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ABSTRACT

This paper presents an argument in support of "training little scientists" based on the requirements of participation in a media-laden, democratic society fraught with scientific claims and counterclaims. This leads to a framework for evaluating the effectiveness of various approaches to science education, including how they play out in practice. The promise of this framework is also demonstrated by examining some results of case study and survey research in project-based science classes at the high school level. (Contains 24 references, 5 tables and 1 figure). (DDR)

Why train "little scientists": The purposes and practices of science education in today's democracy

by

Joseph L. Polman

Department of Education

Washington University in St. Louis

One Brookings Drive

St. Louis, MO 63130

jlpolman@artsci.wustl.edu

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Introduction

In recent years, growing numbers of educators have become interested in approaches to science teaching and learning involving projects or inquiry (e.g., Pea, 1993; Ruopp, Gal, Drayton, & Pfister, 1993) which harken back to Dewey and the Progressive era (Cremin, 1961). Such project-based approaches are touted as a means of promoting students' active engagement with science in ways that are recommended by situated (e.g., Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991) and social constructivist views of learning (e.g., Newman, Griffin, & Cole, 1989; Vygotsky, 1978). Typically, these project-based approaches also stress the importance of learning the "process" of science, such as formulating empirically investigable questions and supporting claims with evidence. This is contrasted with other approaches which stress learning the "content" of science, such as conceptual understanding of established scientific theories. As a participant in the Learning through Collaborative Visualization (CoVis) project (Pea, 1993; Pea & Gomez, 1992) over the past few years, I have frequently encountered a criticism based on the opposition of the inquiry or project approach with a relative emphasis on process or "doing science" to approaches with a relative emphasis on understanding scientific concepts. The criticism can be paraphrased as follows: "Why are you spending all this effort to train 'little scientists', when so few of the children are going to end up becoming scientists? You'd be better off focusing on helping them gain a conceptual understanding of the various domains of science, especially since there is so little time for all the coverage necessary in the science curriculum." This criticism begs the fundamental, value-laden question: "Why do we want children to learn science?" Put within the context of education in a democracy, this question can be framed as, "What kind of scientific literacy is necessary or desirable for citizens in today's world?"

In this paper, I will describe an argument in support of "training little scientists" based on the requirements of participation in a media-laden, democratic society fraught with scientific claims and counterclaims. This leads to a framework for evaluating the effectiveness of various approaches to science education at addressing the requirements specified, as well as their *enactments* in practice. Finally, I will demonstrate the promise of this framework by examining some results of case study and survey research in project-based science classes at the high school level.

Scientific literacy for today's society

In order to understand some important aspects of scientific literacy for today's society, I want to describe a scenario. Imagine you are in the midst of trying to conceive your first child. After two years with no conception, you have begun to contact various fertility clinics in your area. One Sunday, you open up the local newspaper and you find that there are concerns about a number of practices at fertility clinics, and uses of specific drugs for fertility purposes. Being personally invested in the issue, you read the newspaper article from start to finish. Some of the accounts are alarming. People have gotten seriously ill and even died unexpectedly. Health care providers have not always warned patients of known risks. But you, personally, are considering some of these drugs, and you desperately want a child. What are you to do?

This scenario is not purely fictional to me, because I have two close friends to whom this actually happened. Let's step back from the scenario to the concerns of educators. How would we hope an educated adult who is not a biomedical research scientist would react to this article, which appeared in the *Boston Globe* (Kong, 1996)? Perhaps a critical reading of the article would be helpful. The article contains a table tallying all deaths and adverse reactions to a number of fertility drugs reported to the FDA over a 25 year period. The author quotes one expert, who reacted to the table by saying "any reports of deaths made to the FDA need to be carefully interpreted" (p. A34). But the author is careful to point out that that particular expert represents a drug company which manufactures and distributes fertility drugs. This is a useful caution against biased sources, but the expert's caution seems a reasonable one. What would a careful interpretation of numbers of reported deaths and other "adverse reactions" entail? Part of a careful interpretation might include consideration of the other medical circumstances or conditions present in the 45 deaths and 1982 total adverse reactions associated with Clomid in reports to the FDA between 1970 and 1995. Another consideration is which adverse reactions got reported to the FDA and which did not? How many adverse reactions normally occur during pregnancy? None of these things are possible to glean from the article or table, which is careful to mention "reports do not prove that the drugs caused all negative reactions" (p. A34).

At another point, the author cites an account of a woman who was "perfectly healthy" until taking a drug, prompting her sister to form a "victims network." As if to bolster the claim that many others are experiencing problems with the drug, the sister reports that "thousands of people have contacted her organization" (Kong, 1996, p. A34). What kind of evidence is that? How many readers assume that the thousands of contacts translate into thousands of problems? How many question the relevance of the number of contacts?

The newspaper account plants strong doubt in the scientific establishment's ability and willingness to fully test drugs' short and long-term consequences, implying that greed may be clouding the judgment of decision-makers in fertility clinics, research labs, and drug companies. Again, this caution seems warranted, but there is a flip side to the issue not mentioned in this article. Many citizens' rights groups, beginning with groups concerned with developing treatments for AIDS and HIV infection, have argued vehemently for "fast-tracking" important new drugs. Within such an environment, it appears inevitable that individual citizens will be affected by matters that are marked by contradictory scientific studies such as the case of fertility drugs cited here. In addition to fertility and AIDS treatments, recent debates have raged around the danger of living near power lines, hormone treatment at menopause, and the optimal frequency of mammograms *while citizens are in the midst of making decisions about those same issues*. Even if the trend toward "fast-tracking" which citizens and corporations have been pushing were to end, philosophers of science from widely differing perspectives agree that scientific progress inevitably involves ongoing contentiousness and debate. For example, Popper (1959) argued for a strict logic of scientific theory building and testing which relied on the verifiability and refutability of theories; in his system, empirical investigations which refute theories will always be possible and should often be pursued, because knowledge develops through the debate that ensues. On the other hand, Feyerabend (1993) argues for a much less logical system of scientific method, which includes sometimes inconsistent argumentation, but is always characterized by competing theories and observations.

Neil Postman (1992) claims that American society today can be characterized as a "Technopoly," in which individual citizens are expected to bow unquestioningly to the proclamations of experts from tiny domains that no one other than the highly trained can understand. He cites the tendency of Americans to believe any claim, no matter how outlandish, as long as it originated from a "study" done at a reputable research institution (p. 57). He recommends that citizens resist this trend, and do not believe in the "magical powers of numbers" nor "regard calculation as an adequate substitute for judgment" (p. 184). I would like to build on Postman's point and argue that citizens who do not understand how scientific research is done, and how scientific research is questioned on its own terms[1], have very little recourse but to either (1) bow to the recommendations of their favorite expert or friend, and completely ignore the arguments grounded in scientific studies; or (2) follow the recommendations of the last scientific study they encountered.

Although the techniques of Western science are surely *not the only* means of reaching adequate judgments about issues related to science, one means for citizens to participate in the conversations of experts is by gaining an understanding of research design and the statistical techniques used in studies grounded in this tradition. As occurs only too often in education, Dewey (1910/1964) made a similar point at the beginning of this century, and its importance has only increased:

[1] Postman would not necessarily embrace my recommended curriculum, which differ from his own (see below in the section "The promise of project-oriented pedagogy"). He argues for similar goals, however, when he says students should learn about induction, scientific theories and models, and conditions for validity (p. 193).

> "... science has been taught too much as an accumulation of ready-made material with which students are to be made familiar, not enough as a method of thinking, an attitude of mind, after the pattern of which mental habits are to be transformed." (p. 183)

The "ready-made material" of current scientific concepts can only go so far, because science is constantly moving forward (resulting in an explosion since Dewey's time in the amount of material generally crammed into science curricula, which only exacerbates the problem). This point holds as much for physical science, environmental science, and social science as for the biomedical science I have focused on up to this point. Adult citizens participating in a democratic society need to understand the dominant "methods of thinking" from Western science, or they will be unable to participate in the debates based in this tradition. We cannot expect all citizens to know the details of debates in these subjects as well as experts who have devoted years of study to each of these disciplines, but we can strive to enable citizens to at least become "legitimate peripheral participants" (Lave & Wenger, 1991) in the debates that affect their lives.

A framework for teaching and learning today's scientific literacy

As argued in the previous section, today's scientific literacy should enable students to participate in discussions about and critical evaluations of ongoing research results based in the traditions of Western science. In the recently completed *National Science Education Standards* (National Research Council (NRC), 1996), a similar point is made: science literacy is important because "Americans are confronted increasingly with questions in their lives that require scientific information and *scientific ways of thinking* for informed decision making" (p. 11, my emphasis). According to the *Standards*, one way students will develop scientific ways of thinking is by developing the "abilities necessary to do scientific inquiry", which include

- Identify questions and concepts that guide scientific investigations.
- Design and conduct scientific investigations.
- Use technology and mathematics to improve investigations and communications.
- Formulate and revise scientific explanations and models using logic and evidence.
- Recognize and analyze alternative explanations and models.
- Communicate and defend a scientific argument. (Content Standard A, Grades 9-12, pp. 175-176)

In order to "design and conduct scientific investigations", as well as "use logic and evidence" in ways they are often used in science, I propose some more specific important abilities. Students should be able to:

1. formulate *empirically* investigable research questions and problems, including common "epistemic forms" (Collins & Ferguson, in press) of research such as testing against the null hypothesis, isolating variables, and building simulations or models
2. create and recognize explicit and strong links between empirical data and claims
3. recognize threats to the validity and reliability of claims

4. understand the implications of research claims, including generalizability and limits, as well as issues such as statistical significance *vs*. power (i.e., "twice the risk" means different things when the base rate is 1% and the base is 40%, although in both cases statistical significance has been reached)
5. understand the role of debate, consensus and multiple studies taking varied approaches to research issues.

These points should be useful both in the design of curriculum and pedagogy and the evaluation of enacted curriculum. I will now turn to such an evaluation of enacted curricula based on the goals and concerns laid out here.

The promise of project-oriented classrooms

As mentioned above, Neil Postman (1992) has identified many of the same problems I have which today's citizens face, specifically the flood of scientific studies being conducted and how ill-equipped citizens taught science as an "accumulation of ready-made material" are to understand or debate the studies' relevance. In order to address these problems, Postman recommends teaching more history of science and more philosophy of science in school. Another approach is to have students directly "take a hand in the making of knowledge" (Dewey, 1910/1965, p. 188) by conducting science inquiry in the form of research projects.

The *National Science Education Standards* (NRC, 1996) emphasize "inquiry" as vital to the science curriculum. By "inquiry" they mean

> the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world (p. 23).

The emphasis on inquiry, however, "should not be interpreted as recommending a single approach to science teaching ... conducting hands-on science does not guarantee inquiry, nor is reading about science incompatible with inquiry" (NRC, 1996, p. 23). Nonetheless, the *Standards* describe "successful science classrooms" as places where

> teachers and students collaborate in the pursuit of ideas, and students quite often initiate new activities related to an inquiry. Students formulate questions and devise ways to answer them, they collect data and decide how to represent it, they organize data to generate knowledge, and they test the reliability of the knowledge they have generated. As they proceed, students explain and justify their work to themselves and to one another, learn to cope with problems such as the limitations of equipment, and react to challenges posed by the teacher and by classmates. Students assess the efficacy of their efforts—they evaluate the data they have collected, re-examining or collecting more if necessary, and making statements about the generalizability of findings. They plan and make presentations to the rest of the class about their work and accept and react to the constructive criticism of others. (NRC, 1996, p. 33)

This description follows much of what we in CoVis describe as a "project-oriented" pedagogy; by this we mean an approach to science teaching and learning which depends to some degree on students conducting science research projects with the help of their teacher. The *Standards* and the CoVis project both subscribe to a form of Dewey's "learning by doing" philosophy. Dewey claimed that "only by taking a hand in the making of knowledge, by transferring guess and opinion into belief authorized by inquiry, does one ever get a knowledge of the method of knowing" for science (1910/1964, p. 188). In the analysis below, I will evaluate this claim, and seek to understand whether and how "taking a hand in the making of knowledge" through science research projects results in a "knowledge of the method of knowing" for science.

Data sources and methods

The science teaching and learning I will consider comes from two sources: case study research in a project-based classroom (Polman, 1997) and a survey instrument known as the "Project Planning Exercises" administered to classes varying in the degree of their "project orientation."

The case study research focuses on open-ended research projects conducted over a twelve week period at the end of one and a half years of intensive participant observation by the author (the time period was November-January in the 1995-96 schoolyear). It is part of a larger interpretive case study (Polman, 1997) conducted from 1994 through 1996 in Rory Wagner's[2] class, as part of both of our involvement in the Learning through Collaborative Visualization (CoVis) project (Pea, 1993). The term *interpretive* is based on Erickson (1986), and refers to any form of participant observational research that is centrally concerned with the role of meaning in social life, enacted in local situations. One of the central features of the class was that students conduct Earth Science projects *of their own design*; what this meant in practice was that they participated in the formulation of a research question, the gathering of data to provide empirical evidence for addressing the question, analysis of those data, and reporting in both written and oral format. Data collection techniques included written field notes and videotapes of classroom observation at each project phase, collection of artifacts created by the teacher and students, and formal and informal interviews of both the teacher and selected students. Formal interviews were recorded with audiotape and transcribed, while informal interviews were recorded with hand-written notes.

The survey research[3] comes from coding of student responses to open-ended "project planning exercises" from three different CoVis earth science teachers' classes which vary in the amount of

[2]At his request, Rory Wagner's real name is used. All students' names are pseudonyms.

[3]I wish to thank the entire CoVis staff and all teachers who participated in this survey effort, which was substantial. In particular, I want to thank Louis Gomez, who directed the development and piloting of the survey, and Franci Steinmuller, who was the second coder.

time devoted to project pedagogy and the degree of responsibility students must take for research design. One of the three teachers was Rory Wagner, whose class was also examined in the case study. The surveys were administered in the fall and the spring in order to obtain a measure of change across the year. Numbers of surveys and data relevant to project-orientation are in Table 1:

Teacher[4]	Time on projects[5]	Student formulation[6]	Fall 95 Surveys (n)	Spring 96 Surveys (n)
Project-Based (high orientation and time)	75%	100%	50	20
Project-Oriented (High orientation, low time)	3%	100%	72	94
Project-Enhanced (low orientation, moderate time)	20%	25%	84	68

Table 1: Groups, project orientation data, and numbers of surveys

Each set of exercises contained two scenarios, which place the student in the role of director of a research project for a scientific problem. There were a total of eight scenarios created, on four different topics: beach erosion, global warming, snowstorm prediction, and meteor paths. Each scenario came in a short form and a long form, with the latter including example data they could use and guiding questions. Students received different scenarios in the Fall and Spring to avoid practice effects. Table 2 shows the scenarios for the beach erosion topic:

[4]The designation of teachers as project-based, project-oriented, and project-enhanced is intended to convey varying levels of commitment to a project orientation, which in our definition means students' participation in research design (see student formulation column, plus time on projects). Project-based means a very high level, oriented a moderate level, and enhanced a piecemeal level.

[5]As a percentage of all class time. Based on teacher estimates, observation, and communication with teacher.

[6]This refers to student responsibility for formulation of question (as opposed to assigned by teacher) and analysis plan (as opposed to laid out by teacher). Based on teacher estimates, observation, and communication with teacher.

Beach erosion (short form) A small town on the Pacific Ocean is in trouble. They are dependent on tourists who come to their town to enjoy their beaches, but the beaches are losing much of their sand. They have hired you to act as scientific advisor on beach erosion. Your job is to direct a research program to figure out what is causing their beach to erode. Please describe a plan for figuring out the extent and cause of erosion at the town's beach, to report to the town council.
Beach erosion (long form) A small town on the Pacific Ocean is in trouble. They are dependent on tourists who come to their town to enjoy their beaches, but the beaches are losing much of their sand. They have hired you to act as scientific advisor on beach erosion. Your job is to direct a research program to figure out what is causing their beach to erode. The following is a list of data available to you for your research on beach erosion: • Maps showing the coast line and beach size every year for the past 50 years • Wave height data for the past 50 years • Wind data for the past 50 years • Rainfall data for the past 50 years • Data on the amount and location of plant life at the beach for the past 50 years Please describe a plan for figuring out the extent and cause of erosion at the town's beach, to report to the town council. To complete your answer, you may find it helpful to use the following questions as a guide: Who will you ask to help you? What research teams will you form and what will the teams do? Which instruments and data will your research teams use? How will they use these instruments and data? When the research is done, how will you convince others that your conclusions are right?

Table 2: Project planning scenarios for beach erosion

One class in depth: Cases of success and frustration

By his fourth year of conducting a project-oriented earth science class, Rory Wagner has developed and refined the way he conducts his class a great deal. He begins the year with a quarter-long "whirlwind lecture tour" of the earth sciences, coupled with an introduction to the Internet and computer tools his classroom contains (6 computers with the Web, email, spreadsheet and word processing software). This is followed by three rounds of quarter long projects which his students design and implement with his guidance. In order to help them figure out how to conduct projects, Mr. Wagner has developed what can be referred to as an activity structure (Lemke, 1990; Polman, 1997; Polman, 1998) for projects. He has broken the overall process of open-ended research projects into the following phases for his students, each of which culminates in a deliverable artifact or event: (1) selection of research group and broad topic, (2) research on background information related to the topic, (3) formulation of a research proposal, which usually includes a research question and ideas about methods, (4) data collection, (5) data analysis, (6) complete research report preparation, (7) revision of research report based on feedback, and (8) presentation of the research to the class. On a November day, students have formed eleven groups of two to three and are beginning phase one of their project.

Bruce, Cheryl, and Sylvia spend most of their time at the computer table just to the right of their teacher, Mr. Wagner, at the front of the classroom. Bruce is a tall, quiet and somewhat rumpled junior. Cheryl is an outgoing senior who is dramatic in her manner, which is not surprising as she is involved in theater. Sylvia is a senior who is graduating early in December. Like many students over the three years Rory has been allowing students to choose their own research topics, Bruce, Cheryl, and Sylvia express an interest in UFOs and aliens. Rory had been frustrated at all of the previous efforts, because the students had been unable to design a research project on UFOs that relied on empirical data and argumentation. Despite his misgivings, he decides to let the students run with their topic, since he maintains that he cannot predict all the promising avenues students might uncover or generate.

One reason Rory makes a conscious effort to remain open to what may seem at first outlandish ideas from students is that it provides motivational benefits to the students when they get to work on something they are interested in as well as when they have more ownership of their projects. "Kids can come up with some interesting projects ... that you wouldn't think of." An example of how a project that appeared problematic at first worked out is one from 1994-95 on "controlling the movement of the earth's continental plates" at a location on the San Andreas fault. Trying to stop plate movement seemed silly to Rory, and he said he would have rejected the idea in his first year, but he decided to let the enthusiastic group try and develop their idea. They ended up doing an interesting inquiry in which they determined the size of historical earthquakes at that location, and learned about how structures can withstand shearing stresses based on structure and the material from which they are made.

In addition, giving the students real choice on matters that are fundamental to their work, as Lepper *et al.* (1993) mention, means that they are free to make decisions the teacher does not think will be best in the long run. To address this problem, Lepper, *et al.* say expert tutors limit student choices to instructionally irrelevant choices and situations "in which the tutor is not certain what would be best for the student." In Rory's class, decisions about topics and research questions fall into this category. In some cases during this quarter, such as the Woolly Mammoth project and Barb's UFOs & Aliens project, Rory's suspicion that the project will go badly is borne out. At the end of the Woolly Mammoth project, Rory can see in retrospect that they "got derailed in the beginning" from an idea that probably "would have come out better" than the one they chose. Diane, Tom F, and Tom M were considering doing something on woolly mammoth extinction or how the woolly mammoth and the modern-day elephant occupied similar ecological niches; Rory thought the latter idea was much better, but Diane and Tom F's preference for the former led them to pursue it. On the other hand, in the case of the UFO Sightings project and the Black Holes projects, ideas that Rory suspects will be problematic, because they had been tried unsuccessfully by numerous students in previous years, result in successful projects.

As the mixed success of the projects indicates, the problem, as Rory points out, with starting from students' interests is that it is "awful hard" in many cases "to transform something you are really interested in to something you can do" as scientific research. For effective teaching and learning it is not a matter of the teacher simply telling the students what to do; as I have been stressing, Rory wants to ensure that students *participate* in such research design decisions so that they can learn about research design. The difficulty and pitfalls of student participation in the *whole* process of research has been recognized by a number of student-scientist collaborative efforts, but even though it is often messy from scientists' perspective to have students involved in the whole process, it is educationally significant (Pea, Gomez, Edelson, Fishman, Gordin & O'Neill, 1997). A balance between student ownership and teacher guidance in potentially promising directions is key, allowing *both* parties to make crucial contributions. As Rory described it,

> sometimes [students] come up with things that are really creative that I would have never thought about, which then lead me to think of other things that might be doable. And sometimes— [and] this gets in to the negotiating thing—sometimes they get real close to something, or have a neat idea, but it's not doable, so then, how do you turn that into something that is doable? Sometimes they do it, sometimes I can do it.

An example is provided by the way Bruce, Sylvia and Cheryl's project moves from being a project about "whether UFOs are alien space ships" (just as Barb's started out *and* ended up) to a project about confirming or supporting natural explanations of UFO sightings.

Along with the other groups, the UFO Sightings group begin the project by collecting and synthesizing background research on the topic, before deciding on a specific research question. In their interim report of background research , they mention the so-called "Condon report" (Condon & Gillmor, 1968), the only official study of UFO sightings put out by the US government. Condon and his colleagues claimed UFO sightings could be explained by meteor showers, rocket launches, and other known phenomena.

Two days after he gets the Background Information reports, Rory says to me before class, "I should watch out for groups that need support instead of just waiting for it to become a problem. I think I'm trying to back off because I don't want to give them a topic and make it my project." Given the problematic nature of UFO projects in the past, Cheryl, Bruce and Sylvia are obvious candidates for providing with extra support, and Rory and I are both intrigued with the group's description of the Condon report. In our meeting before class, he and I discuss the fact that Condon's analysis took an empirical approach based on supportable or refutable claims about alternate explanations for UFO sightings. We are both intrigued by how Condon was able to take a scientific approach to a problem surrounded by so much hearsay. So during class that.day, Rory initiates a discussion with the UFO Sightings group about potential research questions.

Shortly after completing attendance and answering some procedural questions about the research proposal assignment, Rory says, "OK, you guys," to Cheryl, Bruce, and Sylvia, and sits down with them. The following interaction takes place:

> **Rory:** OK, what do you want to do?
> **Bruce:** We want to show UFOs are alien space ships.
> **Rory:** [doubtfully] Any ideas on how?
> **Bruce:** I don't think there's any way to prove it unless they saw the alien in there and they waved at them. That's the only evidence there is.
> **Rory:** Right. That's the problem.
> **Cheryl:** I don't see why we can't write a report on it if people have written whole books on it. [Cheryl sees Rory's project at this point as essentially the same as an extensive report for an English class. As time goes on, she begins to grasp the importance of using empirical data to support a claim.]
> **Rory:** [does not directly address Cheryl's confusion at this time] You know, Joe and I were talking about the analysis Condon did that you wrote about in your Background Information [report]. It was interesting because Condon claimed to have explained the sightings with known phenomena. [For your project] you could verify what somebody like Condon has done. That's another thing people do in science ..."

He gives them the example of the cold fusion debate a few years ago, and then points to how this could be applied in their project:

> ... these guys said they had created cold fusion in the lab. But when other people tried it, they couldn't duplicate what they said ... In science, once someone says they've proved something, others check it ...The idea is to verify the government's explanations. Say they said it was a meteor shower. You could look at the date, where the meteor shower was, and when and where people saw the UFO. Does it match the same spot? If the sighting was here [points one direction] and the meteor shower there [points another direction] the government's explanation could be wrong.

The students decide to run with the idea. In this example, the students originally present the Condon Report as relevant to the history of the UFO debate, and thus something to be cited. Through their interaction, Rory and the students create a new meaning for the citation: the seeds of a study intended to provide independent confirmation or falsification.

I will not describe the rest of the UFO Sightings project in much detail. I will note, however, that this research formulation succeeds despite the fact that the group is "dysfunctional" in terms of attendance (at one point, on only one half of the project days were all three group members present in class, and on one sixth of the days only one student was present). In addition, Bruce, Cheryl, and Sylvia do not pick up on the technology as quickly as some other groups. In frustration near the end of the project when they are trying to assemble their paper in a word processor, Cheryl comments "I think I'm gonna turn Amish. I hate computers." Instead of high-tech resources, the group almost exclusively uses the library, finding the Condon Report eventually in the Northwestern University library, after striking out at the school library, 4 community libraries, and the Internet. For their final research report, they choose four UFO sightings from the 1960s described in the Condon report, and try to independently confirm or falsify the Condon report's explanation. The independent confirmation is based on printed data sources found in library searches: a nautical almanac (Casey, *et al.*, 1989) confirmed the position of a planet in the exact location where a UFO sighting was reported; NASA launch records (Stanford, 1990) confirmed that a scheduled re-entry of satellite Agena into the Earth's atmosphere occurred at the time an airplane crew reported a UFO over Mexico, and could have been seen in that location; a daily weather book (Thomas, 1979) confirmed that the local conditions matched those associated with mirages caused by refraction through warm, dry air, just as the Condon report claimed. They could not confirm or deny the Condon report's assertion that a rocket launch explained a fourth sighting.

Despite Rory's best efforts to support projects through the activity structure punctuated by milestones, and guide students' work, some projects don't turn out well. Although I did not carry out detailed observations on the following two project cycles of the 1995-96, the data I have from previous years and later in the year suggests that the repetition of the project cycles allows some students to improve who have trouble the first time around. For example, one student in 1994-95 told me that "the second project is going better because we understand Rory's expectations better." During the same year, two others did an abysmal project on UFOs during the fall, but made significant improvements in research formulation and data analysis during the second round when they did a project on geyser eruption patterns in Yellowstone National Park. Later in 1995-96, Mark, who worked on the Zodiac project, and Tom F and Tom M, who worked on the Woolly Mammoth project, teamed up. The group members chose geysers as their topic and built on some of the ideas the group the previous year did not finish. These three who had great difficulty in their first project gathered data and did an analysis of dormancy patterns in geyser basins that lay adjacent to one another. Also later in the year, Patti, Diane, and Marie, who worked on three different projects that ran into trouble the first time around, did an interesting project about the relationship between the number of tornadoes and the number of deaths caused by tornadoes per year. Patti saw the second project as much more manageable than the first one. At the beginning of the project in the third quarter, Rory asks the students for feedback on how they think projects could be improved, and one student asks him to "be more specific what [he] want[s]." Rory tries to, but for many students, the simple repetition may help more than the *way* he explains what he wants.

Nonetheless, as it stands, some students just don't have much chance to succeed in Rory's class. Two prime examples from this class are Cindy and Barb. Both of them could use more structure and guidance than they receive in Rory's class. I have a conversation with Cindy in the middle of her second project, that shows she still doesn't understand projects as involving making original contributions, and not just synthesizing known facts:

> **Joe:** What are you up to?
> **Cindy:** I'm doing volcanoes.
> **Joe:** What about volcanoes?
> **Cindy:** Volcanoes in the Pacific Rim, all around the Pacific ocean basically.
> **Joe:** And where have you gotten to with it?
> **Cindy:** I've collected all kind of information [shows me a pocket folder], and now I have to sort it.
> **Joe:** Do you have any data on it?
> **Cindy:** What do you mean?
> **Joe:** Like numbers of eruptions and stuff?
> **Cindy:** No ... well, sort of. Mostly I've got this information that I have to put together.

She continues to have procrastination problems, and does not seem to be understanding project work any better. She then says she wishes Rory's class were more like the other teachers', where they "do labs and take notes and take tests and everything." She also says, "I feel like this class is a waste of time. Like I come in here and we're just supposed to work on our projects. I can't focus on that during class. I feel like I don't learn anything. *I don't know how to do things this way* ... Some people like it better [this way], but I wish it was more like a normal class." Barb suffers in part because she is hesitant to bring questions and problems to her teacher's attention, and he is so occupied by questions which more proactive members of the class bring to him that he seldom gets to her.

The question this begs is: what can be done to address the needs of students like Cindy and Barb? One possible change is to adjust the level of structure available for students on their second or third time around. This could involve offering such students project ideas, for instance from the list of promising questions Rory has been accumulating for several years. Even more support could be provided if Rory were to recommend such students work on questions for which he knows data resources are available, as another CoVis teacher does. Such a strategy could undoubtedly introduce or exacerbate other problems in the system, such as questions of fairness given the deliberate differences in difficulty of such projects. But to the extent that this strategy could be made workable, it would provide a leg up for a student like Cindy, who is uncomfortable with new practices. When she was confronted with a computer skills exam early in the year, she had an opportunity to get more comfortable by watching others perform successfully; she had much less opportunity to become accustomed to new practices without failure in project work.

These cases demonstrate how students in a class devoted fully to research projects for the last three quarters of the year gain the sorts of tools which I argue will serve them well in today's world. Nonetheless, the complex role changes for teachers and students makes "project-based" science teaching difficult to customize well for all students. In this section, I have described some of the successes and difficulties in trying to maintain a balance between the extremes of overly structuring student activity and leaving it too open. Since each student and group requires a different level of structure and guidance to maintain equilibrium, teaching becomes more difficult. Moving too far in one direction or the other compromises both motivation and learning; only by maintaining equilibrium can students remain challenged and have maximal opportunities to learn. The examples described in this section are intended to show how it is possible, but difficult, to guide student work just enough to maintain that equilibrium.

Several particular directions toward which teachers can steer students became apparent through my case study research. In particular, teachers can steer the difficult task of research question formulation toward independent confirmation or falsification. This is a potentially important leg up for students having trouble formulating research either because their topic is difficult or because they lack confidence. To aid in this process, Rory could ask students to *look* for scientific claims during their background information research that they might like to question or see if they can independently support during the later phases. In addition, students could look for scientific debates like known phenomena as explanations of UFO sightings (and also the question of whether a new object identified in space is a black hole, the debate about whether Pluto is a "proper" planet, or how Plesiosaurs used their flippers in swimming, all of which Rory's students pursued). Such debates may spark student interest and sense of ownership, and demonstrate to students that science involves research and argumentation that they as thinking persons can participate in. As Beth put it when I asked her what the most interesting part of her project was, "I really liked just—it was sort of just like a mystery ... and that I had to like figure it out." Obviously, latching onto scientific debates is not a fool-proof recipe for success, as the Dinosaur Extinction and the failed UFOs and Aliens projects exemplify. Students need to find debates for which they can get and use empirical evidence, and even so, they may still encounter other pitfalls along the way. However, the results can be unexpectedly impressive when teacher and students are able to maintain a balance between openness and guidance.

A broader view: Performance on project planning tasks in different environments

One problem with case study research such as that done in Rory Wagner's classroom is that it is extremely time- and person-intensive. For that reason, it is difficult to do case studies of much depth in multiple settings. For the purposes of formative as well as summative evaluation of a project-oriented reform effort such as CoVis, however, a broader view is extremely helpful. We have conducted a number of multiple choice and Likert-based surveys to assess trends in attitudes and practices, but we endeavored with the Project Planning Exercises (PPE) to create an instrument which could capture richer data on developing student competencies, but still be less time-intensive than direct classroom observations. We make the following assumption about the results of these open-ended planning tasks: although students who describe a plan of action may not be able to carry out all aspects of the task unaided were they given the chance to carry it out[7], students who are able to articulate a plan with specific features will be better off than those who do not. For this analysis, I will focus on three aspects of the student plans, which relate to the concerns for scientific literacy described above: (1) students' unprompted description of specific empirical data they would like to use in their inquiry, (2) students' use of specific analysis strategies which we see as accepted "epistemic forms" (Collins & Ferguson, in press) of science inquiry, and (3) the stated source of solutions to the research questions or problems the students lay out in their plans.

All student responses were coded for the use of empirical data in their proposed project plan. As mentioned in the "Data sources and methods" section, half of the scenarios directly prompted students for data, and gave them examples of data; since these "long versions" provided scaffolding in the question for the specification of empirical data, and resulted in uniformly high use of such data, we did not include them in this analysis. Figure 1 shows the data and chart for students pooled according to the project orientation of their teacher:

[7]In making this point, we hope to indicate our concurrence with the arguments and research of Lucy Suchman (1987), who has shown that abstract plans do not account for all that is involved in situated actions. In order to evaluate the situated knowledge of students, we argue that direct observation of student inquiry (as in the case studies) is necessary.

	Fall	Spring
Project-based	52%	67%
Project-oriented	55%	63%
Project-enhanced	54%	47%

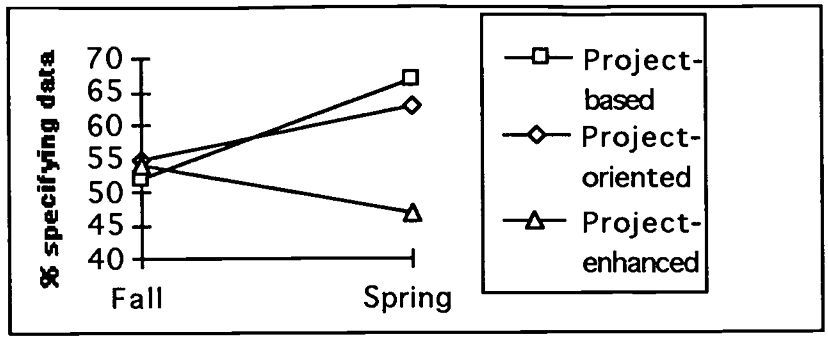

Figure 1: Percent of students in 3 teachers' classes specifying data, unprompted

In the project-enhanced class, where students were not given as much responsibility for formulating research and analysis design, the number of students specifying empirical data to collect for the project actually *decreased.* On the other hand, when students spent a small amount of time on research design in the project-oriented class, but had a teacher who emphasized it, more specified empirical data to use in the inquiry.

We also coded student responses for the sorts of common analysis strategies they specified for their planned inquiry. Table 3 shows the categories which we coded as binary items (simply present or not in all responses), which were then grouped into broader categories that reflect our valuation of increasing sophistication and specificity to natural science. In addition to the presence or absence of each strategy, we determined the highest level broad category of strategy found in each response, and used that numeric data to compare the pools of students taught by the three teachers.

Binary code	**Explanation**	**Broad Category**
Discover	They find answer by looking or "researching" or "studying," but there is no indication of one of the following ways of looking	0. Discover
Find patterns	Find patterns of some sort in some data, but ill-specified	1. Inconclusive Strategies
Invoke strategy	They simply name a strategy but they do not make it clear in any way that they know what that strategy could mean in this case. The use of the term may be token. For example "I would make up some kind of hypothesis of where the meteor is going to hit." In this case, they don't indicate what the hypothesis would be or how or even that they would test it.	1. Inconclusive Strategies
Graph / chart / summarize	Graph or chart some variables, or perform summary calculations such as averaging on a variable	1. Inconclusive Strategies

Copy	Copy another solution and if necessary modify what's been done elsewhere	2. General Strategies
Extrapolate from current conditions	Determine what the relevant conditions are at present and assume they will continue in a predictable way. An example is assuming the weather to the west of a location will continue as is and affect that location.	2. General Strategies
Match current case with historical cases	Try to match the configuration of some conditions/variables with identical conditions in the past.	2. General Strategies
Predict and test	They specify a prediction about what will happen, and test it in situ or in historical data.	3. Experimental Strategies
Verify hypothesized cause	They will try to see if a cause they predicted is borne out (that cause must be specified).	3. Experimental Strategies
Laboratory experiment	They describe a lab experiment which will contribute to their analysis.	3. Experimental Strategies
Model testing	They describe a physical or analytical model they will use to perform tests.	3. Experimental Strategies
Covariation or co-occurence of variables	They look for covarying quantitative variables—e.g., car exhaust increase corresponds with temperature increase—or co-occurence of variables	4. Numerical Strategies
Formula	They create a formula or mathematical model that expresses the relationship between variables.	4. Numerical Strategies

Table 3: Analysis strategies coding scheme

Once again, results from students in the project-enhanced class, where little work on design of research and analysis was done, were discouraging. The percentage of students in the Project-Enhanced class who stated that they would simply "research" in a completely unspecified way to find the answer increased from 27% in the Fall to 44% in the Spring. In the project-based class, there was a large increase in broad category 1 responses ("General Strategies")—from 22% in the Fall to 31% in the Spring. This is probably attributable to the emphasis that the teacher put on graphing and finding patterns in data. In the project-oriented class, there was a moderate increase in General Strategies (from 20% to 25%), and a large increase in numerical strategies (from 4% to 12%). The project-oriented teacher may have worked on numeric strategies outside of projects as well, perhaps in lab tasks.

Another part of our coding involved looking at the source of the given or eventual analytic solution or conclusions to the planned inquiry. We were particularly concerned with whether students clearly saw their *own* contribution as vital to eventual conclusions, rather than relying completely on experts or printed sources. We believe this might indicate their own perception of themselves as at least "legitimate peripheral participants" in scientific inquiry. Table 4 shows the coding scheme:

Number	Code	Explanation

0	Unclear	It is unclear what the source of the solution would be. There is not enough information provided
1	Expert or Printed Text	They leave solving the problem entirely to the experts, which does not include them, or they expect to find the solution written out in a book, magazine, or journal.
2	Student's unspecified previous knowledge	They assert a solution they know somehow already, precluding the need for further investigation.
3	Own original analysis	They plan on using their own original analysis to formulate a solution or conclusion
4	Combo (own + expert)	Combination of their own analysis with expert input or printed text.
5	Consensus	There is an explicit process of trying to reach consensus in a group with possibly conflicting viewpoints to achieve greater veracity

Table 4: Solution Source coding scheme

As in the previous two examples, the students in the project-enhanced did not progress in the direction we would have hoped. Whereas fewer students in the other classes expressed a reliance or experts or print text sources (category 1) for answers in the Spring of the year (6% in the Spring vs. 9% in the Fall, for both groups), *more* students in the project-enhanced class said they would rely on experts or print sources in the Spring (12%) than did in the Fall (9%). On the other hand, the percentage of students who fell into categories 3-5 in the project-oriented and project-based classes increased—moderately in the project-based class from 55% to 60%, and strongly in the project-oriented class from 63% to 72%.

	Reliance on others (code 1)		Reliance on own analysis (codes 3-5)	
	Fall	Spring	Fall	Spring
Project-based classes	9%	6%	55%	60%
Project-oriented classes	9%	6%	63%	72%
Project-enhanced classes	9%	13%	59%	60%

Table 2: Sources of solutions in students' responses

Thus, it appears students in the project-based and project-oriented classes felt more empowered to play a role in solving scientific problems by their experiences, whereas students in the project-enhanced class felt *less* empowered.

Overall, these results indicate that involving students in research projects where they are challenged to formulate the research design and the analysis strategies for coming to conclusions appear to be essential to developing some of the competencies and attitudes I have emphasized. The relative strength of results from the project-oriented class, where very little class time was spent on projects, would seem to indicate that such efforts need not occupy a huge portion of the curriculum. But there are two caveats: first, we do not know how much out of class work students were asked to do in this class, and second, we do not know whether the students in the project-based class may have developed more *situated* competence in the actual carrying out of their plans. Both of these questions could be addressed by further case study research.

Conclusion

In this paper I argued that certain aspects of citizenship in democratic societies today require something other than a knowledge of science as an accumulation of facts. In particular, I focused on the prevalence and importance of decisions related to science and science research studies, ranging from individual decisions made by citizens with their doctors to environmental policy. In this I side with Deborah Meier, the principal of Central Park East Secondary School, and author of *The Power of their Ideas* (Meier, 1995). She recommends that we foster "the capacity to hazard an opinion on matters of science that may pertain to political and moral priorities, and a healthy and knowing skepticism toward the misuse of scientific authority" (p. 168).

In addition, I have presented evidence that reaching these goals may be well-served by teaching children to be "little scientists" to a certain degree—by conducting research projects. Although more research is needed on tradeoffs involving the implications of relative emphasis and amount of time spent on projects, involving students in projects that challenge them to participate in the design of research and analysis strategies have a demonstrable benefit. A final example from Rory Wagner's project-based class illustrates the development of a capacity for engaging in political matters pertaining to science. In her first project of the year, Beth was helped by Mr. Wagner to see that claims about the phenomenon of plesiosaur swimming motion need not be accepted as simple "fact" or "fiction," and together they figured out some strategies for independently confirming or falsifying the claims by assembling independent data. In her next project, Beth chose underground nuclear testing as her topic, and soon encountered claims from environmental organizations and the French government that such testing causes geologic damage. After doing further research on underground nuclear testing, she suggested, with no prompting from her teacher, that the environmental organizations were making catastrophic claims without data to support their conclusions. She had, in an important sense, appropriated some sense of the need for and nature of adequate evidence to support scientific claims.

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