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Some Trends in College Physics and Their Reflections on High School Physics

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This paper was presented at the Iowa Science Teachers' Association, Physics Section, at Des Moines, October 21, 1966.

We are much struck with the desirable results that follow from introducing brief discussions of modern physics topics during the course of ordinary, relatively routine first courses in physics for college freshmen and sophomores. We propose in this paper that teachers of secondary physics courses might well also consider the incorporation of such discussions into their courses.

We claim that generally one can achieve considerable effects by spending only a few minutes of a class period at this, though some topics would require more time for their discussion. In either case, some of the advantages are:

(1) These topics represent physics as it *is* today.

(2) They tend to motivate students by showing use of classical ideas in more exciting modern contexts or by showing the breakdown of classical ideas.

(3) They tend to cause students to look more critically at classical ideas, and to take them less as rigidly and certainly established.

(4) Sometimes students are led to investigate these topics more on their own, and so to extend their areas of awareness.

In the following we attempt to be concrete, rather than philosophical, by showing in some detail how a few selected topics can be dealt with. We also append a suggested list of other topics by title only.

Early in a course in physics, a student ought to realize the kinds of physical theory which exist and something of their interrelations and limitations. For example, Newtonian mechanics is usually the first branch of physics studied, and both overt and subtle effects ought to follow if a student realizes that it is applicable only in a certain domain, and is actually a limiting case of a larger, more general theory.

In a few minutes time, one could draw on a blackboard the chart shown in Figure 1.

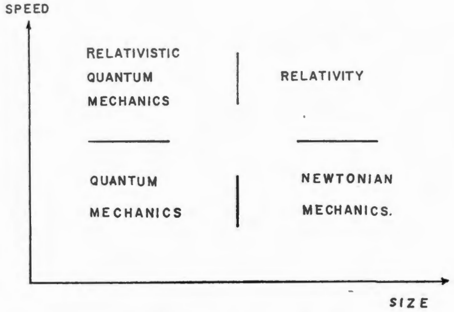

Figure 1. Relationships of the various physical theories to the speed and size of objects.

Among the things to be gained by such a brief discussion are that the student learns at the outset that Newtonian mechanics is a limited theory, and not a cornerstone of a fixed kind of theory, that he at least learns that there is a radically different kind of theory called Quantum Theory and something about when it is important, and that neither relativity nor quantum mechanics is complete, codified, and settled.

Students seem to find it exciting that theories are only tentative, incomplete, and subject to modification. Newtonian mechanics seen in the more general realm of discourse looks better.

At many points in mechanics, one can take a few minutes to say something about how the particular topic being discussed looks in relativistic theory. An example is the second law $F = ma$. Point out that this apparently axiomatically true law, which students tend to swallow whole, is not really true. This might be the thing which would cause the student to consider much more critically all the rest of Newtonian mechanics. It might even lead him to buy a paperback book on relativity theory, and to read it.

Many books still say that mass is a measure of quantity of matter, though good ones point out that this is not really an acceptable definition. One then has an ideal reason for discussing $E = mc^2$ briefly, and then explaining how masses may change. It would not take long even to write out the masses for a set of protons and neutrons, and then to show that the mass of these particles when combined into a nucleus is less than the original total mass.

As soon as the idea of force is introduced, it seems desirable to state exactly what forces exist in nature. There are these: electric, magnetic, strong nuclear, weak nuclear, and gravitational forces. Their relative strengths should be realized.

The fundamental puzzle about why these forces and these only exist is enticing. Also, a student can be led easily (by merely mentioning that the problem exists) to turn his thoughts to the true natures of some forces which his book mentions, but which are not in the list. Such a force is the frictional force. Another is air drag. Another is the force by which a table supports an object.

At the forefront of physics today, one is left with little that is reliable to cling to. Forces and potential energy functions begin to fail one. The weak nuclear force is not understood at all, and the strong nuclear force simply cannot be represented or thought of in a way which compares with the way in which one deals with, say, the gravitational force.

Instead, conservation laws come to the fore. We suggest that when the first classical conservation law comes up in class, that one could well devote a little time to discussing the current basic importance of conservation laws. It might be desirable to list the conservation laws currently known. If an instructor thinks the effort is really worthwhile, then he could well go on to point out relations between symmetries and the conservation laws.

Again, the removal of the idea of physical ideas as being set for all time in the eighteenth or nineteenth centuries, and the insertion of the idea that we have at best an approximate and tentative notion of how the universe hangs together, is important. A student might actually begin to think that he could help mankind learn more, since so little is really settled . . . the door is open to all.

Fundamental Particles

So much of the subject of physics in this mid-twentieth century era is bound up with the mysteries of the so-called fundamental particles, that students should at the very least have an idea of what particles exist, what their leading properties are, and why the questions concerning them are of transcendent importance. A secondary-school course may incorporate these matters in its latter stages, but we suggest that there is advantage in opening up the subject very early in a course. Whenever in the course the structure of matter arises as a topic, as it so frequently does, one can make use of a prior introduction of a list of the fundamental particles. This would tend to give the entire course a much more modern flavor, and to provoke real interest. It would make it possible for a student to read or at least to examine some of the literature more easily—*Scientific American* articles, for example.

As a concrete suggestion, we mention that straightforward collision problems could be made to seem more exciting by having them deal with interactions between neutrons or other particles. Again, centripetal force applied to the simple hydrogen atom would be a welcome addition to rocks being spun at the ends of strings, as has been the study of simple questions about satellite motions. When the subject of electricity is entered upon, hosts of occasions for referring to fundamental particles arise. What would happen if one replaced the proton and electron in a hydrogen atom by a positron and an electron, respectively? By a proton and a negative or meson? Would a pi meson behave according to the principles which explain why an electron can move in a circular path in a uniform magnetic field?

Of the many particular topics in solid state physics which could be used, let me select electrical conduction and discuss how it might be presented to secondary physics students.

Certainly in a development such as this, I make use of concepts that most secondary students have not encountered. Part of the point of this discussion is to convince you that these concepts should be part of a secondary course. After all, these concepts are part of our most basic understanding of nature.

For an electron, moving in the metal lattice, the dominate characteristics will, of course, be of the de Broglie wavelength, = h/p, where h = Planck's constant and p = momentum of the electron. So if we consider what will happen in a periodic lattice, we see that the electron will act very much like a wave traveling through a periodic lattice (X-ray through a crystal for instance). The 8 mm cartridge film gives students a quick and reliable picture of what happens.

Ask the students to note that:

1) a wave is generally reflected,
2) wave is transmitted when wavelength has proper relationship to the crystal lattice dimension and the angle.

Then an interpretation in terms of electron motion in periodic lattice might point out that:

1) in a perfect crystal, an electron would generally not be transmitted and
2) electrons with particular moments, $p = h/$, where the wavelength satisfied the Bragg condition would be transmitted.

The significance in this is that in a perfect lattice, an electron of the proper momenta (and consequently of the proper energy) would be transmitted without resistance. But every student knows that electrons do experience resistance, so an explanation is in order and even your student might quickly spot that the copper wire is not a perfect crystal lattice. You might suggest their looking at it this way. If you consider a more realistic picture of the lattice, it would be composed of many separate crystals joined along their surfaces.

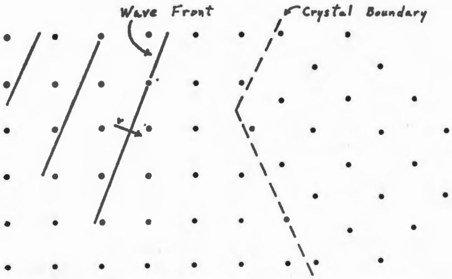

Figure 2. Transmission of electrons in an irregular crystal.

Then based on the ripple tank model, what would they expect to happen to a wave propagating through the crystal on the left (Fig. 2) in the direction indicated? The answer at which they should arrive is, of course, that the wave will probably not satisfy the Bragg condition for the crystal on the right (Fig. 2) and, consequently, will be reflected (or scattered) off of the crystal. In the scattering events, the electron would generally give up some energy to the lattice and this repeated scattering is the phenomena of resistance (the scattering centers are not completely fixed so some motion will result and consequently energy will be transferred).

Going back to the interpretation of the film loop, we can get still more mileage from this simple idea of electron motion through a crystal. The permitted wavelengths, you will recall, were fractional multiples of the fundamental wavelength and the wavelengths were related to the momentum by $= h/p$ or $= h/mv$, where m = mass of the electron and v = velocity of the electron. So then the permitted wavelengths determine a set of permitted energies (Fig. 3).

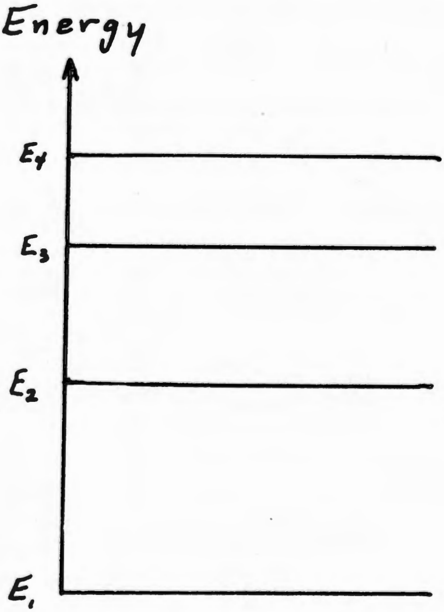

Figure 3. Permitted energies of transmitted waves E_1, E_2, E_3—.

Then point out that this suggests the band structure of solids which is important in the explanation of semiconductor phenomena.

This simple model doesn't say anything about the width of the bands. If you wish to pursue this with your class. you might argue that in a crystal the energy levels have widths by pointing out that for an isolated atom, we expect exact energy levels, but for two closely spaced atoms the exclusion principle (Paulie exclusion principle) prohibits the energy levels having exactly the same value, so two very closely spaced levels appear (Fig. 4). Then it follows that when the order of 10^{22} atoms are put together in a crystal there are the order of 10^{22} very closely spaced levels and these form an energy band with, as with any electron energy levels, two electrons permitted per level.

Carrying this description even further, you could give a quite accurate distinction between insulators and conductors based on the level to which the energy bands are filled by available electrons (Fig. 5).

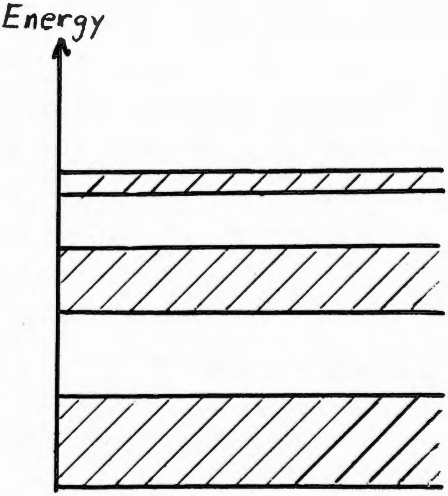

Figure 4. Energy bands that may be occupied by electrons.

Then by considering the energy required to move an electron from a filled level to a vacant (or conduction) level, it will be obvious that this model properly describes the low resistance of conductors and the high resistance of insulators. The description of semiconductors, of course, fol-

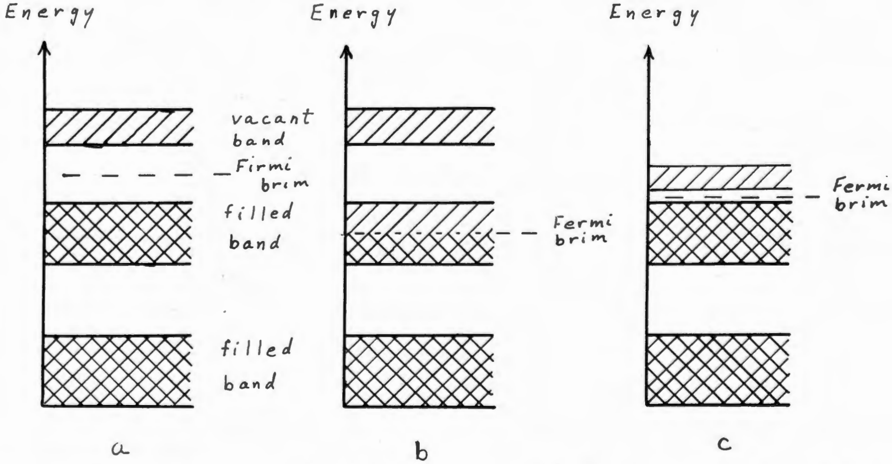

Figure 5. Energy Spectra for (a) Insulators, (b) Conductors and (c) Semiconductors

lows directly by making the energy gap (from filled level to vacant band) less than for an insulator, but still not a conductor (Fig. 5).

This could easily be followed by a discussion of the distinction between intrinsic and doped semiconductors and then a discussion of semiconductor diodes and transistors.

Other topics reflecting a more current point of view could be developed in areas such as: 1) specific heats, 2) emission of electrons from metals, 3) magnetism, and 4) elementary particles, to list a few.

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