Designing Project-Based Science Learning Environments

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From 1994 to 1996, I conducted research in a project-based high school earth science teacher's classroom, which I reported on in depth in *Designing Project-Based Science* (Polman, 2000)[1]. In this paper, I summarize the lessons from this research for the design of learning environments for project-based science, inspired by the kind of insights provided by Allan Collins (1996) for learning environments in general.

Research Context and Methods

The episodes related in this paper are part of a larger interpretive case study (Polman, 2000) conducted from 1994 through 1996 in Rory Wagner's[2] class, one of many participating in the NSF-funded Learning through Collaborative Visualization (CoVis) project-based science reform effort. 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.

I was a participant observer in Rory Wagner's classroom for three years—one and a half years acting as a technical assistant, and one and a half years conducting the formal study (1994-95 through winter 1995-96). 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 Nature of Learning Environment Design

In talking with Wagner and observing his class in the three and a half years after he began doing projects in 1993, I was struck by how he had, as he puts it, "evolved." This evolution included everything from "how to get resources" to "how to convince kids this is a good idea." His initial desire for doing projects was influenced by reading the LabNet book (Ruopp, et al., 1993) chronicling high school physics teachers' use of project-based methods. His desire was also influenced by discussions with other CoVis teachers and researchers, and the powerful learning he'd experienced in his own master's thesis project. But as Pea (1993) and Suchman (1987) have pointed out is the case for educational and work activity, desires that lead to action are often diffuse and ill-specified. They don't prescribe a clear set of steps to follow. Wagner said he felt "like I was making things up as I went along, so I thought the only way to do it now is to jump in and actually do it, and see what happens, and troubleshoot, and fix things up as you go along." The characterization Wagner made of his work as evolving, in reaction to what he

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[1] The majority of this text is a revision of text from *Designing Project-Based Science* (Polman, 2000). Please cite that work, and refer to it for a more complete description of the context for these conclusions.

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

tried out and adjusted along the way, with important contributions by other educators and students, resonates with ideas in the design literature. Specifically, I believe viewing the structures and practices that constitute projects in Wagner's classroom as the object of *iterative, participatory, situated design* is useful.

I turn to Wagner's class to illustrate these design terms. The design of projects is *iterative* in that Wagner goes through cycles of upfront planning of the activity, followed by implementation of these plans with midstream adjustments to the situation as it develops, retrospective reflection on the projects, and redesign for the next round. Between 1992-93 and 1995-96, Wagner completed eleven such cycles. The upfront planning consisted partially in structuring project activity through the refinement of a paper format that served as a blueprint for students' project work. Wagner changed the document detailing the paper format over time. The midstream adjustments Wagner made are countless, ranging from the negotiation of project topics such as those described with Kevin, Alex, Amanda, and Jeff, to looking for ways to deal with grading conflicts. Such adjustments midstream are like "design in use" of the upfront plans (a term borrowed from Allen [1993]; this has affinity to Suchman's [1987] "situated actions" and Schön's [1982] "reflection in action.") Reflection on the projects in earlier cycles led Wagner to see a need for a structure that students could follow, and to encourage students to find out more about their chosen topic before designating a final "question" to answer through their project (similar to Schön's "reflection on action"). The design of individual student projects is also iterative, in that students hand in milestones and receive feedback from Wagner before incorporating them into their final paper.

The design of projects was *participatory* because it was socially constructed. This social construction of design took place at several different levels. Wagner and students like Jeff and Amanda interacted to define and implement each and every project. Sometimes these interactions involved what Pea (1994) has termed "transformative communication." In such interactions, Wagner helped the students transform the moves they made in the research process with limited understanding into more sophisticated moves that neither he nor the students would have originally predicted (see Polman, 2000 or Polman & Pea, 2001 for further details and examples). When the students presented their projects to one another and they were discussed and critiqued publicly, they participated in the group's sense of what valid projects are and how to conduct good projects. Thus, the "Aliens" project conducted by two youth early in one year became emblematic of how important it was to use data effectively to construct an argument *and* to question the veracity of information sources. Finally, students' ideas for projects often acted as seeds or sources for later projects: Wagner's introductory sand analysis project one year grew out of a project that two students devised but had trouble implementing the previous year. Wagner's input to students working on a geyser project was based on another project from the previous year.

Designers often talk about the set of given resources and/or constraints in the environment, each with certain *affordances* (a term introduced by Gibson, 1986, and elaborated by Norman, 1988 and Wertsch, 1998). In Wagner's particular *situated* work, students' interests were a resource, affording a means of students making problems their own, about topics such as salt lakes. Wagner's skills at collaboratively constructing ideas with students facilitated building on students' interests in ways that his experience suggested would be productive and instructive. The paper format Wagner and his fellow teachers constructed afforded a way of structuring classroom activity around milestones corresponding to paper sections. Network tools such as the World Wide Web afforded searching for information and data that can inform students' inquiry. Usenet News and electronic mail afforded contacting and communicating with scientist mentors. Constraints for Wagner included the structure of the school day, limited amounts of time with many student groups working on different problems, and the culture and practices of schooling that students encounter outside of Wagner's class. Making a strong distinction between "resources" and "constraints" can be misleading, however, since "constraints can be turned into resources, and resources can turn out to be severe constraints" (Brown & Duguid, 1990, p. 38). Specifically, one aspect of the same environment or task can be seen as a resource by one person and constraint by another, or a resource for one purpose and a constraint for another. The open campus policy at the school, for instance, acted in some ways as a resource that afforded freedom of movement for students to accomplish aspects of their projects, but acted in other ways as a constraint on Wagner's ability to track student activity.

Designers need to try to optimize for certain purposes, but will often be faced with tradeoffs (Collins, 1996; Pea, 1993). This points to a further reason why I believe viewing the work of teachers as *designing* learning environments can be beneficial. It makes apparent the constructive, intentional nature of the work. As Shweder put it, "intentional persons" interact with and transform cultural meanings and social practices (1990), including the meaning and practice of conducting projects in a high school science class. Teachers such as Wagner have the power to effect change at the classroom level, and are more likely to succeed if their teaching practice is reflective (Schön, 1982) and iterative, in a manner similar to the concept of spirals of reflection and action in the tradition of action research (Lewin, 1946).

Constraints on Project-Based Learning Environments

In order to better enable others to use this case study as a model for thinking about other project-based learning environments (PBLEs), I will provide an overview of Wagner's design. In doing so, I will first focus on elements of Wagner's environment that primarily serve as *constraints* on successful accomplishment of projects, elements that are *mixed*, and elements that tend to be *resources* that afford accomplishment of projects. It is important to keep in mind, however, each element can manifest itself as a constraint that *dis*ables certain functions and a resource that *en*ables other functions. The elements range from personal motivational factors, to cultural beliefs, to practices.

Time

The constraints continually influence activity in Wagner's class, and occasionally spur crises. Time can cause problems in two ways. Some students, like the Zodiac group, can become complacent because they perceive an abundance of time. They mistakenly believe in the early stages that doing a project is not much different from other reports they have done in school, and they inevitably figure out at the end of their project that they should have put in more work earlier. At that late date the time is too short to salvage much, though. Conversely, Wagner's time is clearly limited, especially in terms of the number and length of interactions he can have with students during class. Thus, it's not surprising that some students, like Barb, can get shortchanged when other students like Julie and Amy manage to command a great deal of Wagner's time.

Risk and Grades

Since open-ended projects increase the ambiguity and risk of classroom practice, especially for students like Wagner's who have little experience with comparable learning activities, grades become a salient concern for both the teacher and student. Students can try to reduce their risk and optimize their grades by trying to turn Wagner's written and oral comments into contracts which, if fulfilled according to the letter, should guarantee a high grade. Treating Wagner's feedback as such a contract, however, subverts the organic nature of research and reporting. In order to reduce student risk of failure, Wagner has instituted a system of work grades, which guarantees students points for time on task and punishes them for time off task. This system inevitably causes conflicts and arguments with students that hinge on nit-picking for points; the system also exacerbates Wagner's lack of time, because keeping the necessary records consumes considerable time. For these reasons, it appears that placing more value and attention on Wagner's system of milestones might be preferable to focusing on work grades. Finally, the ambiguity and risk associated with learning how to do projects, while being graded on them, can lead students like Debbie to "explode" after encountering difficulties. Such explosions can result in the development of an adversarial relationship between teacher and student, and the degree of common ground necessary to accomplish guided participation is lost.

Conflicting Beliefs about Teaching and Learning

The transmission epistemology that many students espouse constrains Wagner's ability to successfully institute project teaching, which is rooted in the social constructivist tradition. Seeing teaching as telling and learning as accumulation can lead students to conclude that Wagner lacks the knowledge he should have--memorized facts about minor details in Earth Science--and also to devalue their own learning because they have not accumulated that same kind of facts. The practices students learned of figuring out ways to empirically examine questions about the phenomenon of deaths associated with tornadoes, as well as theorize about their causality, are valued more highly in the opposing epistemology. The transmission view is also associated with students not recognizing certain limits on communication involved in Wagner's teaching of new practices; specifically, they do not make any distinction between Wagner's *telling* them about assignments and their *understanding*, even though the interpretation of meaning by student and teacher can and frequently does widely differ. When students don't recognize the possibility of a gap between what they are told and what they understand, they are likely to accuse Wagner of being unfair. In addition, students who espouse the transmission view cannot recognize or accept the need for projects to be somewhat unpredictable and improvisational, even for an accomplished teacher like Wagner--he should know where every project should be going, or he is deemed lacking in expertise.

Mixed Constraints and Resources for PBLEs

Some elements of Wagner's design for project-based science are mixed in that they serve in some ways as resources that aid accomplishment of projects, and at the same time serve as constraints that hinder projects.

Transitional Activities

Rather than starting the year with activities wholly unfamiliar to his students, Wagner started with familiar activities, such as a lecture tour and teacher-directed assignments to introduce technology. He encouraged transitional practices such as student questioning dialogues during the lecture tour. He had students conduct standard library research and *then* build off that foundation into new areas. The negative aspect of these transitional activities and the positive aspect were two sides of the same coin: their affinity to traditional modes of teaching and learning could mute or hinder Wagner's attempts to move students toward new practices, but they could provide a helpful way station on the path.

Teacher's Personal Beliefs and Proclivities

Wagner's personal beliefs and proclivities can also both constrain and afford opportunities for supporting student project work. His preference for a reactive stance during class makes it more likely that some students he knows need support will fall through the cracks, but it also makes him eminently receptive to students' unexpected problems and nurturing of their excitement. His openness to student feedback about how to conduct the class and support them, as well as his willingness to hear students' complaints and arguments about their projects, helps to maintain an atmosphere where students feel valued and respected; but it also creates time drains and distractions from substantive issues.

Models

Model projects have been used both successfully and unsuccessfully in their many incarnations within Wagner's class. The complete model projects managed by Wagner were subject to the pitfall of allowing students to disengage from critical thought, but summarized example projects do allow Wagner to make the crucial decision processes of research design, data collection, and analysis explicit. These examples can help students gain a conceptual understanding of what they are trying to accomplish. In situ modeling of alternate ways of thinking about problems--genuine thinking aloud and discussion of research decision-making--is part of what Wagner does in discussion with students. Finally, written models in the form of archives have helped students to generate ideas, both of the variety Wagner would like to encourage, and the sort that he would like to discourage. A partial sample of an exemplary research report helped some students as a model for their own research report writing. Annotation could help both of these kinds of written models be more useful to students.

Resources for PBLEs

Finally, a number of elements in Wagner’s design for project-based science serve primarily as resources which enable students’ successful accomplishment of projects.

Student Ownership and Interest

Wagner's policy of giving students ownership of their projects and the final say in strategic decisions afforded giving the students a real voice in the classroom and its practices and in maintaining a high level of interest and motivation in students. Overall, student ownership tended to have positive results, but it did constrain Wagner's ability to control action in the classroom; thus, some students made choices against Wagner's recommendation and his fears were realized. On the other hand, Wagner knew there were some students who made choices against his recommendation that opened up unexpectedly successful avenues.

Technological Tools

Technological tools also played a generally supportive role in Wagner's design. Electronic mail and Usenet enable access to experts working in various capacities in Earth Science. Some experts provided feedback and information for students, most commonly data relevant to an inquiry. Experts who agreed to act as mentors provided more in-depth and ongoing support. The World Wide Web proved useful for data search and gathering by groups such as a group who investigated hurricane patterns. Computer applications such as spreadsheets enabled students to do graphing as part of their analysis. Although the technologies had these many affordances, they did not necessarily reduce pressure on Wagner as teacher because they engendered a significant need to support and train students in their use. Thus, some of Wagner's class time was taken up with procedural issues related to the technology. Although such sessions could result in valuable incidental learning, the problems and stumbling blocks with the technology at times distracted from the core mission of accomplishing science inquiry. As Wagner's expertise with technology has grown over the years, this became less of a problem. But for teachers working at the edge of technology development, adapting to change will always remain an issue.

Activity Structure with Accompanying Artifacts

The activity structure Wagner developed and refined for projects, with a system of milestones associated with artifacts, afforded students a crucial scaffold for accomplishing inquiry. The activity structure broke down the long and complex project into subgoals, and the association of artifacts with the subgoals engendered an intermediate need to know among students about how to do such crucial issues as how to formulate a research question on UFO sightings or how to carry out an analysis of hurricane path shapes. The need to know and the need to turn something in encouraged students to approach Wagner with any confusions they had. The ensuing conversations afforded Wagner an opportunity to provide guidance that was likely to be taken seriously and appropriated. The interim artifacts that students produced serve as externalizations of students' knowledge and current thinking, which Wagner could provide written feedback on. Since the activity structure was designed to correspond to portions of the science research article genre, the feedback that Wagner provided on interim artifacts was not just retrospective. Unlike a set of isolated assignments, students' milestones built upon one another *and* some form of each early milestone was plugged into the final research report. Thus, students iterated their ideas and writing in the Background Information assignment when they prepared the Introduction of their final paper, and they did the same for the Data Analysis milestone for their Results section.

Transformative Communication

On those occasions when students were putting their milestones together, transformative communication among Wagner and the students sometimes took place. The presence of the activity structure, as well as student ownership and interest in their projects, helped engender occasions for transformative communication. In such conversations, Wagner got insights about the students' current thinking and about the possibilities for the students' projects; he also provided students with insights about how they could expand on and use what they had begun to know in the next stages of their inquiry. These conversations with one another and the situation are a powerful way for teachers with expertise in inquiry to guide students.

Tradeoffs of Science Instruction in Schools

Some historians of education have remarked that the 20th century saw the pendulum of reform efforts swing back and forth between traditional goals of education and progressive goals (e.g., Cuban, 1990; Ravitch, 1982). One possible explanation for these pendulum swings is that maximizing a traditional goal often severely compromises a related progressive goal, when in fact both goals are laudable. If a teaching strategy associated with progressive education has a tendency to undermine a reasonable traditional goal, it may lead to calls for "back to basics." Conversely, if a teaching strategy associated with traditional didactic instruction has a tendency to undermine reasonable progressive goals, it may lead to calls for child-centered reform.

Wagner's design of a learning environment for project-based science can be seen as an attempt to find a workable equilibrium between such tradeoffs. For the design elements described above to help rather than hinder Wagner's efforts, he had to maintain a balance along a number of dimensions. Reaching and maintaining the equilibrium point for different students and groups can be difficult.

Familiarity vs. Growth

To optimize the balance of familiarity vs. growth, Wagner had to find a way to "change the game" from traditional schooling and also change the rules *without* casting students adrift. Students may naturally resist such changes, because they are associated with increased risk. As a teacher changing the game, he was prepared to explain, defend, and even "sell" his reasons for the changes he hoped students would make, and also to *acknowledge* students' increased risk. In addition, the changes in practices sometimes resulted in students' misconstruing their teachers' intentions. Wagner thus needed to be concerned with *recognizing* when students were getting off track; the milestones in the activity structure served this purpose. In addition to the milestone artifacts, which to some degree externalized student thinking, the mere presence of looming milestones resulted in many students making their confusions and needs known to Wagner. For the students who didn't do as well at getting milestones in, I have suggested that Wagner could more directly encourage students to make their needs known by proactively approaching the teacher for support. Finally, the changes in the game sometimes resulted in students beginning to flounder. In order to help, Wagner tried to connect to practices students already understand; Wagner did this through transitional activities in the first quarter and at the beginning of projects, and by building later phases of projects on the foundation laid in the previous phase. To solidify student learning of research design, data search and organization, and analysis, Wagner also repeated the project cycle three times during the year. Along the way, Wagner also needed to support students bridging from their current knowledge and practices to new practices. Thus, Wagner frequently asked students what they know or had done so far, and sometimes built on that knowledge through transformative communication.

Structure vs. Exploration

To optimize this dimension, Wagner provided students with a basic framework for their activity, but the interim deliverables required students to actively think and participate in the research design and analysis decisions. However, some students still needed more structure than they were getting. To support students who need more structure, I have suggested that Wagner could provide students who experience trouble the first time around more scaffolding by giving them a list of promising topics for which he has a number of well-developed ideas. For each topic, he could think ahead of time about ways to address the three key phases of projects: research question formulation, data collection, and analysis. In this way, he could provide extra scaffolding as needed while still maintaining as much challenge for the students as possible while the project developed. This strategy has numerous pitfalls, however, including sacrificing student ownership and becoming too rigid in a possible path students could take, and missing opportunities for challenging them to think instead of providing them canned solutions.

Predictability of Coverage vs. Student Interest/Commitment

To optimize this dimension, Wagner made recommendations and gave the students nudges, but left the final say resting in their hands. When the pendulum swings too far toward traditional predictability, the teacher alone has decision-making power, whereas swinging to the other extreme leaves students unguided. In episodes of transformative communication, Wagner was able to establish co-ownership with the students and optimize this dimension by coaching without taking over, as we saw in the research proposal phase and the analysis phase of different projects. Wagner became more effective at this kind of support with increasing experience in project-based teaching. His effectiveness was partly due to exposure to a range of project cases, which provided him a sense of the pitfalls and promise different paths might hold.

Consistency vs. Customization

Optimizing balance along this dimension is important, because greater consistency reduces the risk of failure due to falling through the cracks, but greater customization maximizes teachable moments. Wagner tried to customize the amount and kind of support provided in the form of verbal and written feedback, but still guarantee a minimum level to prevent students from falling through the cracks. During class, he let students make their needs known, and responded to those needs. Since all students were not likely to approach Wagner without some prodding, it was helpful that interim milestones provide more occasions for feedback and support. Since occasions for discussion around substantive science topics appear to be so important, instituting some means of ensuring a level of minimum interaction with students--for instance by increasing the assessment worth of milestones--could increase some students' chances for success.

Isolated Cognition vs. Situated, Collaborative Cognition

Traditional schooling is associated with students being asked to think in isolation from their peers, and without the help of any tools such as calculators (Resnick, 1987), whereas progressive schooling routinely stresses peers working together with authentic tools. Wagner and other project-based science teachers leans more toward the progressive extreme along this dimension, by requiring students to work together, encouraging communication with people who can offer directed expertise, and encouraging students to use any and all tools at their disposal. When students worked in groups, however, problems sometimes developed, where the more confident and able student learned more and the less confident and able student fell further behind. Wagner tried to help students manage troubles with work division that could feed into problems, and also made the students to some degree individually accountable; but more concerted measures would undoubtedly make a difference. The problem with instituting such measures is balancing them with all the other kinds of support and guidance Wagner is trying to carry out.

Interrelations in the Tradeoff Space

Finally, there are important interrelations between the dimensions described above. For instance, when more student interest and commitment was fostered, students were more likely to initiate interactions at the most teachable moments. The students in a project about plesiosaurs shared their enthusiasm for the creature with Wagner from the beginning, resulting in discussions with guidance from Wagner, and also gained vital practice with search tools they used themselves later. As the project continued, the students' growing commitment and interest in plesiosaurs made them eager to share triumphs and difficulties with their teacher. Also, Wagner's design of an activity structure that required a high degree of exploration and thought within it increased the likelihood that students would seek him out for needed guidance at teachable moments. For students who are slower starters, maintaining sufficient levels of consistency helps maintain their commitment.

Continued Change as Inevitable and Revitalizing

Even with all the effort and refinement Wagner put into his project-based teaching, he has never been able to make everything work to his satisfaction. In an e-mail message he once said to me, "You know what, I'm starting to become convinced that the [reworking] is an endless process. Seemed a little depressing at first, but on the other hand it's not all that surprising considering the kids are always changing." And since teaching is an "impossible profession" (Cohen, 1988, p. 55), it can never be done perfectly.

Over the years, continually recognizing needs for improvement can become frustrating and tiring for educators. But in some ways the educators who believe they have reached a stable solution may be the ones who are worse off, because they are fooling themselves. As Zilversmit (1993) said, "Essential for the health of education is the *process* of change. Questioning accepted ways is essential to the health of change [and] schools ... therefore, the reiterated demands for change are not signs of failure; they are part of a process that is essential to keeping education vital" (p. 182). Zilversmit goes on to point out that change can be *revitalizing*. It has certainly provided a great deal of excitement and interest for Wagner in his teaching, along with the frustration of difficulties.

Resources for Guiding Project-Based Science

I would like to stress some of the lessons for teachers and others interested in supporting learning environments for project-based science.

For teachers, making project more successful involves ***creating, fostering, and recognizing seeds for transformative communication.*** Some of the seeds can be built into the activity structure with milestones beforehand. Once students or the teacher find a seed, more opportunities may be developed. In assignments students turn in and comments students make during class, more seeds may become apparent, as long as the teacher recognizes them as something that can be transformed into a productive move in scientific inquiry. This is knowledge-intensive and thought-intensive work for teachers. It may involve making mundane connections between experiences in one volcano project and another volcano project, but it may also benefit from creative and surprising connections, such as Wagner's idea of making a grid and performing counts to analyze hurricane paths, based on his own experience of performing mineral content analysis. At the very least, it involves rumination on students' projects outside of class, or poring over students' sometimes cryptic writing.

For teachers and others interested in designing and creating supportive resources for project-based learning environments, organizing and if necessary creating resources. Such "distributed intelligence" in the environment can allow the teacher to offload some of the supporting. In this way, items such as a set of Time-Life books Wagner thought he would never have use for have become a resource for students beginning their background research on their topics. Additionally, collections of data resources such as a hurricane Web site and a book of volcano eruption data serve as valuable sources of empirical data. There are many opportunities for creating and finding useful and usable collections of data resources to support project-based science teaching and learning. Especially useful are materials that relate to topics that especially appeal to students. In this Earth Science class, popular topics often involved disaster and destruction (e.g., lightning, hurricanes, and earthquakes), aliens or space exploration, and the environment (e.g., global warming, water quality, and energy). As more resources about these topics become available, kids can seize them and build off their interests. In addition, the work of students from year to year can become a growing activity base (similar to a knowledge base) for future projects, in that they both supply ideas *and* potentially supply data collections that can be reanalyzed and refuted or refined, or combined with other data collections for completely new inquiries.

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