Developing and implementing modern physics inquiries, and measuring effectiveness and areas of improvement for use in a high school physics class

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ABSTRACT

For my Masters in Physics final project I created and implemented inquiries to use in my high school International Baccalaureate physics class for the unit on modern physics. I wanted to use a Physics by Inquiry (PBI) approach for this unit because it helps students to develop and understanding of why things are the way they are rather than just memorize answers. I used results from a pretest of the modern physics concepts to identify areas of focus. I then created nine inquiries for my students to use in learning the concepts for the unit. At the end of the unit I gave my students the same unit test that I gave my students last year who had not done inquiries but learned through lectures. I then compared the results of the students from this year with last year to measure the effectiveness of the inquiries. I did not see an improvement on the overall unit test grade, but I did see some improvement on the questions from the test that asked students to explain their reasoning, which is a focus of the inquiries. I also asked students to identify which concepts they think they know the answers to and to identify whether they know because they were told the answer or if they understand what the answer is what it is. In the identified focus questions from the pretest, all but one question had the majority of students say the understand the reasoning for the correct answer. This shows the effectiveness of the inquiries in having students understand the "why" and not just memorize the answers. I also had students give feedback on the inquiries and identified areas that need improvement and what specifically I will do to make these improvements. I will make these improvements and continue to use the inquiries to teach my modern physics unit as I believe that I will continue to see an improvement with students' success in this unit in their understanding of modern physics concepts.

I. INTRODUCTION

Questions: What specific areas within modern physics concepts do students struggle with the most when learning through inquiries? How effectively can I increase high school students' understanding and internalizing of modern physics concepts through a physics by inquiry approach to teaching?
Purpose: I want my students to understand the "why" behind modern physics concepts rather than just memorize what the answers should be.
What I Did: I created, implemented, and evaluated the effectiveness of an inquiry-based modern physics curriculum into my high school International Baccalaureate (IB) Standard Level Physics course so as to gauge areas of improvement needed to make the inquiries more effective.
Outcome: I compared test results of students who went through inquiry based teaching of the modern physics unit with students who went through a traditional lecture based teaching of the modern physics unit. I looked at reflection statements by the students who went through inquiry based teaching of the modern physics unit on how successful they think learning through inquiry was for them. Finally, I evaluated the results from students going through the list of concepts from the modern physics unit and state whether they think they understand it or not, and if they do understand it, explain whether it is because they were told how it works or if they understand why it works. Using each of these means of feedback, I will make modifications to my inquiries to address the areas of common misconceptions and ambiguity so as to make more effective inquiries for my modern physics unit.

A. What is Physics by Inquiry (PBI)?

Developed by the Physics Education Group at the University of Washington, Physics by inquiry (PBI) is curriculum that leads students to understanding physics concepts developed through inquiry. PBI does not ask students to accept what they cannot test for themselves, but requires students to construct a model for understanding and then refine it as they continue to investigate through activities. PBI is understanding challenged over and over: PBI does not let students merely accept what they do not understand. PBI uses questions such as “how do we know?” or “what is the explanation for?” or “[why] does that make sense?” [1].

In a typical PBI class, students work in small groups through guiding questions and activities using hands-on materials to investigate physics phenomena and reason through making sense of their observations. These activities and discussions with each other and with the instructor should lead to conclusions that would otherwise just be directly told to students in a traditional lecture style class. “Teaching is done by asking questions to help students construct a coherent conceptual framework, rather than by telling. The emphasis is not on solving standard problems, but on developing the reasoning ability needed to apply relevant concepts to situations that have not been memorized.” [2]

For example, in a traditional lecture style class, students would simply be told that the equation for kinetic energy is one half of the mass times the velocity squared. Perhaps there would be an explanation of how this equation was derived, or perhaps not. In a PBI class, students would set up a situation in which they take measurements and come to the conclusion through their observations and data analysis that the kinetic energy is modeled by one half of the mass times the velocity squared. There are no lectures in a PBI class. Sometimes there is large group discussions, but otherwise all interactions are in small groups. The teacher goes around to each group to complete “teacher checks”, during which the teacher asks questions to the group members to determine where they are at in their understanding and to address any misconceptions or misunderstandings.

Why is PBI an effective way to teach students physics? There are an overwhelming amount of published lectures online for nearly any topic imaginable. So I ask myself, what can I offer my students in their education that they cannot experience on their own? The answer that drives my teaching method is I can offer opportunities for students build reasoning and critical thinking skills. I believe an effective way to do this is to have students reason through the concepts through guided inquiry and discuss these concepts with classmates while making personal observations that support their developing understanding.

In a time where information is readily available to people virtually at any time or place, teaching facts to students is of little importance. These facts will simply be forgotten if not used, and if they are needed in the future, they can be looked up. What is needed is for people to be able to reason through situations and critically analyze information to draw conclusions and transfer this knowledge to new situations. These skills cannot be taught through lecture. The following is an excerpt from Z. K. Silagadze’s article *Brainwashed by Newton?* in 2011:

> Modern civilization depends on advances in science more than ever before. On the other hand the current practice of teaching does not cultivate the conceptual critical thinking skills and is still oriented on the authoritarian teaching traditions. Archaic concepts in teaching obscure vision of the world offered by modern physics. “Upon failure to develop this vision, necessarily critical, we can find ourselves in a world of machines, both physical and intellectual, that would work fairly well, but we would not understand them any more. This means that the progress of science is not guaranteed”. [3]

In a lecture style class, the teacher is doing the thinking, students are just copying. The lessons move at the teacher’s determined pace, but not all students learn at the same rate. Students do not have time to reason through the concepts before being told the answers. “Toward the end of the unit, the teacher provides the students with a cookbook-type laboratory to verify that the information presented on previous day’s lectures is correct.” However, in an inquiry-based class, students start with hands-on activities and investigations to develop an understanding. “When students act as researchers, they start taking responsibility for their own learning” [4]. These are the types of people we need to have in society today. I want students to move from being dependent to independent learners. “Dependent learners cannot become independent learners by sheer willpower. It is not just a matter of grit or midsent. Grit and mindset are necessary but not sufficient by themselves. We have to help dependent students develop new cognitive skills and habits of mind that will actually increase their brainpower.” [5].

The inquiry process teaches students how to be scientists and critical thinkers. Students need to ‘‘actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills’’ [6]. ‘‘The learning experiences provided for students should engage them with fundamental questions about the world and with how scientists have investigated and found answers to those questions. Throughout grades K-12, students should have the opportunity to carry out scientific investigations’’ [7].

B. My experience with PBI

I first learned about physics by inquiry at the University of Washington during a summer institute hosted by several members of the Physics Education Group and lead by Donna Messina. I participated in an eight week course going through PBI kinematics and the light and color units. The course was for inservice physics and physical science teachers to better develop an understanding of the common misconceptions students may have in these areas of physics by working through several PBI units. The following summer I participated in the summer institute again, and I worked through the circuits and energy units. These summer experiences had a major impact on how I thought about and approached teaching physics. Mainly, the power of learning through struggling through questions and situations in order to develop a sound foundational understanding of a concept.

Ever since going to the first summer institute, I have been developing and adapting my physics units to incorporate PBI lessons, as well as completely change some units to be fully PBI. Some units were easier than others to adapt because of lessons and activities that I had previously been using. For example, many of the activities that I had students do in my waves unit was closely aligned to inquiry-based curriculum, and so I only needed to adapt several of the lessons to complete the unit as a full inquiry-based unit.

I have been using PBI in both my regular physics course as well as my International Baccalaureate (IB) physics courses. IB is similar to AP but on an international level. IB is a rigorous program with a syllabus of required topics for each course. There is a Standard Level (SL) and a Higher Level (HL), which includes all of SL (9 units) plus an additional 4 units. Students take the IB exams in May on the same day as everyone else in IB on the same half of the globe. Some schools complete all of the physics curriculum in one year, however most, including my high school, takes two years to complete the physics curriculum. Thus, students at my high school take the IB physics exams in May at the end of their second year of IB physics. There are three exams that students take. The first one is all multiple choice with both conceptual and simple calculation problems, and the other two exams are written response including a combination of conceptual and calculation problems. My school only offers the SL physics course due to a historically smaller population of students interested in taking physics. The exams are scored on a scale of 1 to 7, where a 7 is typically around 64% raw score on the exams. Each year moderators adjust scores according to the difficulty of the test, and as a result, the percentages corresponding to the scaled grade may vary by a percent or two. For example, the 2017 exams required a 63.5% for a 7 while the 2018 exams required a 64.3% for a 7 [8]. Because of the scaling of the grades, the unit tests that I give my IB physics students near the end of the second year reflect a similar outcome are long and rigorous to help the students practice time management and prioritizing questions. This will be seen in the test results later in this paper. There is great debate among the IB physics teachers around the world on whether or not the exams should be so rigorous as to require only a 64% in order to get the highest mark on the exams and the impact this has on students, however that is another topic for another time.

One of the least developed units I had in my IB physics course was the unit on modern physics. Part of the reason for this is the unit that is the least common for being taught in a high school physics class out of all of the IB physics units is the modern physics unit. Many of the concepts in the modern physics unit were also new to the IB curriculum with the first year for the new content being 2016. Because of this, there are fewer developed teaching materials appropriate for the high school level for this unit. I knew that developing inquires for modern physics would be a challenge because, as far as I could find, there were no inquiry-type lessons already developed. I talked with one of the IB physics teachers at another high school in western Washington who was also an instructor for the summer institute at UW the summers that I participated, and he had yet to develop any modern physics inquiries as well. I did not have to start completely from scratch, however, as I was put in contact with an AP physics teacher, Mike Gearen in Hawaii, who had developed some curriculum similar to inquiry-based curriculum for several of the topics that corresponded to my my modern physics unit. The teacher graciously agreed to share his curriculum with me and allowed me to adapt as needed for my inquiries. I adapted his material on nuclear binding energy for my inquiry 6.

The modern physics unit starts with the fundamental particles and the four fundamental forces. Next are concepts of electron energy levels, radioactive decay, mass defect, and binding energy. Finally are fusion and fission. Most of these concepts are unique to physics, and so students do not typically have prior experience with them, with the exception of electron energy levels and decay as these topics are taught in some chemistry courses. Not all students take chemistry before IB physics, however, so only some students have had experience with these concepts before.

C. What I did to teach the modern physics unit in previous years

Prior to developing inquiries for my modern physics unit, I had taught the unit primarily through lecture with a couple of activities. I started the unit with a pretest based on the learning objectives for the unit to see what students already knew about the modern physics concepts. Then I had students do a group research activity about the fundamental particles and forces. This activity had students identify the different fundamental particles and forces and their properties. The remainder of the unit was lecture style going over the concepts of electron energy levels (which did include an activity using spectroscopes to observe the emission spectra of several sources of excited gases), decay, mass defect, binding energy, fusion, and fission. Throughout the unit I supplied students with old IB exam questions as homework. At the end of the unit I gave students a modern physics exam using old IB exam questions.

D. What I did this year

For this school year (2018-2019) I developed nine Inquiries to use in my modern physics unit with my IB physics class. The titles for each inquiry are as follows:

Inquiry 1 - *The Fundamental Particles*,
Inquiry 2 - *The Fundamental Forces/Interactions and Exchange Particles*,
Inquiry 3 - *Electron Energy Levels*,
Inquiry 4 - *Radioactive Decay*,
Inquiry 5 - *Types of Radiation and Health Effects*,
Inquiry 6 - *Mass Defect and Nuclear Binding Energy*,
Inquiry 7 - *Nuclear Binding Energy per Nucleon and Nuclear Stability*,
Inquiry 8 - *Nuclear Fusion*, and
Inquiry 9 - *Nuclear Fission*.

Just as I had done in the past, I started the unit with giving students a pretest to see what they already know about the modern physics concepts. I used results from this pretest to help create the inquiries so as to better address student misconceptions identified in the pretest. I then had the students work in groups of four on each of the inquiries. While students worked, I went around and asked questions to elicit where they were at in their understanding and to address areas of misunderstandings and confusion. As I had done previously, I also provided students with old IB exam questions as homework. At the end of the unit, I gave students the same exam that I gave last year's students. I did this so that I could compare this year's results with last year's to measure the effectiveness of the inquiries I developed. Additionally, I had students give feedback on the inquiry process as well as do a pretest reflection. I used the feedback on the inquiry process and the pretest reflections as well as the results from the unit test to help me evaluate the effectiveness of the inquiries that I had developed and to determine aspects of the inquiries that can be improved.

II. DEVELOPING THE INQUIRIES

The modern physics unit is a difficult unit to create hands-on activities for as many of the concepts are on the atomic and subatomic level. So rather than having hands-on activities for many of the inquiries, I focused on logical reasoning through the concepts and how different concepts build on each other. For example, in the radioactive decay inquiry, rather than having students just memorize the decay products for beta minus versus beta plus decay, I had students look at conservation of charge and lepton number of each decay process to determine which quarks changed and when a neutrino versus antineutrino was released. I did, however, use a hands-on activity with the electron levels inquiry. I had students use spectroscopes to observe the discrete lines of emission for various excited gases and then connect these lines to the energy differences of the electron energy levels for each element. I would like to include more hands-on activities for future variations on my inquiry lessons but this will be dependent in part on obtaining additional materials for activities. For example, I would like to get some low-level radioactive materials that emit alpha particles and some that emit beta particles to investigation levels of shielding required to block these radioactive decay products. This will take some more planning to safely implement this activity.

A. Pretest Responses

In order to help shape the focus of my inquiries, I looked at the student responses to the pretest questions. I decided to focus on the following questions and results.

1. There were five students who identified the fundamental particles to be protons, neutrons, and electrons, and two students said the fundamental particles are atoms. The rest of the students identified quarks, fermions, baryons, or leptons as the fundamental particles, or some combination of these. This showed me that some students had an idea of quarks and leptons, but not all did. A common area of confusion is that protons and neutrons are not fundamental particles and instead are comprised of quarks while electrons are fundamental particles. Protons and electrons are often used as opposites due to their opposite charge, and so I wanted to make sure students explicitly identified protons and neutrons in the same family while electrons in a completely different family of fundamental particles.
2. Seven students correctly identified the four fundamental forces and thirteen students stated that some of their identified fundamental forces had infinite range and others were finite. In developing my inquiry on the fundamental forces, I decided to approach the concept of different ranges for the different forces by looking at the mass of the exchange particles. The exchange particles for the gravitational and electromagnetic forces have no mass and these forces have infinite range. The strong and weak nuclear force exchange particles do have mass, and the range of these forces are limited. I wanted my students to see the mass of exchange particle and range of force relationship to help make sense of the variance in range of the forces. I did not have students look at the uncertainty principle, which is typically used to relate the mass of the exchange particle to the range of the corresponding force, as this would add another level of complexity to the unit that is not required in the IB curriculum for modern physics. Instead, I had students reason through how mass of exchange particles would limit the range of these particles for the interaction much like the mass of an object being thrown between two people limits how far apart the two people can stand.
3. Fifteen students correctly identified half-life as the time it takes for a substance to decay to half of its original amount. This shows that many students already know about half-life, but I wondered to what extent they understand half-life.
4. Seventeen students correctly identified fission as an element breaking apart and fusion as two elements coming together to make a new element. This shows that many students already know about fusion and fission, but I wondered to what extent they understand these concepts.
5. Not a single student was able to correctly explain what the Higgs Boson particle was. To address this confusion, rather than including the Higgs boson with the fundamental particles in inquiry 1, I had students look at the Higgs Boson after looking at the four fundamental forces and their exchange particles in inquiry 2. Perhaps the most common misconception about the Higgs Boson is that it is the particle that gives all other particles mass [9]. To address this, I asked students to investigate why the Higgs field and Higgs Boson were predicted to exist. This would hopefully lead students to see that the amount by which a particle interacts with the Higgs field determines how

much mass that particle has and that the Higgs Boson in the mediating particle for the Higgs field.

6. The most common incorrectly answered question from the pretest was asking whether or not mass is conserved. Seventeen of the twenty-five students who completed the pretest said they thought mass was conserved. Several others said they were not sure, and the rest said that the combination of mass and energy was conserved. So far in grade school science classes, students have only had to deal with situations in which mass in conserved. Even in chemistry with reactions, students see that mass is conserved. However, this is a common misconception and a misinterpretation of "mass" in chemical reactions. Because of this, I wanted students to see for themselves with calculations that the mass in a radioactive decay was not conserved. In inquiry 6 I had them calculate the mass before and after the decay for several situations and asked them to consider where the mass "went". Looking at a radioactive decay in terms of "missing mass" is an easier situation to visualize the mass being converted into kinetic energy of the decay products rather than energy being stored in the bonds of an atom. After looking at radioactive decay, I then had students look at the mass of the constituents of an atom compared to the mass of the atom. I had them try these calculations with several different elements to see if it was true more than once, and to choose an element themselves to test to verify that I was not feeding them the elements that would results in a mass difference. After these calculations, I had students discuss the concept of nuclear binding energy to reason through the "missing mass" issue. This was so that students had a reason for why the mass was different.

B. Teacher Checks, and Additional Questions to Ask Students

While developing the nine inquiries, I also created "answer keys" or responses to the questions in the inquiries that I would expect students to arrive at. I also created "Additional Questions to Ask Students" targeting potential areas of concern or misconceptions that I saw from students in the pretest, or from known misconceptions through research or my experience with prior years of teaching these concepts. I used the questions when doing the "Teacher Checks" with each group as they arrived at these points in the inquiries according to how they answered the questions in the section in the inquiry that they had just completed. For example, at the second teacher check in inquiry 1, I asked the following additional questions if it looked like they had not made the connections or distinctions between the fundamental particles and their different groups:

1. *What patterns do you notice about how the fundamental particles are organized so far?*
2. *How similar are protons and neutrons?*
3. *How similar are protons and electrons?*

I asked these questions to see if students were making the distinction between the similarities and differences of protons, neutrons, and electrons, which is often a difficult change in thinking for students.

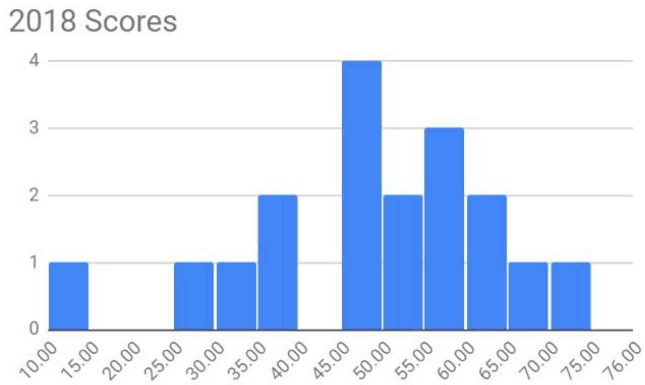
III. MY RESULTS

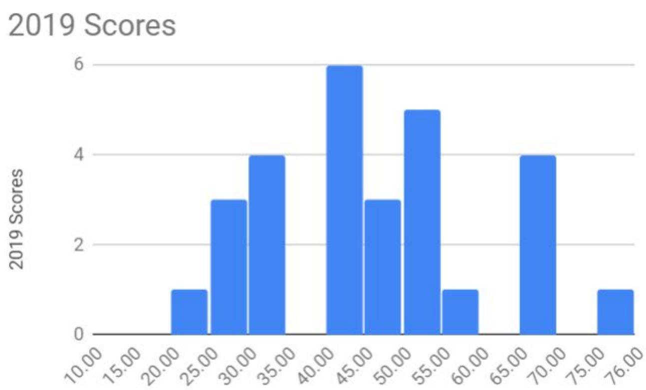
After completing the unit, I evaluated students' performance on the unit test, feedback about the inquiry process, and self-evaluation on the pretest so as to identify areas needing improvement in the inquiries as well as their overall effectiveness for teaching the modern physics unit.

A. Unit test results

In order to determine the effectiveness of the implementation of the inquiries that I developed and to determine areas of improvement for the inquiries, I compared this year's unit test scores to last year's unit test scores (having given the same test both years). Some things to note before comparing the scores. Last year's class had only eighteen students while this year's class had twenty-eight students. The average grade in last year's class at the end of the year was 86.2% while the average grade in this year's class at the end of the year was 86.7%. This shows that the two classes had overall similar grades in the class making them comparable.

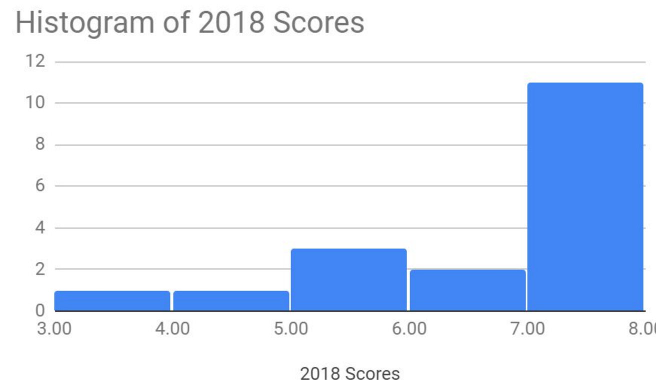
For the Modern physics unit test, last year's class and this year's class had similar results for the total average score. Last year's average was 49.2 out of 76 points (64.7%), and this year's average was 46.5 out of 76 points (61.2%). I was hoping to have a higher average score this year compared to last year, however, the average score this year at least shows that the use of these inquiries were nearly as effective as the previous year in terms of overall performance on the unit test.

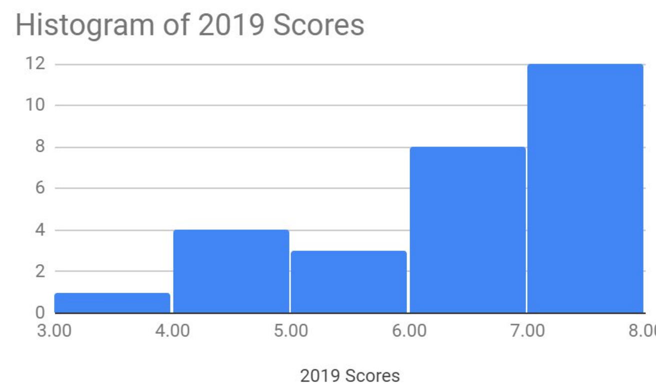




This year there were fewer students in the lower quartile for average test score which may suggest that these inquiries helped the struggling students more. However, there were fewer students in the upper quartile this year. As stated earlier, the IB physics exam is scored on a scale of 1 - 7. In order for a student to get a 7 on the written exam, students last year needed to get around a 64%. Due to the rigour and quantity of the questions on the test that I gave my students for this unit, and since I used old IB exam questions, I did not expect students to get a 100% on the test to demonstrate their understanding. Getting a 64% correlates to an A grade. By doing this, students practice time management and other test taking strategies to help them be more prepared for the IB exam. I used the 2018 IB grade boundaries for the conversion to the IB scale [8].

1	0-7.5pts
2	7.5-13.5pts
3	13.5-23pts
4	23-32pts
5	32-39.5pts
6	39.5-48.5pts
7	48.5-76pts





When the scores are converted to the IB scale of 1-7, the results from the inquiry-based curriculum compared to the traditional lecture-style curriculum show similarities in the number of students in most grade categories. There were 10 more students this year compared to last year. Of these ten additional students, one student earned a 7, six students earned a 6, and three students earned a 4. The remaining eighteen students earned the same scores as last year's eighteen students. This gives a greater upper-end distribution of students scores this year compared to last year.

The purpose of PBI is to focus on student reasoning rather than remote memorization. There were five questions in particular on the test that focused on student reasoning. On these questions, students scored better this year than last year's students for four of the five questions. Since these are old IB exam questions, they are copyrighted, and so I did not include them in this paper in their original form.

Question 1 had two parts - (a) and (b). The first part (a) asked students "Which of the above is not possible for a decay process?", and gave four choices to choose from. The second part (b) asked students "Which quantity is not conserved in the answer you identified above?". This year's students did not correctly answer part (a) of the question as often as last year's students (46% this year compared to 67% last year). However, of those who did correctly answer part (a) this year, 81% also correctly answered part (b), while of last year's students who correctly answered part (a) correct, only 40% answered part (b) correct as well. This shows that students who were able to correctly identify the possible decay from the list this year correctly identified the reason for their answer more often than last year's students. In inquiry 4, students worked through the reason for the existence of each of the decay products due to the conservation rules. This proved effective.

Question 2 was a multi-part question. The first part of the question was a "state what is meant by" question which did not focus on student reasoning but on giving a correct definition. Part (b) and (c) of the question did, however, focus on reasoning. Part (b) gave a Feynman diagram of a proton-neutron interaction with a pion exchange particle. The question was multiple choice as asked students "State and explain whether the meson produced is a positive, negative, or neutral pion." The listed answers to choose from included the charge of pion as well as a statement explaining why. This question was worth two points, and students got one point for the correct charge of pion, and one point for the correct statement explaining why. The average score of this year's students on this question was 0.96 out of 2 as compared to last year's average of 0.86 out of 2. This is not a large increase, but it does show some improvement on this question requiring correct answer and reasoning. Part (c) of this question asked students to "State the strangeness number of the pion and explain your answer". Students got 1 point for the correct strangeness value up to two points for their reasoning. Students' average score both this year and last year were the same (1.32 out of 3). This again shows the effectiveness of the inquiry approach of reasoning the existence of particles based on the conservation laws as was address in inquiry 2.

Question 3 is the one question focused on student reasoning on the test that students this year did not score better than last year's students. Students were asked to "Compare, with reference to the nuclear reaction given, the binding energy of Ra with that of Rn". This question was worth two points, one of which for the correct comparison, and one point for the correct reasoning. The average score students got on this question this year was 0.77 out of 2 compared to an average of 0.92 out of 2 from last year. This shows that students did not reasoning through binding energy per nucleon in a decay process as well this year as they did last year. This shows that the concept of nuclear binding energy's relationship to decay processes. Inquiry 7 was the inquiry that was supposed to address this issue.

On question 4 part (c), students were asked the following: "Stable nuclei with a mass number greater than about 20, contain more neutrons than protons. By reference to the properties of the strong nuclear force and of the electrostatic force, suggest an explanation for this observation." The average score on this question for this year's students was 1.2 out of 4 compared to last year's average score of 1.0 out of 4. This is only a slight improvement, but this question required four statements of reasoning to lead to a valid conclusion, each statement worth one point. This years' students were better able to apply concepts of fundamental forces and their respective ranges than last year's students. Inquiry 2 had students look at the exchange particles and how they related to the ranges of the corresponding interactions.

The final question asked students to compare the mass and binding energy before and after a fission reaction. Students got 0.5 points for the correct mass comparison, and 0.5 points for the correct energy comparison. This year's students average score on this question was 0.70 out of 1 as compared to 0.65 out of 1. Again, this is a slight improvement from last year's results but does show some growth. This question relates to the common misconception of whether or not mass is conserved, which seventeen students at the beginning of the unit thought it was. Although this question does not simply ask students if mass in conserved, it applies the mass-energy conservation law for a nuclear reaction.

This years students did noticeably worse on one non-explaining question on the test which asked students to draw a Feynman diagram for beta decay and a Feynman diagram for positron decay. This year's average score on this question was 1.5 out of 4 in comparison to last year's average of 3.1 our ot 4. This question had the largest difference in terms of how students performed this year compared to last year. This shows that the inquiry lessons did not sufficiently help students learn how to draw Feynman diagrams. This is further supported in the students feedback, which I will address below in “Modifications I will make for next year” in the conclusion section.

The remainder of the questions on the test were not focused on student reasoning and did not show significant differences in student performance between the two years, and so were not as directly evident of students ability to reason through their thinking by using the inquiry approach. I am happy to see some improvement with the questions requiring student reasoning to be shown, but I would like to see more of an increase in order to support the effectiveness of these inquiry lessons.

B. Student feedback from the pretest reflection

I gave the pretest questions to the students at the end of the unit after they got their unit tests back and then asked them to do the following: “For each of the following questions on the pretest, respond with one of the following options (do not leave any blank): a) I still do not know the answer. b) I know the answer, but only because I was told what the answer is. c) I know the answer because I understand why the answer is what it is. If you are somewhere in the middle, then explain that as well.” Asking students to self identify their understanding allows me to see how they think they know what they know. The goal of PBI is for students to develop an understanding of why the answer is what it is, and so the more students think they know the answer because they understand why, the more successful using the inquiries has been.

Question #1 asked students to identify the fundamental particles. Originally, five students identified the fundamental particles to be protons, neutrons, and electrons and two students said the fundamental particles are atoms. The rest of the students identified quarks, fermions, baryons, or leptons as the fundamental particles, or some combination of these.

Question #4 asked students to identify the fundamental forces. Originally, seven students correctly identified the four fundamental forces and thirteen students stated that some of their identified fundamental forces had infinite range and others were finite.

Question #7 asked students to explain what the Higgs Boson particle was. Originally, not a single student was able to correctly explain what the Higgs Boson particle was.

Question #15 asked students to explain what half-life was. Originally, fifteen students correctly identified half-life as the time it takes for a substance to decay to half of its original amount.

Question #16 asked students whether or not mass was conserved. Originally, seventeen of the twenty-five who completed the pretest said they thought mass was conserved. Several others said they were not sure, and the rest said that it was mass and energy that was conserved.

Question #18 asked students to explain what fission and fusion were. Originally, seventeen students correctly identified fission as an element breaking apart and fusion as two elements coming together to make a new element.

Below is a table showing how many students responded with each option from the listed questions above. Each question identified above were my focus questions for the unit as I saw from the pretests that there were a large number of students who did not originally know the correct answer. a) I still do not know the answer. b) I know the answer, but only because I was told what the answer is. c) I know the answer because I understand why the answer is what it is.

	#1	#4	#7	#15	#16	#18
a)	1	0	5	1	1	1
b)	3	6	12	2	4	3
c)	20	18	6	21	19	19

These results show several things that were significant to showing the effectiveness of these inquiries. The first is that at the beginning not a single student was able to correctly identify what the Higgs boson particle was (question #7), and at the end, the majority of the students think they know what it is, but they only know because they were told the answer. This is an area in inquiry 2 that I need to improve. In the pretest, most students said mass was conserved (question #16), and at the end of the unit, not only did all but one student say they knew that mass was not conserved, but most said they think they understand why mass is not conserved. This is significant because conservation of mass is a common misconception that students come in with because they have never had experience with mass not being conserved before. Finally, even though the majority of students correctly identified fission and fusion processes, at the beginning of the unit in the pretest, most students think they understand why fusion and fission happen. I do not know how many of these students understood why fusion and fission happened at the beginning of the unit, but if they did not know the reason and only knew the answer, then now the majority of the students think they now understand why. This is a big part of PBI that I think is easy to overlook. PBI is great for students who come in knowing little as it helps them to build up an understanding of the concepts, but it also helps students who come in knowing a lot of the concepts because it requires them to think through why things happen as they do rather than just accept what they were told.

C. Student feedback about the inquiry process

Below are some quotes for students that gave evidence to the overall effectiveness of using inquiries for teaching the modern physics unit. Notice that not all students said they enjoyed the inquiries or that the inquiries were easy, but that the inquiries made them think and really understand the concepts.

> "I found that the inquiries were helpful but i really needed to work hard at them to understand everything."
>
> "It was pretty successful because of the many inquiry assignments which helped me learn the concepts by solving problems."
>
> "I think [the inquiries] helped by forcing me to gain a concrete understanding of the topic before feeling comfortable enough to continue."
>
> "[The inquiries] went sequentially through the thought process to arrive at the conclusion, rather than just telling me facts."
>
> "It was difficult to understand at first but I think [the inquiries] helped me visualize the concepts we were learning."
>
> "I really enjoyed this unit and I think that I was relatively successful. If I had more time, I would have been able to completely master the concepts."
>
> "I like [inquiries] because it is more guided independent learning which allows me to work at my own pace and ask questions when needed"
>
> "I think this unit went well for learning concepts. Using whiteboards to learn concepts with other students helped to solidify the concepts that we thought about individually when looking at past IB exam questions."
>
> "By working on the inquiries together as a table, I was able to work with my peers trying to figure out the answers by talking through problems instead of thinking inside of my head. This meant if there were mistakes in our logic, someone else could tell us, 'I do not think that is right.' If there was something wrong, I was able learn from my mistakes, if not, the concept was more solidified and engraved in memory since I can just think of the mini debate."
>
> "I think [inquiries] helped by forcing me to gain a concrete understanding of the topic before feeling comfortable enough to continue."

However, not all feedback was positive.

> "I think it was a little hard to learn all the concepts because there were no lectures and we didn't take notes, and studying all nine inquiries was pretty hard. However, I think I still learned the information quite effectively (if it did take a little longer)."
>
> "I know that it's very fundamental, but I definitely think I would have learned more with hands-on learning and more teacher lecturing."
>
> "I would definitely appreciate more lessons/notes style learning, at least for this specific topic, because I think that the inquiries were not sufficient for helping me understand the ideas I was stuck on."

IV. CONCLUSION

I believe that overall I was moderately successful in developing effective inquiries. I did not see an improvement in test scores as I was hoping I would see, but I did see slight increase in students responses to the explaining questions on the unit test. Additionally, most of the identified areas of focus from the pretest questions resulted in most students saying they know the correct answer and know why it is the correct answer. I was very successful in gathering information about what specific areas of the inquiries need improvement. I saw multiple areas that students need more clarification on or more specific direction on. I will discuss these areas in detail below.

A. Modifications I will make for next year

1. More development on teaching Feynman Diagrams, perhaps with group whiteboard presentations, or with a group Feynman diagram construction activity, as well as more practice problems with creating and interpreting Feynman diagrams. One student gave the following feedback about the inquiries: "I think we need to go more in depth on Feynman diagrams, as the concepts are still very confusing to me as well as several of my peers." Another student said "It would be helpful if we did more worked-out problems as a class". Whiteboard problems would address this identified area needing improvement.

2. Encourage students to take notes on the key concepts from the inquiries, and do self-reflections at the end of each inquiry summarizing what they learned, and what they still do not yet understand. The following statements were given by students in the feedback about the inquiries:

> "I feel that taking notes, for me, is a very valuable and effective way to learn the material. Maybe mixing in some note-taking would be good."
>
> "I prefer taking notes as a class and inquiries because it allows both structured time to learn the content and also unstructured time to work with peers to understand the material and work through problems in groups."
>
> "I believe a mix of taking class notes, inquiries and activities would be best. This is because it gives me the opportunity to learn in multiple ways."
>
> "I feel maybe going over the most important part of each inquires as a class"

This feedback tells me that including structured note taking while completing the inquiries may help some of the students to process what they are learning and to keep their thoughts organized. Going over key concepts as a class would be a good way to encourage this structured note taking for those that have a difficult time determining what to take notes on and when to take notes.

3. Have students create an organizer of the fundamental particles and fundamental forces to elicit the relationships between them. Even though most students said they think that they understand what the fundamental particles are at the end of the unit, some students gave the following feedback for suggestions for improvements.

> "Possibly more of an overview. Showing a mind map of how the fundamental particles interact."
>
> "I would try to do more problems that focused on memorizing the different types of particles because there are quite a few of them and they make a huge impact on understanding the concepts."

An organizer or some other visual representation of the fundamental particles and their characteristics may be an effective tool to help students with understanding what fundamental particles are a part of what groups.

4. Address the concept of the Higgs Boson in inquiry 2 better. As discussed above in looking at the pretest reflection, most students thought they understood at the end of the unit what the Higgs boson particle was, but they did not understand why. One way to improve this in the inquiry is to look more directly at fields when looking at the fundamental forces. This way we can have discussions around particles interacting with the bosons in each field that then cause an interaction which we call a fundamental force. Perhaps this approach may help students be able to explain why the Higgs field and boson were predicted to have existed prior to its observance in 2012. In addition, looking at the fields may also help students to better understand the role of the exchange particles.

5. Use additional methods of assessing rather than just a unit test. Although I will continue to use the unit test since it is representative of the IB exam that the students are all wanting to be successful on, I will in the future incorporate additional assessments. "An

appropriate inquiry-based assessment will test not only content knowledge but also science process skills, scientific reasoning skills, and metacognitive skills" [4]. When I participated in the summer institute at the University of Washington, in addition to having written tests at the end of the unit, we also had to write a paper explaining a concept we learned in the unit. I will add to the modern physics unit a paper assignment in which students will choose a concept of modern physics that they learned and have them explain how they learned the concept, and how they know that they know the concept. The student could give a historical development of the concept as well to emphasize the scientific process of discovery and proving theories.

Overall, I am happy with the progress that I made this year in developing the inquiries for my modern physics unit. I have a better idea of what improvements I need to make for future use, and I am confident that after making these modifications, using the inquiries for this unit will be more successful than a traditional lecture style approach to teaching this unit.

B. What limitations did I face?

Time was the main limitation that I faced for this project. This year we had six snow days (in western Washington this is unheard of!) which took away from time that we would have spent on this unit. Time is limited even without snow days in order to get through every unit before the IB exam in May. This decrease in time meant I had to give the students fewer days to work on the inquiries than would be necessary for all students to learn at their own pace.

Additionally, getting to all eight groups for each teacher check on every inquiry did not happen. One student stated in their reflection "I think that answering the inquiries might have reinforced some wrong answers.". With either a smaller class size or more time to spend going through each inquiry in the unit I would have the time needed to check in with each group at every teacher check and to ask the additional questions every time to ensure that the wrong ideas were being addressed right away. Assuming that I do not have smaller class size or more time to spend on this unit, however, I need to find a way to address this issue. Although different from the original intent for the curriculum, I am not the only teacher trying to implement PBI in a larger class, and others have been successful with modifications as well [10]. Having all class discussions on key concepts from each inquiry at the end I think will be the most effective way to address the issue of time.

The other main limitation that I had for this project was using an IB-format test to measure the effectiveness of implementing the inquiries. Typical tests do not measure the skills developed through inquiries. "Assessing inquiry skills is best done over extended periods of time rather than during a test in a single class period" [4]. I chose to use same test that I had used previously to be able to compare data effectively. However, the test results are not the only tool I used to measure effectiveness.

Will I use PBI for the modern physics unit next year? Yes! Although not all students prefer this method of learning, it puts the focus on students being active learners rather than passive learners. Anyone can look up information and facts, but a student who can reason through why something is the way it is has skills that are very useful in today's world. I want my students to understand the "why" behind modern physics concepts rather than just memorize what the answers should be. Using physics by inquiry, I believe, is successful method to accomplish this.

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