THE ROLE OF PHYSICS IN EDUCATION

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"Science is an adventure of the whole human race to learn to live in and perhaps to love the universe in which they are. To be a part of it is to understand, to understand oneself, to begin to feel that there is a capacity within man far beyond what he felt he had, of an infinite extension of human possibilities . . .

I propose that science be taught at whatever level, from the lowest to the highest, in the humanistic way. It should be taught with a certain historical understanding, with a certain philosophical understanding, with a social understanding and a human understanding in the sense of the biography, the nature of the people who made this construction, the triumphs, the trials, the tribulations."

I. I. Rabi

I. INTRODUCTION

The beginning of "modern" science, the science of Galileo and Newton, was physics. This unique blending of experiment and of synthesis, the introduction of mathematics as the cadence of the intimate joining of experiment and synthesis became a model for the development of all science. Experiment provided the clues, suggestions. Creative imagination, inspired guesses emerge from the synthesizers. Once upon a time, there was no division of labor between synthesis and experiment-but this changed as the skills of experiment and the skills of the theoretical physicists separated into distinct although overlapping qualities.

Physics addressed the whys of phenomena, in the beginning, mostly natural like the movement of planets and moons. This processed into simply constructed motions like the trajectory of a thrown object, falling bodies. Physics began the strict process of rigorous definitions and precisely stated laws, laws of motion, the law of gravity; concepts were precisely formulated, e.g. the concepts of energy and momentum, invented because they can each be represented by a number describing a system of any complication, going through whatever internal collisions, processes, but the number never changes. Obviously we tend to some chauvinism in taking full credit for the formulation of what philosophy professors call "the scientific method". The chemists provided the first proof of the existence of atoms and biologists gave the first proof of the law of conservation of energy.

The history of physics is an unfolding of the laws from their accurate accounting of a small domain of observations to bolder generalizations, which could account for a much larger domain. A prime example is Newtonian mechanics with its wide application to astronomical and terrestrial motions, the shapes of planets, its tides, and so many other phenomena.

The study of electricity and magnetism required new formulations -and as the phenomena became better known, the laws of Coulomb, Ampere, and Faraday were brilliantly assembled by Maxwell into a new synthesis, which initially lived very comfortably with Newtonian mechanics. Phenomena extending over a vast spectrum of wavelengths: from the long waves (many meters) of radio through the infra-red, the visible, the ultraviolet to microwaves and x-rays and gamma radiation of 10^{-15-} m and smaller: all electromagnetic. Meanwhile, other workers studied heat, thermodynamics, the properties of dilute gases and this inspired the quantitative use of the concepts of "atoms and molecules". A huge extension of the domain of physics followed the experimental demonstration of disturbing behaviors at the microscopic level. Quantum theory was one of the most extraordinary revolutions of the 20^{th} century. It extended the Newtonian domain to the structural units whose properties and interactions explained chemistry and biology.

Almost all of the phenomena of chemistry now found their explanation in the quantum physics of atoms. Physicists meaningfully translated the chemical statement: "Two elements combine to make a compound" into "two atoms combine to make a molecule". A huge piece of chemistry then had to do with structure of molecules; not only their chemical composition, but their 3-dimensional structure. Physics gave the basic Schrödinger equation and began the process of understanding molecular structures -a subject quickly taken up by computational chemistry aided by the use of huge "atom smashers" invented by physicists, but designed especially as powerful (synchrotron) x-ray sources to deduce molecular structures.

James Watson and Francis Crick both read Erwin Schrödinger's (one of the founders of Quantum Mechanics) 1945 book "What is Life" and this suggestive title set them on the historic course, the discovery of the double helix study of DNA and consequently, the radical change of modern biology to molecular biology.

Astrophysics and biophysics suggests the range of subjects in which physics provides the instruments and fundamental laws. Wherever subjects can supply information from which the types of atoms and their location can be ascertained, that is where physics can help.

A recent NRC report states: "Because all essential biological mechanisms ultimately depend upon physical interactions between molecules, physics lies at the heart of the most profound insights into biology."

Somewhat later in this lecture we will touch on a quality of laws of nature, which provides, perhaps, a clue to a profound unity of the sciences. The key word is symmetry. It will turn out that ideas of symmetry underlie the most fundamental laws of nature. Symmetry, in art and architecture, describes a harmony of proportions. This is applied in organic and inorganic processes, in relativity and quantum theory. We will show that much of this can be conveyed to students in high school and early college. Its omission seems to be inexcusable.

II. COHERENCE IN HIGH SCHOOL SCIENCE EDUCATION

US high schools (ages 14-18, pre-university) do not teach enough science. We are slowly increasing the minimum amount of science taught from one to three years. In many other countries, many more science courses are required with the necessary mathematics. However, if we now focus, not on future physicists, or even on future scientists, but on future citizens, then we find that the public science literacy, i.e. the level of understanding of science by the populations of many nations, developed and developing, is far from what a 21st century world requires.

This indicates that in much of the world, education to age ~18 does not produce science literate citizens who can participate in the decisions of their communities and nations in the vast potentialities of 21st century science and technology. These educated citizens can also participate in decisions as to which technologies are beneficial to the long term future of nations and which may have adverse effects.

There are many similarities in the educational problems of nations. For example, universally, primary school teachers are poorly trained in science and mathematics. This can be disastrous when primary school education is all there is, or even in industrial nations, where the attitudes of students towards science is shaped by the early years of schooling.

Another (almost) universal defect is the failure of school systems to recognize the natural hierarchy of science as a combination of interrelated core disciplines. One can imagine a pyramid (see Appendix, Figure 1), the base of which is mathematics, a pure invention of the human mind (but with its own rationale for existence) that provides the logical structure and the language of the other disciplines. This is followed by physics, which require mathematics as its language and provides the logical underpinning for other disciplines.

Next in the hierarchy is chemistry. The assertion that all laws of chemistry are logically supported by physics is defensible; examples abound. The periodic table lists the elements in a regular order that follows from the quantum structure of atoms and the exchange symmetry (i.e. the Pauli exclusion principle) provided by the laws of physics.

It may suffice to establish the physics-chemistry ordering in the pyramid by simply noting that all of chemistry depends upon the (quantum) structure of atoms and the resultant forces between atoms. In the case of complex systems and the laws that emerge from complexity, again the understanding involves reduction to atoms or molecules. Some examples are Brownian motion, the concept of temperature and pressure, solutions of salts, and electrochemistry. (However, it should also be noted that many principles of chemistry are not usefully reduced to underlying atomic and molecular properties.)

In a similar manner, biology would appear in the pyramid above chemistry, noting that modern, molecular-based biology is underpinned by physics and chemistry. James Watson's (1968/1980) book, *The Double Helix* details how powerfully these subjects entered into the discovery of the structure of DNA. Again, new laws of complex systems emerge out of the complexity but can (usefully or not) be reduced to basic properties of atoms and molecules.

What are the implications of all this for science education? The hierarchy of complexity emerging from simplicity should therefore be the guide for pedagogue. It calls for the exposure of students, at the earliest possible age, to study of the atom, the key to this revolution in science and technology. It would be useful for middle school students to have a reasonable sense of how small atoms are and some idea of the role of atoms in our understanding of the world. This information should also come to them through powerful out-of-school sources such as museums, science magazines, TV science programs, and newspapers that treat science.

Many school systems in Europe and Asia cycle through the core disciplines—for example, teaching a month of physics, then chemistry, and then biology. This is an improvement on the US system, in which about 50% of students study biology for one year, followed by a year of chemistry, and then (for only 20 %) a year of physics. In this proposed hierarchy, a full year of physics must precede chemistry to make use of the logical connections -that everything is made of atoms and that physics *is* the clarification of atomic structure subject to the principles of quantum physics. There is no basis for the pessimistic view that ninth graders cannot grasp such abstract ideas. Because it takes about a billion atoms to occupy a speck the size of the period at the end of this sentence, atoms are indeed an abstract concept. However, with computer simulation, imaging, and modeling, students can be exposed to the idea of atoms long before ninth grade. Ideas of combinations of atoms into molecules whose curious mechanics should replace and explain concepts of combining elements to make compounds. These can be modeled, and even the idea of forces binding atoms together can be qualitatively taught before ninth grade. Descriptive aspects of science should be presented in middle school, where students should also develop mathematical skills such as graphing (slopes and intercepts) and be introduced to algebra, data tables, and mathematical problem solving. By ninth grade, students should have learned enough algebra to begin the formal study of conceptual physics.

Key Elements of a 21st Century Approach to Science Literary

Again, there are many alternative approaches to a detailed, 3-year core curriculum. Here is a summary of the key elements in the present example of a 21st century approach to science literacy for **all** high school students:

- There must be a core sequence consisting of the three key disciplines, in the order of physics, chemistry, and biology. Mathematical applications should be continuous so that biology makes use of all the mathematics up to pre-college level.
- It is essential that there be excellent laboratory work that is closely synchronized with the course work. Here we stress that a key to successful laboratory work is “inquiry” rather than the traditional “cook book” method.
- Each discipline should spend 20 % to 30 % of the course year on process, including selected pieces of history, applications to societal problems, and the social, political and economic issues that entwine science and society. The importance of this recommendation cannot be exaggerated. The stories associated with the core disciplines will be remembered long after $E = mc^2$ is forgotten. The stories embedded in the content will help to create a “science way of thinking”.
- Teachers should have ample time to conference with each other. This is professional development in the best sense. If the nations are serious about the importance of science education, they must support the bold idea that teachers can profitably use one day a week of course time which may include tutorials on line or visiting scientists from local universities. The conversations referred to may be regular weekly meetings of the physics, chemistry, biology, and math teachers. The connections between disciplines should be celebrated by many examples.
- A crucial point is that the impact of atoms, atomic structure, and molecule formation be taught early so that students enter chemistry with a fair command of atomic properties. Ideally, the science, math, and computer learning curricula in primary and middle school should be reviewed to ensure a match with this dramatically new high school sequence.
- Students can be encouraged to select science electives in, say, the third and fourth years after the core P-C-B curriculum. Advanced Placement or honors physics would be especially profitable, as would a course in earth science, which would make use of the students’ knowledge of the core disciplines. Of course, many important subjects are not mentioned here that can be inserted into the core curriculum, offered as electives, or even scheduled as a required fourth year. One is astronomy; another is statistical theory, prediction, and probability. The detailed folding in of computers and educational technologies is also missing from this sample curriculum, but these are important as well.
- As teacher interactions become a serious component of life in high school, one can imagine inviting in the history teacher and the art and literature teacher to these meetings. Discussions could lead to projects, seminars that would illuminate the fundamental unity of knowledge. We would then be truly educating our young students for all possible futures.

III. TEACHING CONCEPTUAL PHYSICS

In the proposed "logical sequence" of introductory courses, we are strongly advocating that the first introduction to a full year study of a discipline be physics, followed by chemistry and then followed by (mostly) molecular-based biology. We expect that high schools would require these core curricula courses for all students, accompanied by mathematics through at least pre-calculus, with many students taking calculus. However, high schools should offer elective courses and, in a truly 21st century school, another full year of science should eventually be required. An ideal candidate for a fourth year requirement is earth science (Geology), which offers the advantage of making use of all three core disciplines. Environmental science is another excellent integrated science that will teach the student the full power of the combination of disciplines. Elective courses would generally include astronomy, a second and more advanced year of physics, chemistry and biology. Often these would serve as examples of university-level instruction.

The difficulty in the physics, chemistry and biology sequence is that ninth grade (age 14-15) students do not yet have the mathematics that usually accompanies physics taken by older students in 11th or 12th grade. Thus the course must emphasize the grasp of concepts. The instructor must be aware of the level of algebra that his students are comfortable with and this implies the ability of the mathematics and physics teachers to communicate with one another on a regular basis.

The pioneer in the US on this kind of physics is Paul Hewitt, who originally devised this type of course for students who were considered mathematically limited. However, as the new sequence of "physics first" started to evolve in the US, Hewitt's approach was modified as were several other efforts at engaging students in the concepts of physics, its powers and processes, but with a dilution of the requirement for any more than an introductory course in algebra. One approach (ACTIVE PHYSICS, Eisenkraft) concentrated on the applications of physics to the immediate interests of these young students, e.g. sports, the kitchen, etc. Another (Concepts in Physics, Hobson) emphasized the modern physics ideas of quantum theory and relativity.

We are now converging on a course which must do several things:

1) Give the student a clear impression of the respective roles of experiment and theory.

2) In spite of the small amount of mathematics, students should be able to appreciate the incisiveness of a mathematical statement, its power to predict the future of a simple system (e.g. a ball rolling on a smooth level surface) and eventually, the value of mathematics in its role of "the language of science". Motivations like these must improve the learning of mathematics.

3) The student should learn some of the history of physics, its heroes and heroines, what kind of characters created the concepts, e.g. Galileo, Newton, Maxwell, Einstein, Feynman..., how physics builds on prior knowledge and how great advances come about. Included here are something of the moral dilemma's which faced physicists (also chemists and biologists in the next courses) as citizens of their nations in contrast to their responsibilities towards the entire world out of which emerged the heritage to which each physicist is beholden.

4) Finally, the concepts enter. It is not often that high school physics instructors can clearly distinguish concepts from facts or parts of a physical system. For example, consider this list: coal, oil, wood, molecule, energy, waterfall, and battery. Which word doesn't fit? It is surprising how many get it wrong. Of course "energy" doesn't fit, it is a concept, invented (discovered?) by physicists in order to simplify the understanding of processes. All the other words describe objects that exist even without physicists. The awesome power of the energy concept is derived from the Law of Conservation of Energy, which tells us that if we precisely define energy in various systems, e.g. kinetic energy, potential energy, electrical energy, nuclear energy, etc., then in a complicated device in which balls are flying around, springs are compressed and released, wheels are turning every which way, Bunsen burners are lit, etc., etc., there is one number, the total energy, which stays constant forever!

Other concepts such as momentum, velocity, force, acceleration, angular momentum, temperature and pressure, are also inventions out of the minds of physicists, not only to torture students, but also to enable the understanding of physical systems. It is out of the skillful use of these and other concepts that we can understand the pendulum clock (and design better clocks), the trajectory of a thrown object, the motion of vehicles, of ocean waves, of continents, the flight of artificial satellites, the motion of planets, stars and galaxies, the microstructure of matter, radioactivity, the production of radio waves, light from the sun and from other sources, the flow of electrons in wires, conductivity, the processes involving heat flow, etc., etc. In short, all of the devices that support our post-industrial societies and which, together with the expressions of human feelings and aspirations, define our civilization.

The teaching of conceptual physics is much more difficult than a senior high school (age 17-18) physics course, even one requiring calculus. Instructors cannot "hide" behind the algebra but must emphasize the need for clarity in definition and the grasp of the concepts as they are introduced. The instructors must find sources (e.g. G. Holton's recent reissue of his Project Physics textbook) for the process of how physics works the telling of stories and, very important, the instructor must choose his topics so that Conceptual Physics becomes a prerequisite for chemistry. This requires more communication between the instructors. The key to a smooth transition to chemistry is atomic structure: the forces between charged particles, circular motion, energy states and the teaching of that curious behavior of atoms: quanta with discrete energy states, shell structure, the concept of angular momentum but now quantized, e.g. spin. Here, we expect that the students' knowledge of atomic physics will be enriched by the chemistry instructor who can review these concepts (most high school chemistry books compress a year's worth of physics into their first few chapters).

In fact, the beauty of the physics, chemistry and biology sequence is just this use of physics in chemistry and of chemistry and physics in biology. However, the student in chemistry and then biology is more advanced mathematically and so concepts are now revised to reflect this mathematics.

In all of this, we emphasize that our design is for all students so that the science way of thinking penetrates into their minds and plays a role in decisions that these future citizens must make as participants in democratic society.

IV. WHAT IS SYMMETRY?

Much of science and mathematics has to do with understanding how change occurs in nature and in social and technological systems. Much of our technology has to do with creating and controlling change. Constancy, often in the midst of change, is also the subject of intense study in science.

The simplest account that can be given about a system is that it does not change. Because scientists are always looking for the simplest possible accounts, they are always interested, fascinated by any aspect of a system (thing) that doesn't change even when many other aspects of the system do change.

Such are the conservation laws of energy, mass, electric charge, momentum or angular momentum. Just imagine a large number of molecules (or steel bee bees) moving rapidly, colliding elastically with one another and with the walls of a container and the assertion: the total momentum of this array of particles ($\vec{p} = \sum \vec{p}_i$, a vector sum!) remains constant through time! A simpler example is an explosion of a steel sphere, which is designed to fragment into hundreds or thousands of pieces. Since the sphere and its explosives were initially at rest, the total momentum $\sum \vec{p}_i$ starts out at zero and therefore remains at zero as the fragments fly out in all directions. This remarkable simplicity may seem to be difficult to verify, yet all physicists will agree that it is a correct statement.

Symmetry is the operative concept of these "quantities that remain constant", the 4-syllable word is "invariance", e.g. the total momentum of a group of particles is invariant (does not change) with respect to time.

Often the symmetry refers to a pattern whose appearance does not change when we rotate (or translate), reflect (as in a mirror), or stretch in all dimensions.

A more abstract form of symmetry is when we compare different classes of particles as in this sentence: the properties of a particle, e.g. mass, lifetime, quantity of electric charge, and spin -do not change (are invariant) when we change the sign of the electric charge (i.e. change particle to antiparticle).

Symmetry is a crucial concept in mathematics, chemistry, and biology. Its definition is also applicable to art, music, architecture and the innumerable patterns designed by nature, in both animate and inanimate forms. In modern physics, however, symmetry may be the most crucial concept of all. Fundamental symmetry principles dictate the basic laws of physics, control structure of matter, and define the fundamental forces in nature. Some of the most famous mathematicians and physicists had this to say about symmetry:

> *"I aim at two things: On the one hand to clarify, step by step, the philosophic-mathematical significance of the idea of symmetry and, on the other, to display the great variety of applications of symmetry in the arts, in inorganic and organic nature."*
>
> Hermann Weyl (in his book "Symmetry")

> *"Special relativity emphasizes, in fact is built on, Lorentz symmetry or Lorentz invariance, which is one of the most crucial concepts in 20th Century Physics."*
>
> C. N. Yang (Nobel Laureate in Physics)

> *"Look at the symmetry of the laws, i.e., look at the way the laws can be transformed, and leave their form unchanged...."* and, *"Symmetry is fascinating to the human mind;*

everyone likes objects of patterns that are in some way symmetrical.... but we are most interested in the symmetries that exist in the basic laws themselves."

Richard P. Feynman (Nobel Laureate in Physics; in his "Lectures on Physics")

"I heave the basketball; I know it sails in a parabola, exhibiting perfect symmetry, which is interrupted by the basket. Its funny, but it is always interrupted by the basket."

Michael Jordan (former Chicago Bull)

The most powerful microscopes humans have built are the great particle accelerators, such as the Tevatron at Fermilab, in Batavia, Illinois. The Tevatron accelerates protons and antiprotons in opposite directions in a great circle, to energies of one trillion electron volts (as though you had a one trillion volt battery hooked up to a vacuum tube). These particles then collide head-on. The quarks and anti-quarks, inside of the protons and anti-protons, themselves collide. By reconstructing the debris from a collision of this kind physicists get a kind-of "photograph" of the structure of matter at the shortest distance scales ever seen, distances as small in comparison to Michael Jordan' s basketball, as the basketball is small in comparison to the radius of the orbit of Pluto.

By studying physics at these tiny distance scales we can see that the forces of nature begin to share a common property, which is unseen at lower "magnification," at the larger distant scales. Today we understand that all of the fundamental forces in nature are unified, in a sense, by one elegant symmetry principle. This principle is subtle, and therefore it has a fancy name: it is called ``local gauge invariance." Later on we' ll try to explain it to you, but for now please accept this as a statement of fact.

The discovery of this unifying symmetry principle has allowed us to leap conceptually to distance scales one thousand trillion times smaller than can be seen with our most powerful particle accelerators. This has allowed us to conceive of what the Universe was like in the first one billionth of one billionth of one billionth of one billionth of a second! At such short distances quantum gravity is active and rejects our normal notions of space and time. There we must use the symmetry principles (and related topological ideas) to imagine theoretically the complete unification of all forces. This leads to new ideas, to something called the "superstring' ' and an arcane mathematical system called M-theory that no one yet understands (we really don' t even know what "M" stands for). Nevertheless, this is, perhaps, the most symmetry-pregnant logical system ever conceived by the human mind.

Preface from a book on Symmetry
by C. Hill and L. M. Lederman

The purpose of this book is to provide a modern perspective on the subject of physics, the basic science of the laws and principles of space, time, and matter. This is intended for use in an introductory high school or college level physics course. It does not replace the standard course material, but rather, supplements it. This is also intended to be informative and entertaining for the beginner or interested reader who, at any stage of life, may seek a deeper understanding of what humans know about the physical world around and within us.

It is not possible to omit the climbing of the traditional ladder if one's goal is the mastery of the subject of physics. Physics is a very vertical subject. Every physicist must learn what $\vec{F} = m\vec{a}$ means, and how to use it. This requires the natural language of physics, which is mathematics, and we all know that Differential and Integral Calculus was invented by physicists! Every physicist must know that energy and momentum are conserved; that these are fundamental conservation laws that come from the basic defining principles of physics. Yet, remarkably, not every physicist knows that these conservation laws and even the fundamental dynamical principles of physics all come from something much deeper… fundamental symmetries of the basic structure of space, time, and matter.

The remarkable connection between the dynamics, i.e., the conservation laws and the forces of nature, etc., and symmetry, is a modern concept that was invented in the 20^{th} century. It begins with the philosophical approach that Einstein brought with his reasoning about nature, but it is most evidenced in the discovery of "Noether's Theorem", which intertwines dynamics together with symmetry. When viewed from this perspective, the subject of physics leaps well into the modern era.

We believe that fundamental ideas about the connection of symmetry to physics are not far removed from the beginning student. It seems to us patently obvious that the best way to make physics as interesting and relevant to beginning students as it truly should be, is to introduce some of he ideas of symmetry principles as early as possible. This should be done with the rest of the curriculum. Basic mathematical ideas about symmetry, e.g., "group theory", can also be introduced into the high school math curriculum, perhaps with an example clearly and completely worked out such as the symmetry of the equilateral triangle. Many examples can then be given of the interplay of symmetry with physics, either in little self-contained problems or in discussing the large framework of conservation laws and the basic forces in nature.

So why doesn't Johnnie know Symmetry? The crucial role of symmetry in physics seems to us to be at odds with the practice of the complete omission of this subject in the teaching of beginning students, not only in the high school curriculum, but in the standard first year college calculus-based physics course. Symmetry does not appear in the US Standards. The absence of symmetry discourse in our teaching of physics represents a throwback to a purely nineteenth century perspective, which seems to permeate the curriculum.

Now, students are always attracted to the modern and "sexy", highly visible end-products of modern physics, e.g., semiconductors, lasers, nuclear and atomic processes, superconductors, superfluids, the formation of galaxies and black holes, the Big Bang, quarks and strings. The process of really learning about these things takes some six to eight years of undergraduate and graduate physics courses. Only then, if the student chooses a very abstract field of specialization, such as theoretical physics, will she begin to see the fundamental role of symmetry emerging in the basic laws of physics. Indeed, even today many practicing physicists have no idea about the concept of, e.g., gauge invariance, which is the basic symmetry principle underlying all known forces in nature!

It is possible, nonetheless, to incorporate elements of these underlying ideas of symmetry and its relationship to nature into the beginning courses in physics and mathematics, at the high school and early college level. They really are not that difficult. When the elementary courses are spiced with these ideas, they begin to take on some of the dimensions of a humanities or fine arts study: *Symmetry is one of the most beautiful concepts, and its expression in nature is perhaps the most stunning aspect of our physical world.* We believe that symmetry will prove to be a vehicle for stimulating and maintaining the student's interest in physics at the outset and a connection to the deeper aspects of the physical world. We have time only to present a few examples.

Application of Symmetry: Space and Time

The operation we chose first to test an aspect of the space provided to us by our universe is to move a laboratory along, say, the x-axis by a number of units, e.g., N meters. This is a space translation say from position A to position B, and the question we ask is: do the experiments performed in the laboratory at position A give results which are, in any sense, different from experiments performed when the laboratory is at position B? One might perhaps expect that the amount of motion, N meters would appear in the results of some measurements at B compared to A. But in fact, we find that there is no effect of the translation, the results of all experiments at A and B are identical. The distance N cancels. Generalizing: the laws of physics are invariant to a translation in space. All points in space are equivalent.

Translations in time give a similar result. The laws of nature are invariant to the absolute time at which these laws are tested.

Rotations of the laboratory in space are another test of a symmetry of space. Thinking of a satellite (so as not to be influenced by our awareness of gravity) way out in free space, its orientation does not influence the experiments carried out in the satellite.

We could apply this to a laboratory on the surface of the earth, but then the rotation would have to include the earth as part of the laboratory. The conclusion then is: The laws of physics are invariant to translation and to rotations in space and to translations in time.

Now we introduce the mathematical physicist Emmy Noether, who in 1913, proved a spectacularly important theorem: for every symmetry there exists a corresponding conservation law. This is not easy to prove, but the consequences can be easily stated.

- The symmetry of space translations corresponds to the law of conservation of momentum.
- The symmetry of space relative to rotations corresponds to the law of conservation of angular momentum.
- The symmetry with respect to time corresponds to the conservation of energy.

Thus, these well confirmed conservation laws teach us about the structure of space and time. These are three examples of continuous symmetry principles. Continuous because the transformations of displacement in space can be any displacement from a nanometer to a light year; the transformations in time can be any amount of time and the space rotations can be any number of degrees about any axis. There are some important discrete symmetries. I will list, without much discussion, the three important ones that emerge from the quantum theory.

1. **Mirror Symmetry**: The transformation is reflection in a mirror. The invariance is the statement that everything seen in a mirror corresponds to a real physical system. One way of stating this reflection symmetry is that all experiments and laws of nature derived from these experiments hold true in the mirror world. The official name for this symmetry is "parity" with symbol "P". To illustrate briefly, if one turns a screw with a screwdriver into a block of wood, the clockwise rotation of the screw advances it deeper into the wood. This is, by convention, called a "right handed screw" (There is a right hand rule in which the thumb points towards the advance of the screw and the fingers naturally curl to indicate clockwise rotation of the screws). But the mirror image of this profound activity indicates a counterclockwise rotation of the mirror screw as it advances into the mirror block of wood. Does this violate a law of nature? No, because the screws in our shop are, by

convention, right handed. However, it is easy to ask the shop to make left handed screws. Such screws exist. No problem! For those of you that are more mathematical, if we have a coordinate system with the z axis pointing to the mirror (the mirror is in an xy plane), the reflection transformation is simply replacing all z values in the laws of physics by –z. We would then state it in grown-up language as the laws of physics are invariant to replacing z everywhere it appears in the equations of physics by –z. In the Noether theorem, it is called the Law of Conservation of Parity.

2. **Another discrete symmetry is the direction in the flow of time: past to future**. So, the laws of physics are invariant to a change such that t (time) is everywhere replaced by –t. Many readers would here bridle and object because the experience is that we get older, hair turns gray, a dropped and hence smashed egg rarely puts itself together and jumps up whole, into the hands of the cook. However, the law finds its validity in microscopic physics where, say, two particles collide and perhaps change their states so that A + BΠC + D. In "normal time" A collides with B, and C and D go off in opposite directions at some angle with respect to the AB line. "T" or time reversal ($t' \rightarrow -t$) invariance says that C + D coming in towards each other (along the previous CD line) will always produce A + B going out.

The examples out of our experience cited above are derived from complex systems and their origins and their relation to T invariance is outside the scope of this discussion.

3. The final discrete symmetry here is a new twist, not related to space and time, but to electric charge. It says: the laws of physics are invariant to a change in the sign of electric charge, i.e. electron → positron. However, it is more general and the better statement is: the laws of physics are invariant to changing matter to antimatter. Its fancy name is "charge conjugation" and the symbol "C". A mythical world composed of anti-people does not obey the same laws of physics.

In summary, out of a plethora of symmetries, we have described six: three "classical" symmetries and three discrete (quantum) symmetries, P, T, and C. We have omitted many important ones, one of which, as we said, merely establishes the theory of relativity and has, as a consequence, the mysterious equation $E = mc^2$. We will close with two important statements.

1) The classical symmetries, to the best of our current knowledge, are always true symmetries in the sense of our definition. The P, C, and T symmetries turn out to be imperfect in the sense that for certain types of quantum processes, they fail! The laws of nature, for certain forces of nature, are **not** invariant to the processes of P (mirror reflection), T (time reversal), and C (matter -anti-matter interchange). The study of this failure is one of the hottest subjects in modern physics.

2) There is a symmetry that is crucial to the understanding of chemistry in the famous chart: The Periodic Table of the Elements. It is called exchange symmetry. Two identical particles, say, electrons, or hydrogen atoms, are so really identical that if we interchange the two particles, the system looks exactly the same (definition of symmetry). We have published the implications of this in *The Science Teacher* (February 2001, page 33). It is nothing less than the "Pauli Exclusion Principle" which guides the structure of the chemical elements!

These examples are designed to give you a glimpse of the importance and the power of the concept of symmetry.

APPENDIX

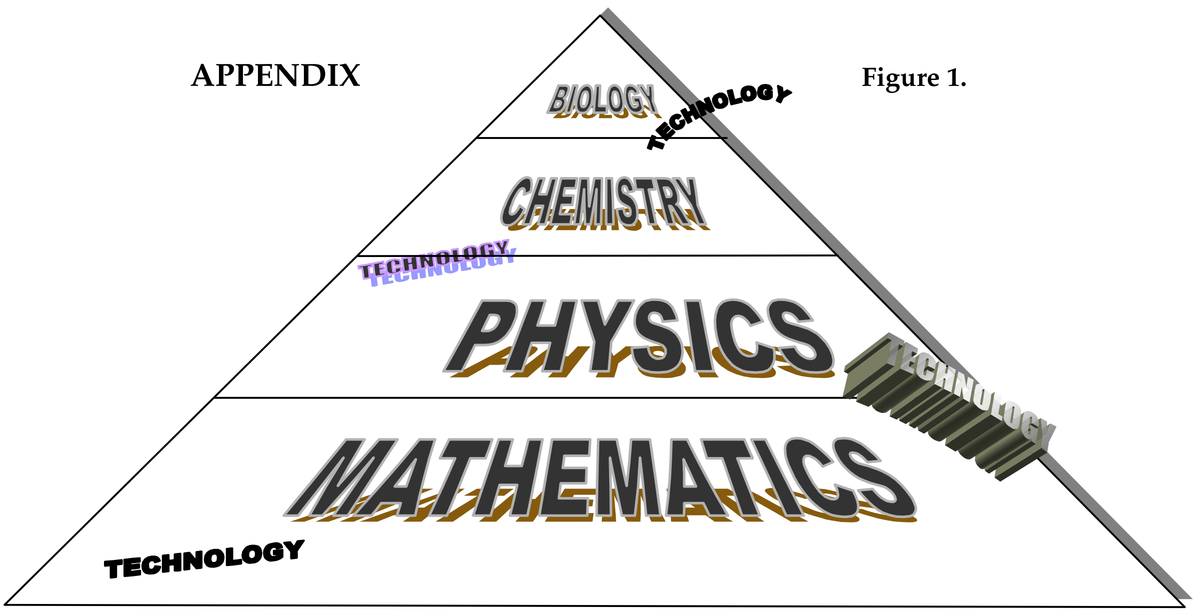

Figure 1.