Can atomic physicists help reinvent Introductory Physics?

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Abstract. Much effort has been and is being devoted to the reform of the teaching of physics. This has led to many new and imaginative approaches to the delivery of the course material, but a perusal of today's Introductory Physics textbooks indicates that their basic structure has changed little in over fifty years. A radical restructuring is proposed that begins with a modern atomic picture rather than a Newtonian world view. The task is discussed in the context of existing practices, factors inhibiting reform, and strategies that could have a significant impact. If the pedagogic advantages of the atomic world view are to be realized, it seems clear that the research-active AMO physics community, and not just pedagogic researchers, must be involved in the development of this new structure.

15 August 2007

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], and many other forums. These efforts have led to many new and imaginative methods for delivery of the material. However, despite many attempts to revise the structure and content of the material delivered, nearly all popular Introductory Physics textbooks today follow a structure that has changed little in hundreds of years.

The first introductory course deals with 18th century mechanics and the second course deals with 19th century electrodynamics, light, heat, *etc.* A third section is sometimes added that describes how fundamental misunderstandings of the 18th and 19th century were recognized at the beginning of the 20th century. Unfortunately, accidents of history have trapped atomic physics in an archaic addendum at the end of the book.

Donald Holcomb [6] has observed:

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‡ This Comment summarizes a series of talks given at the Universities of Arizona, Notre Dame and Toledo, and at the Northwest Ohio Symposium on Science, Mathematics, and Technology Teaching.

> 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*.

Holcomb suggests three examples of possible modifications: The atomic world; The power of conservation laws; and Exponentials. Consistent with this, Richard Feynman elevated to pre-eminence the "atomic fact" in his oft-quoted statement [7]:

> 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 this premise that our current level of scientific knowledge could be more quickly *rediscovered* by starting with the atomic fact, could it not be more efficiently *discovered by students for the first time* 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 Richard Dawkins [8]:

> 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 Gary Bradshaw [9]:

> 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 Inquiry" that can be adequately demonstrated by application to the experiments of Galileo? As Lee Smolin has stated [10]:

> 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 inquiry that led 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 historical perspective on the method of inquiry.

Feynman's parenthetical subtitle in "the atomic hypothesis (or the atomic fact)" was a bold step. If a "fact" is defined as "something that can be demonstrated to be true" rather than "something that defies falsification," then our students encounter few facts that are as secure as the atom. There seems little danger in introducing a few "known facts" that characterize our current world view, 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 [11], "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 the Introductory Physics curriculum could achieve this result. Pedagogically-oriented groups have been much more successful at developing improved delivery methods than at radically reforming content. Moreover, the growing balkanization of physics specialty areas would hinder the achievement of a radically new curriculum by discipline-wide consensus. An approach is suggested here involving an alternative logical structure that begins with the atomic fact, and uses deduction rather than induction to provide a coherent and cohesive modern world view. Since atomic physics was the enabling field that ushered in the 20th century world view, the endeavor would be strongest if it originated within the research-active AMO physics community.

2. Problems versus stories

There is a growing movement favoring "Physics First" in High School education [12]. 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.

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 [13] 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 forebearers. A useful comment on this subject was made by Stephen Jay Gould [14]:

> 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.

David Layzer has also emphasized the importance of language in conveying quantitative concepts [15]:

> 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.

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 Muriel Rukeyser's poem "The Speed of Darkness" [16],

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

3. Must Chapters 2 and 3 be about Galileo and Newton?

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, least action principles, *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.

For example, Frank Wilczek has suggested in an essay [17] 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 Peter Tait [18]

> 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 Bertrand Russell [19]

> 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.

Max Jammer [20] 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.

The preoccupation with the force concept leads to a questionable formulation of the interactions by which atoms form molecules. The statement by Feynman [7] 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 [21] 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 gauge 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 area would be obvious.

For the overwhelming 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 and the "Force Concept Inventory" can produce many persistent misconceptions, such as:

- How can a rocket work in outer space where there is nothing for the force to push on?
- The moon doesn't fall to earth because the centrifugal force holds it out.
- If weight is gravitational force, and orbiting astronauts are weightless, then they must be outside the range of gravity.
- Rutherford proved that nuclei are large because alpha particle beams often hit them, feel a contact force, and bounce backward. If nuclei were small the alpha particles would miss them, feel no forces, and go straight forward.

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 ball) 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 [22] can produce large effects. A recent study by [23] 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.

Edwin Taylor has suggested in his essay "A call to action" [24] 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 exercises [25] to demonstrate its use. It can be argued that action is the most fundamental quantity in physics. One need only consider: (1) application of the principle of least action leads to Newton's laws and the conservation of energy and momentum; (2) it is action (and not energy) that is quantized in quantum mechanics; (3) the number of units of action possessed by a particle determines whether it obeys Fermi-Dirac or Bose-Einstein statistics; (4) the quantized nature of the least action path elucidates the origin of the uncertainty principle; (5) unlike length, time, momentum and energy, action is a Lorentz invariant.

In spite of its central role in physics, the correct meaning of action is not covered in our introductory courses. Donald Simenak provides this entry under "action" in his "A Glossary of Frequently Misused or Misunderstood Physics Terms and Concepts [29]:

> This technical term is a historic relic of the 17th century, before energy and momentum were understood. In modern terminology, action has the dimensions of energytime. Planck's constant has those dimensions, and is therefore sometimes called Planck's quantum of action. Pairs of measurable quantities whose product has dimensions of energytime are called conjugate quantities in quantum mechanics, and have a special relation to each other, expressed in Heisenberg's uncertainty principle.
>
> Unfortunately the word action persists in textbooks in meaningless statements of Newton's third law: "Action equals reaction." This statement is useless to the modern student, who hasn't the foggiest idea what action is.

Why do we permit this archaic statement of Newton's third law to appear in our textbooks? If we accept the Maupertuis-Euler definition of action, then Newton's third law is an unintended statement of the conservation of angular momentum. It would be clearer to dispense with the three laws and replace them with conservation of momentum between a selected object and the rest of the universe.

The concept of action impacts so many aspects of the modern world view that we have placed it as the dominant centerpiece of our proposed course structure.

4. Mathematical level

For the traditional Newtonian development, a background in vector differential calculus is essential to describe the rates of change of position, velocity, acceleration, jerks, *etc.* However, if one compares Newtonian and quantum mechanical descriptions of a system of three or more particles, the instantaneous Newtonian formulation is nearly intractable, whereas the time-averaged position probability density quantum mechanical description is relatively simple. Surprisingly, the advantages of the quantum mechanical approach can be adapted with advantage to elucidate a classical or semiclassical formulation.

By using a position probability density formulation of the classical problem, the dynamics of the system can be characterized in terms of average values of moments of the various quantities. This involves an integral of a length coordinate over the reciprocal of the canonical momentum. Similarly, semiclassical quantization can be introduced by the Einstein-Brillouin-Keller action integral. This involves an integral of a length coordinate with its canonical momentum.

Although differential calculus precedes integral calculus in the curriculum, integral calculus can be performed with little knowledge of either. While solutions to differential equations require a knowledge of mathematics and a closed form result is not always possible, an integral can always be performed. (A summer job of my youth required me to evaluate integrals by plotting a measured curve on graph paper, cutting out the curve with scissors, weighing it on a microbalance, and comparing it with the weight of a piece of graph paper trimmed to a known number of squares.) Today's computer-savvy students can easily perform integrals, either by the trapezoidal rule by other more accurate algorithms.

Numerical variational studies of extremal functions by numerical methods also provide an approach that bypasses the need for sophisticated mathematical training. Computer exercises involving animations exist for expositions of the least action principle and Fermat's least time optical principle. Use of the Hylleraas variational approach is also well adapted to this type of exposition.

5. What factors limit reform?

There are significant factors that impede the implementation of revisions in the content and structure of Introductory Physics courses. One involves the fact that pre-university curricula are often prescribed by State or local Boards of Education. For example, our Ohio State Department of Education has set the following Academic Content Standards for Elementary School Education [26].

- By the end of the K-2 program: Recognize that light, sound and objects move in different ways.
- By the end of the 3-5 program: Describe forces that directly affect objects and their motion.

- By the end of the 6-8 program: In simple cases, describe the motion of the objects and conceptually describe the effects of forces on an object.

Thus, the Newtonian "story" is mandated, and the fact that the same kinematic laws govern the motion of photons, and electrons is "outlawed." Fortunately, these mandates do allow teachers to supplement the curriculum with "enrichment" additions. If teaching materials were developed that provide a modern world view (and do not require special training to administer), this could have a significant impact on student understanding at very early age.

Even in the University environment, where Academic Freedom would seem to allow Professors to determine the content of their courses, the emphasis on performance tests can place students who have not been drilled on Newtonian methology at a disadvantage. These tests include 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. The problems brought about by these instruments has been discussed by Sheila Tobias [27].

6. What can be done to improve the situation?

The traditional structuring of Introductory Physics is deeply entrenched. It has been presented as a formalized static catechism to many generations through indoctrination beginning at a very early age. It is the structure that is expected by students, teachers, parents, client disciplines, and the general population. In our attempts at restructuring we have encountered strong polarization. Although many students and teachers are enthusiastic about the scope and unity of the contemporary world view, others are aggressive and antagonistic, unshakable in their conviction that any alternative presentation must be preceded by a thorough Newtonian grounding.

At the University level, we find that it can be harder to teach well-prepared students than those whose background in science is weak. Having a "clean sheet of paper to write on" avoids both the limitations of the Newtonian picture and the perception that the modern world view consists of puzzling paradoxes rather than new unifying insights.

The *delivery* aspect of physics education is in good hands, and great strides are being made. With the use of Studio Sections, hands-on discovery labs, wireless interactive student response systems, Powerpoint presentations with continuous in-class testing, peer learning groups, interactive computer assignment and grading of homework, and many other innovations, it seems clear that improved teaching of whatever content is prescribed can be achieved.

Despite promising attempts by many commissions and authors, the majority of textbooks that we must select from today differ from the book from which I studied in the 1950's (Sears and Zemansky, xth edition) in only two ways: they are much thicker and heavier (with more disconnected topics), and they contain more (environmentally unfriendly) color plates. Thus, structural revision of Introductory Physics has not been achieved through the writing of revolutionary textbooks, even by an author possessing the wisdom of a Feynman.

Regretably, this is an inopportune time for physicists to undertake curriculum revision. In the face of financial shortfalls, educators are being required to teach larger classes with less support personnel. As the technological component increases, instructors must also use (and develop) new software and hardware, and deal with computer malfunctions. Simultaneously, shifting research funding places pressures on the teacher-scholars whose insights are vital to educational reform. Even the most pedagogically-oriented physicists are tempted to defer curriculum reform.

Since neither incremental changes nor a sweeping revision in the Introductory Physics Curriculum have succeeded to date, we have adopted another strategy to try to effect change. Instead we have sought to develop an introductory front-end module that provides the student with a modern world view, which could be followed by a more traditional course. If this module could be qualitatively adjusted for presentation at various levels of education from elementary school through high school and college, it might have a significant impact.

Earlier we had developed a graduate course in Atomic Structure which was designed to serve as capstone to place courses such as Classical Mechanics, Classical Electrodynamics, Quantum Mechanics, and Quantum Electrodynamics in the context of a modern world view. As part of the project a textbook [44] was produced. It was found that the first few chapters of this graduate course could be usefully adapted to other lower level courses.

These courses have included, in descending order of student preparation: (1) a graduate course in atomic structure; (2) a third year undergraduate course in quantum physics; (3) an Honors Section of the introductory level second semester calculus-based course; (4) a first year (prerequisite-free) General Education course titled "The World of Atoms," and (5) a "Saturday Mornings with Physics" community outreach project for elementary school and high school students, parents, and teachers.

Like all educational experiments (consistent with the Hawthorne effect [28]), each of these attempts yielded demonstrable successes and a great degree of personal satisfaction. However, it is very personalized (one reviewer characterized it as interesting, but "idiosyncratic" and not everyone's cup of tea). Thus it is hoped that our experience might motivate others to make similar personalized attempts, which could eventual evolve into an acceptable structure.

With this aim in mind, I will present an outline of the organization that was used, indicating the reasons for presenting the concepts in this order, and describing a few of the examples that were used.

Following the recommendation of Taylor and coworkers, the presentation begins with the introduction of the concept of intrinsic "Action" and the many different aspects of this quantity that underlie the nature of the physical universe. This will involve the granularly discrete quantum nature of matter, it relation to quantum statistics, the role of the Boson field in the origin of interactions between particles to form atoms, the way that electrical interactions and Fermi statistics produce molecules, and ultimately all matter, the role of least action in the conservation of momentum and energy.

After this introduction, two additional sections are included. One shows that the classical Newtomian formulation in terms of instantaneous positions, speeds and accelerations (like a movie) can equivalently be replaced with a classical position probability density (dwell time, like a time exposure). Since the latter approach is used in quantum mechanics, use of the same approach in classical problems provides a smooth transition from classical to quantum. The last section shows how semiclassical quantization can be added to the position probability with a minimum of mathematics. Rather than involving a tedious solution of the Schrödinger differential equation, it involves an integral that can be evaluated numerically by simple application of the trapezoidal sum.

A short description will now be given of the course that we have developed and implemented.

7. Course Description

UNIT 1: PRELIMINARY CONSIDERATIONS

We begin with a general introduction that describes the scope and goals of the course, and contrasts its structure with that of traditional presentations. Rather than an inductive historical approach, a deductive approach is used that begins with a qualitative description of the physical universe as it is currently perceived. Initially, a layering of concepts is emphasized, defering problems and exercises until these foundations have been achieved.

- **General comments:** We begin with a description of the relative sizes of the macroscopic and the microscopic, and the ultimate atomic nature of all matter. This involves discussions of: the mechanism and electrical origin of the interactions between neutral atoms; the granularity and nearly vacuous constituency of all objects; and the ways that our senses give the illusion of continuous, hard, solid material. The reality of atoms is reinforced by pictures generated by scanning tunnelling microscopes, scanning transmission electron microscopes, magnetic resonance imaging, atomic force microscopes and bubble chamber tracks, and discussions of laser techniques such as optical tweezers and optical molasses.
- **Modelling:** Since conceptual models will be presented, it is important to establish the difference between results obtained by quantitative experimental measurements, and the narrative and pictorial descriptions that are used to make these results seem plausible. While the concepts are introduced through the use of stories and pictures, we emphasize that these are not to be taken literally, and must be subject to refinement or replacement as the knowledge base increases.
- **Basic principles:** The fallacy of Laplacian determinism is discussed in the context of the ultimate limitations on measurement accuracies, the interaction of the observer and the observed, and the (sometimes chaotic) effect of nonlinearities. Noether's theorem and the relationship between symmetries and conserved quantities is mentioned. The principle of least action is briefly introduced, as is optimization as a mathematical tool. The differences between microscopic quantum statistics and macroscopic classical statistics are also briefly sketched.
- **Measuring the large and small:** It is important to contrast at the outset the differences in the way macroscopic and microscopic objects have been studied. Since physics was initially formulated in the study of macroscopic objects, the methods relied on measurement of instantaneous positions, speeds, and accelerations. Having introduced the disturbing influence of the act of observation, it becomes clear that a planet can be bathed in light with little effect, but a single photon impinging on at atom can greatly modify its state. Thus, rather than taking a series of "snapshots" of the motion of a single planet, in atomic studies one must take a "time exposure" integrating the light from many identical atoms, each of which was modified by the light it emitted. An alternative approach to the instantaneous tracking (that is applicable to both macroscopic and microscopic objects) is a "dwell-time pattern" (or position probability density) that specifies where an object spends the most time and where it spends the least time.

UNIT 2: INTRINSIC ACTION

Because of its underlying role in so many aspects of classical and quantum mechanical physics, we begin by introducing the quantity action, and try to make its properties concrete rather than abstract. It is unfortunate that the name "action" has multiple irrelevant definitions, and that its SI units are derived rather than primary.

If we were truly able to reinvent physics, then a unit system based on action-length-time would provide many conceptual advantages over mks (with mass-energy measured in action/time and momentum measured in action/length). Action is made more meaningful when it used as a synonym for intrinsic spin, and when the number of quanta of action is related to the type of quantum statistics followed. (Clearly, if we were starting over, the quantum of action would be one-half Planck's constant, so that Fermions would possess an even number of units, and Bosons would possess an odd number).

Action is introduced through its possession of the following properties, which will be discussed in more detail in subsequent chapters:

- For purposes of this discussion, we ascribe special meanings to the words "intrinsic action" (spin, statistics, anomalous magnetic moment), and "mechanical action" (orbital angular momentum).
- Action is constructed of a basic unit that cannot be subdivided, of magnitude $\hbar/2$ (see comment above).
- Particles composed of an even number of intrinsic action units obey Bose-Einstein statistics (behave coherently, in cadence). Particles composed of an odd number of intrinsic action units obey Fermi-Dirac (behave incoherently and exclusively).
- The photon, which is the gauge baryon for electromagnetic interactions, possess two units of action $2(\hbar/2)$, which is called second quantization. (It should be noted that in the historical textbook examples, blackbody radiation and the photoelectric effect, the energy is continuously distributed. It is the action of the photon that is quantized.)
- If viewed in four dimensional space-time coordinates, the trajectory of a particle from one space-time point (x, y, z, t) to another (x', y', z', t') proceeds by the path that uses the least possible number of intrinsic action units (the least action principle). This can be motivated by animations of Fermat's principle analogue available on the Web. It is also useful at this point to discuss Noether's theorem [30] and the general basis for this approach.
- The least action principle also leads to the laws of conservation of energy and momentum (and, ultimately, is the origin of the force "culture").
- Action is a Lorentz invariant. While length, time, momentum, and energy are not, energy × time and momentum × length are relativistically invariant.
- The fact that the least action path is made up of an integer number of intrinsic action quanta leads to a minimum uncertainty of one of these units, and hence the canonical uncertainty between energy-time and momentum-length.
- The "mechanical action" (orbital angular momentum) is quantized in multiples of two units of $\hbar/2$). Even and odd multiples are associated with the "parity" or handedness of the atomic state.

UNIT 3: QUANTUM STATISTICS

The formulation of the Bose-Einstein and Fermi-Dirac statistics that govern indistinguishable particles, together with the connection between spin and statistics, provide insights into the statements concerning "wave-particle duality" that pervade elementary physics textbooks. With a knowledge of quantum statistics, duality is little more than a misleading historical artifact that could be replaced by a simple qualitative discussion of the connection between spin and statistics. This can be done by noting that all fundamental particles possess localized energy and momentum as well as intrinsic periodicities, and considering the following facts.

Particles that possess an even number of units of intrinsic action have symmetric wave functions and obey Bose-Einstein statistics. Ensembles of these particles exist in a common state with coherent phases, and "do the same thing at the same time." Thus their macroscopic behavior mimics their microscopic behavior, masking their individualities and revealing their periodic coherences. Words such as "fields" and "waves" were coined to describe this behavior before Bose-Einstein statistics were discovered.

Particles that possess an odd number of units of intrinsic action have antisymmetric wave function and obey Fermi-Dirac statistics. This precludes ensembles of such particles from "doing the same thing at the same time." They have incoherent phases and their macroscopic behavior differentiates their individualities and averages out their periodicities. The word "particles" was coined to describe this behavior before Fermi-Dirac statistics were discovered.

The examples cited in elementary textbooks as illustrative of one or the other of these "duality" aspects (ocean waves, sound waves, billiard balls, human beings, *etc.*) are themselves constructed granularly from atoms, but simultaneously possess (both individually and collectively) basic periodic frequency modes. Thus the dichotomy of duality may be more a conceptual impediment than a pedagogical tool, since it introduces a counter-experiential distinction for the express purpose of its subsequent refutation. If duality is considered an essential concept, then its practitioners should be encouraged to give examples of true particles (objects which contain no internal periodicities) and true waves (continua not comprised of atoms).

Another useful conceptual model provided by quantum statistics involves the "dressed electron." Electrons and positrons possess one unit of intrinsic action and obey Fermi-Dirac statistics. Quantum electrodynamics accounts for the electrical interactions among these Fermions through the exchange of virtual photons, which possess two units of intrinsic action 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 would behave like a neutrino. When the electrons and positrons (Fermi-Dirac statistics) are taken together with their absorbed and emitted virtual photons (Bose-Einstein statistics) the two together obey classical Maxwell-Boltzmann statistics.

A simple analogy can be obtained by considering coin flips [31]. 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 wave function 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 heads an one tails, here a certainty. This antisymmetric case is an analog 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), with the same property that the average of the Bose-Einstein and the Fermi-Dirac cases yield the Maxwell-Boltzmann case.

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

A simple intuitive model for the connection between spin and statistics has been presented [32]. Rather than framing the presentation in terms of an operator that exchanges the identities of two arbitrarily labelled particles, this picture utilizes coordinate rotation operators that accomplish the same task. The exchange of two identical particles with parallel spins can be achieved by a 180° rotation. Similarly, the exchange of two identical particles with antiparallel spins requires to perpendicular rotations of 180°. Since each such rotation introduces a minus sign, an even number of rotations produces symmetric wave functions, whereas an odd number of rotations produces antisymmetric wave functions. As a consequence of the connection between the generator of the space rotation and the spin angular momentum operator, the effects of the particle exchange are shown to depend on the even or odd integer characteristic of the particle spin (action).

UNIT 4: QUANTUM ELECTRODYNAMICS

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.

Rather than introducing the interaction by a sensually apparent but conceptually insubstantial and definitionally incorrect "action"-at-a-distance force, the attractive and repulsive interactions between of charged particles are described through the virtual photon field that pervades all of space. The charged fermions dressed with gauge bosons can be thought of as two aspects of a single entity (one with an exclusion principle, the other with a Bose condensation) which merge macroscopically to exhibit classical statistics). Going back to the big bang, when the virtual photon ensemble came to exist, then atoms, molecules, the waters, the firmament, *etc.*, all proceed naturally from their properties. This can be summarized by the statement "Let there be light - take the rest of the week off!"

The traditional "free body diagram" approach of Newtonian physics is temporarily avoided. While it has calculational value in the Newtonian illusion, it is in fundamental conflict with the current world view. QED makes clear that Mach's principle is valid: one cannot consider an isolated system. The mass renormalization of QED 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 affects, and the double counting of the total charge that is perceived as magnetism.

In this way, second quantization can be introduced *before* first quantization (as Einstein did in 1905). In a fortunate accident of nomenclature, second quantization involves a photon with *two* units of intrinsic action, and first quantization involves an electron with *one* unit of intrinsic action.

In order to begin to discuss the atomic fact, the properties of the atom must be introduces. The electron and proton are described to indicate the charge make-up of a neutral atom. It is emphasized that, despite other similarities, electrostatics is difference from gravitation interactions, where there is only one kind of "gravitational charge," and only attractive interactions. For the electromagnetic interactions have two different types of interactants (arbitrarily named plus and minus). In contrast to gravitation, likes have a repulsive interaction, unlikes charges have an attractive interaction. The positively charged protons are heavy and have lower mobility than the negatively charged electrons. The positive charge is concentrated in a very small region at the center of the atom, whereas the negative charge is widely distributed in the electron shells

UNIT 5: INTERACTIONS BETWEEN NEUTRAL ATOMS

The traditional introductory curriculum begins (in historical order) with gravitational interactions. While the inverse square analogy between Kepler's law and Coulomb's law is superficially appealing, differences between gravitation and the other types of interactions make it conceptually confining. For example, if we generalize the concept of "charge," then gravitational dynamics has only a single type of "charge," whereas electrodynamics has two types of "charge," and chromodynamics has three types of "charge." Thus atoms can be electric-charge-neutral with equal positives and negatives, and hadrons can be color-charge-neutral with three quarks.

The fact that there are no gravitationally "neutral" objects that interact by dipole moments conceals from students the ultimate electrical nature of all matter. Thus the gravitational model provides a misleading introduction to the atomic fact.

The van der Waals gas equation $(p - a/V^2)(V - b) = NkT$ provides a useful conceptual introduction to atomic and molecular interactions. Our discussion of Bose-Einstein statistics has already made plausible the b constant. When two atoms are squeezed together, their electrons cannot occupy the same space, so at least one must change its state. The cohesive portion can be motivated by simple discussion of the interactional dynamics of permanent, induced, and oscillating dipoles. The fact that physically differentiating a $1/r^2$ monopole field yields a $1/r^3$ dipole field can be demonstrated a variety of levels of sophistication, and the fact that $V^2 \propto r^6$ yields the desired result. The fact that multiplying out the binomial in the van der Waals equation yields a cubic equation can be used to describe gas, liquid, and condensation phases.

UNIT 6: LEAST ACTION AND CONSERVATION LAWS

A. Path between two space-time points - optimized (Fermat's principal animation)

B. Taylor's java animations.

C. Describe the "Force concept" as a separation of conservation of moment between one object and the rest of the universe.

Thirty-one years ago [1949], Dick Feynman told me about his "sum over histories" version of quantum mechanics. "The electron does anything it likes," he said. "It just goes in any direction at any speed, forward or backward in time, however it likes, and then you add up the amplitudes and it gives you the wave-function." I said to him, "You're crazy." But he wasn't. Freeman J. Dyson, 1983

UNIT 7: POSITION PROBABILITY DENSITIES

A significant distinction exists between the conceptual framework presented in traditional introductory physics courses and that used in the advanced physics courses that follow them. Introductory physics courses utilize historical Newtonian concepts involving forces and accelerations, but these concepts never enter in more advanced formulations. The introductory approach is often characterized as "classical" whereas that of the more advanced is described as "quantum mechanical." However, the primary difference between the two approaches arises not because of quantization, but instead from a nonessential heuristic tendency to describe macroscopic systems by instantaneous values for position, speed, and acceleration, and microscopic systems by time-averaged position probability densities.

The reasons for this are clear, since a macroscopic trajectory is disturbed only slightly when successively interrogated with visible light, whereas a microscopic system may 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 dichotomy produces a serious disconnect between physics as it is taught to non-major students in service courses and physics as it is practiced. Despite efforts to introduce modern topics into a Newtonian presentation, this can widen the gap between physics and society. As discussed earlier, respected authorities [17, 24] have urged that the force approach to the teaching of elementary physics be replaced. Unfortunately, the Newtonian model offers practical advantages, particularly in the testing and evaluation of student performance, that must be addressed in any revision.

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). When the classical problem is formulated in terms of position probability densities, three-dimensional elliptic orbits are automatically included. Moreover, deviations from a pure inverse square law can be included as perturbations, all in a purely classical framework. It is also possible to add semiclassical quantization directly to the classical solution when desired.

Included references to Curtis Haar Kummer paper: perturbations of the planets, etc. Cite all the references which were just position probability dentisities

UNIT 8 - EBK QUANTIZATION

The word "quantum" is still often used to describe the fact that photons are localized particles, each possessing quantifiable values for energy and momentum. This is not to be confused with the word "quantization," which refers to the fact that a condition for observation of a bound system requires that its "action" fulfills certain integer relationships with Planck's constant. The action integral is of the form

$$\text{Action} \equiv \oint p_i(q_i)dq_i \ . \tag{1}$$

While it is sometimes stated that the energy levels of a bound system are quantized, it is the action that is quantized in units of Planck's constant, and the discrete energy levels occur only as a secondary consequence of action quantization.

The postulation of quantized action was made in 1913 by Niels Bohr, in association with the theoretical specification of the discrete line spectrum of the hydrogen atom. He assumed

$$n_i\hbar = \frac{1}{2\pi}\oint p_(q_i)dq_i \tag{2}$$

Bohr treated the unrealizably special case of an exactly circular orbit, which allowed him to limit consideration to the azimuthal action integral. Arnold Sommerfeld and William Wilson later extended this treatment relativistically to include elliptic orbits. This formulation is known as the Bohr-Sommerfeld-Wilson (BSW) quantization. It quickly leads to results that conflict with experiment, and it is routinely dismissed in most modern physics textbooks. However the origin of these errors is not in the general approach, but in a simple mathematical mistake made in its application. If correctly formulated, this action quantization can be very useful, and provides many valuable results.

While the azimuthal quantization made be Bohr is proper, the zenith and radial quantizations are incorrect, as was shown by Einstein in 1917 [33]. In this paper, Einstein pointed out that the contour integral for the r and θ coordinates do not involve rotations, but rather librations, which oscillate between two turning points (caustics). In such cases the integral involves a contour over two Riemannian sheets, which leads to a phase jump at each turning point. The problem was subsequently studied by Léon Brillouin, Joseph B. Keller and Viktor Pavlovich Maslov, and the quantization can be correctly stated as

$$(n_i + \frac{\mu_i}{4})\hbar = \frac{1}{2\pi}\oint p_i(q_i)dq_i \quad . \tag{3}$$

Here μ is the Maslov index, which corresponds to the number of turning points. Thus μ= 0 for rotations, μ= 1 for motions with a single turning point (such as field emission from a cold cathode or the tip of a scanning tunnelling microscope), $\mu = 2$ for librations between two turning points, and μ=4 for an infinite square well (which has two turning points and two reflections).

This formalism is known as the Einstein-Brillouin-Keller quantization. It yields correct values for most of the standard problems of quantum mechanics, and has advantages over fully quantum mechanical treatments in a number of applications.

UNIT 9 - RELATIVITY AND THE MAGNETIC FIELD

The beauty and simplicity of the relativistic formulation can be seen from a pedagogic example. Consider a copper wire one millimeter in diameter through which a current of one ampere passes. Assuming one conduction electron per copper atom, this current corresponds to a drift speed of 1/10 millimeter per second. One of the results of special relativity is the fact that if two extended objects move 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 negative electron charge will appear slightly denser. This is a very small effect, but it is greatly enhanced as seen by a charge that moves with a significantly larger speed relative to the wire.

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

By simple algebra (and a binomial expansion of the relativistic square root) this model yields 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.

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