How do traditionally successful pupils experience inquiry-oriented science instruction? Lessons from a teacher-developed unit

Jeffrey Nordine

Abstract Science education research has widely reported the benefits of inquiry-oriented instruction. Yet, the curricular resources provided by my school were traditional textbooks. I decided to enhance these resources by designing an inquiry-oriented (problem-based) unit for my advanced physics students (16–18 years old). Many of my students, who had been successful in traditional instruction, expressed severe frustration during the unit. I conducted a study to better understand the sources of my students' frustration as well as their feelings of success. I share the results of this study and discuss implications for the design of teacher-developed inquiry-oriented science instruction.

Inquiry in science education

Many studies have documented the effectiveness of inquiry-oriented (e.g. project-based, problem-based, design-based) instruction in science teaching (Duschl, Schweingruber and Shouse, 2007). By organising instruction around relevant and meaningful contexts, inquiry-oriented science instruction can increase students' motivation to learn science (Blumenfeld, Kempler and Krajcik, 2006). However, student attempts at inquiry are not without problems. For example, Palincsar, Anderson and David (1993) reported that middle school students (12–14 years old) often had difficulty working with partners during collaborative problem solving, and that these issues often interfered with their ability to focus on learning science content. Kirschner, Sweller and Clark (2006) suggest that if inquiry-oriented instruction does not offer sufficient guidance, the effectiveness and efficiency of learning for students in middle school and high school (14–18 years old) is likely to suffer.

Although a great deal of research in science education has focused on inquiry-oriented learning environments, nearly all existing studies have been conducted in the context of highly specified instructional units that were developed and actively supported by university-based researchers, and often at the elementary (7–12 years old) and middle school level. Recognising this, Keys and Bryan (2001) have called for more research into teacher-developed inquiry-oriented units, particularly at the high school level where constraints are often greater for both students and teachers. This article focuses on advanced (16- to 18-year-old) students' successes and frustrations during a problem-based unit that was developed by a practising teacher with significant curriculum development experience (myself) within the time- and resource-limited setting of a public high school.

Motivation for the study

I developed a problem-based unit for high school students taking an advanced physics course that was contextualised within the *Super Mario Bros.* video game (Nordine, 2011). In their previous physics course, my students had become highly proficient at implementing problem-solving approaches to well-defined problem situations that had been explicitly taught in class. In the Mario unit, I was asking them to approach problems for which they did not have a problem-solving template and to design and implement methods to empirically test the validity of their own solutions. During an initial version of the unit, a significant fraction of the students became so frustrated that they withdrew from the course. One student who ultimately left the course pleaded during a parent conference, '*I'm an excellent student. Just tell me what to learn and I'll learn it!*' It was clear to me that my students were neither adequately connecting with nor succeeding with the activities I had designed. After observing my students' struggles, I resolved to investigate the source of their frustration, as well as their successes, during the problem-based physics unit.

I designed a study to document the experience of my students – who have thrived in a traditional science setting – as they participate in a teacher-developed inquiry-oriented (problem-based) physics unit. My study addressed the research question 'What are advanced physics students' experiences of studying physics in a student-driven, inquiry-oriented learning environment?'

Overview of the learning environment

I developed the Mario unit to teach my advanced physics students about the concepts of multidimensional uniformly accelerated motion, relative motion and the derivative. Since students in the course had already taken a year of introductory algebra-based physics, I intended the unit to deepen their understanding of uniformly accelerated motion by focusing on the additional predictive and explanatory power afforded by calculus-based methods. Equally important, I designed the unit to engage students in work that more closely resembled the real work of scientists, which involves addressing complex, ill-defined problems and tolerating nonlinear paths to solutions. The problems addressed within the unit arise from situations in the *Super Mario Bros.* video game. These problems are: the 'flagpole' problem, the 'invincibility star' problem, and the 'gravity in Mario's world' problem (for a more complete discussion of the problems in the Mario unit, see Nordine (2011)).

Mario flagpole problem

At the end of each level in the game, Mario jumps onto a flagpole from a fixed distance away; the higher he connects with the pole, the more points he is awarded. Over the course of several 45-minute class periods, students work in groups to develop and test a predictive model that they can use to maximise Mario's height when he connects with the pole. Students typically assume that Mario should jump with an angle such that his jump trajectory peaks when he reaches the flagpole. This intuitively appealing assumption is actually incorrect and leads to flawed predictive models. After students develop their predictive models, they use a small projectile launcher to test them. During their tests, they find that the maximisation angle they predicted is off by at least several degrees. This mismatch between prediction and observation motivates a study of calculus-based methods to maximise Mario's height at the flagpole.

The invincibility star problem

In the game, Mario periodically finds an 'invincibility star', which is then launched from its hidden location. Occasionally, the star is launched such that it falls directly into a chasm and is lost. In order for Mario to catch the star, he must jump with a trajectory that enables him to both span the chasm and intersect with the star. To successfully solve this problem, students must define the parameters of a jump that will accomplish both objectives. There are infinitely many solutions to this problem, and students cannot simply check their jump parameters relative to a solutions manual – it is up to them to justify why they believe that the solution that they identified will work.

Gravity in Mario's world

In this problem, students investigate the acceleration of gravity in Mario's world. Students use a video analysis program to gather relevant data about Mario's motion during a jump. Students must make many choices during this analysis; for example, they must decide how to scale the unit in order to put gravitational acceleration in real-world units (e.g. $\mathrm{m\,s^{-2}}$). Students find that Mario's acceleration due to gravity is quite different from Earth's gravity: it drastically changes magnitude at different points in his jump. This strange acceleration prompts a discussion of why the video game designers would choose to make Mario's acceleration due to gravity so different from our own.

Homework and quizzes

Although students worked during class to study a handful of problems in-depth, I wanted my students to have additional practice approaching multidimensional kinematics problems and using the calculus-based methods they had been learning in class. I relied on school-provided physics and calculus textbooks to construct homework assignments and quizzes (brief formative assessments, for which students are assigned a grade) that aligned with the concepts students were addressing in the current Mario problem. However, problems that I drew from textbooks allowed for only a single solution, dealt with contexts that were often less familiar to students, and were designed to be solved in just a few minutes. Each day when a homework assignment was due (most days), class would begin with a brief review of the homework and an opportunity for students to ask questions. Periodically, I would give 'homework quizzes' with problems that were strongly aligned with the textbook problems students had been assigned for homework. Although I worked to align in-class activities, homework exercises and quizzes, the homework and quiz exercises did not arise authentically from in-class activities and did not emphasise engagement in science practices.

Methods

Setting

I conducted this study in my own classroom, which was situated within a public school that serves approximately 450 in a large city in the southern USA. The 16 students in my advanced physics class (AP Physics C) had successfully completed a year of algebra-based physics (with more traditional pedagogy) and were either 11th or 12th grade (16- to 18-year-old) students. The Mario unit was the first unit of the academic year.

Data sources

The primary data source for this study was reflection forms, which I collected from students at the end of each class period. I designed these reflection forms using a phenomenological perspective (van Manen, 2016). In this perspective, a researcher attempts to represent the 'lived experience' of individuals in a particular context using data sources that are open-ended and as non-directive as possible. As such, the daily reflection form was simply a blank sheet of paper entitled 'Daily Reflection' with a space for students to enter their name and the date. I asked students to complete a daily reflection at the end of each class period during the Mario unit.

As a second data source, I kept careful records of my lesson plans, homework assignments, and in-class assessments during the unit, which enabled me to connect themes in students' reflections to what was happening in the classroom at the time.

Data analysis

I used inductive qualitative analysis (Thomas, 2006) to identify themes among student responses at various points in time during the Mario unit. In this approach, a researcher first conducts a careful reading of text-based data and identifies key segments of data that relate to study objectives. In this case, I identified statements that related to their direct experiences within the Mario unit, and ignored statements relating to external/irrelevant issues (e.g. comments relating to upcoming holidays). Next, the researcher creates initial categories to which initial text segments may be assigned (e.g. successes, frustrations, peer interactions). Single segments may be assigned to multiple categories. A further review identifies areas of overlap and redundancy in initial categories. Finally, the researcher identifies major themes and quotations that illustrate each theme. Because data were gathered from daily reflection forms that were collected at the end of each class period, I was able to connect the major themes and student quotations to specific learning activities within the Mario unit.

Results

Through my inductive analysis, I identified four themes that represent commonalities that were present across many student reflections. First, students expressed that they were interested in and motivated by the *Super Mario Bros.* context. On the days in which new Mario problems were introduced, students often expressed interest in the context of the problem. When the Mario flagpole problem was introduced, Craig wrote, '*The subject was fun and made me pay attention and not get bored.*' (All student names are pseudonyms.) Another student, Norbert, reported interest in applying physics concepts, even though the application was in an imaginary environment: '[This activity] *was a fun way to get back into really thinking about physics, and an actual application of these physics concepts, even though it wasn't necessarily a real-life one.*' When the invincibility star problem was introduced, Pablo said, '*I love these Mario problems. It is something I can visualize and it is fun. It makes me want to do the problem.*' Students felt that situating physics problems within the context of the video game enhanced their connection with the problems, made the visualisation process easier, and augmented their enjoyment and interest.

While students expressed interest and motivation in the contexts for the *Super Mario Bros.* problems, they also expressed frustration. The second theme I identified is that students' frustration stemmed from ambiguity in how they should be approaching problems and from a sense of 'wasting time' when their efforts did not lead them directly to the solution. When students were checking their predictive models during the Mario flagpole problem, Elisabeth wrote, '*Well, I feel way lost. I feel like I try and try again, but there is always something that messes up the entire process and we start again. It's very frusterating* [sic] … *Also, I wish you would point us in the right direction, because we spend so much time wasting time and effort in the wrong process and we get behind.*' At the same point in the unit, Calvin wrote, '*Today was a little frustrating day. Our numbers were totally non-sensical and my brain busted.*' Though many students shared Elisabeth and Calvin's sense of frustration, some students welcomed the opportunity to work in a less guided setting. For example, Jung-Su wrote, '*I like this kind of unguided self - (group) problem solving. Get to think hard (which not happen often* [sic]*).*'

The third theme was another contributor to students' frustration: the perceived disconnect between students' in-class work and homework/quizzes. Although homework problems dealt with concepts relevant to the problem at hand, they were largely taken from available textbook resources and therefore did not tightly align with in-class activities, which were motivated by the Mario problems. Quizzes, which directly related to homework problems, often caused students anxiety and made it difficult for them to focus on the day's activity, particularly if students did not feel they scored well on the quiz. On the day when students were introduced to the invincibility star problem, Daniel wrote, '*The homework quiz cast a dark shadow on the day.*' When the class was first introduced to the derivative as a tool for approaching the Mario flagpole problem, Nathaniel's reflection was primarily about a mistake that he made on his quiz grade, and ended with, '*needless to say, I'm anxious about my quiz.*' A response from Elisabeth exemplified the sense that in-class activities did not include much time to discuss homework problems: '*Today I'm totally lost! I need people to help me when I'm stuck on homework… ARGGGGGGGGG!*' When homework and quizzes did not clearly align with in-class activities related to Mario problems, students became frustrated over concerns about their grade.

The final theme in student reflections was that students' feeling of success was most evident on direct lecture lessons that followed days filled with ambiguity. When I introduced the concept of the limit after students had been struggling with the Mario flagpole problem, Isaiah wrote, '*Oh my god. Everything just got a BILLION times more interesting/easier. I'm just wondering if we can go ahead & use limits for the Mario problem …*' Upon learning unit vector notation to deal with the invincibility star problem, Brad wrote, '*Today I was happy to have finally learned a manageable way to deal with 3-D.*' Although many students expressed frustration with initially ambiguous and ill-defined problem scenarios, it seems that thinking about them on their own ahead of time primed them to see the utility in new tools when introduced via direct instruction.

Discussion

A primary finding of this study is that students were motivated by, and interested in, the context of the *Super Mario Bros.* problems that they encountered in the problem-based unit. This aligns with previous work indicating that inquiry-oriented learning environments can bolster student motivation (Blumenfeld *et al.*, 2006), even when contextualised by virtual environments (e.g. video games) that are not intended to model real-life situations.

Students' interest in the Mario problems did not prevent frustration. Students' frustration during the unit largely stemmed from task ambiguity during in-class activities and a perceived mismatch between textbook-derived homework/quizzes and in-class activities. Using problems from traditional textbooks without building more explicit connections to the *Super Mario Bros.* problems seems to have promoted students' perception that learning and assessment activities were not adequately aligned and that the time spent puzzling over the Mario problems was time wasted. Such misalignment between inquiry-oriented learning activities and more traditional assessments that emphasise 'correctness' may have also undercut students' own attempts at coherence seeking during the unit (Sikorski and Hammer, 2017).

Finally, although students became frustrated during their work on problems without relying on a previously teacher-defined approach, it seems that this time struggling helped prepare them to feel successful during direct instruction lectures that presented methods for solving the problems with which they had been struggling. This finding aligns with previous work which suggests that minimally guided instruction is not optimal (Kirschner *et al.*, 2006), and that direct instruction is a successful mode of instruction if students have been adequately primed for a lecture that provides them relevant analytical tools (Schwartz and Bransford, 1998). While initially a source of frustration, it seems that the Mario problems may have provided students with important opportunities to wrestle with ideas on their own and to establish a perceived 'need to know' about new content and problem-solving strategies when introduced via direct instruction.

Implications

This study has two primary implications for successful implementation of inquiry-oriented units that are developed in the time- and resource-limited context of school teaching. First, while a relevant context may be useful for motivating student interest and connecting problem situations to each other, students may experience frustration relating to the inclusion of this context if other classroom activities – particularly those on which they are graded – do not clearly align with the problem-based context. Teachers who design their own inquiry-oriented units and rely on textbooks to assign problem sets may need to include curricular features, such as reflective discussions during class, to help students explicitly connect between context-driven learning and the exercises they are assigned from textbooks. Further, teachers should consider ways to provide students credit for work that they do which may not be normatively correct (i.e. does not correspond with scientific consensus), but which serves a critical role in helping students construct deeper understanding. For example, students could receive credit for posing new questions that arise from an investigation that does not yield clear conclusions. This approach aligns with the perspective that student questions are a valuable source of information about what students know (Chin and Osborne, 2008; Watts, Gould and Alsop, 1997). Second, while students who are accustomed to more traditional pedagogy may initially struggle and express frustration when asked to work through problem situations with less initial direction than they are used to, it seems that these experiences can be productive for students by providing important cognitive priming for subsequent presentation of physics principles and analytical strategies. That is, rather than direct instruction being in conflict with the idea of inquiry-oriented science teaching, it is a critical component of it. Teachers who design their own inquiry-oriented units should think about how instructional contexts can not only enhance student motivation and interest, but also provide opportunities to make direct instruction more relevant and effective. A careful consideration of when and how to use direct instruction may also help to support students who are accustomed to more traditional pedagogy as they transition into more inquiry-oriented instruction. While I found that some level of struggle was productive for establishing a 'need to know' about new ideas and techniques, my students would probably have benefited from a more scaffolded introduction to the different types of classroom work that are a part of problem-based learning.

Designing truly inquiry-oriented units while also maintaining full-time teaching responsibilities is challenging. This challenge is compounded by the potential for negative reactions from students who may feel more comfortable and successful in more traditional settings. These factors often add up to tremendous disincentives for implementing inquiry-oriented instruction, especially when designing instruction at the high school and post-secondary levels for use with students who have previously experienced significant success within traditional science learning environments. Teachers, parents, and policy-makers must recognise and intentionally address these challenges if the promise of student-driven, inquiry-oriented classrooms is to be achieved on a large scale.

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Jeffrey Nordine is a former high school physics teacher and is currently Associate Professor of Physics Education at the Leibniz Institute for Science and Mathematics Education (IPN) in Kiel, Germany. Email: nordine@ipn.uni-kiel.de