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A 21st century perspective as a primer to introductory physics

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Abstract

Much effort over many years has been devoted to the reform of the teaching of physics. This has led to many new and imaginative approaches in the content and delivery of material. Great strides have been made in the delivery, and the content has been continually supplemented. However, attempts to modernize the basic structure of the presentation have faced resistance, and the majority of introductory physics textbooks in wide adoption today have a general structure that has changed little in over 60 years. Thus, in comparison to biology, chemistry, geology, etc, physics is unique in that its introductory course is not a survey of the current status of the field. In an attempt to circumvent this problem in a tractable way, we have developed a qualitative front-end course designed to create a 21st century perspective that can be embedded into the beginning of a standard introductory physics sequence.

1. Introduction

During the past half century, much effort has been devoted to reforming the teaching of introductory physics. Concerted efforts have been made, e.g., in the Public School Science Curriculum (PSSC) [1], the Feynman Lectures [2], the Berkeley Physics Laboratory [3], the Introductory University Physics Project (IUPP) [4], the National Task Force on Undergraduate Physics [5], the International Commission on Physics Education of the International Union of Pure and Applied Physics (IUPAP · ICPE) [6], the Physics Education Division of the European Physical Society (EPS · PED) [7], and many other forums. These efforts have led to many new and imaginative approaches to the delivery of the material and content. However, despite many attempts to revise the basic structure of the presentation, nearly all popular introductory physics textbooks today follow a structure that has changed little since the 1950s.

Templin [8] has analysed the reasons why the structure of textbooks published at the end of the second world war have continued to dominate the teaching of introductory physics, and why this structure has been so resistant to attempts at fundamental revision. Concerning this structure and its resilience, Templin indicated:

> This was a heterogeneous collection of apparently distinct topics, namely mechanics, heat, sound, light, electricity and magnetism, each with its own set of laws. A major goal of physicists through most of the last century was to attempt to unify these seemingly distinct fields by showing that they were all mechanical in nature. This program was only partially successful.

The structure tends to follow the chronology of historical discovery, with 18th century mechanics followed by 19th century electrodynamics, light, heat and sound. Successful attempts to partially modernize the presentation have been made by inserting modern physics sidebars at various points in textbooks following the traditional course structure, and by adding an additional section at the end of the course describing the crucial experiments that brought about a unification of these seemingly distinct topics. Although many attempts were made to develop textbooks that made a radical reinvention of the basic structure, their adoptions were short-lived. Holcomb [9] has observed:

> The current, standard-model syllabus reflects a 1950 worldview. Although the standard model has been updated, new topics are simply draped across the existing skeleton. This 'classical' (a word with little meaning to today's physics students) structure has, in many cases, been left untouched by evolutionary ways of thinking about physics content or about physics teaching, which have developed over the past 60 or 70 years. . . . Most PER (Physics Education Research) work tacitly accepts the current model as given and focuses instead on better ways to teach within the confines of the *status quo*.

As this statement emphasizes, the criticism is *not* that the current physics curriculum fails to include sufficient topics in modern physics. Instead the problem is that the unifying discoveries of the 20th century have not yet been exploited to optimize and clarify the pedagogic structure of the presentation. Holcomb suggests three examples of possible restructurings: the atomic world, the power of conservation laws, and exponentials. Consistent with this, Feynman elevated to pre-eminence the 'atomic fact' in his oft-quoted statement [10]:

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would convey the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact) that all things are made of atoms—little particles that move around in perpetual motion, attracting when they are a little distance apart, but repelling upon being squeezed into one another.

If one accepts Feynman's assertion that our current level of scientific knowledge could be quickly *rediscovered* by starting with the atomic fact, could it not be more efficiently *discovered* for the first time by students through the use of the atomic fact as a deductive starting point? An explanation for why the atomic fact remained unrecognized for so long has been given by Dawkins [11]:

> But if solid things are mostly space, why don't we see them as empty space? . . . The answer lies in our own evolution. . . . You might think that our sense organs would be shaped to give us a 'true' picture of the world as it 'really' is. It is safer to assume that they have been shaped to give us a *useful* picture of the world . . . designed to understand the mundane details of how to survive in the stone-age African savannah.

It seems clear that we now live in a technological age in which a 'true' picture of the world is more useful to survival than mistaken illusions implanted by the senses.

Physics is unique among scientific disciplines in that the introductory course does not provide a survey of the present state of the field. Instead, it presents a chronological history of the steps by which various models were first proposed and then shown to be incomplete by application of the experimental method. Certainly biology, chemistry, geology, and the other sciences have undergone dramatic new discoveries during the 20th century, but only physics partitions them off into courses reserved for the major.

The historical approach to teaching has been criticized by the psychologist Bradshaw [12]:

> The only justification for a historical treatment is when you must explain how things got so messed up. Many textbooks introduce the topic through history. Why? Because there is a compelling need to explain how things came to be so muddled and confused, and you won't understand the situation unless you appreciate the history.

While some aspects of physics were muddled at the end of the 19th century, these were clarified within the first quarter of the 20th century. Is it prudent to propagate historical muddle to the exclusion of contemporary clarity?

Unfortunately this inductive 'voyage of discovery' approach stops short of putting the complete picture together and makes physics appear to be a large number of disconnected pieces. Modern concepts are added to an incomplete picture as if they were paradoxical. One must ask, does physics constitute a body of knowledge that is useful to all educated persons, or is it only a 'method of enquiry' that can be adequately demonstrated by application to the experiments of Galileo? As Smolin has stated [13]:

> In every (other) area, students are being exposed to things that are challenging because they are new. The fact that we teach 300-year-old physics as introductory physics is just shameful.

Certainly the historical approach provides insights into the scientific method of enquiry that led us to our current understanding of the nature of physical reality. However, similar developments have occurred as a result of the experimental method in both the physical sciences and the social sciences. Only physics sacrifices current knowledge in order to provide the historical perspective on the method of enquiry.

Feynman's parenthetical subtitle in 'the atomic hypothesis (or the atomic fact)' was a bold step. The use of the words 'atomic theory' can be very misleading to the general public. Thanks to instruments such as the scanning tunnelling microscope, the existence of atoms is as firmly demonstrable as the existence of the moon. What is normally intended by the word 'theory' is a calculational model. The existence of the atom is a fact—quantum mechanics is a theoretical model that can be used to describe that fact. Our students encounter few facts that are as secure as the existence of the atom. There seems little danger in introducing a few 'known facts' that characterize our current worldview, provided the methods by which these 'facts' came to be accepted are discussed later in the course. Perhaps we should heed the exhortation of the BBC cult figure Dr Who [14], 'First things first, but not necessarily in that order!'

The record clearly demonstrates that a modern deductive curriculum structure will not be accomplished by a perturbation process, and only a radical reinvention of introductory physics could achieve this result. Moreover, the growing balkanization of physics specialty areas might hinder its achievement by discipline-wide consensus. Even if this could be accomplished, such a revolutionary change could have unintended consequences. Our current educational system is driven at all levels by standardized performance testing. For example, in the United States this includes the 'No child left behind' program, the American College Test

(ACT), the Scholastic Aptitude Test (SAT), the Medical College Admissions Test (MCAT), the Graduate Record Examination (GRE), and Advanced Placement (AP) testing. Such tests are geared to the traditional curriculum, and can place students who know too much at a distinct disadvantage. The problems brought about by these instruments have been discussed by Tobias [15].

Since experience indicates that a complete restructuring of introductory physics is unlikely to be achieved in the near future, we have attempted to develop a short ‘front end’ course that describes the modern physical perspective as an accepted fact, and uses deduction rather than induction to implant a coherent and cohesive modern worldview. This can then be followed by a standard introductory physics sequence that serves as a ‘prequel’ projected on to a contemporary perspective. There are a number of textbooks available (e.g. [16, 17]) that strive to incorporate many modern aspects while retaining a more conventional syllabus structure.

2. Stories first, problems later

Lederman and Bardeen [18, 19] have spearheaded a movement to place ‘Physics First’ in high school education [20]. This involves a reversal of the traditional sequencing of courses, placing the study of physics ahead of the study of chemistry and biology. If a Physics First course is to prepare students for 21st century chemistry and biology, a major paradigm shift in introductory physics is essential. Rigden [21] has observed:

> Except in the rarest of instances, the only way departments of physics touch future national leaders is through introductory physics courses. Those equation-driven courses do not, in my judgment, qualify as a science education. I suggest that the value of an introductory physics course, six months after the final exam, is negligible. Specifically, I wager that adults who once took an algebra- or calculus-based introductory physics course are unable to discuss common physics phenomena and cannot demonstrate a better understanding of basic physical concepts than can those adults who never saw the inside of a physics classroom.

Similarly, Carroll [22] has suggested:

> What we need to do is to find a new way to teach the spirit of physics. What we do now is water down what professional physicists do and make it into this dry puzzle-solving thing with little pictures of pulleys and things like that. We ought to teach kids more about the Big Bang and entropy and particles. Every high school graduate should know that everything is made out of a handful of particles. That’s not a hard thing to know, but that’s not what’s emphasized.
>
> Yes, there is a quantitative aspect to science that should not be denied, but it can be in the service of interesting rather than boring problems. But they still want to know about the expansion of the universe and about cool things in atomic physics and lasers—which they’ll find interesting and fun.

The heavy use of problem assignments has long been central to the teaching of introductory physics. Problems provide clear expectations that are easy to convey to clients and students, simple to construct from test banks by instructors, straightforward to study for by students, and definitive to evaluate to the satisfaction of both students and instructors. However, Hewitt [23] has indicated that there are striking differences between the meaning of these problems as perceived by students and instructors. Hewitt observed:

> Contrast the way the professor and the students view problems. The professor classifies problems in terms of physics concepts, while the students classify them by situations. There are 'pulley problems', 'inclined plane problems', 'pulleys-combined-with inclined-plane problems' and so on. Since most students don't see the experience of solving such problems as building their careers (by then, rarely physics), they yearn for the end of the course.

The students refer to these exercises as 'story problems', but most of the 'stories' we tell are very old, and contain subtle hidden misconceptions held by our forbearers. A useful comment on this subject was made by Gould [24]:

> We have to extract meaning out of the confusion of the world around us. We do it by telling stories, and by looking at patterns. And whenever we see a pattern, we have to tell a story about it.

In the teaching of physics, most of the stories we tell were formulated long ago, and contain false assumptions and misunderstanding that have been corrected by subsequent experimentation. Today's teaching of physics demonstrates how these models were shown to be false by the application of the scientific method, but we lack alternative stories that characterize our current understanding. Instead of Newtonian and Galilean stories, perhaps stories that involve gauge boson interactions, quantum statistical facts, and the effect of the act of observation are more useful than learning literal formulae that describe unattainable idealized situations.

Layzer has also emphasized the importance of language in conveying quantitative concepts [25]:

> There is a peculiar synergy between mathematics and ordinary language . . . The two modes of discourse (words and symbols) stimulate and reinforce one another. Without adequate verbal support, the formulas and diagrams tend to lose their meaning; without formulas and diagrams, words and phrases refuse to take on new meanings.

Clearly our stories are intended only to convey a general perspective, and attempts to make them rigorously correct would rob them of their pedagogic utility. Haan [26] has discussed numerous examples of venerable stories that we routinely tell in introductory courses that are not completely correct, but comprise models that are nearly correct within a prescribed context. In the course discussed herein, new stories are needed that make plausible the seeming puzzlements of contemporary physics. For this we require similar latitude to be nearly correct, with the *caveat* that these are simplified models constructed to elucidate phenomena that initially seem counterintuitive. Bohr has been quoted [27] as stating that 'truth and clarity are complementary'.

The language that we speak when we teach an introductory physics course has little overlap with the language that we speak in upper-level courses and with our colleagues. Quoting Rukeyser's poem 'The Speed of Darkness' [28],

> Time comes into it. Say it. Say it. The universe is made of stories, not of atoms.

3. Limitations of the force approximation

Virtually all introductory textbooks begin with a thorough grounding in Newtonian mechanics, requiring students to 'think Newtonian' before progressing to concepts such as the conservation of energy, momentum and angular momentum, the least action principle, etc. Attempts at other organizations of material have been made, but such textbooks have either reverted to the standard organization in subsequent editions, or their adoptions have rapidly diminished. However, voices questioning this have been raised.

3.1. Historical criticisms

For example, Wilczek has suggested in an essay [29] that the force concept is more a 'culture' than an algorithm. He states that

> Newton's second law of motion, $F = ma$, is the soul of classical mechanics. Like other souls, it is insubstantial. The right-hand side is the product of two terms with profound meanings. Acceleration is a purely kinematical concept, defined in terms of space and time. Mass quite directly reflects basic measurable properties of bodies (weights, recoil velocities). The left-hand side, on the other hand, has no independent meaning.

He buttresses this statement with an 1895 quotation by Tait [30]:

> In all methods and systems which involve the idea of force there is a leaven of artificiality . . . there is no necessity for the introduction of the word 'force' nor the sense-suggested ideas on which it was originally based.

and a utopian 1925 quotation by Russell [31]:

> If people were to learn to conceive the world in a new way, without the old notion of 'force', it would not only alter their physical imagination, but probably also their morals and politics.

Jammer [32] has suggested:

> the concept of force has reached the end of its life cycle . . . (suggesting) its disbarment from the inventory of fundamental concepts in physics.

3.2. Statistical nature of forces

The preoccupation with the force concept leads to a questionable formulation of the interactions by which atoms form molecules. Even the statement by Feynman [10] that atoms are 'attracting each other when they are a little distance apart, but repelling upon being squeezed into one another' is open to misinterpretation by students who are unfamiliar with quantum statistics and the Pauli exclusion principle.

Mullin and Blaylock [33] have addressed the tendency of textbooks to discuss an 'exchange force' as though there were an effective repulsion between fermions and an effective attraction between bosons. They caution against this practice and indicate (with examples) that the suggestion of an 'exchange force' is

> . . . a dangerous concept, especially for beginning students, because it often leads to an inaccurate physical interpretation and sometimes incorrect results.

They propose that the explanations of quantum statistics avoid the idea of an effective force completely, and suggest other more appropriate physical insights that can replace it.

If the fact that the ultimate source of interactions resides in impulsive exchanges of bosons (which has a macroscopic analogue in the impulsive collisions that produce atmospheric pressure) were given at the outset, the fact that the force illusion requires a finite sampling time over a finite sampling area would be obvious. Moreover, the statistical limitations of sharpening a pressure determination by narrowing the sampling time or reducing the sampling area make the concept of *uncertainty* self-evident.

3.3. A diminished role for linearized force problems

For the majority of our students, introductory physics is a terminal course, and they are never exposed to the methods of contemporary physics. As anyone who has taught these courses can attest, the Newtonian contact force can produce persistent misconceptions. How many times have we heard the question 'How can a rocket work in outer space where there is nothing for the force to push on?' or the statement 'The moon doesn't fall to earth because the centrifugal force holds it out' or 'If weight is gravitational force, and orbiting astronauts are weightless, then they must be outside the range of gravity'.

Our teaching and testing methods both emphasize literal formulae. These involve linearizations of interactions that we would not apply to a problem in current research. For example, in projectile motion the student is told that the horizontal and vertical motions are completely independent. In any realistic problem on earth (for example, the trajectory of a baseball), the viscous drag of the air depends on the scalar speed, and couples vertical and horizontal in ways that require a numerical solution. Moreover, the aerodynamics of the Magnus effect due to backspin [34] can produce large effects. A recent study [35] has shown that treating an elliptic orbit as a parabolic orbit by the use of 'flat earth coordinates' (treating gravitational lines of force as parallel and independent of altitude) is a poor approximation. While textbook formulae that produce inaccurate results can have pedagogic value, one must question whether a more modern approach could be found that is both simpler and more accurate.

4. Proposal: insert a short introduction to the modern perspective at the beginning of a standard introductory physics course

For many reasons, a comprehensive contemporary restructuring of introductory physics courses is unlikely to occur soon. Therefore, we have attempted a much simpler approach that prefaces the standard course sequence with a short (2–3 weeks for a course typically meeting 4 h per week for 30 weeks) qualitative introduction to various unifying aspects of the modern physical perspective. This front-end module can then connect to any standard model introductory physics curriculum, with the various units of the traditional course placed in the context of the modern perspective.

This approach requires more than a reordering of the modern physics materials that are usually introduced at the end of standard introductory textbooks. These sections tend to describe details of the (now archaic) experiments that first revealed the breakdown of the classical model, and thus stress apparent paradoxes rather than unifying insights.

In developing this module, attempts to include various aspects of the program were made at a number of academic levels, both at the University of Toledo [36] in the United States and at the University of Lund [37] in Sweden. These included: a graduate course in atomic structure; a senior level introductory quantum mechanics course; a third year 'modern' physics course; the algebra- and calculus-based introductory courses, a first-year general education course (with both open and honours sections); a 'Physics Summer Camp' outreach program for area high school students; and a 'Saturday Mornings with Physics' community outreach project (for elementary and high school students, parents, and teachers). The approach was also used in a course 'Physics and the Theatre' in which the students analysed theatrical plays containing plots involving physics. The course was team-taught by a professor of theatre and a professor of physics.

In discussions with students who had taken these courses, some useful patterns emerged. Frequent criticisms of the standard model syllabus were that there are too many disconnected topics. Every day brings a new chapter with a new set of formulae, and new 'tricks' to solve a narrow class of problems. It was observed that physics is advertised to provide a small set of fundamental principles from which all problems can be solved by deduction, yielding new insights. Instead, physics comes wrapped in thick multivolume textbooks, and for each problem there is a special trick that must be memorized.

In response to these comments, we sought to develop a concise narrative introduction to the course, stressing the unifying rather than the puzzling aspects of the contemporary physical perspective. When this introduction is followed by a course taught from a standard model textbook, it was anticipated that connections could be drawn between the apparently separate topics mechanics, light, heat, sound, electricity and magnetism. This can conceptually connect, for example: mechanics and electricity through the microscopic nature of the 'contact force'; electricity and magnetism through relativity; electricity and optics through the photon exchange model, etc.

Although adjustments were needed to serve various audiences, there were certain broad concepts that, if presented qualitatively in the preliminary module, brought about enhanced insights and spawned interconnections in the subsequent standard model curriculum. Although the Hawthorne effect [38] (individuals work harder when they are participants in an experiment) predicts that all educational experiments are successful initially, the results obtained were nonetheless gratifying.

5. A sample set of areas for a qualitative introduction

In order to stay within a narrow time frame, it was necessary to limit the range of concepts introduced. We found that we obtained positive results by stressing the fundamental aspects of the atomic nature of matter and the electromagnetic nature of our interactions with the physical world.

While aspects of topics such as nuclear structure, elementary particles, cosmology, etc capture students' interest, they are less essential to an understanding of mechanics, light, heat, sound, electricity and magnetism that can be added at the end of a course rather than at the beginning.

As an illustration of the approach, we selected the following six topics for inclusion in our qualitative introduction:

(5.1) trajectories versus dwell times
(5.2) least action principle and conservation laws
(5.3) quantum statistics
(5.4) electromagnetic interactions
(5.5) relativity and the magnetic field
(5.6) interactions between neutral atoms.

This list was selected because it contains concepts that we planned to revisit in the teaching of the standard model course that follows it. Brief descriptions illustrating the qualitative nature of these presentations are given below. However, many possibilities exist, and it hoped that others will consider alternative approaches.

5.1. Trajectories versus dwell times

A basic distinction exists between the conceptual framework presented in introductory physics courses and that used in the advanced courses in the physics major. Introductory courses use concepts involving forces and accelerations that never enter in more advanced formulations.

The introductory approach is characterized as 'classical' and that of the more advanced courses is described as 'quantum mechanical'. However, the primary difference between the two approaches arises not because of quantization, but rather from a nonessential description of macroscopic systems by instantaneous values for position, speed, and acceleration, and microscopic systems by time-averaged position probability densities.

This is analogous to recording macroscopic systems with moving pictures and microsystems with time-exposure pictures. The two methods contain the same information: for moving pictures through the variation of images on successive frames; for time-exposures by the degree of exposure over a single frame, indicating the dwell time. The moving picture uses a differential calculus to trace changes; the time-exposure uses an integral calculus to obtain average values. Surprisingly, the latter approach is less demanding mathematically, since the integral of a quantity of any complexity can be obtained as the geometric area under the curve (easily obtained as a closely spaced discrete sum using the simplest of computers).

The reason for these alternative approaches is clear, since a macroscopic system is disturbed imperceptibly when successively interrogated with visible photons, whereas a microscopic system can be destroyed by interrogation with a single short-wavelength photon. Thus, the description of the microscopic system requires the superposition of many similarly interrogated systems. Unfortunately, this produces a disconnect between physics as it is taught to non-major students and as it is practised.

Efforts can be made to describe modern topics in a Newtonian context, but use of such characterizations for many electronic devices used by today's students fails completely. The 'flash memory' is an excellent example. These devices are found in flash drives, MP3 players, and many other products. Their function relies on quantum tunnelling technology, and their cell sizes can be less than 20 nm. Tunnelling is classically forbidden, and optical tracking of electron trajectories would require interrogation with photons of hundreds of eV of energy.

In contrast, the consideration of the position probability density of an electron in one of these devices is analogous to the dwell time of a time exposure of a pendulum illuminated by a strobe lamp.

It is sometimes argued that initial use of the Newtonian approach is necessary, because a quantum mechanical formulation would be too demanding mathematically. However, the problems attacked in elementary textbooks tend to be simpler than those treated in quantum mechanical textbooks. If one examines problems of similar complexity, a Newtonian formulation is often much more complex mathematically than the corresponding quantum mechanical solution. For example, elementary textbooks describe the two-dimensional Kepler orbit problem, but it is invariably restricted to the special case of a circular orbit (and, in the flat earth approximation, to a parabolic trajectory).

A classical solution to the three-dimensional Kepler problem in terms of position probability densities has been presented [36, 39, 40], and has been applied to elliptic orbits in both a multiplanetary solar system [39] and a multielectronic atomic system [41]. When the macroscopic and microscopic systems are both expressed in the position probability density formulation, the understanding of both limits is clarified, and the role of quantization in the microscopic case is unencumbered by calculational differences.

When the classical problem is formulated in terms of position probability densities, three-dimensional elliptic orbits are automatically included [39, 40, 42, 43]. Moreover, deviations from a pure inverse square law can be included as perturbations, all in a purely classical framework [39, 40, 42–44].

It is also possible to add semiclassical quantization directly to the classical solution when desired [41]. Problems with the old Bohr–Sommerfeld–Wilson quantization have long ago been corrected [36, 39–43] by the Einstein–Brillouin–Keller quantization through inclusion of the Maslov index.

5.2. Least action principle and conservation laws

Taylor has suggested in his essay 'A call to action' [45] that physics can be taught without $F = ma$ and without vectors through the use of the principle of least action, and has developed a set of computer-based, user friendly exercises [46] to demonstrate its use. For example, the student can randomly vary the kinetic energy T and potential energy V at points along a spacetime trajectory, and discover that when the sum of values T–V at the points on the trajectory is minimum, the value of T+V is the same at every point. No mathematics is needed.

It can be argued that action is the most fundamental quantity in physics. It is a quantized building block of nature, the number of units of which specifies the statistical behaviour of fundamental particles, it is a Lorentz invariant that yields conservation of energy and momentum through the least action principle, and it elucidates the uncertainty principle.

In spite of its central role in physics, the discussion of action in introductory textbooks is usually deferred until it arises in a discussion of Planck's constant. Moreover, even the word is given multiple meanings. In 1687, Newton chose the word *Actioni* in his *Axiomata sive Leges Motus* to describe what we now denote as linear momentum. A few decades later, the word 'action' was re-associated with a quantity (having units of angular momentum, but more general than that concept) by Euler, Liebniz and Maupertuis in the 'least action principle'. This creates confusion that could be clarified by replacing Newton's three rhetorical 'laws' with a statement of the conservation of linear momentum between a selected object and the rest of the universe.

The concept of action impacts many aspects of the modern worldview, yet its occurrence in elementary textbooks is generally limited to discussions of blackbody radiation and the photoelectric effect. To counteract this situation, we have placed action as the dominant centrepiece of our course structure.

Applied to elementary particles, it has the following properties.

(1) Action exists only as integer multiples of an indivisible basic unit $\hbar/2$.
(2) Particles with even $\hbar/2$ units obey BE statistics (cooperate).
(3) Particles with odd $\hbar/2$ units obey FD statistics (compete).
(4) The photon mediates EM interactions, and defines second quantization.
(5) The total action of a fermion system defines first quantization.
(6) Viewed in spacetime, the trajectory of a particle proceeds on the path that contains the least number of action units (least action principle).
(7) The least action principle yields the laws of conservation of energy and momentum.
(8) Action is a Lorentz invariant. Energy (action/time) and momentum (action/length) are conserved quantities.
(9) Since the least action path contains an integer number of $\hbar/2$ units, minimum uncertainty is one such unit: hence, certainty in energy–time and momentum–length.
(10) The 'mechanical action' (orbital angular momentum) is quantized in multiples of $2(\hbar/2)$, and is associated with the 'parity' or handedness of an atomic state.

5.3. Quantum statistics

One of the most intriguing aspects of intrinsic action is the connection between 'spin' and statistics. Particles possessing an odd number of units of $\hbar/2$ obey Fermi–Dirac statistics (and are called fermions), and particles with an even number of units of $\hbar/2$ obey Bose–Einstein statistics (and are called bosons). There exists no accepted elementary explanation for this connection [47] and the implementation of the theory is beyond the scope of this presentation. However, it is possible to construct a simplified model that can make various features of the theory plausible.

5.3.1. Competition and cooperation. To illustrate the consequences of these statistics, one can metaphorically characterize fermions as 'competitive' and bosons as 'cooperative'. In this model, when in close proximity no two fermions do the same thing at the same time, whereas bosons in close proximity all tend to do the same thing at the same time, collectively and in cadence.

This provides a macroscopic analogy of the concept of 'duality' whereby fermions and bosons sometimes exhibit particle properties (substantive, spatially localized) and at other times wave properties (oscillatory, spatially extended). Individually, both fermions and bosons are localized particles that also possess characteristic oscillatory properties. Because the individual members of an ensemble of fermions cannot do the same thing at the same time, their individual identities as particles are apparent. Because the individual members of an ensemble of bosons share a common collective cadence, the macroscopic ensemble mimics the behaviour of the microscopic individuals, and (like photons) the ensemble is interpreted as a continuous wave.

The popular practice of spectators at a football match to form 'the wave' provides a macroscopic analogue. Without the wave, the spectators are perceived as individuals. If instead neighbouring spectators sit and stand in an appropriate rolling cadence, the appearance (at a distance large compared to the width of a seat) is of an extended, oscillating object.

5.3.2. The dressed electron. Another useful conceptual model provided by quantum statistics is that of the 'dressed electron'. Electrons and positrons have one unit of $\hbar/2$ and obey Fermi–Dirac statistics. Quantum electrodynamics accounts for the electrical interactions among these fermions through the exchange of virtual photons, which have two units of $\hbar/2$ and are the 'gauge bosons' that mediate the interaction. Thus, there is an inseparable relationship between the electrons and the photons—an electron with no virtual photon accompaniment would have no charge, and thus behave like a neutrino. When the electrons and positrons (Fermi–Dirac statistics) are observed macroscopically together with their absorbed and emitted virtual photons (Bose–Einstein statistics) the renormalized sum of the two distributions become classical Maxwell–Boltzmann statistics.

This will be discussed in more detail in the section on electromagnetic interactions.

5.3.3. Classical and quantum coins and dice. A simple analogy to quantum statistics involving coin flips has been suggested by Chow and Cohen [48]. If two coins are flipped, each can result in a heads (H) or tails (T) with equal likelihood. Thus, the possible outcomes are (HH, HT, TH, TT) and there is a 25% chance of either two heads or two tails, and a 50% chance of one heads and one tails. If these are indistinguishable 'quantum coins' (that is, they have no pre-existence, and only come into being when the wavefunction collapses in the measurement process), then it is not possible to discriminate between HT and TH. In this case, all three outcomes are equally probable at 33%. This symmetric case is an analogue of the Bose–Einstein distribution. If there is an exclusion principle that precludes both coins from having the same heads or tails property, then the only possible outcome is one head and one tail, now a certainty. This antisymmetric case is an analogue to Fermi–Dirac statistics.

If the Bose–Einstein and Fermi–Dirac distributions are averaged, it yields an analogue of the Maxwell–Boltzmann distribution.

Similar examples can be constructed with multisided coins (like dice). For a pair of six-sided classical dice, it is possible to roll 36 outcomes with totals between 2 and 12. A score of 4 can be achieved with (3,1), (2,2), (1,3), so its likelihood is 3/36. For the Bose–Einstein dice, (3,1) is equivalent to (1,3), reducing the favourable outcomes to 2 and the total outcomes to 21 for a probability of 2/21. For a Fermi–Dirac dice, (1,1) is excluded, so there remains only 1 favourable and 15 total outcomes, with a probability of 1/15. Combining and renormalizing the two quantum distributions gives back $21 + 15 = 36$, recovering the Maxwell–Boltzmann distribution.

It can be a useful conceptual insight into the nature of our physical reality to note that the Maxwell–Boltzmann macroscopic statistical behaviour that we observe in daily life subdivides on a microscopic level into Bose–Einstein and Fermi–Dirac components.

5.4. Electromagnetic interactions

Although electromagnetic interactions were studied much later than gravitational interactions, they provide the basis for an understanding of chemistry, biology, and many other disciplines that impact our lives. While physics courses traditionally begin with gravity, gravitational interactions are much weaker, are purely attractive (so possess no dipole interactions), and their unification with the other types of interactions is incomplete.

Physics courses at both the introductory and intermediate levels treat electric charge through differential elements containing many individual charge quanta. In most practical examples, this is a very good approximation, owing to the large magnitude of Avogadro's number. In this approximation, the convenience of calculus can be utilized, with sums performed as integrals and differences described by differential equations. By extending the electrodynamic 'story' to include the discreteness of both the quantum of action and the quantum of charge, insights into the fundamental nature of electrodynamic interactions can be gained.

5.4.1. Interaction by boson exchange. These considerations can provide deeper insights into the dynamical origin of interactions than are provided by a sensually apparent but conceptually insubstantial 'action'-at-a-distance 'force'. Qualitatively, the attractive and repulsive interactions between charged particles can be modelled in terms of the virtual photon field that pervades all of space. The charged fermions dressed with bosons can be thought of as two aspects of a single entity, having one part with a Fermi (Pauli) exclusion principle, and another part with a Bose condensation, which combine macroscopically to exhibit classical statistics.

The traditional 'free body diagram' approach of Newtonian physics can be misleading. While it has calculational value in the Newtonian illusion, it is in fundamental conflict with the current worldview. Quantum electrodynamics mirrors Mach's principle (local physical laws are determined by the large-scale structure of the universe), and one cannot consider interactions as occurring within an isolated system. The mass renormalization of quantum electrodynamics requires that the interaction of any charge take into account all of the other charges in the universe, since they are all interacting by exchange of photons. Moreover, the variation of the distance and state of motion of the other charges (and finite speed of photons) leads to retardation effects, and the double counting of the total charge that is perceived as magnetism.

Wheeler's famous suggestion to Feynman [49] that 'the reason that all electrons have the same mass is that they are all the same electron' not only charms students, but also contains an important insight into an elegant theory. Wheeler's model took the fact that a positron behaves like an electron travelling backwards in time, and applied it to the vertices of pair creation and annihilation events. By connecting an electron (or positron) created at one vertex with a positron (or electron) annihilated at another vertex, and continuing this process, he created a zigzag path oscillating between the past and the future that would be interpreted as an electron (or positron) each time it passes through the here-now.

Although this is only a story, students have indicated many years later that they recall this model, and the implication that every electron is connected by the virtual photon field to every other electron in the entire universe.

5.5. Relativity and the magnetic field

The subject of special relativity is usually presented in introductory physics courses as a counter-intuitive revision to Newton's laws. However, the title of Einstein's 1905 paper [50] on this subject ('On the electrodynamics of moving bodies') reveals an elegant exposition of the origin of the magnetic field. This can be illustrated through a simple intuitive pedagogic example [36].

Consider a copper wire 1 mm in diameter through which a current of 1 A passes. Assuming one conduction electron per copper atom, this current corresponds to a drift speed ≈ 0.1 mm s^{-1}. One of the results of special relativity is the fact that if two extended objects move parallel relative to each other, each underestimates the length of the other along the direction of motion. Thus, to an observer who is stationary relative to the wire, the drifting negative electron charge cloud will appear slightly denser. This is a very small effect, but it is greatly enhanced as seen by a positive point charge that moves at a significantly larger speed either parallel or antiparallel to the electron drift.

If the point charge moves in the same direction as the electron drift, then its speed relative to the positive charge cloud is greater than its speed relative to the negative charge cloud. In this case, the positive charge cloud will appear to be denser than the negative charge cloud, and the positive point charge will be repelled by the wire.

If the test charge moves in a direction opposite to the electron drift, then its speed relative to the negative charge cloud will be greater than its speed relative to the positive charge cloud. In this case, the negative charge cloud will appear to be denser than the positive charge cloud, and the positive point charge will be attracted to the wire.

Note that the magnetic interaction is either attractive or repulsive, and the introduction of a transverse vector by the 'right-hand rule' is a scheme for selecting between these two alternatives.

By simple algebra (and a binomial expansion of the relativistic square root), this model yields [51] the Biot–Savart law. This simple model demonstrates that the Biot–Savart law is a consequence of Coulomb's law and relativity, and not a separate experimental fact.

5.6. Interactions between neutral atoms

5.6.1. The mechanism of 'contact forces'. The illusion that 'solid objects' consist of continuous matter in 'contact' with its surroundings is pervasive and misleading. The concept of 'weight' provides an example of the confusion that can occur. While a standard dictionary definition of weight is 'the force with which an object is attracted toward the earth', it is also commonly stated that an object in free fall is 'weightless'. A student of physics in the 21st century should be aware that the concept of weight involves gravitation, electrostatics, and the Pauli exclusion principle.

When I stand on the floor, the gravitational interaction between the earth and my body draws the atoms in the soles of my shoes closer to the atoms in the floor material, causing their electron clouds to overlap. Because of Fermi–Dirac statistics, negatively charged electrons are excluded from this interface, leaving positively charged nuclei in the shoes and floor with reduced electron screening. The interactions between the positive charges lead to a repulsion that offsets the gravitational attraction. It is 'action-at-a-distance' mediated by photon exchange, with no 'contact'.

Thus, it might be argued that 'weight' is not the pull of the earth, but rather the push up of the floor that occurs as a consequence of the Pauli exclusion principle.

5.6.2. Dipole–dipole interactions. Since there is only one kind of gravitational mass, and its interactions are exclusively attractive, there are no 'neutral' gravitational objects that interact by dipole moments. Thus, the first course in a two-course introductory physics sequence lacks a model for the dipole–dipole interaction that governs the ultimate electrical nature of matter.

Moreover, the standard introductory course in electricity begins with a study of free charge, using glass rods/silk cloths, amber rods/cat fur, Wimshurst machines (and their technological-advanced counterparts) to dramatically 'electrify' objects. This emphasis on free charge provides a symmetry between Kepler's and Coulomb's laws that can be applied to the solution of homework problems. However, free charge is not commonly experienced in daily life, and this approach conceals the important phenomenon of the electric dipole–dipole interactions that govern everything that we touch and feel.

The electric E_1 field at a point r from a charge q is given by $\mathsf{E}_1 = kq/r^2$. If two point charges of opposite sign are displaced from each other by a distance a, the electric field E_2 along the direction of the displacement is given by $\mathsf{E}_2 = 2kqar/(r^2 - a^2/4)^2$. If $r \gg a$, this becomes $\mathsf{E}_2 \cong 2kqa/r^3$, and a permanent dipole field decreases as $1/r^3$. If the field originates from two non-polar atoms that induce dipole moments in each other, the energy of interaction between them is proportional to $(\mathsf{E}_2)^2$, and so varies as $1/r^6$.

5.6.3. van der Waals interactions. If the ideal gas equation $PV = NRT$ is adjusted to include the attractive induced dipole–dipole interaction and the repulsive Pauli exclusion interaction, the van der Waals equation $(p + a/V^2)(V - b) = NkT$ [52] is obtained. (Here the 'culture' of forces can be avoided by consideration of pressure as energy/volume.) If the factorization in this equation is expanded for constant T, a cubic equation in V results that, when plotted on a PV diagram, accurately describes the gas phase, the condensation process, and the liquid phase.

The b constant corresponds to the portion of volume that is inaccessible because of the Pauli exclusion principle. The a constant accounts for the attraction produced by the induced dipole–dipole interaction. This average interatomic separation r can be related to the total volume of the container V by the relationship $V \sim N(4\pi r^3/3)$, which yields $1/r^6 \sim 1/V^2$.

Although van der Waals interactions are much weaker than chemical bonding, they provide a useful and intuitive introduction to interactions between neutral atoms and molecules.

6. Concluding remarks

The front-end module described here was constructed with specific goals in mind for providing a conceptual foundation for the standard course that follows. It is intended only as a sample of this teaching philosophy, and we encourage others to develop their own list of foundational topics, selected on the basis of individual taste, teaching style, and educational goals.

It is emphasized that the primary purpose of this proposal is *not* to improve student scores on tests based on the standard model curriculum (although such a result is possible), but rather to provide students who never take another physics course with insights into contemporary physics that they are not currently receiving.

Our results indicated that the presentation of this short qualitative introduction made contemporary physics seem less abstract and counterintuitive to the students, and permitted them to look backwards to unify and place in historical context the classical topics in the standard course. In the words of Hartley [53], 'The past is a foreign country; they do things differently there'.

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