THE NATURE AND PROCESS OF SCIENCE: A PRIMER FOR SCIENCE TEACHING IN SCHOOLS

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Perhaps, the sermon was boring. But, as medical student Galileo Galilei watched a chapel chandelier being lighted, he noticed an odd regularity: it seemed that as the swings died down, the smaller, slower swings took just as long as the wider initial ones. Excited, he felt his pulse and counted its beats to check his initial observation, and "confirmed" it (within the limitations of his "apparatus").

As simple and almost idle as it seems, this four hundred year old pendulum "experiment" had within it the seeds of the Scientific Method -- and Revolution, and Age. But also -- in an era where the Roman Church had to contend with challenges posed by Reformation and Renaissance -- fifty years later, it led to poor Galileo being hauled before the Inquisition, threatened with torture, forced to "recant" (from the theory that the Sun was the centre of the Solar system!) and placed under house arrest for the last decade of his life. Why? Because he had published a book discussing the merits and demerits of the theories that the earth or the sun was at the centre of the solar system, and managed to offend the Pope -- who was also a Scientist -- by putting papal remarks on the limitations of scientific thinking in the mouth of a simpleton (who was obviously bested in the book's discussion).

Right from the beginning, then, the characteristic themes and vital importance of Modern Science were sounded; they have continued to echo right down to today. Let us therefore first explore the basic structure of Science (and its relationship with Education), then pause to explore "the Scientific Method" and how it relates to teaching and learning the process skills of scientific investigation. Finally, we shall develop a list of practical hints and exercises which will help us develop some of the skills we will need as we work as Science Educators here in Montserrat.

The Nature, Relevance and Power of Science

If we start with how Sciences emerge, grow and work into our community, it will help us put Science Education in its context; this contextualising will help us to be effective in teaching Science:

1. **Science:** Science is a method for discovering and testing new knowledge about the observable world. Its observations, laws, theories and experimental or observational tests, however, are limited by the available technology and our creativity in devising tests; scientific laws, theories and knowledge are thus subject to revision or rejection in light of new evidence. *Science is provisional knowledge about the world based on observation, analysis, theorising and experimental or observational testing.*

2. **Empirical Testing:** The key contention of Scientists, from Galileo on, is that *ideas about how*

the world works ("hypotheses" or "theories") must be subject to Empirical Tests. That is, *repeatable* observations and measurements of what happens in fresh contrived (experimental) or "natural" (observational) situations must decide which theories we will accept or reject. Dogmatism and closed-mindedness -- whether in the name of religion, reason, political ideology or even "Science" itself -- are enemies of true Science.

3. **Problem-Solving:** *Scientific Theories draw their problem-solving power from their ability to make accurate, detailed and (especially!) unexpected predictions about the way nature behaves*. This gradually unfolding ability to describe, explain, predict and control natural forces and effects has enabled us to construct vast wealth-generating engines, which drive industry, agriculture, transportation, medicine, and now information technology, to the growing benefit of mankind.

4. **Impact:** *Scientific thinking and its consequences, sooner or later, seep out into the real world*. First, as we just noted, they deepen or extend the technologies we use to solve problems and build a comfortable and effective living and working environment -- but may also create or worsen other problems, such as pollution. More importantly, they affect our world views -- how we understand ourselves, our world and our relationship with the Creator.

5. **Integrity:** This impact on world views is vital, but often controversial. Sometimes, Scientific integrity has been suppressed, as with the Inquisition's mishandling of Galileo, or the infamous businessman's publicity stunt and ACLU test case on teaching the Theory of Evolution which is popularly called the Scopes Monkey Trial (Dayton, Tennessee, 1925). At other times, Scientists and Educators have forgotten the inherently tentative nature of Scientific knowledge, and have turned Science into dogma. Clearly, *Science and Science Education will have to balance on the tight-rope of integrity, if we are to avoid the damaging impact of dogmatism, indoctrination and arrogance (under whatever labels).*

6. **Dominance:** From the late 1600's on, with Newton's great successes in Optics, Mechanics and Astronomy -- not to mention co-inventing Calculus along the way to handle the Mathematics he needed -- *Science became the dominant approach to knowledge in the modern world*. Branch after branch emerged until today there are literally hundreds of specialities, each characterised by the development of an agreed upon body of theory and knowledge, published in peer-reviewed Journals (Professional Magazines) circulated among the scientific community.

7. **Journals:** Such Journals, whether printed or circulated on the Internet (and with the aid of conferences during which experts discuss issues of great interest and publish Proceedings, summaries of the results), are the means by which new knowledge is checked and communicated to the world. *Peer-reviewed Journals play the decisive role as the Gate-keepers for new scientific knowledge.*

8. **Science Education:** Soon after a new branch of Science emerges, pioneer investigators in the field supervise interested research and undergraduate students, so degree programmes emerge, multiplying the number of workers in the field. At length, as the related technologies impact the world at large, educators develop pure and applied Science syllabi. *New fields of Science thus arrive on the educational scene as their problem-solving power impacts the world.* This growth of new branches of Science leads to new topics or even subjects in primary or secondary schools and community colleges, creating opportunities for teachers and students to contribute to the progress of Montserrat and other communities through Science Education.

The Scientific Method

As we have seen, Science is a global enterprise with hundreds of branches. Each has its own specialised methods for discovering, critically reviewing and communicating knowledge, but a core Scientific Method -- summarised in the mnemonic **O, HI PET** -- gives a *basic* framework within which we can think and work scientifically:

O **OBSERVATION** -- using our senses and instruments, with the aid of who-what-where-when-why-how questions, to recognise patterns (and exceptions) in nature. We may also observe problems or issues in the literature and/or in light of well-tested knowledge claims or analysis in other fields, such as Philosophy.

H **HYPOTHESIS** -- making and formulating educated guesses (preferably quantitative) about the principles giving rise to the observed patterns (and, one hopes, explaining "exceptions").

I, P **INFERENCE & PREDICTION** -- drawing logical deductions from the hypothesis, specifying expected observations and/or measurements in new situations. (These situations will be used to test the predictive and explanatory power of the hypothesis.)

E,T **EMPIRICAL TESTING** -- setting up and making the required repeatable observations, measurements and analysis to see if the hypothesis successfully predicts and explains what happens in nature, or is disconfirmed. Galileo's pulse-timed pendulum is a classic Experiment; volcano and earthquake monitoring -- in the hope of being able to predict disasters -- is a rather relevant case of an Observational Study being done here in Montserrat.

In principle, all hypotheses are still under test, but after many successes, confidence in a given hypothesis becomes so high that we call it a "law," and embed it in our general theories about the world. Such theories attempt to unite the widest possible body of facts, laws, experimental results and observed patterns in nature; they use a few broad, powerful (and preferably mathematical) assumptions which logically account for what happens in the real world and enable us to pose and solve fruitful and interesting problems.

For instance, Newton's theory of motion under the action of forces (Dynamics), as noted above, was the first triumph of Modern Science. It starts with three Laws of Motion: (i) mass is the property of matter which resists acceleration; (ii) for a given body, the force to accelerate it is proportional to the resulting acceleration [also, for a given acceleration, force is proportional to the mass of the body]; (iii) bodies interact in pairs, by exerting on each other equally sized but oppositely directed forces. If we add the Law of Gravitation and apply Calculus (the mathematics of rates and accumulations of change) we will be able to account for the motion of bodies on Earth and in outer space, save those at the molecular scale or smaller and/or moving with speeds faster than about ten percent of the speed of light. Quantum Physics and the Theory of Relativity were developed to deal with these exceptions.

By contrast, "Models" are simplified -- often false -- frameworks for analysis, which give useful results within their ranges of validity, without resorting to the often tedious complexities of full-blooded theories; there's no sense in resorting to Quantum Physics if simple "Equivalent Circuits" based on idealised electrical generators will do just as well! On this point, we note that computer simulations -- which are *not* experiments -- are based on models, and so may well be misleading. In the end it is the real world, not our theories or models, which must prevail.

Scientific laws and theories are usually so well confirmed by such a wide range of data that Scientists and Engineers freely use them in their day-to-day work. If and when new data builds up showing serious limitations, crises result, often leading to revolutionary new theories. For instance, this happened a bit less than a hundred years ago with Physics, which is now divided into Classical (Newtonian) and Modern ("Einsteinian") Physics.

During the nineteenth century, the two Sir Charleses -- Lyell and Darwin -- led similarly sweeping revolutions in Geology and Biology, respectively building modern Uniformitarian Geology and [Macro-]Evolutionary Biology. Mendel's peas and Pavlov's salivating dogs were foundational for Genetics and Experimental Psychology. Mendeleev's Periodic Table of the Chemical Elements (1869 - 1871) transformed Chemistry, and John Meynard Keynes' Aggregate (Macro-) analysis of the 1930's in his *General Theory* radically shifted the classical tradition of thought in Economics, which grew from Adam Smith's 1776 book: *The Wealth of Nations*. Gauss' pioneering work on non-Euclidean Geometry -- also in the nineteenth century! -- forever changed Mathematics, and thus helped provide the analytical tools (such as Riemannian Geometry, Matrix Algebra and Boolean Algebra) needed for modern scientific theories and technologies. And in our computerised era, we look to Charles Babbage's magnificent failure, the Analytical Engine, as the dawn of the Computer Age.

Doing "Real" Science in School

All of the above is fine, and important, but how can it be brought into the classroom, with the limitations of time, money, knowledge, equipment -- and even interest -- which we face as teachers?

The key lies in what Science is: growing *provisional* knowledge of the world based on observation, analysis, theorising and empirical (experimental or observational) testing. Thus, as we do Science, we discover and provisionally validate knowledge about the world. But discovery is a powerful personal experience, and it remains so whether one is a Research Seismologist gingerly probing the frontiers of knowledge at Soufriere Hills or a student finding out for himself the regularities in the swinging of a pendulum or the germination of a red pea seed. For that matter, a Mechanic fixing a car, a Manager trying to improve her business, or a farmer trying to find the best fertiliser blend for his tomato crop may all be powerfully applying the general Scientific Method in their work, though of course what they are doing is not *pure* (research) "Science." Of course, the two should not be wedged apart: "Knowledge divorced from use is barren; skill acquired without understanding will fail in an emergency." [Nancy Catty.]

Our strategy, then, should be to apply the O, HI PET process in the classroom, the lab, the field work assignment, and homework projects:

1. **Example:** Teaching is a kind of leadership, and all leadership in the end is by example [cf. Luke 6:39 - 40]; if we are to train pupils to think and work scientifically, so must we. Do we habitually solve educational and general problems by observation, experiment and analysis? Do we check our proposed explanations or solutions against further systematic observations of the situation? Do we revise our thinking and working in this light?

2. **Time Required:** The Scientific Method is a way to learn from organised experience by exploring, discovering, analysing (who-what- . . . ?), checking and revising findings in light of further investigations. While it would take too much time for pupils to try to learn everything this way, such methods are powerful, especially for Mathematical or Scientific concepts and principles. Class experiments or field work exercises, the drawing out and organising of common experience by guided discussion, and simple small group or individual experiments performed in the class or set as homework are all effective.

3. **Shoebox Kits:** "Lack of equipment" is the bane of Science teaching in schools, and given the high cost of apparatus in our tight times, it will remain so. However, if we scrounge, improvise and gradually build up "shoebox" lab kits for various topics, over time we will accumulate a considerable body of effective exercises and equipment. For instance, a keen group of pupils could tackle a Science project in Electricity, scrounging and/or building the required apparatus. Once their Electricity Kit is assembled, it can be kept, used, fixed up and added to. After a few years, especially if teachers share experiences and ideas, our Science programme would be considerably strengthened. (Of course, there are several books of such exercises -- and kits -- to get us off to a flying start.)

4. **Readiness:** Students mature at different rates, so that ability to handle abstraction is not rigidly age-linked; moreover, it is also strongly tied to the home and general environments. Often, these factors frustrate attempts to study Science. Thus, we are forced to make significant student-by-student judgements about the level of school science teaching.

5. **Curiousity:** Generally, we should first of all take the primary-age child's questions seriously, thus encouraging, not crushing, natural curiousity. Gentle stimulation to think about day-by-day experiences, plus deliberate educational exercises -- such as field trips and simple experiments -- should reap a rich harvest of often surprisingly deep questions. The awesome power of video can then multiply the range of a child's experience of the natural world, through viewing appropriate Nature Documentaries, opening the door to even more questions. (One should, however, train students to recognise and adjust for bias and over-simplification of issues in such videos.) As the technology becomes more available, interactive CD-ROMs can also be used to great effect. A rich basis of experience, observation, discussion and factual knowledge is an excellent foundation for concept-formation and powerful abstract thought.

6. **Skill-building:** On the skills side, we should stress systematic observation, important simple measurements, smooth equipment/tool manipulation and effective data recording/display, especially safety, alignment, accuracy, and attending to significant patterns in results. Given today's highly visual world, we dare not neglect the ability to interpret and create diagrams and simple graphs. Being able to work in groups and to follow instructions in their proper order are also vital. These emphases build a basis for effective practical work in later school years and for the world of work. Then, as the child matures, difficult concepts (such as those of Mathematics), and problem-solving strategies such as the Scientific Method are best introduced through direct experiment and the stories of great Scientists and their work.

7. **Designing Experiments:** Practical work in Science typically aims to explore and record what happens in a new situation, or to test a hypothesis, or to measure an important quantity. Sometimes, all three can be going on at the same time, within the O, HI PET framework. So, as we design an experiment, the first step is to clarify its aims and the value of those aims. Next, a quick rough sketch of possible apparatus (emphasising layout, alignments and manipulation steps) will help us see if our approach makes sense and is SAFE. Similar rough drafts for tables of results, observation notes, calculations and/or graphs will help organise data collection and analysis. A mental "dry run" will show up items we have forgotten, and paves the way for an apparatus list and points-style summary of method. At this stage, the experiment should be run, and adjusted until it seems adequate. A draft Lab Sheet -- perhaps in a fill-in-the-blanks (and tables and graphs) format -- should be prepared, and a pilot-test group of students should do the lab. A critique of the lab exercise and further adjustment and pilot-testing should yield a "Kit" to be proud of.

8. **Controlling Experiment Variables:** This is the key step in designing an experiment (but, is a bit technical, so skip this on the first reading, then come back). Ideally, we should identify, isolate and control ALL the variables which significantly affect the results. So, fixing all but one variable, say x_1, the length of a pendulum's string, we adjust it over a range of interest and see how the system's responses y_1(say, the period), y_2, etc. behave. Next, fixing x_1, vary the weight on the string, x_2, keeping other inputs, $x_3, \ldots x_n$ fixed. In turn, we do this for x_3 etc. After this, vary x_1 for a different set of fixed values of $x_2, x_3, \ldots x_n$ (to see if these different fixed values change our results [y's] for the same range of x_1). And so on, until we have as wide a picture as possible of how the system under study, eg. a pendulum, behaves. Real-world science is quite methodical and meticulous.

9. **Control Experiments:** If we can't easily identify, isolate and control the variables like this, we select two or more groups of subjects, $G_0, G_1, \ldots G_k$, which should be as similar as possible. G_0, the control group or experiment, is left "untreated"; this gives us a picture of what happens with "no treatment." Then, $G_1, G_2, \ldots G_k$ are given different experimental "treatments," and the results are compared with those for G_0. (As can be seen from the term "treatment," this approach is often used to test new drugs -- and new teaching methods.)

10. **Observation Studies:** In some cases, we cannot even do this much, so we try to observe natural variations in different factors we can identify and measure, and see if and how well these factors and their variation correspond with results which are of interest. Such studies, for instance, first linked smoking and lung cancer.

11. **Measurement:** (Also skip this and come back!) Usually, in Science, it isn't good enough to say "hot" or "cold," "long" or "short"; we need to specify HOW hot or long. We do so by comparing the amount of a quantity we are observing with the standard amount for the quantity, its Unit. The result of this process of measurement is stated as "five centimetres" or whatever, meaning that the length is five times the unit of length used, the centimetre. Thus, we can now say that, "Burning 0.5 cm of the given candle heated 20 cm^3 of pure water from room temperature [30 degrees Celsius] to its boiling point [100 degrees] in 6 minutes, where the surrounding atmospheric pressure was 760 mm Hg (i.e. able to support a 760 mm high mercury column)." This makes our observations far more exact, and allows us to quantify our hypotheses, laws and theories, which makes them far more powerful. [Later on, in doing scientific calculations, students will learn to add or subtract only the same kind of quantities, and to multiply and divide units as well as numbers. Indeed, the "5" in "5 cm" above is, strictly speaking, a ratio.]

12. **Inventory Control and Maintenance:** Science equipment is often "permanently borrowed" or broken, and will eventually simply wear out or become outdated. Therefore, to build up a well organised, smoothly running lab and field work programme, we shall have to control where apparatus is, its preventive and restorative maintenance schedules, who accesses it, how it is

used, and how it is checked for pilferage and/or breakage and returned to storage after use. Thus, our Shoebox Kits must be kept in organised, locked storage areas, with the key under the control of a designated stores officer. Issues, returns and faults discovered must be recorded, and scheduled maintenance work checked off on a dated check list. If fault report forms are used, it will ease the repair task when faults are found, and help to keep records of equipment history and fault patterns (which can, over time, speed up repair work and justify the need for replacement). It will help if a list of Supply Houses is kept, along with Order Correspondence, and up to date Catalogues. Older Catalogues often are helpful if the inventory has a fair number of discontinued items, but this is no excuse for a packrat policy. It is also vital to keep Manuals, Reference Books and Data Sheets under lock and key.

13. **Safety:** This is the first rule of Science and Industry. Safety Rules for lab and field work should be posted and applied consistently. First Aid techniques should be taught and practiced. The medical evacuation drill for serious casualties should be well-oiled, as should the fire evacuation drill -- and, rooms used as class labs should have two separated exits to facilitate safe evacuation. Finally, First Aid Kits and appropriate Fire Extinguishers should be kept in good working order and ready to hand for immediate emergency use.

Exercises for Research, Discussion and Practical Work

It is not sufficient to simply read about Science, if we are to apply and teach it effectively in School. The following exercises will help build up the requisite skills.

Research and Discussion Topics

1. Draw up a table: ITEMS, TECHNOLOGIES USED, SCIENTIFIC BASIS. Examine the room in which you are working, and fill out the table -- don't forget how it was designed and built, and its electrical and water supplies; medicines you are taking, your glasses, and your clothing are also important. What would your life, play and work be like if the Science-based items were not "there" in the world? How valuable, then, are Science and Engineering for modern life, education and work?

2. Examine the key words: Science, Scientific Method, Technology and Engineering; refer to a good Dictionary and/or a set of Encyclopaedias. In this light, what do you think of the claim that "a Mechanic fixing a car, a Manager trying to improve her business, or a farmer trying to find the best fertiliser blend for his tomato crop may all be powerfully applying the general Scientific Method in their work"? How should this affect our approach to school Science?

3. The careers of great Scientists have much to teach us about the process of Science. Starting with Encyclopaedia articles, survey the careers of Galileo, Newton and three other great

Scientists (perhaps, some of those listed above). Is there a pattern to their work? How can we profit from their example, as teachers, students and working people?

4. In discussing Scientific Integrity, we noted "Science and Science Education will have to balance on the tight-rope of integrity, if we are to avoid the damaging impact of various forms of dogmatism, indoctrination and arrogance." Dig up more details on Galileo's clash with the Church, and the Scopes Monkey Trial and its aftermath down to today; try to find several distinct secularist and religious perspectives. How do they select and cite facts and draw out conclusions? What are your own conclusions? How should you handle these and similar issues in the classroom?

5. Today, Science is the dominant way to discover and validate (however provisionally) knowledge; which has led some to question the validity of other knowledge-claims, such as self-awareness, intuition, philosophical or historical argument, insights due to Story, Proverb, Poem or Drama, and especially Divine Revelation. Examine the claims of A J Ayer's Logical Positivism and its Verification Principle, which asserts that knowledge claims which cannot be directly empirically tested are "meaningless"; contrast the counter-argument that this assertion fails its own test and so cuts its own throat. Also look at Skinner's Behaviourism and the recent rise of Cognitive approaches in Psychology. What do you think? Why? How will you avoid closed-mindedness and arrogance without becoming wooly-minded and gullible?

Teacher and Class Exercises

6. Set up and run a simple pendulum experiment in light of the points made in this paper. How will you collect, analyse and display your results? What are your conclusions? Was Galileo's original observation right?

7. Make up a Shoebox Kit for students to do simple pendulum, falling body and telescope investigations and also learn how Galileo's work with these items led to the birth of Modern Science. How will you handle the exploratory, testing and/or measurement aims? What is your strategy for communicating the O, HI PET framework and the historical element, hammering home their importance and relevance?

8. Plan a field trip exercise for visiting a Soufriere and/or the Volcano Observatory. State your aims and outline a strategy for motivating and briefing the class, managing the actual field work, and debriefing and reinforcing learning. How will you handle arrangements with parents, School Administrators and contact people in the field? What about Emergencies? What would students get out of such an exercise that warrants the extra effort?

9. List ten ideas for other Shoebox Kits, to cover a wide cross-section of the Science Curriculum. How could you work with other teachers to make up and share the Kits during the course of a

year's work? What are some useful reference sources? Who can you list as resource persons? What would you put in the Kits to help keen students "go further"?

10. We have discussed the importance of Science in the working world. Plan a *Science at Work* panel discussion for your class (or a group of classes!); try to make sure the members represent manufacturing, services and agriculture, with both public and private sectors present. Would it be important to see that both men and women are on the panel, and that business people, professionals and artisans are included?

Suggested Readings

1. **Encyclopaedias and General Reference:** *Britannica, Collier's, Americana,* Grolier's *Books of Popular Science,* the Van Nostrand *Enc. of Science and Technology,* Hamlyn's *Tell Me Why* series, etc.

2. **Kit Ideas:** UNESCO's books on improvised equipment, Nuffield guides, etc.

3. **History of Science:** Bronowski's *The Ascent of Man* (Little, Brown, 1973); various Encyclopaedia articles; Hummel's *The Galileo Connection* (IVP, 1986); Dampier's *History of Science,* (); Kuhn's *The Structure of Scientific Revolutions,* (Univ. of Chicago, 1970).

4. **Evolution/Creation Debate:** Eldredge's *The Monkey Business* (); various works by Stephen Jay Gould; Johnson's *Darwin on Trial* (IVP, 1991); Hummel's *The Galileo Connection* (IVP, 1986); Morris' *Biblical Basis of Modern Science* (Baker, 1987) and *Scientific Creationism* (Master Books, 1985).

5. **Philosophical Issues:** Trueblood's *General Philosophy* (Baker, 1981); Del Ratzsch's *Philosophy of Science* (IVP); *Philosophy of Education* (IVP).

6. **Educational Psychology:** Barlow's *Educational Psychology* (Moody).

7. **Catalogues:** Philip Harris (UK), NES Arnold (UK), Griffin & George (UK), Edmund Scientific (USA), Carolina Biological (USA), Radio Shack (USA), etc.