An Implementation of *Physics by Inquiry* in a Large-Enrollment Class

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As physics instructors, we enjoy access to a variety of powerful instructional materials. Among them are classroom-tested inquiry-based laboratory curricula such as *Physics by Inquiry*[1] and *Workshop Physics*.[2] Unfortunately, such materials are often tested in conditions unattainable in introductory physics courses. In particular, the recommended instructor-student ratio tends to be larger than we can afford. This article describes an implementation of *Physics by Inquiry* in a liberal-arts physics class with 70 students and one instructor. I discuss the choices I made with the materials under these circumstances, describe the challenges that arose, and offer evidence that the course was fairly successful. Examples such as this one show that proven instructional materials can be put to good use even in circumstances that fall outside the tested conditions.

Teaching at The Evergreen State College

The Evergreen State College is a four-year public liberal-arts college. The curriculum consists mainly of full-time (16 quarter-hour) interdisciplinary team-taught "programs." These programs may last up to three quarters, with mostly the same students participating throughout. There are no departments, no grades, and no faculty ranks. Students at The Evergreen State College are in many ways characteristic of the national population of undergraduates. In other ways they form a unique population; for example, they have an unusual amount of experience in interactive literary seminars.

At Evergreen in the 2000-01 academic year, I co-taught two programs that were fairly representative of the curriculum. "Technology, Cognition, and Education" was a two-quarter program offered once, only to first-year students. The program had students investigate whether and how new technologies (such as the alphabet or photography) change the way we think and learn. The faculty team consisted of a literature professor with a background in developmental psychology, a computer scientist, a video artist, and myself (in my role as a physicist and an education researcher). I taught that course in its first quarter only. In the second two quarters of the academic year, I co-taught "Introduction to Natural Science" with a chemist and a biologist. Introduction to Natural Science is a two-quarter program offering a foundation in physics, biology, chemistry, math, and related areas; it is offered every year to students with at least one previous year of coursework at Evergreen.

This article presents my experience as the physics instructor for Introduction to Natural Science. Students in the program are inexperienced in the sciences or math. Most are headed for careers in health or environmental sciences; some are rounding out a liberal-arts education. Expectations for the program are determined mostly by Evergreen's institutional goals, which include collaborative learning, synthesis, and active application of knowledge to real-world situations. There are no specific coverage goals; the quantity of physics taught in a particular year depends strongly on the instructors teaching the program. Our year had about six hours of physics instruction per week.

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Physics by Inquiry

The nature of instruction at Evergreen left me entirely free to determine the form and content of the physics part of Introduction to Natural Science. I selected *Physics by Inquiry* as uniquely appropriate for the situation. *Physics by Inquiry* is a laboratory-based, step-by-step, in-depth introduction to the physical sciences. It offers students direct experience with the process of science; it is explicitly designed to develop scientific reasoning skills and provide practice in relating scientific concepts, representations, and models to real-world phenomena. It provides a strong foundation for continued study, or a substantive excursion into science for liberal arts students. Finally, it produces well-documented conceptual gains.[3] *Physics by Inquiry* is especially designed for the preparation of preservice and inservice K–12 teachers, but it has also been used in courses to strengthen the background of underprepared students aspiring to science-related careers, as well as in courses for nonscience majors.[4]

At the University of Washington, where *Physics by Inquiry* was developed, students work through the exercises in pairs, at their own pace. Feedback is through homework, exams, papers, and "checkouts." In a checkout, students articulate and reflect on their progress, and instructors ask questions of individual students and small groups to diagnose conceptual understanding. Checkouts usually last less than five minutes and occur after every hour or so of student work. Such individually tailored feedback is possible because the instructor-student ratio is small: *Physics by Inquiry* courses at the University of Washington range in size from 20 students with one instructor and one teaching assistant to 50 students with an instructional staff of eight. I expected to be able to approximately replicate the UW teacher-student ratio at Evergreen, with two co-instructors and 25–30 students expected to enroll.

Before arriving at Evergreen, I had been a *Physics by Inquiry* instructor at the University of Washington for seven years, where I was surrounded by a phalanx of gifted, experienced co-instructors. I contributed to the development of several modules in the curriculum. As I discuss in the following section, I drew heavily on this experience in adapting *Physics by Inquiry* to Evergreen's circumstances. In forming the syllabus for Introduction to Natural Science, I selected the topics in which I had the most teaching experience: properties of matter (mass, volume, density, etc.), electric circuits, astronomy, kinematics, geometric optics, electrostatics, and magnetism. In this article I will mainly discuss my implementation of the "Properties of Matter" module of *Physics by Inquiry*, which I had taught on the order of 10 times.

Modified *Physics by Inquiry*

Unfortunately, the situation at Evergreen did not approximate the University of Washington ideal. My two co-instructors did not have much time to dedicate to preparing for the physics part of the course, so I was the sole instructor. Further, I was responsible for 70 students instead of the expected 25. No teaching assistants were available.[5]

These circumstances necessitated certain modifications to the traditional *Physics by Inquiry* format. I couldn't provide equipment for more than 20 groups, so I had students working in groups of four or more rather than in pairs. Most dramatically, because I could not hope to interact with each group on request, I made the class instructor-paced instead of self-paced and replaced individual checkouts with "class checkouts." These checkouts hardly merit the name; instead of being individually tailored conversations, they were class discussions that I ran from the front of the room. Only those students who spoke up had their individual issues addressed, or had the benefit of explaining their reasoning to a critical expert.

The change from individual to class checkouts was structurally dramatic, and I feared it would alter the *Physics by Inquiry* experience beyond recognition. I was surprised to find that in practice, class checkouts bore striking similarities to individual checkouts. For example, in the first experiment in the Properties of Matter module, students experiment with balancing assorted objects on a pegboard balance. At the first checkout, I asked the same questions of the whole class as I would have asked of individuals: "What changes that you made in your experiments affected balancing? What changes did not affect balancing? What does 'balance' mean? What similarities do you notice among objects that balance one another?" Students' responses raised the conceptual issues I was familiar with from my previous experience. For example, students objected to the operational definition of mass as the number of square nuts that balance with an object; they wanted to call that "weight" because "mass," they felt, had more to do with how much space an object takes up. My years as a traditional *Physics by Inquiry* instructor had taught me not to treat this issue lightly; in many instances, this type of response reflects an inability to distinguish the concepts of mass and volume from each other. I had students record their concern in writing for careful consideration as they worked through other exercises and returned to it in later class checkouts.

The conceptual content of *Physics by Inquiry* was similar in the traditional and modified courses, and that similarity made Introduction to Natural Science feasible for me as an instructor. However, there were a number of important differences as well.

- **Students began as skilled communicators and active learners.** Students in Introduction to Natural Science had all been at Evergreen for at least one academic year. They already had experience with inquiry learning in other Evergreen courses; they had only to translate that experience to a science class. In this, they were well ahead of typical university undergraduates. Further, since an interactive seminar was central to virtually every Evergreen program, students arrived in our program already able to listen and respond to other viewpoints, construct arguments, and explain their thinking. Many students did not initially expect their seminar skills to be relevant to the study of science, but they adapted quickly.
- **Students had too little (or too much) time for particular exercises** because the course was instructor-paced instead of self-paced. Some teams had to skip exercises that would have helped them, or do them out-of-sequence on their own time. Other students finished early and lost their intellectual momentum waiting for a class discussion.
- **Students did not have issues addressed individually** unless they spoke up in class discussions (and I judged their contribution to be worth pursuing with the whole class). Fortunately, as I have said, issues that I knew to be universal usually arose in class checkouts. I circulated among teams as much as possible between class discussions, but with up to 20 teams in the room, most students were on their own most of the time.
- **Students had little opportunity for reflection.** Because the teaching load was so heavy, I did not assign any papers or give written feedback on students' work until quiz time.
- **There was "constructive interference."** In any *Physics by Inquiry* course, individual teams experience dramatic ups and downs as they work through the exercises. Lows of confusion or frustration are followed by highs when contradictions are resolved and ideas come together. The pattern of experience is predictably associated with the sequence of exercises in the text. At any one moment in a traditional *Physics by Inquiry* course, different teams are at different emotional locations in the curriculum. The instructor tends to experience something like the "average" of the student teams, which is more even than any individual team's experience. In the modified *Physics by Inquiry* course, by contrast, every group experienced near-identical highs and lows simultaneously. The emotional intensity on those days was a palpable presence in the room. One part of the Properties of Matter module, for example, has students seeking a rule to predict balancing of square nuts hanging from a pegboard balance. The exploration is difficult, and for two whole class sessions 70 students were increasingly angry. The day students found the rule that governs balancing, the news spread like wildfire from table to table, and the triumph in the room was electrifying.
- **I experienced the "constructive interference" alone.** In a traditional *Physics by Inquiry* course, students' anger over the balancing rule would have been spread over several instructors, but in the modified course I weathered their wrath by myself. Their victories were equally intense and nearly as strenuous to experience. In class checkouts, I felt like I was channeling 70 highly stimulated intellects, sensing and guiding their crackling energy as best I could. I left class each day completely drained.

In summary, the modifications to the traditional implementation of *Physics by Inquiry* essentially converted the course to an interactive lecture format. The modified course, although challenging, was manageable for me. However, it was important to me to document student learning in the course before judging its success.

Did It Work?

To assess the modified course's effectiveness, I compare student performance on two written questions with performance in other *Physics by Inquiry* courses, as well as in more traditional courses. I also discuss student attitudes toward the course and factors that contributed to its success.

Learning Outcomes

A small number of exam questions that have been administered in courses at the UW and in the modified course at Evergreen permit limited comparisons between learning outcomes in these courses. These questions test concepts covered in the Properties of Matter module of *Physics by Inquiry*—in particular, ideas about mass, volume, and density. The two questions below were designed by members of the Physics Education Group as part of a research project on student understanding of hydrostatics.

• *The Five Blocks Question.*[6] In the Five Blocks question, blocks labeled 1–5 have the same volume but different masses, with $m_1 < m_2 < m_3 < m_4 < m_5$. Each block is held halfway down in an aquarium filled with water and released. The final positions of blocks 2 and 5 are shown (see Fig. 1); block 2 floats just at the surface of the water, and block 5 is at rest on the bottom of the tank. Students are asked to sketch the final positions of blocks 1, 3, and 4. A correct response shows block 1 floating higher than block 2, and blocks 3 and 4 at the bottom of the tank. (Since block 2's density is only slightly less than that of water, denser blocks would probably sink. However, responses explaining that block 3 and perhaps even block 4 might be neutrally buoyant were counted as correct.) The most common incorrect response is the "descending line" response, in which blocks 1–5 appear at successively lower levels in the water. Student explanations for this response suggest confusion between the concepts of mass, volume, and density: One student stated, for example, that "[the denser block] would displace more water.... I can't think of the displacement as a volume, I have to think of it as a mass."

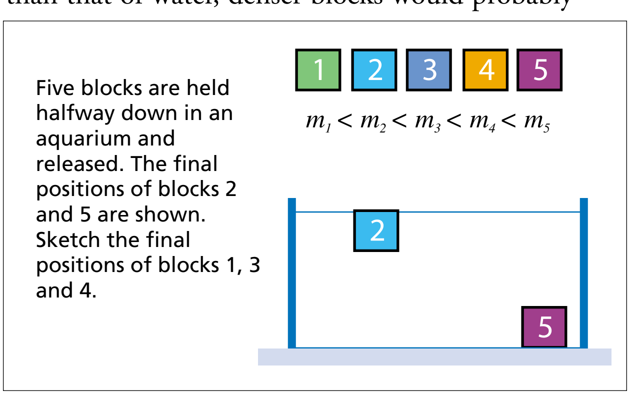

Fig. 1. The Five Blocks question.[5]

Table I. Results of the Five Blocks question.

Population	% correct after instruction
Algebra-based introductory course (*N*=369)	18%
Calculus-based introductory course (*N*=765)	41%
Second-year course in hydrostatics and thermal physics (*N*=101)	49%
Traditional *Physics by Inquiry* course (*N*=82)	83%
Modified *Physics by Inquiry* course (*N*=63)	84%

The Five Blocks question has been administered after instruction at various institutions in traditionally taught algebra-based introductory physics courses, calculus-based introductory physics courses, sophomore-level courses in thermal physics and hydrostatics, and traditional *Physics by Inquiry* courses, as well as in the modified *Physics by Inquiry* course. The student population in the modified *Physics by Inquiry* course is most similar to that in an algebra-based introductory physics course. Results are shown in Table I. They indicate that on certain conceptual questions, students in the modified *Physics by Inquiry* course perform comparably to those who have had traditional *Physics by Inquiry* instruction, and much better than students who have had lecture-based instruction.[7]

• *The Oil Displacement Question.*[8] In the Oil Displacement question, two identical cylinders are filled to the same level. One is filled with water and

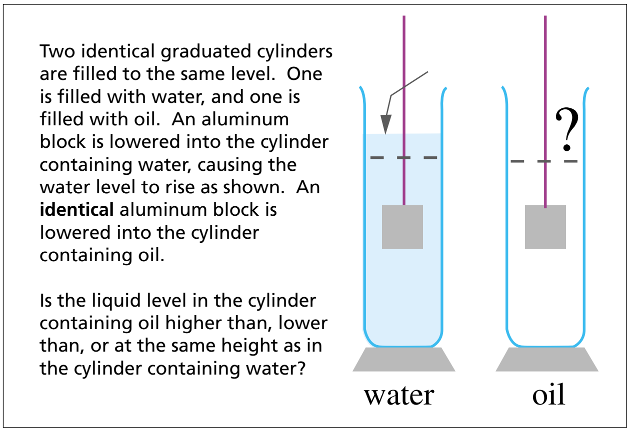

Fig. 2. The Oil Displacement question.[8]

Table II. Results of the Oil Displacement question.

Population	% correct after instruction
Algebra-based introductory course (*N*=70)	57%
Modified *Physics by Inquiry* course (*N*=63)	98%

one is filled with oil. An aluminum block is lowered into the cylinder containing water, causing the water level to rise as shown in Fig. 2. An *identical* aluminum block is lowered into the cylinder containing oil. Students are asked whether the liquid level in the cylinder containing oil is higher than, lower than, or at the same height as in the cylinder containing water. The correct answer is that the liquid level is at the same height in each cylinder, since identical blocks displace the same volume of liquid. Incorrect answers suggest confusion about the operational definition of volume, stating, for example, that more (or less) oil will be displaced since oil is less dense than water.

The Oil Displacement question has been given in an algebra-based introductory course at the University of Washington after traditional instruction and in the modified *Physics by Inquiry* course. Results appear in Table II and indicate that, like other *Physics by Inquiry* students, students in the modified course perform much better on certain conceptual questions than students in lecture-based courses.

Other Outcomes

Instructors naturally care not only about conceptual improvement, but also about student attitudes toward the course. Anonymous written feedback collected after five weeks of the modified *Physics by Inquiry* course indicates that students in that course, like students in a traditional *Physics by Inquiry* course, have difficulty adjusting to inquiry learning in the sciences:

- "*Without learning formulas, I don't feel like this is preparing me for further studies.*"
- *"I understand the philosophy behind the 'deconstructivist' approach but feel it is condescending."*
- "*All this explaining reminds me of my childhood.*"
- "*What are we doing? What do you want me to learn? Can we have more of a focus here?"*

Further anonymous feedback collected after 20 weeks of class suggests that, like students in traditional *Physics by Inquiry* courses, students in the modified course reflect on the program favorably:

- "*Five months ago I opened the text for the first time and was immediately turned off by its approach. I am happy to say that my opinion of its tactics has changed completely.*"
- "*The answers always came from within us and not from an outside voice. I don't believe I would have learned or retained as much without being taught in this way.*"
- "*Because my learning style has been acquired from traditional teaching methods, the way in which physics was taught was challenging for me. But within every challenge lives a great opportunity. I found myself thinking in intensive ways that I had not been used to.*"

Both initial frustration and eventual satisfaction are typical responses to *Physics by Inquiry* courses I have helped teach. I was pleased to find that the modified course elicited similar responses.

Lessons Learned

We would be foolish to expect proven instructional materials to survive an arbitrary level of distortion.[9]

My situation with a modified *Physics by Inquiry* course included specifically skilled students and years of preparation with the curriculum, and I expect that those factors are crucial to the success I observed. However, by describing my experience, I hope I have demonstrated that research-based instructional materials can retain much of their power even when we're not able to use them in the manner recommended by their developers. My case shows, for example, that under certain conditions the instructor-student ratio for a good *Physics by Inquiry* course can be quite a bit larger than I would have thought possible. To me this means that as instructors, we should feel free to consider adapting such materials to our own circumstances. The more we can learn about what modifications particular curricula can sustain, the more we as a community can maximize our teaching opportunities.

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5. In future years, I would have been able to recruit peer instructors from among students who had taken the course.
6. The Five Blocks question and the associated data are from M.E. Loverude, C.H. Kautz, and P.R.L. Heron, "Helping students develop a functional understanding of Archimedes' principle, Part I: Research on student understanding," accepted for publication in *Am. J. Phys.*, and P.R.L. Heron, M.E. Loverude, P.S. Shaffer, and L.C. McDermott, "Helping students develop a functional understanding of Archimedes' principle, Part II: Development of research-based instructional materials," accepted for publication in *Am. J. Phys.* Additional detail on the study, including student quotations, can be found in M.E. Loverude, Ph.D. dissertation, University of Washington, 2000.
7. Only differences of about 20% or more are considered significant by the developers of the curriculum.
8. The Oil Displacement question and the associated data are from personal communication with P.R.L. Heron, University of Washington, 2000.
9. For an example of an unsuccessful implementation of research-based instructional materials, see M.C. Wittmann, "On the dissemination of a proven curriculum: RealTime Physics and Interactive Lecture Demonstrations," submitted to *Am. J. Phys.* 2002.

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