Visualizing Complexity in Science Classroom Learning Environments

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Abstract

Theory supports the utility of multiple representations as enhancing flexible thought in complex domains, including science teaching, science learning, and scientific problem solving. The Multiple Representation Model (MRM), a theoretical model developed for this study, and the Science Classroom Observation Protocol (SCOPS), an instrument developed for use in teaching and research settings, are used to describe complex science learning environments in a number of contexts. Differences in the practices and patterns of science teachers and learners are discussed.

Keywords: Classroom observation, science teaching and learning, urban education, educational research, supervision, problem solving, modeling, multiple representations

1. NEED

Opportunities to learn in school and work in the society of today require applications of mathematical skills and scientific concepts in the everyday lives of the earth's inhabitants (American Association for the Advancement of Science 1993; National Center for Education Statistics (NCES) 1999, 2001; National Research Council (NRC) 1996). Children of all races and backgrounds enter school with the capabilities to do mathematics and understand science; as they progress through the educational system, minority and poor children become underrepresented in mathematics and science classes and fail to fulfill their potential. The 2000 National Assessment of Educational Progress provides data for the five major racial/ethnic subgroups, children of poverty, and children living in different types of communities (NCES 2001). Comparisons across subgroups indicate that white students' mathematics and science scores were higher than other subgroups consistently across grade levels. Children eligible for free/reduced price lunch programs had an average science scale score significantly lower than that of students not eligible, with differences between the two groups widening between grades 4 and 8. Furthermore, trends in mathematics indicated lower scores in central city schools than in other types of community. Consistent across all data comparisons are pronounced differences between subgroups in 8th grade and even wider gaps in high school. The Third International Mathematics and Science Study–Repeat shows similar trends. In the early grades, American students perform on a comparable basis with students from other countries; by high school, however, American students are outperformed by most high school students from other countries (NCES 1999).

Various explanations have been offered for achievement gaps. Educators have suggested the problem may lie in the kind of instruction prevalent in settings with diverse populations (Ferguson in Jenks & Phillips 1998; Haberman 1995). The achievement gap may be a harbinger of problems with a passive educational delivery system that is inadequate for all students (Singham 1998). Challenging environments for culturally diverse and language minority student populations are still rare in many urban schools. Some evidence exists that these student populations do better with supportive teachers who engage students actively in challenging activities that require them to think, work cooperatively, and link classroom content to student experiences and interests (Waxman & Padron 1995). Others (e.g., Kaput & Roschelle 2002) call for "deep reform" in mathematics and science, suggesting that curriculum for all students must "crack[ing] the formalism barrier between mainstream students and important ideas by providing multiple ways of learning, representing, and using ideas that exploit naturally occurring human … capacities" (p. 2).

While several approaches exist that provide meaningful instruction, a particular challenge lies in identifying and evaluating the classroom processes associated with these types of approaches. Systematic observation traditionally has been used for more direct approaches that feature observable, quantifiable behaviors typically associated with basic skills instruction. Few systematic observation instruments exist for instruction focused on complex, higher order processes. Current knowledge is limited in terms of identified practices, patterns of behavior, and perspectives of teachers who are successful in increasing the academic achievement of learners in schools with complex student populations, particularly at the secondary school level. This effort was initiated to characterize the processes of teaching and learning in science that develop all students' deep understandings about science and how the natural world works.

2. THEORETICAL FRAMEWORK

Modern scientific understanding about natural and designed systems demands both mathematical and scientific knowledge, as well as facility in using multiple representations. Objects, symbolics (numbers and words), and pictures are the core components of representations of the natural and designed world. Growing systems of multiple representation, including those which can be represented and manipulated electronically, are used by scientists, teachers, and learners in new-generation science to think flexibly about complex domains (NRC 2000). Model-based approaches in which a model is invented or selected, explored, and then applied to answer a question of interest are facilitated by the use of multiple representations.

Representations are omnipresent in mathematics and science, but learners often interpret representations in unintended ways (Janvier, Girardon, & Morand 1993). "We cannot assume that students can readily create or interpret representations. They need instruction on how to use them" (p. 79). Deeper/higher order learning and problem-solving in mathematics and science are closely linked to how well learners are able to interpret external, "real world" representations, translate them from one form to another, and transform them into their own internally constructed conceptual models. Conceptual understandings and problem solutions occur when learners are able to map from "real world" situations into a "model world." Transformations may occur within the "model world" to produce predictions about an event back into the modeled situation, and then to test the prediction from the "model world" back into the "real world" situation. A series of modeling cycles may be required in order to solve a given situation or construct an understanding of a complex natural system (Lesh 1990; (NRC 2000).

Information technology, with its powerful image-processing capabilities, extends the scope of possibilities for transforming "real world" situations into modeled situations. Information technology includes tools and applications for animation, scientific visualization, modeling, and manipulation of complex data sets. These new tools assist the research scientist in modeling and interpreting natural phenomena, predicting and observing the results of manipulating components of complex systems, and making discoveries regarding direct and indirect effects of one component on another within a system.. In a similar way, information technology also provides the science learner with new tools for manipulating and understanding the interactions among components within complex systems. Strong foundational conceptual frameworks of understanding allow students to construct, build, translate, and reconstruct external and internal models, thus facilitating the processes of interpreting and constructing complex, multifaceted representations of natural and designed phenomena.

3. A MODELING VIEW OF SCIENCE LEARNING AND PROBLEM SOLVING

The modeling view of the way learning and problem solving patterns are constructed by learners is closely linked to models-based views of the nature of mathematics and science knowledge. When instructional goals stress the acquisition of deeper, higher order understandings about the real world, teachers of mathematics and science must have the knowledge and skills to use multiple representations to bring their students towards those understandings. Teachers are successful when they themselves have higher order scientific understandings and sophisticated content pedagogical knowledge that together allow them to design effective classroom learning experiences for their students. More and more, these experiences integrate and blur the edges among technological innovation, instructional design, assessment, and implementation (Lesh 1990). As components change in the complex learning environment of the classroom, teachers themselves orchestrate changes of other components in the classroom system to achieve balance, order, and hopefully to maximize learning. Teaching with multiple representations in science and mathematics requires a "flow" in changing from one representation to another; an exchange of feedback between learner and teacher to support transitions from one level of modeling to another; and the ability to structure instruction at a level that neither over- nor underwhelms the student model-builder.

The Multiple Representations Model

The development of the MRM began with my attempts to facilitate preservice teachers' understandings of the cognitive foundations of lesson design (Stuessy 2001a,b). From these beginnings, the MRM has been used to address questions of the complex interactions that occur between students, teacher, and instructional materials when science is taught and learned in elementary, middle, and high school classrooms.

The Multiple Representations Model (MRM) requires the science educator to look at lesson design from a systems perspective. (See Figure 1.) The lesson is viewed as a dynamic system of interacting components. The components that interact include an awareness through experiences with a real-world phenomenon and then external representations of it, whether through the manipulation of objects, examination and study of pictures, reading and hearing explanations, and participation in the building of external models. Within a lesson, iterative experiences with external representations are planned to allow students to build their own internal representations, or mental models of the phenomenon under study.

Deep understanding of a natural system occurs when a learner who is familiar with the multiple representations of the system can meaningfully manipulate and transform words to pictures to objects to numbers while applying that understanding to a novel situation or problem. The MRM addresses not only how science and mathematics are taught and learned but how science and mathematics are done, as well as how deeper-higher order teaching and learning in mathematics and science can be assessed. The MRM relies on Wiebe's Model of Mathematics (1998) and work in the field of mathematics and science on multiple representations (Kaput 1987; Goldin 1987; Lesh 1990; Kaput & Roschelle, 2002).

4. DEVELOPMENT OF THE OBSERVATION PROTOCOL

The first version of the Science Classroom Observation Profile (SCOPS; Stuessy 2001a) was developed with the belief that the use of a properly constructed observation instrument could facilitate novice teachers' abilities to differentiate between external and internal representations and translate their experiences in classrooms to their own external and internal representations of those experiences. The SCOPS was initially developed for use with preservice teachers in mathematics and science methods classes to assist them in understanding how hands-on experiences, instructional materials, and student-centered instructional strategies can be used to facilitate conceptual understanding (Parrott & Stuessy, Stuessy 2001a, b). For research purposes the SCOPS has been extended to include more formal distinctions of complexity in science teaching and learning. However, a version of the original SCOPS is still used as an instructional tool in preservice science teacher preparation classes. The SCOPS links the theoretical relationships in the MRM with actual classroom practice, which can be modeled for preservice teachers through the use of videotapes, still pictures, and actual classroom observations.

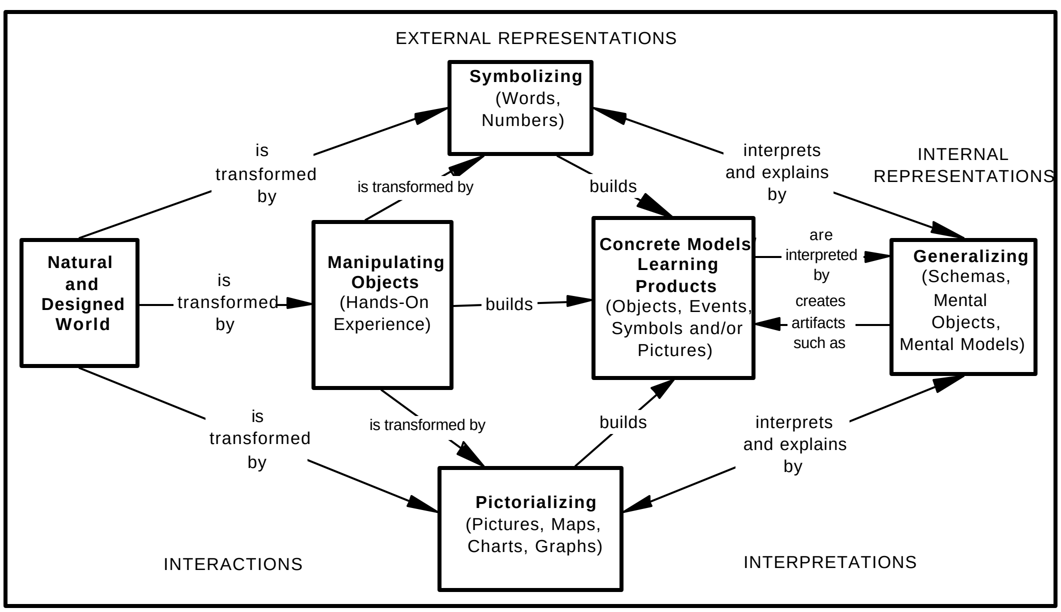


Figure 1. Multiple Representation Model (MRM) demonstration relationships between and among external and internal representations with interactions and interpretations of the natural and designed world.

Figure 2 shows a SCOPS scripting sheet for recording classroom activities, which includes data for (a) characterizing the flow in use of representations by the teacher and students; (b) segmenting the lesson, in terms of numbers and durations of segments in the lesson, (c) recording types of representations received and created by learners during a lesson, and (d) coding the levels of student-centeredness in each of the particular segments of the lesson.

Flow

Many researchers in mathematics and science education recommend that instructional plans be organized around the idea of a spiral movement based on enactive-iconic-symbolic distinctions. Several science instructional models (i.e., Karplus' Learning Cycle; the BSCS 5-E Instructional Model; guided inquiry models) pattern instruction so that students first use "manipulative" or "hands-on" external representations to "make sense" of the representation before introducing more abstract levels of representation. Lesh (1990) explains that mathematics teachers understand that they may at any time induce movement back down the spiral to restore confidence in the learner. At each stage, the learner engages in actions with each representation in such a way that the experience is internalized as a preliminary model, or internal representation, of the experience. Explicit instruction in the transformation of external representations to internal constructions therefore prevents the teacher from prematurely introducing a new external representation for which there has been no internal representation constructed. Sequencing of learning tasks, therefore, is an important feature of lesson implementation that may easily be "lost" in some classroom observation protocols.

Segmentation

The classroom observer uses the SCOPS to record teaching and learning activities as they occur by time segment during a lesson. A time segment is defined as a distinct time period that can be characterized by what the classroom learners are doing. When the classroom teacher directs the activity of the learners from one type of activity to another, a new time segment begins, and the observer describes what the teacher is doing, what the students are receiving, and how the students are performing in the new time segment.

For instance, a teacher may begin a lesson with directions regarding the use of materials for an activity that requires students to get materials and work with them at their desks. In a lesson sequence called "Number Cards," the teacher shows number cards to students as she explains the task. This segment of the lesson takes ten minutes, which the observer records on the scripting sheet. The first time segment is scripted to describe what the students are doing: watching the teacher model the beginning stages of working with the number cards and listening to her directions. After the directions have been completed, the students then acquire the materials and work in pairs at their desks to complete the activity. The second time segment begins when the activity of the students change, that is, when students begin to work in pairs with the cards. After the students have completed their work with the cards, the third segment of the lesson occurs, and so on.

Representations

The types of representation received by learners in each lesson segment are also recorded, as well as the type of representations used by learners in communicating or responding. Representational aspects of the lesson segment are recorded on the scripting sheet: under the R&D and P&I colums. (See Figure 2). In the first segment of Number Cards, for instance, the students receive verbal directions with a general demonstration by the teacher of what the students will do with the materials. In segment 1, therefore, the observer would mark a check in the Receiving (R&D) column for "Symbols" for words and numbers and under "Objects"

Teacher_____________________**Class**__________________**Grade**______ **Lesson**___________________

Describe Learning Goals [ ]

Time					Student Centered-ness		What the teacher does	Levels of R&D and Levels of Representations				Descriptions of P&I and Levels of Representations			
Seg	Beg	End	Min	%	R&D	P&I		What students receive	Sym	Obj	Pic	What students do	Sym	Obj	Pic
1															
2															
–															
end															

Figure 2. Science Classroom Observation Protocol (SCOPS) scripting sheet. Observers record beginning and ending times for each segment, which changes when the activity of the student changes. Also recorded are level of student centeredness, Reception and Direction (R&D) and Performance and Initiative (P&I), what the teacher does, what the students receive and do with representations: symbols (Sym), objects (Obj), and pictures (Pic). When the SCOPS is used as a research tool, Student centeredness and levels of representations are coded (see Tables 1 and 2) as to level of complexity.

for the teacher's demonstration of the cards to be sequenced. In terms of the Performing (P&I) column, the observer would see that the students have observed the symbols and the teacher's demonstrations of the useof the cards. The observer therefore checks both the Symbols and Objects columns in the Responding column.

Student-Centeredness

Each segment is also characterized by the level of Student-Centeredness. The SCOPS scripting sheet indicates that there are two columns for recording Student-Centeredness, one for the level of student Reception and teacher Direction (R&D); and the other column for the level of student Performing and student Initiating (P&I). The student-centeredness construct is operationally defined as the combined levels of Reception and Direction with Responding and Initiating. Levels of Student-Centeredness are recorded on the SCOPS according to a hierarchical framework developed by Stuessy and Knight (2001).

The framework in Table 1 is structured so that the level of R&D decreases as the level of P&I increases. A most extreme instance of Student-Centeredness on the scale, which would be a "6" for R&D and a "0" for P&I, does not actually occur on the scale. A "6-0," if it did exist, would indicate no response and initiative by the learner; with the teacher directing instruction at no one. Stuessy and Knight reasoned that the likelihood of this particular situation occurring in a classroom would be practically impossible, as the assumption is always that students are responding internally to instruction under the teacher's direction, even though there may be little external evidence of student response. On the other hand, there is a "0-6" situation included at the other end of the scale. Depending on where individual students are in their learning, they may indeed come into a classroom and work independently at their desks or computers with little or no direction from the teacher. The student could still be receiving information from another source but may not be receiving any direction from the teacher.

Table 1

Student-Centered Instructional Strategies Coded by Levels of Reception and Direction (R&D) and Participation and Initiative (P&I)

R&D/ P&I	Instructional Strategy
5/1	Individual students listen as the teacher or another student talks to the group; students read silently; direct instruction models
4/2	Individual students in whole group respond orally or in writing to the teacher's questions
3/3	Students in pairs or small groups talk and/or work together on the same task assigned task; guided inquiry with higher levels of teacher direction; some cooperative learning models
2/4	Groups of students and/or individual students work on different assigned tasks, loosely supervised by the teacher; guided inquiry with negotiated tasks; more advanced cooperative learning models
1/5	Students in pairs or small groups discuss, formulate and implement plans, with teacher input upon request; open-ended laboratory/ computer/project work, authentic inquiry
0/6	Individual students carry out plans independently with minimal teacher input

5. USE OF THE SCOPS

Two forms of the SCOPS have been used in science teacher preparation classes, in professional development sessions with intern teachers, in research involving classroom-based observation, and in the professional development of intern science teachers working towards teacher certification. Although the contexts have varied the manner way in which the SCOPS has been used remains consistent. The steps are sequenced so that (1) the significance of the MRM in the teaching and learning of science is discussed; (2) training occurs in the use of the SCOPS, (3) scripting of science class-rooms is practiced, (4) scripts are transformed into visual profiles and drawn by hand or electronically using PowerPoint, and (5) the MRM is revisited in the light of students' experiences with the SCOPS. In teaching situations, I usually begin with an orienation to the SCOPS-I, which replaces the coding of representations with check marks. In research contexts, the adapted SCOPS II is used so that overall classroom complexity can be estimated.

Teacher Preparation Classes

My preservice teachers have experience the SCOPS-I in four ways: (1) observing classroom science and mathematics instruction and identifying the use of multiple representations by classroom teachers and students; (2) designing, implementing, and evaluating their own science lessons; (3) making comparisons of their own lesson designs with those implemented by teachers who had been observed; and (4) evaluating exemplary science activities published in science teaching journals as to their use of multiple representations in suggested instructional formats. As I work with preservice teachers I find that the use of the SCOPS by preservice teachers enhances their understanding of the MRM as a useful organizer in structuring classroom learning experiences. The observation protocol is effective in structuring preservice classroom observation and research, in facilitating the analysis of mathematics and science lessons, and in focusing novice teachers' attentions on salient features of mathematics and science instruction. Using the SCOPS in field-based observations and teaching activities provides preservice teachers with concrete experiences aligned with the theoretical aspects of the MRM. Preservice teachers who at first have difficulties in distinguishing the external from the internal representation demonstrate that they can describe and discuss the role of instruction in facilitating students' interpretations of external representations.

Stimulating Classroom Discussions About Theory

The SCOPS also provides an effective advance organizer for more theoretical discussions centering on the MRM. The SCOPS initially serves as a heuristic for preservice teachers in structuring and translating concrete classroom experience into symbolic and pictorial representations, to build concrete models of teaching and learning, and to translate these experiences into internal representations of effective mathematics and science teaching and learning. Extended use of the SCOPS also provides the scaffolding necessary for teachers to recognize the significant contribution that multiple representations (with and without information technology) can make in their teaching and their students' learning. In light of the need for instructional models that lead students (and preservice teachers) to set higher-order goals in science instruction that include systems thinking and model building, I have found the use of the SCOPS to be, in itself, a promising external representation of the complex learning environment of the modern science classroom.

Estimating Classroom Complexity in Research Settings

The initial work with the SCOPS-I with preservice teachers has been extended to include research on science classroom complexity. Research efforts have centered on extending the characterization of science lessons from description of the lesson to estimations of the complexity of the lesson. The SCOPS-II is an adapted version that includes estimates of complexity, which are explained in more detail below. Basically, with the understanding that lessons should neither under- nor overwhelm the learners but should mediate learning so that it occurs within learners' zone of proximal development (Vygotsky 1989), the focus of these efforts has been on defining the optimal design specifications for effective science lessons. The SCOPS-II adds the dimension of complexity on the data sheet so that numerical data can be transformed into a visualized representation, the classroom profile.

For estimating complexity in representations, Stuessy and Knight (2000) developed a hierarchical framework that assigns complexity levels on a scale from 1 to 6 for each representation received and visibly acted on (or responded to) during each segment of the learning sequence. (See Table 2).

Table 2
Levels of Complexity in Actions of Students in the Classroom

Level	Actions of Students in Receiving and Performing
Replicate 1	Listen to, attend to, observe, manipulate, count, record, recall, measure, reproduce
Replicate 2	Identify, give examples, explain, describe, clarify, calculate, collect information, document, duplicate a pattern, interpret
Rearrange/ Transform 3	Organize, compare, group, sort, sequence, balance, classify, take things apart, recognize patterns
Rearrange/ Transform 4	Choose, decide, differentiate, put parts together to make a whole, distinguish, arrange into patterns
Generate/ Create 5	Connect, relate, infer, predict, plan, make analogies, hypothesize
Generate/ Create 6	Analyze, evaluate, summarize, conclude, construct, design, model

In the development of SCOPS-II, the hierarchy developed to represent student-centeredness was integrated with the complexities of representations to provide more information about the lesson in terms of its overall complexity. Generally, the classification system relies on an analysis of each lesson segment in terms of the complexity levels at which the student: (a) receives the representation of the information, (b) responds to the information that was received, (c) how much direction and responsibility is required of them in the segment; and (d) how many lesson segments there are within the entire lesson. For instance, a pair of learners may be required to act on a set of math cards consisting of words (e.g., one-half, one-third, ten percent), decimals, and fractions by sequencing them from the smallest number to the largest. An accurate sequence of the cards is evidence of a performance of the students that would require them to read the cards, make sense of the words and symbolic representations, and then order them from smallest to largest.

Classroom observer-researchers use the SCOPS-II much as preservice teachers use the SCOPS-I. Researchers observe the lesson and record what occurs during each segment of instruction, segments are still determined by shifts in the learning tasks of the students. The SCOPS-II extends the observations, however, to include estimates of classroom complexity in terms of interacting components. Classroom complexity is estimated visually by examining (1) number of variables, including (1) number of segments in the lesson; (2) student-centeredness; (3) numbers of representations used in both R&D and P&I; (4) and levels of representations.

Visualizing Lesson Complexity

Coded data on the SCOPS scripting sheet are used to create a profile of the teacher's lesson in terms of the complexity of the students' learning experiences in the classroom. Salient features easily recognized on the profile include the number of segments in the lesson, the "balance" between students' Receiving and Performing, the types of representation used and required in the lesson, and overall complexity as an additive feature of the lesson segment complexities.

6. CONTINUING RESEARCH

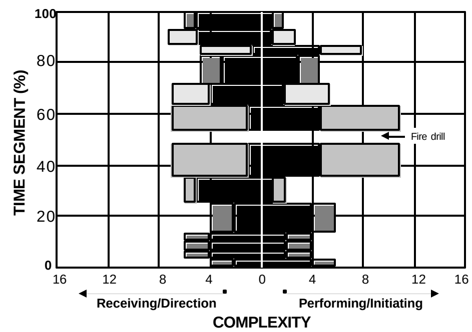
Classroom data have been collected, analyzed, and profiled using the more complex coding system in the SCOPS-II to represent secondary science classrooms, including those of exemplary science teachers in urban middle and high schools of two large metropolitan school districts (Stuessy & Foster 2002; Stuessy, Foster, & Knight 2002; Stuessy & Knight 2000) and intern teachers engaged in an alternative certification program (Stuessy & Foster 2002).

A significant finding of our research to date relates SCOPS profiles to time on task. Figure 3, for example, shows two profiles of classrooms exhibiting highly motivated, engaged students. Figure 3a profiles a middle school lesson in which learning tasks changed often with a number of different representations. In comparison, Figure 3b profiles a high school science lesson, which shows fewer segments than the lesson of the more physically active middle school students. In this high school classroom, there were fewer segments and representations used and high levels of P&I were achieved for approximately 40 percent of the time. We have just begun to use the SCOPS in mentoring novice teachers and identifying patterns of science teachers' classrooms known to consistently produce high-performing, successful students in mathematics and science.

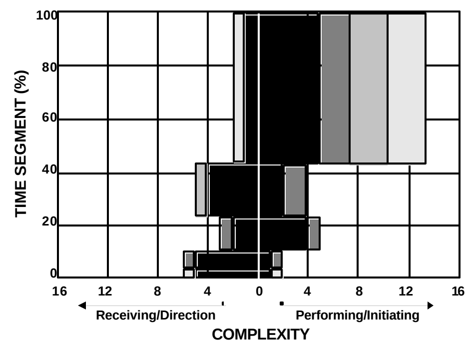
Regarding the SCOPS technology, our research group is in the very early stages of designing a computer-based system to facilitate all aspects of the SCOPS-II: data entry, data storage, data manipulation, visualization, and animation. Programming that coordinates these stages is planned for the school year 2002-2003.

7. CONCLUSIONS

Systems thinking, models-based reasoning, and the use of multiple representations facilitate sense making.



3a. Middle school classroom



3b. High School Classroom

Figure 3. Profiles of sixth grade and ninth grade classrooms showing differences in number of segments, complexity, flow, use of representations, and student-centeredness. The vertical line at point 0 separates Receiving/ Direction from Performing/ Initiating student activities. The lesson flows from bottom to top, with the horizontal axis indicating time segments of the lesson. Overall complexity of each segment is additive.

Visualizations of lesson flow and complexity can provide teachers and researchers alike with an instrument that assists them in describing and understanding effective patterns of science instruction. Data collected from classroom observation using the SCOPS provides important information for organizing, interpreting and making conclusions about effective practices. The SCOPS provides a heuristic for understanding the complexity of classroom learning environments, including those which are technology mediated, in order to facilitate deep/higher-level conceptual understanding about the natural and designed world. The SCOPS adds a new dimension to the traditional data sets and artifacts collected in describing "what actually goes on" in science classrooms.

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