Restoring Falsifiability to High School Physics Education

A portfolio submitted in partial fulfillment of the requirements for the degree of

Master of Education

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Abstract

The idea that scientific theories and conclusions are provisionally true is essential for students to understand. There are limitations as to what passes for science and epistemological limitations to scientific knowledge. These limitations of science cannot be taught in one lesson but must be infused within science teaching practice.

This portfolio is a coaching document. It highlights areas where this important aspect of the *nature of science* (NOS) can be included within regular teaching activities. The participating demonstrations (PD) are guides to help teachers develop their class materials. The idea of the exemplar or teacher prompt is a second opportunity for teachers, both new and seasoned, to develop their understanding of NOS. After which, it is easier to impart that understanding to students in their classroom.

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"Water, water, everywhere, And all the boards did shrink;

Water, water, everywhere, Nor any drop to drink."

Rime of the Ancient Mariner

Samuel Taylor Coleridge (1834)

"Follow the science" is a phrase that on the surface means so much, yet with ready access to the internet there is still discord, from the Covid-19 pandemic issues to climate change. Scientific information is abundant, but there is often no clear understanding. Specifically, with Covid-19, Mandavilli (2021) observes that the scientific understanding of Covid-19 seems to change constantly. Society is in much the same predicament as the Ancient Mariner, where science, science, everywhere, with no one able to think. The core of the problem to understanding science is the difficulty in understanding the nature of science (NOS).

Good science teachers cherish the experience of having students explain a theoretical assumption and make a prediction of considerable certainty, only to have that conclusion dashed by evidence or the demonstration results. Philosophers of science understand this process as a student learning to falsify their findings. This vital and critical process inevitably results in understanding that all scientific conclusions are *always* provisionally true. The provisional truth of a finding is what makes the conclusions scientific. All scientific truth can, should and must be challenged, or progress is made impossible. Students graduating without this understanding of provisional truth go on to believe that science can be settled or irrevocably true, and this is a dangerous and damaging mindset to develop in anyone. A degree in science teaches the logic of scientific discovery but neglects to explore the philosophy underpinning the method we use to make a scientific discovery. Science professors, technicians and students understand the nature of science (NOS), but few share a common language for discussing it.

Studying philosophy gave me the language to discuss the philosophy of science. It allowed me to understand the Popperian school elements and realize that including those elements in the physics curriculum is essential. In numerous works, Sir Karl Popper (Popper, 1972; Popper, 1992; Popper, 2002) makes a critical distinction between *verification* (looking for evidence you are right) and *falsification* (looking for evidence you are wrong). No number of verifying results can prove a theory true, yet a single falsification result can definitively prove a theory is false. The classic example is gravity, understood to be a force. Thousands of experiments carried out around the world designed to prove the force of gravity were upset by a single observation from a patent clerk, who noted that if gravity were a distortion in space and time, then the light would be observed to bend around a mass in space, like a star or planet. It took many years before the technology to observe how light behaves at such a distance was possible. During that time, countless more verifications of the force of gravity were carried out. Still, once the technology arrived, it was determined that light did indeed bend around a distortion in space and time. Einstein was correct that no force of gravity exists, but rather the illusion of force was a distortion of spacetime. This example illustrates perfectly why a belief in "settled" or "stable" science is so pernicious. Such a belief impedes the discovery of new and important understandings about the very nature of our universe and, more importantly, undermines the simple yet profound axiom that science is a process, not an answer.

Falsification is an unfortunate term that semantic slide has eroded, to the point that it is taken as a synonym for fraudulent or fake, and this is not the case. To better understand the term falsification as Popper intended, it is necessary to look at two related problems Popper was trying to solve. *The Problem of Induction* relates to philosophical problems separating cause from effect. *The Demarcation Principle* refers to distinguishing science from that which is not science or what is commonly called pseudo-science. Popper found that falsification solves both of these problems. First, all beliefs that are scientific must be falsifiable - there must be some way to prove them wrong. If a belief cannot be proven wrong, then it is more akin to a religious belief and does not belong in the realm of science. This change in logic solves the demarcation issue. Can you prove that X is wrong? If yes, then it is possible that a scientific claim is being made. If no, then the claim cannot be considered as scientific. From the demarcation principle, Popper concluded that truth from inductive reasoning could not exist. There can never be an Absolute Truth that is scientific, as science and scientific truth is always evolving and is true enough or good enough for the time being.

While Popper was a philosopher concerned with truth, it was not only philosophers that addressed such concerns. Closely related to the idea of falsification is the *Advocatus Diaboli* (The Devil's Advocate), obvious to learned clergy back in 1587. "The term referred to an official whose ostensible position was to represent the devil in discussions concerning the awarding the titles of 'blessed' or 'saint' to candidates due to enter the church's pantheon" (Pascovich, 2018, p. 855). When petitioning that a particular person be sainted, the process involved a promoter who would argue for the various actions and events that would support a person for sainthood. Church officials were educated men, and logical reasoning was important and easily contained with Aristotelian thinking. Officials found the idea of verification logically problematic. It is easy to prove anyone a saint if you are only looking for saintly behaviour. It was logically necessary to have a lawyer arguing on the Devil's behalf to provide some disconfirming evidence and argue that the candidate was no saint after all. The amount of effort given by the lawyer arguing for the Devil is beside the point. He may not argue strongly but as a perfunctory logical necessity. An attempt at falsification, even in principle, is astounding to me, for it would be 348 years later that Popper addresses this in the Logic of Scientific Discovery.

The modern iteration," playing the Devil's advocate," refers to someone who makes a contrary point not necessarily because they believe or support the position but to reveal potential falsification. I wanted the wording to be exactly repeated here, and so the quotation by Pascovich is important. It reads, "The purpose is to prevent the emergence of unanimity and to stimulate fresh thought regarding the accuracy of the dominant position" (Pascovich, 2018, p. 855). The parallels between church and science are extraordinarily close. Providing a counterargument is similar to providing an alternate hypothesis or theory and evidence to counter an established hypothesis or theory. The process of science has taken a long time to move forward from early Catholic Canonization cases.

Lawyers tend to understand falsification immediately, as it is critical for their training and professional duties. By way of example, circumstantial evidence is not sufficient when there is even one piece of disconfirming evidence. In stark contrast, science teachers, philosophers of science, and popularizers of science have made little in-road in understanding science, its theories, or conclusions. Failing to understand that scientific conclusions *are and can only be* provisionally true exists in all areas of human endeavour. By way of illustration, during November 1, 2019, HBO Real Time episode, Bill Maher complained that doctors do not know whether drugs are safe or not when they are prescribed. Mahar was further shocked that doctors would change their minds about safety in light of new information developed from a process of continuous discover*y* (Real Time with Bill Maher - 33 - Episode 513, 2019). Mahar is decrying the entirety of scientific discovery without seeming to understand that he is doing so.

The situation described above would be exactly the type of problem (problem of induction) the philosophy of science has answered. Maher does not appear to understand a vitally important aspect of the nature of science. Judging from the applause, his audience does not understand this aspect of NOS either. Scientific conclusions are always and can only be provisionally true. Maher complains to a receptive audience about a lack of certainty. In sharp contrast, this is not the way that science works. The tentative nature of conclusions is a product of science. The confusion of Mayer highlights a dramatic failure of science education as a whole. Suppose Mahar alone believed that scientific truths are akin to absolute truths. In that case, we might look to his teacher, but that essentially an entire audience appears to agree with Maher suggests a widespread, systemic failure in science education. While this does not by itself constitute proof, there are formal studies that do. When religious practitioners in 1587 can grasp the importance of falsification, but ordinary people in 2020 modern America cannot, we have a serious problem that must be remedied. Falsification is the understanding that science is *never settled* and *can never be.* This nature of science must be embedded again in the high school science curriculum.

For purposes of this portfolio, the literature review will trace the development of several important facets of science teaching and falsifiability. I will examine how key ideas have evolved in the literature and note where seepage occurred.

First, falsifiability has gradually been and is still recognized as a necessary component of the nature of science. The first source of information considered was science teaching associations. I searched for the idea of a tentative nature of scientific conclusions and theories clear and unmistakable from the science organizations. I considered the *United States' National Science Teachers Association* (NSTA) to represent many science teachers across a diverse country. Located at their webpage, the NSTA has maintained a similar position statement about the nature of science for the past twenty years. NOS statements clearly and unequivocally point to an expectation that students leave high school with a firm understanding of conclusions and theories' provisional or tentative nature. Similarly, I looked at the *Science Teachers Association of Ontario*'s (STAO) position statement found in Ministry of Education science curriculum documents and at the STAO website. Looking at the mandated curriculum for the *International Baccalaureate* program (theory of knowledge and the physics curriculum) and the *Advanced Placement Physics* program, I expected to see references to NOS.

Second, the philosophy of science has much to say about science and, therefore, science education. Popper's philosophy of science deals with induction and the necessary result that scientific conclusions are potentially only probably correct. Popper was an advocate for falsifiability as the criterion for certitude. Conjecture and refutation were the two parts of the Popperian *Logic of Scientific Discovery* (Popper, 1992). Thomas Kuhn's (1977) distinctions and claims about ordinary science need to be compared to Popper's. While ordinary science goes on for most human scientific endeavour, the "paradigm shift" is an important concept. Still, the Popperian logic of that discovery or shift is equally important too.

Besides the professional associations, researchers have articulated several concerns. For example, pre-service teachers do not have a firm understanding of the nature of science. There is a need to make NOS elements clear in both teachers' and students' minds. It is evident that NOS concerns have been a perennial concern and could explain a disparity in science education between the US and Canada.

This portfolio has several presentations and activities that will help any teacher understand the nature of science in terms of falsifiability. At the core is the demonstration of the problem of induction. Understanding what is meant by the problem of induction and sharing this with other teachers and students will be fundamental. The problem of induction would be the philosophy section and gives grist to the mills of mentor-teacher arrangements. Such a mentor-teacher arrangement is unique and was studied and reported on with engaged teachers of science. The Melville and Bartley (2010) article was focused on a different approach and examined the role of teacher mentoring. While positive aspects were found in terms of inquiry science, a cautionary note is telling. There are problems in trying to improve science teaching in isolation (p. 824). The mentor-teacher arrangement is a very personal one but an exceptional approach to making NOS clear in the minds of teachers. It is difficult to evolve as a teacher and particularly to do that in isolation. Working with another, or by extension, a small group is a positive approach to more than simply NOS concerns. My research shows that young teachers having a mentor in teaching is a net positive. Professional development at the inter-board level is mandated and popular in countries such as Finland. Mentors abound. This mentoring could be why Finland has scored rather high in PISA scores over the years.

In Ontario, additional statements that flesh out the STAO position statement with examples, and to add clarity, would go a long way in making NOS an important part of the science curriculum and clearer in teachers' minds. The research shows that richly considered stories of history and complimentary demonstrations allow NOS to flourish in teachers' and students' minds. Later in this work, this historical case study approach will be seen in the exemplary participating demonstrations. "There is also some encouraging evidence that well-designed historical case studies can be effective in bringing about NOS understanding" (Wong & Hodson, 2009, p. 113).

Philosophical determinations and proofs are easily imparted to both teachers and students. I will provide these demonstrations/proofs in this portfolio. These conceptions and potential analogies are important to teachers defending hard-won provisional true science ideas. Naturally, I find the philosophical examination and proof to be the most persuasive.

Pragmatically, I will reproduce several experimental activities and demonstrations that can be performed to show how falsifiability has been used to change theoretical understandings. A verification-only experiment is often easily converted to one that has falsification associated with it. Showing side-by-side contrasts to the verification and falsification of scientific activities will make NOS better understood. As a former science teacher, I have used science activities that focus on falsification successfully in the past. These activities help to demonstrate and solidify for students the tentative nature of conclusions in science. Of course, all experiments repeated in a classroom, or for that matter, demonstrations, are parts of science history. Such exemplars will help physics teachers.

Lastly, there is the matter of making a change or revision to the next science curriculum. The Ontario Ministry of Education has a template to bring necessary items and suggestions to add or change in an organized manner. This template has yet to be shared with me by the Ontario Ministry of Education at the time of this writing.

In the summer of 2008, I was the lead writer for the Philosophy curriculum. Many stakeholders had addressed their concerns and hopes for both the grade 11 and grade 12 philosophy courses. Some stakeholders were very clear about the positive, interesting, and negative outcomes from such a revised course. This time, as a graduate student working in science education, I am the stakeholder; I will make my case for the elements of Popper's philosophy of science to be integrated in a real way into the curriculum. Rational curriculum changes are required. The *Teacher Prompt* is an element of the social studies and humanities curriculum, and I can see its implementation being important in the science curriculum. The teacher prompts can sometimes be more like pedagogical exemplars. To be clear, I will borrow this idea for this portfolio.

The physics curriculum mandates specific experimental activities, and I will describe and change current experiments with inquiry-based experiments to ones that demonstrate falsifiability. Several examples of this paradigm shift to science teaching should be sufficient to begin the change. With the coaching information included with this portfolio, teachers will challenge student thinking and bring a clearer understanding of NOS.

Chapter 2: Literature Review

Preamble

"Be very suspicious of those who want to cut off debate with 'this is against settled science.' Appealing to authority is a sign of weakness, not strength." Excerpted from Dr. Arnold Aberman's presentation at Lakehead University's convocation on May 30, 2014 (Blinkered thinking in academia, 2014). This quotation and the change to the current science curriculum document are two pivotal events in my life. This quotation, and of course Aberman's felt need to state it at the LU Convocation, was a very important part of my motivation to instill a meaningful approach to understanding science. Simultaneously, meaning is not sufficient, and I am motivated to ensure that the epistemological claim staked out by the scientific process is logically clear and valid.

Falsifiability is an essential component of the process of science (Hossenfelder, 2019). The term has several synonyms. The *nature of science* (NOS) is a phrase that contains the idea of falsifiability. Falsifiability is also expressed through phrases such as *provisionally true, tentative conclusions,* and *tentative theories*. The phrase "theories must be changed in light of new evidence" points to the idea of falsification. I have cast my net wide to capture these synonyms of the concept, if only because there is much less formal language in these areas.

Looking for NOS in science education commentary, I have considered writings from several categories: science teacher associations, philosophers of science, and Nature of Science (NOS) Educational Research. Other researchers draw nuances to scientific research and quibble about the nature of a tentative conclusion or other technical phrases in the philosophy of science literature. Ultimately, NOS must be considered in pragmatic terms as well.

> For all practical purposes, the force of gravity is not a tentative idea, whereas string theory is quite tentative. Philosophically, there are many ways of interpreting the sources of tentativeness: it could be due to our imperfect ability to comprehend the world; we could be inching closer and closer to some ultimately knowable truth, or we may simply be constructing our reality. It is not my aim to evaluate these positions, and I leave it to others to argue whether or not such philosophical debates ought to be part of science education (Sandoval, 2005, p. 641).

I agree with Sandoval. For the same reason, high school mathematics teachers do not teach the Peano system to prove numbers. Such details are not for everyone, but what is integral for everyone should be prioritized. In the same way, nuances or degrees of falsification are less important to secondary school science students. So, when it comes to defining science terminology too narrowly, Wong and Hodson (2009) argue,

> the astrophysicist, high-energy physicist, and molecular biologist all commented that the term ‘law’ should no longer be used in science because it is a confusing term that indicates an unjustifiable status as “definitive and not subject to change.” They were adamant that all scientific knowledge, including “laws,” is subject to modification when there are appropriate evidence and a convincing argument. (p. 122)

This type of discussion should be included in high school NOS for simple clarification. Even a naïve formulation of NOS is better than no formulation of NOS. By way of example, science content can be idealized, for example, the Ideal Gas Law. That simple clarity can exist in the minds of students taking science. Those students going on in post-secondary science can learn about the nuances to both gas laws and fine distinctions of words such as law, conclusion, and theory.

Teacher Associations

Many factors go into the writing and the organization of science curriculum documents, including creating specific content items, skills, and thinking. Science education stakeholders voice their opinions through various venues. One such venue would be science teacher associations or similar groups. Science teachers can voice their opinions, based on their extensive experience, through organizations like the US National Association of Science Teachers (NSTA) or the Science Teachers Association of Ontario (STAO). Teachers are also responsible for curriculum written for specific organizations, such as International Baccalaureate courses or Advanced Placement courses.

National Association of Science Teachers

The US National Association of Science Teachers' *Nature of Science* position statement is not one opinion but the combined work of at least twenty-six researchers dealing with the entire position statement on the nature of science. There is also the consensus and agreement of the majority of NSTA members. As there are more than 57,000 paid memberships, this represents a lot of agreement with NOS. Provisionally true conclusions and theories are only one aspect of the position statement. From their position statement and their webpage:

1. Scientific knowledge is simultaneously reliable and subject to change. Having confidence in scientific knowledge is reasonable *while also realizing that such knowledge may be abandoned or modified in light of new evidence or a re-conceptualization of prior evidence and knowledge.* The history of science reveals both evolutionary and revolutionary changes. *With new evidence and interpretation, old ideas are replaced or supplemented by newer ones. Because scientific knowledge is partly the result of*

inference, creativity, and subjectivity, it is subject to change (AAAS 1993; Kuhn 1962, each cited by Nature of Science | NSTA, 2021)

2. Although no single universal step-by-step scientific method captures the complexity of doing science, a number of shared values and perspectives characterize a scientific approach to understanding nature. Among these are a demand for naturalistic *explanations supported by empirical evidence that are, at least in principle, testable against the natural world*. Other shared elements include observations, rational argument, inference, skepticism, peer review, and reproducibility of the work. This characteristic of science is also a component of the idea that "science is a way of knowing" as distinguished from other ways of knowing (Feyerabend 1988a; Moore 1993; NGSS Lead States 2013, each cited by Nature of Science | NSTA, 2021)

The NSTA has eight recommendations that high school graduates should understand, and these are quoted below:

- Scientific Investigations Use a Variety of Methods;
- Scientific Knowledge Is Based on Empirical Evidence;
- Scientific Knowledge Is Open to Revision in Light of New Evidence;
- Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena;
- Science Is a Way of Knowing;
- Scientific Knowledge Assumes an Order and Consistency in Natural Systems;
- Science Is a Human Endeavor; and
- Science Addresses Questions About the Natural and Material World. (*Nature of Science | NSTA*, 2021)

The expectation is that science students will conceptually understand provisionally true conclusions or tentative theories. This concept is a felt need by the NSTA and should be included in high school science education outcomes.

Science Teachers Association of Ontario

The Science Teachers Association of Ontario (STAO) position paper is not as lengthy as the NSTA's nor well researched; the two-page position paper on the Nature of Science references the provisional sense of theories. "Scientific laws and theories must be logical, testable…" (*Position Papers | STAO*, 2021). Testability is a synonym for falsifiability as the verified conclusion is not assumed. The authors include the phrase "scientists continuously assess and judge the soundness of scientific knowledge claims by testing laws and theories and modifying them in light of compelling new evidence or a re-conceptualization of existing evidence" (*Position Papers | STAO*, 2021, paragraph 1). Scientists will consider theories as true until other disconfirming information might be discovered.

The Science Teachers' Association recognizes the importance that students understand the nature of science. STAO members are supported by book selections that address the nature of science. These are mirrored from the NSTA store section, and three of these works deal with teacher preparation and inquiry. While the word inquiry does not necessarily include falsifiability, the inquiry books written for high school teachers include the idea specifically.

The Ontario Ministry of Education curriculum guidelines from 1987 shows the tentative nature of science clearly. "When dealing with any theory in the classroom, the teacher is expected to discuss the strengths, limitations, and the tentative nature of the theory with students" (The Ontario Ministry of Education, 1987, p. 55). This reference is from the part one document and “sets the stage for the science program; it establishes the framework within which each of the science courses is to be taught” (the Ontario Ministry of Education, 1987, p. 2).

My research into other Ontario Ministry of Education documents from that time indicates data and evidence to support NOS.

> Traditionally, many science courses have been designed around only one emphasis, Solid Foundations. The introduction of alternative curricular emphases constitutes one factor that should positively affect student achievement and student retention. Research has shown that student achievement is closely related to such approaches to the teaching process. A recent Ontario example is found in the report on the 1983 OAIP[1] Field Trials in Chemistry. This report cited evidence that student achievement was positively correlated to the discussion of scientific issues and values while negatively correlated to doing problems (The Ontario Ministry of Education, 1989, p. 6)[2].

The Ontario Assessment Instrument Pool (OAIP) questions were oriented toward a wide selection of NOS concerns. The data collected for Chemistry demonstrates that students prefer higher-order questions when compared to calculations. The revised science guidelines have diluted the NOS's statement and adopted the phrase *stable science*. In stark contrast, the Ontario Ministry of Education pivots on the process of science after this STAO position paper quotation.

> Occasionally, theories and concepts undergo change, but for the most part, the fundamental concepts of science – to do with phenomena such as the cellular basis of life,

[1] OAIP refers to a much older document referred to as the Ontario Assessment Instrument Pool.

[2] There were two 6 teacher committees for the Review and Implementation Branch for the Ministry of Education. One was for Chemistry, and I was on the Physics committee. The Ontario Assessment Instrument Pool (OAIP) had questions that were selected oddly as I don’t remember the same NOS questions selected for the Physics testing, and this was only for Chemistry tests. This was referred to as A Report Card for Ontario

> the laws of energy, the particle theory of matter – have proved stable (The Ontario Ministry of Education, 2008, p. 4).

Sometimes an association may make recommendations. Still, through the confluence of stakeholders, writers, and supervisors, all the suggested elements are not included in the final product.

International Baccalaureate

The International Baccalaureate (IB) curriculum is an established and standardized curriculum worldwide (Become an IB World School, n.d.). Examining the curriculum document demonstrates that the IB physics curriculum has an emphasis on the nature of science. NOS is spelled out clearly in their "Nature of Science Pilot Guide" from 2017 (*IB Documents Team Resources Repository*, 2021, p. 12). The curriculum writers for 5,000+ high schools have made NOS important in their documentation. Challenging conclusions are an element of NOS, as well as a theory of knowledge (TOK). Students taking senior physics are primed with ideas concerning the tentative nature of scientific conclusions. These connections between the TOK and Physics course curriculum are documented clearly.

> It is now widely accepted that there is no one scientific method in the strict Popperian sense. Instead, the sciences utilize a variety of approaches to produce explanations for the natural world's behaviour. The different scientific disciplines share a common focus on utilizing inductive and deductive reasoning, the importance of evidence, etc. Students are encouraged to compare and contrast these methods with the methods found in, for example, the arts or in history. (Nature of Science Pilot Guide | *IB Documents Team Resources Repository*, 2021, p. 11)

The explicit mention of Popperian, deductive and inductive reasoning makes it obvious that NOS is explored. There are references given to teachers, and there are curriculum connections made to the TOK course. Knowledge questions are open-ended questions about knowledge and include questions such as:

- How do we distinguish science from pseudoscience?
- When performing experiments, what is the relationship between a scientist's expectation and their perception?
- How does scientific knowledge progress?
- What is the role of imagination and intuition in the sciences?
- What are the similarities and differences in methods in the natural sciences and the human sciences? (Nature of Science Pilot Guide | *IB Documents Team Resources Repository*, 2021, p. 12)

The curriculum writers have clarified what needs to be questioned and what discussions need to be experienced by students. This IB statement is much more specific than the position statements of the NSTA and STAO. NOS with specific references to Popper and falsifiability are made. Those graduating students will have had a rich experience in the philosophy of science.

Advanced Placement

The Advanced Placement (AP) Physics 1 (Algebra) program is a rigorous physics instruction program done at the pre-Calculus mathematics level. This level of study for physics is taught in the province of Ontario.

Any high school that wishes to have its students write the AP examinations in the spring of each year must apply for this. Physics teachers must have gone through a professional development period and obtain AP certification. The course outline used by the AP physics teacher must comply with the immediate agency, that is, the Ontario Ministry of Education. Course outlines must satisfy the conditions detailed by the Advanced Placement College Board (Teaching AP for the First Time? - AP Central | College Board, 2016).

The AP examination compels students to become proficient at performing calculations. This series of skills tests for problem-solving through a thorough understanding of the physics content: "6.5 The student can evaluate alternative scientific explanations - Not tested in AP Physics 1" (*AP Physics 1 - AP Central | College Board*, 2017, p.199). This large document provided to AP physics teachers examines many pedagogical matters for the physics teacher. Still, there is nothing concerning NOS.

NOS questions would take a much more considered assessment which at this time is not readily available. AP students are not as well versed in NOS. I include this only because NOS requires time and effort to assess after a specific and concerted teaching effort. The AP Physics program would not support NOS and is interested in only the excellence associated with problem-solving. By inspection of the guidelines and the nature of the assessment, NOS ideas are not addressed. It would appear that the Advanced Placement College Board decided to ignore NOS as their job is to demonstrate competency in core content and skills (Teaching AP for the First Time? - AP Central | College Board, 2016).

The Philosophy of Science Perspective

As a necessary aspect to the nature of science (NOS) or the nature of scientific knowledge (NOSK), falsifiability dates back to Sir Karl Popper, a Philosopher of Science. His seminal work, The *Logic of Scientific Discovery,* was published first in German in 1934 and later in English (Popper, 2002). The premise is based on the logical asymmetry to the verification of results versus the falsification of results. No verifying results can prove a scientific conclusion, yet one falsifying result can definitively disprove the scientific conclusion. "Scientific theories are perpetually changing. This is not due to mere chance but might well be expected, according to our characterization of empirical science" (Popper, 2002, p. 50). Provisional conclusions and theories take on a different complexion, with corroboration being how a tested conclusion or theory could be assessed (Veronesi, 2014). We use theories to explain results until we find that the theory no longer suffices. The process continues with new conjectures.

Paul Feyerabend, a former student of Sir Karl Popper, has argued that science is not especially rational. This claim of irrationality is a theme in Feyerabend's works, *Against Method* and *Farewell to Reason.* There is an implied debate against Popper's ideas that would include the logic of scientific discovery is a rational activity (Feyerabend, 1988a; Feyerabend, 1988b). Still, there is a disconnect between the logic of scientific discovery and the method of scientific discovery. There is more in common between the two philosophers than there is a difference; "the central theoretical terms used in Feyerabend's paper have a traceable Popperian pedigree" (Collodel, 2016, p. 40). The fine distinctions made in the philosophy of science are academic and of no practical use or discussion with high school students. Those distinctions are well past the understanding of a high school science student, but Popper's ideas are within their understanding. Even though naïve falsification is being promoted, this is sufficient for high school students to understand the aim and limitations of science.

Popper's work points to two important ideas that are integral to any discussion of the Nature of Science. They are the "problem of induction" that verification situated science needs to explain, and the "principle of demarcation," or the ability to discern science from non-science. "I shall not require of a scientific system that it shall be capable of being singled out, once and for all, in a positive sense; but I shall require that its logical form shall be such that it can be singled out, by means of empirical tests, in a negative sense: *it must be possible for an empirical scientific system to be refuted by experience*" (Popper, 2002, p. 18).

To use the idea of testability criteria is a simple one to determine whether human activity is science or not and should work nicely. Due to the testability criteria's simplicity, academic counterexamples are not a concern for high school science teachers. Philosophers and scientists note these counterexamples as exceptions, and we find both in Pigliucci and Popper. Pigliucci writes the following.

> There are also philosophers like Larry Laudan (1983) who simply think that the whole project of demarcating (as Popper [1961] famously put it) science from pseudoscience is hopeless and misguided and should therefore be abandoned. The truth, I think, lies somewhere in the middle: some claims made by evolutionary psychologists and neurobiologists may be questionable, and if so, they need to be scrutinized and may end up being rejected, without this necessarily leading to impugning the whole discipline as pseudoscientific (Pigliucci, 2015, p. 571).

Scientists in those fields can look at counterexamples and argue what science is and what is not science. Popper's demarcation principle is easy to perform and sufficient for the vast majority of citizens and for the rest of society.

Contra the Laudan argument, there is actual, well-identifiable pseudoscience out there, including, but not limited to, astrology, homeopathy, ufology, parapsychology, and the like. To reject the whole idea of a demarcation problem would fail to make important distinctions that are both of theoretical interest (to epistemologists and philosophers of science) and sometimes great practical import, for example, in public policy discussions about vaccines, climate change, so-called alternative medicine, and many others (Pigliucci, 2015, p. 571).

Testability, even if only in principle, is an important principle for science students to understand when assessing whether knowledge is scientific or not. Knowing what science is and is not is important when making decisions. Holding to an incorrect assumption would happen if there was a pre-existing belief in that phenomenon. With the Afonso and Gilbert (2010) study, the subject was water dowsing, and the test subjects were high school students. Suggestions by some of the students involved, "'science does not require evidence'; 'empirical designs'; 'impossible to enquire,' underlying the idea that beliefs cannot be tested by science; and 'unable to enquire' (Afonso & Gilbert, 2010, p. 336). This, of course, is nonsense but a problem with early expectations. The resistance to challenge the phenomenon is a clear indicator of something other than science being employed or considered. This water-dowsing example is a wonderful example of the impotence of verification. The obvious question would be, where in the world can you not find water? Dowsers do not report on how deep the water might be. Fossil or paleowater are other sources of water that have been sequestered naturally for thousands of years. These also populate our world. It might be difficult not to hit water should the drilling length not be in question. Water from the surroundings might fill a dug well and verify the veracity of the water dowser or dowsing phenomenon. Arguably, the process cannot be falsified, and with that, water dowsing cannot be explored scientifically.

Water dowsing and other pseudoscience examples are deftly characterized by the demarcation of science versus non-science and their resistance to authentic testing. While some science is still too complicated or chaotic to be tested for conditions, they can be in principle. Such is the case with the Einstein space-time exploration with the Eddington Expedition and the solar eclipse. At the time, at least in principle, an experimental condition could authentically test the space-time assertion.

As an outcome of falsification, Demarcation is another important aspect of NOS. It provides a “rough and ready” solution that, with practice, a class of high school students could acquire this skill. The skill being creative, of course, but experimental too. The techniques needed would be the answer to the generic question, “what evidence would you need to see to reject the current theory?”

Science is not just simply the refutation of conjecture; there are other activities. When conjecture is shared in the science community, the refutation of that conjecture is not an ordinary event. However, discovery is an extraordinary event. For Popper, that is the focus of the philosophy of science (Popper, 1972, p. 191). Popper’s philosophy of science is about the logic of discovery and, as a result, represents the extraordinary science events that lead to scientific discovery. These events are few and far between in any real sense of the word. They are the turning points in science and have much historical significance.

When scientists are not making discoveries, they are still performing scientific activities or ordinary science. Such normal science is practiced every day and needs to be contrasted with discovery. Thomas Kuhn explores ordinary science and posits the paradigm. He explores the nature of the paradigm as both a framework that allows scientists to work coherently and as something that becomes a problem for scientists who need a different way to make sense of new observations. Those scientists would perform a paradigm shift, and the new theories would be considered different (Kuhn, 1977). So, for Kuhn, there are two aspects of science that need to be considered. First, the paradigm should attract a group of scientists who find it easy to work within its scope. Second, the paradigm should have unresolved aspects to it which allow for further study. Should a paradigm explain all that is known and leaves no room for further exploration, science stops progressing (Kuhn, 1970).

> Achievements that share these two characteristics I shall henceforth refer to as 'paradigms,' a term that relates closely to 'normal science.' By choosing it, I suggest that some accepted examples of actual scientific practice – examples that include law, theory, application, and instrumentation – provide models from which spring particular coherent traditions of scientific research (Kuhn, 1970, p. 10).

The understanding of the paradigm or framework is important for its juxtaposition of the philosophies of science by Karl Popper and Thomas Kuhn. Thomas Kuhn has made considerable advances in making ordinary science understood by educators of science and other academic fields of study. The phrase "paradigm shift" is owed to Kuhn and describes scientific discovery. "It has been said that in Structures, Kuhn used the word "paradigm" in 22 different ways. He later focused on two different meanings" (Hacking, 1983, p. 10).

For Kuhn (1970), scientists must always work within a paradigm explaining their view of investigation entities, such as that electrons are negatively charged objects. For example, paradigm-as-an-entity is one perspective. In contrast, the "regularities are features of the ways in which we construct theories in order to think about things" (Hacking, 1983, p. 38). Then, of course, the paradigm-as-a-theory is another perspective. In the case of an electron, the paradigm-as-a-theory would dictate the behaviour of the electron.

There is an interplay between these two senses of paradigm that are required to understand ordinary science. It is important because it gives falsifiability two areas to consider. The experiment with results that falsify the theory could point to a problem with how the entity is viewed. Still, it can also point to the theoretical presumptions required to make sense of the behaviour, for example, is light a particle or wave? That is an entity-based question, while how entities behave is a theoretical question. Falsifiability could be considered for either of the paradigmatic tests.

Matthews (2004) submitted that Kuhn's work has been well received, but Kuhn and Popper did not immediately make inroads into science education. Both were integral to understanding science but perhaps not understood enough to be immediately included in science education published works.

> The very first science education book to deal with the place of philosophy of science in science teaching was published in 1968. This was John Robinson's *The Nature of Science and Science Teaching* (Robinson, 1968). Kuhn is nowhere mentioned in its 150 pages. Robinson's book was entirely predicated upon the then dominant, logical empiricist analysis of science. Not even Popper, whose antipositivist *The Logic of Scientific Discovery* appeared in 1959, is mentioned (Matthews, 2004, p. 94).

While Kuhn and Popper did important work, there is an obvious reluctance to change science education philosophy in the 1960s. The reason given by sociologist of science Steven Fuller is that by the middle of the 1960s, Kuhn and Popper were better known "by reputation than readership" (Fuller, 2003, p. 29). Without a readership, there is no real understanding of the subtle differences integral to making sense of NOS. Fuller describes "scientists not being taught to be mentally flexible" (p.38). If it is difficult for scientists to keep two paradigms in mind simultaneously, it would be so for teachers and students. Ironically enough, it could mean that the current paradigm of educational research needs to change before a new paradigm takes over.

NOS Educational Research

At the outset, the literature points to falsifiability and its utility in interpreting conclusions. Falsifiability is considered outside of science education. The epistemological outcome is of importance to researchers. However, philosophically, the value of Popper's ideas has not made sufficient inroads into scientific research and is not second nature to educators, but not because of the strength of Popper's arguments. There are research papers critical of not adhering to the requirement of falsifiability in allied research areas, such as Sports science. Wilkinson (2013) argues,

> The well-documented solution provided by Popper's falsification theory, the majority of publications are still written such that they suggest the research hypothesis is being tested. This is contrary to accepted scientific convention and possibly highlights a poor understanding of the application of conventional significance-based data analysis approaches. Our work should remain driven by conjecture and attempted falsification such that it is always the null hypothesis that is tested. (p. 919)

Philosophically, Wilkinson sees potential problems with statistical research in terms of verification and falsification. Science-oriented research is always an error-correcting process, but it is easy to think that scientific research is being done, but at the very core, it is not scientific. Wilkinson is not alone in this appeal to correct the scientific viewpoint. Stephanie Chitpin (2013), while not a philosopher of science, has seized on the deductive logical processes to assessing educational research.

> The intent of this article is not to persuade educators to adopt Popper's approach uncritically to build their professional knowledge. Rather, it presents a discussion on the need for teachers to adopt a critical approach in eliminating what is inadequate and

preserve what is adequate by modifying or abandoning whatever traditions or practices that are inadequate to improve their teaching practice (Chitpin, 2013, p. 833).

Epistemologically there is a change in how knowledge is critically examined and used in fields outside of science. Popper's falsifiability criterion is used to provide deductive conclusions that are always absolute, favouring the quasi-probably true knowledge claims of inductive conclusions. Chitpin's (2013) work with falsifiability being successfully employed in other areas only adds credence to falsifiability being a very important knowledge-creating technique. Just like the IB program emphasizes the TOK and favours those students immensely, Chitpin's work does the same for educators of teachers.

In an email communication with Dr. Chitpin, I was amazed at the scope of falsifiability used in educational leadership at the University of Ottawa. A portion of Chitpin's bio explains, "Dr. Chitpin's principal contribution to leadership and the professional development of principals rests on her rejection of the inductive method. She argues that knowledge is acquired by hypotheses deductively validated as 'falsifiability criteria'" (Biography | Proximify, 2021).

Inductive methods or repeated similar results of any kind present a difficulty. The verifications bring with them a psychological certainty or something that feels correct. This affects educational research and is an example of NOS not being clear in the mind of a much larger sample of people. Psychological certainty is a problem that has some researchers wrestle with their research (Chitpin, 2013; Hyslop-Margison, 2010; Wilkinson, 2013). Popper correctly recognizes that it is notoriously simple when collecting data to obtain confirmations or verifications of particular hypotheses when researchers actively seek out such findings (Hyslop-Margison, 2010). Psychologically, confirmation bias is a precursor to this problem of not testing conjecture for at least potential refutation.

There is a need for teachers and preservice teachers to understand NOS. According to Melville and Bartley (2010), “in 1988 a new curriculum was implemented across the province [of Ontario]. According to the new curriculum, science was a human construct that was to be viewed as tentative, subjective, empirical, and integrative” (Melville & Bartley, 2010, p. 813). From my research into the last one hundred years of Ontario Ministry of Education curriculum documents, this was the first time an explicit tentative nature of scientific theories was expressed. Even though twenty years passed from the published document to when Melville and Bartley performed their research on NOS and other issues in teacher mentoring, what was explicitly stated was “one result is that inquiry is not common in schools” (Yager, 2005, as cited in Melville & Bartley, 2010, p. 924).

Theory change is yet another way of saying theories are tentative and subject to change in the face of disconfirming evidence. Abd-El-Khalick & Lederman (2000a) look at this specifically, but with biology students and evolution. After taking a biology course on evolution, a group of students tested the tacit assumption that students in university science courses understand NOS sufficiently. Even though the idea that scientists do not prove theories to be true was explicitly taught, the concept is hard-won.

> Two examples would suffice to demonstrate the tenacity with which many participants held some of their pre-instruction NOS views. Twelve Evolution course participants had indicated at the beginning of the study that scientific theories do not change or are merely elaborated. Theory change was a major theme of the Evolution course, and the course professor made several explicit references to the tentative nature of theories. Despite all that, eight of these 12 participants (67%) still maintained after the study that ``a scientific

> theory does not change through time . . . It can, however, be expanded or added on to with the development of modern science. (p. 1083)

A staggering result because the students involved in the testing are seeking a degree in science. At its most basic understanding, the NOS points are lost. As NOS is the basis of all the sciences, the most fundamental ideas are not understood first.

Students with a background or degree in science can become science teachers, and the admissions from science teachers indicate that nothing has changed. “Many teachers feel that their NOS knowledge is insufficient for the task” (Hodson, 2006, p. 305). There are currently NSTA resources that support teachers with NOS and inquiry issues in the class. However, the situation in 2006 may have been different as the complaint from the same investigation was, “few have sufficient ready-made curriculum materials on which they can draw” (Hodson, 2006, p. 305).

If science courses as written currently are not sufficient to bring out NOS items, what would be a good approach? Scientists have faced the same dilemma and exploring the experimental situation and the possible conclusions would be a good approach. History itself has the answer for us but looking backwards and cleaning up the process would make it more efficient.

Wong and Hodson (2009) explore the historical approach and find, “there is also some encouraging evidence that well-designed historical case studies can be effective in bringing about NOS understanding” (p. 113). What is special about the well-designed historical case studies is discussing previous theories and the challenges to those. A well-designed historical case might present the process of science in a tidy manner. The noise of other objections or conjecture, which ultimately did not add to the scientific thinking line, does not need to be explored with students. The history of scientific discovery abounds with many other conjectural offerings, but they were short-lived.

History demonstrates that scientists use a metaphorical understanding of science. Understanding the changes in metaphor illustrate the changes to the theories. By way of example, the atomic theory for a time considers the J.J. Thomson “raisin bun” model of the atom as a worthy metaphorical conception. Metaphors can assist the scientist in understanding and, by extension, the student of science.

It is not surprising then “that scaffolding authentic modelling activities will promote students’ understanding of models as well as of content knowledge. We seek to address this important question as our work on this project unfolds, thereby contributing to this important area of science education” (Gobert et al., 2011, p. 679). Further, Gobert et al. make it clear that students be required to:

> (1) learn the use of models, that is, to explore scientific phenomena and conduct experiments, (2) learn to revise models with new evidence or feedback, and (3) learn how to construct models of scientific phenomena. It is believed that these instructional activities will foster students’ modelling knowledge, including their understandings of the nature and purpose of models. (p. 679)

While instructional activities may be designed to motivate and monitor the way students produce experimental results and document classroom activities, the success of understanding NOS is due to the degree of play involved. Experimental play can be seen from exchanges with students, phrases such as: “Lina: Mm [Yes], I don’t know, but the actual word ‘experimenting’ feels more like play and fun than ‘laboratory task’” (Gyllenpalm & Wickman, 2011b, p.915). Further, Gyllenpalm and Wickman (2001b) state:

> The objective of an experiment is to test hypothesized links of causation or functional relationships, that is, tentative explanations. Often an experiment will be motivated by either an observed or a hypothesized correlation. (p. 911)

There is a wide spectrum of scientific activity, and motivations need not be rational either. Motivations and play have much more to do with the conjecture and with the refutations. The Eureka moment is a much-desired outcome for scientific activities.

Perspective: The Science Teachers

NOS has been included with the testing of scientific literacy for PISA examinations, but only since 2006. Commenting on PISA scores of 2006, students were for the first time asked a deceptively simple question, “What is important for citizens to know, value, and be able to do in situations involving science?” (Bybee et al., 2009, p. 862). Knowing the nature of science is integral to answering this type of question. The top PISA scores for Finland demonstrate a deep understanding of the nature of science and not just concepts and calculations. The nature of science comes from many projects Finnish students complete, both in class and outside of class (Symeonidis & Schwarz, 2016). Phenomenon-based teaching and learning demand authentic and real-world problems to solve. The Finnish student holistically learns this, as I will later refer to it as, phenomenon-based learning. Being multidisciplinary in scope, science forms only one aspect of learning.

> Inquiry is not used in textbooks. There is only one concept for different kinds of activities in Finland where students are doing activities with their hands and then making conclusions based on that activity. Practical work can also be very inquiry-oriented, even though teachers do not emphasize inquiry terminology.
>
> (Lavonen & Laaksonen, 2009, p. 937)

Consistently high PISA scores in science before and after 2006 speak to the success in teaching NOS through projects and hands-on activities. Curiously, scores have changed since then, but the Finnish educational system is still moving forward with phenomenon-based teaching where scientific inquiry forms only one aspect. The phenomenon-based teaching also compels the Finnish Educational system to move toward an integrated approach to teaching, and there is less attention spent on the subdivision of science.

This approach is not the case for the North American science education system. So far, the focus has been on physics, but science is not just physics and chemistry, but biology too. Studies have shown that biology students experience the same problems of understanding the NOS as the physical sciences. There is no real difference with biology either. The provisional nature of theories and any conclusions is not obvious. Sandoval (2005) concludes his study into NOS concerns by explicitly tying together two lines of research. Sandoval considers that students' practical epistemology is important (experiments and demonstrations) but must also be connected to the ideas presented in a formal manner that constitutes what he calls "formal science" (Sandoval, 2005, p. 652). Regardless of the branch of science, common problems are understanding NOS at the high school and post-secondary levels. Afonso and Gilbert (2010) suggest that "although an understanding of the nature of science is a core element in scientific literacy, there is considerable evidence that school and university students hold naïve conceptions about it" (p. 329). Not only is this a common problem in the sciences, but it is also a perennial one. "Over the last 40 years, many studies have shown that there is a widespread weakness of understanding of NOS" (Afonso & Gilbert, 2010, p. 330).

According to Abd-El-Khalick and Lederman (2000b), teachers believe that scientific knowledge is not tentative (p. 669). Given this belief by their teachers in the conclusive and final nature of scientific claims, it is not surprising that science students' ideas and attitudes do not include the provisional nature of scientific conclusions.

Clearly, “a major *affective* [emphasis added] goal of science teacher education should be the enhancement of the philosophical viewpoint that science is a tentative enterprise, and that scientific knowledge is not absolute” (Abd-El-Khalick & Lederman, 2000b, p. 677). This can only be realized when the ideas that clear this misunderstanding of tentative conclusions are concise, cogent and activity oriented.

Abd-El-Khalick and Lederman (2000b) conclude that effective science teaching employs science activities that provide pre-service teachers time to reflect on aspects of NOS. While such activities may be engaging, there is still the problem of giving those philosophical ideas persistence within science teachers' minds. As such, forgetfulness is a problem. As Khishfe (2015) reports, “five months after instruction, these newly acquired understandings were not retained by all preservice teachers, where several of the teachers reverted to their earlier naïve understandings” (p. 1642). Khishfe is not alone with this problem either. Aflalo (2014) shows that after considerable experience with preservice student teachers, they “consider scientific knowledge to be objective and permanent, revealing the absolute truth and tending to flawed idealization of science” (p. 299).

The importance of preservice science teachers' experience cannot be understated. Their teaching and learning about NOS should be a part of their practical training in teacher training schools (Aflalo, 2014). Making this a regular part of science teacher education would make it less likely to be something that is forgotten or, worse yet, ignored. The Finnish science teachers often see this as another important aspect of science teaching.

There are specific skills to isolating those aspects of NOS within experiments, demonstrations, and discussions of the history of the science. Scientific modelling practices should be taught explicitly and emphasized as an authentic scientific practice. Gobert et al. (2011) suggest “a modelling framework, which describes how modelling should be taught in classrooms so that learning is authentic for students. The components described by Justi and Gilbert are consistent with theories of model-based teaching and learning” (p. 679). This approach is not unique as Schwarz and his co-researchers also promote the explicit teaching of models and modelling and suggest a need for meta-modelling knowledge (Schwartz et al., 2004).

The literature presents a strategy with students' engagement and puzzling through a deep understanding of models and scientific inquiry. Gobert et al. (2011) demonstrate that engagement and reflection with authentic modelling experiences are essential, but this must also align with the content.

The literature does make it clear that we know what does not work. There are inefficient ways to teach NOS. While Melville and Bartley demonstrate the success of a mentorship approach, they make it clear that working in isolation is not a good approach. A teachers' isolation should be avoided, with time given to each to have professional development experiences that encourage authentic modelling and thinking about inquiry processes (Melville & Bartley, 2010).

Conclusion

NOS, in terms of falsifiability, is an essential aspect of a high school science curriculum. NOS is specifically called for by teacher associates in both the US and Ontario. While it is missing from some science curricula, all science teachers do not firmly understand NOS. Several approaches have been explored that ensure NOS has its place in science curricula and high school science classes. A notable conclusion is that NOS needs to be understood by all science teachers so that more laypeople will understand NOS when decisions are needed to be made.

There needs to be a philosophical underpinning prepared for science teachers in terms of teacher education and preparation. Teachers in the classroom currently need to understand NOS. Some teachers do, but the literature shows that many do not.

Science teachers should understand the logical implications of inductive logic and deductive logic. Science teachers must understand that there is a probabilistic truth to inductive logic. Inductive logic must be compared to the certainty of deductive logic. After that comparison of logical types, there will not be a question as to why falsifiability must be included in NOS considerations of any science. These scaffolding ideas make provisional truth an easier concept to understand and retain.

Second, the next rendition of the Ontario Science Curriculum document needs to be revised. Rather than the misleading term "stable science," a better phrase needs to be used. The NSTA has a much better way of explaining scientific conclusions, that is, "scientific knowledge is simultaneously reliable and subject to change. Having confidence in scientific knowledge is reasonable *while also realizing that such knowledge may be abandoned or modified in light of new evidence or a re-conceptualization of prior evidence and knowledge*" (*Nature of Science* | NSTA, 2021).

Third, students require the time and the occasion to deal with experimental design, but this must be appropriate to their level of understanding. While inquiry science is highlighted in the Science Fair Handbook (Fredericks & Asimov, 2005) it is not explicitly explained. After the

5Es[3] are established in elementary school, greater rigour with falsifiability should be included (Fredericks, Anthony, personal communication, June 3, 2020). Research in high school shows that students like this aspect of doing science more than content and problem solving (The Ontario Ministry of Education, 1989, p. 6). This attitude is supported by Blackie (2012), who argues, "the role as an educator is not so much to 'teach' problem solving as to provide an environment in which the innate problem-solving ability of students is evoked" (p. 162). Exemplars accomplish this implicit engagement in scientific problem-solving.

There are historical examples of theory change that can be used to illustrate this problem-solving process. Specifically, a particular model being falsified by experimental findings that can be done within a typical science lab, for example, transitions from the atomic model of 1808 to the plum-pudding model of 1904, to nuclear model of 1911, to the planetary model of 1913 to a quantum mechanical model of 1926 and onward. Each transition is a classic experiment where the predicted outcome does not occur, and the entity-as-a-paradigm and the theory-as-a-paradigm must change.

Exploring the active and participating demonstration-style depicting the history of theory change is needed to highlight the scientific process. That is, science progresses when there are conditions where predicted results are not achieved. All of this can be engaging but needs to be organized throughout the curriculum and textbooks. McComas (2004) illustrates this process as weaving NOS lessons. Making the concepts integral is necessary and should not be simply introduced at the beginning of the unit.

The talent and skill of good teachers start from producing and using engaging materials and activities. The success of inquiry science in the elementary grades is a testament to that

[3] This is a framework for Inquiry Science, and typically the 5Es is the abbreviation for these steps to the process of scientific inquiry, and they are: Engage, Explore, Explain, Elaborate, and Evaluate.

statement. Building on that and blending in the critical elements of falsification is the way to successfully “weave NOS lessons” into the secondary science curriculum.

At the risk of sounding trite, science teachers simply need to reproduce the historical examples of awe and have students relive Eureka moments. Help in this regard is needed and another aspect of this portfolio’s plan.

Chapter 3: Plan for Portfolio

The Two Perspectives

Nature of Science (NOS) needs attention. Evidence shows at least two different approaches are required to help make NOS better understood by students leaving high school science classes. While I chose physics as my focus, other areas of science, such as Biology and Chemistry, can be adjusted to encourage the understanding of NOS.

I will use this double-barrel approach to help the science teacher with specific examples. These examples or exemplars will help illustrate the idea of falsifiability during the performance of experimental activities. Employing these and others in any science teaching curriculum will help science students fully understand NOS in falsifiability. Another facet to this idea is the logic of scientific discovery. More than the title of Karl Popper's seminal work, the logic of scientific discovery provides both the science teacher and the science student the mental conviction of NOS.

The illustrative names for my two perspectives are: (1) The Participating Demonstration Perspective (PD) and (2) The Science Curriculum Perspective. To the new science teacher, the PD perspective provides concrete exemplars of how scientific discovery has worked. Science teachers experience the PD in several ways to bring the logic of scientific discovery to the foreground of their thinking about science teaching. I think that the exemplars given will seed the minds of teachers. Teachers will develop their PD exemplars, for the field of science is a wide and ever-increasing expanse of provisional thought.

A teacher proficient with PD can even mime events so that questions can be formed in the minds of students without specific verbal cues. In the privacy of their thoughts, students can think of the expectations and be challenged by the reality of the experimental result. I draw attention to this mime version, which might not be the teacher's toolbox's favourite tool, but top drawer or not should be ready to be employed when appropriate. Other times there can be a buzz of student activity with questions, observations, and suggestions.

Science teachers may remember classic experiments or demonstrations. The notable elements may come from the classic experiment or demonstration, and NOS is then extracted. For this reason, one could argue that PD forms a top-down approach to understanding how NOS fits into any science curriculum. Examining curriculum documents could be considered the bottom-up view. Science teachers do not need to begin with experimental work but look to planning and curricular expectations as the prime concern. For teachers who begin their thinking in this way, the curriculum perspective involves teacher prompts or suggestions that focus on the type of situation and questions that should be asked regarding specific curriculum expectations. As my examples show, nearly every experiment or activity can have at least one question or scenario that draws attention to NOS in terms of authentic testing.

The Participating Demonstration Perspective

The PD perspective deals with demonstrations provide opportunities for questions that directly deal with the idea of falsifiability. Except for PD #2, as listed below, the other five necessarily fit into any high school physics curriculum as the concepts are integral to any physics curriculum. I would expect all physics teachers able to use the exemplars and do this effectively in the classroom. I have provided these exemplars for their simplicity.

Chapter 4 will be an exploration of six different PDs. These PDs are titled:

1. Heavy Things Fall Faster Than Light Things
2. Experimental Design with Falsifiability

3. Why Do Meteors Burn Up on Hitting the Atmosphere?
4. Monkey Hunting Gun
5. Mass On a String
6. Wave Phenomena in the Hallway

Each PD will focus on questions that help students express an expectation and formulate a conjecture. These, of course, are critical and more than mimic the thinking process of science. A sample discourse illustrates to the reader how the process might play out, but this is only a thumbnail sketch as students do not necessarily do what teachers expect. Prompting students to think through their expectations is important, and not telling them what to expect is key. Being the devil's advocate and providing a competing expectation may be needed. From my experience as a teacher with experience teaching science to this grade level, I would fully expect most students to believe that heavier things fall faster than lighter things. Other students may have already learned that there is no difference, but it might require additional prompting to ask whether lighter things fall faster than heavier things. Of course, this is intuitively false, but students must consider the logical possibilities.

Once the expectations are expressed verbally, teachers attempt to have students explain why they believe in their expectations. This is the conjecture and can be simple in nature. The pièce de resistance is the experiment to see whether the expectation is falsified. In the case of the first PD, heavy things do not fall faster than lighter things.

It is vital that the teacher does not encourage students to understand that all things fall at the same rate before the experiment. This action short circuits the logic of scientific discovery. The experiment then becomes a simple verification of what was related to the students. Verification might appear to be efficacious in that it might be easy for students to remember what they are told. However, it does not support the inquiry process nor allows students to experience NOS.

Once a PD has been experienced, it becomes a landmark for teachers to refer to during the remainder of the course or courses. Bringing students back to this point is as easy as asking questions such as: What did we learn about dropping books? Another expression of the same question might be: Did two books fall faster than one book? Questions must be expressed in this way. The challenge of the common expectation by experiment must be paramount. The question should not be asked in this manner: How do we know that all things fall at the same rate? The point is to have students work with their expectation and falsify it. Students should remember their intuition or expectation and what happened to disprove that notion.

By way of example, in grade 11 physics, the first PD should demonstrate that heavier things do not fall faster than lighter things. Establishing that movement due to gravity is independent of mass is important. Later in physics, the curriculum is directed towards projectile motion in two dimensions. These equations do not contain a mass value and confuse students because there is an intuition regarding movement with heavy things and lighter things. Referring back to the first PD and the landmark status the results provide, students are reminded of this, or more accurately, the students' established fact.

The derivation of the formula for projectile motion can be accomplished with only kinematic equations. As they do not involve masses either, it should be obvious in the beginning. This curriculum connection shows the importance of pairing some PD too. This pairing is demonstrated with Heavy Things and the Monkey Hunting gun. The first PD provides background so that the monkey hunting gun PD is easier to understand. The scaffolding of ideas is an important aspect of physics development, and the PD is not an exception. The monkey hunting gun PD provides two components of motion for students to consider. The vertical component relies upon an understanding that motion is independent of mass. The acceleration due to gravity is always the same. Students may need the security of this idea to move forward with the two-component system explored in the monkey hunting gun. Referring to the first PD on my list is necessary to remind students of what they understand.

The Science Curriculum Perspective

Using the current physics curriculum as a template, the idea of the teacher prompt will be included with both the grade 11 and grade 12 curriculum. The curriculum documents generally advise the physics teacher of the experimental and activity experiences of big ideas. These big ideas are blended with the specific experimental activities printed in two different physics textbooks. The popularity of the textbooks was one criterion. They were also chosen by the Thunder Bay District Roman Catholic School Board to be used by both their high schools. Another reason was that I had used the textbooks previously and for many years. I was quite familiar with the textbooks. I was a reviewer for the grade 11 physics textbook and know firsthand the publishers' efforts to ensure that their textbooks are consistent with curriculum guidelines. Looking for consistency is standard practice.

Every textbook used in Ontario must comply with the Ontario Ministry of Education guidelines. It makes my work directly applicable for any physics teacher in Ontario. Page numbers would vary between textbooks, but the experiments and activities would vary only by nuance or form. The content would necessarily be the same for all Ontario physics teachers.

This perspective would be less directly applicable to teachers from other systems of education in Canada and around the world. By definition, a physics teacher from anywhere in the world would recognize the big ideas of the Ontario curriculum. While the textbooks used by other teachers in other parts of the world would differ, this is only an organizational matter. The focus of this second perspective in this portfolio applies directly to Ontario physics teachers, and it would take very little work to expand this to other areas of the world.

By linking the physics textbooks with the curriculum document, the teacher prompts suggested directly aid the teacher in including falsifiability and NOS into the physics classroom. There are more than enough teacher prompts to begin the process of changing student perspectives. I have provided a number to allow a teacher new to the profession to begin including NOS features from any unit of study in physics.

Generically, teacher prompts have certain common features. First, there is always attention drawn to the expectations the student might have. Of course, sometimes tinkering with the experimental equipment is required to have students formulate their expectations. The example I provide here is from the grade 11 curriculum, and the big idea is: Conduct an inquiry into the projectile motion of an object. To that end, often, the experimental procedure is written down, and students follow directions. It is essential that through thorough preparation and questioning, teachers can follow through with the following teacher prompts. Specifically, what is your prediction for the acceleration of the object travelling upwards? Second, what is your prediction for the acceleration of the object travelling downwards? Third, what is your prediction for the acceleration at the highest point when it is not moving or at its Apogee?

It is important to have those expectations articulated clearly. In small groups, students work best at puzzling through these situations. Historically I have found that students find it easy to see that the acceleration due to gravity is a constant for objects falling. Still, there is some difficulty understanding that this is the same constant value for objects moving upwards. The expectation is not the same, but the experiment easily remedies this. The expectation that it would be something else is disproved. The problem with the high point in any movement up and down is that students often think that the acceleration is also zero during the instant the object is motionless.

Generically, the point is to draw out the expectations and determine how this is tested experimentally. Verifying the expectation is necessary, but there are ranges to the experiment. There are experimental conditions where the expectations are not met. There will be unexpected situations for at least one part of the activity. The outcome challenges the student. The students learn to accept that expectation has been disproved and the current conjecture is not sufficient. It may be good enough but not complete. All the teacher prompts share this feature too.

In this specific case, helping students with problem-solving becomes easier. When students can review an experimental activity in their minds and relate that to the problem at hand with the inclusion of a diagram, a question to simply remind the student of what has been discovered makes the problem solving easier. The question is, what would happen if the acceleration were zero at the top of the projectile's motion? The questioning is much more than simply asking any question but asking a question that disproves their expectation.

Not all questions need to be posed this way, but it should be done when there is the opportunity to do so. This is how all people learn to understand the idea of falsifiability. It is too easy to see things through the lens of confirmation or verification.

I am confident that between the two perspectives outlined above, the NOS idea of provisionally true theories becomes clear in the minds of teachers and students. Learning to look for disproof of an expectation is the first step. To reconsider the conjecture or theoretical understanding due to disconfirming evidence is the next step. Provisionally true theories will be a better-accepted understanding.

Chapter 4: The Participating Demonstration Perspective

Teaching science is about using simple, convincing, and elegant experiments that students can perform. Through the examination of experimental phenomena, expectations are developed and come with some theoretical understanding. Students then examine their theoretical understanding. For these demonstrations, students will find aspects of their understanding to be disproved.

Such demonstrations must be interactive and not simply watched. The teacher's role is to control how the demonstration unfolds and engage students in expressing their expectations or predictions. Each expectation has some type of theoretical understanding. These demonstrations are easily tested authentically. Students associated the "Eureka!" moment when the experiment challenges their expectations, and the theoretical understanding must be changed to accommodate the falsifying observations.

Student participation is encouraged through engagement associated with the activities. Manipulating the experimental conditions is a teacher-directed exploration of the phenomena. Questioning the students' understanding of their expectations or vocalized predictions is paramount, but more importantly, an explanation for their expectations or predictions is required. The greater the elaboration, the greater the opportunity for the teacher to challenge the conjecture the students might hold to be true.

The experiment is an important aspect of the PD, and the test of the conjecture is either verified or, more importantly, the student conjecture is disconfirmed. The logic of scientific discovery is a process that becomes much more real for the student when emulated in the demonstration. It is this experience, the exploration and explanation, that are key. In this way, a new understanding begins.

Demonstration exemplars engage students. Students make predictions and articulate those explanations with a sense of theory too. Those expectations are then tested against the experiment. These exemplars are a beginning for all science teachers as they make NOS clearer in the minds of their students.

1. Heavy Things Fall Faster Than Light Things

Many students believe that heavier things will fall faster than lighter things. Heavy things falling faster is an intuitively obvious statement, and the error of this thinking is a pernicious one. A way to deal with this is by bringing attention to the obvious disconfirming evidence.

But how to test this easily? It does not take long to have students suggest that one textbook dropped from a particular height is done alongside two textbooks tied together. If heavy things fall faster than lighter ones, and one textbook is twice the weight of the other, there should be an observed difference in the time it takes to fall the same distance.

Before the students test the book dropping, it is best to document the possible observations of the experiment. Demonstrating with your two outstretched hands and modelling the movement of falling objects, it is easy to say that the left one will strike the table, followed by the right hand. The second possibility could be both left, and right hands strike the table at the same time. Finally, the other possibility is that the left hand will hit the table after the right hand. Demonstrating with your hands and slapping the table to provide the sound as feedback engages student sight and sound observation skills – priming students for the rest of the experiment.

It is not necessary for the moment, but students can be asked why they expect heavy things to fall faster than lighter things. Theoretical assertions may include the idea that the heavier stack of books has more mass and the force on the greater mass is a greater force. There are many renditions of this but committing to the expectation is important.

Allowing students to drop their physics books in various combinations, students can gain sufficient data. By this, I mean two identical books may be dropped simultaneously. Then two books in one hand and one book in the other hand may be dropped simultaneously. After the students have tried the experiment a few times, it is important to gather their observations. Some will be bewildered because instead of hearing a splat sound followed by another splat sound (heavy things fall faster than lighter), they hear simultaneous splats. Challenging the integrity of the experiment and, therefore, the observation, some will postulate that a one-metre drop is insufficient. Students could think that the one-metre drop is insufficient to sufficiently separate the books to hear the two distinct splat sounds. Dropping the books from the one-meter height above the tabletop can be essentially doubled by having the books fall beside the table and to the floor. Now the distance has been approximately doubled.

Simultaneous splats are irritating to most students, and while some might want to increase the height to three metres, good sense and safety should prevail. There can be locations within the school that would allow for much higher demonstrations. Schools with a stairwell allow for much higher drops, and allowing for ordinary safety procedures, very high heights can be used to test the experiment. The other potential parameter is the weight of the books. Students can increase the weight to three books, and the other book is only one book in weight.

The repeating of the experiments in different heights and differing weights fair no better. There are only simultaneous splats. Their conjecture is disconfirmed. After the activity, there is ordinarily doubt in the minds of many students. They do not believe their eyes and ears. In a simulated science discovery, they also witness what must have gone on in people's minds.

There are video accounts of this type of experiment published by NASA. One such experiment was done on the Moon with its absence of an atmosphere.

> During the final minutes of the third extravehicular activity, a short demonstration experiment was conducted. A heavy object (a 1.32-kg aluminum geological hammer) and a light object (a 0.03-kg falcon feather) were released simultaneously from approximately the same height (approximately 1.6 m). They were allowed to fall to the surface. Within the accuracy of the simultaneous release, the objects were observed to undergo the same acceleration and strike the lunar surface simultaneously, which was predicted by well-established theory (*The Apollo 15 Hammer-Feather Drop*, 2021).

This same demonstration can be done in a high school setting but is much more difficult in the high school laboratory. Still, an electromagnet can hold two different objects with different surface areas and masses at the top of a tube with much of the air removed. Evacuated or vacuum tubes and the falling metallic objects inside pose an increase in the probability of an accident. Even though the tube can only implode, there is the matter of moving glass shards. It is up to the technical understanding of the teacher that makes this direct observation of the problem worth the minor risk.

Nonetheless, the same predictions of a feather with a small sliver of metal glued to it and a piece of iron are not likely to fall at the same rate, but they do. Air resistance, which ordinarily confuses students, is reduced significantly. The greater sophistication of this experiment should convince a greater number of students, but there may always be ad hoc explanations.

Matthews (1994), an early pioneer in looking at the role of history and philosophy in the teaching of science, notes that the story of Galileo dropping two different masses of identical volume was a story and not an example of an experiment that he orchestrated (p. 103). While it is amusing to recreate this story with students performing their character roles, the veracity of the tale is suspect. Rather, after the PD has been performed, a thought experiment can be reproduced. This thought experiment was performed and written by Galileo (Stadlbauer et al., 2018). The thought experiment is a comparative to a lighter mass and a heavy mass falling. The heavy mass would fall faster than the lighter mass, but what if the two collide? From the lighter mass perspective, this mass would slow the united mass down, as it would need to be sped up by the heavier mass. From the heavier mass perspective, the united mass would be heavier than either separate mass and would have to travel faster than either. Again, this thought experiment can be demonstrated only after the paradox of the two different final united velocities is clear in students' minds. The experimental trial demonstrates what happens for students who are still not convinced, and there is no paradox (Stadlbauer et al., 2018, p. 903).

2. Experimental Design with Falsifiability

Thought experiments are useful tools for students. Even Grade 9 students are eager to question things to do with science. Designing an experiment to examine a claim is another facet of the NOS elements of understanding, even if it is only in principle.

The question that I use in this exemplar was asked by a student many years ago. The question asked was whether Vitamin C has any positive effect on the common cold. High school students cannot perform this experiment, but they can think through the scientific process. From many science fair projects, I have noticed that students try to study and use statistical methods and think this is an experiment. These statistical methods are unneeded. Let me explain, with a fictional science class as my audience.

Designing the experiment is rather straightforward. A large group of people, separated into two groups, are studied and compared. Of course, the two groups should be as similar as possible, including genetically; monozygotic twins are the best group to study. The National Human Genome Research Institute defines identical twins. Taking that definition from their webpage, the definition is as follows.

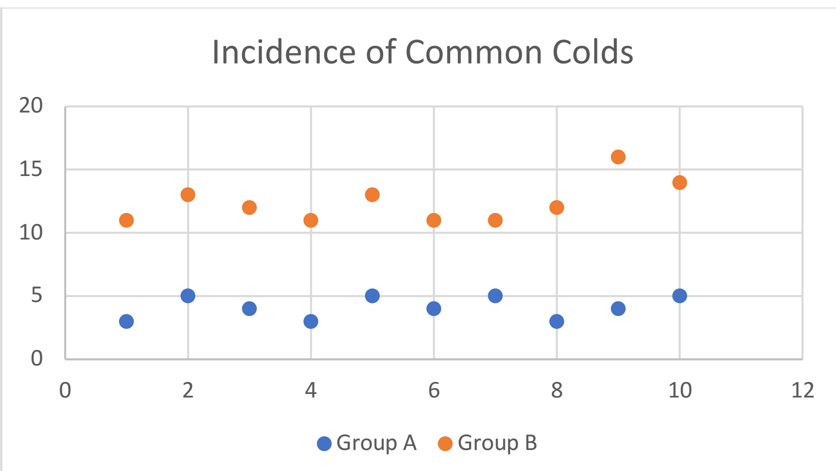
> Identical twins are also called monozygotic twins. They result from the fertilization of a single egg with a single sperm. And as those cells divide and multiply, at some point very early in embryonic growth, they split into two individuals. So that you can imagine that the genetic material in these two identical twins is identical to each other, hence the name (*Identical Twins*, 2021).

Many monozygotic twins are required, and while there are statistical treatments that will dictate the sample size based on other information, it is easy to choose 1,000 as that is a large number. Financial reasons often determine the sample size, but the idea of a large number is important. We are not doing this experiment but only designing the experiment.

A double-blind method is employed, so the twins should not know who is receiving the Vitamin C and who is receiving the placebo when treating the A and B twins. But it is always possible that the people conducting the experiment, giving out the pill, and taking down information about whether the test subjects have a common cold, could be influenced by personal bias, so, that experimenter must also not know who is getting which treatment. The key that allows for identification should not be known to the people conducting the experiment. Only after the results are in, can the key be opened, and data analyzed.

A year has often been suggested by students in my classes before. While we can give every member a common cold, this is not a perfect thing either. So, waiting and monitoring for one year would be sufficient. Let's presume that our scatter plot looks like the following diagram with the number of colds on the vertical axis and the numbered month on the horizontal axis (see Figure 1),

Figure 1



The analysis begins with the following two questions:

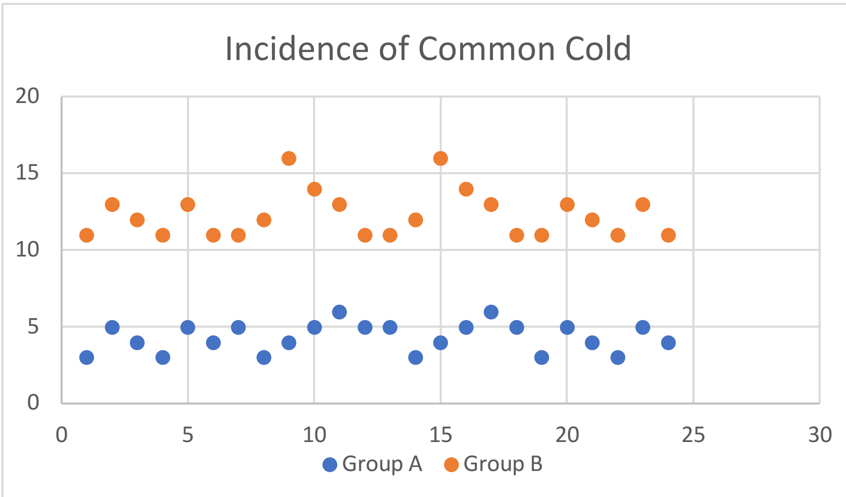
1. Are the two groups sufficiently different from each other?
2. Are they different groups?
    a. There are tests to see if the variability in each group is not too great.
    b. There are tests to see if the difference between the two groups is significantly different.

If Group A is the Vitamin C group and Group B is the placebo group, the difference between the two groups could be arguably different. Vitamin C does affect the occurrence of common colds. At this point, these results do not have any scientific validity. The error in this analysis is due to a deep misunderstanding of science.

For the experiment to continue to be scientific, trying to disprove what we believe to be true is necessary. Switching the pills given out and not telling anyone is the approach. The test subjects would not know that the dosages are switched, nor do the people conducting the experiment. Only the person administrating the experiment would know this. With doses switched, and the experiment lasting for double the time, there are two possible results, and each has its own unique and convincing conclusion.

Possibility one:

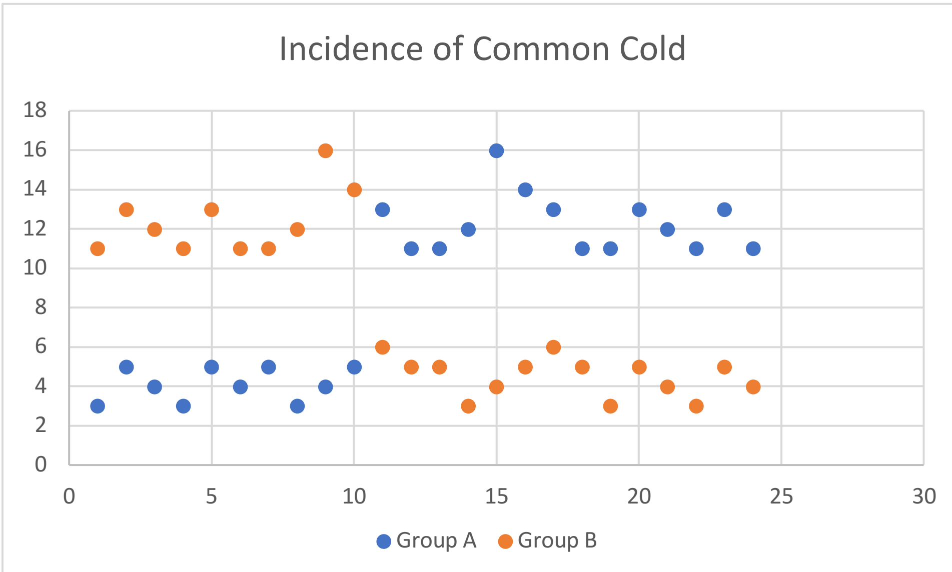
Figure 2



With the increased time of the experiment and the Vitamin C and placebo pills switched, the data does not show a response (see Figure 2). Therefore, the data disconfirms the hypothesis that Vitamin C affects the frequency of the Common Cold. There are still two distinct groups, but the behaviour of the groups has not changed at all.

Scenario two:

Figure 3



Here, the groups had switched when the dosages were switched (see Figure 3). If we learn that Group A started with Vitamin C, we can say that there is a difference in common cold incidence between the two groups. The groups switch their performance after the Vitamin C and placebo are switched.

The science experiment satisfies the falsifiability condition, and students see the hypothesis ruled out. So, beginning with the rational and skeptical hypothesis, Vitamin C does not affect the incidence of common cold infections, the first 12 months might arguably be considered true or false. But the switch or the manipulation of the conditions at a given time has an effect that rules out a null effect. So, the new hypothesis must be that Vitamin C will affect the incidence of common colds.

Continued manipulation of the experiment enhances certainty. It is the switch or the absence of the switch that is the difference. In this case, it is the pursuit of falsifiability that compels this design of the experiment.

Students should understand that data verification is not proof for anything scientific but does provide psychological assurance – nothing more. It is the potential of allowing for falsifiability to occur that gives this design its utility. Again, a hypothesis or prediction is disconfirmed, and this is deductively done.

3. Why Do Meteors Burn Up on Hitting the Atmosphere?

"Meteors burn up in the mesosphere when they encounter the molecules from that layer and rub up against them" (*Why Do Meteors Burn up in the Mesosphere?*, 2021). This question is a perennial favourite that students often ask, and as the study of the solar system does find itself in the Intermediate Science program is to be expected. A prominent answer is that the Meteor will burn up due to air friction (*What in the Earth's Atmosphere Causes Meteors to Burn Up?*, 2006, para 1).

Science teachers do a disservice by answering the question correctly. To solve that dilemma scientifically is the point of any science course. Teachers also do a disservice by answering the question incorrectly. Answering questions readily provides no process which promotes an understanding of the logic of scientific discovery. Students do not understand the provisional nature of scientific conclusions. With falsifiability in mind again, the theoretical understanding is tested scientifically. This is an interesting and easy approach.

Posing the question, “Why do meteors burn up in the atmosphere?” invites many different answers. Some are easily questioned and proven wrong immediately. For example, the meteor changes from very cold to much warmer quickly due to air friction, etc., (Shanil Virani, 2018). Seizing on the air friction explanation, it is easy to have students explain what they mean by this. Once the explanations for the air friction hypothesis are collected, it is easy to create air friction and test for temperature changes.

Positioning a thermometer appropriately (Boreal # 470005-888 – range from -20 to +110C) and firmly securing it, the bulb can have air run past it using either a compressed airline or a tank of compressed air. When the air is released and moves from high to low pressure, there will be a temperature change. This temperature change only confuses students when the thermometer does not go up in temperature but goes down. A secret to the demonstration is to use a long hose with the airline. This longer length of hose allows for the freshly released gas to come to room temperature and to use a long metal nozzle that further allows for time for the air to reach ambient temperatures (#399-5777-4 - Hymair Heavy Duty Air Blow Gun & Accessories Kit, 7-pc from Canadian Tire). The metal nozzle increases the length of the tube, but there are different bores of the tube. The bore choices are a necessary part of this inquiry.

All students, particularly those who believe in the air friction myth, must compare their thinking with the obvious null result to the increased air. The largest diameter nozzle produces no effect—the next smallest diameter produces a higher-pitched rush of air and ostensibly faster air movement. The kit will allow for $1/10^{th}$ of the nozzle area, resulting in very much faster air rushing past the thermometer bulb. It does not take much effort to falsify the air friction hypothesis. Nothing happens to the thermometer's temperature despite fast air rushing past it, as air velocity is made faster and faster.

Students can be very inventive and suggest that surfaces of the experimental equipment are very smooth, and air friction would be increased if the surfaces were roughened. A rough surface is closer to the objects falling from space. Changing the thermometer to an IR thermometer (#025-1043-4 - Innova 3370 MicroTherm Pocket Infrared Thermometer from Canadian Tire) allows for easy comparison of a rough and smooth surface at almost the same time. A rough piece of wooden doweling can have one area finely sanded. The same pressurized air can be directed on it for a long time. A temperature difference would support this thinking, but again it is the authentic testing of the conjecture at work.

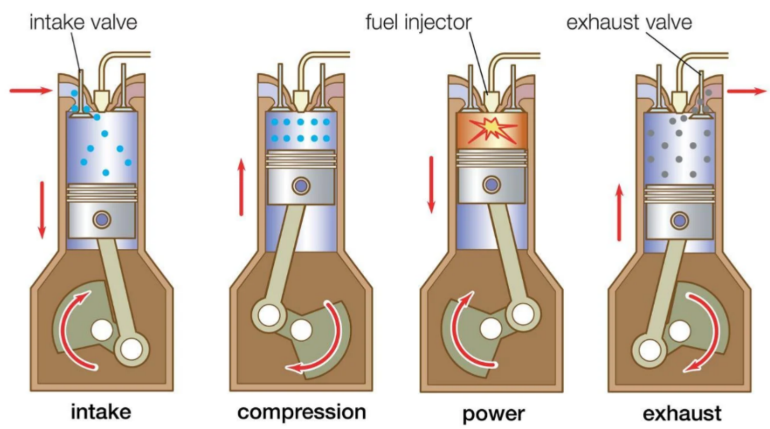
Exploring the air compression hypothesis, if air particles are forced together very quickly, the force between the particles in normal air accumulates. Recalling that Work = Force x Displacement, to exercise force through a displacement and force air particles much closer together, work needs to be done. But that work expresses itself as heat. A bicycle pump needs to be pumped a few times, and the pump's base gets warmer to the touch. An IR thermometer registers the increasing temperature. More pumps with the air pump and higher temperatures are recorded. This evidence is the beginning of support to the air compression hypothesis. The verification of this theory is not sufficient. Is the temperature sufficient to cause something to burn or catch fire?

The Fire Piston or Fire Syringe (#470006-372 Fire Piston Demonstration Apparatus) is designed to produce fire with cotton fibres on the bottom of the transparent tube. A very quick depression of the piston and the cotton fibres burst into flames. Slow depression of the piston does not produce this. The result verifies the air compression hypothesis, but the air friction hypothesis has been falsified.

The compression of air-producing heat has experimental support[4]. Yet, all conjectures and hypotheses can be tested further. So, if rapid compression of gas produces heat, what about a rapid expansion of air? Expansion of air is the opposite of compression. If energy is given off with air compression, energy must be absorbed when air is expanded quickly.

Figure 4 illustrates the process and shows the compression of the gas particles. This is an excellent application of the effect. That compression of particles must be in the imagination of students for this to make sense.

Figure 4: (002-How-a-Diesel-Engine-Works.Webp (WEBP Image, 1400 × 788 Pixels), 2021.)



Students should discuss what will happen when a can of air is suddenly released into the atmosphere. Predictions should be made and recorded, along with an explanation given the newer theory. If particles of air produce heat when compressed together very quickly, it would seem that rapidly expanding gases would produce the reverse. Will the thermometer temperature

[4] Students preparing to enter post-secondary engineering programs may take technical courses too. Any student who has taken Grade 11 Automotive courses, already knows that Diesel Engines work exactly this way. There is no need for a spark plug to cause ignition, but Diesel fumes drawn into a cylinder and compressed quickly will produce intense heat. This physical process of producing heat will start the chemical process of ignition and explosion of the fuel vapour. Being prepared for enthusiastic conclusions is anticipated by considering student's timetables. Making the student a confederate to the workings of the demonstration is a way of managing premature conclusions.

go up, stay the same or go down when a compressed air can is opened to the air, and the compressed air is directed at the thermometer?

MG Chemicals markets a can of compressed air. MG Chemicals 403A 134A Super Cold Spray, 285g (10 Oz) Aerosol Can (Amazon.ca code: #403A-285G) can chill electronic components -50 C and can easily do the same to a thermometer. This can's purpose is unknown to students but pressing on the aerosol container and directing it towards the bulb of the thermometer will immediately show a drop in temperature. Seconds later, there is an effect. The rapidity of the temperature change is the same as the fire syringe.

This demonstration effectively looks at the falsifying or disconfirming experiment testing of the air friction hypothesis but verified the air compression hypothesis. But that is simple verification, and good theories can be further tested. A good theory will have other ways to be tested, so the opposite of air compression is tested. The air expansion predicts a drop in temperature, and that is what is confirmed by the testing. This is a more sophisticated version of the previous demonstration because of the additional attempts at refutation by the air compression conjecture.

4. Monkey Hunting Gun

Other names are known for the "Monkey Hunting Gun" demonstration, for example, "the monkey and hunter demonstration," "shoot the monkey demonstration," and so forth. As the equipment can be set up to encompass the entire classroom, stage, or gymnasium, there is an engagement factor built-in if only through the largess of the apparatus and setup.

The problem setup involves two stages. First, there is a setup of the game situation. A ground-level hunter aims a gun at a monkey hanging from a branch high in a tree. The intelligent monkey does not want to be shot and is educated enough to know that light travels faster than bullets. So, the monkey presupposes that should he let go of the branch after the flash from the gun. He will fall and not be shot (*OVS | Monkey and a Gun | Video Detail*, n.d.). Second, there is an explanation for how the demonstration works. The monkey is being held up by an electromagnet which turns off when the gun fires. The mechanism details change depending on the construction of the equipment. The construction of the equipment is a valuable learning lesson. (Note: Equipment can be purchased from science equipment vendors such as Boreal [#470220-606 - Parabolic Collision Monkey and Hunter Apparatus]. The equipment does not wear out significantly and serves as a demonstration for a teacher's lifetime.)

Students are asked whether: *they believe in simian science? Does the simian escape being shot?* This demonstration can start the projectile motion section of the study, and students will have expectations of what will happen and have some form of theoretical interpretation.

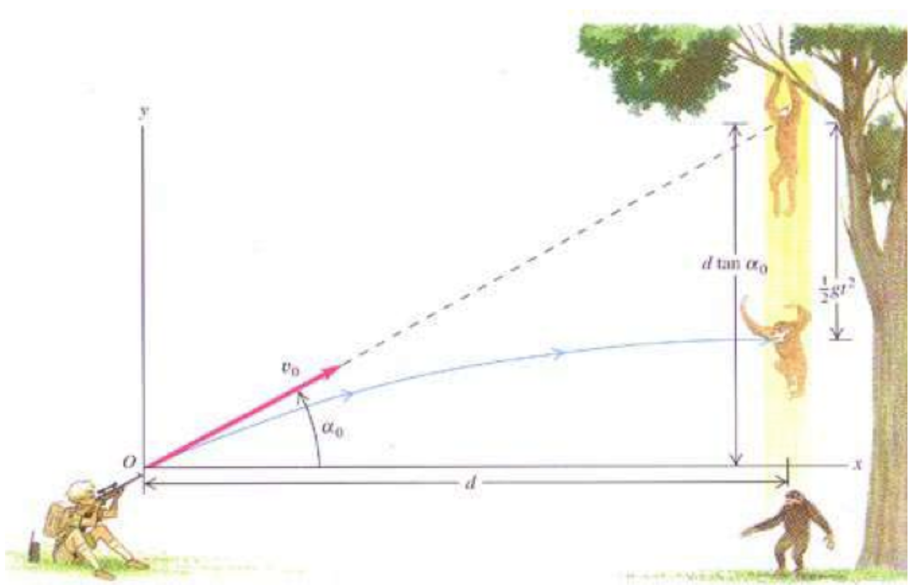
The simian has not considered the gravitation acceleration that acts on his fall and acts on the bullet. Both the monkey and the bullet accelerate downwards at the same rate. Interestingly, once the first instance has been explained, the distance from the monkey's "tree" and the "gun" can be changed in angle, or the distance from the gun to the monkey lengthened or shortened. The same question can be asked, and of course, the equipment is changed to test the prediction, which has now no doubt changed. Students should have evidence to conclude that it is irrelevant to the monkey being shot. The same question can be asked, and while there has been a theoretical explanation, the experiment illustrates the independence of the two velocity components.

The gun's muzzle velocity can be changed. Depending on the mechanism, and I am partial to springs, it is easy to double and then half the initial speeds to demonstrate the irrelevancy of the bullet's velocity. These results produce other student predictions. Again, the experimental results will verify or falsify the student predictions. Then an explanation and further testing will need to take place. The height of the monkey can be changed too. Again, by changing that parameter, other predictions are made by students. Their theoretical understanding can be articulated and tested.

It is best to illicit different predictions with different theoretical explanations from the students in all the situations above. After the trial, the experimental results will falsify at least one of the different predictions. The falsification does dispense with misunderstandings and emulates the logic of scientific discovery.

Not everyone has observed this monkey hunting gun apparatus. It is impossible to demonstrate this on paper adequately, the following link shows the monkey hunting gun demonstration (see Figure 5).

Figure 5



https://youtu.be/cxvsHNRXLjw

5. Mass on a String

Considering the apparatus (see Figure 6), students are asked what would happen if the lower string were pulled. Students should explain there is tension on the upper string. It provides the force for the mass to remain suspended. The lower string, when pulled, will provide another force on the mass and the upper string.

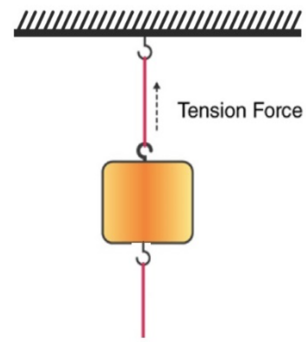


Figure 6: (Modified Tension-2.Png (PNG Image, 750 × 380 Pixels), 2021)

Pulling slowly on the lower string proves exactly that. The upper string has greater tension, breaking before the lower string. To sharpen students' skills, their expectations can be disconfirmed by pulling sharply on the lower string. The lower string will inexplicably break before the upper string.

This unexpected event as students consider inertia and change their theoretical understanding by considering that the sharp pull will introduce a large force to the lower string. The upper string is isolated momentarily by the inertia of the mass. This presentation should be used to disconfirm the first theoretical assumption, and there should be a lack of confusion after the demonstration.

6. Wave Phenomena in the Hallway

Wave propagation must be understood in at least two ways; the illustrations to the side reflect the two operations of waves (see Figure 7). For purposes of acquainting students with the necessary features of wave propagation, this demonstration uses transverse waves.

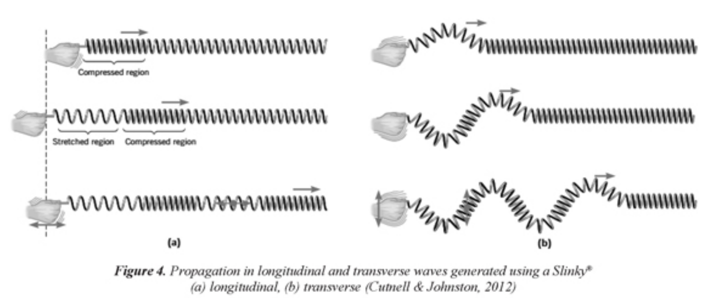


Figure 7: (V17n2a11-Fig04.Jpg (JPEG Image, 580 × 244 Pixels), 2021)

Long coiled springs, known as wave demonstrators (# AP9023 from Flinn Scientific), are approximately 2 metres long but can be stretched to much greater lengths than with very little force. While the prescribed experiments recommended with this equipment will work satisfactorily, the demonstration I propose and have used previously is superior in pedagogical effect.

Any demonstration must be engaging and truly memorable. One showmanship technique is to have many of a particular piece of equipment. During my teaching career, I had a great many coils twisted around in a 5-gallon plastic pail. Another showmanship technique is to make the demonstration exceptionally large. Again, it is the largess of this experiment that gives oxygen to its engagement.

To that end, these coiled springs can be attached and stretched to very long distances, such as in a school hallway. A student volunteer at either end with a tool holding the end of the spring (endpoint students) completes the experimental setup. The coiled springs can be secured with crimp connectors[5] or trimmed zip ties, but it isn't needed for the demonstration to work. The students then walk apart about ten metres and then face each other. Each student needs to kneel on the floor to bring the coil to the surface of the floor.

[5] Safety is always a concern in science. I did not worry about the springs coming loose because they are fastened together very well, and the material is very strong. One year, the two students at either end of this enormous length of coiled springs were boyfriend and girlfriend to each other. I did not know that they were not speaking to each other, and the girlfriend accidentally let go of her end of the spring. While no one was in any danger, and there was more noise and action than threat to the boy, I was cautious for every year afterward. All students were required to wear safety goggles and leather gloves for the students at each end. I would think this notation is prudent so that anyone reading this demonstration and performing this does have safety on the mind too.

It takes a few minutes to explain to the endpoint students how to produce a pulse or wave. Some practice of this process needs to be done, and at the same time, students are amazed at how the coiled spring can produce a pulse that takes many seconds to go to the end of the hallway and then reverse the wave and return polarity. This exaggerated time is the beauty of this demonstration over the feeble nature of the 2-metre version. Phenomena should not be so quick and so slight that it is difficult to see. With the grandiose version of that coiled spring (or slinky experiment), the pulses or waves are large – about one-metre amplitudes. Figure 8 shows the features of a wave that need to be defined for students.

In the beginning, students are prepared and practice generating only one half of the wave, which is called a pulse. The pulse disturbance travels down the coiled spring, and most of the time, students will ask me questions such as, *what determines the speed of the pulse?* Students can ask these questions as the endpoint students get good at generating pulses – positive or up pulses and negative or down pulses. Positive and negative pulses make more sense to the students watching the wave.

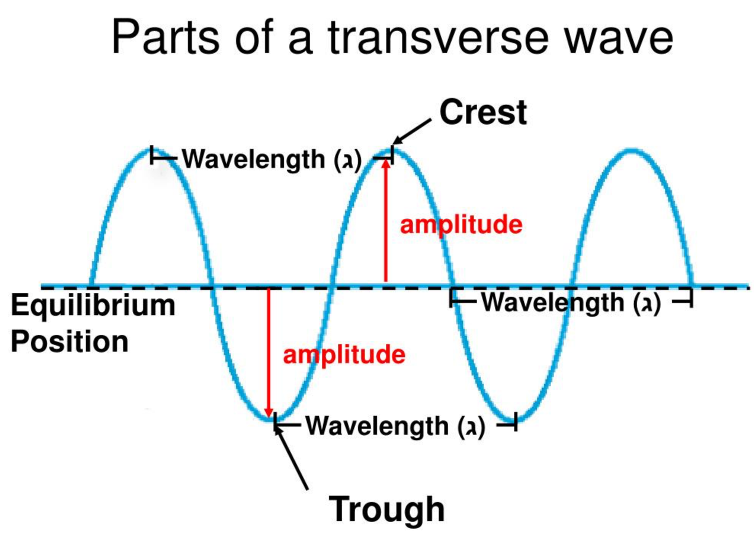


Figure 8: (Parts-of-a-Transverse-Wave-l.Jpg (JPEG Image, 1024 × 768 Pixels), 2021)

Asking the question, "what determines the speed of the pulse?" of the students watching the pulse moving down the coiled spring and then returning the trip, the first prediction is typically the same. The height of the pulse must determine the speed of the pulse in the spring. The reasoning is often something to do with the energy going into the generation of the pulse. A student producing the pulse does have to move their arm nearly a metre from the middle outwards. There is some effort expended in doing that. As students can predict and have some theoretical understanding of how that is done, the next is to test that. Most students want to use a timer to see how long the pulse takes to go down the coiled spring and back to the starting point. While this is good, there should be more than one way to accomplish this. With quantifiable data, conclusions or misunderstandings can be lost in the noise of measurements; for example, 14.0 seconds, 13.5 seconds, 14.5 seconds are arguably the same measurement.

This demonstration lends itself to obvious comparisons. The test can generate a pulse with one-half of the amplitude followed by another pulse of the full one-metre amplitude. Students can easily explain that if the larger pulse moves faster than the smaller ones, the larger pulse should catch up to the smaller one. The pulses will then blend and not be two distinct pulses. The pulses are generated, and several trials are run. The large pulse does not catch up to the small pulse. Of course, students will suggest making a quarter amplitude pulse followed by as large a pulse as can be created. Student thinking is that there is not enough time for the effect to take place. Again, this would never be resolved with one 2 metre length of coiled spring. The large setup is made for finding the hard-to-find effects. Nonetheless, even with the extremes of pulses, that is, very small and very large amplitude pulses, one does not catch up to the other.

To be thorough and to add to the mystery, the reverse could be hypothesized. A reverse relationship could exist, and the small pulse will catch up to the large pulse. That expectation is tested, and that hypothesis, too, is disconfirmed.

There are very few features to a wave, so students then look to the wavelength or the horizontal or base distance, technically half of the wavelength in the diagram. Students working the nodes become adept at changing the base of the pulse. They can produce equal amplitudes but different base lengths, and the experiment is repeated. Again, there is a certainty of the disconfirming evidence. Some students want to try and produce the pulses themselves, so there is the time taken to retrain endpoint students. Additional trials are done.

A teacher, a confederate to the experiment, will then come out and ask to be an endpoint. While there is a fuss with the endpoint tool, the confederate teacher will surreptitiously back up a meter or two. The confederate teacher asks the former endpoint student to ensure that everything is being attached properly. All the while, the confederate teacher moves back a decimeter at a time. It takes only a few metres of extra stretch, and the tension has changed enough that when the confederate teacher produces a test pulse, the movement of the pulse is noticeably faster.

While the hypothesis might involve some other difference the confederate teacher is pretending to fabricate, students see that the length has changed and more tension to the long spring assembly. Wide hallways allow for identical spring setups, and students then quickly set up a second coiled spring assembly. The new one will be just as long but have fewer coiled springs, for example, five lengths in one and six lengths in the other. Lying side-by-side, comparisons can be easily made. There is now a clear difference in tensions between the two coiled springs. Students eagerly express the hypothesis as "we predict that the pulse will travel faster in the more tense spring than the pulse travelling along with the less tense assembly." The experimental result easily compares one pulse of the same size moving very noticeably faster than the other. Both pulses leave simultaneously, and the faster arrives back and, without any argument, earlier than the slower pulse.

I will demonstrate that this setup can be used for several different experimental expectations in Table 1 (Appendix A). Those expectations, requiring considerable time as addressed in the curriculum document and echoed in the Grade 11 textbook, can be done efficiently and quickly. To address the curriculum and deal with disconfirming evidence and emulate the logic of scientific discovery makes this an excellent addition to the next curriculum revision. Sadly, it is not easy to do by remote instruction unless a recording is made from a previous year, and the teacher starts the video and stops for students to consider the questions. An immediate loss of engagement is my prediction for this demonstration being viewed only.

This one-wave demonstrator can handle all aspects of the wave phenomenon section. Rather than simply answering questions that focus on verification, questions can help students further understand falsifiability and its role in the logic and the method of scientific discovery. This information is summarized in Table 1 (Appendix A).

This wave demonstration is easy to perform and involves teacher questioning, which engages students in thinking about what will happen. In real-time work, students go through exploration, explaining, elaborating and then evaluation. This inquiry is complete with falsifiability. Many guesses/predictions/expectations are made, and there is an opportunity for students to continue to learn about disconfirmation.

Students can refer to many different wave properties in later curriculum questions, concepts, and ideas. Many specific problems rely upon knowing what the speed of a wave will be. To help look at all the demonstrations together and where they exist in the physics curriculum, this is summarized in Table 2, Appendix B.

PD Summary

Through the presentation of the experimental activity and the timing of questions regarding student expectations, each demonstration promotes learning NOS. Each demonstration is more complex than the previous one. There is only one variable highlighted in the testing of weight and the rate of fall of an object. While there is a problem with air and surface area, the same surface areas deal with that issue. The experimental design demonstration is important for students as it deals with a control group and an experimental group. There are similarities required for that, and considering human variances is easy for students. Problems with variables in other experiments are learned and not intuitively obvious.

The Meteor demonstration also has ad hoc changes to experimental conditions. For example, perhaps the air velocity coming from our equipment is not as fast as the air rushing past a meteor. However, showing no effect with the first velocity of the air and with two stages of increase also showing no effect, the demonstration is persuasive. The theory is disconfirmed. A reasonable objection is that students think that perhaps faster velocities of air might show the heating effect. This doubt about disconfirmation is reflected in other pivotal experiments in the history of science. The solution here is to move forwards with a provisional understanding of the alternate explanation (the compression of air theory). When that theory is confirmed by experiment, and the previous hypothesis is disconfirmed (with a potential exception), there can be confusion. Accepting the compression of air theoretical understanding provisionally is logically acceptable. The assertion is then tested authentically. For example, does the reverse experiment show reverse results as predicted? Does gas expansion provide corroboration of the air compression theory? Falsifiability is maintained, and the confirming evidence corroborates or supports the air compression theory differently. The process and outcome are persuasive.

For critics of the first disconfirmation, it is possible to take equipment to the school's auto shop. The compressor there is likely set for 150 psi which produces an even faster-moving stream of air. The experiment can be set up to test the air friction theory with even faster-moving air. Even with the tremendous increase in airspeed, there is no appreciable increase in temperature. Having students double the ruling out of the air friction hypothesis and resorting to this much greater wind speed available only in one spot in a high school is a good option. It should be encouraged. Science does not always proceed along with rational means. Paradigms of thinking do have a resistance to change. Students should understand this as well. This demonstration and the students thinking through NOS do emulate the process of science.

The Monkey Hunting gun demonstration deals with a more complex science too. Apparently, two different movements need to be dealt with separately: the vertical and horizontal components. This demonstration setup allows for many other parameters to be changed: the initial velocity, the distance separating the gun and the monkey, the height of the gun, the weight of the monkey, and the height of the monkey. All the while, each trial is counterintuitive. Increasing the monkey's weight is a potential factor to consider, but it should remind students of falling objects and the previously provisional truth. Viewing the apparatus from the side and potentially using an overhead (if they are still around, and obviously should be) to display a large coordinate system brings this experiment's results to paper. The parabolic nature of projectile movement can be directly demonstrated. Having a strobe light makes the comparison and the connection to graphs even more clear. Like other experiments, the trials are not perfect. The near-miss or near hit does not constitute a disconfirming trial but something systemic to the experiment. It is important to have students experience this as well. Decisions made beforehand are the important part, but ancillary to the NOS and falsifiability.

The last demonstration, the wave demonstrator, combines elements of all the other demonstrations. Many parameters are being tested. There is much disconfirming evidence. There are multiple ways to make measures. Other features indicated in Table 1 (Appendix A) are also demonstrated efficiently, for example, wave propagation, reflection of waves, superposition of waves, interference of waves, and so forth. Those situations allow for the same questioning regarding expectations, and theoretical understandings can be tested authentically.

Chapter 5: The Curriculum Perspective

In 2008, the Social Sciences and Humanities revision of the curriculum had included for the first time the idea of a "teacher prompt." As many Social Studies or Humanities teachers did not hold degrees in the various courses offered, the teacher prompt was a good addition. It provided clear guidance to anyone teaching a course. From the Ontario Ministry of Education document, the teacher prompt is considered an example and a way to focus attention on specific expectations and outcomes for learning. The ministry is clear as "Both are intended as suggestions for teachers rather than as exhaustive or mandatory lists" (The Ontario Ministry of Education, 2013, p. 36)[6].

To illustrate the teacher prompts, I have created a table with exemplar teacher prompts integrated into the curriculum (see Table 3, Appendix C). This addition will augment the scientific activities. The curriculum sections will be quoted from the current curriculum document. Both the Grade 11 and Grade 12 Academic Physics courses (The Ontario Curriculum, Grades 11 and 12: Science, 2008 (Revised), 2017) will be used here is no reason why this cannot be done at the applied or college level, but the more technical nature of the college-level course lends itself to studying how questions and not why questions.

For the Grade Eleven Course, the inquiry experiments come from *PhysicsSource 11* (Sandner & Anjuli Ahooja, 2011). I thought it important to see the alignment clearly, and more expectations have less to do with scientific theory and more to do with typical myths or

[6] The current Physics curriculum does list sample questions, but those questions direct thinking towards the physics content, e.g. *What aspects of the principles of motion are applied in archery? How does the equipment used by competitive skiers reduce friction and resistance? How does a "pop bottle" rocket use the principles of motion? How does the spin cycle of a washing machine use circular motion to remove water from clothes?* These do not direct student thinking along disproving an expectation. There needs to be additional questions of a different sort.

misunderstandings. The Grade Twelve course has more latitude to scientific investigations, but I refer to *Nelson Physics 12* (Hirsch, Stewart, Martindale, & Barry, 2002).

Often the teacher prompts follow a cookie-cutter style where the student must have an expectation, express that expectation in terms of what will be experienced, and then the experimental test is performed. The student's expectation is deemed disproved or supported by the evidence observed.

Other times, and in senior classes, the expectation has a theoretical expression too, for example, "heavier things fall faster than lighter things because there is more mass for the earth's gravity to pull on." The expectation or prediction is now tested, and the theoretical assertions are falsified. The scaffolding of this process, going from the *what* expectations to the *why* expectations, will be important.

The expectation is important for each teacher prompt and question, but specific mention must be made to what happens. Each student must attend to the expected action and compare that to reality or the experimental result. A few minutes must be given to attend to that and could be further prompted by, "Let's take a summary of what you expect to have happened." There will be commonalities, and there could be other expectations. Documenting all of the possible expectations is important. After the activity has been performed, expressions such as, "years ago when I saw this experiment the first time, I expected or guessed that [activity details go here] and was shocked to find that [experimental results go here]. Some people thought what I thought too [while pointing at the board or similar]." This step needs to have some tact as some students might not enjoy "being wrong" or even "accepting that." This psychological situation needs careful attention, for scientists and inventors accept "failure" or falsified conditions easily, and this might be due to learning and training, but could be innate amongst science students. Students need to be comfortable with this by either approach.

Grade Eleven Physics

Teacher prompts bring meaning to the experiment to the student. Each of these teacher prompts makes a difference in how a student will learn to understand the NOS. Verification is necessary, as the reproduction of experiments is necessary to show that nature is not capricious. Yet, the most important part of these activities includes becoming familiar with the experiment in general. This part of the activity might simply be playing with the equipment and relating it to something they might have done. Without exception, the teacher must encourage the appropriate play with the equipment and assure that each group of students can proceed. That degree and kind of play with the experimental equipment will depend on how obscure the experimental experience. For illustration purposes, I will use the activity of generating horsepower as students run up a flight of stairs.

After considering issues of safety[7], both student and environment, the experimental design is straightforward. Each student will have their mass determined, and this may be considered secret information and the data recorded on everyone's index card. The height of the stairs needs to be determined and the time measuring instrument secured. There should be some agreement as to how the timing will start and when it will end. In previous years, some students have been wily enough to specify that timing starts when the last foot leaves the bottom and

[7] A student who had survived the Dryden air crash, 10 March 1989 Air Ontario Flight 1363, had been physically and emotionally scathed. She had a pacemaker installed to keep her heart from racing at times. This situation and others are not trivial. It is important that health conditions be considered to the best of a teacher's ability. It is always a good idea to announce the day before any experimental activities. I was also warned by a parent about my using strobes in the classroom, as the student was prone to epileptic seizures under those and similar conditions. The world of experiences does bring in the very real considerations of health and safety.

stops when the first foot reaches the highest step. Some want to gain an advantage because they realize their center of mass may not be at the top of the stairs, but their leading foot has reached the step. Later, of course, the extent to this cheating can be mathematically approximated. Students will begin the race up the stairs once the experimentation standards are examined and agreed to. With their mass values and the height traversed, the change in potential energy is calculated by students. Power ratings only require the potential energy change to be divided by the time to complete the race of the stairs. Wattage is the value determined in this way, and it is easy to express this in horsepower.

With the individual data calculated, there are questions to be asked before sharing the group's data. Students are asked for their expectations. These expectations should be considered before summarizing the data. Experimenting first gives all students the necessary background to have expectations and even provides some conjecture about why they have their expectations.

Questions should be asked of students, such as, which of the students in your class do you expect to generate the greatest power? Students should be asked to write down their expectations and their reasoning on the index card provided. Again, having students commit to an expectation and then test it is important to this process.

Storing the information in a spreadsheet is an excellent way to manipulate the information when students share their conjectures regarding the greatest power generated. The power generated by students does present a myriad of conditions. There is a physical limit as to how fast stairs can be traversed. There are limits of a kind to the parameters that describe students (e.g., weight or mass of students, leg length, height, etc.). Predictions are made with an explanation, but there are confirming and disconfirming examples. Sorting the data allows students to consider one by one the factors they believe are important. It is the process rather than the answer that is important. Their expectations are challenged, and of course, not all expectations can be correct. It is important to use a good pedagogical style and repeat the suggestions given by members of the class. Repeating the proposed expectation clearly and for all to see before sorting the data is important. The expectation should take the following form. If we believe that height has something to do with leg length and that longer legs will allow faster movement, we expect the tallest to generate the greatest power. The sort of spreadsheet data easily confirms the statement or disconfirms this.

What is exceptionally good about this activity is that it is a combination of factors that demonstrate a fully examined conclusion. Students do not understand multivariant statistics, and so this will be paradoxical. It takes someone to suggest that power per weight (or mass really) might be a better predictor of the experiment. It is immaterial the conclusion students arrive at, but students know that expectations are tested, and there is a certainty to the disconfirmation of the expectation. There is no certainty to verifying the expectations or conclusions.

Generically, each of the teacher prompts provided allows for a rich discourse of similar tact. Each provides an opportunity to discover falsifiability, and each student takes a step closer to understanding the NOS. The Grade Eleven curriculum expectations are tabulated in Appendix C and show additional teacher prompts and how they are used throughout the curriculum.

Grade Twelve Physics

The process of working with teacher prompts in this section is no different than the grade eleven, but there is an increase in the complexity. By way of an illustrative example, the section on terminal velocity will be expounded on here. The terminal velocity investigation should include the parameters of mass, surface area, and shape. The effects of each can be determined by repeated tests of the objects, each time changing only one of the parameters. Before doing the experiment, it is necessary to ask for student expectations and conjectures to explain their written results.

The idea of terminal velocity will be new to most students. Having objects reach a maximum velocity is ordinarily not observed. Furthermore, this idea is paradoxical because the idea that all things fall at the same rate has been demonstrated previously. Some students could be primed to say that there is no difference due to weight because of previous work and the conceptual landmark created in the previous year. Nonetheless, students can simply be given the materials and asked to work experimentally with the following pairs of objects and record their data in terms of apparent terminal velocity:

- Both pairs of objects have the same number of coffee filters.
- One pair has twice the number of coffee filters stuck together than the other pair.
- One pair has ten times the number of coffee filters stuck together than the other pair.

At the outset, students could fall back to their thinking that heavy things fall faster than lighter things and perhaps expect many coffee filters to fall faster than a single coffee filter; and in thinking so, be necessarily confused with simply double the weight of filter papers. It is the comparative maximum velocity that needs to be compared from one experimental condition to another. Students will likely need many more experimental trials to determine the nature of terminal velocity.

Coffee filters are relatively inexpensive and can be reused. Having an enormous abundance of filters allows students to take the three trials and expand that to accommodate their incorrect expectations and the confusion caused by the disconfirming evidence. Students should be encouraged to produce many trials.

Students in grade 12 have already gone through a previous year of physics. They will quickly develop a framework for their experimental process and methodically try many trials of even more different combinations. This framework of investigation should be encouraged.

Ideas about precision will begin to be questioned. Some questions such as, how close to each other are the weights of each filter paper? By now, students should know where some standard equipment is located and quickly answer their questions by themselves, such as weighing them to see if there is a large difference or weighing the coffee filters to select ones that are essentially the same weight.

Fluted coffee filters work very well and come in various sizes, but #2, #4 and #6 are sufficiently different. The areas are different, but the shapes are the same. (Area being tested with different filter sizes, the masses should also be changed.) Students have written their expectations here, and then sample questions can be asked of students. Questions about the factors that affect the terminal velocity reached should be asked, and some of the questions could be, which predictions were confirmed and which disconfirmed? Students can then predict the force of friction (drag due to the air) when the object's surface area is doubled and again tripled.

Students should find that predictions or expectations might feel appropriate, but the experimental process disconfirms their thinking. Because terminal velocity is proportional to the square root of twice the weight divided by the frontal area, there will be confusion. Other factors such as the gas density and the drag coefficient are constant in this experiment.

The activity is inexpensive to perform. It is rather quick to do many trials, and the direct measurement of the factors is easily expanded upon. The mass of filters can be weighted out if students wish to explore more quantitative aspects, as are the areas of the filter papers.

Expanding on the teacher prompts from above, the entire Grade Twelve Curriculum is detailed in Table 5 (Appendix D) with many more teacher prompts.

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Appendix A – The Large Wave Participating Demonstration

The left-hand column contains several curriculum expectations form the Grade Eleven Physics curriculum. This is compared to the methods suggested for a PD. The point being illustrated is that one experimental design, through a series of appropriate questions can provide experience and understanding for a large section of specific outcomes.

Table 1: Wave and Sound Unit of Study – Laboratory and Inquiry Big Ideas

Curriculum Documentation Waves & Sound Unit of Study	**Large Wave Demonstrator Hypothesis Testing**
Conduct laboratory inquiries involving mechanical waves and their interference	Students already know how to create different-sized pulses, so testing with a large pulse and a small pulse interacting with each other makes their conclusions easy to make. *Do pulses bounce off of each other?* With the hypothesis that pulses will bounce off each other, students must commit to what they predict or expect to see. The two different pulses are created and interact. This hypothesis is disconfirmed. *Do the waves pass through each other?* Similarly, this is tested, and the results do not disconfirm the hypothesis. So, this is the provisionally true theoretical knowledge for wave knowledge. While standing waves are created and will move from left to right, the nodal points are perfect for students' experience. They can stand over a nodal point. A large wave comes towards them and travels past them and seemingly through the gap produced by their stance. Students can narrow their feet, and still, the wave passes through the small gap. This idea about waves is of enormous importance for chemistry with electron wave functions and several experiments in Grade 12 Physics next year.
Plan and conduct inquiries to determine the speed of waves in a medium	This was explored in the details of how this equipment works. It is important that through questions, the planning and conducting of the experiment were done in an impromptu manner. Just like co-created exemplars for assessment purposes, the planning should be arrived at by students. The demonstration unfolds but Socratic-like questions geared for falsification of student expectations.

Curriculum Documentation Waves & Sound Unit of Study	**Large Wave Demonstrator Hypothesis Testing**
Investigate the relationship between the wavelength, frequency, and speed of a wave	This big idea was explored in the above explanation as well with the same implementation as above.
Plan and conduct inquiries to determine the speed of waves in a medium.	The above demonstration has already answered this question, but it is easy to leave a few coiled springs outside during the winter. On a cold day, the spring can be tested against one that has been in hot water. Students go through the same hypothesis-making procedure, testing and often, students disconfirm their first hypothesis.
Investigate the relationship between the wavelength, frequency, and speed of a wave	This aspect has already been accomplished qualitatively, but other groups can work with stopwatches for timing and metre sticks for distances now for another session. To quantify this demonstration and make it more of a small group investigation is easy to do - the power of this exemplar.

Appendix B – Summary of PDs and Their Location in the Ontario Physics Curriculum

Table 2: Summary of Demonstration Name, by Grade with Commentary

Demonstration Name	Grade	Unit	Commentary
Heavy Things Fall Faster	11	Kinematics Dynamics – review	Before any quantitative experiments are done with motion and the acceleration due to gravity, this qualitative experiment needs to be done to clear up potential misconceptions. As well, to prepare students for the other experiments. With perhaps an accelerated demonstration procedure, such a review would help remind students of this counter-intuitive idea.
Experimental Design – Drugs	11 12	During any unit.	For both grades, the development of this experimental design is important for students to understand. While the basic understanding that the null hypothesis is disconfirmed, there is a manipulatiabilty that helps convince a cause.
Why Do Meteors Burn Up?	11	Energy & Society	Work = Force x Displacement – the overarching formula Air Friction is easily disconfirmed. The compression of gas hypothesis is confirmed, but conjecture about the expansion of gas is tested too with its bold conjecture, i.e. a drop in temperature.
Monkey Hunting gun	11 12	Kinematics B 2.9 – projectile motion Dynamics – review	The isolation of components of movement, both linear (horizontal) and accelerative (vertical), requires practice and repeated experimentation as vertical movement ($1/2a\Delta^2$) responds differently with time. Two separate components are covered again in this unit of study. The demonstration will be a helpful review and good assessment of the class's already understood starting the unit of study.
Mass on a String	11	Forces – inertia	The process has a way to dispel myths of how forces work, but as well it begins the idea of vectors too. Inertia is understood with ordinary situations, but can become elusive in other situations. While technically this closely allied to the way a roll of toilet paper, it is insufficient for students to see through this experiment. Their answers are falsified, but their paradoxical nature can be explained. This illustrates a theoretical stance and how it needs a more thorough understanding to encompass more observations.
Wave Demonstrator	11	Waves & Sound	The demonstration is memorable and allows for a point of reference for all other questions about waves and sound, e.g. it is the medium that sound travels through that changes the velocity of sound.

Appendix C – The Curriculum Specific Outcomes and Textbook Inquires with Teacher Prompts

Table 3: Grade Eleven Academic Curriculum – Textbook Inquiry Activities – Falsifiability Teacher Prompt[8]

Unit	Big Idea	Text Reference	Example Teacher Prompt *(with brief illustration / explanation)*
Kinematics	B 2.4 Conduct an inquiry into the uniform and non-uniform linear motion of an object	p. 24	Considering the ticker tape timer, would you expect fewer or more dots if the tape were tugged on twice as fast during the 3.0 seconds? What about if the tape were tugged with only ½ the speed? How would you test this? *A theoretical disconnect may occur here, but the number of dots created by the ticker tape timer is the same regardless of how quickly the ticker tape timer is pulled.*
	B 2.6 Plan and conduct an inquiry into the motion of objects in one dimension	p. 39	Before you do the activity, what do you expect an acceleration-time graph to look like when moving with uniform speed? *Uniform speed demands not a constant acceleration but a zero value for acceleration.*
	B 2.9 Conduct an inquiry into the projectile motion of an object	p. 54	Predict the acceleration of the object travelling upwards? Predict the acceleration of the object travelling downwards? Predict the acceleration at the highest point when it is not moving or at its Apogee? *The acceleration due to gravity is the same value when the object goes up, is motionless for a fraction of time at the Apogee, and is the same on the way down as well. It is a constant.*
	B 2.9 Conduct an inquiry into the projectile motion of an object	p. 65	If the mass of the metre stick were doubled, how would you expect the movement of the meterstick to change? What are the three possible outcomes? How would you test this? *Possible outcomes could be faster, the same and slower.* *Mass does not affect the acceleration due to gravity, and it is a constant. So, increasing the mass by a double does nothing to change the movement of the meterstick speed. The resulting reaction times will be the same.*

[8] Potential Confusion:_Capital letter references in the second column refer to The Ministry of Education curriculum guidelines. The relevant sections were simply cut and paste from the document. The Capital letter references in the fourth or last column are references made to the textbook used and their unique numbering system. These are simply documented this way, there is no connection between B in one column and B in another.

Unit	Big Idea	Text Reference	Example Teacher Prompt *(with brief illustration / explanation)*
	B 2.9 Conduct an inquiry into the projectile motion of an object	p. 83	Predict what would happen to the measured forward velocity of the shuffleboard dart if you doubled the initial velocity? Predict what would the measured forward velocity be if you doubled the table height? *These two questions and the one incorrect prediction clarify the problem of independent components of movement. Horizontal movement is based on velocity only (d = vt). Vertical movement is based on acceleration due to gravity ($d = ½ vt^2$).* *Doubling the forward velocity would mean doubling the distance it covered in the time required to fall.* *Doubling the height changes the amount of time that the object is in the air, but* $t = \sqrt[2]{\frac{2d}{v}}$ *demonstrates the non-linear relationship.* *Doubling the height makes the new time* $t = \sqrt[2]{\frac{4d}{v}}$ *which does not double the time.* *Students will make a mistake for the vertical component and work through the disconfirming evidence to their prediction. Ultimately the forward velocity does not change, but the calculation can be victim to an incorrect prediction of the time it takes to drop.*
Forces	C 2.2 Conduct an inquiry that applies Newton's laws to analyze, in qualitative and quantitative terms, the forces acting on an object	p. 104	The ordinary experiences of inertia each relate to expectations that are not supported by the evidence. There are a host of these examples, but this is dealt already with in a PD #1 and #4.
	C 2.2 Conduct an inquiry that applies Newton's laws to analyze, in qualitative and quantitative terms, the forces acting on an object	p. 122	B4 activity (as indicated within the text) should be done without the hint of the pendulum equation[9]. Predict the effect of doubling the mass of the "bob" in the pendulum activity? Predict the effect be on halving the mass of the "bob" in the pendulum activity?

[9] So ignored are NOS items in grade 11 physics, that the B4 activity prompts students for a prediction given the mathematical equation. Rather than allow inquiry to determine the variables qualitatively and then allow experimental results to determine quantitatively the mathematical relationship. Ruling out the effect of mass is a classic problem, a pernicious mythical understanding and as well demonstrate clearly how falsification works, e.g., heavy things fall faster than lighter things is wrong.

Unit	Big Idea	Text Reference	Example Teacher Prompt *(with brief illustration / explanation)*
			Students essentially fall victim to the same myth of movement that heavy things fall faster than light things. At its essence, this is the same problem. The student's theoretical understanding is disconfirmed. After the experiment has been completed, the data suggests a formula that is mass-free. Students should learn to expect that with time. *The formula for the period of a pendulum is* $T = 2\pi\sqrt{(L/g)}$.
	C 2.2 Conduct an inquiry that applies Newton's laws to analyze, in qualitative and quantitative terms, the forces acting on an object	p. 122	B5 activity is done the day after B4. Before the equipment is given out, questions should be posed. When you drop two objects at the same time, what are three possible outcomes? What do you expect to hear when a single quarter and a twinned quarter are dropped at the same time? *The first possibility is that object A hits the ground before object B.* *The second possibility is that object A hits the ground at the same time as object B.* *The third possibility is that object A hits the ground after object B hits the ground.*
	C 2.3 Conduct an inquiry into the relationship between the acceleration of an object and its net force and mass	p. 129	When the paper is pushed out of the way, what do you expect to see? When the paper is flicked out of the way, what do you expect to see? *While this is the prescribed experiment with the textbook, the demonstration, mass on a string is far more memorable and is a better falsifiable and more engaging experience.*
	C 2.3 Conduct an inquiry into the relationship between the acceleration of an object and its net force and mass	p. 137	B8 activity (as indicated within the textbook) should have masses available where words such as doubling masses and tripling masses can be done. What would you expect if the dangling mass were ½ the mass of the cart assembly? What would you expect if the dangling mass were the same as the mass of the cart assembly? What would you expect if the dangling mass were double the mass of the cart assembly? What is your thinking regarding each of the three situations?

Unit	Big Idea	Text Reference	Example Teacher Prompt *(with brief illustration / explanation)*
			This experiment does compel predictions but is the only victim to variability in measurement. There are no falsifiability-related problems.
	C 2.3 Conduct an inquiry into the relationship between the acceleration of an object and its net force and mass	p. 142	What would you expect to see if each cart were of the same mass? What do you expect to see if one mass is double the other? What do you expect if you reversed the cart's masses and others were double the mass? What would you expect if the one cart were ten times the mass of the other? *This experiment does compel predictions but is the only victim to variability in measurement. There are no falsifiability-related problems.*
	C 2.3 Conduct an inquiry into the relationship between the acceleration of an object and its net force and mass	p. 151	B11 What would you expect the applied force to be if the normal force were doubled? What do you expect the static friction to be should the normal force be doubled? B12 Similar questions but on a different day. *It is much more interesting to use different surfaces and use different surface areas as additional elements. This is better down with a PD (detailed elsewhere in this portfolio), and that affords a complete laboratory experience with confirming evidence and disconfirming evidence.*
Energy & Society	D 2.4 Plan and conduct inquiries involving transformations between gravitational potential energy and kinetic energy	p. 182	Both C1 and C2 are not easily adapted to falsifiability questions as measurements typically have wide ranges.
	D 2.4 Plan and conduct inquiries involving transformations between gravitational potential energy and kinetic energy D 2.7 Compare and contrast the input energy, useful output energy, and percent efficiency of selected energy generation methods	p. 193	C3 Once you have determined the efficiency of a ramp with any angle, considering other efficiency determinations, what possible outcomes are there?[10] Which of those possibilities do you expect to happen with an increasing angle to the incline? *As the effective weight of the mass is a function of the angle to the normal, that trigonometric function makes the effect non-linear.*

[10] Students should have become quite adept at realizing that an effect could be positive, neutral, or negative. In this case, the efficiency could be greater with greater angle, the same and independent of angle, or be a lesser efficiency with greater angle.

Unit	Big Idea	Text Reference	Example Teacher Prompt *(with brief illustration / explanation)*
			Confirming evidence is available at a small angle, while disconfirming evidence occurs at a larger angle with intuitive predictions. C4 Which of the students in your class do you expect to generate the greatest power? Explain your reasoning. What are some of the factors that help you make your expectation? *The power generated by students does present a myriad of conditions. There is a physical limit as to how fast stairs can be traversed. There are limits of a kind to the parameters that describe students, e.g. weight or mass of students, leg length, height, etc. Predictions are made with an explanation, but there are confirming and disconfirming examples.*[11]
	D 2.6 Conduct inquiries and solve problems involving the relationship between power and work	p. 200	C5 This an exploration into Fuel Cells, and students likely have no expectations to articulate. C6 [After listing all of the sources of energy] Which form of energy do you expect is the largest? [After listing all of the consumer products that use energy in the household] Which consumer product at home do you expect the most energy? *Ancillary information provided with the laboratory activity would provide context for the expectations above, but this is very much less than performing an experiment. Nonetheless, it is still a habit of mind that is being created here too.*
	D 2.9 Conduct an inquiry to determine the specific heat capacity of a single substance	p. 218	C7 [Mixing differing amounts of the same substance at different temperatures is the articulated version] Given the masses of water,

[11] On a personal note, I have always enjoyed adding my own times of traveling the stairs too. I ordinarily have the greatest mass in the class, by a good margin, and am over average speed, and I often generate the greatest power in the class. My data tends to have students think along another measure, and that is Power / kg. There is fairness when everyone's power is compared this way, and suddenly predictions are more confirming. At the end of all this, there is no real answer to the question as it has multiple variables, but it provides for discussion, repeated trials, and sometimes modification. Very competitive students will grab weightlifting weights and run the flight of stairs with the additional weights. While the work done is greater, the amount of time has not been affected by much. There is an increase in the power generated. Aside from healing their egos, they do demonstrate that the mass variable can be changed to get a better understanding of who might generate the greatest power in a differing sense of things. It is the logic of discovery that is of primary importance, and correct calculations are secondary.

Unit	**Big Idea**	**Text Reference**	**Example Teacher Prompt** *(with brief illustration / explanation)*
			what is the final temperature that you would expect on mixing the hot and cold-water samples? [Differing liquids version of the same experiment] Given the masses of water, what is the final temperature you would expect to mix the hot water and cold mineral oil samples? It is not guessing but a prediction based on less information. C8 [Measure out the mass of the metal and pour out the same mass of water into the styrofoam] What final temperature do you expect when the hot metal is placed into the cold water? If you used twice the same water and repeated the process, what final temperature would you expect now? *Students tend to think that everything has approximately the same specific heat capacity. Having their predictions demonstrated to be wrong brings home that point. The theoretical construct of specific heat capacity ranges is the conjecture that comes from the falsified intuition. Again, conjecture followed by refutation becomes a routine habit of mind.*

Appendix D – The Grade Twelve Academic Curriculum Specific Outcomes – Inquiries – Falsifiability Teacher Prompts

Table 4: Grade Twelve Academic Curriculum – Textbook Inquiry Activities – Falsifiability Teacher Prompt

Unit	Big Idea	Inquiry Ref[n]	Proposed Teacher Prompt
Dynamics	Analyze, in qualitative and quantitative terms, the relationships between the force of gravity, normal force, applied force, force of friction, coefficient of static friction, and coefficient of kinetic friction	p. 58 p. 39	Constant Acceleration: Before doing the parabolic flight experiment, make the following predictions: • Predict the acceleration due to gravity immediately after a ball is thrown upwards. • Predict the acceleration due to gravity at the Apogee of the balls parabolic flight. • Predict the acceleration due to gravity on the way down after reaching the Apogee. • Explain your predictions. Investigation: Hang Time *Write your hypothesis and predictions to the following questions, and then explore these concepts further by conducting the lab exercise.* *(a) What factors affect the hang time of a punted football? How do they affect hang time?* *(b) What launch angle of a punt maximizes the hang time of a football?* [emphasis added] *These questions were included within the textbook. The above is contrived and does not allow for a theoretical understanding of any prediction.* Old physics teachers have old and well-used equipment, as there are at least three common sizes of football, namely, "mini size 6", "Junior size 7" and, "Official Size 9", their respect masses can be recorded once on the side of the ball. The question should be while pointing at a school football player in class or invited to class. Predict which of these footballs can be punted the greatest distance? Predict which of these footballs will go the highest in the air? Explain your prediction.

Unit	Big Idea	Inquiry Ref[n]	Proposed Teacher Prompt
		p. 39 p. 113	*This is then tested. While falsifiability is genuinely adhered to here, not all students will predict the same way. Some have their predictions (and the theoretical suppositions) falsified.* Terminal Velocity: Comparing the various objects to be dropped. Predict which of the pairs of objects (several coffee filters) will hit the ground first given: • Both objects have the same number of coffee filters. • One has twice the number of coffee filters stuck together than the other. • One has ten times the number of coffee filters stuck together than the other. • Explain your predictions in terms of forces. • Which predictions were confirmed by the experiment? Which were disconfirmed by the experiment? Predict the force of friction when the weight of the object be doubled and again tripled. Predict the force of friction when the surface area of the object is doubled and again tripled. Explain your prediction in terms of the experimental findings?
	Predict, in qualitative and quantitative terms, the forces acting on systems of objects (e.g., masses in a vertical pulley system [a "dumb waiter"], a block sliding off an accelerating vehicle, masses in an inclined-plane pulley system), and plan and conduct an inquiry to test their predictions *Students will be confused by the two different tracks taken and the steepness of one over the other. As the potential energy (mgh) is the beginning energy, and this energy will be converted to kinetic energy at the bottom of the*	p. 177	The apparatus shows to different tracks, each starting from the same height and ending at the same level. If two identical bearings are used, and one is released for one track and the other on the other track, make your predictions for the following conditions: • Which bearing will reach the bottom of their respective track in the shortest amount of time? Explain your thinking to the prediction. • Which bearing will be travelling the fastest when it reaches the bottom of the track? Explain your thinking to this prediction. What can you conclude? (see column to the left) Applying the Law of Conservation of Energy In reality, there are often factors that detract from the ideal case. In this investigation, consider the factors that complicate the results.

Unit	Big Idea	Inquiry Ref^n	Proposed Teacher Prompt
	track (½ mv^2), the velocity of the objects are described by $(\sqrt[2]{2gh}$. *As 2g is a constant, only the height will determine the velocity at the bottom of the track. The way that the bearing gets there is disconfirmed as being a factor.*	p. 220	Predict which factor has the greatest effect. Explain your prediction in terms of the dynamics studied. After the experiment is done performed, explain your prediction and your experimental findings.
	Conduct inquiries into the uniform circular motion of an object (e.g., using video analysis of an amusement park ride, measuring the forces and period of a tetherball), and analyze, in qualitative and quantitative terms, the relationships between centripetal acceleration, centripetal force, the radius of the orbit, period, frequency, mass, and speed	p. 152	The textbook in question has very many more intriguing problems than activities. While the prescribed lab activity is sufficient, *my experience has demonstrated that it is interesting to let students work in triplets to design a "bola[12]" for hunting purposes. At times, less direction is important. By now, looking for what does not work becomes a habit of mind. In this case, many experimental runs serve to "improve" design. This is falsifiability at work.* *The design must be drawn to scale, and factors need to be articulated. Predictions are made as to how the Bola will behave. Students then build the Bola with materials provided or brought to school.* *The Bolas are then tested against their predictions and theoretical understanding. Eager to improve their results, time is taken to make changes, and the apparatus is tested again with the tacit predictions written down for "Bola 2.0[13]". Each group can then explain what aspects of Bola design were poorly understood at trial one. Their explanations moving towards a better "theory change," e.g. we tried*

[12] Obviously, this activity depends entirely on the maturity of the particular class in question. The construction of Bola should have safety in mind, e.g., tennis balls with holes drilled are much safer than stones. Safety glasses and "laboratory distancing" outside would be needed to keep the practice runs under control. Equipment must be accounted for and returned to the appropriate storage box, as some students can take the equipment and "hunt" younger students at lunch period. Of course, bad behaviour can be an outcome of truly engaged students.

[13] It is necessary to collect the written responses with appropriate details for assessment of learning. Each student should get a copy of the group's work, and this should be sent home for purposes of feedback to parents. As well, should students make their own Bolas for purposes of bedevilment, the parents can at least recognize the efforts and the final product. Many products of science and science experiments can be used inappropriately and increase the risks of injury. Engaged parents are excellent and much needed partners in education. This should be mandatory, but this caveat is outside of the direct focus to this portfolio. I don't know who will read this in the future, and so this safety message is needed and included.

Unit	Big Idea	Inquiry Ref^{n}	Proposed Teacher Prompt
			with more tennis balls and increased the swinging masses, but that did not work.
Energy & Momentum	Use an inquiry process to analyze, in qualitative and quantitative terms, situations involving work, gravitational potential energy, kinetic energy, thermal energy, and elastic potential energy, in one and two dimensions (e.g., a block sliding along an inclined plane with friction; a cart rising and falling on a roller coaster track; an object, such as a mass attached to a spring pendulum, that undergoes simple harmonic motion), and use the law of conservation of energy to solve related problems	p. 220	Testing Real Springs is a verification-oriented experiment where the understanding of physics and its relation to mathematics needs to be confirmed. During the experimentation, students are required to answer similar falsification questions: What do you predict would happen if the spring constant were double? Tripled? Explain your answer. What do you predict would happen if the spring constant were halved? Halved again?
	Conduct a laboratory inquiry or computer simulation to test the law of conservation of energy during energy transformations that involve gravitational potential energy, kinetic energy, thermal energy, and elastic potential energy (e.g., using a bouncing ball, a simple pendulum, a computer simulation of a bungee jump)	p. 222	Analyzing Forces and Energies in mass-spring systems is the experiment for this section. Many verification-oriented items must be calculated to be sure that the predictive mathematics agrees with the established values. From this comes a task where prediction, and in principle, falsifiability is at work. *A truck or car's tires, springs and shock absorbers act as one unit and could be approximated by a Hooke's Law scenario. This class was responsible for moving large 60-pound patio stones using a trailer. One of these patio stones decreased the distance between the wheel and hub by 0.75 cm. How many patio stones would you predict be moved with one load of this trailer? How would your prediction change if there were 5.0 cm high-speed bumps on the pavement in the parking lot on the way to where the patio stones needed to be dropped off? What advice would you give the driver of the vehicle?*
	Analyze, in qualitative and quantitative terms, the relationships between mass, velocity, kinetic energy, momentum, and impulse for a system of objects moving in one and two dimensions (e.g., an off-centre collision of two masses on an air table, two carts recoiling from		Analyzing One Dimensional Collisions is the contained experiment is complete from a verification perspective, but there are no falsification questions that challenge the theoretical understanding and test those predictions. These should include: *If a stationary Cart A has the same mass as Cart B, what would you predict for the two velocities?*

Unit	Big Idea	Inquiry Ref^{n}	Proposed Teacher Prompt
	opposite ends of a released spring), This *aspect of the two laboratory setups will allow for more qualitative predictions, e.g. heavier, twice as fast, etc.,* [emphasis added].		*If a stationary Cart A had five times the amount of mass as Cart B, what velocity would Cart B have after a collision if it were set to move towards the cart A with 0.25 / s velocity? What velocity would Cart A have? Estimates of expectations are required – not the results of a calculation.* *If a stationary Cart A had only 1/5th of the mass of Cart B, and this experiment would be repeated, what would you predict for both velocities?*
	Conduct laboratory inquiries or computer simulations involving collisions and explosions in one and two dimensions (e.g., interactions between masses on an air track, the collision of two pucks on an air table, collisions between spheres of similar and different masses) to test the laws of conservation of momentum and conservation of energy. *This aspect will be centred on the replication of experimental results. The falsifiability questions were asked in the analysis portion of the previous big idea.* [emphasis added]	p. 279 p. 295	Analyzing Two-Dimensional Collisions is the same type of experiment where the experiment results should be the same as the teachers. This is for purposes of manipulating the experiment controls and equipment properly. The falsifiability challenge comes from making the same changes to the two pucks on an air hockey table. As well, angles make the non-linear relationship or trigonometric values problematic for simple guessing – only because students have very little practice with this. The students must be able to estimate and simply using simple fractions be able to make predictions. The explanation for what will happen is important too. Still, there are unexpected things because of negative momentum values when one puck has a much larger mass. While technically, these predictions can be accurately made by the formulae derived in this chapter, this experiment should come before the finalized formulae. Not an experimental, but the geocentric worldview and the heliocentric worldviews should be discussed here. This is an example where the difference from predicted to experiment was not that large. Still, the epicycles required to keep predictions of the geocentric world intact required a large complication to those orbits, i.e., epicycles. While the geocentric theory can be discarded for obvious reasons, so great was the

Unit	Big Idea	Inquiry Ref^n	Proposed Teacher Prompt
			belief in an earth-centred worldview that this was not immediately accepted. At this point, falsifiability is not being accepted, but eventually the complexity and Occam's razor that made the change begin.
Electric, Magnetic & Gravitational Fields	conduct a laboratory inquiry or computer simulation to examine the behaviour of a particle in a field (e.g., test Coulomb's law; replicate Millikan's experiment or Rutherford's scattering experiment; use a bubble or cloud chamber)		The questions given in the experiments outlined in the textbook and the curriculum can involve simulations. A simulation is a series of calculations. This would mean that these are calculated values being compared against student-created calculated values. As the same formulae are being used, this type of activity does not have a falsifiable element. It is not a thought experiment but a detailed solution to a problem. The falsifiable questions and conditions come out of the historical details provided outside of the laboratory component of this unit - not here.
The Wave Nature of Light	Conduct inquiries involving the Diffraction and interference of waves, using ripple tanks or computer simulations Conduct inquiries involving the diffraction, refraction, polarization, and interference of light waves (e.g., shine lasers through single, double, and multiple slits; observe a computer simulation of Young's double-slit experiment. measure the index of refraction of different materials; observe the effect of crossed polarizing filters on transmitted light)		Falsifiability is not readily possible here. Even the historical aspects are not portrayed here. If this unit dealt with light phenomena, the challenge between the particle model and the wave model could be highlighted. Some phenomena verify both models, other phenomena that falsify the particle model, and still other phenomena that falsify the wave model. There are no experiments given or mandated to be done with this type of theory comparison, and so there are no predictions required. Again, these experimental activities are experiential and acquaint students with the wave phenomena. There is no theory change contained within the text or the curriculum. *While two cross-polarized filters help explain the wave explanation of polarization, the addition of a third one between the two cross-polarized filters is a surprising result. Something students would not be able to predict. It could be argued that the wave theory is, in fact, falsified, but the complexity of the explanation of three polarizers and the surprising result is well beyond the high school physics course.*

Unit	Big Idea	Inquiry Ref^{n}	Proposed Teacher Prompt
Revolutions in Modern Physics: Quantum Mechanics & Special Relativity	Conduct a laboratory inquiry or computer simulation to analyze data (e.g., on emission spectra, the photoelectric effect, relativistic momentum in accelerators) that support a scientific theory related to relativity or quantum mechanics	p. 561	The Thought Experiment is considered at this point and is an excellent prelude to further experimental examination. There are options where a particular theory would demand certain observations, and another theory would demand other observations. Being able to perform the experiment finally falsifies one theoretical view. Michelson-Morley's (MM) experiment and looking for Aether is another thought experiment with recorded experimental results.
		p. 565	If there is an Aether that light travels through, the MM experimental equipment would have different results depending on the orientation of the equipment. The split light beams would arrive at different times if there were an Aether wind. Predict qualitatively what the interference pattern would look like if there were no Aether wind. Predict what the interference pattern would look like if there is an Aether wind. *There was no interference pattern. The null results support the non-Aether view but falsify the Aether view.*
	Identify Einstein's two postulates for the theory of special relativity, and describe the evidence supporting the theory (e.g., thought experiments, half-lives of elementary particles, relativistic momentum in accelerators, the conversion of matter into energy in a nuclear power plant) *These laboratory expectations have no experimental component to them but are calculations only. Again, verification. Demonstrations might be a better fit for demonstrating falsifiability here.*	p. 654	Analyzing the Photoelectric Effect. This experiment is contrived as the student does not experiment but uses published data. If you were to increase the intensity of light being used, what do you predict will happen to the photocurrent? If you were to increase the frequency of the light being used, what do you predict would happen to the photocurrent of the circuit? If you were to use different materials to eject the photoelectrons, what would you predict the difference? *Unexpectedly, the intensity of the light does not affect the current, but the frequency of the light does.*

Unit	Big Idea	Inquiry Ref^{n}	Proposed Teacher Prompt
			That cutoff frequency is unique to every material being used. *Like scientists before them, students expect that there would be more photoelectrons being ejected with brighter light. The results falsify that view. The newer view explains the result, and so classical views for the atom and light do not apply.*