Reasoning and Explanation in Physics - I*

Modes of Reasoning

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In this article, we briefly review and illustrate the evolution of reasoning modes in science, from the pre-modern to the modern era, with particular reference to physics. This can help students demarcate explanations that are unacceptable in modern science from those that are possible explanations subject to experimental confirmation. The discussion bears directly on some common learning pitfalls in physics.

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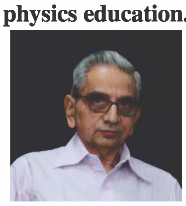

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Introduction

What kind of explanation is basically unacceptable in modern science? This question becomes meaningful when we look at the origins of modern science. We are all taught that the Scientific Revolution in Europe in the 16th–17th centuries overthrew the earlier conceptual frameworks in astronomy and physics and ushered in the new experiment-centred methodology of modern science. Less emphasized is the fact that while attending this methodological change, there was also a subtle change in the acceptable modes of reasoning in physics, which eventually covered all of modern science.

The phrase 'mode of reasoning' adopted here needs some clarification. We know that modern science adopts a combination of deductive and inductive logic or elaborations thereof. In the so-called hypothetico-deductive method, a hypothesis is made, and its deductive consequences are tested experimentally. Where several alternative hypotheses work, we choose the one that appears to be the most plausible based on some intuitive criteria ('infer-

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ence to the best explanation').

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But these logical frameworks are not unique to modern science. They were used in natural philosophy (the antecedent of modern science in ancient and medieval times) too, with the caveat that there empirical observations (not controlled experiments) served as tests of inferences. Indeed deduction, induction and 'inference to the best explanation' are ubiquitous, even in common reasoning in our daily lives.

What then demarcates reasoning in modern science from its pre-modern versions? The answer lies in the kinds of premises that embed any logical argument. Some kinds of premises, widely prevalent in pre-modern eras, are no longer acceptable in modern science, and some kinds are regarded only as heuristic ideas that are accepted only after experimental verification of their consequences. By modes of reasoning, we basically refer to the kinds of premises underlying the logical/mathematical arguments in science.

Some of the modes of reasoning before the emergence of modern science are very natural and therefore seen even at present in school and college classrooms, where young students try to cope with learning science through their mix of spontaneous and tutored reasoning.

The issue is not merely of historical interest but directly bears on science education, for some of the modes of reasoning before the emergence of modern science (now unacceptable or qualified) are very natural and, therefore, unsurprisingly, are seen even at present in school and college classrooms where young students try to cope with learning science through their mix of spontaneous and tutored reasoning.

This article aims to describe and illustrate in simple terms the different modes of reasoning in science from pre-modern to modern times and the learning pitfalls associated with some of them. We must note that the topic of reasoning and explanation properly belongs to the discipline of philosophy of science. Our presentation here is not a philosophical analysis, nor does it meet the rigorous standards of one. But we believe it can have pedagogic use in helping students acquire a more nuanced view of the nature of reasoning in modern science.

Needless to say, we are focusing here on a very limited aspect of modern science. Several other epistemological issues, such as the interplay of theory and experiment, the relation of mathematics and science, the central role of modelling and approximations in science, etc., are not discussed here. Also, though the ideas expressed here are relevant in general, our discussion is mainly confined to physics.

1. Modes of Reasoning Unacceptable in Modern Science

Consider the following assertion: *That which is divine must be perfect. The orbits of planets around the Sun are in the celestial domain, the domain of divinity. The circle is the perfect 2D shape in nature. Hence planetary orbits must be circular.*

Modern science does not accept this reasoning not because it is logically flawed but because it is based on premises invoking divinity and its perfection. Any explanation of a physical phenomenon based on such premises is now regarded outside the realm of modern science.

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This stance took millennia to take root. Historically, 'natural philosophy' was a rational attempt to understand nature going beyond the earlier explanations in terms of specific deities and gods. It created impressive conceptual frameworks. Yet it still did not explicitly depart from such premises.

Indeed, the above (italicized) reasoning held sway for two millennia —from Aristotle through Ptolemy to even Copernicus. This is why Kepler's discovery of elliptical orbits of planets was such a turning point in history. That, along with other great developments (due to Galileo, Descartes and others), triggered the Scientific Revolution.

That modern science does not employ this kind of reasoning is now too well-known to belabour on. But there are some other kinds of reasoning too that modern science does not accept, as we see next.

1.1 *Teleological Reasoning*

Teleological reasoning is a mode of reasoning that invokes a purpose for an action, which amounts to ascribing agency and intent to physical systems and processes. Teleological reasoning is all too common in our daily lives. ("*He is leaving home now to catch the train an hour later*".) Since it seeks the cause of an event or a phenomenon in the final state of the system, it is also called final causality-based reasoning.

This is distinct from 'initial causality', which characterises any causal explanation in modern physics. Thus an acceptable explanation of why a projectile hit a certain point on the ground is that it had a certain initial position and initial velocity when projected, which together with the law of motion under the force of gravity (and any other complicating effects like air resistance, wind, etc.), determined its final state. This will be regarded a correct causal assertion even if we are unable to actually compute the final state due to the complications mentioned.

The theory of evolution as now understood in modern science is non-teleological.

However, teleological reasoning was pervasive in physics before the modern era. Aristotle gave two categories of motion: natural and violent. The natural motion followed a teleological law: bodies left free tend to move so as to reach their 'natural places'. In the Aristotelian scheme, the four 'basic elements' had a natural hierarchy of places (earth at the centre, then water, air and fire in ascending order). The end state is what drives the natural motion of the body. As late as the 17th century, Leibniz, who discovered Calculus (independently of Newton) believed in teleological reasoning. It disappeared from physics following the phenomenal success of Newtonian mechanics.

Teleology still persisted in biology. The structure of an organ is so marvellously tuned to its function that it seems natural to think that the organ was 'designed' for the purpose. The theory of evolution by Darwin and Wallace[1] proposed in the mid-19th century, as now understood in modern science, is, however, completely non-teleological. Species evolve through the blind processes of natural selection accumulated over a long time. Evolution has

[1]Historically, though both Darwin and Wallace proposed 'natural selection' as the mechanism for evolution, Wallace did invoke teleological ideas for the evolution of the human mind. [2]

no purpose. With the success of this theory, teleology is banished from all modern natural sciences that deal with non-volitional domains (see Weinberg [1]).

1.1.1 *Teleological reasoning in science, though flawed, is natural and a source of learning pitfalls*

Despite its rejection in modern science, teleological reasoning persists implicitly among students. A plausible reason is that much of our daily experience pertains to our volitional domain—actions carried out by us (agency-based entities) for a purpose, an end goal. Teleological reasoning, essential for survival, seems to be an essential ingredient of our general cognitive faculty and hence students' spontaneous reasoning in physics.

Despite its rejection in modern science, teleological reasoning persists implicitly among students. It fulfils the need for an explanation in 'a cognitively cheap way'.

This shows up in the informal discourse in science classrooms. The words 'tendency' or 'tends to' are quite common: "*a body tends to go to the point of minimum potential energy*"; "*an atom like sodium tends to lose its outermost electron and a chlorine atom tends to accept it in its outermost shell in order to achieve stable electronic configuration*"; "*a gas in a closed chamber, initially with non-uniform density, tends to the equilibrium state with uniform density*", and so on. These statements have unintended teleological connotations and are best replaced by the following: "*the force on a body is in the direction where the potential energy decrease per unit distance is the largest; the lowest energy configuration of a bound NaCl molecule is one with an ionic bond between Na^+ and Cl^-; the probability of the given non-equilibrium state of the gas changing through collisions to the final state of uniform density is overwhelmingly large compared to any other configuration*".

As we see above, the correct non-teleological statements need more careful verbalization. That is why their teleological counterparts are so common. Teleological reasoning fulfils the need for an explanation in 'a cognitively cheap way' [3]. However, this comes with a price: a lack of appreciation of the nature of causality in physics.

1.1.2 *Some laws of science may appear teleological but are not actually so*

The best examples of this are the so-called 'action principles'. For mechanics, the principle states that the action of a system S is defined as a functional of paths $q_i(t); i = 1, 2, ..., n$ of a system with n degrees of freedom, as below:

$$S = \int_{t_1}^{t_2} dt L(q_i(t), \dot{q}_i(t)),$$

is an extremum for the actual path. Here, $L(q_i(t), \dot{q}_i(t))$ is the Lagrangian of the system. Superficially, it appears that the particle goes on a path with an end goal, namely to extremize the above integral. The difficulty is resolved when we see that the global extremum condition

The particle path satisfies a local law—no end goal, no teleology there. It is just that the path governed by the law results in a certain integral to be an extremum.

$$\delta S = 0; \quad \delta q_i(t_1) = \delta q_i(t_2) = 0; \quad i = 1, 2, ...n,$$

is actually equivalent to a local law for the path: the Euler–Lagrange equations:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i(t)}\right) - \frac{\partial L}{\partial q_i(t)} = 0; \quad i = 1, 2, ...n.$$

Turning the argument around, the particle path satisfies a local law—no end goal, no teleology there. It is just that the path governed by the law results in a certain integral to be an extremum.

Another significant context is the conservation laws in physics. What ensures that the final state of a system of interacting parts has a certain physical quantity for the system as a whole, unchanged from its initial value? When the value of the quantity of a part of a system changes, how do the values of the remaining parts adjust themselves to conserve the quantity? The answer again is that conservation laws follow from the local dynamics of the system. And a local law does not entail any teleology since it connects quantities at the same space-time point.

For example, two colliding hard spheres conserve total momentum since Newton's third law ensures that the the momentum change in one during the collision is equal and opposite to the momentum change in the other. Where this law is not applicable, as for example, for charges interacting via electromagnetic fields, the law of momentum conservation of the total system of charges and fields is a consequence of Maxwell's equations and Lorentz force equation, all of which are local equations.

For some domains of physics, the mere locality of laws does not help. For example, the second law of thermodynamics that the entropy of the universe never decreases in any process cannot follow simply from a local law of interaction since the latter is time-symmetric. In that case, the explanation must lie in the initial conditions, not in the final state. More generally, it is not even clear if all laws of physics are expressible in local terms. There may be topological laws at work, or systems may have fundamental non-local correlations. However, whatever the subtleties, teleology is unacceptable in standard accepted physics so far.

1.2 *Anthropocentric Reasoning*

Anthropocentric, i.e., human-centred reasoning was basic to the worldview before the modern era in science. It is premised on according a privileged status to humans, and by implication, a special status to the earth in the cosmic order. The latter was demolished by the heliocentric theory, but the former stubbornly held ground until the acceptance of the modern theory of the evolution of species.

Anthropocentric reasoning, premised on according a privileged status to humans, and by implication, a special status to the earth in the cosmic order, has no place in modern physics.

Historically, teleological and anthropocentric reasoning belonged to the same conceptual framework that posited an agency beyond local physical laws. Though they have now no place in modern physics, a more innocuous form of anthropocentric reasoning persists in science classrooms that is responsible for many learning pitfalls among students.

One principal source of these pitfalls is the common use of the word 'observer' in the contexts of relativity, Doppler effect, etc. The basic conceptual construct in relativity is a frame of reference conceived as a three-dimensional grid of infinitesimal grid

Such a view fails to appreciate that relativity of simultaneity arises not only because the speed of light c is finite, but fundamentally due to c being constant across all inertial frames.

cell size, with clocks placed at each cell, which are at rest and synchronized with respect to each other. In short, it is just an idealized measurement system. Equating this uncritically with a human observer sitting at the origin receiving signals from different events is basic to several problems in learning relativity.

A common misconception is to equate the time of an event in a frame of reference to the time this 'observer' at the origin receives the signal. The basic feature of special relativity—the relativity of simultaneity—is then understood by many students to arise due to the different times that signals from two events take to reach the 'observer'. Such a view naturally leads them to believe in the 'relativity of simultaneity' even for observers in a given frame, depending on their location. Further, they think that it would disappear if we took into account the travel times of the different signals, even for inertial frames in uniform relative motion [4].

Clearly, the view fails to appreciate that relativity of simultaneity arises not only because the speed of light c is finite, but fundamentally due to c being constant across all inertial frames.

Another example which shows up anthropocentric reasoning is that of a person sitting in a horizontal merry-go-round. Physics says that an inward physical force must act on the person to keep it in a circular motion. This should be so for every part of the body. The seat (its back, arms, etc.) provides the necessary external force on the person as a whole. But what about a part of the body, say the head, which may not be in direct contact with the seat? Clearly, internal stresses and strains generated in the body (which keep it one piece) ensure that there is a net inward force on the head, the external agency for the force being the rest of the body.

How this complicated physics situation is 'felt' by the person is a different matter altogether. Yet many students would equate forces to the forces 'felt' by the person (the feeling of being pushed outward).

2. Modes of Reasoning Accepted as Conjectural

2.1 *Metaphysical Reasoning*

Metaphysical reasoning (in the sense meant here) assigns fundamental principles and aspects to nature that are not directly suggested from observations. It invokes speculative general ideas, such as unity, beauty, parsimony, symmetry, and simplicity of nature. Some of these, like beauty and simplicity, may not admit precise formulation, while others, like symmetry and unity, may have a precise (mathematical) formulation.

Consider an example of metaphysical reasoning of the kind common in ancient science. (The following is a slight extension of the argument due to Plato.) There are only 5 possible regular polyhedra with the number of faces (which are regular polygons) F equal to 4 (tetrahedron), 6 (cube), 8 (octahedron), 12 (dodecahedron) and 20 (icosahedron). In ancient times, it was thought that the universe had 5 fundamental elements: earth, water, air, fire and ether. This coincidence was regarded to be not accidental but suggestive of a fundamental unity of nature. Accordingly, the shapes of 'atoms' of these elements were thought to have one to one correspondence with the regular polyhedra.

The important ways in which metaphysical reasoning invoked in modern physics differs from ancient reasoning are: one, the speculation usually builds on earlier similar attempts which turned out to be successful; two, it admits of precise (mathematical) formulation; and three, its deductions are testable experimentally.

This may seem like an implausible argument now, but that is because our present knowledge of atoms is much deeper. Actually contemporary physics too, uses metaphysical reasoning, though we now prefer to use the words 'speculative' or 'intuitive' in its place. Einstein's extension of the principle of special relativity to all frames of reference (all coordinate systems) and his later pursuit of unification of gravity with electromagnetism were not directly suggested by any observations; they were, at least in part, metaphysical drives. The important ways in which modern physics reasoning of this kind differs from ancient reasoning are: one, the speculation usually builds on earlier similar attempts which turned out to be successful; two, it admits of precise (mathematical) formulation; and three, its deductions are testable experimentally. When numerous such deductions are found to be in accord with experiment, what was once a speculation becomes part of established physics.

2.2 *Analogical Reasoning*

Yet another kind of reasoning which is pervasive in pre-modern science is one that uses analogies. In an analogy, the elements of a model in one domain are put in correspondence with those in a second domain. Then the laws and behaviour of the system in the first can be used to guess or predict the behaviour of the second.

Modern physics does not accept analogical reasoning as justified per se but can admit it as conjectural to be tested against experiment.

Consider an example from ancient science (an argument by Aristotle). On a warm day, we perspire and leave an earthy residue (sweat) that is salty. Sea water also gives out heat during hot seasons. Hence sea water is salty. This is analogical reasoning. It is a nice analogy, but modern science will not accept it purely on that account. For ancient science, the elegance and plausibility of an analogy were enough to regard it as a justified explanation.

Modern physics does not accept analogical reasoning as justified per se but can admit it as conjectural to be tested against experiment.

As a simple example, Rutherford's model of an atom (electrons orbiting around a central nucleus) seemed analogous to the heliocentric model of planets orbiting around the Sun; the inverse square law of force operates in both. However, the atomic domain needed new laws of quantization, and the analogy turned out to be only partially fruitful.

As another example, the differential equations for an LCR circuit and a damped harmonic oscillator are identical in form. This is a mathematical analogy different from the intuitive sweat and seawater analogy. The knowledge of one system in a mathematical analogy can be usefully carried over to the other system, even though they are physically different. Besides, such analogies have much pedagogical value since they help students understand the less familiar domain from the more familiar one.

The highly successful developments of modern theoretical physics have, in many cases, proceeded from mathematical analogies. An elegant example is Einstein's calculation (in 1905) of the volume dependence of entropy of thermal radiation (in the high-frequency limit). This was found to be mathematically similar to that of a molecular gas. Since the latter consists of discrete units (molecules), Einstein made the heuristic proposal that radiation too had discrete units (photons) and used the idea to explain some puzzling observational features of the photoelectric effect. Still, it was regarded as a suspect conjecture for nearly two decades. Experiments like the Compton effect (1923) and theoretical progress like Dirac's quantization of electromagnetic field (1926) led finally to the acceptance of the notion of photons.

An elegant example of the use of mathematical analogy is Einstein's calculation (in 1905) of the volume dependence of entropy of thermal radiation in the high-frequency limit, found to be mathematically similar to that of molecular gas.

Fundamentally, even Dirac's quantization of EM field proceeded from a mathematical analogy. Dirac had shown that the one particle harmonic oscillator problem in ordinary quantum mechanics could be solved using only the fundamental commutator between coordinate q and the momentum p: $[q, p] = i\hbar$. Now the coefficients in momentum space in the Fourier decomposition of the classical radiation field satisfy equations like that of a harmonic oscillator. Dirac postulated analogous commutators for these objects and quantized the electromagnetic field. The theory worked. Such examples of successful mathematical heuristic reasoning are quite common in physics.

3. Evolution of Reasoning in the Modern Era

The era of modern physics, beginning with Galileo, Descartes, Newton and others (16th–17th centuries), had expunged teleological and anthropocentric reasoning. From this time to the contemporary era in physics (20th century onward), physical reasoning evolved to accommodate two subtle changes.

3.1 *Beyond Mechanistic Reasoning*

In the beginning, the revolutionary zeal to banish theology and metaphysics out of science led to the view that physics must be based on purely mechanistic reasoning involving material/concrete form for each concept (reification). Ours was a mechanistic universe.

Newton initiated an epistemic stance in science that continues till the present, which first seeks the answer to 'how' before turning to 'why'.

Descartes, who discovered analytical geometry (independently of Fermat), was among the earliest advocates of this emerging view. He proposed a vortex theory of planetary motion which conceived of circulating material bands for each planet. His followers and also Leibniz strongly opposed Newton's theory of gravity because it involved 'action at a distance', which seemed to them 'occult', not science.

But as we know Newton's theory triumphed. Newton refused to give a mechanistic explanation of the gravitational force in his famous line "I do not feign hypotheses". He initiated an epistemic stance in science (which continues till present), which first seeks the answer to 'how' before turning to 'why'.

Despite this, the drive for the reification of concepts continued through the early modern era. Heat was conceived of as a fluid (caloric theory), and even the initial insight of the second law of thermodynamics was arrived at by Carnot adopting the caloric view of heat. It was around the mid-19th century that heat came to be regarded as energy in transit, nothing material by itself.

Faraday argued in terms of lines of force as if they were material, though it is not clear if he really meant it. He introduced the concept of field in physics. 19th century physics could not accept a physical yet non-material view of electromagnetic fields. A material medium (ether) was hypothesized to carry and propagate the fields. Fields in this view related to mechanical stresses and strains in this medium. Maxwell used the ether model for his theory of electromagnetism (Maxwell's equations).

The mechanistic view of electromagnetic fields ended with Einstein's abandonment of ether. Physics, at the beginning of the 20th century, then regarded electromagnetic fields as distinct from material particles but just as physical. This was an important ontological change. (The field-particle distinction got blurred later in quantum field theory, but that is another matter!).

As usual, the cognitive tendencies seen in history are also encountered in students learning physics. Young school students tend to reify every concept, i.e., see it in material terms. Potential energy is a kind of 'stored' energy. Many young students regard a ray of light as a substance. The tendency persists even at higher stages. Investigations reveal that college students cannot conceive of an 'aerial image' without a screen to 'hold' it [5]. Similarly, college students literally equate frames of reference to the associated bodies and thus localized by their boundaries [6]. Ask any student to state the pseudo-forces on a person standing outside on the ground with respect to the non-inertial frame of a horizontal rotating merry-go-round. Many students are aware that centrifugal and Coriolis forces exist in the non-inertial rotating frame. But few will invoke them for a person on the ground since, in their view, the non-inertial frame of the merry-go-round 'terminates' at its boundary.

Cognitive tendencies seen in history are also encountered in student learning. Young students tend to see every concept in material terms. College students literally equate frames of reference to the associated bodies and thus localized by their boundaries.

3.2 *From Absolutism To Relativism*

Absolutism prevailed through the history of science for a long time. The Earth was at absolute rest, said the geocentric astronomers. Heliocentric theory did not remove absolutism. It only changed the object that is at rest (from the Earth to the Sun). Later, the frame of fixed distant stars became the frame of absolute rest.

Galileo was aware of the principle of relativity in mechanics. Newton's laws that captured Galilean insights in mathematical terms naturally did not require a frame of absolute rest. Yet Newton spoke of absolute space—this was primarily to establish absoluteness of acceleration (Newton's rotating bucket experiment)—and he regarded time as absolute.

In contrast to Newton's laws, Maxwell's equations of electrodynamics contained a constant c interpreted as the velocity of electromagnetic waves. Using the kinematic ideas of space and time prevailing then since Newton, the appearance of velocity in a fundamental law clearly suggested a frame of reference at absolute rest with respect to which the electromagnetic waves traveled with a velocity c. The hypothesized ether needed for EM field propagation was the natural choice for this absolute frame.

As we know, Einstein rejected the notion of the frame of absolute rest and postulated the Relativity Principle for all of physics (known already to Galileo and Newton for mechanics), for inertial frames (special relativity) and all coordinate systems (general relativity). Thus absolutism of early modern physics gave in to the relativism of contemporary physics.

With special and general relativity, the absolutism of early modern physics gave in to the relativism of contemporary physics.

The meaning of the relativity principle is often trivialized [7]. A common misinterpretation of this principle is to equate it to kinematic reciprocity: "*If a frame S_2 moves with uniform velocity $\vec{v}$ with respect to an inertial frame S_1, then the frame S_1 moves with uniform velocity $-\vec{v}$ with respect to S_2*". What is not appreciated is that this kinematic reciprocity is always true; if S_2 were to move with acceleration $\vec{a}$ with respect to the inertial frame S_1, S_1 would move with acceleration $-\vec{a}$ with respect to S_2.

The relativity principle is not these reciprocal assertions but the statement that the laws are identical in the two frames S_1 and S_2 in the first case, where two inertial frames S_1 and S_2 are in uniform relative motion. This identity prevents us from privileging one frame over the other. In the second case, where S_1 is given to be an inertial frame, the frame S_2 is non-inertial, and the law of motion contains a pseudo-force. This helps us in asserting, despite the kinematic reciprocity mentioned, that acceleration of S_2 is absolute and that S_1 is unaccelerated.

4. Conclusion

We have dealt with some kinds of premises (teleological, anthropocentric) that modern physics does not accept at all, as well as some others (heuristic reasoning informed by analogy, intuitive principles of unity, parsimony, symmetry, etc.) that it accepts tentatively, subject to experimental confirmation. We have also described some common conceptual pitfalls surrounding different modes of reasoning based on physics education research literature [8] as well as our own teaching experience.

These modes of reasoning, however, do not sufficiently characterize modern physics practice, which basically comprises developing increasingly detailed mathematical models of nature whose consequences agree with observations. What kinds of approaches inform the large variety of models in physics? A summary description of these broad approaches or explanatory frameworks should be useful to undergraduate students. This is taken up in the second part of this series of two articles.

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Reasoning and Explanation in Physics - II*

Explanatory Frameworks

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In this part of the article, we briefly review and illustrate the different explanatory frameworks used in modern physics within the acceptable reasoning modes in science (reviewed in the first part). This can help students improve their appreciation of the nature of physics.

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1. Introduction

In the first part of the article[1], we reviewed the modes of reasoning in modern physics, mainly highlighting the premises prevalent in pre-modern science that are now abandoned. Physics no longer accepts teleological and anthropocentric premises in its logical arguments. It does adopt heuristic conjectures based on analogies or intuitive metaphysical ideas of simplicity, symmetry, unification, etc., in its exploratory phase but accepts them only after experimental verification of their consequences.

We also saw that the period from early modern (17th to 19th century) to the contemporary era in physics saw a slight but subtle change in its outlook on what a physical entity is. From a purely mechanical picture of the universe, we came to accept the classical electromagnetic field as a non-material entity yet as physical as a particle. Later developments, however, blurred this ontological distinction. Another significant development was the replacement of absolutist ideas regarding rest and motion with a relativistic viewpoint.

The basic epistemic strategy of modern physics is to build mathematical models of physical reality, reason within the models and

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deduce experimental consequences to test their validity.

[1] See *Resonance*, Vol.28, No.7, pp.1049–1064, 2023.

Keywords
Physics, explanatory frameworks, student cognition.

To implement this strategy, several different explanatory frameworks are used in modern physics [1]. We attempt to overview them in terms of several pairs, each consisting of two opposite (but complementary) aspects. There is no claim to either uniqueness or completeness of this classification. Indeed our approach is somewhat restrictive. There will certainly be several other significant frameworks not mentioned here and different ways of classifying them. Also, a physical theory usually involves several of these frameworks; they are not mutually exclusive.

2. Explanatory Frameworks

2.1 *Time-dependent versus Equilibrium Frameworks*

There are two distinct themes in physics—dynamics and equilibrium.

There are two distinct themes in physics—dynamics and equilibrium. Dynamics is about change in the system with time under the given environment. The change with time is attributed to some cause (force or temperature gradient or pressure gradient, ongoing chemical or nuclear reaction, etc.). It is expressed in terms of differential equations involving time t as an independent variable and some physical quantity as the dependent variable.

The physical quantity depends on the context. It can be the position vector $\vec{r}$ of a particle changing with t under some external force, say, the gravitational force or the Lorentz force on a charged particle. The dynamical law here is Newton's second law. Or it can be the temperature of a body that is cooling down from a high temperature in a colder surrounding in accordance with the empirical Newton's law of cooling, or the amount of a radioactive substance in a sample that is decaying with time, governed by the empirical law of radioactivity, etc.

The solutions of the equations with suitable initial conditions in these examples give, respectively, the instantaneous position vector $\vec{r}(t)$ (and hence the path or trajectory of the particle), the instantaneous temperature $T(t)$ of the body and the instantaneous amount $N(t)$ of the radioactive substance.

The physical quantity in question may be a field or wave that generally varies from point to point. The dynamical equation for a field (e.g., displacement of a string from its rest position, pressure and temperature fields, electromagnetic field, the wave function in quantum mechanics, etc.) is then typically a partial differential equation with space variables, in addition to time t, as the independent variables. In this case, the initial or boundary conditions required for a unique solution of the field configuration can be a non-trivial problem.

Equilibrium or time-independent frameworks handle different types of problems. Equilibrium (translational and rotational) in mechanics just means that the net force and the net torque on a body are zero. Equilibrium in thermodynamics is a different notion. It means the thermodynamic variables (e.g., P, V, T of a gas) are time-independent. The mathematical equations of equilibrium thermodynamics naturally do not involve any time variable. Yet, interestingly, much of thermodynamics deals with processes that involve changes in thermodynamic variables. How? This is accomplished by the idealization of a 'quasi-static process'—an infinitely slow process where the system passes through a succession of equilibrium states.

Equilibrium in mechanics just means that the net force and the net torque on a body are zero. Equilibrium in thermodynamics is a different notion, and means that the thermodynamic variables are time-independent.

In a statistical mechanical view, a bulk system in macroscopic equilibrium goes through different molecular configurations with time. Here, time is eliminated using the theoretical artefact of an 'ensemble'. We imagine a large number of copies of the system, which have the same macrostate but are in different possible microstates. Each member of the ensemble is represented by a point that moves in time in the phase space of the system. The density function $\rho(q, p, t)$ stands for the density of representative points in phase space. In equilibrium, ρ does not depend explicitly on time. The long-time average of a physical quantity is taken to be its ensemble average (ergodic hypothesis).

2.2 *Macroscopic versus Microscopic Frameworks*

Physics is basically a reductive science. It aims to explain macroscopic properties from a microscopic picture involving elementary constituents and their interactions.

Physics is basically a reductive science. It aims to explain macroscopic properties from a microscopic picture involving elementary constituents and their interactions. However, several parts of physics do not go into the microscopic details of matter. For example, classical continuum mechanics (rigid bodies, deformable bodies, fluids, etc.) is macroscopic. Newton's laws are applied to every infinitesimal element of the system, but the element is infinitesimal at the macroscopic scale—we do not delve into its microscopic structure. A similar remark applies to macroscopic electrodynamics.

Thermodynamics is the prime example of a macroscopic approach. The laws of thermodynamics are inferred from empirical observations and expressed in terms of macroscopic variables only. Some of these are common to all systems (internal energy, temperature and entropy), and some are specific to the system in question—pressure and volume for hydrostatic systems, magnetic field and magnetization for magnetic systems, emf and charge for electrochemical cells, and so on.

Thermodynamics cannot predict the value of any physical property in terms of basic constants. Yet, its macroscopic laws do yield relations between bulk properties of a system, such as specific heats, expansivity, and compressibility. It gives the criteria of equilibria and directions of change when systems are away from equilibrium (e.g., Gibbs free energy of a system at fixed pressure and temperature must decrease till it attains its minimum).

Thermodynamics is the prime example of a macroscopic approach. In contrast, kinetic theory is based on a microscopic approach.

In contrast, kinetic theory is a good example of a microscopic approach. It goes into a detailed molecular description of the system and succeeds in interpreting macro variables like pressure and temperature in molecular terms. A more general microscopic approach is that of statistical mechanics. This basically looks at the energy levels of the system and the population distributions of the microscopic constituents (molecules) of the system at these levels.

Roughly put, the laws and averages of macroscopic thermodynamic variables correspond to the most probable molecular configurations of the system. However, such a treatment gives not merely the averages but also their fluctuations from the equilibrium values. The fluctuations generally vanish in the thermodynamic limit ($N, V \to \infty$, keeping N/V fixed). Statistical mechanics also yields insights into a whole range of phenomena, such as phase transitions, universality and scaling near critical points, the relation between fluctuations and dissipation, and so on.

The laws and averages of macroscopic thermodynamic variables correspond to the most probable molecular configurations of the system.

In general, a microscopic description of a macroscopic phenomenon is always more predictive but dependent on the available microscopic theory. On the other hand, pure macroscopic laws gleaned directly from observations are more robust and remain true even if our microscopic theories change over time. The laws of thermodynamics discovered in the mid-19th century (the III law came much later) have survived major conceptual upheavals in physics during the intervening years.

It is worth noting that a macroscopic property of a system may be explained in microscopic terms but may not by itself be defined at the elementary level. For example, the viscosity, heat conductivity and self-diffusion coefficient of a gas can be related in the kinetic theory of transport phenomena to the size of the atoms or molecules and their (average) velocities but are not defined for the individual microscopic constituents. The qualitatively different properties that appear only at the macroscopic level but arise from the cooperative interaction effects of a very large number of microscopic constituents are sometimes called 'emergent properties'.

It is worth noting that a macroscopic property of a system may be explained in microscopic terms but may not by itself be defined at the elementary level.

Examples of emergent properties are superconductivity and superfluidity in physics, dissipative structures in chemistry, and self-organizing systems in biology. It is a moot question if all emergent properties in nature, including such things as consciousness and free will, are finally reducible in microscopic terms. At any rate, reductionism is the dominant paradigm in physical sciences.

The term 'elementary constituent' has been used above in refer-

What is regarded as an 'elementary constituent' depends on the scale of interest.

ence to a microscopic framework. What is regarded as an 'elementary constituent', however, depends on the scale we are operating. At the macroscopic scale, atoms and molecules may be thought to be the elementary constituents. At the atomic and molecular scale, they are electrons and nuclei. At the nuclear scale, we might regard protons, neutrons and electrons as elementary. At still lower scales, the current scale of interest in particle physics, quarks and leptons are the fundamental elementary constituents.

The lower the length scale, the higher the energy of the probe required. For example, Rutherford, in 1911, used α-particles in the range of a few MeV to probe the structure of an atom. But in similar experiments in 1968, electrons of energy around 20 GeV were used to probe the structure of a proton. The quark constituents of the proton were inferred from such experiments. As is well-known, at the scale of atoms and molecules and lower scales, classical theory needs to be replaced by quantum theory.

A subtle feature is that a microscopic theory at a particular scale works even if we do not consider (or are ignorant of) the finer lower-scale physics. Nature seems to admit of 'effective' physical theories at different scales. For example, the theory of electrons and photons (quantum electrodynamics) works exceedingly well at the length scale of 10^{-18} m or so, though there is still no universally accepted theory at the Planck's scale of 10^{-35} m or so, where quantum gravity effects are likely to operate. Similar remarks are true about the more general theories of contemporary particle physics.

2.3 *Deterministic versus Probabilistic Frameworks*

A deterministic framework in physics is one in which there is no element of chance in its basic laws. Newtonian mechanics, for example, is completely deterministic.

A deterministic framework in physics is one in which there is no element of chance in its basic laws. Newtonian mechanics, for example, is completely deterministic—given the required set of initial conditions at some time $t = t_0$, the laws determine with certainty all observable properties of the system at all future times $t > t_0$ (as also at all times $t < t_0$ in the past since Newton's laws do not have any preferred direction of time). Newtonian mechanics entails the picture of particle trajectories.

The deterministic view also applies to the laws of classical fields, such as electromagnetic and gravitational fields, which do not admit of particle trajectory picture. (In classical physics, particles and fields are two distinct physical entities satisfying different laws.) Thus, with the required initial conditions, the evolution of the electromagnetic fields in time is determined by Maxwell's laws of em fields and the Lorentz law. If the sources of the fields are discrete charges, the latter will move along definite trajectories.

The deterministic view also applies to the laws of classical fields, such as electromagnetic and gravitational fields, which do not admit of particle trajectory picture.

In short, in the classical view, if the present state of the universe is known in full detail, its past and future are, in principle, completely determined. This view sometimes goes by the name 'Laplacian determinism'.

In practice, such a deterministic framework is useful for systems with a small number of degrees of freedom. This happens when, for example, the interest is only in the translational motion of a macroscopic body as a whole and not in the motion of its internal parts. For example, for the orbital motion of a planet around the Sun, it is reasonable to neglect the size of the planet compared to its orbital radius or, equivalently, to focus on the motion of its centre of mass, which has just three translational degrees of freedom. Besides these, for an ideal rigid body, there are three rotational degrees of freedom, adding up to a total of six degrees of freedom. The rigid body rotational dynamics is governed by Euler's equations.

Fluid mechanics, on the other hand, deals with systems of infinitely many degrees of freedom. It is a classical field theory involving density, pressure and velocity fields governed by deterministic field equations (Euler's equation of non-viscous fluid dynamics and, more generally, the Navier–Stokes equation.)

For studying the internal states of macroscopic systems (with the number of constituents of the order of Avogadro's number), it is obviously not practical to track the trajectory of each microscopic constituent. The deterministic framework is then perforce replaced by a probabilistic framework, even when the microscopic constituents follow deterministic laws. The disciplines of classical statistical mechanics and kinetic theory arise from this circumstance.

Very large number of degrees of freedom of the system leads to an important simplifying feature—randomness.

It is interesting to note that the very large number of degrees of freedom of the system leads to an important simplifying feature—randomness. Derivation of Maxwell's velocity distribution of molecules in a gas in equilibrium in kinetic theory is a nice example of how considerations of randomness, homogeneity and isotropy (no privileged position or direction in space) are enough to arrive at a detailed property of a system that is time-independent at the bulk level (macroscopic equilibrium), even though individual molecules are continually changing their velocities due to collisions. Randomness also makes plausible the assumption of 'equal a priori probability' of different molecular configurations for a given isolated system (the 'microcanonical ensemble') in statistical mechanics.

We generally think that if a simple system is governed by deterministic laws, its behaviour is predictable. That, of course, is true, provided the initial conditions are known absolutely precisely. In practice, there is always some margin of error in knowing the initial conditions. Now in some non-linear systems, it can happen that in a certain regime of the values of its parameters, this initial error, however small, exponentially amplifies with time. In such a case, the initially close trajectories in phase space diverge away in time. This hypersensitivity to initial conditions leads to a loss of long-term predictability and is known as 'deterministic chaos'. Chaos can characterize simple systems (e.g., the population of a species with limited resources of food modelled by the logistic map (a difference equation)), or it can be a feature of complex systems (e.g. the weather) described by complicated coupled equations; non-linearity is common to both.

Classical physics is fundamentally deterministic, though practical constraints can and do introduce indeterminism or loss of predictability.

To sum up, classical physics is fundamentally deterministic, though practical constraints can and do introduce indeterminism or loss of predictability in the senses described above. However, the classical laws fail in the domain of atoms and molecules and at still lower length scales. The presently accepted quantum theory that is found to be successful in this domain is indeterministic and fundamentally needs a probabilistic framework for its formulation.

Quantum mechanics replaces the trajectory-based picture with one in which the state of, say, a single particle system is described by a wave function $\psi(\vec{r}, t)$ (ignoring intrinsic spin for simplicity). Now $\psi(\vec{r}, t)$ contains, in general, only probabilistic information about every observable associated with the system. This is inherent to the formalism and not due to poor specification of conditions or limitations of measurement. This probabilistic picture has stood the test of experiments.

Indeterminism of quantum mechanics is inherent to the formalism and is not due to poor specification of conditions or limitations of measurement.

There is a sense in which determinism is resurrected in quantum mechanics. The basic object of the theory, the wave function $\psi(\vec{r}, t)$, satisfies a definite time-dependent Schrödinger equation. Given the initial state of the system $\psi(\vec{r}, t_0)$ at $t = t_0$, the wave function is determined for all other times in a given external potential. Similarly, in time-independent problems, the probability distributions of physical observables are well-defined.

For example, in a double-slit experiment using a beam of identically prepared electrons, the path of an individual electron is probabilistic, i.e., we cannot say through which slit the electron passes through. But the overall diffraction pattern (built by the accumulation of a large number of electrons) is known and definite; it does not change from one experiment to another if the quantum state is prepared similarly.

2.4 *Local versus Global Frameworks*

The laws of physics that we usually come across are local laws. Newton's second law of motion is local: the acceleration $\vec{a}$ of a particle at time t is related to the net force $\vec{F}$ at the same instant t: $\vec{F}(t) = m\vec{a}(t)$, or $\vec{F}(t) = \frac{d\vec{p}}{dt}(t)$. The Lorentz force on an electric charge moving with velocity $\vec{v}$ at the space-time point $(\vec{r}, t)$ is determined by the electric and magnetic fields at the same space-time point:

$$\vec{F}(\vec{r}, t) = q\vec{E}(\vec{r}, t) + \frac{q}{c}\vec{v} \times \vec{B}(\vec{r}, t).$$

Cause and effect in physics are associated with space-time points that can be connected by signals with, at most, the finite speed of light, in accordance with relativity.

A general requirement in physics is that effect cannot precede cause (causality). Cause and effect are either at the same space-time points, or when cause precedes effect, they must be associated with space-time points that can be connected by signals with at most the finite speed of light c, in accordance with relativity. The causality requirement is obviously met by the local Lorentz force law; if we regard the fields as the cause and force as the effect—both refer to the same space-time point. If we consider, in turn, the fields as the effect and the sources of the fields (some charge configurations) as the cause, then the observation point $(\vec{r}, t)$ and the source point $(\vec{r'}, t')$ must satisfy the stated requirement.

Newton's law of gravitation is an 'action at a distance' theory and does not satisfy this requirement. Relativistic physics takes care of this requirement by viewing forces from a field point of view. Thus in classical electrodynamics, sources create electromagnetic fields; the fields propagate with the finite speed of light and interact locally with the charges under consideration in accordance with the Lorentz force law. In short, local laws of forces (interactions) and the field point of view ensure causality and the relativistic requirement of a finite upper limit to the speed of a signal. (Locality of basic laws, however, does not preclude non-local correlations that do not amount to causality violations as in two-particle entangled quantum states, but this point is not pursued further here.)

The field equations (classical or quantum) in the established part of modern physics are local field equations. In the Lagrangian formulation, the Lagrangian density of the field $\mathcal{L}(x)$ is a local object defined at every space-time point x. Usually, this dependence is implicit through the dependence of $\mathcal{L}$ on the field $\phi(x)$ and its first order derivative $\frac{\partial\phi(x)}{\partial x^{\mu}}$. The global object constructed from $\mathcal{L}(x)$ is its integral over any arbitrary region Ω of space-time, called 'action' denoted by S, which satisfies the variational principle:

$$S = \int_\Omega d^4x\, \mathcal{L}\left(\phi(x), \frac{\partial\phi(x)}{\partial x^\mu}\right) \quad ; \quad \delta S = 0,$$

subject to vanishing variations on the boundary. (We follow the treatment and notation of [2].) This variational principle of a global object is found to be equivalent to Euler-Lagrange equations for the field (differential equations for the field), which are local laws.

The nice interplay of global and local frameworks is best seen in modern physics in connection with symmetries and conservation laws. For example, if the Lagrangian density $\mathcal{L}$ is invariant under translations in space and time: $x'^\alpha = x^\alpha + \delta^\alpha$; ($x^\alpha$ for $\alpha = 0, 1, 2, 3$ denote the time and space coordinates), we get local continuity equations for the 4-symmetric stress tensor $\tau^{\alpha\beta}$ built out of the fields and their derivatives:

The nice interplay of global and local frameworks is best seen in modern physics in connection with symmetries and conservation laws.

$$\frac{\partial\tau^{\alpha\beta}}{\partial x^\alpha} = 0; \quad \beta = 0, 1, 2, 3.$$

The four global objects constructed by space integration of $\tau^{0\beta}$ are the energy and c times the 3-momentum of the system of fields:

$$cP^\beta = \int d^3\vec{x}\,\tau^{0\beta} \quad \beta = 0, 1, 2, 3.$$

It follows from the continuity equations that these are conserved quantities. Similarly, invariance of $\mathcal{L}$ under rotations results in the conservation of angular momentum.

Invariance of $\mathcal{L}$ under a phase transformation of field $\phi_r \longrightarrow \phi'_r = e^{i\chi}\phi_r$ has assumed deep significance in current physics. (Here, r denotes the possible components of the vector or spinor field; a neutral scalar field requires just one component.) The terms ‘global’ and ‘local’ are important in this connection. If χ is independent of space-time point x, i.e., when the field everywhere is multiplied by the same phase factor, it is a global phase transformation. If $\chi(x)$ varies from point to point, we speak of a local phase transformation. It is easily found that global phase invariance leads to a continuity equation

$$\frac{\partial j^\mu}{\partial x^\mu} = 0,$$

which leads to the conservation of the quantity Q:

$$Q = \int d^3\vec{x}\, j^0 \quad ; \quad \frac{dQ}{dt} = 0.$$

For example, the Lagrangian density for a free Dirac field given by

$$\mathcal{L}_0 = c\overline{\psi}(x)(i\hbar\gamma^\mu\partial_\mu - mc)\psi(x),$$

is evidently invariant under global phase transformations of $\psi(x)$; the conserved quantity Q can be interpreted as the charge operator of the field. However, importantly, $\mathcal{L}_0$ is not invariant under local phase (gauge) transformations.

The familiar minimal interaction of relativistic electron and electromagnetic field satisfies local gauge invariance.

To ensure local gauge invariance, a new field A_μ needs to be introduced and ∂_μ replaced by $D_\mu = \partial_\mu + \frac{iq}{\hbar c}A_\mu$, where $q = -e$, e being the magnitude of the charge of electron. Also the local gauge transformations of the Dirac fields $\psi(x)$ and $\overline{\psi}(x)$ need to be supplemented by the local gauge transformations on A_μ:

$$A_\mu \longrightarrow A'_\mu = A_\mu + \partial_\mu f(x).$$

(Note that $\chi(x) = \frac{ef(x)}{\hbar c}$.) With all this in place, $\mathcal{L}_0$ is replaced by $\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_I$, where

$$\mathcal{L}_I = e\overline{\psi}(x)\gamma^\mu\psi(x)A_\mu.$$

This is the familiar minimal interaction of relativistic electrons with electromagnetic field. It is easily seen that the Lagrangian density $\mathcal{L}$ is invariant under the simultaneous local gauge transformations of the Dirac ($\psi(x)$, $\overline{\psi}(x)$) and the electromagnetic (A_μ) fields. The full Lagrangian for the system of interacting Dirac and electromagnetic fields must also include the Lagrangian density $\mathcal{L}_{\rm em}$ for free electromagnetic field, which is invariant under the gauge transformation of A^μ given earlier.

In the case of electrodynamics, the basic minimal interaction was known classically. Local gauge invariance is then an interesting feature of the theory. In modern particle physics, this reasoning is turned around since the strong and weak interaction forms are not known in classical physics. Local gauge invariance then becomes a heuristic requirement to develop theories of these interactions. The current standard model of elementary particles and their interactions is a successful result of this effort [2].

In modern particle physics, local gauge invariance is a heuristic requirement to develop theories of strong and weak interactions.

Finally, the role of global frameworks appears in the topological laws of physics—an area of much interest in the last several decades. A rather simple example is Gauss's law in electromagnetism which relates electric flux through a closed surface to the charge inside it. The flux remains invariant under any topological transformation of the closed surface. The line integral of the magnetic field over a closed loop being equal to the total current passing through an open surface bounded by the loop (Ampere's law) is another example of a topological invariant.

Non-trivial applications of topological ideas in physics are seen in topics like magnetic monopoles, solitons, the Aharonov–Bohm effect, and several others, which are beyond the scope of this article. It should be noted that we have been concerned here with some interesting global aspects of local frameworks. It is unclear if complete explanatory frameworks that are global exist.

3. Student Cognition of Explanatory Frameworks

At the college/university level, experience shows that students find causal microscopic explanations easier to grasp conceptually. For example, in quantum mechanical scattering theory, the picture of a wave packet moving from far away at an earlier time, colliding with the target and scattering away to large distances later, is easy to imagine, though its mathematical treatment is hard. In the technically easier time-independent approach, the asymptotic wave function contains both parts together—a term for the incident wave and a term for the scattered wave, a confusing situation for many students. Likewise, students generally find

At the college/university level, experience shows that students find causal microscopic explanations easier to grasp conceptually.

kinetic theory-based arguments conceptually easier (though often mathematically more involved) than pure thermodynamics-based reasoning.

Another observation is that there is little appreciation of the locality of laws in physics. Even the locality of Newton's second law is not clearly appreciated. A well-known example is students invoking impetus theoretic ideas when explaining, say, the motion of a body thrown up from the ground. Many undergraduate students associate 'upward acceleration' with the body during its upward journey due to the initial force used to throw it up. Students' understanding of several other particular concepts like force, pressure, heat, temperature, energy and entropy, and their ideas about kinetic theory, thermodynamics, introductory quantum mechanics and relativity have been documented in the literature [3]. But as far as we know, students' appreciation of explanatory frameworks discussed here has yet to be examined in physics education research.

4. Conclusion

The perspective of explanatory frameworks developed here brings out holistically the general organization of the subject and has much educational relevance.

This work is part of our continuing physics education programme that aims to unravel different aspects of implicit expert knowledge and make them explicit for educational use. In earlier works, we dealt with expert epistemic knowledge concerning mathematical derivations in physics and the expert strategy of approximations in physics [4, 5]. Similarly, experts implicitly know the modes of reasoning and explanatory frameworks in physics discussed in the first and second parts of this article. This is what underlies their stable and coherent knowledge organization of the subject, their ability to judge the acceptability of an explanation and their facility in adopting suitable epistemic frameworks in their own work. This work is an attempt to summarize this wide-ranging implicit expert knowledge.

The perspective of explanatory frameworks developed here has important educational relevance. Physics instruction at higher stages is generally piecemeal, categorized into topics and areas. It comprises highly technical details of individual topics (undoubtedly important) but rarely brings out holistically the general organization of the subject. We believe that some emphasis on explanatory frameworks in instruction should help students improve their content organization and enhance their appreciation of the nature of physics.

As a final remark, we must note that the explanatory frameworks are quite distinct for different subjects. This means any curriculum for interdisciplinary education (that is currently much advocated) cannot be just a superficial mix of different subjects but must incorporate awareness of differences in explanatory frameworks across disciplines and address the pedagogic challenge of harmonizing them.

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