Einstein’s Searches for a Fundamental Theory

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12 November 2005

These notes accompany the overheads for the talk which I delivered as part of the DACE day-school on *Einstein’s Legacy*, on 12 November 2005. The notes aren’t meant to be a continuous standalone text, with or without the overheads; they are instead intended to expand on a few slides which are otherwise fairly opaque, or about which I did not have time to say as much as I wanted.

Introduction

Einstein’s quantisation paper of 1905 (it’s a distortion to call it ‘the photoelectric effect paper’, since that was only an aspect of it) was a considerable achievement, but quantum mechanics has changed hugely since 1905, unlike Special Relativity, so that this paper is now mostly of interest to the historian and to the connoisseur (it is mathematically sweet, and contains intimidating physical insight). What is interesting to me is not this paper’s achievements, but what Einstein saw as its *lack* of achievement – why was it, that having effectively introduced the quantum as a physical entity rather than a merely mathematical one, Einstein never felt that quantum mechanics introduced any truly fundamental physical insights?

Einstein’s intellectual network

Quantum Field Theory covers both Quantum Electrodynamics (QED – the theory of electrons and photons) and Quantum Chromodynamics (QCD – the theory of quarks, and the Strong and Weak nuclear interactions. This was first developed in the decades following the second world war, and is the framework which contains the current Standard Model (so called) of fundamental forces and particles. Einstein was aware of it, and of its mathematical and conceptual problems, but didn’t make any contributions to it. The special thing about QFT is that it is a version of quantum mechanics which is compatible with SR, and which can thus described high-energy particles. It is not compatible with GR, however, and so necessarily exists in a gravity-free spacetime, which means it cannot describe situations where a quantum system spreads over a volume which is large enough to experience gravitational tides. The only time *that* matters is when you are attempting to describe the early universe, so that although this imposes essentially no practical limitation, it rules out QFT and GR as truly fundamental theories of the early universe.

Statistical mechanics

I want to emphasise a point I only mentioned in the talk, concerning Boltzmann’s recovery of thermodynamics from statistical mechanics. You may regard this as demoting thermodynamics from a fundamental theory to a merely effective one, summarising the results of statistical mechanics. I don’t believe Einstein would have agreed with this (and I don’t either, for what that’s worth). For Einstein, I believe, thermody-

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namics was independently true, and its relationship with statistical mechanics attests more to the consistency and truth of the latter than the former.

Thermodynamics is a theory of the universe in which the fundamental entities are not particles and fields, but energy and entropy. With such fundamentals you cannot say very many things, but what you can say is of fundamental importance, and appears to be a deep truth about our universe.

Electromagnetism, transformations and symmetry

If I look at two objects connected by an elastic band, then I can explain their movements using Hooke’s Law (‘the force is proportional to the extension’) and their mutual separation. If I wish to explain the motion of a similar pair of objects far away from me, or which are moving past me at a constant speed, I can use *the same explanation*. That is, there is a range of changes I can make to my point of view (my ‘reference frame’ in the appropriate technical vocabulary) which do not change my physical theory about why the objects move as they do. This group of changes consists of changing my reference point and my constant speed – the so-called ‘Galilean transformations’. I can turn this argument around and say that I believe the Galilean transformations are a fundamental property of our world, and in consequence I can exclude as a physical theory anything that depends on my absolute position or my absolute speed; that is to say, I will refuse from the outset to give credence to any theory that is not *invariant*, or *symmetric*, under a Galilean transformation.

The problem is that this would cause me to reject Maxwell’s electromagnetism, since Maxwell’s equations are not symmetric under Galilean transformations. These equations are instead invariant under the *Lorentz transformation*, which is very close to the Galilean transformation at low speeds, but deviates increasingly at high speeds. This had the then-perplexing consequence that if I am moving towards or away from a light source, at no matter how high a speed, Maxwell’s equations tell me that I will see the speed of that light as the *same* as if I were stationary with respect to the light source. Special Relativity is the theory that I get if I demand that this same symmetry be true of particles and light.

If I want to explain the motions of a pair of elasticated objects moving past me at some significant fraction of the speed of light (or a pair of magnets, since we can now talk about electro*magnetism*), then the mutual separation which I measure as they whizz past is smaller, in an easily calculated way, than the separation that I must quote when making my Hooke’s Law explanation (this is special relativistic length contraction).

What has happened here is that we have increased the range of possible transformations (to transformations in a four-dimensional spacetime, from a three-dimensional space plus separate one-dimensional time), but discovered that it is the Lorentz group of transformations which is important as a theory-filter, rather than the Galilean group. Since the Lorentz group is larger than the Galilean group (in the sense that all Galilean transformations are Lorentz transformations, but not vice versa), the demand that a theory be invariant under all Lorentz transformations is a more restrictive demand – in the sense that it excludes a larger set of otherwise plausible theories – than the demand that it be invariant under only the Galilean transformations.

When we move to General Relativity, we enlarge this transformation group still further, and thus make still more stringent demands of any putative physical theory, so that Einstein’s equations for empty space (that is, his theory of how gravity warps empty spacetime), though they are very complicated, are the simplest equations possible which satisfy the requirement of invariance under the required transformation. In this sense Einstein’s free-field equations have the inevitability that he saw as a hallmark of a fundamental theory. Einstein aspired to go still further, and find a still larger fundamental symmetry, which would produce an equally inevitable (though necessarily more complicated) simplest-possible theory for non-empty space.

No-one has yet done this, though it is effectively the same programme that motivates some branches of string theory.

The EPR paradox

By the time that Einstein, Podolsky and Rosen produced the paper which contained what is now known as the EPR paradox, Einstein had given up trying to prove that QM was *wrong* – Bohr had persuaded him of this through a long sequence of thought experiments contained in what is now described as the Bohr-Einsten Dialogue. Thus Einstein was happy (-ish) to agree that QM gave accurate predictions of what would happen in a given situation. The point of Einstein’s remaining criticisms was to convince others that there must be more to reality than the things that QM suggested.

The fact that the Aspect experiments ruled out hidden variables tells us that the universe is indeed odder than Einstein supposed, but this would not, I think, cause Einstein to conclude that it was odd in precisely the way that quantum mechanics fundamentally suggested.