Goals, models, frameworks and the scientific method

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The distinct nature of goals, models and frameworks in physics is highlighted and this is used to re-examine to what extent criteria like empiricism and falsifiability can be applied to them. The contemporary frameworks of quantum fields and strings are discussed in this light.

It is sometimes claimed that certain branches of science are violating the basic tenets of scientific enquiry. According to the arguments, these research areas ignore the primacy of empiricism and fail the concepts of testability and falsifiability. The present note tries to examine the situation with some attention to the precise words used as well as the unstated assumptions. Thereby, it is hoped that a more rational appreciation of the issues will emerge. The scope of this discussion will be limited to research in physics, but it is within this discipline that the controversial claims have come up in the first place; so perhaps this is natural.

Goals, models and frameworks

One of the most confusing words in philosophical discussions of science is 'theory'. Even within the physics community there is no widespread agreement on its meaning. Compare the following: quantum theory, density functional theory, Fermi liquid theory, BCS theory, big bang theory, theory of elasticity, gauge theory, quantum field theory. One can recognize that the word 'theory' is being used here with very different meanings. This makes any question about whether a given 'theory' should be testable, or falsifiable, rather ill-defined.

It is more useful to consider three related but more unambiguous concepts: 'goal', 'model' and 'framework'. A goal is something one would like to understand. Some popular goals in physics are superconductivity, nanomechanics, molecular motors, quark–gluon plasma, photonics and quantum gravity. A goal typically has an experimental and a theoretical side: for example, an experimentalist may study quark–gluon plasma at an accelerator, while a theorist may formulate a model to describe its transport properties. But typically there is no symmetry between the experimental and theoretical sides. For example, photonics is largely an experimental effort to transmit, modulate, amplify and detect light. It is driven by its potential application in telecommunications, medicine, metrology and aviation, to name just a few. As such, it is more experiment-driven than theory-driven.

Now let us consider some models, for example, the nuclear shell model, Hubbard model, Yukawa model and dual resonance model. Each of these is an attempt to understand a specific class of physical phenomena. Respectively, the above models try to understand the energy spectra of nuclei, the metal–insulator transition, the nature of strong interactions, and resonances in high-energy scattering. Each model is aimed at describing a specific system or process, and is somewhat successful in this goal. But each one also has obvious limitations. The shell model fails to explain multipole moments of nuclei, while the Yukawa model does not provide accurate numbers for scattering amplitudes. In fact, all the above models are 'wrong' – in the sense that they are contradicted by definite experimental measurements. In some cases they have been superseded by better models that also do not work completely; for example, the nuclear shell model was replaced by the collective model that won the 1975 Nobel Prize for Bohr, Mottelson and Rainwater[1], but this too has had limited success.

Even though they are contradicted by specific experiments, the models listed above continue to be used by scientists. This may surprise a layperson, or even a scientist, who has heard about Popper's criterion of falsifiability[2]. Surely models that have been 'falsified' should be abandoned? For better or worse, that is not how science works. Scientists typically formulate a model to suit some known set of data and then hope it will make a prediction that is confirmed by additional data. If the predictions fail to be confirmed, rather than saying 'this model is wrong' we simply claim it is not applicable to that particular context. In other words, a model works only when it works. For example, a 'non-Fermi liquid' is a system for which Fermi liquid theory (which is really a model) fails to work. This may not seem like a perfect way to do things, but without this approach most areas of research – at least in physics, and very likely in other sciences too – would come to a swift end.

The third concept of interest is 'framework'. This is less familiar to the general public than a goal or a model because it is usually technical, though it embodies profound physical concepts. A framework is not a model of a specific system, but a way of formulating and studying a variety of systems. Classical mechanics, quantum mechanics and statistical mechanics are all really frameworks. In and of themselves, none of these makes direct predictions that can be 'tested' or 'falsified'. For example, in classical mechanics one can write down the Hamiltonian of a hypothetical system and study the solutions of this problem, even if such a system has no existence in nature and therefore, the solutions cannot be compared to any experiment.

Within a framework we can make a model of a chosen physical system and try to experimentally test it. If the model has been designed with suitable hindsight, it usually works up to some level of accuracy. We then test it by working to greater accuracy or varying the experimental parameters. What if the predictions of a model disagree with an experimental observation? There are several different conclusions that may be drawn: (i) the model is incomplete and can be improved by tweaking it; (ii) the model is inappropriate to the problem at hand, or (iii) the framework within which the model was formulated is actually inadequate.

An example in category (i) would be a model of fluid dynamics that lacks some important feature of the fluid under study; this may be redressable by putting in a new term that captures the missing feature. In category (ii) we have Fermi liquid theory, mentioned above, which is inappropriate to describe certain classes of materials. Category (iii) is exemplified by the fact that the hydrogen atom simply cannot be described by any Hamiltonian within classical mechanics. One might say the framework of classical mechanics is thereby falsified and replaced by quantum mechanics. But it is better not to think of frameworks as 'falsified'. They remain useful in some situations, but lack applicability in others. This is why we continue to teach and use classical mechanics, more than a century after it was officially 'falsified'.

Within frameworks, one often finds mechanisms or effects. These originate in a particular physical situation, but often turn out to be more general. Some examples are the Raman effect, the Meissner effect, the Zeeman effect, the Mossbauer effect and the confinement mechanism. Within this list one should include certain types of behaviour, such as phase transitions and asymptotic freedom, and even symmetries like conformal invariance. It is well known that the Meissner effect describes superconductivity in materials and is essentially the same as the Higgs mechanism which describes the electroweak interactions of fundamental particles. Thus two vastly differing physical systems rely on the same mechanism. We will return to this example below.

An illustration of this kind of generality is the notion of 'renormalization group evolution', a phenomenon encountered in physics across many different areas. This teaches us how to follow the evolution of any microscopic system over a change in the effective length scale, and introduces the notion of 'fixed point', a universal behaviour to which a wide class of different systems may converge. This notion originated in particle physics in 1954 and was developed by Kadanoff and Wilson in the 1960s and 70s in the context of statistical systems. Wilson won the 1982 Nobel Prize in Physics for this far-reaching work[3]. Wikipedia[4] tells us that 'The renormalization group was initially devised in particle physics, but nowadays its applications extend to solid-state physics, fluid mechanics, cosmology and even nanotechnology.'

There is a profound lesson here. A mechanism like renormalization group evolution does not even know what system we are talking about. It would be absurd to ask whether it is falsiable. In order to test it, one has to first propose a model where it is applicable and then test that model. When the renormalization group idea was proposed in 1954, quarks had never been thought of. Subsequent developments led to the formulation of a model of quark interactions: quantum chromodynamics or QCD. Within this model, written in the early 1970s by Gross, Politzer and Wilczek, the renormalization group plays a crucial role. The model was experimentally verified[5] and won these authors the 2004 Nobel Prize[6].

To summarize the discussion thus far, frameworks and mechanisms are not 'verified' or 'falsified'. They are applicable and useful, or not – depending on the system under consideration. History teaches us that the most powerful frameworks apply in a variety of contexts to situations that could not have originally been anticipated. This makes them incredibly valuable.

Quantum field theory

The framework that describes elementary particles and fundamental forces is quantum field theory (QFT). It encapsulates both classical and quantum mechanics and extends them to the relativistic domain. QFT was originally formulated by Feynman, Schwinger and Tomonaga[7] to study the quantum theory of electromagnetism, leading to the model of quantum electrodynamics or QED. Historically the study of QFT (the framework) and QED (the model) went hand in hand, but such a coincidence need not always hold. Had QFT already been invented for some other purpose, physicists interested in QED would have simply taken over its methods and results, and progress in the latter field would have been faster.

As is well-known, QFT also has applications to condensed matter physics. It can be reformulated to describe a many-body system such as a crystal with local interactions between different sites. The framework is essentially the same, but the physical models one studies are quite different, being related to excitations in some material rather than to elementary particles in a vacuum. This fact has played an important role in 20th century physics. An excellent example is the theoretical proposal and experimental discovery of weak vector bosons. Such particles were proposed by Schwinger[8] in the late 1950s as mediators of the weak interactions. By the early 1960s, many physicists were looking for a mechanism to assign a mass to such particles without contradicting gauge invariance, a crucial consistency condition. A possible mechanism was first suggested in 1963 by Anderson[9], using an analogy with the Meissner effect in superconductors. These embryonic ideas were converted in 1964, by Englert and Brout[10], and Higgs[11], into a generic mechanism within QFT: the Higgs mechanism.

At that time there was no definite prediction of how the Higgs mechanism should be tested, and no definite model – just a mechanism within a framework. But by the end of the 1960s, using both the Higgs mechanism and a novel class of QFT models due to Yang and Mills[12] which dated back to 1954, a single unified model of the electromagnetic and weak interactions was achieved by Glashow, Salam an Weinberg[13]. This model had many predictions some of which, like the existence of W and Z bosons, were soon tested – at first indirectly and then directly. Other predictions like the Higgs boson were only verified after 50 years. Incidentally, this story makes it plausible that future predictions in physics may take more than the human lifespan to be verified. As scientists we are obliged to accept this humbling possibility.

In the meanwhile, a model of the strong interactions (QCD) was proposed in 1973 and this relied on a different mechanism in QFT called confinement. QCD and the electroweak theory together form what is today called the standard model of fundamental interactions. This describes all elementary particles in nature and all the fundamental interactions among them, except gravity, and is a stunning success at extremely high levels of precision. Such an all-encompassing model was surely not anticipated by Feynman and co-workers when they initially formulated QFT. However, if they had been different people, or the age had been different, they might have ambitiously declaimed in 1948 that the QFT framework would enable a model of all the fundamental forces relevant for terrestrial particle physics – a 'theory of everything'. For saying this they would probably have been ridiculed, but they would have been correct in a very precise sense (It goes without saying that such a 'theory of everything' would not explain the behaviour of very complex systems and would scarcely spell the end of physics or science. The phrase 'theory of everything' should simply be understood as shorthand for 'model of all fundamental interactions').

String models and framework

It is not widely appreciated that QFT has been falsified, in the same sense as classical mechanics, by an experimental fact. This fact is the existence of gravity. QFT combined with gravity is not 'ultraviolet (UV) complete' and this means it must inevitably break down at very high energies, exactly as classical mechanics breaks down at short distances. One may take the position that we should not worry about this problem until we are able to perform measurements at those energies, but that would be short-sighted. Gravity undeniably exists, and it must be a quantum force like the others; otherwise we could use it to violate the uncertainty principle. This would leave us with a lack of faith in quantum theory itself and one could never be sure when it might break down.

A direction to address this difficulty arose serendipitously with the discovery of string theory. It arose out of a model, but came to constitute an entire framework on its own, much as the framework of QFT arose out of the model of QED. The original string model proposed by Nambu, Susskind and Nielsen[14], attempted to describe the binding of quarks in a proton. Experiments on deep inelastic scattering indicate a strange property of this binding force: it is stronger at large distances and becomes weaker at short distances. An analogy in classical physics is the behaviour of a rubber band. Hence Nambu *et al*. proposed that quarks behave as if they are connected by a (relativistic, quantum) version of rubber bands. Based on previous experience with QFT, it was possible to develop a formalism to describe this model in some detail, and this framework is string theory. The Nambu–Susskind–Nielsen model remains of interest: it has been successful in explaining certain qualitative features of the strong interactions, and has been considerably refined in the last two decades. It has not yet made accurate numerical predictions about hadrons, but such a breakthrough is very much a possibility.

As has happened before in physics, the string framework is able to encompass far more than was originally imagined. From its initial role as a model for quark interactions it grew to provide a consistent framework of quantum gravity, satisfying the very criterion ('UV completeness') that the framework of QFT fails to satisfy. Indeed the string framework is not especially radical: at low energies and in weakly curved spacetimes it reduces to QFT, just as at long distances and for large systems quantum mechanics reduces to classical mechanics.

Some features of QFT, such as the existence of gauge symmetries, have a more natural explanation in string theory. String theory is intrinsically unified in a way that QFT is not: in the latter one has to postulate an independent field for every particle in nature, while in the former there is a single type of string (that may be open or closed), not made up of anything else, and its excitations describe different particles with different masses and spins. A bold proposal was made in 1984 that using the string framework one may be able to find a complete 'theory of everything', a unified model of all fundamental forces, including gravity.

String-based models are motivated by experimental facts, including the complicated nonlinear nature of gravitational interactions, the known types of gauge interactions, the existence of fermions that are incredibly light relative to the intrinsic energy scale of gravity and the violation of parity. The hope was that a sufficiently compelling model would cause a lot of disparate known facts to fall into place naturally. Such a model could have predictive power even at observable energies. For example, a model that naturally possessed the known $SU(3) \times SU(2) \times U(1)$ structure of the gauge forces, as well as parity-violating fermions occurring in three generations, as well as a very small cosmological constant (which was thought to be exactly zero in 1984), as well as the absence of extraneous particles and forces, would fit the bill.

Models with specific compelling features are known, but no single 'most compelling' model has been discovered to date. Some of the theoretical leads that were followed do not seem to have led to a definite endpoint. As a result, work on string model-building has been scaled down considerably since the early days, but may revive if a new principle is found that satisfies the rather rigorous physical conditions spelled out above.

Uses of the string framework

The string framework provides an ultraviolet completion of gravity, and reduces in a smooth and natural way to the general theory of relativity at low energies and for small curvatures. This is reminiscent of the way in which quantum mechanics reduces to classical mechanics in a suitable limit. However, the departure provided by quantum mechanics is radical: one has to abandon familiar notions like position and momentum, and deterministic trajectories in favour of quantum states and operators. In going from general relativity to string theory, such a major change in language is not required. For many purposes one can continue to use the language of general relativity, and incorporate 'stringy corrections' only as needed. From this perspective string theory is general relativity, with the added ability to make precise statements about how gravity could work in regimes where classical relativity would break down.

Because of the reasons described above, any physicist who works with general relativity (either from a theoretical perspective or for applications to cosmology) needs to have a 'policy' on quantum effects. A common policy is to avoid physical regimes where these are important, which is honest even if limited in scope. Another policy, not so honest, is to venture into these regimes ignoring the invalidity of classical relativity. In discussions of singularities, including that associated with the big bang, one is not allowed to use classical gravity – any more than one can use classical mechanics to describe a laser. As one of the most compelling UV completions of gravity known, the string framework therefore has an essential presence today. There can be other compelling completions of gravity besides string theory, and these can equally claim to have an essential presence. The important point is that the need for a high-energy completion of classical gravitation is indisputable.

The string framework has been used in the last two decades to gain an incredibly precise and detailed understanding of what black holes mean and how their existence may or may not challenge fundamental principles of quantum mechanics. An important consensus, emerging entirely from theoretical work, is that the rules of thermodynamics must be modified to include gravitational contributions to entropy arising from the area of horizons. A likely arena where string-modified gravity will become more important in future is in the understanding of inflationary cosmology.

The second important use of the string framework today is in addressing questions in diverse areas of physics using effects and mechanisms that have universal applicability, much like the Meissner and Higgs effects. A string theorist today is not necessarily someone who wants to understand gravity or elementary particles, but someone who has expertise with the framework and can apply it to all kinds of goals of contemporary interest. It may surprise outsiders to the field that a 'string theory' conference today features talks on topics ranging from quantum phase transitions in superconductors to black hole physics to fluid dynamics to quantum entanglement to cosmological inflation. Many of the works presented do not even use the string theory framework in detail, but are merely inspired by it. In many cases the topics of interest are firmly rooted in empirical reality and are rapidly evolving due to better experiments, but conventional theoretical work (without inspiration from the string framework) has provided only a limited understanding of them. In this connection the reader might find it instructive to look at a recent paper[15] by leading string theorists, which starts 'We conjecture a sharp bound on the rate of growth of chaos in thermal quantum systems with a large number of degrees of freedom'. Such works would not have come into existence without inspiration from the string framework, but in the long run they will be judged by their relevance to very real systems.

Conclusion

I have argued that one should clearly distinguish goals, models and frameworks before applying various criteria to test their validity. These concepts are more precise than 'theory', a word that is sometimes used ambiguously and with confusing results.

The frameworks of quantum fields and strings are the most powerful in physics today and have widespread applicability to different goals via specific models. The string framework, in particular, is a useful way to study fundamental principles of gravity, quantum mechanics and thermodynamics, as well as a diversity of physical phenomena about which comparable insights have not been obtained by other means. This is a testimony to its power and widespread applicability. The development of this framework is completely consistent with the tenets of scientific enquiry.

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