Phys. Educ. 29 (1994). Printed in the UK

Providing a contextual base and a theoretical structure to guide the teaching of high school physics

A Stinner

The teaching of high school physics should not only be grounded in motivating contextual activities but also connected to a philosophically and historically valid theoretical structure, namely the *contexts of inquiry*, that guides the organization and the presentation of concepts.

It is a truism that appropriately designed contexts which attract students' interests often create great motivation to learn science. This truism is backed up by strong evidence that we must connect cognitive activity to context, that learning methods imbedded in context are not merely useful, they are essential (Roth and Roychoudhury 1993). However, setting appropriate contexts may only be a necessary prerequisite for successful science (physics) teaching. We must also ensure that a philosophically and historically valid theoretical structure is connected to the context.

The large context problem (LCP) approach was originally developed in response to the commonplace discovery that learning in physics could be well motivated by a context with one unifying central idea capable of capturing the imagination of the students. LCPs are contextual settings that generate questions and problems that seem inherently more interesting than similar problems presented in textbooks. Examples of LCPs are: Physics and the Bionic Man (1978, 1980), A Solar House for Northern Latitudes (1978), The Physics of Star Trek (1981) and Physics and the Dambusters (1989).

Arthur Stinner is Associate Professor of Science Education, specializing in physics, at the University of Manitoba, Winnipeg, Canada. He taught high school physics for 20 years before moving to the university, and he has published extensively in journals of physics and science education on topics including the history and philosophy of science and science teaching.

However, physics teachers encounter problems when trying to incorporate large contextual settings, such as LCPs, into the conventional textbook-centred teaching of physics. It will be argued that these problems are due to the nature and the demands of textbook-centred teaching. This paper recommends a shift from the textbook's centrality to imbedding LCPs into a philosophically and historically more valid theoretical structure.

The proper placing of the LCP

While teaching the conventional senior high school physics programme, teachers could incorporate LCPs into daily teaching for each major topic, namely kinematics, Newtonian dynamics, planetary motion, electricity and magnetism, wave motion and radiation. For the topic of kinematics and dynamics students could work with 'Physics and the Bionic Man' (Stinner 1980), 'Physics on the Moon', 'Physics and the Dambusters' (Stinner 1989a) or 'The Story of Force' (Stinner 1994); for planetary motion with 'A Rotating Space Station' or 'The Physics of *Star Trek*' (Stinner and Winchester 1981); for electricity and magnetism with 'A Fossil Fuel Power Plant', 'Electricity in the Home' or 'The Experiments of Faraday'; for radiation and thermal physics with 'Sun Power in the Pyrenees' and 'A Solar House for Northern Latitudes' (Stinner 1978). Students should be asked to form small groups of three to four and together choose *one* LCP that attracted their common interest.

Each LCP should be so designed that most of the physics for a particular topic would have to be used for the successful completion of the problems suggested by the context. What is so attractive about this kind of setting is that the questions and problems are generated naturally by the context and will *include* problems that are given out of

0031-9120/94/060375+07 $19.50 © 1994 IOP Publishing Ltd

context in a textbook for a given topic. Moreover, students' responses to the LCP approach suggest that LCPs should be designed cooperatively by students working with the instructor. A cooperative effort also gives the instructor the status of researcher and the student the feeling of participating in an on-going research programme. Indeed, many of the questions and problems generated do not have obvious answers for the student or the instructor. The ability to answer questions and solve problems that do not have textbook answers, using elementary physics only, is very rewarding for both students and teacher.

The immediate benefit of contextual problem-solving seems to be that it enlarges the student's understanding of basic laws and principles. In addition, the student often goes *beyond* just the successful mastery of the problem situations. For example, for the study of kinematics, if the student chose, say, 'Physics and the Bionic Man', he/she investigated the current research in the physics of bionic parts; or if the student chose 'Physics on the Moon', he/she investigated the physics of moon architecture and the general problem of adaptation to a low-gravity environment (Stinner 1989).

Can we place LCPS in a central position in existing curricula and teaching practices? Within the confines of a conventional textbook-centred approach teachers are generally encouraged to reinforce core material by optional contexts of their choice, but only to the extent that time for it is available.

A pedagogically sounder approach, however, would be to *begin* with a well developed context that attracts students' interest and is connected to their experiences. Ideally, the teacher would involve the students in generating questions and problems, propose simple experiments and then develop the appropriate equations in response to those questions and problems. Developing the appropriate physics in this way would relate to students' interests, and the direct contextual application of the 'formulas' might enhance their understanding of how theory is related to practice.

Unfortunately, the curriculum, as enshrined in the core material, is often perceived as being covered first. This leaves little time or incentive to concentrate on contextual material. Moreover, the material in the textbook is to a great extent decontextualized for the student to memorize and apply to textbook problems. Connecting an interesting contextual setting to a textbook then seems artificial and contrived to students.

The activity of teaching physics must not only be connected to a contextual base but also to a clearly articulated and philosophically and historically valid theoretical structure. The contextual base consists of the appropriate placing of LCPs to attract students' individual interests, while making provisions for continued student engagement in questioning, problem-solving and experimenting. The theoretical structure, on the other hand, can be thought of as a pedagogical scaffolding that illuminates the status of theory, establishes what counts as evidence, clarifies the relationship between experiment and explanation, and makes connections to the history of science. Such a theoretical structure then guides the organization *and* the presentation of physics.

Textbooks seldom imbed their content in a clearly laid-out theoretical structure of physics, nor is the history of physics discussed beyond anecdotal vignettes. Indeed, textbooks generally implicitly or explicitly promote an empiricist-inductivist picture of science, namely the belief that laws and discoveries are a guaranteed consequence of systematic observation based on a specifiable scientific method.

The contexts of inquiry

A theoretical structure that is philosophically and historically valid may be called collectively *the contexts of inquiry*. I have described the contexts of inquiry in detail for the physics of Aristotle, Galileo, Newton and Einstein elsewhere (Stinner 1989b). Essentially it is argued that each major tradition in science, from Aristotle to Einstein, is based on a particular picture of the world, each is based on a set of assumptions (presuppositions) that required a particular set of ordered questions for working out the consequences of 'seeing' the world in a certain way.

Arguing along these lines suggests that in order for the students to come to grips with the nature of scientific thinking in physics we must establish a theoretical–pedagogical scaffolding that may be collectively called the *contexts of inquiry* in scientific thinking. These are:

Context of Questions,
Context of Method,
Context of Problems,
Context of Experiments,
Context of History.

How these contexts can be written out for Newtonian dynamics in detail is shown in box 1. I have discussed the context of inquiry approach more fully elsewhere, including a detailed discussion of kinematics in terms of Galileo's work and Einstein's special theory of relativity (see Stinner 1989b).

Box 1. The Contexts of Inquiry for Newtonian Physics

Presuppositions
Mathematics is the core of physical description and explanation.
Mass points interact via central forces.
Space is Euclidean.
Time is absolute.
Mass points interact instantaneously (Action-at-a-distance).

Foundation questions
1. Is there an axiomatic system, containing a small number of laws and expressed in the language of mathematics, that can describe both celestial and terrestrial phenomena?
2. What are the fundamental physical quantities that can describe accelerated motion of a mass, like in free fall and in collision?
3. How should we define accelerating force?
4. Do the same laws describe the dynamics of free fall, the motion of a conical pendulum and collision?
5. How can we describe the force between the planets and the Sun?
Using the laws of terrestrial motion can we describe the complex celestial motion of the planets around the Sun?

Foundation problems
1. To show that Galileo's law of free fall is just a special case of the second law of motion.
2. To show that elastic collision can be described using the second and third laws of motion.
3. To find the mathematical description of centripetal acceleration.
4. To combine the laws of motion with centripetal acceleration in order to find the period of the Moon's rotation around the Earth.
5. To show that a spherical homogeneously distributed mass has the same gravitational effect as a point equivalent mass.
6. To find the nature of the path of a planet obeying an inverse-square force law.
7. To show that Kepler's laws are just a consequence of the laws of motion and the universal gravitational law.

Foundation experiments
1. Collision experiments with pendulums.
2. The conical pendulum.
3. Atwood's Machine ($\simeq$1780).
4. Cavendish's experiment ($\simeq$1790).

Thought experiments
First law of motion.
Rotating bucket.
Rotating spheres (in the void) connected by a chord.

New questions
1. Why are inertial and gravitational masses equivalent?
2. Is inertia a local effect or is it dependent on the mass of the universe?
3. Can force and mass be expressed in a non-circular way?
4. Newton's question: How can we quantitatively demonstrate how particles of matter in motion endowed with forces produce the observed phenomena in nature, for both large- and small-scale phenomena?

Pedagogical questions
1. Given a force (unbalanced)–time graph, how can you find the average unbalanced force? (Simple).
2. How can you find the period of a pendulum for small displacements using Newton's second law? (Difficult).
Note. Many of the questions generated by the LCP, prior to solving the problems that the context generates, will resemble these.

Pedagogical problems
1. What is the unbalanced force on a 1000 kg car that accelerates the car at 2 m s^{-2} on a level road? (Simple).
2. Example from a LCP (Physics on the Moon). Speculate about Olympic records on the Moon inside a geodesic dome. How will they compare with Olympic records such as high jumping and sprinting on Earth?

Pedagogical experiments
Type I. (Discussed in textbooks)
1. Study the motion of a dynamic cart when accelerated with a constant unbalanced force.
2. Study the motion of a cylinder rolling along an inclined plane using the computer (sensor-based) PSL program.
Type II. (Generally not discussed in textbooks)
1. What is the relationship between the time it takes to empty a large tin can, with a small hole in the bottom, and the initial height of the water?
2. How does the force between two parallel bar magnets vary with distance?
3. Example from LCP (Physics and the Bionic Man). Investigate the forces on the knee joints of the bionic man when he jumps to a height of 10 m.
Type III. (Individual research problems)
1. Build an accelerometer and test it in a car.
2. Study the trajectory of a baseball using a video camera.
3. Example from LCP (Physics and the Dambusters). Investigate the motion of a bouncing tennis ball using a video camera.
Type IV. (Thought experiments)
1. Newton's bucket experiment.
2. Newton's rotating spheres in the void (connected by a chord) experiment.
3. Example from LCP (The Physics of *Star Trek*). How do you turn a spaceship around in deep space?

LCPs: Physics and the Bionic Man
The Physics of Star Trek
Physics and the Dambusters
Physics on the Moon
The Revolving Space Station
The Physics of Driving

The following is a brief description of the contexts of inquiry that refers to Newtonian *dynamics*. However, the development here is sufficiently general to guide the physics instructor in outlining the contexts of inquiry for other major topics in physics, such as kinematics, light, electricity and magnetism, and modern physics.

The *Context of Questions* refers to the claim that scientific fact is the answer to a scientific question. Scientific questions in turn are related to the basic assumptions of a science, often not explicitly articulated. We want to show students how these assumptions, often referred to as the presuppositions of a science, produce a small number of *foundation questions*. An example of a foundation question (for Newtonian physics) is: What are the laws of motion that describe seemingly disparate phenomena such as free fall, the motion of a conical pendulum and elastic collision?

Physicists, however, seldom refer to the foundation questions of Newtonian physics; they consider them answered. They ask only questions that relate to their research. These may be called *research questions*. An example of a research question is: Does the electric force from a point charge decrease inversely as the square of the distance like the gravitational force? This was a research question for Coulomb in about 1800.

Textbooks pose many questions in order to elucidate the laws, principles and definitions on which a science like Newtonian physics is based. These questions are *pedagogical questions*. An example of a pedagogical question is: How is the second law of motion related to the first law?

The answers to the foundation questions shape the particular science. The research questions that the physicist would ask, on the other hand, assist in working out the details of the application of the theory to appropriate phenomena. Textbooks, however, deal primarily with pedagogical questions and seldom discuss foundation questions and how these shaped a science, nor do they discuss research questions that the physicist may be interested in.

Finally, in the working out of details of a science, like Newtonian physics, problems are sometimes encountered that prompt scientists to re-examine the presuppositional structure of a science. This activity begins with new questions that may signal the beginning of a major shift in scientific thinking. Examples of such questions in Newtonian physics are: Are space and time absolute? Why are inertial and gravitational masses equivalent?

The *Context of Method* is the method of science (not 'the scientific method'), especially the relationship between scientific induction and deduction. We want to show the student that scientific method spans the whole spectrum from specifiable mechanical procedures to high-grade science that uses scientific imagination, intuitive thinking and a sense what we may call aesthetic components. The 'scientific method' as enshrined in textbooks generally stresses mechanical procedures only. We must, however, also acquaint the student with intuitive, non-mechanical procedures of the type used by Galileo, Newton and Einstein in developing their physics.

The *Context of Problems* involves the identification of the small set of problems that ultimately shaped a science. These are the *foundation problems* of a science. An example of a foundation problem in Newtonian physics is: To find the nature of the path of a planet obeying an inverse-square central force law. Problems that physicists solve will be called *research problems*. Euler's solution of the problem of the spinning top in the eighteenth century is a good example of a research problem in Newtonian physics.

What kind of problems are those that have evolved in textbooks that students routinely solve? In inducting the young student into a science like Newtonian physics he or she must practice worked-out typical problems that both illustrate and characterize certain areas of interest. Kuhn, in his influential book *The Structure of Scientific Revolutions* (1962), called these *exemplars*, and argued that they cluster around such prototype problems as the motion of a conical pendulum, the elastic collision of billiard balls and the study of Keplerian orbits. It seems that these exemplars are the archetype problems of Newtonian physics and are supposed to remind the student of the foundation problems. These problems can therefore be seen as a stylized version of these original foundation problems. Exemplars are well defined, their solution is guaranteed and the answers to them are known. Such problems will be called *pedagogical problems*. Unfortunately, students often memorize their solutions in terms of algorithms, often without understanding the questions and contexts that generated them. Here are examples of pedagogical problems: How far does a heavy object fall in three seconds close to the surface of the Earth? What unbalanced force will produce an acceleration of $2\ \mathrm{m\ s^{-2}}$ on a 1000 kg car travelling on a straight level road?

Textbooks generally concentrate on pedagogical problems only and seldom discuss explicitly the foundation problems of a science or the research problems of the practising physicist. When teaching is based on the contexts of inquiry, however, the foundation questions and problems would be discussed. Granted, when teachers and students investigate a context like *Physics and the Bionic Man*, most of the questions and problems generated will resemble pedagogical ones. But many of the questions and problems will go beyond these and can be considered students' research questions and problems. These problems are those that do not fit into a known algorithmic procedure, do not have known answers, but can still be solved by the student using only elementary physics.

The *Context of Experiments* is first concerned with the foundation experiments, namely those that shaped a science. An example of a *foundation experiment* for Newtonian physics is Newton's experimental study of elastic collision using hardwood balls. Foundation experiments are seldom discussed in physics classes. Textbooks generally fail to report them and physics teachers are seldom acquainted with them.

Research experiments are those designed by physicists. An example of a research experiment (for Newtonian physics) is Cavendish's famous experiment to find the numerical value of Newton's universal gravitational constant.

Physics teachers should also be concerned with the proper placing and classification of experimental work in physics education. Traditionally we involve the student in elementary physics in the execution of *pedagogical experiments*, which will be called type I experiments. Type I experiments are those that are conducted in a rigid step-by-step format that leads the student to an expected conclusion. These experiments seem to serve the purpose of 'proving' or 'verifying' such laws as Newton's second law of motion. First, it should be pointed out that it is not possible to 'verify' a law by doing an experiment. Second, physics teachers must be honest with students and let them know that what they engage in when doing laboratory work is not a *bona fide* scientific experiment, i.e. a research experiment. However, these activities can still be made more exciting and student-centred.

In order to make them more interesting and pedagogically more valid, type I experiments should be rewritten, made less of a cookbook affair and identified by teachers for what they are. One way to make type I experiments more appealing to students is to use such computer programs as PSL (Personal Science Laboratory), which are now using sensors that measure time, sound and light intensity, temperature, pressure and force. In addition, one could ask students to replicate some of the classic experiments of physics. Galileo's inclined plane experiment, Newton's experiments with colliding hardwood balls, Faraday's experiments to show electromagnetic induction and J J Thomson's experiments using his electron gun are a few experiments that one could easily develop and place in a historical context in an interesting way.

Going beyond type I experiments, physics teachers should make provision for a number of other types of experiment. These experiments can be called *students' research experiments*. Type II experiments are those that are based on 'real problems' (meaningful to the student), require simple apparatus, produce results little or not discussed in textbooks, are amenable to elementary physics, but do not have obvious answers. Two examples might be: What is the relationship between the time it takes to empty a large tin can, with a small hole in the bottom, and the initial height of the water? How does the force between two parallel cylindrical magnets vary with distance?

Type III experiments are small individual projects that have their origin in the imagination of the student. For example, a student might wish to build an accelerometer and test it in a car, or take stroboscopic pictures of a baseball and study the trajectory of a ball in the medium of air. Even such projects as investigating the motion of falling 'propeller seeds' are acceptable, provided the student is able to outline the problem well and ask good questions.

Finally, type IV experiments are essentially thought experiments of the type Galileo, Newton and Einstein 'performed'. Well known examples of these are Galileo's thought experiment to show that all heavy objects on the surface of the Earth must fall at the same rate, Newton's bucket experiment to clinch his argument for absolute space and time, and Einstein's elevator thought experiment to illustrate the equivalence of gravitational and accelerated frames of reference.

The *Context of History* is concerned with giving the student a good sense of how scientific theories are the product of historical setting and are paradigm-driven. In this context we could discuss confrontations in science and confrontations between the sciences and the humanities. Examples of the first would be the dispute between Newton and Huygens concerning the nature of light and that between Huygens and Descartes as to whether the quantity mv or mv^2 is conserved in collisions. An example of the second would be the confrontation between Galileo's heliocentric solar system and the teachings of the church having adopted an Aristotelian geocentric view of the solar system.

In summary, for each major topic, namely Galilean kinematics, Newtonian dynamics, electricity and magnetism, radiation and wave motion, and elementary relativity theory, physics teachers can outline the *contexts of inquiry*. The placing of the LCP now, however, is seen as central and connect-

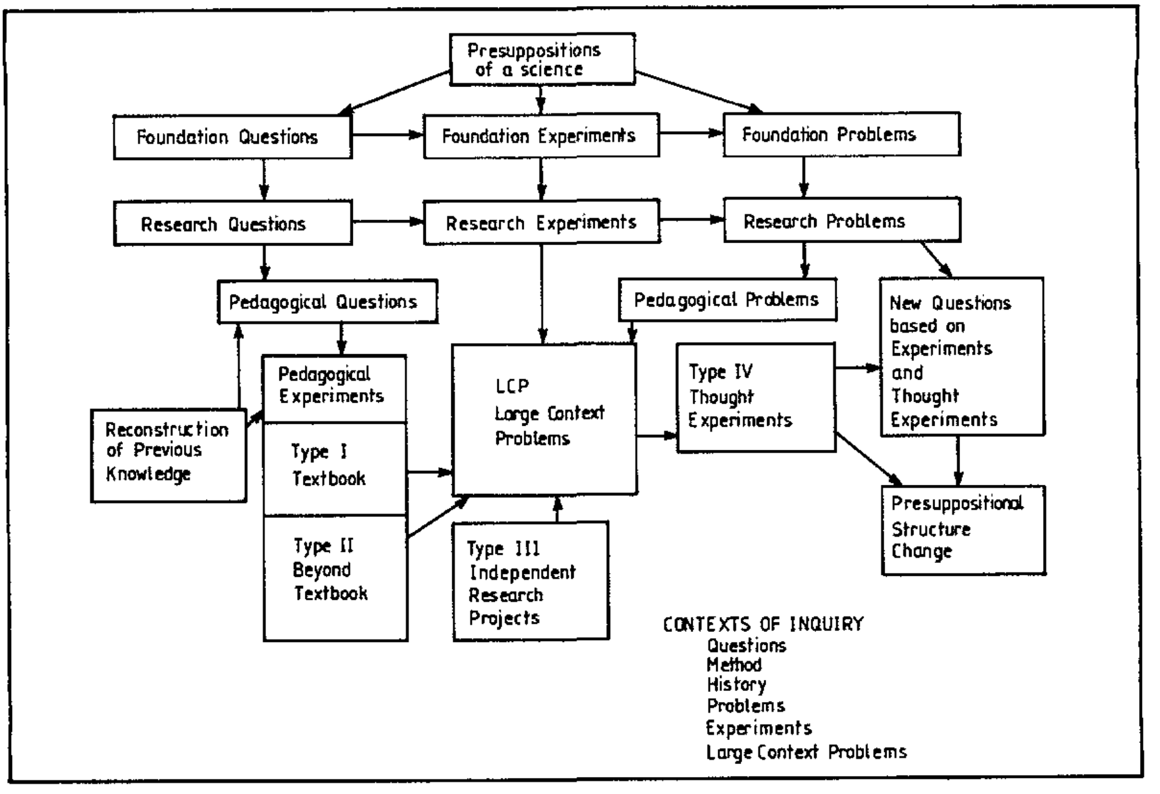

Figure 1. The Contexts of Inquiry.

ing to the contexts of inquiry in a given area of physics, as shown in figure 1.

Conclusions

This paper has tried to show how one approach to contextual teaching evolved from the modest hope of enriching the core of textbook-centred physics to teaching physics using LCPs imbedded in a philosophically and historically valid theoretical structure. It became clear at an early stage that the teaching of physics that was grounded in contextual activities had to be also connected to a theoretical structure that guided the organization as well as the presentation of concepts and ideas. This theoretical structure, collectively called *contexts of inquiry*, can also be thought of a pedagogical scaffolding that allows physics teachers to design and relate their material to the structure of physics. Imbedding the LCPs in the contexts of inquiry has the effect of liberating the teaching of physics from the grip of the textbook. Moreover, outlining a theoretical structure in this way places the study of physics historically. This will force the teacher as well as the student to engage in an inquiry process that clearly states what the presuppositions, the major questions, the central problems and the key experiments of a science are, and what new questions the science generates.

For each major topic in physics then, physics teachers can outline the contexts of inquiry in detail. I have given here an outline of Newtonian mechanics that will allow the reader to see how LCPs are placed and fit centrally into the contexts of inquiry of Newtonian physics (see box 1). One could easily outline this approach for other major topics as well, namely kinematics, light and optics, electricity and magnetism, and modern physics.

Granted, the success of using LCPs in physics in a few classrooms does not constitute an overwhelming argument for abandoning textbook-centred physics teaching. However, in my long association with physics teachers, I am convinced that the majority of the experienced ones use textbooks only as a reference. These teachers could easily be persuaded to use a theoretical structure such as the contexts of inquiry as a guide to organize their notes as well as to incorporate well designed contextual materials into their teaching. Many of them are probably already using an approach roughly along the lines suggested in this paper. What is needed, however, is a more conscious and collective effort by teachers to teach physics in motivating contexts and to anchor the concepts and ideas in a clearly presented theoretical structure that is philosophically and historically valid. If this can be achieved on a large scale, perhaps then we will improve the general physics literacy (Stinner 1990) as well as the readiness of students for further study of physics at the university level.

References

Kuhn T 1962 *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press)

Roth M and Roychoudhury 1993 The conceptual map as a tool for the collaborative construction of knowledge: a microanalysis of high school physics students *J. Res. Sci. Teaching* **30** 503-34

Stinner A 1978 A solar house for northern latitudes *Phys. Teacher* **16** 25-30

—— 1980 Physics and the bionic man *Phys. Teacher* **18** 352-62

—— 1989a Physics and the Dambusters *Phys. Educ.* **24** 260-7

—— 1989b The teaching of physics and the contexts of inquiry: from Aristotle to Einstein *Sci. Educ.* **73** 591-605

—— 1990 Philosophy, thought experiments and large context problems in the secondary school physics course *Int. J. Sci. Educ.* **12** 244-57

—— 1994 The story of force: from Aristotle to Einstein *Phys. Educ.* **29** 77-85

Stinner A and Winchester I 1981 The Physics of *Star Trek* *New Scientist* **92** 884-8