A Lab by Any Other Name: Integrating Traditional Labs and Computer-Supported Collaborative Investigations in Science Classrooms

Matthew Brown and Daniel C. Edelson

Northwestern University, Institute for the Learning Sciences and School of Education and Social Policy

Abstract: Among the most common form of collaborative discourse in middle school science classrooms is the carefully planned laboratory investigation, where groups of students follow prescribed procedures in order to reproduce and measure some scientifically explainable event. While there are clear pedagogical benefits to replicating scientific processes in a controlled classroom setting, students often have difficulty comprehending how such phenomena manifest on larger scales and connecting their lab results to the real world. The WorldWatcher data visualization software adds a novel dimension to classroom investigations by allowing students to investigate and discuss global climate phenomena within a globally situated geographic context. This paper will discuss the design of an integrated classroom curricular unit on global warming in which WorldWatcher activities and traditional classroom labs complement each other in order to support student collaboration in classroom science investigations. Based on analyses of students collaborating in pairs and in whole-class discussions, we will argue that our two-pronged approach to curriculum design represents an effective framework for introducing innovative computer-supported inquiry tools in urban middle school science classrooms while remaining sensitive to the existing practices of teachers and students in these contexts.

Keywords: curriculum, project-based learning, inquiry, design framework, conceptual change, partnering, shared knowledge

I. Introduction: beyond traditional science labs

The role of traditional labs

Among the most common form of collaborative discourse in middle school science classrooms is the traditional classroom lab experiment, where students engage in prescribed tasks involving controlled variables, measurement tools, and data collection in order to observe or deduce some scientifically explainable event. In a typical lab, students may discuss a scientific phenomenon, make predictions, design an experiment , and discuss findings. Typically, such labs focus on isolated scientific phenomena, where classroom scale events are reproduced in an easily digestible format.

Traditional labs can help students to sharpen their investigation skills, facilitate understanding of the scientific method, and make difficult to comprehend events visible within a straightforward setting that allows novices to interact with scientific ideas. Furthermore, labs provide opportunities for students to work together (whether it be to design experiments, solve problems, or analyze outcomes) and provide stimulus for group discussions around a set of commonly observed events.

Limitations of traditional labs

However, there is a wide range of scientific topics which involve abstract, large-scale phenomena which are difficult to replicate on a classroom scale. For example, students investigating the issue of global climate change must understand concepts such as global variations in incoming solar energy, albedo (the reflectivity of solar energy), and carbon emissions, and how these factors correlate with surface temperature, surface characteristics, and human population. These concepts and the relationships among them are difficult to comprehend with conventional lab tools. In the absence of a means to explore the global datasets required for such investigations, the potential scope and scale of scientific inquiry is significantly narrowed.

Furthermore, most traditional classroom lab experiments simplify and decontextualize scientific phenomena such that novices fail to see their connections to scientific events outside the classroom. Research on student conceptions of scientific phenomena reveals that students often fail to make meaningful connections between scientific knowledge acquired in the classroom and "everyday events" (e.g., McCloskey, 1984; Reif & Larkin, 1991). Also, students are challenged to connect the experimental procedures of classroom labs with larger scientific issuesó they have difficulty understanding the goals of science experiments and are often unable to coordinate investigation strategies with the explanation of science concepts. In their discussion of studentsí understanding of classroom experimentation, Schauble et. al. (1995) point out the difficulties that students have making connections between classroom experimentation and events in the world. Traditional approaches to classroom science investigations "reflect the somewhat artificial fragmentation of science into isolated skills... [S]tudents in hands-on programs too often engage in a string of unrelated, one-period, 40-min activities that emphasize the use of science materials and equipment but are often poorly or entirely unmotivated from the studentís point of view" (p. 132). They cite the difference between procedural knowledge and skillful reasoning with that knowledge, the difficult balance between processes and concepts, the tendency of many teachers to emphasize performance of tasks and "right answers" rather than reflection and conceptual understanding, and the difficulty of managing the vast array of student-generated knowledge and procedures that arise in inquiry-based classrooms. These findings point to the shortcomings of traditional lab environmentsó where investigations are fragmented, unrelated and decontextualized from meaningful scientific issuesó in helping students to comprehend and integrate science concepts and experimental processes.

Addressing the issues: WorldWatcher and the Global Warming Project

What is needed to extend the scope and scale of classroom science inquiry beyond its traditional boundaries are investigation tools that provide classrooms with access to abstract, large-scale, scientific phenomena as well as curricula which create meaningful contexts for ongoing, integrated scientific investigations. One way we have been attempting to support student investigations of global scientific phenomena is through WorldWatcher, a computer-based data visualization environment that provides students with access to global datasets in the form of interactive color maps (Edelson, Gordin & Pea, in press). WorldWatcher visualizations invite students to identify patterns in complex data, providing a catalyst for student conversations about global scientific phenomena (Gordin, 1997). By providing learners with opportunities to investigate abstract, large-scale phenomena, WorldWatcher thus provides one example of how computer-supported data investigation environments can augment classroom investigations of complex scientific phenomena.

However, the large scale and abstract nature of WorldWatcher representations presents significant conceptual obstacles to student comprehension of the phenomena they are investigating. To respond to this challenge, we have developed a curriculum design strategy of creating paired labs that associate classroom scale, physical labs with computer investigations of global data. While many traditional physical labs may fail to support studentsí connections between classroom experiments and scientific events outside the classroom, many of them nonetheless remain effective means of representing complex scientific phenomena in an easily digestible (if not decontextualized) format which is amenable to the settings of most classrooms. So rather than "throwing the baby out with the bath water," we seek to build upon and extend the reach of such existing classroom practices by combining them with computer investigations of global data. The Global Warming classroom project (GWP) represents a combination of these two approaches, where the strengths of traditional labs in exploring scientific events on an easily digested classroom scale are combined with the strengths of WorldWatcher investigations in exploring abstract phenomena on a global scale. By creating settings in which students can investigate scientific phenomena on both levels, the GWP attempts to support knowledge acquisition by extending the scope and scale of classroom investigations ().

Furthermore, the GWP attempts to support the coordination of investigation strategies with the explanation of science concepts (e.g., Schauble et. al., 1995) by integrating multiple investigations within an overarching project scenario. Throughout the GWP, students use their knowledge to advise various nations of the world on the socially pertinent climate change debate by explaining the scientific basis of the debate, highlighting potential impacts of climate change on various regions of the world, and exploring solutions to the potential problems posed by climate change. Integrating the various investigations within a meaningful project narrative helps students to connect their experiments to the larger goals and processes of an ongoing scientific investigation, combating the fragmentation that is common to traditional science lab settings.

In the Global Warming project students engage in laboratory investigations of scientific events in order to investigate how a climate-related phenomenon manifests on a *decontextualized* classroom setting and then use WorldWatcher to investigate how that same phenomenon manifests on a *recontextualized* global settingó exploring how it interacts with other phenomena and impacts different geographic regions. WorldWatcher activities augment classroom investigations by providing what traditional science labs often lackóopportunities to investigate climate phenomena within a global context using actual climate data. By designing activities that take advantage of the affordances of classroom scale and global scale experiments and through attentiveness to the issues involved in bridging these two approaches, we have attempted to forge a "two-pronged" approach to the design of classroom investigations that attempts to coordinate the development of complementary physical labs and visualization activities. What follows is a discussion of how we designed this project, an example of integrated curricular design, an analysis of how students and teachers engaged in these activities, and discussion of how this approach to the design of software-supported curricular materials supports student collaboration in middle school science classrooms.

II. Integrating physical labs and computer-based data investigations

What is a "lab" anyway?

Designing a curriculum which effectively integrated innovative computer investigations and traditional physical labs meant capitalizing on the respective expertise of software developers and classroom teachers. The Global Warming curricular unit was created through a design partnership between Northwestern University researchers and middle school teachers from two Chicago Public Schools as part of the Center for Learning Technologies in Urban Schools (LeTUS). The aims of this collaboration were to design a classroom learning environment that integrated technological and pedagogical innovations with the established practices and beliefs of students, teachers, and classrooms. Integrating traditional and innovative approaches to science investigation required that the design partners understood each othersí conceptions of scientific inquiryó namely, what constitutes an effective science investigation.

Bridging these two communities of research and practice often proved challenging. During the design process it became apparent that the two communities did not always share common conceptions of scientific inquiry, as evidenced in a debate that emerged over whether WorldWatcher investigations could be considered another type of "lab investigation." While both parties agreed that labs should involve the testing of hypotheses, designing an experiment, collecting data, and open-ended analysis, the teachers initially failed to see how WorldWatcher, which provided access to existing datasets, could be used to such ends. While this view changed as teachers learned more about how to use the software in classroom situations, the debate regarding what constitutes a "lab" nonetheless prompted both parties to reconsider their established beliefs and examine the ways in which physical labs and computer-supported investigations of global data were pedagogically similar and different. The process of negotiating shared meaning led us to a mutual appreciation of each type of investigation and opened the door to an integrated approach to curricular design. While the two parties may never have established complete consensus, articulating their respective definitions of "labs" provided an open dialogue about how traditional physical labs and WorldWatcher-supported investigations could augment each other, thus facilitating the design goals.

An example of the two-pronged approach to activity design

A vivid example of how to integrate traditional labs and WorldWatcher-supported data investigations emerged in our design of an activity sequence exploring the reflectivity of sunlight. This sequence was tested in a 7th grade Chicago Public School classroom as part of a complete pilot test of the entire Global Warming curriculum. The following section will describe the design of the activity sequence, using the experiences of the class to illustrate how the integration of a physical lab and a computer investigation of global data supports student comprehension of the concept of solar reflectivity on both classroom and global scales.

Global temperatures are affected in large part by the extent to which energy from the sun is absorbed or reflected by Earthís surface and atmosphere. In order to model the manner in which the color of surface features impacts the absorption of sunlight, the lab engages students in the measurement of temperature increases over time of different colored envelopes under a heat lamp. After measuring the temperatures of the different-colored envelopes at multiple intervals over a 15-20 minute time span, students graph the changes and then discuss the extent to which lighter or darker colors absorb more or less energy. Their graphs yielded a pattern whereby darker colored envelopes achieved greater net increase in temperature than lighter colored envelopes. In this activity, students were able to note how a phenomenon (the absorption of light energy) was impacted by a variable (the color of a substance). However, aside from an ensuing discussion of studentsí experiences wearing black versus white t-shirts on a summer day, the lab itself did little to help students understand how reflectivity and absorption manifested naturally on Earth.

At the same time, other students engage in a WorldWatcher investigation that seeks to answer the question "What impacts the reflectivity and absorption of sunlight on Earthís surface?" involving the comparison of Albedo (or percentage of "Earth-atmosphere reflectivity) and Vegetation datasets. This activity has been designed to accompany the lab described above, and, depending on the number of students in the class, the available computing and lab facilities, and the schedule, the two activities can either be done simultaneously by dividing the class in half for each activity (and switching activities during the following class period) or in sequential order by the entire class. In order to help teachers support two classroom activities simultaneously (2), the WorldWatcher activity is designed in a rather structured fashion, where the comparison of two specific datasets is prioritized over a more open-ended approach to student investigation (the investigations adopt a more open-ended approach later in the project, once students have had the chance to gain more familiarity with WorldWatcherís features). In addition to addressing logistical constraints, dividing the class can also provide a basis for students in the different activities to share what they learn with their colleagues, similar to the "jigsaw" method discussed by Brown and Campione (1994).

The example described here involves a pair of boys, randomly selected by the teacher for observation, who completed the WorldWatcher investigation *subsequent* to doing the Envelope Lab. They begin the activity by listing any factors they can think of which would cause sunlight to be reflected away from Earthís surface. Their list ranges from "buildings" to "sand" to "skin." One of the students notes that different shades of skin pigment will absorb different amounts of energy, just as different colored envelopes heated up at different rates. His comment constitutes a direct reference to the Envelope Lab, revealing a strong understanding of the role that color plays in an objectís energy absorption. Interestingly, though the worksheet prompt asks them to list "factors" which might cause sunlight to be reflected, both students focus their initial comments about reflectivity mostly on tangible objects from their surroundings, such as buildings and cars. Since they have not yet developed a contextual framework for talking about more abstract geophysical characteristics (such as the atmospheric features or different categories of ground cover), their preference for concrete rather than categorical variables is to be expected. (Chi, Feltovitch & Glaser, 1981; Smith, di Sessa & Rochelle, 1993).

Next, they are prompted to analyze WorldWatcherís "Energy Balance" diagram (Figure 1), which uses pictures and arrows to illustrate the interactions between the different elements of Earthís energy budget, and asked to explain "what happens to solar energy when it reaches Earth." Upon seeing the diagram, Marcus exclaims "Oh yeah, the *atmosphere* [reflects solar energy] too!" As they explore further, they begin to discuss other planetary features that might impact solar reflectivity.

> Charlie: Whatís happening?
>
> Marcus: You can see that energy is being reflected,
>
> *He points to the area in the Energy Balance diagram where the arrow from the sun points downward and then up again towards space.*
>
> Charlie: Energy is being reflected off the oceans.
>
> Marcus: Just write energy is being reflectedó
>
> Charlie: Off water.
>
> Marcus: No, it could be anywhere.
>
> Charlie: No, but it seeÖ
>
> *He points to where arrow is hitting a region of the Earth that is blue, signifying that it is reflecting off an oceanic region of Earth.*
>
> Marcus: It just means Earth, anywhere!

Though they still lack a clear understanding of the specific characteristics of the surface which impact reflectivity, the mere fact that their discussion has shifted from local objects to global features signifies that they are now prepared to think of reflectivity on a more abstract global scale. Discussing reflective properties of atmosphere and oceans rather than buildings and windows represents a shift in the scale of their thinking about climactic phenomena. The visual model provided by the Energy Balance diagram thus provides a foundation for the students as they begin to connect what they have learned in the Envelope Lab to an actual geophysical setting.

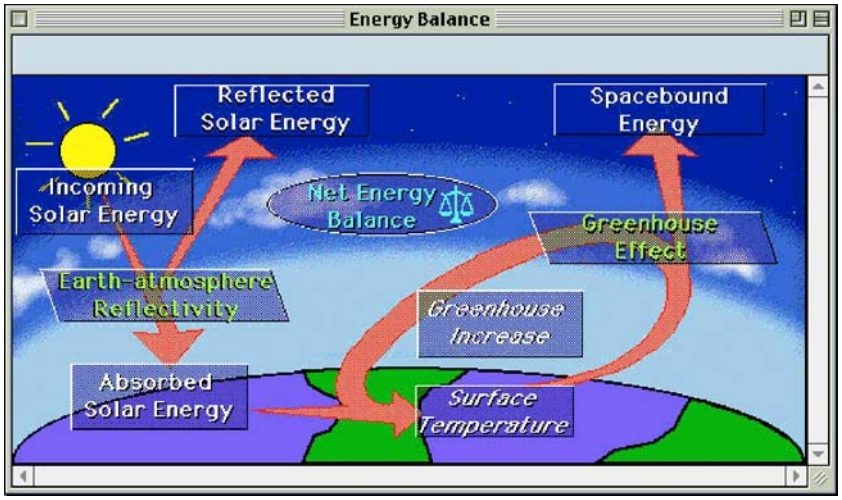

Figure 1: Energy Balance Diagram, which helps to contextualize datasets

Students then use the Energy Balance diagram as a menu to access a dataset which shows the percentage of sunlight that is reflected away from Earth (albedo) visualization, which shows the geographic variation in reflectivity on Earth (Figure 2). So that they may observe the reflectivity of the surface only, the students use a dataset specially generated under "clear sky" (i.e., cloudless) conditions such that the atmosphere is factored out. Once they have selected the clear-sky albedo dataset, the students immediately begin to interpret what they see.

> Charlie: The darker areas mean less solar energy is reflected and the lighter areas mean more solar energy is reflected.
>
> Marcus: Oh so thatís all being reflected!
>
> *He points to the north polar region, which in this visualization is mainly "white" (thus representing a high percentage of reflectivity).*
>
> Charlie: ëCause its all ice there so it gets reflected.

Their analysis combines an informal geographic knowledge (that the poles are covered in ice) with a basic understanding, stemming in part from the previous dayís Envelope Lab, of the reflective properties of color (that white envelopes absorb the least about of light energy). Even before they fully understand the meaning of the visualization, they informally apply familiar bits of knowledge towards the task of understanding the geographic variation of reflectivity. In this manner, the geographic interface of the WorldWatcher visualization, combined with the visual patterns evident in the data, provides students with an opportunity to connect their existing knowledge of reflectivity within a global context.

As the students begin more formal analysis of the visualization, they continue to draw upon knowledge of reflectivity acquired in the Envelope lab in order to understand phenomena on a global scale.

> Charlie: And which parts reflect the most sunlight?
>
> Marcus: The lower part.
>
> Charlie: No, no, noÖ
>
> Marcus: Look.
>
> *He scrolls down so that Antarctica, which was off the screen, is now visible.*
>
> Charlie: Whoa!
>
> Marcus: Yeah!
>
> Charlie: So the southern, yes. Because thatís white.
>
> *They record their observations.*
>
> Charlie: Which parts of the earth reflect the least amount?
>
> Marcus: Near the equator
>
> Charlie: No. [*he looks for himself*] Yeah, youíre right, near the equator. Like a little less than the equator.
>
> Marcus: Below the equator. Or below the equator and above the southern part.
>
> Charlie: And a little lower.
>
> Marcus: A little lower than the equator.
>
> Charlie [*reads*]: "What do you think makes some parts of the earth reflect more than other parts?"ó The ice!

Marcus: The snow.

By navigating around the visualization map the students begin to understand geographic variations in reflectivity, though they seem to have an easier time explaining high-reflectivity areas given their knowledge that ice is white and white is highly reflective. They readily appropriate the language of the simple "black and white" colorscheme in order to spot trends in the data and begin exploring the geographic variation in these trends. While the WorldWatcher visualization is not introducing a new concept (they have already learned in the Envelope Lab that white substances are the most reflective), it is providing an opportunity for the students to test out their theory about the reflectivity of different colors and expand it from mere colors to the colors of actual substances on Earthís surface such as ice.

In the final stage of the activity, students open a dataset that reveals physical composition of Earthís surface, namely a ground cover (or *vegetation type*) visualization. After making some visual comparisons between the two datasets, the students shift to a more quantitative analysis, using WorldWatcherís selection tools to *select by value* all the areas above a certain percentage of reflectivity in the Albedo visualization. With the *synchronization* feature activated, WorldWatcher automatically selects the same regions in the Vegetation Type visualization (Figure 2). Students can then observe which types of ground cover correspond to areas of high reflectivity (and visa versa, where they use the same WorldWatcher features to "select by vegetation type" and then find the specific reflectivity values for each type of ground cover).

Charlie [*reads*]: What types of ground cover are the most common types in areas with over 30% surface reflectivity?"

Marcus: The lighter because itís white. So its like the uh, the uh [*points to the Sahara Dessert*] peach colored areas are also common types.

At this point the students begin formally to map their knowledge regarding the reflective qualities of dark versus light colors to specific features of Earthís surface. They notice that in addition to the polar ice caps, dessert regions also reflect a large amount of incoming solar energyó establishing a pattern regarding the high reflectivity of light colored ground cover that corresponds to their experiences in the Envelope Lab. The presence of geographic cues in the Vegetation Type visualization, such as several different types of "light colored" ground cover, provide an opportunity for theory confirmationóby noticing that desserts, like ice, also reflect a large percentage of solar energy.

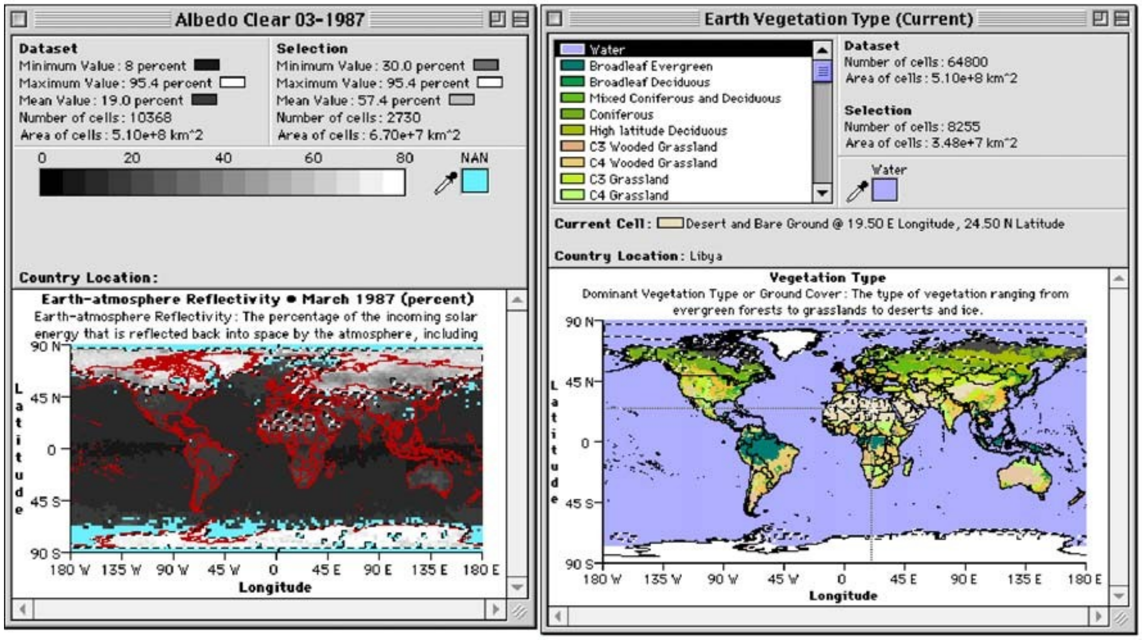

Figure 2: Albedo (reflectivity) and Vegetation Type visualizations. With the "synchronized mouse" feature activated, the areas with greater that 30% reflectivity have been selected in both visualizations.

With the help of the Vegetation Type visualization, the students move beyond their basic "ice reflects because itís white" to incorporate new types of ground cover in different regions of the world. They explore these findings further by selecting one by one various other types of ground cover in one visualization and observing its reflectivity value in the other. In doing this, students can quantitatively analyze the reflective properties of each type in order to establish a clear pattern in the data and confirm their theories.

The WorldWatcher activity illustrates how global data visualizations provide opportunities for students to expand their understanding of scientific concepts by exploring how they manifest on a global scale. The data diagram and visualizations and strategic prompts in the worksheet provide "conversational stimuli" that prompt the students to reason with knowledge gained in a traditional lab. Furthermore, the activity reveals a deepening of their understanding as they expand, contextualize, refine, and test their theories about the relationship between reflectivity and color.

Connecting physical labs to computer investigations of global data: Conversations across activities

Students must have a sense of the purpose and rationale of their experiments to be able to make sense of their experimental procedures and connect their findings to larger concepts. Exploring a given scientific phenomenon via multiple forms of classroom investigation not only reinforces conceptual understanding of that phenomenon; it also provides a crucial sense of perspective regarding the experimental procedures. However, this does happen merely by token of strategic activity juxtaposition. Schauble et. al. (1995) observe that "[b]ecause students do not share this understanding of the overall structure of the discipline, the logic behind the sequence may be apparent to teachers but a mystery to students" (p. 133). Understanding the broader experimental context of classroom investigations often requires explicit teacher support -- while it is evident that the two students in the previous example established conceptual linkages between the Envelope Lab and WorldWatcher investigation, we cannot automatically assume that the experimental rationale for pairing the two activities is evident to the students.

After half the class had done each of the investigations (prior to the groups switching tasks), the teacher conducted a reflective discussion which prompted the students to (a) share procedural aspects of each of the activities with their peers, (b) reflect on what was learned in each activity, (c) connect the main findings of each activity to each other in order to see how they relate, (d) discuss their findings within the overarching context of their ongoing project, and (e) attempt to integrate what was learned to a real world scenario. The discussion marks an attempt by the teacher to help the students to understand and appreciate the larger goals their experiments. By explicitly drawing linkages between the two activities, the students begin to integrate the concepts involved in the two activities and construct a shared understanding of reflectivity.

> Teacher: The class was not doing two different activities today. You were doing 2 parts of the same activity. Can someone from each group describe what they did in their activity?
>
> *After this opening question, students representing the Envelope Lab groups and the WorldWatcher groups each summarize the procedures of their investigations.*
>
> Teacher: Who thinks they see a similarity between what the 2 groups did?
>
> Justin: The similarity is that both groups, they were comparing types of surface and how much light they collected to each other. Because the reflection map shows how much light comes in and is reflected out and with the lab it shows which color takes in the most light and which reflects.
>
> Teacher: Someone who did the lab, did the results which you got confirm what you expected to happen?
>
> Zack: No. I thought the white one would be hotter because the light goes in easier. I thought it would be the hottest one but it isnít.
>
> Shirley: I thought the white will be the hottest because when you wear dark colors you get hot.
>
> Teacher: Then why would white be the hottest?
>
> Shirley: I meant the dark colors would be the hottest.

Once the students have described each of the two activities, the teacher then asks them to draw deeper comparisons. Justin, a student who did the WorldWatcher activity, is able to see the conceptual linkages to the Envelope Lab described by his peersóthough he obviously has a deeper knowledge of the WorldWatcher activity. To achieve balance, the teacher asks a question targeted at the Envelope Lab students. Zack responds by explaining how his initial theory was challenged by the results. Shirley attempts to relate the results of the lab to her everyday experience.

By asking students to explain why the two groups were in fact "doing two parts of the same activity," the teacher encourages students to reflect on the underlying goals of the two experiments. He moves the discussion freely between the two activities, providing opportunities for students from each group to contribute to the shared understanding of the community. This provides a clear example of how students, when prompted, can effectively reflect on the goals and purposes of their classroom investigations, publicly test and refine their theories and hypotheses, and attempt to articulate findings in everyday terms. These are all crucial elements to the shared construction of ideas within a classroom scientific community and represent an important means by which students can think about classroom science in broader terms. Further analysis of similar discussions is needed in order to develop a clearer sense of how best to facilitate such discussions. However, such activities show how teachers can help students negotiate the meaning of scientific concepts by reasoning from their experiences in different types of classroom investigations.

III. Discussion

Curricular innovations must exist within the context of existing classroom practices, not only because the beliefs of practitioners dictate the ways in which they enact such innovations, but also because existing classroom practices have benefits which should be not be overlooked when implementing classroom innovations. Traditional classroom labs can provide a highly accessible means for students to explore scientific phenomena. However, such experiments all too often represent a decontextualized setting for scientific concepts. Our discussion illustrates how data visualizations can help students to integrate scientific concepts acquired in a traditional laboratory investigation within a real-world global context. Furthermore, our discussion of a teacher-led, whole-class discussion illustrates a means by which students understand the high-level goals of classroom experimentation by discussing multiple methods of investigation and publicly refining emerging theories about scientific concepts. Embedding innovative tools for collaborative inquiry within the existing contexts of science classrooms holds promise not only for the effective implementation of curricular innovations, but also for the enhancement of student learning. This process involves working closely with teachers in order to find ways to translate promising innovations into the language of typical classrooms.

Acknowledgements

The authors also wish to express gratitude to the teachers with whom we have collaborated on the development of the Global Warming Project, Bernie Bradley, Mary Pat OíConnell, Gloria Pritikin, Susan OíNeill, Kim Fryzel, and Carmen Gomez. We also wish to acknowledge the help of Kim Williams, Kylene Chinsio, and Duane Griffin. WorldWatcher was programmed by Brian A. Clark.

This work was completed as part of the WorldWatcher Curriculum Project, which is supported, in part, by the National Science Foundationís Instructional Materials Development Program (grant # ESI-97206987), and the Center for Learning Technologies in Urban Schools (LeTUS), which is supported, in part, by the National Science Foundation (grant # REC-9720383). Opinions expressed are those of the authors and not necessarily those of the foundation.

Bibliography

Brown, A. L., Campione, J. C. (1994). Guided discovery in a community of learners. (pp. 229-270) In *Classroom Lessons: Integrating Cognitive Theory and Classroom Practice*, Cambridge MA, MIT Press.

Chi, M. T. H., Feltovitch, P. J., Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, pp. 121-152.

Edelson, D. C., Gordin, D. N., Pea, R. D. (in press), Addressing the Challenges of Inquiry-Based Learning through Technology and Curriculum Design. To appear in *Journal of the Learning Sciences*.

Gordin, D. N. (1997). Scientific Visualization as an Expressive Medium for Project Science Inquiry. Unpublished doctoral dissertation, Northwestern University.

McCloskey, M. (1984). Naïve Theories of motions. In D. Gentner & A. Stevens (Eds.), *Mental Models* (pp. 289-324), Mahwah, NJ: Lawrence Erlbaum.

Reif, F., & Larkin, J. H. (1991). Cognition in scientific and everyday domains: Comparison and learning implications. *Journal of Research in Science Teaching*, 28, 733-760.

Smith, J.P., di Sessa, A. A., & Rochelle, J. (1993) Misconceptions reconceived: A constructivist analysis of knowledge in transition, *Journal of the Learning Sciences*, 3(2), 115-163.

Schauble, L., Glaser, R., Duschl, R. A., Schulze, S., & John, J. (1995). Studentsí Understanding of the Objectives and Procedures of Experimentation in the Science Classroom. *Journal of the Learning Sciences,* 4(2), 131-166.

Authors Addresses

Matthew Brown (matt-brown@nwu.edu)
Northwestern University; School of Education and Social Policy; 2115 North Campus Drive, office #319; Evanston, IL 60208. Tel. (847) 467-3869. Fax. (847) 491-8999.
Daniel C. Edelson (d-edelson@nwu.edu)
Northwestern University; School of Education and Social Policy; 2115 North Campus Drive, office #332; Evanston, IL 60208. Tel. (847) 467-1337. Fax. (847) 491-8999.