Fundamental Physics and the Nature of Reality – Part 1
Introduction

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Preamble

I have two, partly conflicting, aims in this course. The first is to give you a hint of what physics has to say about how Nature works, at its most fundamental level, which I hope to do by describing a number of areas of modern physics, concentrating on the picture they give us of the universe's workings. Although I will mention such exotica as black holes and superstrings, I will spend little time discussing them. Instead, I will concentrate on relativity and quantum mechanics, because these topics are, I believe, genuinely intelligible in outline without mathematics, and because they form a crucial part of the world-view of 20th- and 21st-century physicists.

This will shade into the second aim of the course, which is a more philosophical consideration of what it means to have a 'picture' of reality, to what extent we can say that there is an independent reality out there, and on what grounds science can claim a priviledged insight into this reality.

1 Overview of the course

I'm going to spend most of my time talking about Physics. There are a number of reasons for that: one is that Physics is what I know most about; another is that Physics is full of the most excitingly exotic ideas; another is that Physics, because it is concerned with the most basic components of the world – the matter that makes us up, and the shape of the universe we live in – means that we very quickly and naturally confront the most basic questions of how science is done; finally, it is also because Physics deals with very simple things – you're obviously dealing with theories of *how things work*, without having to deal with a great deal of descriptive apparatus.

I plan to break the course into five parts:

1. Introduction, giving an overview of the course, and a description of the notion of mathematical models.

2. Relativity, special and general (we'll cover some cosmology in this section, too).

3. Quantum mechanics: the phenomemology of QM, and its interpretation.

4. Philosophy of science: realism and idealism, and the (attempted) demarcation of science from non-science.

5. The sociology of science, and Conclusion.

Before we make a start on these topics, we need a map. In Fig. 1 we see that physics covers a huge range of circumstances, from very large to very small scales, and from (normal) small energies to very large ones (where this high energy refers either to objects moving at speeds near that of light, or to the energies required to

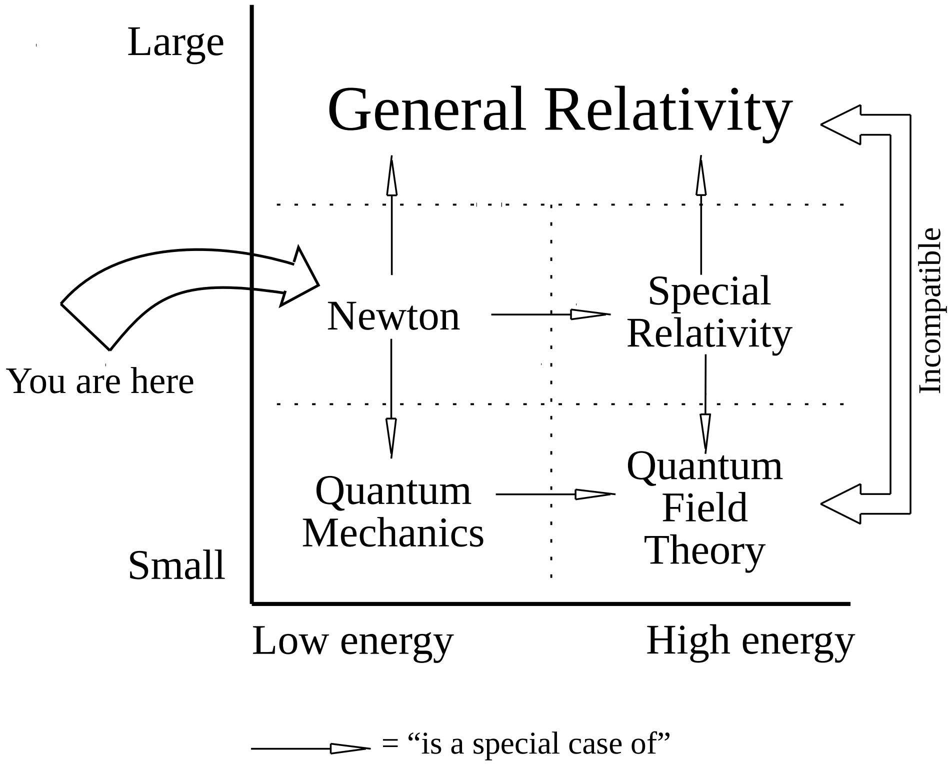

Figure 1: Physics covers a huge range of situations from very large to very small scales, and from (normal) small energies to the very large. This diagram shows how different physical theories cover different areas of this range.

examine the nuclear constituents of matter). This map depicts some of the physical theories which cover this range.

Look at the arrow marked ‘You Are Here’, pointing at ‘Newton’. This denotes the physics that describes our everyday world of gravity, aeroplanes, weather and so on. This area of the map is described by an area of physics which has a lineal descent from the insights which Newton achieved – it’s still called ‘Newtonian’ mechanics. Though Newton would have a lot to learn, he would find the fundamental concepts and the assumptions of this field familiar. When in this area we can talk of time as an absolute quantity, and we can talk with confidence of the strictly causal links which bind events together.

When we go to very high speeds, however, speeds comparable with the speed of light, Newton’s picture of the world no longer matches the world itself. In the physics which replaces it, we find time playing a slightly different role, and no longer passing sublimely independent of everyone. This is the field of *Special Relativity*, and will be the subject of part 2.

If, instead of going to very high speeds, we examine the very small – objects such as atoms, or the electrons in a TV tube – we find Newton’s mechanics fails us again. This time, we have to replace it with the perplexities of *Quantum Mechanics*, which we will cover in part 3.

You might expect that since we now have a successful theory of the very energetic, and a successful theory of the very small, we must now have a successful theory of the small *and* energetic. This, however, is not so: certain features of Quantum Mechanics violate conditions that Special Relativity insists on – the two theories are inconsistent. It took a great deal of work to produce *Quantum Field Theory*, which is a generalisation consistent with both, and which we will discuss, in its most normal guise of Elementary Particle Physics, in part 3.

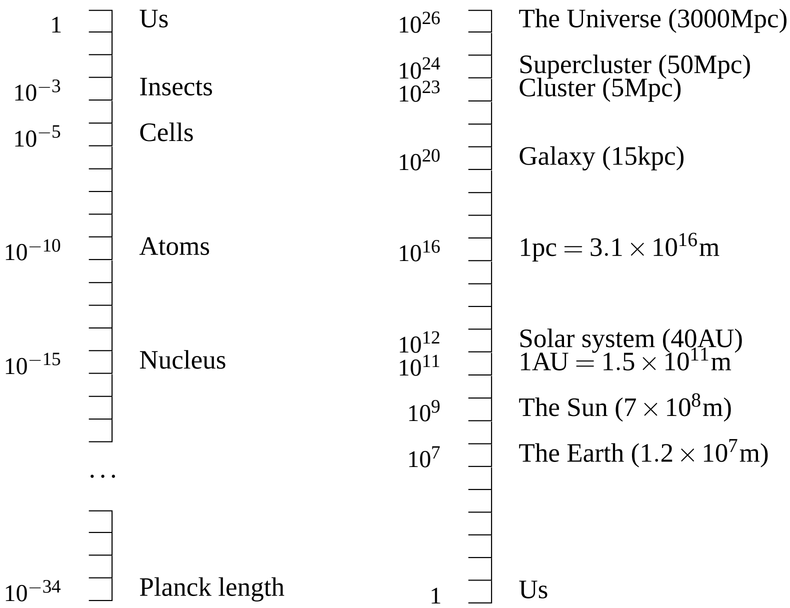

Figure 2: Size scales in the universe

Going in the other direction, we find that both Newtonian physics and Special Relativity start to go wrong when we move to very large (astronomical) scales. At this level, both theories are replaced by *General Relativity*, which we will look at in part 2, and from which we will naturally move on to a discussion of *Cosmology*, the physics of the Universe on the largest scales.

To give you an idea of the range of scales we will be discussing in this course, take a look at another map, Fig. 2. This shows the range of sizes that physics discusses, from the unimaginably tiny scale of the Planck length, which has probably never been of significance later than a few nanoseconds after the Big Bang, to the scale which characterises the size of the Universe as a whole.

Our wander round this map has led us to two termini, Quantum Field Theory and General Relativity. Although, between them, they cover the four forces that are believed to underly all the interactions in the Universe, they are not, in fact, consistent with each other. That is, there is no fully successful quantum theory of gravity; the two theories cannot both be correct.

The different areas of physics I have mentioned above all have radically different pictures of how the world works, and each one has a reasonable claim to be fundamental. The arrows on the diagram indicate which theories are *special cases* of which others. For example, if you were to make a relativistic description of a car moving along a road, much slower than the speed of light, you would find your description identical to the Newtonian one. If you were to make a quantum mechanical description of a macroscopic object like a ball being thrown, it would again reduce to the Newtonian description. This has to happen – it simply means that the relativistic and quantum mechanical descriptions are *extensions* of the classical one, appropriate to a situation more exotic than the simple world-picture that Newtonian mechanics is based on, but nonetheless including that picture within it.

Does this mean that Newtonian physics, in company with each of the other cases which ‘is a special case of’ another picture, is simply *wrong?* In a sense, yes. They do not give a picture of how the world works that is accurate at all scales and all energies. However, imagine how complicated such a Theory of Everything would be, and how useless it would be to help us really understand how things worked in all but the most artificially simple circumstances. Although it is the earliest of all the theories of mechanics shown here, Newtonian mechanics and its developments give us important insights into how the world works, and so improve our understanding in ways we would not achieve by studying more sophisticated theories alone.

The first big point I want to make here is that physics does not give us one single picture of the how the Universe works. Instead, it gives us a patchwork of pictures, each apparently equally fundamental, each of which gives us an insight into one aspect of the Universe's working. The fundamental truth may be some combination of them all.

The second big point is about the difference between Physics and Engineering. Now that we have covered all of the map in Fig. 2 with theories which *work*, in the sense of giving numerically accurate answers, an Engineer might feel the matter closed, as she already has enough information to build a bridge that won't fall down, or a particle accelerator that will keep going. Physics, on the other hand, is interested in more than numerically correct models: it is part of the essence of Physics that it seeks models which *match reality*, in that they give us some insight into what is *really there*. This is why physicists are interested in Theories of Everything, and why the more reflective of them naturally ask the questions: how will we know when the models match reality? what does it mean to match reality? how do we know there's a reality there to match? do we *make* that reality by inventing the models?

2 What is mathematical physics?

I'll make some use of the term 'mathematical model': what is a *mathematical* model? It's obviously not a model made out of Meccano and string – instead it's made out of mathematics. Different people have different views of exactly what is going on here, but the way I explain it to myself is that we try to build up a picture of how the world works by putting together a bit of mathematics *which has the important parts of the behaviour* of the bit of physics you're interested in. That's very like a mechanical model, such as an orrery, for example.

For example, look at Hooke's law, $F = kx$, which says that the force F produced by a spring is some constant k multiplied by the distance x that the thing is stretched. At one level that's purely descriptive – it allows you to calculate that if you stretch a spring by 10 cm, say, then it'll pull against you with a force of 1 N, say (about the weight of an apple, by the way). But in doing that you have actually constructed a mathematical model: you're saying that the force and the extension are related in a particular way – if you double the extension, the force doubles in response, and so on. However, this expression wants to tell you that, if you can supply enough force, you can keep stretching an elastic band for miles. The expression – the model – contains nothing which corresponds to a spring breaking, or even to the damage you cause to a spring if you stretch it beyond its elastic limit. In other words, the model has limits and, like the spring, it'll break if it's pushed too far.

An interesting question: is Hooke's law merely a *description* of what happens when you extend a spring, or is it something more? At one level, Hooke's law simply allows you, the engineer, to work out how much force will be supplied by by a spring stretched a certain amount. But at another level, it *expresses something fundamental* about a spring – you might say that Hooke's law expresses something about *what a spring is*.

Another type of mathematical model, which appears a lot in physics and which is another good illustration of what I mean by a mathematical model, is a *differential equation*. Now, the mathematical details of differential equations are rather sophisticated, and I'm certainly not going to go into them here, but at base they express not how A is related to B, but how *changes* in A are related to B and possibly even to A itself. For example, Newton's law of cooling says that the rate at which things lose heat is related to the difference between their temperature and the temperature around them.

These models are almost always simplifications – either very crude ones, or very subtle ones; that is, they are *approximations* – they miss things out. If you like, you can say that mathematical physics consists of arguments about which models are valid in which circumstances; about whether or not one lot of approximations are good ones.

3 The birth of physics

3.1 The Greeks

Thales of Miletos in 6th century BC is usually the first to appear in histories of science. It seems that he was the first to state that things in the world must be related by *causal explanations*, rather than the whim of gods, even though his explanations, and the explanations of those who came after him are still rather fanciful and exotic. *Pythagoras* merged some mysticism and some mathematics with this, and started a tradition that generated a series of cosmologies which are progressively more sophisticated, and closer to what we recognise. One branch of Pythagoras' influence culminated in *Aristarchus'* heliocentric model (3rd century BC), which is essentially the same as Copernicus'. But he seems to have had no followers, so the idea died. You have the impression that they are on the verge of Newton's insight, namely that the terrestrial and supramundane worlds are made of the same stuff.

Part of the other branch of Pythagoras' influence, *Plato* (428–348) and *Aristotle* (384–22) had a huge (baleful) influence on all that came after them. Plato was violently anti-materialist: "let us concentrate on (abstract) problems, said I, in astronomy as in geometry, and dismiss the heavenly bodies, if we intend truly to apprehend astronomy". This is a very clear statement of the way in which they seemed to withdraw from the material world: it wasn't that they didn't look at the heavens, or didn't have good observations, but that they didn't *care* – they didn't perceive the material world as giving any valuable insights. It looks as if they didn't see the material world as being particularly *real* – the geometry was reality.

Koestler suggests this might have been a response to the on-going collapse of Greek society – both saw any change, or any progress, as intrinsically bad, and Aristotle seems to have crystallised this in an explicitly geocentric cosmology, where everything moved in circles, and everything above the sphere of the moon was perfect and unchanging, and everything below the moon – the earth – was made of different material, was constantly changing, and was corrupt. This view seems to have dominated the next 1500 years.

But it does not match what you see. It's in an attempt to "save the appearances" that the model was developed more and more, culminating in *Ptolemy*'s 2nd century AD model, which is essentially Aristotle's model, with many additions bolted on. But it was just 'sky-geometry', and its 'physical' justification seems to have been careless and garbled.

3.2 Copernicus, Kepler and Tycho Brahe

We shall leap over the next 1400 years. A number of cosmologies were developed, and there were a few developments in natural philosophy, but the Platonic, Aristotelean and Neo-Platonist hegemony seems to have held firm. There were a number of aggressive noises about 'pagan cosmology', but in a period obsessed with heresy, there seems to have been no-one condemned for teaching a heretical cosmology.

Copernicus it was (1473–1543) who broke from the mediaeval view of the cosmos and brought us back to a 'heliocentric' cosmology, very timidly, and circled round with qualifications and protestations of faith. The remarkable thing is that Copernicus' system, which is still based on epicycles, actually uses *more* epicycles than Ptolemy's (depending on how you count things) – 48 or so. It is, however, a bad system, and no-one ever used it. What's special about the system is its fundamental idea, that all the elements of the solar system, including the earth and the sun, have orbits which are controlled by, and centred on, the same thing. It doesn't actually work better than any other system, but what it *doesn't* have are special rules for the earth, for the moon, for the other planets, and for the sun. In other words, it's a more cohesive and intellectually satisfying model. Furthermore, Copernicus asserts that this means that the earth really does move, that this is not just sky-geometry.

A good deal of to-ing and fro-ing culminated, possibly, with *Kepler*. Kepler was conceived at 4.37am on 16 May 1571, and born at 2.30pm on 27 December, after a pregnancy lasting 224 days, 9 hours and 53 minutes. We know that because Kepler cast a detailed horoscope for himself, and took great heed of its predictions. Kepler was not what we'd recognise as a modern scientist – to an extent, he was a mediaeval mystic, who spent a great deal of time trying to fit the (sun-centred) orbits of the five known planets into a geometrical construction based on the five Platonic solids, and never quite managing it. At the same time, he worked with *Tycho Brahe*, who generated excellent astronomical data. In this respect, he was a modern astronomer: he knew how accurate Tycho's data was, and he insisted that any picture of how the planets move *had* to agree with Tycho's data. If you further insist that your description of this be simple, and not involve an obscene number of epicycles, and the like, then you're practically forced towards ellipses, and against the consensus of the last millenium and a half.

3.3 Galileo and Newton

Most of the points I want to make, I have made by now – with Kepler we have the seeds of an essentially modern approach, but I'm going to finish with a passing look at Galileo, and the position that Newton holds for us now.

Galileo (1564–1642) made a number of astronomical observations, to do with sunspots and, with the benefit of the telescope, the moons round Jupiter. He also concerned himself with the terrestrial physics of time and motion – he, crucially, contrived experiments, both mechanical ones and thought experiments, to investigate or discuss phenomena. As such, he looks forward to Newton.

Little of *Newton*'s (1642–1727) work seems remarkable now, because it's so comprehensively part of how we see the world ourselves. We know that things fall to the ground because of gravity, and that that gravity is the same gravity that keeps the planets in their orbits – there is no longer a distinction between terrestrial and celestial mechanics. He talked in terms of detailed mechanical causes for each event. He put his work on a quantitative mathematical footing. He took it for granted that if a model disagreed with an observation, then the model was wrong to a greater or lesser extent.

This is fundamental physics – it's all about how the world works – but it has turned into common sense.

4 Booklist

4.1 Introductions to the physics

[Schwartz and McGuinness, 1999] is a lighthearted, but nonetheless very thorough, description of Special Relativity. It's very accessible, but not very detailed. [Gamow, 1965] is a whimsical account of the phenomena of relativity and quantum mechanics, which is entertaining, even if it is a little old-fashioned. Beyond these two, there seems a shortage of books which make serious popular (ie, non-mathematical) attempts to introduce special relativity.

[Polkinghorne, 1984] is a very straight account of quantum theory and its meaning. It's a little mathematical in places, but the author never relies on the maths to do anything more than amplify.

[Davies, 1984] is a roller-coaster ride through some of the more exotic parts of particle physics and cosmology. It's hard going in places, but rewarding and accurate.

4.2 History, philosophy and sociology of science

[Chalmers, 1982] is a very readable introduction to the philosophy of science, which covers all of the important areas, and includes some of Chalmers' own ideas as well. [Richards, 1987] is another general introduction to both the philosophy and the sociology of science, but is unfortunately out of print right now. Covering the same field, [Hilgevoord, 1994] is an excellent collection of essays based on talks given at an Erasmus symposium in 1992. The scope of the essays is very similar to the scope of the philosophy of science parts of this course.

[Collins and Pinch, 1993] is a series of case studies of scientific experiments and controversies, showing an unexpected, but accurate, view of how science actually works.

[Gregory, 1988] describes the view that physicists do not discover the world, but rather invent, through language, a physical world which matches the external one. [Atkins, 1992] is a provocative and slightly eccentric book, which takes an exhilirating gallop round the fundamentals of the natural sciences, to leave you gasping at the conclusion that the universe has that of necessity in it, that it could slide unbidden and uncreated into existence.

[Koestler, 1968] gives a very good account of the revolution in physics that Copernicus, Galileo and Kepler achieved between them. Good for both the history and the sociology of the time.

4.3 More advanced material

The Principle of Relativity [Lorentz et al., 1952] is a collection of (translations of) original papers on the Special and General theories, including Einstein's paper of 1905 [Einstein, 1905], but also some earlier papers by Lorentz suggesting interpretations of the Michelson-Morley experiment. The first few sections, at least, of the 1905 paper are worth reading as a current introduction to SR.

[Taylor and Wheeler, 1992] is a more advanced book. It's an undergraduate textbook, and so it doesn't pull any punches when it comes to the maths. The level of maths required is, however, relatively modest, so if you can cope with that and are prepared for some hard thought, you will benefit from the book's immense insight.

[Baggott, 1992] gives a very thorough account of quantum mechanics and its interpretation, with a good bibliography. Baggott does not pull any punches when he discusses the mathematical formalism of the theory, and although this does not assume much more than a familiarity with calculus, this is enough to classify the book as 'advanced' here. Nonetheless, the book concentrates on the interpretation, rather than the mechanics, and even if you skipped all the mathematics, the later chapters of the book would, I think, be both intelligible and illuminating.

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