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LAWS OF PHYSICS AND NATURE OF PHYSICS THEORIES

Introduction

In this course, we will investigate the smallest components of matter, discuss about counter-intuitive phenomena, ideas, theories and objects, and we will try to understand how scientific activities led to the particle physics conception of the world. This must therefore naturally bring us to start this course by thinking about what is the nature of physics theories.

Most people think that science work according to the naïve picture pioneered by Robert Boyle and formalized by Claude Bernard in the first half of the XIXth century, which Michel-Eugene Chevreul defined as:

A Phenomenon hits your senses, you observe it with the intention to understand its cause, you draw on hypothesis about such cause, you set an experiment to verify your hypothesis, and you establish your conclusions based on the results of the experiments.

While this was a breakthrough in natural philosophy of classical sciences, no philosophers and probably very few physicists now think that this is an adequate picture of the method actually used in science. Since the middle of the XVIIIth century, many alternatives conceptions of what the laws of physics are, and what is the nature of physics theories have been developed: positivism, realism, constructivism, structuralism, etc. While some approaches have been now abandoned, others share a large set of virtues and vices. No definite answers exist yet. The developments of modern physics played and continue to play a leading role in the debate about this subject. With the vast deployment of abstract entities and the experimental success of particle physics, this field presents all the complex elements allowing discussions and tests of the various options about the nature of physics theories. Some conceptions of physics disappeared, some get modified, and some more emerged along the progresses of physics. Discussing philosophical questions about science and knowledge in the context of particle physics is therefore equivalent in doing experimental philosophy, where the various conceptions of physics are tested against the meta-data of concrete examples of physics theories. Progresses can be made in philosophy!

It is however not the purpose of this class to study in details the questions of what is a law of nature, how they are established, how physics theories are structured, how they are tested, etc. It is nevertheless important to do a brief overview of the various epistemological options available, as it is virtually impossible to disconnect them from the understanding of particle physics. Clarifying these options before the fact, will allow us to not naively adopt a simple picture of the world, but rather to keep a critical view about the set of knowledge to be presented in this class. When we will study the basic ideas of quantum mechanics, and special relativity, when we will explain how experimental facts about particles are obtained, or how the fundamental theories about the femtoscopic[1] world are used to understand phenomena set on astronomical scale, it will be important to always keep in mind the various epistemological options that will be briefly presented here. That will allow us to appreciate how big is the revolution of thinking these physics theories brought, and how complicate is the task of understanding what science is doing. It will also allow you to see how the present stage of knowledge in physics doesn't definitely close the debate on the nature of physics theories, but force to adopt highly non-trivial conceptions of science. It will hopefully help you to shake your *a priories* about science and about the world…

Connection between epistemology and science

Most conceptions about what physics is, including the naïve approach of Claude Bernard presented above, share some common ground, which tells a lot about how physics is being made and conceived:

- Experimentation plays a critical role in the evaluation and the formulation of physics theories;
- Mathematical formalism provides the back-bones of the physics law, determining to a large extend relationships between formalized concepts;
- The mathematical skeleton receives a physical meaning that allows to make the connection between the theory and the experiments, so the various meaningful concepts of physics have an empirical meaning;
- A physics theory implicitly or explicitly involves a physical interpretation explaining what we are doing when we are using the theory, for example by specifying which are the physics objects included in the theory, and what is the meaning of abstract entities.

This last part is where epistemological considerations play a role. Typically, these questions are rather raised at an early stage of a theory, or during a crisis where the theory is in embarrassing contradiction with a set of experimental results. They, for example, played and they continue playing a crucial role in the development of quantum mechanics. This is because these epistemological questions are not only academic, but contribute to the development of physics theories themselves:

- Progress in philosophy of sciences means a better understanding of what physics is and how it works, which, in turns, helps making the research and educative activities more thorough and efficient;

[1] Use this term to mean smaller than microscopic scale: a micron is 10^{-6} m, while a femtometer, the size of a proton, is of 10^{-15} m.

- It provides some branches of physics with methodological and conceptual tools needed to progress in the field (e.g. use or misuse of anthropic principle in cosmology);
- It provides the tools for solving potential future crisis that might emerge from possible tensions between theories and experiments;
- It allows the development of new field of knowledge. For example, quantum cryptography, quantum computing and quantum information theory emerged from the problem of the measurement, one of the biggest issues in the interpretation of quantum mechanics.

This explains why the physical interpretation of a theory is considered as one of the fundamental component of the theory itself. Because the question of the physical interpretation of physics theory already assume a choice of epistemological options about what a theory must be, and what it can say about the world, we will review the spectrum of the various epistemological options that could be adopted to address interpretational issues and helping us understanding the meaning of particle physics.

A debate on abstract entities

We can cite three fundamental questions about science the answer of which will determine the various options about the nature of physics theories that could be used to provide a context for physics interpretation of particle physics theories:

1. What is the aim of science?

   Answer: Usefulness:

   Understood as "to predict, control, and produce natural phenomena", this is the minimal answer we can provide to this question. Conceptions for which science is nothing else than this are called: *instrumentalism*.

   For many other conceptions, the aim of physics theory is more than this:

   Answer: Truth:

   Truth can, here, be understood as a very broad criterion of adequacy. In this approach, science is more than a know-how, it is a knowledge, a discourse about what things are, or are not. At this point, many different conception of truth are possible: truth-correspondence, truth-adequacy, truth-consistence, etc. A second question can disentangle the various options gathered under this category:

2. What are the entities that exist?

A distinction is typically made between two types of entities:

A) Observable entities, i.e. those that are directly accessible via the 5 senses (chair, stones, liquid, light, etc.);
B) Theoretical or abstract entities, i.e. those not directly given by sense data, but rather inferred by a scientific reasoning (gravitational field, phlogiston, ether, quarks, etc.). The abstract entities are postulated by theories.

Answer A: Only observable entities exist, the others are only the summary of the results of a class of macroscopic experiments, or of the construction of a scientific image of the world: *operationalism, empirical constructivism*.

Answer B: Abstract entities exist, because there is an external reality, and these objects are part of science.

Again, that leads to various options that can be further disentangled by the last question:

3. What can we know about abstract entities?

   Answer A: We can't really know what these things are, we can only make statements about what can be observed, the phenomena, i.e. about how the thing gets given to us. The rest we can't know and most not speak of: *positivism, phenomenalism, and conventionalism*.

   Answer B: We can learn what the thing is, or at least, we can learn about some aspects of it, it's structure for example, and asymptotically reach knowledge of the thing: *realism, convergent realism, and structural realism*.

The questions of the abstract entities are central to particle physics because all the fundamental particles are not directly observable by human senses. These entities are described and only make sense in quantum mechanics. Our direct experience of the world is however not quantum mechanical, but through macroscopic apparatus that we can build, manipulate and modify. Quantum mechanics is therefore a theoretical framework designed to make sense of the results obtained from some macroscopic devices but which postulates entities not accessible to our macroscopic world. These experiments, in turns, provide the empirical content to the concepts of quantum mechanics. This is the context in which fundamental particles physics is formulated. From this complicated interplay between macroworld and microworld (femtoworld) in the formulation and tests of the theory, we can see that the epistemological status of abstract entities is far from being obvious in particle physics. This field of knowledge is therefore ideal to discuss about abstract entities, about progresses in philosophy of physics and about progresses in the physical interpretation of the quantum theories. [2]

In the following, we will give a brief overview of the various epistemological options outlined above, and will provide brief comparisons between the most popular options in order to understand why the question of the nature of physics theory is not yet settled.

Empiricism

Conceptions that fall in the categories of answer A of questions 2 or 3 are gathered into the term empiricism. What is common to the various epistemological options gathered into this term is that theories consist in mathematical models and physics laws that describe our observations, but must not be used to infer anything about what could be underlying to the observed phenomena. Despite we concentrate our discussion on the status of abstract entities in the physics theories, empiricism is more than a statement about non-observable entities: it is a statement about how we can know things about the world from our theories. It therefore plays a role in the formulation of the theories themselves. Although the impact of such questions on the development of quantum mechanics has been more spectacular than on the development of classical physics, it nevertheless threw great debates that changed the aspect of classical physics too.

> E.g. The Newton universal law of gravity left people very uneasy about the fact that it consists in an "action-at-distance" theory, where the action of a body on another one is propagated via a hypothetical field crossing empty space.
>
> - Some suggested that this field was an abstract entity only used to describe motions of planets, but not related to any element of reality and tried to reformulate the theory without it;
> - Some others considered the theory as incomplete and tried to supplement it;
> - Some others considered that it was a physical object existing in reality and applied Newton's 3rd law[3] to it.

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[2] One of correlated fundamental problem in quantum mechanics is the problem of measurement: where, in the process of a measurement, the transition from a quantum to a classical world operates, given that these two descriptions of the world are incompatible (we will discuss, for example, the wave-particle duality later in the semester)?

[3] Law of action-reaction: the force exerted by body A on body B is equal and opposite to the force exerted by body B on body A.

> This debate would only become settled after Einstein theory of general relativity where the gravitational field is propagated as a deformation of the geometry of space-time.

We can therefore see, again, that philosophical issues about the nature of non-observable entities contributed in the development of the physics theories.

Observer play a role in the formulation of physics theory

The impact of these questions about the nature of abstract entities is wider than what has been expressed above. The empiricist view of the laws of physics led to the fundamental integration of the observer in the formulation of the physics theory, opening the avenue for special relativity and quantum mechanics. From then on, natural phenomena couldn't be considered independently from the observer that performs the observation: the point of view of the observer plays a central role in the laws of physics forming particle physics. This came from a long succession of physical and philosophical developments.

Let gets back to Newtonian physics. While Newtonian mechanics has a strong predictive power and make use of logical-deduction to establish many results, the laws of physics imply very counter-intuitive understanding of the world. Here, "counter-intuitive" can be understood as: against what the senses teach us. For example, when a body is doing a circular and uniform motion, there is no force that push the body away from its circular trajectory, the force is directed inward. This is not what our experience of driving a car in a curve would teach us, but is the right way to make predictions for such motion. Similarly, the blocking of a light source by a small disc yield an intensity pattern on a screen behind the disk which features a maximum right at the position where the center of the disk is. Classical physics contains many more examples where our sense would not guide us to the right understanding of the physics phenomena. The consequences of this are:

I. We don't have a direct contact with things we want to understand, we can only provide an abstract description of these things and everything become phenomena;
II. We can develop many critical views on how knowledge of things is acquired. For example, Hume criticizes the notion of causality as a necessary relationship of consequence between an events and its effect, replacing it with a psychological habit of the perception of succession.

These empirical considerations about physics theories brought Kant to develop a detailed conception of knowledge. The objective of Kant was, against empiricism as the ultimate way to acquire knowledge, to restore the reason at the center of the epistemology, establishing the finality of Newtonian mechanics from *a priori* reasoning. For Kant, there are not 2 but rather 3 fundamental components in human knowledge:

1) Logical consistency
2) Empirical observability
3) Categories of thinking

This last component is the crucial addition which allowed Kant to escape from the empiricist skepticism of Hume. This will have profound influences on the development of the laws of physics. It means that the mind doesn't play a passive role in experiences: there are mental forms that automatically shape our experience of the world. Knowledge does not concern the things-as-they-are (noumena), but the things-as-they-appear-to-us (phenomena). That restored some objectivity in the knowledge we can get about nature, but introduce an intrinsic limitation in our ability to understand nature. As such, Kant's conceptions of abstract entities are very far from the empiricist's conception of such entities, but they criticize realism too.

One of the consequence of this epistemology is that space and time are no more considered as substance or entities that we can learn by experience, but are rather elements of a systematic framework that we use to structure our experience. Many critics to the Kantian conception of knowledge bear on the place attributed to the notion of space, time, reference frame and geometry in the physics theories. These considerations led to the consideration of the place of the observers in the formulation of the physics theories and to the development of various other versions of empiricism.

<u>Phenomenalism:</u>

Widely developed by Mach, this version of empiricism advocate that laws of physics and theories in general must ultimately be formulated in terms accessible to the senses. Physical theories must contain no "metaphysical" components. Mach advocated for a principle of economy: no introduction of abstract entities must be tolerated in science.

When applying this to the question of space and geometry, the phenomenalism advocates for the rejection of absolute reference frame: it is impossible for an observer in a pure vacuum to know if he is in any inertial state of motion, and so our physics law must make the economy of absolute reference frame. We therefore cannot have an absolute reference frame hardcoded in the mind. As a consequence, all laws of physics must be formulated with respect to an arbitrary reference frame set by the observer. In order to be universal to any observer, the laws of physics must however be independent of any particular choices of a reference point.

⇒ Physics theory must be supplemented with a theory of the observation affecting the laws of physics themselves: the invariance with respect to a choice of reference frame became a fundamental constrain on what the theory will be. Pushed at its limit, it eventually led to theory of the relativity of Einstein, probably one of the most powerful and successful theories that have been made in physics.

The drawback of the phenomenalism is that it rejects the introduction of abstract elements that have, in many occasions, incommensurably enriched the physics understanding of nature.

Logical Positivism:

This sophisticated version of positivism reintroduced the possibility of having abstract entities in an empiricist approach to physics theories. The main idea was to replace the mental focus of empiricism by a linguistic approach: objects in physics theories are not elements of reality, but rather their linguistic representation logically elaborated from primitive observation statements. Physics statements that are not representable in this way are meaningless and must be evacuated from science. Unobservable entities could thus be understood as a complicated set of statements about observations, combined together by the laws of physics, and therefore tolerating some theoretical entities in the theory.

Failure to establish such language essentially kills this approach.

Operationalism:

In this new version of empiricism, widely defended by Percy Bridgman, all physical concepts are synonymous of a set of experimental operations. The laws of physics are therefore essentially a prescription on how to perform such empirical operations. This approach guarantees the continuity of the concepts over time: concepts are not right or wrong; they are limited or extended by measurement procedures. Since all concepts and laws of a theory are intrinsically linked to a set of experimental setups, we speak of an instrumental interpretation of physics concepts. The same rule applies to abstract entities. For example, "electron" would be a summary-word for what is common the Thompson experiment, the Millikan experiment, the Wilson experiment, etc. The spin of the electron, one of the fundamental property of particles, would take its meaning from the Stern-Gerlach experiment. In this approach, sciences satisfies all constrains one expects from reality, but rather than talking about how our world is, it talks about a scientific world only, one made of experimental devices, setup and technological apparatus. Extension of the properties of particles to our complete world (outside the boundaries of sciences) is metaphysics; it is not in the theories themselves.

This could be considered as the minimal approach to be adopted when thinking about physical interpretation of physics theories.

Constructive empiricism:

Developed mainly by Bas van Fraassen, this is an attempt to keep the lessons of empiricism, while trying to go a little further than operationalism. In this approach, what matters is the empirical adequacy of the theory. It allows claims about unobservable entities, provided that the predictions obtained from the theory are consistent with observations.

This reveals another crucial aspect about sciences, shared by any epistemological options and by the practice of science: repeatability. This criterion is mandatory to establish the consistency of a theory with observations. The idea is that the same type of experiments, testing a given law of physics, must all agree. Of course, there are fluctuations in data, in the way the experiments are being carried on, in the calibration of the apparatus used for the measurements, in the validity of the assumptions taken to be true for the measurements, etc. In order to be comparable, uncertainties on all measurements must be carefully assessed. These uncertainties serve as the repeatability criteria that must satisfy any scientific theory. Without them, there would be no science, no way to establish any laws of physics, because all measurements testing the same law would disagree. The uncertainty quantifies to which extend experimental results are expected to agree. This is not specific to constructivism; this is recognized by all approaches and is at the very heart of the products of science and at scientific activities themselves.

However, it takes a special impact on the motivation for the constructive empiricism. From the above perspective of having quantitative margin inherent to any experiments within which experimental results are assumed to be empirically equivalent, the same experimental results can be used to establish the empirical adequacy of various different theories. Different theories can predict different outcomes of a given experiment, but if they were closed enough to be integrated within the uncertainty margin of the experimental results testing the theories, they would then both be equally empirically adequate. From the standpoint of constructive empiricism, this is not a problem, as the objective is not to understand the underlying reality, to yield truth, but rather to build a useful consistent conception of the world that get mapped onto the world and produce a scientific meaning of the empirical operations being carried in the experiments. In other words, entities get constructed through their use in empirically adequate models projected onto the world, rather than being discovered. In this way, the experimentations and operations that determine a physics theory get integrated into a scientific image of the worlds in which there is a large place for abstract entities. The laws of physics therefore get a meaning that extends beyond the sum of empirical procedures being carried out in order to establish them, but that doesn't need to assume identity to an underlying reality.

So far, we investigated various empiricist epistemological options about the nature of physics theories, the meaning to be attributed to the laws of physics and about the status of the abstract entities included in physics. We saw that these options, often quite sophisticated, led to fundamental developments in physics. Of course, there are a very large number of arguments justifying why such approaches should be adopted when considering the physical interpretation of quantum mechanics. However, the empiricist options are not the only one, and it is important to give a survey of some of the most important alternatives as they also play an important role in the edification of physics laws and theories.

Instrumentalism

Instrumentalism is not to be confused with the instrumental interpretation of the laws of physics. The idea, here, is that science itself is simply an instrument for human being. This is very different than saying that the meaning of the laws of physics lays in the set of experiments that constitutes the physics knowledge. The instrumentalism means that the ultimate goal of science is that theories are useful for us to describe our experiments, to anticipate on future experiments, to control our environment and even to have a social impact. This approach makes stronger statements about what the nature of physics theories and abstract entities are than what operationalism does. It is a bit like the comparison between agnostic and atheist positions on the existence of divinities: instrumentalism deny any epistemological meaning to the theory of physics; they are just tools.

Similarly as for the empiricism, instrumentalism takes many various flavors. Some of the most popular ones include: pragmatism, and several version of sociology of sciences.

Pragmatism:

This approach has been mainly developed by American philosophers such as Pierce, James, and Dewey, and more recently defended by Richard Rorty. This version of instrumentalism is rather close to empiricism, although it differs on few points. For them, the practice of sciences is to be modeled on a very successful enterprise. Scientifics build hypothesis, drive tests through experimental investigations, modify their theoretical constructs in light of the results, apply the results to technological goal, etc. This hard work is not done in order to find what is right and what is wrong about the world, but to come up with something useful. In this approach, satisfaction replaces truth, and satisfaction can be wide.

For pragmatics, the abstract entities of a theory are just tools, like any other physics concepts, and they are successful if they help us to establish links between the various experiments. One of the biggest distinctions with empiricism is that there are no distinctions in pragmatism between observable and non-observable entities: both are judged not on their empirical meaning, but on their capacity to increase the usefulness of the theory. In addition, the goal is not the economy of descriptions, but rather efficiency in the use of the theory in a practical sense. If introducing elements beyond observable phenomena makes the theory a better instrument to control the world or to bring some satisfactions, then the introduction of such abstract entities will be encouraged. For the pragmatists, there is no need to keep a continuity of the concepts: what was useful yesterday will not necessarily be useful tomorrow. Progresses in science are therefore not considered from the point of view of an increasingly wide range of experiments connected by an increasingly economical set of descriptions, but rather in terms of efficiency and the increasing practicality of a set of theories.

<u>Sociologies of science</u>:

Several versions of sociological approaches to the question of the nature of physics theories have been developed since the 60'. The *Structure of Scientific Revolutions* by Thomas Kuhn certainly pioneered and popularized these approaches. For Kuhn, sciences do not progress linearly, but through a series of discontinuities following what he called a scientific revolution in which a paradigm shifts operate. Many factors intervene in a paradigm shifts, but the large novelty is that they also include sociological factors. In this approach, the specific (historical) way by which science is made, is developed, has a genuine impact on the structure of the theory itself. The paradigm of particle physics would therefore be seen as a set of practices of how physics is being developed in this field, i.e. by a set of methods, concepts, tools and metaphysical view of the worlds in which all the various problems and questions are understood, and outside which the theory is absolutely non-understandable. According to this view, the aim of the course you are now following about particle physics would be to slowly convert you to the paradigm of High Energy Physics, to allow you to understand the practice of science in this field. In such view, there is nothing special about non-observational entities.

There are many other versions of sociology of sciences, from the research program of Lakatos, which constitutes some kind of heuristic[4] approach to the question of the nature of physics theories, to the radical view developed by Feyerabend which propose an anarchist epistemology where methodological rules to establish scientific knowledge are completely denied. In this last case, culture, ethnic, gender and age could be factors justifying the introduction of abstract entities in a theory…

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[4] An approach is heuristics when it is made of strategies that are simple, incomplete and loosely applicable to the problem of interest, but which are creative and inventive, therefore allowing new ways to attack and solve a problem useful for human beings.

Scientific Realism

Scientific realism is the epistemological alternative which defends a certain knowledge about how the world is. In its “strongest” version, the *convergent realism*, physics theories aim at the true association of abstract elements with physical object and their attributes, and provide a successfully better approximation of the truth over time. For a realist, science therefore aims to provide a true story about what the world is like and to provide a genuine knowledge of both observable and unobservable entities. It is, in one version or another, the most common view shared by physicists. It joins the old dream of sciences as the quest for certainty. Scientific realism is sometime contrasted with the metaphysics realism, an approach in which the structure of reality is given by large metaphysical systems, similarly to the epistemology of the German idealism of the XIXth century (Hegel for example).

One of the principal reasons for the popularity of realism in the scientific community is the inter-subjectivity: everybody agrees on what the phenomena are, how the experiments are made, what the results are, etc. Physics results appear to be universal, in contrary to sense data. If this is so, it is very tempting to conclude that they are independent of us and that the laws of physics therefore really describe the world we live in. If something exists, it must indeed exist independently of our minds. In fact, universality is so important that it is raised as another fundamental criteria that physics theories must satisfy: if the results rightly obtained in compatible conditions are not the same for observer A and observer B, then either they haven’t investigated the same phenomena or something new, possibly unobservable, is about to be discovered. Of course, this is not related to realism, but it gives the impression that something objective is questioned by our scientific enquiries and encourages people to believe that this corresponds to an element of reality.

One of the advantages of realism is that there is no fundamental distinction between observable and non-observable entities. They both correspond to elements of reality more or less easy to observe. This is an advantage because it does not need to specify at which scale entities stop being observable and become unobservable. Typically, empiricism treats cases where, for example, the size of an entity is smaller or much bigger than de Broglie wavelength[5], but doesn’t much discuss cases where the objects are slightly bigger than this characteristic wavelength. Is a cell observable or not? What about a virus, a chromosome or a macromolecule such as DNA? For a realist, they are all treated on equal footing: they all have identical ontology, they all exist. This question can still be answered from an empiricist perspective by saying that entities are unobservable if they are given by any apparatus, but this leaves some ambiguity (for example: what about objects that can

[5] We will see later that the de Broglie wavelength characterizes the length of one cycle of the wave associated to each quantum particles. When distances involved in a physics process are of the scale of de Broglie wavelength, quantum mechanics is needed to describe that process and the system in general.

be seen through optical microscope or telescope?) and still creates a dichotomy between entities. Note that for operationalism or empirical constructivism, this is not a problem as both macroscopic and microscopic objects are treated as scientific products: they both only make sense in an experimental context, removing the dichotomy between observable and unobservable entities.

All epistemological approaches for which it is meaningless to ask whether or not abstract entities correspond to an underlying reality are called anti-realism. This includes instrumentalism, operationalism, constructivism, etc. For them, theories only provide functioning models, not at all an adequate representation of nature. Tenants of anti-realism formulated many strong arguments against realism. These critics led to the development of softer versions of realism. In the following, we will give an overview of the major arguments in favor of convergent realism, followed by the major counter-arguments that have been brought by anti-realist against convergent realism. We will finally summarize the softer realist positions that emerged from this debate.

Convergent realism

As mentioned above, convergent realism is the strongest realist epistemological option: theoretical entities postulated by physics theories really exists, and the physical statements about the properties of these objects become more and more precise in the course of the development of physics and converge to the truth[6]. The crucial point, here, is that there is some sort of continuity in the evolution of physics theories that brings our understanding of nature closer and closer to what reality really is. Demonstration of such continuity and of the convergence of physics theories would provide strong support in favor of convergent realism. In addition of inter-subjectivity, which argues in favor of any realist approach, there are three major arguments in favor of convergent realism, all essentially bearing on the continuity and convergence of the laws of physics. These three arguments go as follow.

First argument in favor: historical progresses in science

Convergent realism seems to be backed by the history of science: since the XVIII[th] century, there is an undisputed successive improvement in the success of physics theories, in the “discovery” of new phenomena, and in the technological consequences of these theories. After all, mankind walked on the moon, cloned animals, and measures time with an accuracy of 10^{-9} seconds per day (atomic

[6] We can think of stronger versions of realism, but concretely, no serious philosophers or scientists claim that the present state of the laws of physics provides the final right description of reality.

clocks). Such progresses are naturally expected when we consider that physics allows us to learn about reality.

Second argument in favor: limiting cases and correspondence principles

Earlier theories of modern physics are still in use whenever accuracy permits, which can be contrasted with Aristotelian physics which vanished completely. For example, while the formalism of general relativity is needed to compute the anomalous perihelion advance of the planet Mercury[7], Newtonian mechanics is still used to send rockets in the space. Past theories are still valid in their limits of applicability, while newer theories complement them in extreme cases compared to the conditions in which typical human activities are held (very high speed, very dense environment, very low temperature, very small distance scale, etc.). Theories are even often endowed with correspondence principles providing a formal transition between successive theories. Bohr correspondence principle, for example, states the convergence of the laws of quantum mechanics to classical physics in the limit where the distance scales are much larger than de Broglie wavelength (or when the action is much bigger than Planck's constant h). This continuity in the physics theories argues in favor of a convergence toward the truth.

Third argument in favor: Putnam miracle argument

One of the biggest arguments of realism is that science works. We do predictions, they get tested, they eventually integrate the body of statements constitutive of a physics theory and this leads to new experimental and technological developments. Putnam formulated this argument in clearer terms: "realism is the only philosophy that doesn't make the success of science a miracle". For example, the deviation of light by a gravitational source has never been observed and even considered before it get predicted by Einstein theory of general relativity. This phenomenon is also very counter-intuitive (our daily experience tells us that light travels on straight trajectories). The observation by Sir Arthur Eddington in 1919 of the deviation of the light emitted from a distant star by the gravitational field of the sun, in agreement with Einstein's general relativity predictions, looks like a miracle when anti-realist approaches are considered, but makes complete sense in view of convergent realism, because it simply corresponds to what reality is.

Counter-arguments, complemented by other important critics, however place convergent realism in a delicate position. Let summarize now what are these counter-arguments and critics.

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[7] This is the rotation, around the sun, of the point of the trajectory of the planet which is the closest to the sun. The term "anomalous" means, here, that there is a deviation between astronomical observations and predictions obtained from Newtonian physics.

Critics of the convergent realism

First argument against: mind-independence doesn't mean reality

Realism implies that there is a reality independent of us, which, in turns, implies that observations and predictions are mind-independent. This, in a realist perspective, would explain the inter-subjectivity of the products of science, one of the major characteristics of sciences, agreed by everybody. Inter-subjectivity is therefore a logical consequence of realism, which we can logically write as $A \Rightarrow B$. However, the argument brought above was that realism must be the right epistemological approach because of the evidences for inter-subjectivism. This is an inference of the cause from the effects. This is not a logically valid inference because, the truth of $A \Rightarrow B$ doesn't guarantee at all the truth of $B \Rightarrow A$. For example, it is not because when somebody drinks a beer he stops being thirsty, that if somebody is not thirsty it is because he drank a beer… The conclusion of realism from inter-subjectivity is not valid; realism is only one context in which inter-subjectivity can make sense.

Second argument against: inextricability of theory and experiment

The idea of realism is partly built on the impression that sciences consists in establishing hypotheses on what the world can be, and confirming or invalidating these hypotheses using experimental tests, therefore establishing an understanding, at least approximate, of what reality is. However, statements that constitute a physics theory are established in a far less straightforward way. There are generally several theories that are compatible with a set of data and not just one. Experimental results would therefore not support one theory, but all of them[8]. This is the underdetermination of theories by experiments. Alternatively, it is the structure of a theory as a whole which is tested by an experiment, including the experiment itself, and not just a given hypothesis[9]. There are therefore no crucial experiments in science, i.e. that hypotheses which are disfavored by an experimental test, don't necessary get rejected[10]. Confirmation and invalidation of hypotheses are not properly possible in sciences. From the way scientific statements get validated, it is therefore far from obvious that they tend to any truth at all.

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[8] Note that we don't talk about "confirmation" because it is not a definitely valid inference of truth. Carl Hempel and Nelson Goodman discussed lengthily of this question.

[9] Holism is the basis of the Duhem-Quine thesis.

[10] In many instances, the principle of energy-momentum conservation has been contradicted by experiments without having been expelled from physics theories. It allowed, for example, the discovery of neutrinos.

Science corresponds to a complicated network of interrelated theoretical and experimental statements forming a system similar to the idea of incommensurable paradigm dear to Kuhn. Experimental statements are constituents of the theory itself, and not independent elements coming from the outside reality to determine if the theory represent well this reality or not. It is very difficult to see where, in this intricate system of statements, the connection to the real world would be. Physics theories rather seem to talk about themselves than about the world.

Third argument against: discontinuity in the semantic of the terms of the theory

Abstract entities emerge from theories and indirect observations in specific experimental contexts. In order to have convergence toward a truth, we must have continuity in the meaning of the terms referring to these abstract entities in the theories and experiments that give access to them. However, the meaning of terms in a theory is fixed by the whole theory, i.e. by the entire body of statements of the theory. The meaning of the same terms used in successive theories is therefore incompatible, and even incommensurable, to borrow Kuhn's terms. If the meaning of the terms referring to abstract entities change with time, then the ontology changes too: we are speaking about different things. This is in opposition with a continuous progress, a convergence toward truth. This is the argument of the non-persistence of the entities, against convergence realism. In fact, this argument could even go further: even the results of experiments can't be established and interpreted without the intervention of a theory. Experiments, observations and phenomena are therefore not in continuity from a theory to another. We cannot therefore say or even conceive that there is a persistent underlying nature that we understand better and better with time, if there is no continuity in the objects and phenomena that give access to this underlying reality.

Fourth argument against: indeterminacy of the concept of convergence

The idea of the convergence of theories is vague and ill-defined. How this convergence can be established? How can we show that two recent theories are closer to each other than two distant theories? What is the element that quantifies this convergence, i.e. how the distance between two theories is defined such that their convergence can be investigated? All these questions haven't hitherto been answered. The concept of convergence is however well-defined in mathematics. The criteria under which a series converge to a function are, for example, very well known. Such convergence is obtained as the limit of an infinite succession of terms[11]. Of course, there is not an infinite succession of theories. So even the concept of convergence we understand the most cannot be applied to scientific

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[11] For example, it is the sum over n from 0 to infinity of $x^n/n!$ which corresponds to the function e^x when $x<1$, not the finite sum.

theories. Saying that scientific progresses converge toward reality is therefore only a qualitative appreciation and not an argument that we can use to prove realism.

Fifth argument against: illusion of correspondence between theories

The correspondence principles are not formal elements of successive theories establishing a bridge between them. They simply consist in the addition to the new theory of trivial statements based on the fact that the numerical value of the predictions obtained from both theories are the same for the experimental conditions in which both theories apply. The experimental results are nevertheless still understood fully inside the new theory and stay incompatible with the old theory. Correspondence principles are therefore ad hoc statements of continuity between two theories, adjoined to the new theory. They cannot be used to prove realism, since they are added as realist hypothesis. Such postulates are needless to the theory and must be abandoned.

Sixth argument against: the miracle is a mirage

There is nothing that guarantee that a theory valid at a given time stays valid in the future, including the existence of the abstract entities predicted by such theories. There are many examples of entities that where suppose to exist but get evacuated by future theories. Phlogiston, caloric, ether, and action-at-distance are a few examples of such entities that disappeared with time. Some more disappeared, and got back to later theories with the same name but with a completely different meaning. There is no reason to believe that this will not happen again many times in the future concerning the abstract entities that we cherish nowadays in particle physics. So, theories that work today might not work tomorrow (it happened many time in the history of sciences), and entities that exist today might not exist tomorrow. There are so many instances where predictions have not been verified, where test failed and where theories died, that it doesn't look like a miracle if some successes happen from time to time. The level of failure in science is probably larger that the number of success[12], such that the miracle does rather seems to be an impression from textbook than a real epistemological argument.

These critics severely shook the convergent realist approach to the nature of physics theories. The position has been weakening in many different aspects to evade some of these critics. We will now give a brief overview of some these softer realist options.

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[12] And even this dichotomist way of seeing science product as failure and success is a little bit naïve as often, in research, some ideas get introduced in some form, and get modified and modeled until it reaches its final form, that will eventually stay or disappear.

Entity realism

It is possible to be a realist about entities and an anti-realist about the theories. We could for example claim that quarks are real, but that there is no true theory about quarks that would correspond to reality. In this approach, it does simply not make sense to ask what an abstract entity really is, but we can nevertheless say that the abstract entities exist for real. This position has been defended by Ian Hacking. The reason why he claims that abstract entities really exist is because we can manipulate them, control them and make interesting use of these entities. Physics theories rightly refer to these entities and their attributes, but cannot claim that these attributes correspond to reality. Hacking say: "if you can spray them, they exists".

Note that particle physics is a particularly interesting ground to discuss this version of realism. In fact, the status of quarks is singular: because of the asymptotic freedom (we'll see in few classes what it is…), quarks cannot be manipulated directly. Applying Hacking reasoning, they would therefore not exist. However, the distinction between quarks and many other fundamental particles is purely theoretical. The distinction with electron, for example, is on the attributes taken by these particles in the theory, and are therefore not considered as faithful to reality. If quarks don't exist, why electron would (and vice versa)? The question of the existence of the quarks therefore put entity realism in an uncomfortable position.

Internal realism

This is an approach presented by Hilary Putnam in his later writings. The idea, here, is that the elements of a physics theory and the elements of the external world get associated only in the context of the theory at stakes, and not in a global correspondence to reality. That allows creating a picture of the reality which is neither true nor false, but only simplifying the understanding of the phenomena within a physics theory. The objective is to favor the convergence in the agreement between experts in order to reach a more and more mature phase of the theory development which will forge the "truth" accepted by all. This approach of realism is very close to the empirical constructivism, except that here, the focus is on the understanding of the phenomena while the empirical constructivism focuses on the empirical adequacy in describing the phenomena. There is obviously also a large pragmatic component in this approach.

Structural realism

This realist position has been initiated by John Worrall in the late 80's. The main idea is that despite the fact that entities are not very stable and are not good candidates to support a realist interpretation of physics theories, the mathematical structures of the physics theories look stable. Later theories incorporate the mathematical structures of the earlier theories, which would explain why the old and the new theories yield the same numerical values for the predictions that are made in limiting cases where both theories apply. Such numerical coincidence between two theories is expected to hold in future theories too, as they will be required to explain phenomena that are understood today. It therefore seems like if the mathematical core of physics theories is persistent and therefore corresponds to reality. In this approach, physics theories and laws of nature don't tell us how the world is, but allow us to know what the fundamental structures of nature are.

While this approach concedes a lot to empiricist epistemologies, it is not obvious that such concessions are enough to evade the critics presented above. For example, it is difficult to identify what are the persistent core structures of physics theories and to get convinced that they will survive over time. In addition, while necessary, it is not clear that the stability of the structures is a sufficient condition for realism. It also gives a too large impact of the formalism over the physics content and the interpretation of the physics theories. It therefore leaves a very abstract conception of the world, quite unsatisfactory to those who believe in a scientific explanation of reality.

Motivational realism

This version of realism has been defended by Arthur Fine who got inspired by Albert Einstein's late writings. In this version, realism doesn't have an epistemological motivation, but is rather driven by research. Believing in realism is something that helps researchers to progress in the development of physics theories, it drives research programs forward. The truth about the laws of physics is not relevant; the only important question is the viability of a theory, i.e. its empirical adequacy. Viable theories allow us to extract more benefits from science and to be more efficient in pushing theories further. This approach claim to be realist, but it has very strong constructivism and pragmatism components. This version of realism also dangerously shakes hands with psychology…

Conclusion

We presented some of the most important epistemological approaches which attempt to address the question of what is the nature of physics theories. We presented the advantages and inconveniences of these various approaches. Suffering from over one hundred years of thorough critics, convergent realism is now abandoned by a large number of philosophers. This position nevertheless keeps the favor of the physicists, the practitioners of physics, because of the strong impression of grasping something about the world they have when they do research and make discoveries. On the other hand, the philosophers that tried to reconcile realism with the critical arguments formulated against this epistemological approach ended up defending so softer versions of realism that they are essentially defending empiricism or instrumentalism disguised under the name of realism. Is realism viable? Is realism a dogma that people want to believe despite counter arguments? It is still hard to decide, but it seems that the interpretations of physics theories formulated in an empiricist perspective are easier to defend. This is at least what careful study of particle physics tends to indicate (remember, for example, the critics brought to Hacking's entity realism from the considerations of quarks). Relativity and cosmology also play an important role in these discussions (remember the role of the observers in the formulation of these theories). It might well be that physics and sciences in general can't say anything, from the way they are structured, about the world, but it doesn't mean that we can't adopt a metaphysical realism, where the connection to the world is made not from inside sciences, but from outside. In such case, the last word would have been given by philosophy, not by physics. Do physics and sciences in general explain everything? Do they explain themselves? One thing is clear: those questions are very exciting, and very important to understand what is it that we are doing when we are doing physics.

The objective of this course is not to decide on the best epistemological position about the nature of physics theories consistent with particle physics, but to learn some of the most up-to-date ideas physicists have of what the world might be made of. It was nevertheless important to discuss about what could be the nature of particle physics theory as now we will be able to see things with a critical view. Every physicist should be initiated to those questions… In the following, we will try, when needed, to adopt a minimal approach. We will be careful in not assuming realism, in contrary to what is typically done in physics textbooks. The advantage of this will be to help understanding what is the empirical content of the various concepts. After all, physics is an experimental science and many concepts get demystified when we understand what they empirically mean. Nothing prevents us later from extending this minimal position to realism.

There are various points that have been discussed in our epistemological investigations that are central to the development of physics theories and their interpretation, regardless of the epistemological options adopted. We discussed, for example, the essential place formalism and mathematical structures take in physics theories. We saw how the idea of science itself relies on the empirical adequacy of the theories and on the conditions of repeatability establishing the consistency of experimental results. We also saw that modern theories all include a theory of the observation, i.e. take into account the fact that observers participate in the experiments that produce the results integrated to physics theories. We saw, for example, that invariance with respect to choices of an observer lead to powerful constraints about what the physics law can be. This will lead to the idea of symmetry, an idea at the very core of particle physics (we will devote a class or two on this subject). There are however other guiding principles that are not established by a solid epistemological position, nor by formal mathematical proofs, but that have been proved very successful in bringing physics to very important developments. Unification and naturalness are two of the most important such principles.

Unification is the idea that physics will ultimately consist in a minimal set of laws and entities, sufficient to describe the very large spectrum of phenomena composing our entire perceived reality. This somehow corresponds to an economy principle, similar to the Ockham's razor argument. Naturalness can be formulated in simple terms as: the parameters of a theory must enter naturally in the theory, i.e. without the needs to adjust them to very high precision in order to account for the observations. Under this condition, a theory which would require a large fine-tunings of its parameters in order to reach empirical adequacy would be considered as problematic. This would be considered as an indication that an important ingredient is missing to complete the theory.

Unification and naturalness principles adopted in the development of physics theories correspond to esthetical criteria. They are not formal or epistemological principles. They are nevertheless widely used in physics, and, as you will see, they are at the heart of the most recent developments in particle physics. They are used as guiding principles, helpful to perform research, to get new ideas and to solve problems. Scientists often use many more crude esthetical arguments to choose between two competing solutions. You will often hear physicist or mathematician praising the elegance of their solution. Such extensive use of esthetical arguments in the justification of physics development sounds like another argument against the realism of physics theories…

This completes our discussion about the laws of physics and the nature of physics theories. We will now see how the various particles have been discovered and integrated into a consistent theory of the microworld: the Standard Model. We will see how the predictions of this theory can be tested in accelerators and particle detectors. After introducing what is the Standard Model of particle physics, we will comeback to the notions of symmetry and invariance, and their consequences. As the field is not close, we will finally discuss problems and possible extensions of the Standard Model and its impact on cosmology.

Small incomplete list of sources of inspiration

- A. Chalmers, *What Is This Thing Called Science?*, Open University press, Hackett,1999;
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