exist in quantum gravity? If so, how are these types of fluctuations implemented in the theory? Is the microscale described better in terms of a discrete structure than a continuous manifold? If so, what is the nature of this discrete structure?

  - Why is classical space-time 4-dimensional? Why does classical space-time have a local Minkowski structure? What is the origin of classical law?
  - What is the rôle of matter in quantum gravity? How can gravity be unified with the other forces of nature?
  - If singularities are avoided by quantum gravity, how does this avoidance manifest itself?

  "The difficulties presented here, coupled with the failure to find satisfactory solutions to them despite numerous attempts, lead to the unavoidable conclusion that the development of a theory of quantum gravity must be approached from a radically new direction. Pregeometry as proposed by Wheeler, may be the key to defining that direction" [176].

- "Attempts to formulate a quantum theory of gravitation have not met with success to date [150]. The main attempts have been based on:

  1. Perturbation theory based on expansions about Minkowski spacetime
  2. Canonical Hamiltonian formalism
  3. Path integral formalism
  4. String theory.

  [The author gives specific shortcomings of each]" [177].

- "... quantum gravity without topology change manifests in general an infinity of physically inequivalent quantum 'sectors', an embarrassment of riches which seems at odds with the conception of quantum gravity as a fundamental theory" [178].

- "... experimental evidence according to the expectations determined by the standard model, is not very well supported at all, because ... most testable predictions have all failed to be confirmed so far. ... comparing this lack of success with the considerable success the standard model had in the past, leads to the assumption that there might be some principal limit to further following this path" [179].
- "It is unfortunately true that we do not yet have a completely satisfactory quantum theory of gravity" [180].
- "So far, no approach to quantum gravity can claim even a single piece of experimental evidence" [151].
- "... the author offers the following problems in quantum cosmology:

  Problem 1: What principle determines the initial condition of the Universe?

  Problem 2: How can quantum gravity be formulated for cosmology?

  Problem 3: What is the generalization of quantum mechanics necessary for quantum gravity and quantum cosmology?

  Problem 4: What are the definite predictions of the initial condition for the Universe on large scales?

  Problem 5: What are the definite predictions of the initial condition for features of the Universe on familiar scales?

  Problem 6: What are the definite predictions of the initial condition on microscopic scales

Problem 7: What does quantum cosmology predict for IGUSes[7]?

Problem 8: Is there a fundamental principle that would single out both a unified dynamical law and a unique initial quantum state for the Universe? Could that same principle single out the form of quantum mechanics from among those presented by generalized quantum theory?" [181].

- "The problem [that time is not present in a quantum theory of cosmology] is one of the key conceptual problems faced by theoretical physics at the present time. Although it was first raised during the 1950's, it has resisted solution, despite many different kinds of attempts ... one wants any theoretical construction that we use to describe the universe to be something that can be realized in a finite time, by beings like ourselves that live in that universe. ... One of the things we would like to demand of a quantum theory of cosmology is that it not make any reference to anything at all that might be posited or imagined to exist outside the closed system which is the universe itself" [168].

There can be no doubt that the majority of research effort expended on quantum cosmology stems from efforts to derive (or contrive) a quantum theory of gravity. Nor can one doubt the brilliance of mathematical sophistication exhibited by physicists engaged in this work. But clearly quantum gravity is extraordinarily difficult, being problematic not only in terms of mathematical methods but also in terms of profound conceptual and philosophical concerns and there is little in the way of empirical evidence to serve as a guide. Moreover, present day physics is, in many ways, a "victim

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[7] IGUS: information gathering and utilizing system (e.g. humans, bacteria, and certain computers). IGUSes are complex adaptive systems in the context of quantum mechanics.

of its own success" [92] and for many it will not be easy to give ground so that present theories might be reconciled or replaced. But it is inevitable that concessions must be made: the collective endeavours of the best minds produced by the human species surely amounts to many of millennia of thought, yet the problems of quantum gravity and quantum cosmology appear little closer to a meaningful resolution. Even the most conservative of physicists must at least begin to ponder whether the questions posed by the main-stream approaches admit the possibility of a sensible answer. Or whether the wrong questions are being asked.

2.4.3 Lessons from quantum gravity and quantum cosmology

The problems listed above notwithstanding, it is a fundamental principle of science that most advances proceed from observations revealed by problems and failures. It is no small task to survey the literature emanating from the various quantum gravity and quantum cosmology research programmes undertaken over the past forty or so years, let alone to gain mastery of the vast array of technical and philosophical issues that pertain to each endeavour, at least sufficient to authoritatively re-state and summarize those activities. Fortunately, there are numerous excellent accounts such as that of Butterfield and Isham cited above (and related works by those authors). Another is Gibbs's invaluable essay [148]. Since the pursuit of *Process Physics* is not about quantizing gravity *per se*, rather than attempt here to emulate those laudable literary efforts, it will suffice to 'skip to the chase' and relate such consensus as may be found illuminating for the present purpose.

Quantum gravity, the yet-to-be-built quantum theory of gravity, suffers from problems [150, 158, 159] that have remained unsolved for decades and, in spite of some progress, the goal appears now as elusive as ever it was [182]. The difficulties are conceptual, mathematical and, in current approaches, severe: the framework of present theories involving standard concepts of space and time is likely to have a complicated and unfamiliar relationship to the corresponding concepts forming the framework of any successor theory [158]. The problems originate both in the fundamental contradictions between the formulation of quantum field theory and that of general relativity [31] and also in that, unlike any other physical interaction, the reference frame for gravity is spacetime itself, which is a passive frame for all non-gravitational interactions. When gravity is brought into play, the spacetime frame becomes dynamical, experiencing the quantum fluctuations of the other interactions as well as introducing, with even greater effect, its own fluctuations, thus becoming an active agent in the theory [183, 184, 185, 186].

Discreteness

That the world might be discrete rather than continuous stems at least from the time of Zeno (see §1.2 on page 11) since when mathematics and physics have endured an uneasy dichotomy between the continuum and the discrete – with rational versus irrational numbers, with idealized quantities versus discrete measurements, with the apparent smoothness of space and time versus atomic divisions of matter. Riemann remarked on the disparity between the mathematical properties of the real numbers and measurement [187]. He had earlier observed [188] that

> "... it seems that the empirical notions on which the metrical determinations of space are founded, the notion of a solid body and of a ray of light, cease to be valid for the infinitely small. We are therefore quite at liberty to suppose that the metric relations of space in the infinitely small do not

> conform to the hypotheses of geometry; and we ought in fact to suppose it, if we can thereby obtain a simpler explanation of phenomena".

Early justification for small-scale discreteness of space-time was largely metaphysical with the only 'evidence' being the fact that physical measurements do not precisely correspond to the mathematical properties of real numbers. The atomic structure of matter, the unexpected discovery of discrete quanta in the properties of matter, and the Heisenberg Uncertainty Principle led physicists of the 1930s to speculate that spacetime may be discrete. Heisenberg noted that physics must have a fundamental length scale and in 1936 Einstein stated [189] that

> ... perhaps the success of the Heisenberg method points to a purely algebraic method of description of nature, that is, to the elimination of continuous functions from physics. Then, however, we must give up, by principle, the space-time continuum ...

Increasing numbers of modern physicists contemplate that a granularity of apparently continuous quantities is a universal feature of nature [156] and it is well recognized now that the usual notions of space and time will have to be relinquished, at least at the Planck scale, where most models agree that space and time should become discrete. That is, the continuum of general relativity must be viewed as an idealization of a deeper discrete structure [148, 190, 191], for which continuum quantum gravity can hope to provide only an effective low-energy description [178]. A major reason for this view is the problem of infinite amplitudes and the need for renormalization in quantum field theories and also singularities arising from infinite spacetime curvatures in GR [156], with supporting evidence for discrete spacetime coming from the quantization of general relativity [192, 193], string theory [194]–[199] and the thermodynamics of black holes [200]–[205].

Some of the most compelling evidence for discretisation comes from Hawking (ironically, since he is not a proponent of discrete theories[8]) in his work with Bekenstein on black hole thermodynamics [207, 208, 209, 210] and the black hole information loss paradox [211], where one approach supposes that no more information enters a black hole than can be displayed on the event horizon and that it comes back out as the hole evaporates by Hawking radiation. Bekenstein has shown that if such is the case then, counter-intuitively, very strict limits must be placed on the amount of information held in a region of space [148, 212, 213].

The discreteness-continuity debate is "an ancient tension in natural philosophy that re-emerges in every era in new dress" [38], as Barrow puts it. He goes on to emphasize the immense difference in complexity engendered by these disparate approaches: possible continuous transformations between sets of real numbers are an order of magnitude fewer than possible discontinuous (discrete) transformations; the 'laws of physics', in their present form, are a subset of all continuous transformations and, similarly, a discontinuous world would necessarily draw its 'laws' from a pool of possible transformations that is vastly greater in scope. Being less constrained, it must admit greater possibilities and be "infinitely more complex in its potentiality"

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[8] In a lecture given by Stephen Hawking as part of a series of six lectures with Roger Penrose on the nature of space and time sponsored by Princeton University Press, Hawking said, "Although there have been suggestions that space-time may have a discrete structure I see no reason to abandon the continuum theories that have been so successful." [206]. One must be suspicious of this view, though – not the least because many physicists clearly do not share Hawking's optimism as to the 'success' of continuum concepts, particularly in the context of work in quantum gravity and quantum cosmology.

([38], page 37). Smolin [180] notes that, from the outset, a principal theme of quantum gravity has been the hypothesis that the combination of general relativity and quantum theory leads to a discreteness of the geometry of space or spacetime and that substantial modifications in sub-Planckian scale physics have been necessary in all of the quantum gravity endeavours that have enjoyed even partial success, suggesting an ultimately discrete spacetime structure (which raises the question of consistency with Lorentz invariance though, in fact, that had been answered by Snyder in 1947, "It is usually assumed that space-time is a continuum. This assumption is not required by Lorentz invariance. In this paper we give an example of a Lorentz invariant discrete space-time" [162]).

The conclusion has been reached by many different routes that there exists a fundamental minimum length, a lower bound to any output of a position measurement, so that any notions that rely on a metric structure (including notions of distance and causality) have no meaning at the Planck scale; Garay has reviewed several scenarios that yield this conclusion as a consequence of uncertainties due to measurement-induced quantum fluctuations of the gravitational field and found that this 'lower bound' seems to be a model-independent feature of quantum gravity [183]. Sorkin clearly states that discreteness applies to space*time*: "in the 'deep quantum regime' of very small distances, gravity is no longer described by a tensor field living on a continuous spacetime manifold (the metric field). Rather, the notions of length and time disappear as fundamental concepts, and the manifold itself dissolves into a discrete collection of elements related to each other only by a microscopic ordering that corresponds to the macroscopic notion of before and after" [156]. 't Hooft [93] has shown that certain discrete systems following deterministic rules can evolve chaotically and so mimic, by coincidence with quantum statistics in their long distance behaviour, quantum mechanics and quantum field theories, thus bypassing the “nâive and wrong approach of reducing quantum mechanics to a deterministic theory with hidden variables” [214]. Such conjunction of uncertainty and discreteness is a well established feature of non-linear dynamical and complex systems that display resultant stochastic behaviour. So too, stochasticity appears to be a feature of quantum gravity.

Stochasticity

Besides the measurement-induced fluctuations noted by Garay, there is another source of uncertainty – the quantum fluctuations of the gravitational field due to the effect on the source of the field of the Heisenberg uncertainty relations. The idea, proposed by Calogero [215], augmented by De Martino, De Siena and Illuminati [216], and mentioned earlier by Nelson ([121], p.65), is a simple and quite appealing (from the classical view-point) source of the quantum.

Quantum uncertainty in the position and momentum of a massive particle implies uncertainty in its gravitational interaction with all other matter-energy and thus uncertainty in the geometry, which in turn affects the position of the particle and creates further uncertainty. Another way of thinking of this is that quantum fluctuations *weigh*, as evidenced by the Casimir effect, and thus should affect the evolution of the geometry in the same way as matter forms and gravity [182]. The result is that the geometry is subject to intrinsic quantum fluctuations, as distinct from measurement-induced fluctuations [184, 185] – though the distinction must in some way be artificial, since Mach’s principle implies that the universal gravitational interaction means that, in some sense (at least), no massive particle can escape measurement-induced fluctuations (both in the direct sense that the universal interactions may be viewed as mutual 'measurements', and in the indirect sense that an observer-mediated measurement of a single particle is felt by all other matter in the Universe). This is the random *zitterbewegung* [216] that every particle experiences due to its interaction with the stochastic background gravitational field of the Universe (itself caused by all other particles of the Universe and their motions), generating a chaotic component in the motion of each particle.

In Calogero's approach, Planck's constant of action h, rather than being a fundamental 'constant of Nature', is derived to correct order of magnitude. Calzetta took up a similar theme in the context of noise induced inflation and there geometry is regarded as "an open system evolving in the environment provided by the matter quantum fluctuations" [182], where the evolution is a non-equilibrium dissipative process and the noise of stochastic quantum fluctuations is taken to be a Gaussian source, as this is the only form compatible with the fluctuation dissipation theorem [217]. In the De Martino *et al* reformulation, *zitterbewegung* becomes a 'universal Keplerian tremor' in the form of a *fractal* spacetime relation – equivalent to a generalization, on the microscopic scale, of Kepler's third law – and the Calogero fluctuative hypothesis is shown to be universal, holding for systems with few degrees of freedom (rather than the N elementary components of which the Universe is said to be comprised, as in Calogero), and applying to all known interactions as well as those of gravity, leading in all cases to formulas again "linking Planck's constant with the proper fundamental constants associated to each considered interaction" [216].

Dimension, Topology, Foamy Spacetime, and Information

One interpretation of current string theories is that their lack of geometric foundation suggests that spacetime must be dynamical not only in the sense of fluctuations but also being capable of dimensional and topological changes [218, 219, 220]. Knots are topological objects and examples such as the central rôle of knot theory in the Loop Theory of Quantum Gravity and topological field theory [160, 161] and the relationship between Quantum Groups and knot invariants [221] lend further support to the idea that dynamical topological properties should be a key feature of fundamental spacetime notions.

The conjecture that spacetime could be subject to topology fluctuation at the Planck scale was first put forward by Wheeler in 1957 [222, 223] with the notion of 'spacetime foam', which has become a ubiquitous conception of high-energy physics in many contexts; see, for instance, [38, 154, 156], [183]–[186], [214], [224]–[232]. According to Hawking, "One would expect spacetime to have a foamlike structure on the Planck scale with a very high topology" [233]. Since Wheeler's initial proposal, various components have been suggested, such as simply connected topology fluctuations manifesting as virtual black holes [154, 226, 233], simply connected topology fluctuations manifesting as virtual wormholes [154, 183, 234, 235], and inflationary bubbles [224, 236], with the spacetime foam frequently envisaged as "an ensemble of vacuum bubbles, or cells of spacetime, each characterized by its own geometric phase and vacuum energy density" [224]. Garay employs a graphic metaphor: "quantum fluctuations of the metric would convert spacetime into a boiling magma in which topology change is continuously happening" [183]. These Planck-scale topological fluctuations are attributed with microscopic event horizons and are said, by Ellis, to "appear spontaneously out of the vacuum and subsequently evaporate back into it" [226] – another colourful description but conceptually misleading without a careful definition of 'vacuum': the terminology suggests that the foamy aspect is regarded here as a defect structure secondary to an idealized smooth background (like the bubbling of boiling water).

Zhuk [237] has noted that quantum fluctuations in the metric might result in 'baby universe' connectivity due to spacetime foam in the 'conventional' sense and, moreover, added the speculation that at Planck distances spacetime may have complex topology and dimensionality greater than four, giving rise to 'topological foam' and a *topological fractal* structure of the Planckian multi-dimensional universe.

The foaminess of spacetime is taken by Ng and van Dam to be real, with phenomenology potentially accessible to measurement with gravity-wave interferometers. They note the properties of spacetime foam to include [228]:

> (i) decoherence phenomena
>
> (ii) a simple connection between spacetime quantum fluctuations and the holographic[9] principle
>
> (iii) metrics can be defined only as averages over local regions [which] gives rise to some sort of non-locality ... we would not be surprised if this feature of non-locality is in some way related to the holographic principle

This insight that Planckian and sub-Planckian physics may correspond to some sort of *information theoretic* schema is now widely shared, for example, by Dzhunushaliev,

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[9] The holographic principle is a speculative conjecture, proposed by 't Hooft and improved and promoted by Susskind. about quantum gravity theories claiming that all of the information contained in a volume of space can be represented by a theory that lives in the boundary of that region. In other words, if you have a room then you can model all of the events within that room by creating a theory that only takes into account what happens in the walls of the room. The holographic principle also states that at most there is one degree of freedom per Planck area in that theory, implying a limit on information density so that a fundamental particle is actually a *bit* (1 or 0) of information. [238]

who associates non-differentiable structures of the spacetime foam with the Kolmogorov algorithmic complexity [239] of those structures as a measure of the topology change they induce [225]. Outside of cosmology and gravitation, the connection between information theoretic principles and quantum theory are well known, for example [240, 241], and there is a very active school of thought that looks to information theory to provide an ultimate understanding of the laws of physics [148] at the deepest level. The amount of information in any physical system is related to its entropy, with the basic unit of information being the binary digit (*bit*), and Wheeler famously enunciated the basic philosophy of this line of enquiry: "every physical quantity, every *it*, derives its ultimate significance from *bits*, a conclusion which we epitomise in the phrase, *It from Bit* " [242]. According to Wheeler, spacetime is to be understood in terms of more fundamental *pregeometry* [243, 244, 245] – a deep, information theoretic conception in which there are no direct notions of causality, dimension, or physical law, and from which the apparent endophysical[10] structure of spacetime, with its geometric, quantum, relativistic, and classical properties, must be an emergent feature as a coarse-grained idealization.

The answer to how this might be achieved lies, in part, in an understanding of algorithmic information theory (particularly algorithmic complexity) and the general behaviour of complex adaptive systems that exhibit *universality*, together with recognition that physical law finds its origin and meaning in the universal behaviour of a very general class of complex systems [148]. Ultimately, the goal is to implement Wheeler's programme of "*law without law*" [250]:

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[10] 'Endophysics' (literally, 'internal physics') is a concept originated by Finkelstein and Finkelstein [246] and Rössler [247]. Kampis provides a lucid description in [248]; see also [171] and [249] by that author.

> ... particles, fields of force, spacetime, and 'initial conditions' are only intermediate entities in the building of physics... at bottom there is no 'law' ... What is the order that we seek to understand? The structure of spacetime and the particles and fields... What is the order out of which, in my view, we must hope to see this structure built? The higgledy-piggledy, the randomness, the unpredictability of billions upon billions of elementary quantum phenomena, each unlocalized in space and time... the laws and initial conditions of physics arise out of this chaos by the action of a regulating principle the discovery and proper formation of which is the number one task of the coming third era of physics.

Wheeler's "third era" finds correspondence in the comment of Witten, while contrasting the classical, quantum, and the string theory views of physics and speculating on a full theory that would incorporate notions from each: "Contemporary developments in theoretical physics suggest that another revolution may be in progress, through which a new source of 'fuzziness' may enter physics, and spacetime itself may be reinterpreted an an approximate, derived concept" [251].

If spacetime is to be derived, then derived from what? One view is the evaporation of the spacetime condensate at or near the Planck scale, leaving a 'vacuum' characterized by an effective *fractal* geometry [252]. From whence could such fractal geometry arise, if not from some *pregeometry*?

2.4.4 Pregeometries

There have been many approaches tried under the umbrella of 'pregeometry', often with intricate relationships between many of them, but the main classes can be summarized [148] (in no particular order):

- quantized spacetime
- cellular automata
- lattice field theories
- quantum metric spaces
- causal nets
- poset models
- simplicial quantum gravity
- topological quantum field theory
- field theory on a cell complex
- non-commutative geometry
- event-symmetric spacetime
- inflationary bubble cosmology

Without recounting details of these various programmes, it will suffice to say that while most have intriguing elements, they also, without exception, carry flaws or limitations in one or more of the following forms, inasmuch as they purport to provide a viable and *fundamental* alternative to more conventional approaches:

1. lack of justification for the axioms and assumptions of the proposal

2. existence of hidden philosophical/metaphysical/mathematical assumptions
3. insufficiency or incompleteness – the proposal lacks scope, raises more questions than are answered, or is effective as a 'toy' model but cannot be realized more comprehensively
4. excessive richness of construction – it is difficult to imagine how the proposed schema might arise *ab initio*

One of the more intriguing scenarios, in that it contains many aspects that resonate with the emergent cosmological-scale features of *Process Physics*, is the 'self-reproducing inflationary universe' (an inflationary bubble cosmology) of Linde [236] (one of the originators of inflationary theory first proposed by Guth). However, the model *assumes* some cosmogonic event yielding scalar fields, upon which the rest of the theory is constructed, thus it fails as a fundamental theory according to the second and/or third criteria above. Nonetheless, Linde's model along with other endeavours in pregeometry have contributed much, albeit indirectly, to the thoughts leading to the development of *Process Physics.*

2.5 Concluding remarks for paradigms in physics II

The two pillars of modern physics, relativity and the quantum, inherited and advanced the Newtonian mathematical tradition to great effect, with many worthy and indisputable achievements. Nonetheless, each pillar suffers flaws and inconsistencies that appear incapable of resolution without a radical revision of their founding principles and assumptions. Moreover, each pillar is, in essence, a theory of measurement for its domain, ill-equipped to reveal much of the 'why' and their ontology is meagre, at best. The goal of physics has always been to attain a profound understanding of Nature and reality at their very deepest yet modern physics is stymied, possibly impotent, in the face of apparently irrefutable, profoundly difficult and irreconcilable differences between GR and quantum theory, and the rigid, albeit impressive, edifice of mathematical formalism that holds sway – a predicament that is further frustrated by the strident appeal to our everyday physical world-view of continuity and the continuum model of spacetime. Quoting Manthey [253]:

> Lacking the compass of a trustworthy mechanism, we have been collectively doomed to purblindly wander the jungles of mathematics, as Einstein well appreciated. For mathematics, in spite of appearances, does not really describe *how* things happen, but rather only their essential *what*.

Within the great difficulties, however, and the efforts of those who have toiled to overcome them, lie clues to progress by way of a different approach:

- turn from the objective to the relational
- surrender geometry, the continuum, and spacetime as fundamental concepts
- acknowledge the primacy of the discrete, the random and the stochastic
- accept the precept of 'law without law'
- attend to the science of complexity

and try again, guided now by considerable prior knowledge of the physics that must emerge on the classical side of the Planck scale. Most importantly, if there is in mathematics an "unreasonable effectiveness" in its application to the natural sciences

[254], ask why it has seemingly failed physics now, in the pursuit of the ultimate unification of the laws of physics.

The answer to *that* question, as will be seen, is perhaps the greatest clue of all.

Chapter 3

Complexity

We are star stuff. We are the universe made
manifest trying to figure itself out.
– Mira Furlan, Babylon 5

3.1 Introduction

Just as GR and quantum theory provide disparate views of the Universe, so too there is confrontation in the duality of description between the static view of classical dynamics and the evolutionary view associated with entropy [66]. The highest aspiration for classical dynamics is encapsulated by the words of Helmholtz [255]:

> The problem of the sciences is, in the first place, to seek the laws by which the particular processes of nature may be referred to, and deduced from, general rules... We are justified, and indeed impelled in this proceeding by the conviction that every change in nature must have a sufficient cause ... until we at length arrive at final causes which are unchangeable, and which therefore must ... produce the same invariable effects. The final aim of the theoretical sciences is therefore to discover the ultimate and unchangeable causes of natural phenomena.

For the classical dynamist, the irreversibility of thermodynamics seemed impossible to reconcile until Boltzmann introduced to physics the laws of probability, associating with macroscopic phenomenology the collective properties of ensembles of microscopic entities. The inception of thermodynamics combined with Boltzmann's 'order principle' and his invention of statistical mechanics marked a new age in physics and the birth of the science of complexity. Mathematical biologist Robert Rosen [256] took the position that 'simple' and 'complex' systems are of a fundamentally different character, not "merely quantitatively different values assigned to a single system attribute", with distinctions between the two providing challenges for basic issues in the theoretical sciences generally, and for physics in particular. He defined a simple system as a system whose mathematical images are dynamical systems, the class of which contains a unique maximal image, which behaves like a free object. In contrast, there is no such maximal description of a complex system – it is one which possesses mathematical images that are *not* dynamical systems. It was Rosen's further view that, in particular (*op. cit.*),

> ...contemporary physics is essentially the science of simple systems, and is neither directly applicable nor adequate for natural systems... the problems associated with complex systems, particularly in biology, pose problems for contemporary physics at least as serious as those posed by e.g. atomic spectra or chemical bonding in the last century.

The purpose of this chapter is to recount and highlight the essential features and phenomenology associated with the concept of complexity[1], since an appreciation of the ethos embodied by these notions was central to the formulation of *Process Physics.*

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[1] For a particularly clear and complete analysis of compexity and randomness, beyond those aspects related here, the excellent account by Kampis [257] is highly recommended.

3.2 Complexity

Thermodynamics may be divided into three regimes – (i) equilibrium, where forces, fluxes, and entropy production all are zero; (ii) near-equilibrium, where the flux rates are linear functions of weak thermodynamic forces; and (iii) far-from-equilibrium, or the *nonlinear* region [66]. It is the third regime that holds particular interest. Far from equilibrium, a system may still evolve to some steady state, sustained by some connection with its environment, but the stability of the state and its independence from fluctuations cannot be taken for granted and 'unusual' things can happen. The laws of thermodynamics require that entropy, and thus the state of disorder or uniformity of the Universe must increase yet one can always find 'local' regions where, instead, it is order and complexity that increase. Such regions, or systems, exist only by drawing upon their environment – they cannot be isolated, or closed off, but open and out of equilibrium. Closed systems in equilibrium evolve towards a uniform state whereas open systems that are out of equilibrium can evolve towards states that display macroscopic order and patterns.

3.2.1 Far-from-equilibrium dissipative structures

Far from equilibrium, a steady state attained by the system can no longer, in general, be characterized in terms of some suitable potential such as, for example, entropy production required for near-equilibrium states, which would guarantee its stability (the second law of thermodynamics protects near-equilibrium states from fluctuations). Instead, a far-from-equilibrium system is exposed to fluctuations that may lead to new behaviour, where fluctuations may resonate or otherwise be amplified so that the system evolves towards a new regime that may be qualitatively quite different from the stationary states of minimum entropy production. That is, the order that can arise in non-equilibrium states is dynamic and 'interesting' in comparison to the uniform and uninteresting order of equilibrium states. Moreover, a profound feature of far-from-equilibrium states that give rise to pattern formation is that the emergent structures, when regarded as entities in their own right, may be possessed of characteristics that bear little or no resemblance to the characteristics of the substratum from which they derive.

The term '*dissipative structures*' was coined by Prigogine [66] to describe such systems operating far from equilibrium within an environment that exchanges energy, matter or entropy. An inflow is required to maintain the system out of equilibrium, while dissipation simultaneously decreases its entropy (while, of course, raising the entropy of the environment to a greater extent) and maintains stability by allowing excess energy or matter to be expelled. A simple example is that of Bénard cells, the convection cells that appear as liquid (say, water) is heated and which undergo a spontaneous and random symmetry breaking in their alternate clockwise/anti-clockwise rotations. Another example is vortices in fluids, the formation of which breaks the symmetry of the constituent fluid.

Such examples of non-equilibrium pattern formation, or creation of order, have some characteristics that are similar to second-order phase transitions in equilibrium systems. Firstly, in each case, pattern formation depends on a parameter exceeding some critical value; secondly, crossing that threshold value is marked by a change of symmetry; and thirdly, at transition long-range correlations (compared to the intrinsic or characteristic microscopic scale length) arise that allow self-organization at a collective level.

On the other hand, the two classes of phenomena differ in two specific ways: firstly, the state of an equilibrium system following the phase transition is unique, being determined by extremal principles, such as minimization of free energy, while for the dissipative system, the precise detail of how the symmetry will break is generally indeterminate (being usually very sensitive to small perturbations in the initial conditions – what has been termed the 'butterfly effect' associated with chaos); and secondly, away from the transition point the characteristic length scale of the new pattern in equilibrium systems returns to a value similar to that of the original structure, whereas the new patterns in non-equilibrium systems have no such relation. The typically large correlation lengths of dissipative structures is generally regarded as a typical example of an *emergent* property.

3.2.2 The creativity of noise

Return to the equilibrium or near-equilibrium configuration where there exists just one parameter-dependent steady state. Small (i.e. linear) perturbations will see the second law of thermodynamics impose a return to the attractor steady state. As the system is pushed further from equilibrium, it must eventually encounter the critical threshold for the control parameter, or what is termed the "thermodynamic branch" [66], to reach a 'bifurcation point', which may be, for example, enantiomorphism or 'handedness' in the breaking of symmetry. There is a random element determining which path the system will follow that cannot be predicted by any macroscopic governing equation.

Prigogine claims that far-from-equilibrium states are extremely sensitive to very small external fluctuations, that non-equilibrium amplifies or magnifies the effect of the source of those fluctuations, that "external fields can be 'perceived' by the system, creating the possibility of pattern selection" ([66], p.163). This situation gives rise to a standard far-from-equilibrium phenomenon, the coexistence of multiple stationary states (so, for instance, occurs the phenomenon of hysteresis, whereby the system can be 'pushed' from one stationary state to another). If now a formerly constant input is instead randomly fluctuating, the situation is changed radically and "the zone of coexistence between the two stationary states increases, and for certain values of the parameters coexistence among three stationary stable states becomes possible" ([66], p.166). The point here is that random fluctuations – noise, whether extrinsic or intrinsic – may fulfil a creative rôle, engendering new types of behaviour.

It is now well known that, while noise in dynamical systems is usually considered a nuisance, it is itself a signal and a free source of energy and in certain feedback nonlinear systems it can perform a useful, even a constructive and creative rôle. For example, in the phenomenon of '*stochastic resonance*' [258, 259] adding the right amount of noise can enhance the response of some nonlinear dynamical systems by amplifying a faint signal, even though too much noise can swamp the signal. The implication is that the optimal noise level in a system need not be zero and even that nonlinear signal systems with nonzero-noise optima may be the rule rather than the exception. There is a class of complex systems that employ *adaptive* stochastic resonance in a 'gradient-ascent learning' process to find the optimal noise level – operating as iterative mappings, the noise parameter is updated at each iteration [259]. Other examples of the constructive rôle of noise include fluctuation driven transport, Brownian ratchets, noise-induced phase transitions, and noise-sustained waves in sub-excitable media [260].

Whereas in stochastic resonance noise resonates with a given time-scale, transferring energy to the system at a characteristic frequency, a similar phenomenon called '*stochastic coherence*' induces coherence to the system but does not have any intrinsic length scale. These phenomena have been observed to exhibit noise-induced ordering phenomena both globally (synchronization) and locally; it has been suggested that stochastic coherence, in particular, may be related to structure formation in extended systems [261]; also, the presence of noise can help sustain structures which otherwise would have been absent in an evolving dynamical system [262]. Noise is an inexorable aspect of physical systems that is often ignored, or regarded merely as a troublesome interference in measurement; however, as Pattee stressed, not only is noise inevitable in all measurements, it is *essential* for evolutionary processes [263].

3.3 Complex systems, their properties and features

The study of systems far from equilibrium is no longer in its infancy, but it is yet young and much remains to be discovered. Such systems are generally categorized as *complex systems*, a broad term that also encompasses ideas and methods arising from chaos theory and such fields as artificial life, evolutionary computation and genetic algorithms. Although a relatively new field of research, a number of properties of complex systems have been identified:

1. ***Emergence.*** Perhaps the pivotal distinguishing feature that separates complex systems from those that are merely complicated is the spontaneous appearance or *emergence* of order and behaviours that result from the patterns of relationship between the elements in a complex system. The following definitions give some qualitative idea of emergence:

> "In (complex adaptive) systems, agents residing on one scale start producing behavior that lies one scale above them: ants create colonies, urbanites create neighborhoods ... The movement from lower-level rules to higher-level sophistication is what we call emergence." [264]

> "Emergence is understood to be a process that leads to the appearance of structure not directly described by the defining constraints and instantaneous forces that control a system. Over time some thing new appears at a scale not directly specified by the equations of motion. An emergent feature also cannot be explicitly represented in the initial and boundary conditions." [265]

2. ***Openness.*** Far-from-equilibrium complex systems must (as noted previously) be open to their 'environment' so that energy/matter/information is constantly imported and exported across system boundaries. It is this continual flux that, paradoxically, gives the appearance of stability.

3. ***Nonlinearity.*** Typically, the internal relationships are nonlinear and hence may be very sensitive to small perturbations whereby a large effect may arise from a small stimulus (the 'butterfly effect') – or, perhaps, there is no effect and the system is robust to certain stimuli.

4. ***Short-range relationships.*** Typically (but not necessarily exclusively), the relationships between elements in a complex system are short-range;

that is, information is normally received from near neighbours, and connectivity between neighbours is sufficiently rich (but not too rich) that 'communications' traverse the system quickly, probably being modified by 'local' conditions.

5. ***Feedback.*** The set of nonlinear relationships constantly adapts by the action of negative and positive feedback so that the effects of an interaction involving an element of the system comprise part of the input to that element, modifying its future behaviour by either damping or amplifying its sensitivity to that particular form of interaction.

6. ***Parts cannot contain the whole.*** No element of the system can control the system. That is, there is no sense in which an individual element can have 'knowledge' of the system as a whole, otherwise all of the complexity would be present in that element – which is impossible because the complexity is created by the collective.[2]

7. ***Complex systems have a history.*** Taken together, sensitivity to small perturbations, feedback, and nonlinearity serve to ensure that the future state of the system depends in some way on earlier states; that is, complex systems have a *history* or *memory* comprised of the random outcomes at bifurcation points. This can be explained by recognizing that

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[2] This feature would seem to deny the possibility of any sort of holographic paradigm ('whole-in-each-of-the-parts'). However, one might conjecture that complex adaptive ***bootstrap*** systems possessing a cyclic hierarchy or ***fractal*** structure may yet display holographic properties such that inspection of structure and behaviour at any given level in the hierarchy is essentially indistinguishable in its detail from similar inspection at a 'different' level; in all instances there are characteristic features such that one attains the view that the 'whole' is being observed. As will be seen, *Process Physics* is rather like this.

a pattern of (frozen) configurations of critical/stable sites is imprinted on regions affected by 'active' sites. If sites in the same region subsequently become active, they necessarily operate from that residual reference point (depending on the dynamic, this can result in a mere local random walk for such sites, or they can 'ramp' up – the so-called Brownian ratchet effect [266] – moving further from equilibrium, or succumb to an avalanche, or cascade effect). This behaviour is essentially a memory effect that creates long-range (i.e. non-local) interactions, both spatial and temporal, among diffusing active sites [267]. Without such history, the butterfly effect could not arise.

8. ***'Fuzzy' boundary.*** Usually, it is difficult to define or determine with precision the boundaries of a complex system (this is particularly so of complex adaptive systems), perhaps because of the nature of the interface where entropy is being exchanged with the environment. A boundary decision tends to be 'context-sensitive' and determined extrinsically rather than being an intrinsic property of the system itself.

The property of emergence indicates coherence in such systems. They exhibit long range order that could be said to correspond to global forms, or patterns of information, and when global information is available to the entire system it becomes possible for distant parts to be coordinated so effectively that small fluctuations can propagate throughout the system essentially with no dissipation or destructive interference. Coherent large scale behavior resolves and evolves from the random behaviour of an enormous number of (relatively) tiny elements while, simultaneously, each individual random motion is conditioned by the collective – large scale activity conditions the properties and scope of individual elements and their interactions [268]

A range of apparently generic characteristic features arise from the properties listed above, including:

- ***The 'whole' is more than the sum of its parts.*** The behaviour of the ensemble is seen to be very different from, and richer than, the behaviour of constituent elements and complex macro-patterns emerge from simple systems with simple rules [269]. Properties of ensembles are permitted but not determined by properties of elements; some ensemble properties cannot be inferred from the properties of elements. Moreover, ensemble properties can be dramatically changed by modifying the nature of the interaction among elements – enumeration of 'parts' cannot account for 'wholes'.
- ***Reciprocal causal relationship.*** The behavior of elements both influences and is influenced by the behavior of ensembles.
- ***Stability of ensemble properties.*** Global or *holistic* properties of ensembles may be largely resistant to variations in the properties and behavior of individual elements.
- ***Change does not necessarily require an external agent.*** Ensemble properties may be dynamic for reasons entirely internal to the ensemble.
- ***The relation between 'parts' and the 'whole' may change.*** A particular change in some element property may give rise to a large effect on ensemble order at one time but only a small effect at another time.

- ***Stochasticity can give rise to interesting 'wholes'.*** Random or chaotic variations in element properties or behavior may be the driving force for ensemble order and ergodic behaviour to explore all possible states in the ensemble phase space may arise from randomness. Deterministic systems will not, generally, explore all such possible states.

3.3.1 Complex adaptive systems

A complex *adaptive* systems (CAS) will display all the features of complex systems identified in the previous section but takes the 'game' to an entirely new level. In general there are interaction strength thresholds above which an interacting set of elements, or 'agents', spontaneously *self-organizes* into distinct patterns of collective behaviour. If the nature and dynamics of the interactions are inviolate then the pattern formation is independent of the agents themselves. But, if agents have the capacity to adapt to the environment then the co-evolution of the process as a whole is strongly determined by the nature of the ensemble behaviour [269].

CAS's, almost generally, are multi-tiered: macro-patterns emerge, formed when sub-assemblies interact with other, similar sub-assemblies, themselves aggregate or collective patterns obtaining from interactions of sub-sub-assemblies, and so forth, in a hierarchy of emergent structure. The folding of components into a new layer in the hierarchy occurs, akin to simple complex systems, as the system evolves, driven further from equilibrium and at the transition regions between order and disorder. Each new level of self-organization has its own characteristic scale and properties.

3.3.2 Bootstrap, hierarchy, and fractals

A *bootstrap* complex adaptive system may be considered to possess cyclic (or, cycle) hierarchy, so that there is no 'top' or 'bottom' level and there is, instead, a general symmetry, expressed by Manthey as "outside is as inside" [270]. That is, the 'boundary' separating the interior from exterior is, in principle, arbitrary inasmuch as the internal and external relationships may be represented in the same form.

The 'bootstrap[3]' tag is a colourful metaphor for the notion that the system is inherently circular in the sense that it cannot be reduced to fundamental entities or building blocks, but has to be understood entirely through self-consistency so that structures exist and persist by virtue only of their mutually consistent relationships, not by rigid fundamental principles or 'laws'. In a *universal* modelling, as would be the case for *Process Physics*, the environment is formally unbounded in its complexity and it follows that the hierarchy must be as well (this is an instance of *combinatorial hierarchy* [273, 274, 275]) [270].

There may appear to be something of a weak reductionism in cyclic hierarchy, since any 'higher order' phenomenon must be grounded in the collective behaviour of 'lower order' phenomena. However, such a view could only arise as an artefact of an external viewpoint that 'breaks' the circle in order to inspect it. The cyclic hierarchy of a bootstrap CAS is a particularly appealing conceptual schema for *Process Physics* because phenomena at all scales are referred, ultimately, to the 'rest of the Universe', reflecting the relational philosophy of Leibniz in contrast to the objective stance of Newtonian reductionism.

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[3] First usage of this term in mathematics is attributed [271] to statistician Bradley Efron [272] in 1979. The phrase is widely thought to be based on one of the eighteenth century *Adventures of Baron Münchausen*, by Rudolph Erich Raspe. (The Baron had fallen to the bottom of a deep lake. Just when it looked like all was lost, he thought to pick himself up by his own bootstraps.)

Manthey [270], citing Simon [276], notes that a hierarchical organization reduces complexity logarithmically and, therefore, is a critical bioengineering tool. Common examples of hierarchical complex structures are *fractals*[4] [278, 279] and their time-like counter-part, $1/f$-noise [280, 281]. Fractals are self-similar hierarchical structures that look the 'same' on different scales of observation, having no intrinsic length scale overall (though coarse graining any arbitrary choice of level in the hierarchy may yield an apparent characteristic length). Their spatial correlation functions are power laws and well-known natural examples are cloudscapes, mountain landscapes and coastlines. Manthey also notes that he believes that "moving upward in the morphic hierarchy corresponds to a shift to a more powerful system in the context of Gödel's incompleteness arguments" [270].

3.4 Self-organization and self-organized criticality

Descartes, in Part 5 of *Discourse on Method* [282], presented the (then) hypothetical notion that the dynamics, alone, of a system could tend to increase the inherent order of the system; that is, the ordinary laws of nature tend to produce organization[5], echoing the Ancient Atomists; he elaborated on this considerably in *Le Monde*[6].

Psychiatrist and engineer W. Ross Ashby generally is credited with coining, in

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[4] The word fractal was first coined by Mandelbrot to describe the self-similar fluctuations that are generic to dynamical evolution of systems in nature. Fractals signify non-Euclidean or fractional Euclidean geometrical structure. Traditional statistical theory does not provide for a satisfactory description and quantification of such nonlinear variability with multiple scaling. [277]

[5] Shalizi notes the irony that there are "...people, taken seriously by fellow scholars, who say that self-organization u.s.w. represents a break with the Cartesian, mechanistic, reductionist, etc. tradition of science" [283]

[6] Hearing that Galileo had been forced to recant the Copernican doctrine, Descartes decided to not have *Le Monde* published until after his death. Friends persuaded him otherwise and the book was published in 1637. Soon after his death, *Le Monde* was placed on the list of forbidden reading by the Catholic Church.

1947, the term 'self-organizing', which was used in general systems theory in the 1960s. The term started to appear more frequently in the scientific literature after it was adopted by physicists and researchers in the field of complex systems in the 1970s and 1980s [5]. Self-organization is at the root of complex systems. It is largely moot whether a system self-organizes because of complexity or is complex because it displays self-organized order (as in, say Bénard cells). The key point is that above some critical threshold, where the system is far from equilibrium, interesting behaviour takes place.

Of course, it is customary to look for spontaneous organization of interacting units to explain the emergence of order in nature. But *self-organized criticality* (SOC) [284, 285, 286, 287] is considerably more than mere spontaneous organization: *criticality* does not usually occur spontaneously, without fine-tuning various parameters. By fine tuning, it may be possible to demonstrate that a given system is capable of scale invariance, say, at some point in its parameter space but one needs to establish that the system can find the critical point, and maintain itself there, before claiming that the system exhibits SOC. Or, equivalently, a demonstration that scale invariance is generic; that criticality is exhibited over a non-vanishing range of parameter space [288].

According to Morowitz [289], "...there is a statement, sometimes called the fourth law of thermodynamics, which states that the flow of energy from a source to a sink through an intermediate system orders that system. Here the word order must be taken as increased complexity." The discovery of SOC, illustrated in the now infamous sandpile [284, 285] and forest-fire models [281], is widely attributed to Per Bak (1948–2002), who extends this notion with the view that slowly driven systems naturally self-organize into a critical state, implying that criticality and complexity may be the rule, rather than the exception, in non-equilibrium systems [287].

The two notions here, (a) self-organization, and (b) criticality, were elucidated with disarming simplicity by Bak, Tang, and Wiesenfeld in [285]: in physics the customary methodology is to seek to reduce a problem to a minimal number of degrees of freedom and treat these perturbatively or, by coarse-graining in a 'mean-field' approach, to reduce the difficulty of the problem. It is sometimes the case that a complicated dynamical system may reduce to just a few collective degrees of freedom, thereby achieving an effective dimensional reduction in what is termed the 'slaving principle' [290], which allows one to compress into a few order parameters the information that is necessary to describe complex systems. This is possible if systems are close to their instability points. Bak *et al* associate the term '*self-organization*' with such dimensional reduction when it is attained without detailed specification of the initial conditions or fine-tuning of parameters. In contrast, other dynamical systems operate so that individual degrees of freedom provide an uneasy balance that cannot be described perturbatively or collectively. This quasi-stability makes these systems highly susceptible to small fluctuations or noise, although they cannot be *too* sensitive (nor too insensitive), otherwise they could not have reached the observed state. Qualitatively, Bak *et al* associate the term '*criticality*' with this feature (a more exact quantitative basis can, however, be established but will not be reproduced here).

In a dynamical system, a measure of the response rate for divergence of trajectories for each point of the phase space is given by the system's *Lyapunov exponents*, the number of which is equal to the number of dimensions of the embedding phase space (though it is common to just refer to the largest exponent, because it determines the predictability of the system). It has been noted that in situations where the interactions of agents with sensitive dependent dynamics are complicated by the presence of a resistive or retarding factor, the only agents that successfully evolve are those that are stressed the greatest [7]. When the number of agents is large, this 'sequential dynamics' gives rise to the effective Lyapunov exponent being close to zero – a situation that appears to be associated with the phenomenon of self-organized criticality, where a system seems "poised on the edge of criticality" [269]. As Paczuski and Bak put it, "It is intuitively clear that complex systems must be situated at this delicately balanced edge between order and disorder in a self-organized critical (SOC) state ... Self-organized critical systems evolve toward a scale-free, or critical state naturally..." [291].

3.4.1 SOC and non-locality

After almost two decades of research the precise significance of SOC is still controversial [267]. In its earliest conceptions, SOC was presented as a general theory to understand $1/f$ noise and fractals as the natural outcome of the dynamical evolution of systems having many coupled degrees of freedom. Computer models were employed to demonstrate that scale-free avalanches obtained as a stationary state of certain systems driven slowly by some external parameter [284, 285]. Experimentally observed avalanche behaviour features in a range of phenomena such as magnetic systems (the Barkhausen effect, in which a series of minute jumps occur in the magnetization of a ferromagnetic material as the magnetizing force is increased

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[7] The reader might keep this point in mind; it will be seen to be pertinent to *Process Physics* in the behaviour of the model described in Chapter 7.

or decreased), geological microfracturing processes[8], earthquakes, and flux lines in high-T_c superconductors [267].

There have been many efforts, involving a number of theoretical methods, to find a general descriptive mechanism for SOC. While it has been claimed that SOC corresponds to the tuning to zero of the *order* parameter of an ordinary critical phenomenon [293], analysis by Vespignani and Zapperi using a mean-field-theoretic approach is reported to show, rather, that "criticality arises from the fine tuning to zero of one or more *control* [emphasis added] parameters (driving rate, dissipation) and there is no coupling between control and order parameters" [294] (this finding is supported by other researchers; see, e.g. [295]). Concentrating on models driven by stochastic noise, such as the sandpile [284, 285] and the forest-fire [281], they show that criticality in these models corresponds to the limit in which the dynamical rules become non-local and thus to the onset of long-range correlations. Other researchers have noted this relationship between SOC and non-local dynamics; see, for instance, [296, 277, 297].

3.4.2 Examples of self-organization and SOC phenomena

Examples of self-organization include a range of structural (order-disorder, first-order) phase transitions and spontaneous symmetry breaking in the classical domain, such as spontaneous magnetization, crystallization, and droplet formation [298]. In the quantum domain, but with macroscopic manifestations, examples include the laser, superconductivity [299], and Bose-Einstein condensation. The latter produces a new phase of matter – a gaseous superfluid formed by atoms cooled to very near absolute

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[8] Microfracturing of rocks, with consequent DEPTolar distributions of electric charges due to electrokinetic, triboelectric and piezoelectric phenomena, is of interest in relation to earthquake forecast [292].

zero temperature (see figure 3.1). The first such condensate was produced by Cornell and Wieman in 1995, using a gas of rubidium atoms cooled to 170 nanoKelvins (nK) so that a large fraction of the atoms collapsed into a single, lowest, quantum state. The phenomenon had been predicted in the 1920s by Bose and Einstein, based on Bose's work on the statistical mechanics of photons.

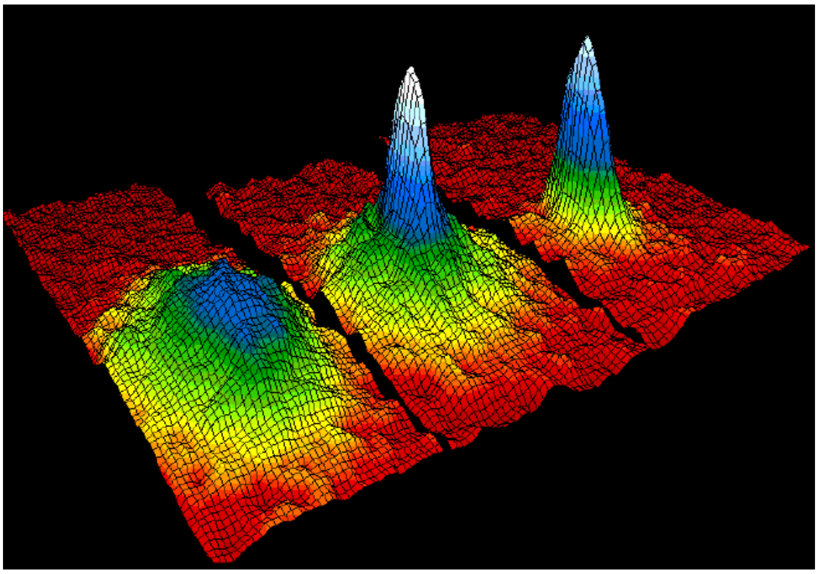

Figure 3.1: Bose-Einstein condensate
Velocity-distribution data confirming the discovery of a new phase of matter, the Bose-Einstein condensate, out of a gas of rubidium atoms. Artificial colours represent the density of atoms at each velocity, with red being the fewest and white, the most. Areas appearing white and light blue are at the lowest velocities. *Left*: just before, and *Center*: just after, the appearance of the condensate. *Right*: after further evaporation, leaving a sample of nearly pure condensate.[9]

'Critical opalescence' is a second-order phase transition phenomenon in liquids close to their critical point, in which a normally transparent liquid appears milky due to density fluctuations at all possible wavelengths.

Studies in all branches of science indicate that self-similar multi-fractal spatial

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[9] This image is in the public domain and was retrieved from Wikipedia at http://en.wikipedia.org/wiki/Image:Bose_Einstein_condensate.png

pattern formation by self-similar fluctuations on all spacetime scales is a generic feature of natural dynamical systems and is identified as a signature of self-organized criticality [284, 285, 286, 300, 301, 302]. Many examples of structure formation are now attributed (though not unequivocally, it must be said) to SOC. For instance, turbulence and convection in fluid dynamics (where parallels have been noted with high-power ferromagnetic resonance [303]), and the formation of stars, nebula clusters, galaxies, galactic clusters, and super-galaxies in astrophysics and cosmology [5].

Widely cited examples of terrestrial- and social-scale SOC phenomena include avalanches, earthquakes, forest fires, traffic jams, blackouts in electric networks, size of cities, size of companies, mass extinctions [5].

3.5 Complexity, SOC, and random graphs

Interactions, state changes, neighbourhoods, and many other phenomena all define links or connections between objects and many aspects of complexity stem from connectivity issues for a given system [304]. Green ([305], [306]) proved the following theorems:

> **Theorem 1.** *The patterns of dependencies in matrix models, dynamical systems, cellular automata, semigroups and partially ordered sets are all isomorphic to directed graphs.*
>
> **Theorem 2.** *In any automaton or array of automata, the state space forms a directed graph.*

Green expresses the view, "The implication is that virtually any complex system inherits properties of graphs. The most important of these properties is that, starting from a set of isolated nodes, a phase change in connectivity occurs in any random graph as edges are added to the system [307]. This feature of graphs is therefore responsible for many kinds of criticality" [304]. Earlier, he conjectured that "connectivity underlies all criticality" [308].

The relationship between SOC and random graph theory has been pursued by a number of researchers – see, for example: [309] (doctoral thesis – Bak-Sneppen process on random graphs), [310], [311] (in particular, related to Extremal Optimization), and [312] (random Boolean networks, autocatalytic sets).

3.6 Self-organization, autopoiesis, and self-reference

The concept of 'autocatalysis' derives from chemistry (particularly, organic chemistry) and carries the meaning that a reaction product is itself the catalyst for that reaction; a set of reactions is 'collectively autocatalytic' if a number of those reactions produce, as reaction products, catalysts for enough of the other reactions that the entire set of reactions is self-sustaining. This is an example of self-organization in chemistry, closely related conceptually with homeostasis (the self-maintaining nature of biological systems), but the idea lends itself naturally to generalization in complexity theory and the theory of random graphs (e.g. [313], involving the self-organization, growth and percolation of autocatalytic sets (ACS); and the above exemplar [312]). Both autocatalysis and homeostasis may be regarded as belonging to a broader concept, that of 'autopoiesis', which literally means 'self-production' and expresses a fundamental complementarity between structure and function. The term was introduced by biologists Varela and Maturana ([314], cited in [315] as "the first English language publication of the theory of autopoiesis to an international audience") and, more specifically, it refers to the dynamics of dissipative systems with non-equilibrium structures that remain stable for long periods despite being subject to a continual flux of matter/energy.

The essence of autopoiesis is two-fold: first, that of spontaneous (that is, without external direction or imposed 'law') creation of *form*; and second, the persistence of that form independently of the detail or 'identity' of its component parts. A vivid example is the Great Red Spot on Jupiter, the immense whirlpool of gases in the gas giant's upper atmosphere. This vortex has persisted for a much longer time (on the order of centuries) than the average amount of time any one gas molecule has spent within it. The canonical example of an autopoietic system, and one of the entities that motivated Varela and Maturana to define autopoiesis, is the biological cell but it is an effective paradigm for complete biological organisms, as well as many non-biological entities.

Early computational models of autopoiesis drew on von Neumann's 'self-reproducing automata' [316] approach. More recently, the phenomenology of computational autopoiesis figures large in the field of Artificial Life in computer science and the paradigm is finding its way into more general applications. Manthey has presented a 'pure process' computational model that departs from traditional algorithmic thinking. The model is reported to be capable of expressing emergent phenomena via the acquisition and adaptive use of information from its environment as a consequence of representing activity in terms of "patterns of synchronization among the events constituting an organism" [270]. These patterns can, apparently, express the concepts of event, information, space, time, action, structure, self-reflection, and intent, and do so without recourse to extrinsic mechanisms. Notably, Manthey also makes the connection that "this same model can also be described in terms of algebraic topology" [270].

The long-term goal of the programme by Fontana and Bus is to develop a formal understanding of self-maintaining organizations. In [317], they point out a fundamental methodological difficulty:

> "the traditional theory of 'dynamical systems' is not equipped for dealing with constructive processes. Indeed, the very notion of 'construction' requires a description that involves the structure of objects. Yet, it was precisely the elimination of objects from the formalism that make [*sic*] dynamical systems approaches so tremendously successful."

Conventional dynamics treats only of quantitative properties of objects, not the objects themselves; it is poorly suited to deal with interactions in which the objects undergo some transformation. On the other hand, 'real' interactions involve objects directly. There is a circularity akin to Gödelian *self-referencing* implicit in the recognition that real interactions between real objects may change the objects, which changes the interactions, which...... According to Fontana and Buss, this is a key observation for any endeavour aiming to achieve a more fundamental description. Their response is to seek to represent objects and their interactions alike as 'self-maintaining collectives' by way of a purely relational representation. The approach leads to a concept of organization that is "arguably indistinguishable" from Varela and Maturana's concept of autopoiesis and Fontana and Buss conclude that "the autopoietic system is, at essence, a matter of constructive relationships closed upon interaction" [317].

3.7 Concluding remarks for complexity

Even the most casual of observers cannot fail to notice that complexity is ubiquitous at every level and scale of Nature's description. Collective behaviour may be discerned at every turn, as ensembles of similarly classified entities interact in ways conducive to sustaining their own existence and identity while also giving rise to higher-order structures in a hierarchy of coherent, stable and quasi-stable states, and all the time struggling to maintain a balance between order and disorder. The nature of hierarchy, particularly when it is fractal or cyclic, might – should, even – lead one to question the validity of settling on *any* level of object-based description; the lesson from the science of complexity (and from history, *vide* Heraclitus, Empedocles, Anaxagoras, Leibniz *et al*), strongly suggests otherwise: complexity punctuates the priority of the relational view.

These collective behaviours seem, moreover, to arise without prior specification. In less enlightened times, Man appealed to the supernatural to find reason and cause in the world. Now (inasmuch as the present era may be thought superior), dynamical laws have been discovered that are much more attractive by way of explanation and predictive ability. But dynamical laws are always formulated from an exophysical perspective, where the system of interest is, as far as practicable, isolated from the 'rest of the world' and the phenomena accessible to dynamical methods comprise a miniscule sub-class of all possible phenomena, as is easily evidenced by the notorious 'many-body problem'. The situation reflects the mathematics of differential equations, where the class of analytically solvable equations is minute compared to those that do not admit analytic solutions. It also reflects the primacy of number theory as the 'queen' of mathematics[10] and the fact that numbers capable of exact representation are very much the exception; most numbers require infinite information for their precise specification – they cannot even be named (this notion leads to the ideas of algorithmic complexity, to be discussed in the next chapter).

As noted by Fontana and Buss, conventional dynamics cannot deal with construction processes, yet these are the very essence of Nature. To obtain a construction process using dynamics requires not only the description of relevant forces and equations of motion and such, it requires also a set of meta-rules, a specification or plan containing instructions for how the construction must proceed. Yet, it seems that the Universe is happily unaware of this fact and simply gets on with the job at hand, presumably without recourse to a 'higher authority' or book of rules, and epitomizing Wheeler's 'law without law'. The various programmes under the umbrella of the science of complexity offer much insight as to why and how this can be so, not just in particular cases but universally. Central to every self-organizing, emergent, and self-sustaining phenomenon (that is, autopoietic phenomena) is the delicate interplay between order and disorder, the balance of which both gives rise to and is sustained by stochastic noise, as inescapable in complex systems theory as it is in quantum theory and the zitterbewegung of Machian cosmology. Whatever else it appears to be, surely the Universe is the quintessential autopoietic complex adaptive system, and so the three critical lessons from this chapter are:

- a further appeal to the primacy of fundamental discreteness
- a further appeal to the primacy of relation and 'law without law'

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[10] So dubbed by Carl Friedrich Gauss: "Mathematics is the queen of the sciences and number theory is the queen of mathematics." Gauss, himself, is referred to as the 'prince of mathematics'.

- a further appeal to the primacy and universality of stochastic noise

If stochasticity and randomness – noise – is to play a such an essential rôle, what is the source of that noise? Wherein lies the imperative for its primacy? These answers are to be found in the vitally *self-referential nature* of complex adaptive systems capable of autopoiesis and the crisis in mathematics, described in the next chapter, that both signalled and ushered in Wheeler's "third era of physics".

Chapter 4

The limitations of logic

Every exit is an entry somewhere else.

– Tom Stoppard

4.1 Introduction

According to John von Neumann [318] (quoted in [319]),

> . . . there have been within the experience of people now living at least three serious crises. . . There have been two such crises in physics – namely, the conceptual soul-searching connected with the discovery of relativity and the conceptual difficulties connected with discoveries in quantum theory. . . The third crisis was in mathematics. It was a very serious conceptual crisis, dealing with rigor and the proper way to carry out a correct mathematical proof. In view of the earlier notions of the absolute rigor of mathematics, it is surprising that such a thing could have happened, and even more surprising that it could have happened in these latter days when miracles are not supposed to take place. Yet it did happen.

In this chapter this "third crisis" is examined for purposes that are two-fold. The first is to demonstrate that the crisis in mathematics, and the reasons for its occurrence, reveal emphatically that the mathematization of physics, although undeniably productive, necessarily limits the scope of investigation into the fundamental nature of reality because of the inherent constraints that mathematics imposes on scientific theories expressed in the language of mathematics. The second purpose is to reveal how this crisis, dubbed the 'limitations of logic', rather than stifling enquiry instead led to an understanding of the barriers encountered by physics that was profoundly suggestive for the invention of *Process Physics.*

4.2 Gödel and unprovable truths

Austrian Kurt Gödel[1] (1906-1978), while studying at the University of Vienna, became interested in mathematical logic, in particular through the lectures of Moritz Schlick, one of the main members of the 'Vienna Circle', whose goal of 'logical positivism' (later referred to as logical empiricism) was to reconstitute philosophy by separating out its metaphysical elements and replacing them with principles guided purely by logic. They held the view that philosophy should provide strict criteria for evaluating statements as true, false, or meaningless, and thereby strive to emulate the rigour of science. Although interested, Gödel held contrary views, had little faith in attempts to so reduce philosophy and mathematics, and was convinced that mathematical objects were every bit as real as the physical objects of everyday reality. Hilbert and Ackermann's *Foundations of the Theory of Logic* [321] came to

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[1] Much of these biographical and background notes have been abstracted from [320], chapter 12, and also the Stanford Encyclopedia of Philosophy, on-line at http://plato.stanford.edu/

his attention and it was here that Gödel first encountered Hilbert's programme in metamathematics, which was to formalize all existing theories by showing that:

1. all of mathematics follows from a finite system of axioms; and
2. that such an axiom system is consistent.

and so place the formulation of mathematics on a solid and complete logical foundation. In addition to consistency (that is, freedom from contradictions), Hilbert also argued that a formal axiomatic system must be 'complete' (representing all of the truth) and, further, that any well-posed mathematical problem in that system must also be 'decidable', in that there must exist a mechanical procedure, or algorithm, by which the truth of any statement or theorem can be determined by proceeding logically from the axioms [322]. Hilbert had proposed that the consistency of more complicated systems, such as real analysis, could be proven in terms of simpler systems and that, ultimately, the consistency of all of mathematics could be reduced to basic arithmetic. It is not clear what motivated Hilbert in this but it surely had been prompted, at least, by his earlier success at providing the first correct and complete axiomatization of Euclidean geometry (in his 1899 *Grundlagen der Geometrie*– (trans.) 'Foundations of Geometry'), which reduced geometry to arithmetic, thus completing the task begun 250 years earlier by Descartes with his discovery of analytic geometry. In this, Hilbert had demonstrated that *if* arithmetic is complete and consistent, so too is geometry.

Gödel also came in contact with Russell's and Whitehead's *Principia Mathematica* (published in three volumes, in 1910, 1912 and 1913), written as a defense of logicism, the view that mathematics is in some significant sense reducible to logic, and widely considered to be the most influential book on logic ever written. However, the primary goal of *Principia* was confounded by substantial difficulties: although successful in several endeavours, two axioms were especially problematic – the axiom of reducibility and the axiom of infinity, both of which are (arguably) non-logical in character. The former was introduced, in essence, to avoid contradictory statements such as may be found in 'Russell's paradox', which arises by considering the set of all sets that are not members of themselves, i.e. such a set appears to be a member of itself if and only if it is *not* a member of itself. It is logically equivalent to Epimenides' paradox, "I am a liar", the truth of which cannot be determined. Similarly, the Barber paradox, also attributed to Russell, considers a town with a male barber who shaves daily every man who does not shave himself, and no one else. Such a town cannot exist: if the barber does not shave himself, he must abide by the rule and shave himself. If he does shave himself, according to the rule he will not shave himself. Thus the rule results in an impossible situation and all such statements are undecidable due to their self-referential nature. The preceding forms are illustrative and they were re-stated in the formal language of logic and set theory, the details of which are unnecessary here. Russell's paradox led directly to the creation of modern axiomatic set theory and also crippled Gottlob Frege's project of reducing mathematics to logic.

Russell was never able to fully resolve the problem and his response was his aptly named theory of types. Recognizing that self-reference lies at the heart of the paradoxes, he was only able to achieve a partial resolution by defining a hierarchy of classes of elements, classes of classes, classes of classes of classes, *ad infinitum*, so that no function's range will ever be able to include any object defined in terms of the function itself (i.e. thus removing the possibility of self-reference). Critics concluded that the axiom of reducibility was too *ad hoc* to be justified philosophically and so the question of whether mathematics could be reduced to logic, or reduced only to set theory, remained open.

Hilbert apparently realized that any formal logical system, such as that presented in *Principia Mathematica* was itself subject to epistemological considerations of completeness and consistency, but it was Gödel who saw this most clearly and he later stated, "A complete epistemological description of a language A cannot be given in the same language A, because the concept of truth of sentences of A cannot be defined in A" ([323], p.105; cited in [320]).

4.2.1 Gödel's Incompleteness Theorems

Gödel completed his doctoral dissertation in 1929, in which he proved the completeness of first-order predicate logic, that states that any sentence that holds in every model of the logic is derivable in that logic. In 1930/1931, he proved his most famous result, the heralded 'incompleteness theorems', which state that any not too weak formal theory, in particular any reasonable formalization of number theory, cannot prove everything that is true, i.e. such theories are necessarily incomplete. (More specifically, in any axiomatic mathematical system there are propositions that cannot be proved or disproved within the axioms of the system. In particular the consistency of the axioms cannot be proved.) Gödel first announced the result at a meeting in 1930 at Königsberg, where also Hilbert and von Neumann were present, and it was published the following year [324].

Contrary to the hopes of Hilbert, Gödel showed that the mathematical system of Number Theory, at the heart of mathematics, could not be formalized. He proved that there would exist certain true theorems of number theory that could not be proven *within* number theory: they were *undecidable*. To compound matters, he further proved that the insertion of additional axioms, with the aim of inducing decidability into all the theorems of number theory, necessarily must be a futile endeavour.

In much simplified form, the first of Gödel's incompleteness theorems, known as the theorem of undecidability, states [325]:

> **Theorem** *In any consistent formalization of mathematics that is sufficiently strong to axiomatize the natural numbers – that is, sufficiently strong to define the operations that collectively define the natural numbers – one can construct a true statement that can be neither proved nor disproved within that system itself.*

This theorem in *formal logic* is one of the most widely known outside of mathematics. It is also easy to misinterpret and one of the most misunderstood. There are many statements that sound similar to Gödel's first incompleteness theorem, but which are not, in fact, true. Gödel's second incompleteness theorem states:

> **Theorem** *No consistent system can be used to prove its own consistency*[2].

The paradoxes of the previous section underlie the proof of Gödel's theorems, the second of which is proved by formalizing part of the proof of the first within the system itself, and his key result is summarized simplistically as follows[3]:

1. Define 'normal' $\Rightarrow A \not\subset A$ is a set that is not a member of itself.

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[2] 'Consistency' refers to the proposition that a formal or physical theory is free of contradictions. It asks whether *mutually inconsistent* statements can ever be derived from the same set of axioms.

[3] Gödel's proof indirectly constructs self-referential statements by assigning 'Gödel numbers' to statements, so reducing them to arithmetic where mathematical assertions are represented by large integers. A well-regarded 'standard' text on Gödel's proof is that of Nagel and Newman [326].

2. Define 'non-normal' $\Rightarrow B \subseteq B$ is a set that is *is* a member of itself.
3. Define N to be the set of *all* normal sets.
4. Question: is N normal?

Assume that N *is* normal:

- then $N \not\subseteq N$ but now N does not contain itself, so it does not contain *all* normal sets, so it is *incomplete*, contradicting the definition of N.;
- on the other hand, if N *is* complete then $N \subseteq N$, which implies, by definition, that N is *not* normal, contradicting the assumption.

That is, N cannot be both complete *and* consistent. The irreconcilable conflict is a direct consequence of the problem of *self-reference*, which is a necessary condition for the application of Gödel's incompleteness theorems, although it is not, of course, a sufficient condition. The theorems only apply to 'sufficiently strong' axiomatic systems that are capable of the coding constructions necessary to prove the first theorem. In essence, this requires that any such system be rich enough to permit the natural numbers to be defined, in which case the first theorem shows the system is necessarily incomplete since it must contain statements whose truth or falsehood cannot be proved. A broad re-statement to paraphrase the result is that a syntactical system sufficiently rich so as to admit self-referencing necessarily contains *unprovable truths*.

The impact of Gödel's incompleteness result was far reaching and even more profound than its impact on Hilbert's programme. The number theory results were to prove but the most prominent example. Frege, and then Russell and Whitehead, had tried to construct an axiomatic foundation for mathematics so that all of mathematics would rest on a pure syntactic base, free from troublesome semantics. Gödel extinguished the possibility of that aim by demonstrating that most of mathematics was not so innately axiomatic as many had believed. Rather, that most mathematical systems were instead linked inseparably to semantic elements that could not be formalized.

A qualifying remark is necessary here – it must be emphasised that the Gödelian incompleteness is a valid result *provided* that the formal system is sufficiently rich so as to admit the formulation of self-referential statements. Ordinary arithmetic qualifies but removing the multiplication operation from arithmetic gives a smaller system known as Presburger arithmetic, which is not rich enough to admit self-referencing. Gödel showed that Presburger arithmetic is complete [327].

4.3 Turing – undecidability

Gödel had demonstrated the impossibility of the first two of Hilbert's stipulations (consistency and completeness) for formal axiomatic systems. The third condition, that of 'decidability', was determined in 1936 by Turing and his famous 'Halting Problem' [328], an informal statement of which is:

> *Given a description of an algorithm and its initial input, determine whether the algorithm, when executed on this input, ever halts (completes). The alternative is that it runs forever without halting* [329].

Turing showed that no computational (i.e. mechanical) procedure can determine whether a given computer programme will ever halt and the halting problem became the first problem to be proved undecidable, finally ending Hilbert's dream.

4.3.1 Universal Turing machine

Turing introduced the concept of an abstract 'universal computing machine' to give a mathematically precise definition of algorithm or mechanical procedure. Such a universal computer (universal Turing machine) is an idealization that can perform any and all tasks that any other computer can perform [72]. Turing's result extends to any logical system that is 'Turing-complete', i.e. if it has computational power equivalent to a universal Turing machine. It turns out that there are entire categories of physical systems that can serve as universal computers. For example, the 'billiard ball' model of Fredkin and Toffoli [330] gives proof that a hard sphere gas within a suitably-shaped container is a universal computer[4].

4.4 Chaitin and random truths

In 1975 a more modern version of Turing's halting problem was developed by Chaitin in the invention of his 'Omega number', which is the probability that an arbitrary computer program will eventually halt ([322] citing [332]). Chaitin's showed that Turing's assertion that the halting problem is undecidable has the corresponding result that the halting probability is random or irreducible mathematical information.

In the mid-to-late 1960s, Chaitin, Kolmogarov, and Solomonoff independently developed ideas about complexity that are known today as 'algorithmic information

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[4] Inspired by the ballistic models of Fredkin and Toffoli, Feynman designed a model of a quantum computer in which spin waves would travel through the device to monitor the computational progress [331].

theory' involving 'Kolmogorov complexity' or 'algorithmic complexity' (closely related to 'algorithmic probabilty' invented by Solomonoff). The principal notion is that the computational complexity of a string of information can be measured by the length of the shortest program whose output precisely reproduces that information.

Chaitin draws the analogy between algorithmic information theory and Boltzmann's theory in thermodynamics, noting that the size of a computer program may be related to the degree of disorder in a physical system: it might require a large program to specify the location of all the atoms in a gas, whereas a corresponding program for a crystal may be quite small because of the regular structure of the crystal [333]. Another analogy is to scientific theories and the principle of Occam's razor, that 'the simplest theory is the best'. In mathematics, computational experiments are compressed into axioms; in science, experimental observations are compressed into scientific laws and theories. Chaitin observes that a 'theory' is a computer program for predicting observations and so "a concise computer program constitutes the best theory... A theory is good only to the extent that it compresses the data into a much smaller set of theoretical assumptions and rules for deduction" [333].

Continuing the analogy, if the most concise program for reproducing a given set of data is no smaller than the data set then the theory is meaningless: the data are unpredictable and therefore, by Chaitin's definition, random. In short, he uses program-size complexity to define randomness, with the result that incompleteness is found to be ubiquitous. Chaitin's proof of that fact was achieved by examining solutions to exponential Diophantine equations to determine whether the number of solutions to such equations is finite or infinite; he showed that the answer to the question must be considered to be a random mathematical or arithmetical fact. That is, more than mere incompleteness or undecidability, Chaitin discovered “an extreme form of randomness, of irreducibility, in pure mathematics” [334] and thereby greatly extended and generalized the prior findings of Gödel and Turing.

The key result in interpreting the significance of Chaitin’s work is that there is an infinite amount of mathematical truth ‘out there’ but any given set of axioms captures just a minute fraction of these truths so that, from the perspective of an arbitrary formal system with a given set of axioms there exist infinitely many logically and computationally irreducible mathematical facts that are true for no reason – they are *random truths* and, in essence, their only ‘proof’ is by assumption as new axioms. Chaitin’s very significant and appropriately self-referential contribution was a logical proof of the limitations of logic.

4.5 Self-reference

At the heart of Gödel’s incompleteness, Turing’s undecidability, and Chaitin’s algorithmic complexity and random truths, lie formal systems that are self-referential. Self-reference occurs when an entity refers to itself, implying the existence of two (or more) logical levels, a level and a meta-level. As noted previously, self-referential statements can lead to paradoxes by establishing a circularity that may involve not only referential but also causal or instrumental relations and thereby constituting a unity of their own.

Self-reference is seen in the concept of recursion in (say) mathematics, computer science, or, for example the situation of autopoiesis (recall §3.6 on page 112), where the logical organisation itself produces the physical structure by means of which it is created. It may also be associated with self-similarity and fractal structures

– particularly those with cyclic hierarchy – since these tend to be the product of recursive processes.

In mathematics, the problem of self-reference is more than two thousand years old [335]. Kampis (*op. cit.*) notes that the related idea of self-modification, a response to the 'stiffness' of formal systems, has emerged from recent ideas of 'goal-seeking systems' and 'dissipative structures' and draws attention to the parallel between the cognitive and evolutionary domains repeatedly noted by numerous researchers, with the notion that higher level organization emerging from some lower dynamics presents novelty that is only partially explicable by the lower order descriptions. The distinctiveness is not attributable to some observer's particular interest but, rather, presents the dynamics with a new domain and establishes a bilateral organization in terms of which the emergent properties can be considered self-referential [336].

Most instances of self-referencing are incomplete (or partial), like Russell's paradox and the others of its ilk stated previously as exercises in logic, and this is because the self-referencing is mediated through an 'external' interpretive agent. Complete, or full, self-referencing has been shown to be *possible* [337] (and as noted by Kampis [335], citing the same); however, any completely self-referential system – necessarily, also, a bootstrap system – must be opaque: that is, semantically closed and devoid of any external meaning or interpretation; it is not possible for one to take the rôle of an exophysical observer of such a system and thereby make sense of its behaviour. A completely self-referential entity is a "perfectly closed class ..., a Leibnizian 'Monad' " [335] and any and all meaning resides therein, accessible only by the endophysical viewpoint of an internal sub-class or inner entity. This is because the axiom of self-reference, as shown by Löfgren [338], is independent from set theory and logic, and thus can be added to it as a new primitive (and, as such, complete self-referencing cannot be decomposed or derived in terms of the other axioms).

The debate on the actuality of *complete* self-reference, as continued by Kampis, appears to founder on what he terms the "separability of *software* from *hardware* [335], which is overcome by the proposal of the 'causal theory of self-reference' yielding the possibility to unfold every closed self-definition as a temporal sequence of ordinary definitions whereby the processes that elicit self-referencing are conceived as the ones whose definitions arise in the course of their own execution by means of a growing universe of 'basic' elements.

4.5.1 Syntax and semantics

Pattee [263] has examined such 'evolving' self-reference and 'semantic closure', which he considers to be the autonomous closure between the dynamics (physical laws) of the material aspects and the constraints (syntactic rules) of the symbolic aspects of a physical organization for which self-reference has open-ended evolutionary potential. His Semantic Closure Principle is a required self-referential relation between complementary physical and symbolic aspects of material organizations with open-ended evolutionary potential. In computer science this is called the hardware-software distinction, to which Kampis referred (above); for biologists it is the phenotype and genotype; philosophers call it the brain-mind problem. The distinction amounts to that attributed to Löfgren [339, 340], between the 'descriptive' (syntactic) complexities measured on *objects* and the 'interpretive' (semantic) complexities measured on *processes* providing relational support for those objects in some relative framework.

The idea is that only such material organizations as are capable of performing autonomous classifications in a self-referential closure, where matter assumes both physical and symbolic attributes, can maintain the functional value required for evolution. Pattee describes the function of symbols as the communication, from one material structure to another, of the properties they symbolize; symbols are not disentangled from matter nor is syntax uncoupled from semantics, as is the case in formal systems. He emphasizes that the distinction implicit in semantic closure is necessary to separate laws and initial conditions in the formulation of physical theories. In physics, laws and initial conditions are defined by employing a fundamental epistemological classification between things that change and things that do not, implying a self-referential "impotency principle that unchanging events cannot completely describe changing events" [263]. The corresponding principle in formal systems is the Gödelian statement that such systems cannot prove their own consistency and their axioms are undecidable. According to Pattee, a purely material, reductionist, conceptual approach to modelling systems with complete self-referential properties is necessarily ineffective, since it overlooks the symbolic traits of matter necessary to describe function or significance. A proposed alternative approach is based on a complementary model where the dual aspects of matter, physical and symbolic, can be usefully exploited. Rosen [341] stated this equivalently as the requirement for semantics and syntax to coexist in a relational framework based on the complementarity of different predicative fragments forming a self-referential, non-predicative whole.

The matter-symbol distinction – indeed the entire aspect of semantic closure as problematic – *could* be viewed as an artefact of exophysical thinking, since semantic closure is problematic only if one is on the 'outside looking in'. From the *Process*

Physics perspective, Leibnizian monadic semantic closure may be seen to be a desirable, even necessary, property of a bootstrap model of reality. Nonetheless, the boundary between the domain of semantic information and that of syntactical information, between random truths and provable truths, is a profound observation and certainly a significant issue.

4.5.2 Self-referential noise

The randomness in mathematics discovered by Chaitin follows as a direct consequence of self-referencing. In particular, it flows from the *degree* to which self-referencing is complete. To illustrate, there is neither incompleteness nor randomness in Presburger arithmetic, which is not self-referential. At the other extreme lie the completely self-referential systems that are semantically closed and devoid of external meaning, they make no sense outside of themselves and so cannot be compressed algorithmically; they are necessarily entirely random. Between these extremes lie formal systems that are algorithmically compressible (non-random) in inverse proportion to their degree of self-referencing. At the least, noise must fit Chaitin's definition of randomness so it can be said that self-referencing is a noisy activity. This provides the concept of *self-referential noise* (SRN), the noise of self-referencing (coined in [342]), which will be shown to be a vital component in the formulation of *Process Physics.*

4.6 Concluding remarks for the limitations of logic

The limitations of logic recounted here demonstrate that self-referential syntactical systems (which include basic mathematics) have inherent limitations imposed by the fact that not all truths can be compressed into a consistent axiomatic structure and so formal systems are much weaker than previously assumed. That this is the consequence of self-reference provides an imperative to face the distinction between syntactical information and semantic information and provides an awareness of the boundary between the two. Awareness of that boundary is a key conceptual element of *Process Physics*, as too is the recognition of the primacy and relevance of self-referential noise.

Chapter 5

A prescription for *Process Physics*

Inventions have long since reached their limit, and
I see no hope for further development.

– Julius Sextus Frontinus

5.1 Introduction

The preceding chapters have skimmed ideas from more than two and a half thousand years of theoretical physics with the aim of obtaining a perspective on the development and limitations of the prevailing views in modern physics and so map a path towards overcoming those limitations in an effort to arrive at a more effective paradigm for modelling reality.

The aim here is to provide a 'prescription' for the theory of *Process Physics* developed and presented in Part II.

5.2 Clues and cues

Each chapter has provided vital clues and cues, lessons from the past to suggest a new and very different approach, *viz*:

- Chapter 1
    - try the 'road less travelled' and adopt a relational view, after Heraclitus, Empedocles, Anaximander, and Leibniz
- Chapter 2
    - adopt a minimalist model with no *a priori* structure i.e. no geometry, no continuum, no spacetime, no objects
    - adopt Wheeler's "law without law"(p. 86) precept by considering not dynamics but *process*
    - adopt an endophysical view over the exophysical philosophy of conventional modelling in physics
    - recognize the pervasiveness of the underlying stochasticity in both the quantum and cosmological domains, not merely as an aberration of uncertainty, but rather as a signature of deeper, more fundamental behaviour
- Chapter 3
    - recognise that the endophysical view obviates appeal to meta-rules
    - model the Universe as an autopoietic complex adaptive system manifesting emergent properties and behaviour that derive from the collective interactions of vast numbers of some abstract entity

  - utilize the correspondence between the connectivity of SOC and that of random graphs
  - look to the limitations of logic for the origin of stochasticity

- Chapter 4
  - recognize that stochasticity is a fundamental and creative resource that flows as a consequence of autopoiesis manifesting as SRN
  - recognize that complete self-reference requires a bootstrap model
  - recognize and learn to exploit the boundary between syntax and semantics by constructing a semantic information system

Bringing these elements together, what is required of *Process Physics* is a pregeometric theory that is a minimal, autopoietic complex adaptive system. By definition, it will necessarily be discrete, relational, stochastic, self-referential, and devoid of *a priori* constructs. In particular, it must overcome the limitations of logic inherent in traditional approaches and so provide a deeper, unifying description of Nature from which geometry, spacetime, and the phenomenology of objects are emergent features. Moreover, at some coarse-grained level, those emergent features must be consistent with the observations of the conventional quantum and relativity measurement theories (modulo the erroneous components occasioned by their intrinsic limitations); that is, *Process Physics* should be capable of yielding relativity and the quantum as higher level effective measurement theories.

5.3 Syntactical and Semantic Information Systems

In the traditional approach to modelling reality with formal, syntactical information systems – the language of mathematical physics – physicists assume that a full account of their investigations can, in principle, be compressed into axioms and rules for the manipulation of the symbols from which their theories are constructed. For three-quarters of a century, mathematicians have known of the crisis brought upon mathematics by the failure of Hilbert's programme; most, however, have been able to suppress their concerns without detriment to their work so long as it avoided the 'no-go' zone identified by Gödel (arguably, rather fewer will have been particularly aware of the further extensions by Turing and Chaitin). For the majority of physicists, however, one suspects that the issue is simply considered irrelevant to their practice, while the deep implications for the development of fundamental theories are neglected.

5.3.1 Self-referential systems and Gödel's theorem

In physics, syntactical information systems have always been used together with meta-rules and metaphysical assertions lying outside of the formal mathematical language and designed to overcome the limitations of syntax (in effect, informally applying Russell's axiom of reducibility). Figure 5.1 provides a graphical representation of self-referential syntactical systems. Note here, the presence of the 'boundary' separating the syntactic from the semantic – the provable from the unprovable – in some arbitrary formal system. The domain to the right of the boundary represents the 'random truths' identified by Chaitin – this is the domain of things that are "true for no reason", that are not algorithmically compressible and so cannot be condensed or encoded in the axioms of the system.

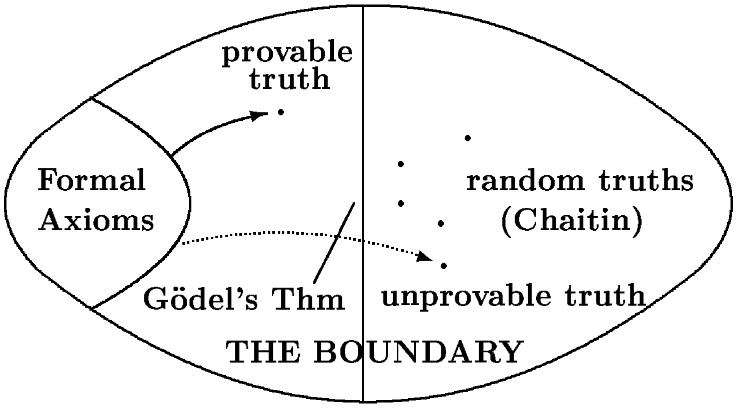

Figure 5.1: Self-referential syntactical information system
Graphical depiction of the 'logic space', showing the formal system consisting of symbols and rules, and an example of one theorem (a provable truth). Also shown are unprovable truths which in general are random (or unstructured) in character, following the work of Chaitin. The Gödelian boundary is the demarcation between provable and unprovable truths.[1]

It should clear that the device of supplementing the formal system with meta-rules etc is only effective so long as it is able to insulate the physical theory from self-reference. This, in itself, imposes constraints on the capacity to freely develop theory and places increasing demands on the theorist to devise creative new ways to circumvent the latest difficulty. Theory cannot help but become more and more convoluted and obscure until the next researcher determines a means of re-stating the problem with a changed set of axioms, thereby opening the way for a new set of meta-rules. However, Chaitin's result, in particular, illustrates how ultimately futile such efforts must be since most truths (infinitely many) are true *for no reason at all* – there must always be vastly more experimental observations that are possible than can be compressed into syntactical scientific laws and theories. This illustrates the

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[1] These conceptions are adapted from those by Cahill, which first appeared in [18]

limitations imposed on physics by the traditional axiomatic formal systems approach.

That the present structure of quantum theory is analogous and may be similarly represented in its syntactical form is illustrated by figure 5.2.

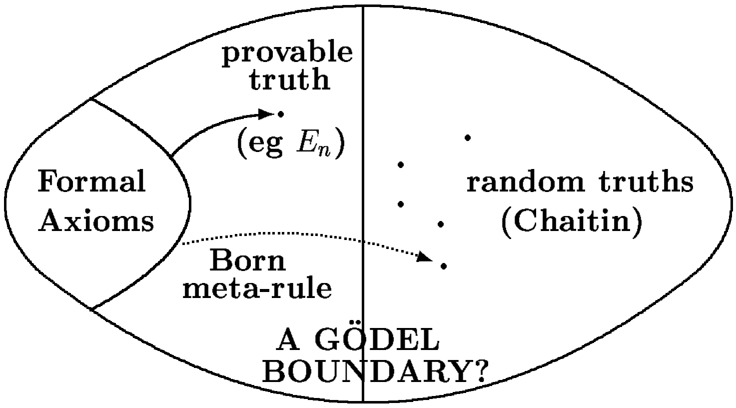

Figure 5.2: Representation of the syntactical form of quantum theory where, for example, the Born measurement meta-rule appears to bridge a 'Gödelian boundary'.[1]

The formal synactical mathematical structure is capable of producing many provable truths, such as the energy levels of the hydrogen atom, and these are also true in the sense that they agree with reality. But a specific event, such as the localization that occurs with a single quantum measurement, has a random characteristic that escapes the formalism and so the Born measurement meta-rule was introduced from the inception of quantum theory to side-step the issue, in effect invoking Russell's reducibility axiom.

Of course, the structural aspects of the probability meta-rule are consistent with the mathematical formalism, in the form of the usual 'conservation of probability' equation and such like; if it were otherwise, the meta-rule would serve no purpose. Quantum theory has always been subject to various metaphysical interpretations, and a number of these were considered in Chapter 2. In the context of the dichotomy of syntax and semantics discussed thus far, a natural interpretation is that successful meta-rules, like that of the Born measurement postulate, bridge what might be termed a 'Gödelian boundary'. Then it may be seen that to fully model quantum aspects of reality demands a bigger system than formally acknowledged within the standard theory and that the Gödelian boundary is evidence of self-referencing in that system.

5.3.2 Semantic Information Systems

To overcome the limitations of logic represented by the Gödelian bridge, and made manifest by the combined successes and failures of physics previously noted, requires a generalization beyond the traditional syntactical methods. Proceeding from the insights gained thus far suggests that *Process Physics* should be implemented in the form of an autopoietic semantic information system as a means of capturing the fundamental complementarity between function and structure.

Because *Process Physics* is to be a *universal* modelling, its schema can have no external referents and necessarily must accommodate the characteristics noted in section §3.3.2 on page 104, namely it must be a bootstrap system with a cyclic or fractal hierarchy.

With no exophysical meaning, some method of interacting with its conceptual foundations is required to effect the modelling. By 'breaking the loop', the system may be envisaged as possessing a 'seeding' mechanism, the details of which must be independent of any realization so that emergent hierarchical forms exhibit universality. In effect, this mandates some means by which the seeding system is hidden, essentially removed from the internal endophysical ontology. It is envisaged that self-organized

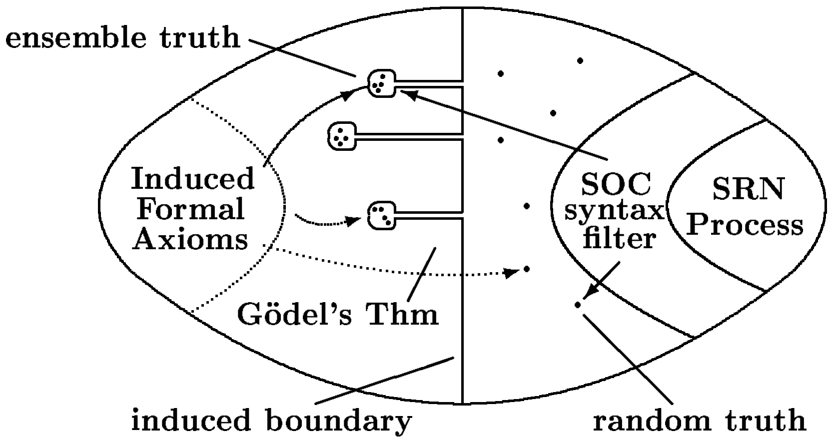

Figure 5.3: Bootstrapping a self-referential syntactical information system showing the emergence of an *induced formal system*, corresponding to conventional syntactical modelling, and the associated accessible *ensemble truths* of quantum statistical measurement protocols. The induced (Gödelian) boundary is an emergent feature that represents the inaccessibility of the random or contingent truths from the formal syntactical domain. SOC acts as a filter for the seeding syntax of the SRN process.[1]

criticality, necessarily present in the autopoietic framework, will achieve that end by acting as an effective filter. Figure 5.3 on the current page illustrates the concept. In view of the previously noted pervasiveness of stochasticity, it is envisaged that self-referential noise will act to drive the seeding process.

From the bootstrap process system, so driven, there are emergent truths. Some of them, as ensembles, will be generically true, while others remain contingent (random). The 'ensemble truths' are also accessible from the induced formal system but not so the contingent truths, since these cannot be compressed into the axioms of that induced system. In this manner, the boundary that was explicitly represented in figures 5.1 and 5.2 emerges as an *induced* Gödelian boundary, the existence of which leads to the necessity of meta-rules to enhance the induced formal system, if that is used solely to account for higher order emergent phenomenology.

5.4 Concluding remarks for a prescription...

The conclusion of this chapter brings about the conclusion of Part I. Proceeding from considerations of the historical, philosophical, and metaphysical foundations of the prevailing main-stream theories in physics and an excursion into complexity science and the limitations of logic, the discourse has led to the prescription for the construction of a new type of information-theoretic modelling of reality, called *Process Physics*, which is a radical departure from the conventional techniques.

The task, now, is to demonstrate how this prescription can be given effect, how the broad concepts arising from this discourse can be developed into the fundamental formulation of the theory of *Process Physics*. The remainder of this thesis documents how this is achieved.