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Exploration zones: A framework for describing the emergent structure of learning activities

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Introduction

The theme of this book—learning environments as spaces of contact between students' and disciplinary perspectives—implies a general orientation toward instruction in which the perspectives of students are taken seriously. This orientation has some important entailments. If students' perspectives are to be well-represented in the classroom, students must take an active role in shaping and guiding ongoing classroom activity. Teachers must relinquish to students some control over the classroom explorations, actively incorporating students' questions and products into the classroom inquiry. We call this kind of classroom practice *student-directed*.

The design of student-directed activities poses specific challenges. On the one hand, our job as instructional designers is to specify classroom activities. On the other hand, if our activities are to be truly student-directed, our designs must not fully define the course of classroom events. We want to leave enough space for students' ideas, interests, and perspectives to drive the activity.

The difficulty of this challenge is mitigated by an important observation. Even when we allow an activity to be directed largely by the students involved, we often have a reasonably good idea of how events will proceed. We may not know exactly what will happen, but we frequently have a good idea of the space of possibilities, or the territory that students are likely to explore in a given activity. This knowledge may be based on previous trials of similar activities, or on a more general understanding of the knowledge, capabilities, and experiences of our students.

The task that we take up in this chapter is to develop a way to capture wisdom of this sort; we want to develop a way to talk about this "space of possibilities" and, based on this understanding, to design more engaging and effective student-directed activities. To reach these ends, we develop a framework and terminology around a notion that we call *exploration zones*. The phrase "exploration zone" is meant to describe the territory that students might explore in a student-directed activity. In using a spatial metaphor such as "territory," we do not mean to imply that an exploration zone exists as a well-defined space of possibilities; instead, we believe this territory is constructed in, or emerges from, the joint action of teacher and students. But this construction process may exhibit regularities across contexts and trials, and it is these regularities that we wish to understand and capture.

To illustrate the idea of exploration zones, consider a teacher-led classroom discussion in which the teacher proposes a question for students' consideration. In a unit on the physics of motion, a teacher might ask students to predict the path that a tethered ball might follow if the rope is cut while the ball is spun around on the end of the rope. The teacher might have anticipated a few answers that students might give initially, such as: (1) the ball continues to move in a circular path; (2) the ball moves in a direction tangent to its trajectory at the time the string is cut; (3) the ball moves inward in relation to its original trajectory; and (4) the ball continues to move along a curved trajectory, but the path gradually straightens.

Furthermore, the teacher might have a reasonably good idea about the directions the discussion might take when one of these initial answers is examined, including conceptual hurdles students might encounter. The teacher might even have planned additional sub-tasks that are based on some of the possible answers or expected student reactions to such answers. For example, the teacher might propose that students enact some experiments that add empirical evidence pointing to the plausibility or implausibility of one particular answer. Additionally, she might deploy a number of props, collected prior to the task, to help students better visualize and work through the problem. Because the teacher has a relatively good idea of how the discussion might proceed, she can plan for a manageable set of contingencies.[1]

In sum, a map of the exploration zone for a discussion of this sort might be comprised of anticipated initial answers and several paths of exploration, including those that students naturally follow, those that provide important conceptual leverage, and those that should be avoided. The map might also contain techniques and props that nudge students into or out of certain areas of the exploration, thus providing a means for managing movement through the exploration zone. Other map parameters, such as established norms and values that support collaborative inquiry, are equally important because they make up an important part of the substrate in which the exploration zone exists.

In advancing the notion of exploration zones, our goal is to develop a framework that is general enough to support the analysis and design of a broad range of student-directed activities, from reasonably constrained ones (such as the example above) to radically open-ended tasks. As a way to organize this endeavor, we divide it into four complementary sub-goals:

1. *Devising a terminology and methodology for describing the structure of exploration zones*. If we think of an exploration zone as a landscape that students move through, our first goal is to find a means of describing the structure of this landscape. We will do so by crafting a language that captures general classroom phenomena and dynamics. Many of these phenomena are familiar to us in our experimental work, and we believe they are likely familiar to teachers, curriculum designers, and researchers more generally.
2. *Explaining how the structure of an exploration zone depends on various factors, such as student capabilities and contextual constraints*. We want to understand what factors determine the structure of an exploration zone, as well as how those factors act to determine this structure. This item defines a long-term research agenda, and our goals for this chapter are modest.
3. *Describing the trajectories that students take through exploration zones and developing techniques for guiding students as they move through an exploration zone*. As a pedagogical concern, we want to be able to describe how students may move through an exploration zone, taking various possible trajectories, and understand how to guide students along trajectories without destroying the student-directed nature of the activity.
4. *Describing desirable properties of an exploration zone*. Finally, we want to articulate desirable properties of an exploration zone in terms of the terminology developed in meeting the above goals. In this regard, we are particularly interested in understanding what properties of an exploration zone make for engaging explorations and generate commitment on the part of students.

Situating the exploration zones framework

Before proceeding with our main presentation, we briefly situate this work within the larger body of educational research. The work we present in this paper fills an unusual niche, one that has

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[1] "Benchmark lessons," as described by diSessa and Minstrell (1998), rely heavily on this kind of cumulative teacher knowledge.

been only thinly populated with prior research. Thus, our purpose in this section is not to describe competing approaches. Rather, we seek only to describe this niche, and to give a sense of its relation to other educational research.

Broadly speaking, our goal is to contribute to attempts to develop principles and frameworks that guide the design of learning environments (e.g., Brown & Campione, 1996; Collins, 1995). More specifically, our intention is to contribute to theories of *classroom activity*. We want to provide a framework for describing and understanding the unfolding of classroom events, particularly for student-directed activity.

Our analysis of the unfolding of classroom events is targeted at a particular timescale. Our intent is to describe specific patterns in *moderate* time-scale activity, on the order of a few minutes to a few hours. On the low end in timescale, our work nearly reaches the grain size of analyses of the structure of classroom dialogue, which look at patterns in the utterances of participants such as turn-taking structure in classroom discourse (e.g., Lemke, 1990; Mehan, 1979). However, unlike our own work, these small time-scale analyses have tended to be content-independent, in the sense that they are not focused on the semantic content of utterances.

At the high-end in time-scale, our work is bounded by analyses of the month- and year-long evolution of such things as classroom norms (e.g., Yackel & Cobb, 1996), and the roles that individuals play within the classroom culture (see, for example, Lave & Wenger, 1991, on legitimate peripheral participation).

Attempts to describe and design *activity structures* address the same time-scale as our own work. In defining activity structures, researchers specify formats for the organization of interaction within the classroom. These formats include, for example, small group discussion, whole-class discussion, reciprocal teaching, and jigsaw classrooms (Brown & Campione, 1994). However, like the discourse analyses described above, activity structures are generally defined in a manner that is content-independent. An activity structure describes the roles played by individuals in a classroom, and the rules that govern how those individuals interact, such as who can talk, and at what time. In contrast, we are concerned with structure in an epistemic space — the space of ideas that the group can explore. In addition, most treatments of activity structures focus on prescriptions that are more or less enforced, as opposed to fluid, spontaneous organization of activity, which is more our focus.

Attempts to understand classroom progress and learning in terms of the zone of proximal development (ZPD) (Newman, Griffin, & Cole, 1989) are a close match to this work in time-scale. Indeed, the notion of a ZPD is grounded on a similar metaphor to our own: Ideas and activities are located within a larger space. Furthermore, like our exploration zone, the structure associated with a ZPD analysis is seen to emerge from the capabilities of participants and the resources that are available to them. However, the original purpose for ZPD-based analyses was measurement of competence—what things a person can do, with and without help. Hence use of the spatial metaphor is limited, essentially, to "in or out." We aim for a more refined description of structure. By the same token, analyses of sequences of elements of activity forming a larger whole ("exploring a zone") are emphasized in our analysis, but not in ZPD-oriented work.

Finally, one part of our orientation deserves particular mention, our focus on *engagement*. There have been almost no modern cognitive analyses of learning that deal with engagement in a central and principled manner. Furthermore, where issues of engagement are addressed, they are addressed in a very different manner than we propose. As we discuss later, prior analyses have tended to focus on such things as the intrinsic interest of the subject matter, or "motivation" viewed as a trait possessed by individuals. In contrast, an exploration zone analysis targets the *structural* features that make an activity engaging. In this regard, some of the closest prior work to ours was done by Csikszentmihalyi (e.g., Csikszentmihalyi, 1988), as we elaborate later in this chapter. Also related are diSessa's (2000) arguments concerning engagement and the structure of activities, especially as they relate to individuals' capacities and interests for participating in certain activities and the long-term development of these capacities. In the present analysis, these would count as background factors that influence the smaller-scale exploration structure that is examined here.

A plan for the chapter

In the next section we consider two open-ended, student-directed activities in which students design representations of natural phenomena. For each of these activities we present the work students produce and some of the activity dynamics, including places in which impasses are encountered, and aspects of the activity that are more or less engaging to students.

Following that we tackle, in order, each of the four sub-goals listed above, using the example activities to illustrate our points. Finally, we review the contributions of the chapter and reflect on the limitations inherent in our use of a spatial metaphor. In addition, we propose further work to advance the general research program.

Representational design activities: Two examples

Since 1991, we have been engaged in the investigation of students' meta-representational competence (MRC)—the ability to design, critique and use representations of natural phenomena. These natural phenomena include motion, landscapes (i.e., the varying altitude of some terrain), and wind information (Azevedo, 2000; diSessa & Sherin, 2000; diSessa, 2002; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Sherin, 2000). The theoretical goal of this research is to uncover what students know about representations in general, rather than their knowledge of particular scientific representational forms. Consonant with this orientation, our approach has been to involve students in a creative process through which they design novel representations. Pedagogically, we want to devise ways to engage students' "natural" abilities and knowledge about representations, while helping them construct more canonical understandings of the representations of science.

Of all representational design activities we have tried with students, two have received particular attention: *Inventing Graphing* (IG) and *Inventing Mapping* (IM). Inventing Graphing refers to a set of activities in which students design representations of motion. Inventing Mapping consists of activities in which students design representations of landscapes.

We believe that Inventing Graphing and Inventing Mapping are good examples of student-directed activities, and they are ones that we know quite well. We have run several IG sessions in a number of contexts, including "real-world" classroom situations and mini-classes with volunteer students from a public high school. In addition, IG sessions were carried out during two six-week courses that we taught on the subject of representational design. These courses were part of the Berkeley Academic Talented Development Program (ATDP), a K-12 summer enrichment program intended for students who wish to engage with non-traditional or advanced subject matter. In a nutshell, we have extensively tested the activity with students in grades 6 to 11, and thus far we have amassed a total of roughly 20 hours of IG video data.

Inventing Mapping is relatively less tested, but the results we obtained from session to session, and across contexts, are quite consistent. Thus far, we have enacted IM with students grades 7 to 11 in the context of open-ended, one hour-long group interviews with students from a local public school, as well as during the six-week ATDP summer courses to which we referred above. Overall, we have collected about 6 hours of IM video data.

Given this history with IG and IM, we feel we have developed a good understanding of how these activities tend to unfold—what designs students are likely to create, what criteria they generally apply in assessing the merits of their designs, and the pitfalls students encounter. In addition, we have collected pedagogical moves that are effective in guiding students in these design activities without wresting undue control from them (Madanes, 1997), and we have described how students and teachers negotiate a common understanding of such design tasks (Granados, 2000).

In what follows, we present a synthesis of our findings about IG and IM activities. For details regarding Inventing Graphing, readers are referred to diSessa et al. (1991), Sherin (1997) and Sherin (2000). A full description of Inventing Mapping is found in Azevedo (1998) and Azevedo (2000).

When we present IG and IM examples in the sections that follow, we will refer to these different classroom settings by our pseudonyms for their respective schools. Our regular classroom situations were in Benson Middle School and City High School. Students in our after-school mini-classes were from Trenton High School. Our summer course will be referred to as the ATDP course.

Designing representations of motion

Originally, Inventing Graphing was conceived as an activity in a larger curriculum aimed at teaching the physics of motion to grade 6 students at Benson Middle School (diSessa et al., 1991). In particular, IG was to serve as a one-day prelude to focused work on Cartesian graphing. Somewhat unexpectedly, however, by the end of that day students had created an impressive array of representational forms. Because students had much to say about their representations, and because they appeared so deeply invested in the activity, we decided to extend Inventing Graphing to a full week of activities (a total of five days).

During the next four days students created many more representational forms. As a group, they argued cogently for the positive qualities of their representations and also discussed limits and how one might overcome them. Throughout the five days of activity, students maintained a level of engagement that made the activity nearly self-sustaining. In fact, the students were so enthusiastic that, for long stretches, the only role of the teacher was to guarantee an orderly voicing of opinions. Near the end of the week, students seemed to arrive at a consensus that Cartesian graphing of speed versus time was, indeed, the best among the representations they generated.

The activity and its organization

The Inventing Graphing activity typically proceeds through repeated cycles. Each cycle begins with the teacher briefly describing a motion or enacting it for students. A common starting point for the activity has been "the desert motion": A motorist is speeding across the desert and she's very thirsty. When she sees a cactus, she stops short to get a drink from it. Then she gets back in her car and drives away slowly.

Following the description of the motion by the teacher, students work alone or in groups for about 5 or 10 minutes using paper, pencil and colored markers. Students then present their work to the class. During these presentations, the teacher helps the class as a whole to critically compare and evaluate the qualities of their representations. As is appropriate for a design task, the emphasis of these evaluations is not to achieve a correct answer; rather, students are encouraged to discuss the tradeoffs involved in the design of each representation, in light of the uses the representation is to fulfill.

Thus, in idealized form, the IG activity consists of a series of rounds in which: (1) The teacher describes a motion, (2) the students represent the motion, and (3) the class discusses the various representations produced. Occasionally, the teachers do deviate from this formula. For example, sometimes groups are asked to practice using the representations of other groups. On other occasions, problems are couched as challenges where each group represents a particular motion pattern not known to the others. Then, during the presentation and discussion phase, groups read each others' representations in an attempt to figure out the original motion. On occasion, a teacher may also instigate the comparison of representations by involving the class in sorting representations, grouping together those that appear similar. This pedagogical strategy may serve conceptual and pragmatic goals.[2] Conceptually, working on comparing and categorizing representations may focus students attention on issues such as clarity (which representations show motion patterns cleanly), quantitative precision (which representations allow for precise readings of relevant parameters), and consistency (which representations adopt a consistent set of conventions). Pragmatically, comparing and categorizing often functions to narrow the existing pool of representations, thus making the exploration more manageable for students.

Students' designs

From the very beginning of the activity, students produce a variety of representational forms. We have argued in prior work that students' designs fall roughly into three broad categories of representations: drawings, temporal sequences, and graph-like depictions (Sherin, 1997; Sherin, 2000).

Drawings refer to depictions that are based on a set of conventions and techniques for portraying three-dimensional scenes on paper. As an illustration of a drawing, consider Damon's representation of the desert motion (Figure 1).[3] In the figure, one can see many elements of the desert motion story, including a side view of the road (represented as a single line), some cacti, snapshots of the car, and the driver. To a large extent, Figure 1 can be understood as an assemblage of conventional drawing elements. These conventional elements, such as the stick

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[2] See diSessa, et al. (1991) for more details on what we mean by "conceptual" and "pragmatic."

[3] All names are pseudonyms.

figure of a human and cars portrayed from a side view, are part of the standard repertoire of elements possessed by students in U.S. schools (e.g., Willats, 1985).

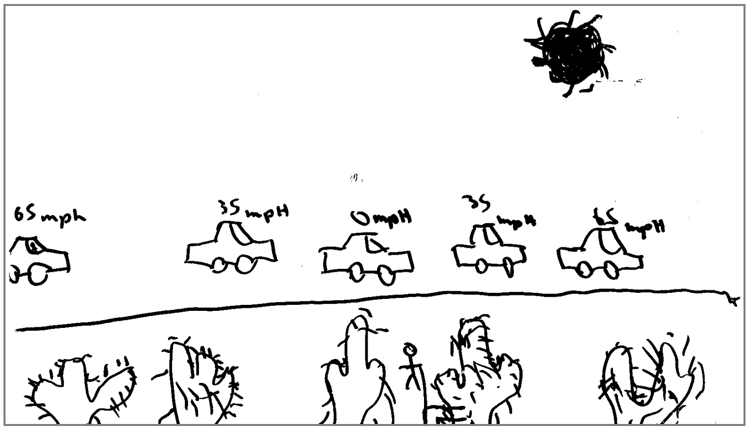

Figure 1. Damon's representation of the desert motion. Trenton, session 1. Scanned from original.

Two points about drawings that are worth noting. First, drawing techniques are very flexible and can be adapted in many ways. Indeed, Damon has somewhat "bent" strict drawing conventions when making his representation. Although the desert motion describes the movement of a single car, Damon used several renditions of a car to represent snapshots of its movement. Damon is not alone in adapting drawing elements; most students readily capitalize on drawing's flexibility to produce a wide range of representations.

The second notable point about drawing is that essentially all individuals in our culture have some experience with it. Although individuals are certainly not equally proficient, most can produce recognizable drawings, and virtually all have the ability to understand drawings produced by others.

A second class of representations that prominently appears in IG sessions is what we refer to as *temporal sequences*. A temporal sequence is a linear array of representational elements, each of which refers to a specific part of the motion being represented. As with written text, temporal sequences are read one element at a time in an order defined by the designer (e.g., left to write, or top to bottom).

In the temporal sequence in Figure 2, each element tells us something about the speed of a jogger at a given moment in time; the length of the arrows represent the speed at which the person is moving, and a circle indicates that the person is stopped. Thus, the representation in Figure 2 shows a person moving fast (a long arrow), stopping for a short period of time (one circle), then gradually increasing his speed (arrows increasing in length), stopping for a longer period of time (two circles), and finally speeding up again.

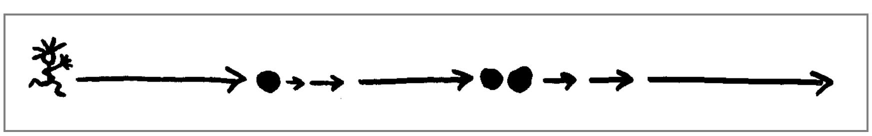

Figure 2. Representation of a person who stops twice during his daily jog. Trenton, session 2. Scanned from original.

As might be evident, the nature of the elements in a temporal sequence can vary widely. Students have represented speed by using the size of an icon (such as a triangle), as well as the slant, thickness, height, and color of a line segment. The variability of elements in temporal sequences makes for a very flexible class of representations, which can support quite a range of exploration.

The third and final class of representations students generate in IG is *graph-like* depictions. Graph-like representations include standard Cartesian graphs of a situation as well as adaptations that overlay drawings or other representational elements onto graphs. As an example of a graph-like depiction, consider Ryan's representation, shown in Figure 3. In the figure, we can identify many elements from standard graphs, including labeled axes and a curved line whose height represents an object's speed. Ryan's graph shows speed as a function of position. In some cases, however, the quantities graphed by students are non-standard and idiosyncratic.

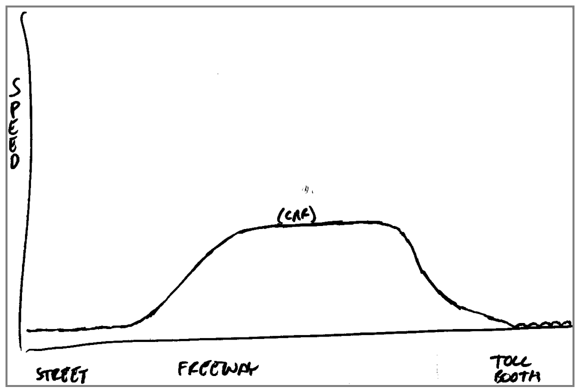

Figure 3. Ryan's graphing representation. Trenton, session 1. Scanned from original.

Elsewhere we have argued that the appearance of graph-like depictions in IG sessions is almost always a gradual accomplishment of the students involved (Sherin, 2000). Furthermore, the appearance of the first graphs does not constitute the end of an IG session; much work typically remains to be done even when graphs are suggested. For instance, most students are not immediately convinced of the advantages of graphing, and many prefer to continue making temporal sequences instead of graphs.

"Getting stuck" and moving beyond it

Our many trials of IG have convinced us that students are capable of engaging competently in the activity. However, IG activities do not always unfold smoothly. To exemplify this point, we recount an episode that occurred at City High School.

On that occasion, students had largely committed to representing motions through a subclass of drawing representations they called "Dots." Essentially, Dots representations are depictions in which a trail of dots is laid out along the path of the moving object, with dots dropped at equal intervals of time. The separation between successive dots allows one to infer the speed of motion (the farther apart the dots appear, the faster the object is moving), while the dots themselves show spatial displacement. Figure 4 shows a rendition of the desert motion using the Dots representation.

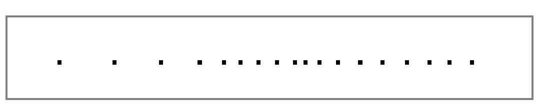

Figure 4. Dots representation of the desert motion.

Although the Dots representation is extremely schematic, it is still strongly tied to drawing conventions. In particular, Dots implicitly works according to a drawing convention in which displacements on the page correspond to displacements in the real world of the motion. As discussed in Sherin (2000), this strict correspondence makes this class of representations inherently limited. For example, attempting to show backward motion with a dot representation leads to solutions that are difficult to read because dots may overlap or intersperse.

For a significant part of two class periods, the students at City High School focused only on creating versions of Dots representations. Although the teacher regarded Dots-based representations as acceptable, she had hoped to foster a richer discussion in which students discussed the merits of multiple representational forms. In an attempt to break the logjam, the teacher asked students whether the representation in Figure 4 showed the *duration* of the stop at the cactus. Students were quick to respond that it did not. The teacher then asked students to revise the representation in Figure 4 so that it showed the duration of the stop. The intervention was effective; students struggled with this question briefly and then began creating new representations in which the vertical dimension had various meanings. Some of these representations were temporal sequences.

Designing representations of landscapes

Following the success of our investigations of Inventing Graphing, we decided to explore students' meta-representational competence in a number of domains. Given the prominence and importance of mapping practices in western cultures (Wood & Fels, 1992), Inventing Mapping was a natural direction to explore.

The activity and its organization

In Inventing Mapping sessions, students are shown a number of props that stand for elements of a landscape. These props are made of Styrofoam or similar material and have many different shapes—elliptical mounds, hemispherical domes of various sizes, domes with the top portion cut off, washboards, and ramps.

In a typical IM activity, the teacher/researcher places props inside an empty cardboard box and asks students to represent the assembled landscape. Students then work individually or in groups for 10 minutes or more, depending on the complexity of the landscape. Work is carried out with paper, pencil, and colored markers.

Following the initial round of designs, students present their work to the class and, as in IG, all engage in critically examining the existing pool of representations. After all students have presented their work, a new landscape is presented. In general, IM activities progress from simple to more complex landscapes, which include a larger number of landscape elements and more irregular objects. Every IM activity thus far has included representing a fairly complex landscape, which we sculpted out of hardened sand poured into a 25''L X 18''W X 3''H cardboard container (Figure 5).

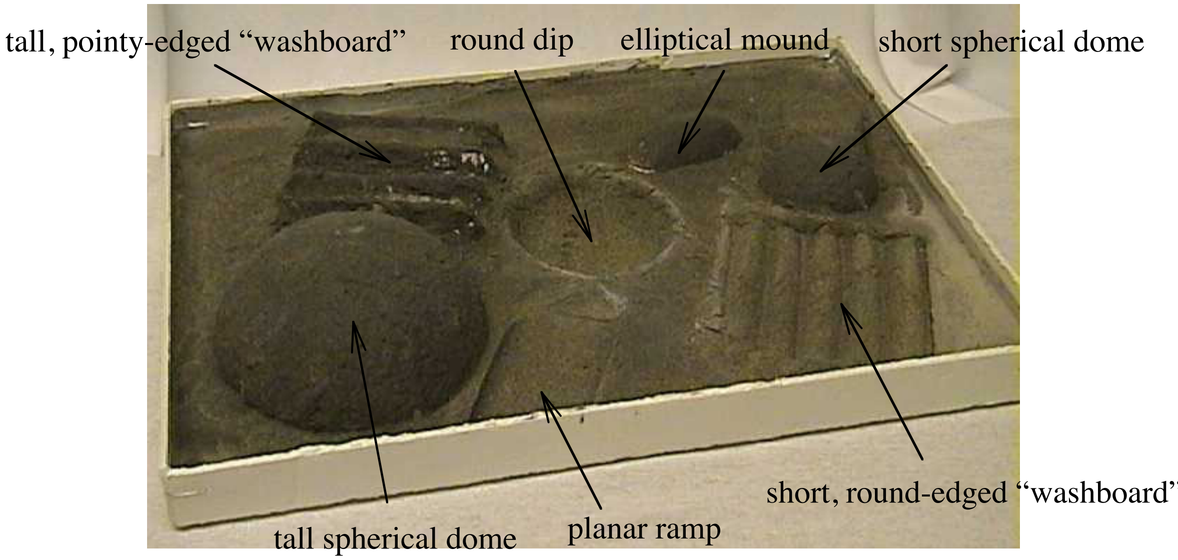

Figure 5. A complex landscape made of hardened sand.

Students’ designs

In prior work, we argued that students’ designs in Inventing Mapping fall into two broad classes of representations: drawings and quasi-topographic maps (Azevedo, 2000).

Drawings are a prominent class of representations in Inventing Mapping. As in Inventing Graphing, drawings produced in IM are based on a flexible set of techniques that are commonly learned by children in our culture. Although the IM task context may seem to require significant drawing abilities, in practice we have observed that most students can produce drawings that others accept as representationally effective.

Roughly speaking, the drawings students produce in IM may be said to occupy a continuum from “simple” to more “sophisticated” drawings. Simple drawings are renditions that portray the main elements of the proposed landscape from a single point of view. Figure 5 shows one such representation. In it, Nina has drawn two domes of different sizes, the larger of which has a dent. Between the domes, a human figure, not present in the original landscape, has been used to index the height of the domes. As Nina explained, “if you were walking in this landscape, everything around you would look really big.” Nina’s strategy again illustrates the flexibility with which students adapt drawing conventions and elements in order to achieve certain representational effects.

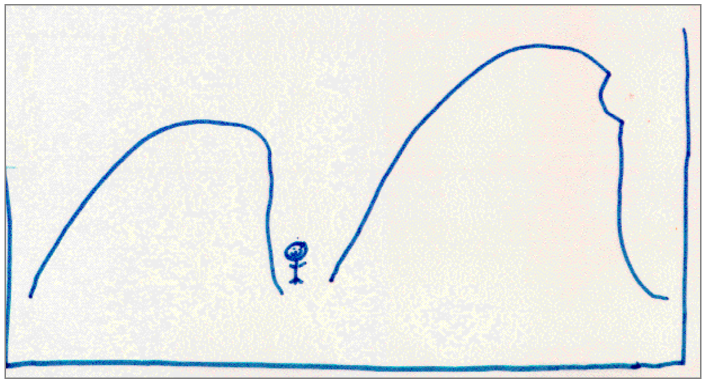

Figure 6. Nina's representation of two domes of different sizes, one of which has a dent. Trenton, session 1. Scanned from original.

More sophisticated drawings include depictions that coordinate several renditions of the landscape, each drawn from a different point of view. When showing complementary views of the landscape, students usually remark that their intention was to portray all aspects of the given landscape. This rationale drove Lisa's production of Figure 7. In the Figure, we see a front, top, and oblique renditions of a two-dome landscape.

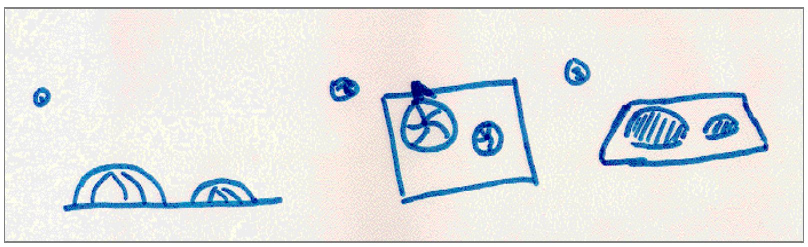

Figure 7. Lisa's representation of two domes of different sizes: (a) side view, (b) top view, and (c) oblique view. Trenton, session 2. Scanned from original.

Quasi-topographic maps form the second class of representations that students create in IM. Although these representations share many elements with common topographic maps, they also depart from the standard in important ways. For example, in Figure 8, Tamara has used colored lines inside landscape objects to serve a function akin to contour lines. Furthermore, the height represented by each color is shown on a legend, another element appearing in topographic maps.

Contrary to canonical contours, however, Tamara's "contour lines" do not generally connect points of the same height in the landscape. Instead, the drawings seem to be based, in a more impressionistic manner on the wavy contours she has probably seen in topographic maps. Although other students' use of contour lines was more in accordance with standard conventions, virtually all such representations deviated from the standard conventions in important respects.

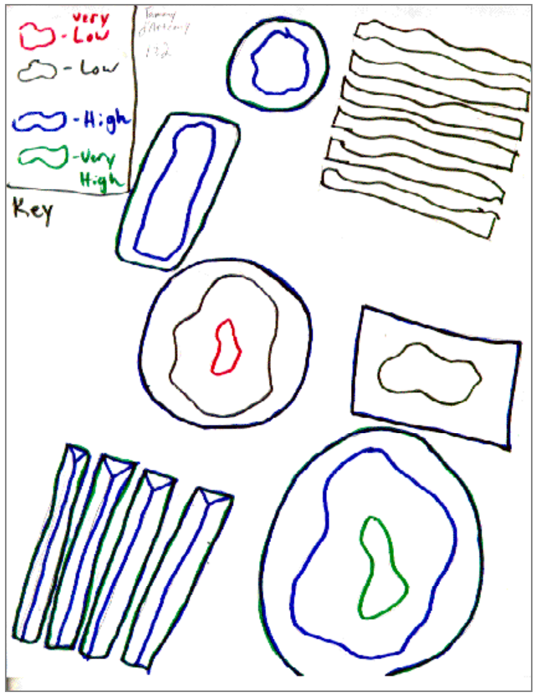

Figure 8. Tamara's representation of the large sand landscape. ATDP '97. Scanned from original.

Colors as representational devices

Although students can proficiently participate in Inventing Mapping, the activity does not appear to engage students as much as one might hope (and in the way IG generally did). When comparing the representations produced in a round of design, students frequently offer minimal comments. And, from round to round, students often stick to their original representational techniques without attempting any significant innovations. Compared to the frenzy of activity that IG seems to inspire, IM seems generally a bit dull.

However, there is one sub-topic within IM that creates very different dynamics of engagement: the use of colors to represent altitude information. Using colors as representational devices is a strategy that surfaces almost exclusively when students work with quasi-topographic maps. In that context, students consider the coloring of contour lines, contour intervals, or both. Design solutions are often based on coloring schemes such as light-to-dark or dark-to-light sequences of colors, and students suggest many such sequences. Students also cogently consider the benefits and drawbacks of adopting schemes based on varying saturation of a single hue.

Discussions around the uses of colors in quasi-topographic maps are usually quite lively. Within any single IM session, these discussions are the ones in which students articulate the greatest number of design criteria. In this regard, students' concerns relate mainly to the ease of reading and interpreting map information.

The exploration zones framework

We now tackle the main elements of the exploration zones framework. In our presentation, we proceed, one-by-one, through the components of our program listed in the introduction: (1) devising a terminology and methodology for describing the structure of exploration zones, (2) explaining how the structure of an exploration zone depends on various factors, (3) describing the trajectories that students take through exploration zones and developing techniques for guiding students, and (4) describing desirable properties of an exploration zone. Throughout this presentation, we draw primarily on examples from IG and IM to illustrate our points.

Characterizing exploration zones

We begin by introducing terminology for describing exploration zones, -to capture their phenomenological structure. For instance, one familiar phenomenon is that some tasks or discussions provide richer grounds for students' explorations than others. Another familiar phenomenon is that students sometimes limit themselves to small areas of the exploration; they "get stuck," so to speak, and seem unable to consider alternative solutions or arguments. Our terminology should be suited to describing such phenomena.

We first identify three basic structural components of exploration zones: *pockets*, *pathways*, and *landmarks*. Then we introduce a typology of pockets.

Pockets

The first basic structural component of exploration zones is the pocket. A pocket is a collection of specific moves in the exploration that tend to be mutually activating and reinforcing in discourse and action. For example, two responses—call them Response A and Response B—are within the same pocket if mentioning Response A tends to lead to mentioning Response B. Moves can include any of a large number of action types, including responses, explanations, questions, arguments, examples, hypotheses, and proposals.

For an illustration, let us return to the tethered ball scenario discussed in the introduction. As a starting point, suppose a student argues that the ball will move in the direction of its original trajectory (around in a circle) on the grounds that moving objects tend to continue their current motion. That answer, together with the set of relevant considerations (including at least, we see, an argument in favor of the proposal based on persistence of action), constitutes a pocket. A second student might then counter this idea by arguing that this is only true in a vacuum; in the real world, the ball will continue in a curved path, but that curved path will gradually straighten. (Both of these arguments are common, yet fallacious.) The second answer defines a second pocket ("gradually straightening"), and the rationale "only in a vacuum" may be considered part of both pockets, tending to validate one, and undermine the other contention. Yet a third student might support the "gradually straightening" conjecture by volunteering an example; he might claim he has seen racing cars skidding forward and outwards as they try to round a curve. The example belongs to the second pocket.

The central point is that the set of mutually cuing and supporting moves in the exploration characterize a unique portion of the exploration zone—a pocket within that zone. Repeated observations of the activity in a number of contexts informs us about the number of pockets typical of the activity and, furthermore, the characteristic features of each pocket. Thus, we might find that our hypothetical tethered ball exploration zone has four pockets, the four mentioned in the introduction.

Within the IG activity, we can imagine several ways that moves may be mutually cuing and supporting:

1. The description of a motion phenomenon associated with any representation will, by necessity, attend to some features of the motion phenomena and not others. Such a description may lead to further moves that attend to these same features. For instance, if some student starts attending to speed, other students are likely to do so.
2. A representational form proposed by one student may possess a certain structure that can be appropriated and used, in new ways, by other students. For example, if one student makes a temporal sequence representation, this can lead to the production of similar representations by other students.
3. Finally, the pragmatics of discourse may naturally lead from one move in the discussion to another. For example, a proposal for a representational form may lead naturally to a move that is a justification for the proposal. Widespread aesthetics of judgment of representations may determine whether justifications or critiques are more common, and whether agreement in the group tends to be quick, or involve extended debate.

Empirically, the type of cuing and support in case (2) seems to us responsible for the primary top-level structure in the IG activity. Thus, the main pockets in IG correspond to the categories of representational forms students create: drawings, temporal sequences, and graph-like representations. These categories of representations appear to strongly define the character of IG explorations, although a very large number of issues cut across the exploration of individual IG pockets.

These categories of representations, however, only describe the top-level pocket structure in the IG activity. In the IG exploration zone — and all other exploration zones — pockets may nest, one inside the other, thus forming a hierarchy. This nesting may be of two distinct types. In the first type of nesting, we may see pockets within pockets, simply because we look at the activity at a finer grain-size. For example, within any of the three main pockets of the IG exploration zone, we can imagine a description in terms of pockets that captures the relatedness of some moves within the larger pocket. For instance, while considering a category of representations, students might start listing all the negative characteristics of the category. (This is mutual cuing of type 3.) When pockets nest in this manner, we have our choice as to what level we want to consider. If sub-pockets flow easily into one another, the higher level pocket is likely the most natural level of consideration. If distinctions among sub-pockets align with important conceptual issues, we may want to consider both levels.

The second type of nesting is subtler. In some cases, an activity may tend to spawn a new exploration, with its own integrity. For example, in the IG activity, students have sometimes fallen into a discussion of whether an object, when reversing its direction of motion, must necessarily stop (diSessa & Minstrell, 1998). Within this little bubble in the IG activity, the very currency of the discussion has changed. The students are no longer proposing new representational forms and debating their merits; rather, they are having a debate about the physics of motion. The nature of the likely or allowed moves is thus profoundly different.

Pathways

The second structural element of exploration zones is the pathway. A pathway is a transition that takes students from one pocket to another pocket. To exemplify pathways, let us recount in greater detail the Dots representation episode as it played out at City High School. In our prior discussion we noted that, early in the activity, the students became stuck in using Dots. Up to that point, no other pocket had been explored, and the exploratory moves were becoming repetitive. Then, the teacher made a crucial intervention. She began by asking students to represent the desert motion with their existing versions of Dots. The pool of representations resulting from this activity consisted mostly of drawings, with Dots placed over the trajectory of the car. Next, the teacher suggested that students erase the "unnecessary" features of the representations, such as the car, cactus, and road. By stripping off extraneous details from the representations, the teacher simplified the display, making it easier for students to recognize the unused vertical dimension in Dots.

Focusing on the resulting picture, shown in Figure 4, the teacher then queried students about whether the representation showed the duration of the stop at the cactus. Students recognized that it did not and, following the teacher's suggestion, they attempted to amend the representation. Eventually, students proposed adding a vertical row of dots to represent the duration of the stop, with each dot standing for a unit of time (Figure 9). Following this proposal, the space of inventiveness opened up and students began creating a variety of temporal sequences. The progression observed in the Dots episode indicates that there is a pathway leading from a certain class of drawings into the temporal sequences pocket.

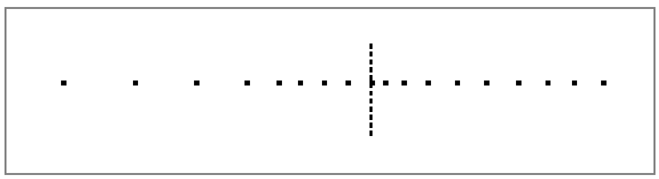

Figure 9. Using a vertical row of dots to show duration of a stop. City High School. Our rendition.

The teacher's intervention may have facilitated, in multiple ways, movement along this pathway. First, she highlighted common features of the existing pocket, helping students see elements of it as the same. Second, she highlighted features unused in the current pocket (the vertical dimension) that could be used in a new pocket. Third, she motivated the need for a new class of designs by eliciting a critique that would be difficult to accommodate inside the current pocket.

As a further example, consider Inventing Mapping activities. Our repeated observations of IM show that students readily create landscape drawings that are orthographic projections made from a top view. However, the production of quasi-topographic maps is more spotty. This suggests the need to find pedagogically accessible pathways between orthographic projections and topographic maps. Our observations suggest that such pathways exist. Suppose, that a class of students has failed to create any quasi-topographic maps. The teacher might explicitly guide the class by asking students to first draw orthographic renditions of a given landscape. Then, resorting to another idea with which students are fluent, the teacher might ask them to represent height information by "color coding" their representations.

Landmarks

Landmarks are specific contributions to an exploration that, for one reason or another, are particularly prominent to participants. For example, in a simple class discussion, a landmark can be a specific answer or argument proposed by one of the participants. In a representational design activity, a landmark can be a specific representational form and (possibly) some of the arguments surrounding its design rationale.

Landmarks may play important roles in organizing classroom activity. For instance, references to a landmark might have the effect of invoking the larger context of the pocket within which the landmark lies, effectively returning the exploration to that pocket. Additionally, invoking a landmark might bring to attention some conceptual issues that were investigated when the landmark/pocket was first considered. In the hands of teachers and students, then, landmarks might function pragmatically (i.e., by transferring an exploration back to a particular pocket) or conceptually (i.e., by highlighting particular key issues in the exploration). Teachers might productively think about the properties of landmarks—for example, their proximity to a pathway and/or their relations to important conceptual issues—and then use them instrumentally. A teacher has less control over how students use landmarks, although she might subtly encourage productive landmarks, and discourage those that have little productive function.

During enactments of the IG activity at Benson Middle School, the "Slants" representation (Figure 10) played the role of a landmark. Slants is a temporal sequence in which the slope of each line represents the speed of the object at a given moment. According to the convention established by Mitchell, the inventor of Slants, a horizontal line depicts "as fast as it (the car) can go," whereas a vertical line indicates the object is stopped.

Slants was often referenced, both by teacher and students, and these references seemed to have a range of felicitous effects. In some instances, invoking Slants worked to raise for consideration general issues concerning the task as a whole. For instance, on the second day of activities, Mitchell compared Slants to other representations in an attempt to decide which representation showed *all* aspects of the desert motion. The issue of completeness was thus linked to Slants and could, on other occasions, be invoked by considering if a representation was "like slants."

On another occasion, invoking Slants caused the initiation of an extremely productive line of exploration, essentially making movement along a new pathway possible. On the third day of activities, Mitchell suggested hooking slants end-to-end, as a means of representing continuous motion. Another student, Steve, then quickly proposed adding a grid to the resulting representation, essentially transforming it into a graph. A teacher, understanding the proximity of Slants to graphing and what final steps might accomplish the transition (in this case, introducing continuity to Slants), could nudge the exploration forward by invoking Slants. This could be accomplished immediately or further upstream, by reintroducing Slants or helping to solidify its landmark status.

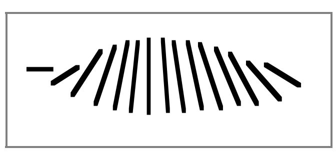

Figure 10. The "Slants" representation.

Landmarks can gain their prominence for many reasons. Although we cannot pinpoint the reasons why Slants functioned as a landmark at Benson, we conjecture that at least four factors were influential. First, Slants contrasted significantly with the existing representational forms when it was first introduced. Second, it made substantial contact with a number of issues that were central to many discussions, leading it to be considered on several occasions.[4] Teachers and

[4] Thus, in the best of circumstances, things become landmarks for the good reason that they embody many important issues.

students thus variously returned to Slants throughout the activity in order to make important points. Third, the Slants creator was outspoken and articulate. Although he sometimes argued in favor of other representations, he often acted as an advocate for Slants and other representational forms that were inspired by Slants. Finally, the fact that the representation was given a name by the class—"Slants"—likely helped to solidify it as a landmark. In fact, the teacher at Benson encouraged students to name invented representations that she deemed to be particularly novel or noteworthy, illustrating the strategic facilitation of the creation of landmarks by teachers.

A typology of pockets

Inspired partly by our data, and partly by observations of other activity types, we begin developing a typology of pockets. The first pocket of significance is the *pit*. Pits are pockets with "deep topography," which results in students being stuck in a narrow region of the exploration zone. For instance, the episode in which students at City High School could not create alternatives to Dots representations may illustrate a pit.

Pits can exist for various reasons, such as students' attraction to particular types of solutions, perceived authority, or the nature of the intellectual leap needed to escape the pit. As an example where perceived authority could have resulted in a pit, consider an episode that took place at the first IG session in one of our summer courses. On that occasion, soon after the teacher had proposed the desert motion task to the class, Tamara declared that "obviously, graphing is the best way to show it." The teacher deflected Tamara's assertion by stating: "I'm suspicious of single best answers." He then stated that although Cartesian graphs could well solve the problem, he wanted the class to explore more broadly, and briefly suggested that different representations work better or worse depending on context. The class took the teacher's suggestion and generated a variety of representational forms. But it is conceivable that students might have focused on Tamara's idea, particularly since it is known by students to be an officially sanctioned school representation. Had they focused quickly on graphing, they might have missed a lot of learning about the advantages of other representations, and a gradual appreciation of a diversity of criteria that are possible. Although we worried initially about this dangerous pit, our experience has been that graphing is seldom introduced early on. Even students quite familiar with graphing do not immediately associate it with the function of conveying information about motion.

The second significant type of pocket is the *plain*—pockets in which a large number of solutions are perceived to be equally good, and thus progress, in the form of the production of perceived-to-be improved representations, is hard to obtain. For example, the drawing pocket within IM may be plain-like. There are many ways to draw a landscape, each with its own merits. So choosing among them is likely to be difficult and would likely not provide grounds for a productive exploration.

The characteristics of pits and plains combine naturally. If a broad range of accessible representations are perceived to be equally good, and, in addition, there is some conceptual or other barrier to escaping the pocket, we have a *crater*.

The factors that shape the structure of an exploration zone

We understand exploration zones as emergent patterns in activity that arise from a complex conjunction of multiple influences, including individual, social, and environmental factors.

Building an account of how an exploration zone emerges from these factors is beyond the scope of the present chapter. In fact, the complexity of this problem is one of the motivations for introducing the notion of exploration zone in the first place. By introducing exploration zones, we have reified a level of consideration of emergent patterns in student-directed activities. This level of consideration, we believe, provides the basis for a useful and empirically tractable research program, while stopping short of a complete analysis of underlying influences. Here, we restrict ourselves to two brief points that pertain to the factors that shape the structure of an exploration zone.

Stability of exploration zones and the time-scale of classroom explorations. Implicit in our discussion thus far is the assumption that the topography of an exploration zone (i.e., the collection of pockets and pathways, and their characteristics) remains stable over time-scales that are characteristic of classroom explorations. Essentially, the metaphor we have adopted presumes a stable landscape over which the exploration proceeds. Thus, we have been implicitly assuming that the factors that are shaping an exploration zone, especially student knowledge, remain largely stable over the course of classroom events. However, the structure of an exploration zone might well change during an exploration, particularly as students acquire new knowledge.

Cases in which one factor is particularly important in shaping an exploration zone. Note that the enactment of the IG activities requires no special-purpose props beyond pencil and paper. The exploration zone of IG is thus not primarily defined by physical resources that are particular to these activities. Instead, most of the defining resources for IG are embodied within the participants, particularly the students. Once the teacher has given the simple specification of the task, students propose and discuss alternatives with only some simple guidance from the teacher. Indeed, we have essentially been arguing that the structure of the IG exploration zone can be identified with families of representational forms and that these, in turn, substantially mirror the representational capacities that students bring to the task. For example, all of the (speculative) features we identified for the existence of pockets—common perceived features, shared form, and relatedness via familiar rhetorical strategies—are all purely conceptual.

This conceptual basis for the structure of IG's exploration zone is highlighted if we contrast IG with a quite different set of curricular activities. A curriculum called "Struggle for Survival" has been developed by researchers at Northwestern University in collaboration with Chicago Public Schools (Reiser et al., 2001). In this curriculum, students investigate why, on one of the Galapagos Islands, the population of finches declined sharply during the late 1970s. To support this investigation, students are given a specially designed computer database and tools for exploring this database. The database contains a variety of kinds of information. It includes field notes made by fictional biologists. Students can browse these field notes and read about observations of individual finches. The database also includes quantitative data concerning environmental conditions during the years in question (e.g., rainfall), as well as data concerning characteristics of the finches (e.g., wing length and beak length). For the data concerning finches, the software allows the students to produce a number of kinds of data plots, which they can use to form and support their hypotheses. All of this work is supported by a set of curricular activities that include tasks both on and off the computer.

The factors that give the exploration zone its structure are very different in Struggle for Survival compared to IG. In IG, the exploration zone is generated largely by what students know about representations and does not depend on supporting materials. In contrast, the exploration in Struggle for Survival would be impossible without the computer database, and the exploration zone takes its structure, in large measure, from this database. In a sense, the exploration in Struggle for Survival is *over* the data and the queries permitted in the database, rather than over a space defined mainly by ideas available to students. For example, the software has data concerning the beak length and wing length of individual finches. The students can thus entertain hypotheses such as "the finches with large wings were more likely to survive."

This contrast suggests a possible simplification in our attempts to understand how an exploration zone is shaped by various factors. Although an exploration zone will always emerge from a complex conjunction of factors, there may be some interesting prototypical cases we can think about in which we can understand the exploration zone as principally defined by one type of factor. For example, IG may be an example of a *brainstorming* exploration, a prototypical type of exploration in which the exploration zone is principally defined by the ideas of student participants. And Struggle for Survival may be an example of another prototypical type, a *data-based* exploration, in which the exploration is over a collection of data or other reference materials provided for students. Understanding such prototypical types may be a more manageable task than attempting a full description of how different factors contribute to the topography of an exploration zone.

Describing and guiding movement through an exploration zone

As designers of learning environments interested in helping students to acquire scientific and mathematical competence, it is not enough that we understand the space of possibilities that students can explore. We have an agenda; we usually want students to move through an exploration zone in a specific direction or, at least, to have them visit certain locations. This requires an understanding of trajectories through an exploration zone and how to guide students along those trajectories.

In discussing the structure of exploration zones above, we have done much of the preliminary work necessary to understand trajectories; a trajectory can be thought of as movement through an exploration zone, within pockets and from pocket-to-pocket along pathways. The movement within pockets occurs because of the natural chaining of moves that results from the mutual activation and reinforcement of ideas, arguments, and products within a pocket. By definition, then, movement within a pocket is relatively easy to accomplish.

In contrast, movement between pockets can be difficult and may require intervention by the instructor. We have partially addressed this point in our discussion of pathways above. In this section, we want to expand on that discussion to consider the instructional techniques that guide students along various trajectories, including interventions that facilitate transitions across pockets and those that are used as a means to organize the activity as a whole.

As a starting point, it is important to note that trajectories through a given exploration zone will certainly differ across enactments of an activity. For example, in the enactments of IG at Benson Middle School and City High School students began the exploration within the drawing pocket. City High students got stuck there, whereas Benson Middle students did not. With the progression of the activity, both Benson's and City's students eventually explored drawings, temporal sequences, and graphing pockets. In Trenton High's trials of IG, we witnessed explorations of drawing and temporal sequences pockets right from the beginning, with the graph-like pocket appearing later.

In spite of the differences in the activity dynamics that will always exist across trials of an activity, it is sometimes helpful to speak in terms of *canonical trajectories* that are followed through an exploration zone. For example, in the case of IG, there is a canonical trajectory from drawing to temporal sequences to graph-like representations. Likewise, in IM there is a canonical trajectory from drawings to quasi-topographic maps.

Identifying one or more canonical trajectories can help teachers to understand and guide exploration in their classrooms. Moving students along a canonical trajectory can be an explicit initial goal for a teacher, and perhaps one that is most achievable by a novice teacher unfamiliar with details of the exploration zone. Still, reacting to unforeseen contingencies along the canonical trajectory may require high-level expertise of the sort only more expert teachers—who would be more prone to improvise rather than try to force a canonical trajectory—would possess.

Once a canonical trajectory is identified, we can collect instructional techniques that can guide students along this trajectory and that help ameliorate exploratory difficulties. Here we list a few categories of instructional techniques, illustrated with examples from our experiences with IG and IM.

Socratic questioning

One technique for moving students through an exploration zone is an old stand-by, Socratic dialogue. Socratic dialogue helps students progress by asking them questions and posing challenges. In the IG activity this questioning takes a particular form: students are presented with a sequence of motions to represent that are devised to test their current representational techniques. For instance, after students create their first representations of the desert motion, the class is asked to represent a motion with an extended stop. Students are thus faced with the task of adjusting some of the conventions deployed in their original representations. Students are then asked to represent a motion with stops of different time lengths, followed by one in which an object reverses its direction.

Sequences such as the one just mentioned do double duty. First, they foster extended exploration within already-discovered pockets because many of the proposed motions can be realized (more or less successfully) within the pockets we have identified. Conceptually, fostering exploration of individual pockets is important because it allows students to investigate the limits and strengths of particular classes of representational forms. Second, towards the end of the sequence of motion problems, one finds more complicated motion patterns that pose difficulties that eventually force students to consider alternative representational schemes. In other words, the sequence of problems may motivate a spontaneous transition to other pockets.[5]

It is worth mentioning that within a student-directed perspective, Socratic questioning and other intervention strategies are intended mainly to move students from pocket to pocket, rather than to get them to produce some particular answer or insight, as might be the case in other contexts.

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[5] In addition, introducing challenges can obviously "unflatten" plains and craters by shaping and sharpening the evaluation criteria that distinguish proposed representations.

Locating, consolidating, reifying

When an exploration is long and complex, the participants in the exploration need techniques for keeping track of the territory that has been explored and for consolidating gains that have been made. In the context of IG, we have identified a number of techniques that have proved effective. For example, after several rounds of design have been carried out, the existing set of representations may be quite large. At this point, it is sometimes productive to engage students in a whole-class effort to sort representations according to some community-established criteria. As previously stated, this exercise may be used to narrow the working pool of representations and to focus students' attention on particular attributes of classes of representational forms.

A related pedagogical strategy is to involve students in collectively naming individual representations and, depending on the teacher's goals and style, this exercise may follow the sorting task. Naming representations facilitates future references to representational forms, and it gives students a sense of ownership over the products they generate (Madanes, 1997). As discussed above, naming individual representations may function as a strategy for establishing landmarks.

Transforming

In some cases, it might not be enough to ask questions and consolidate gains. One additional possible class of instructional techniques involves the transformation of pocket-specific ideas into products that belong to a new (target) pocket. For example, using the Sonar representation (Figure 11.1) as a departing point, one may draw envelopes over each part of the temporal sequence to suggest plots akin to those found in graphs (Figure 11.2).

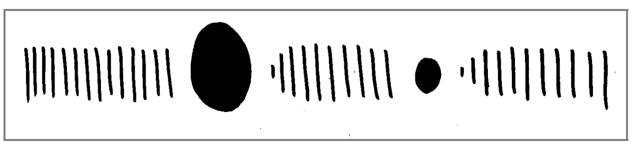

Figure 11.1. Sonar representation, as drawn by students at Trenton.

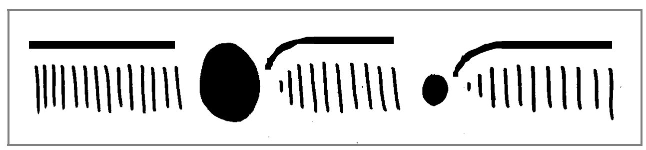

Figure 11.2. Sonar representation with an envelope added.

Similarly, in the Dots episode discussed earlier we saw that erasing features of a representation simplified the display so that students could more easily attend to unused dimensions of the paper. More generally, erasing features of a representation may suggest representational approaches that motivate exploration of a new pocket. As an example, consider annotated drawings—drawings with diverse elements added to suggest specific motion information—such as the one in Figure 12. In the figure, Adam has represented the moving object as a small circle and marks that stand for the object's speed emanate from the object's rear. In Adam's scheme, the greater the speed of the object, the more marks appear behind it. Now if we erase the object and the road (the single line at the bottom of the representation), we are left with the essential elements of a temporal sequence; an array of discrete representational elements (i.e., the marks), each conveying a particular piece of the motion story, which should be read from left to right. It is even possible that students could pick up "erasing extraneous elements" as a common spontaneous move. Doing so would establish a new line of affinity among moves, altering the structure of the exploration zone.

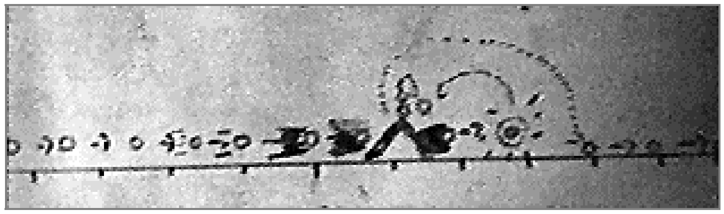

Figure 12. Adam's representation of a motion that includes a reversal in direction. City, Session 1. From video capture.

What makes an exploration zone engaging?

Student engagement has received increasing attention in the literature (e.g., Hidi & Harackiewicz, 2000; Lepper & Cordova, 1992; Marks, 2000; Newmann, 1992). These researchers generally propose models of engagement based on factors such as students' intrinsic motivation toward academic achievement and students' interest in particular topics. Thus, for example, students interested in science tend to engage in science-related subjects for longer periods of time and to persist in the face of complex problems. Similarly, academically oriented students are more likely to engage and participate in classroom activities.

Our approach here departs from this usual treatment of engagement in the sense that we are concerned with describing how structural features of an exploration zone—its configuration of pockets and pathways—might heighten the opportunities for student participation and engagement. Hence, the assumption underlying our arguments is that the structure of the exploration zone is largely orthogonal to variables such as students' interests and motivation. With that in mind, let us consider how activities differentially engage students by drawing upon a comparison between the two representational design activities we reviewed above.

As stated previously, our experiences with Inventing Graphing convinced us that the activity is generally very successful in engaging students. Our perceptions of student participation are that they feel strongly engaged and committed to the ideas being generated. At each design round, students demonstrate a strong ability to refine their previous designs, to appropriate ideas proposed by others, and to create new products. In addition, students actively engage in the classroom discussions, generating a number of comments and design criteria that are then used to feed overall design improvements.

In contrast, Inventing Mapping has proved to be a less engaging activity. In their initial attempts to represent a given landscape, students promptly create a number of drawings and quasi-topographic maps of the landscape. But the discussions that follow this initial round of designs have tended to be terse and uninspired. Subsequent rounds of design present a similar picture; brief, slow-paced discussions and few or no class-generated design innovations. Overall, our perception is that in IM students do not feel very engaged or committed to the ideas they put forth. The exception to these dynamics occurs when the theme of using colors as representational devices in quasi-topographic maps arises. This theme elicits increased response from students, both in terms of the number of products and in terms of the quality and quantity of comments on each other's designs.

An hypothesis

In terms of our framework, then, how can we explain this noticeable difference in engagement fostered by IG and IM activities? In an initial formulation of our hypothesis, we follow Csikszentmihalyi (1988). Like us, Csikszentmihalyi has been concerned with identifying the structural features that make for engaging activity, although his emphasis has been on individual activity, rather than group design. In particular, he proposes that more clearly structured activities are best suited to sustaining extended engagement (Csikszentmihalyi, 1988, pp. 30). Among the many properties he lists for clearly structured activities, three are particularly relevant for our purposes here: (1) Opportunities for self-expression must be abundant, yet (2) such opportunities must be constrained by a relatively clear set of rules for action, and (3) individuals must be able easily to assess their progress in achieving the activity's goals. An engaging exploration zone thus maintains a balance between clear structure and room for self-expression. To use one of Csikszentmihalyi's examples, a game of chess offers good grounds for extended engagement because play variations are nearly infinite. Yet, action in the domain of chess playing is guided by rules that constrain moving options at each point. Furthermore, many moves are clearly improvements in positioning, or, after an opponent's response, can easily be evaluated as failed attempts at improvement.

The hypothesis applied to IM and IG

We can now look at our analysis of IM and IG in terms of our framework, and we can see where and how the balance between creativity and constraint is maintained in the two activities. As a first analysis, we look at the major pockets in each activity. We saw in our analysis that IG has three major pockets and IM has two major pockets. Crudely speaking, two pockets may simply not provide enough room for exploration to make for an engaging activity.[6]

We can also apply Csikszentmihalyi's hypothesis to the within-pocket structure of the exploration zones of IG and IM. In IG we find extended class activity in the temporal sequences pocket, more so than in the other two pockets in that zone. Recall that temporal sequences are linear arrays of elements strung together, each conveying a piece of the story being told. In practice, this specification constitutes a template that loosely defines what needs to be done at each round of IG design. The temporal sequences template thus can be seen as providing a clear structure for action (property 2), productively constraining possible design solutions. At the same time, such a template allows for enormous personal expression because so many of its parameters can be tweaked (property 1). The tweaking of elements in temporal sequences can be more or less significant, and we have observed a very wide range of inventiveness in students' works (from idiosyncratic signs to "vectors"). Importantly, because these elements can be systematically varied and compared to previous solutions, the crafting of temporal sequences allows students to gauge their progress and to decide on future design improvements (property 3).[7]

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[6] Our considerations in this section should not be taken as dismissing the potential of IM activities. Rather, our arguments point to the fact that, in practice—with the insights we currently have and the interventions we have considered—IM activities profitably sustain engagement systematically for a shorter period of time relative to IG.

[7] For example, some students complained that certain temporal sequences contained too many kinds of signs, which were unrelated to each other. These establish goals for improved design.

No other pocket in the IG exploration zone seems to us to do so well with the conditions listed above as the temporal sequences pocket. For example, the drawings pocket allows for a lot of individual self-expression (property 1). On the other hand, drawing conventions are so plastic that almost anything goes. To use our terminology, this pocket is too much of a *plain*, as we discussed earlier. This makes it hard for students to assess progress and to choose relevant aspects for design refinement. In fact, students appear less able to comment on the limits and strengths of drawing representations, an observation that may reflect the lack of clear parameters for judging such representations (property 3).

The graph-like depictions pocket also suffers from problems when measured against our criteria. To be sure, there are clear rules governing the making of graphs (property 2). But because such rules are strict, the possibilities for self-expression are reduced in relation to those offered by the temporal sequences pocket (property 1).[8]

Finally, we can apply the same reasoning to explain the lower levels of student engagement observed in IM. As in IG, the drawing pocket in IM offers a much too broad space of possibilities and makes it hard for students to evaluate progress (properties 2 and 3). Quasi-topographic maps offer a relatively clear set of rules for action, but these rules allow for very little variation and creative expression (property 1). The theme of using colors as representational devices overlays onto quasi-topographic maps the possibility for individual expression, while keeping the structured rules for the making of quasi-topographic maps. This may explain why activity within that theme elicits heightened engagement from students. Still, students seem to exhaust the possibilities for creating coloring schemes relatively quickly.

Pathways and engagement

Our considerations of the engaging nature of exploration zones thus far have revolved exclusively around the number and character of pockets. Pathways, however, also play an important part in sustaining engagement. If there are too few pathways, or the pathways are too difficult to traverse, then some pockets may remain largely unexplored (effectively decreasing the amount of room for exploration). For example, in demonstrating pathways between temporal sequences and graph-like depictions, we listed three pathways, some of which have appeared in more than one edition of the activity. This fact, once again, helps us to understand why IG is so engaging.

Variations in engagement during an activity

Regardless of the structure of an exploration zone, student engagement is almost never constantly high. Even in activities that are generally highly engaging, such as Inventing Graphing, engagement fluctuates, increasing or decreasing depending on the nature of classroom events. Certain conditions are notably detrimental to engagement. For example, when students find themselves inside a pit, engagement suffers a marked drop. The Dots representations episode at City High School empirically illustrates this point, and it is also in accordance with Csikszentmihalyi's (1988, pp. 32) observation that engagement suffers when one has difficulty making progress.

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[8] As an added problem, students are not fluent with graphing, which drives them away from strong engagement with graphs, at least initially.

Incidentally, the observation that overall difficulties reduce engagement levels leads us to postulate that engaging exploration zones must have one or more pockets within easy initial reach. In practical terms, this means that students can get to work rather quickly. To understand this idea, it helps to consider its opposite: an activity that makes it hard for students to get started is equivalent to putting students in a pit right from the start. Empirically, we have observed that IM and IG are equally engaging in their initial moments because, in both activities, there is at least one pocket that is immediately within reach. Difficulties may systematically be less of a problem later in explorations. Students may develop a strong commitment to succeeding (or improving), and may have faith, borne of prior success, that they can succeed.

Conclusion

Review

The goal of this paper has been to propose a way to think about the nature of open-ended, student-directed activities. This way of thinking should synthesize and explain (at some level) regularities in the conduct of such activities, such as repeated patterns we perceive when "running an activity again" (e.g., with different students). We are not focusing on conceptual development or learning, per se, but on things like engagement, the flow of ideas, and interventions teachers make to move the activity along, or change its direction, without wresting control from students. In our case, we use group design of representations as an inspiration and testing ground for these ideas.

Our analysis is based on a systematic use of a spatial metaphor, of students being *at a particular place* at a given time, and *moving around in a landscape* of known properties. One of the principle regularities we observe is that certain moves (proposals for design, comments, criticisms, etc.) seem to come in clumps. This gives rise to the concept of a *pocket*, a collection of "places" that allow relatively easy movement among them. Pockets come in different forms, which have systematically different properties. *Pits* are narrow pockets that are difficult to escape. Generally, one wants to avoid pits, or to design ways to escape them. *Plains* are relatively rich pockets, yet which do not allow significant differentiation among places. Plains may be as boring as pits.

Pathways are viable transitions between pockets. Knowing about pathways and ways to scaffold their associated transitions can be highly strategic in a teacher's promotion of an active, effective exploration. We described several fairly general strategies for facilitating transitions across pathways. *Landmarks* are particularly interesting and memorable "points" in an exploration zone. Like pathways, teachers and students can use existing landmarks (or foster the development of new, useful landmarks) for many purposes.

We discussed features of exploration zones that promote active engagement. One needs good starter pockets, and a sufficient number of pockets to keep the exploration going. In addition, we found that our framework and observations mesh well with some of Csikszentmihalyi's (1988) ideas, in particular, in our observation of the need for (1) room for expressive diversity, (2) constraints on possible moves, and (3) the possibility of effective judgment.

Limits of the spatial metaphor

We are under no illusion that the level of consideration contemplated in exploration zone analysis will prove to be complete. The complex dynamics and many influential parameters underlying engagement in activities will eventually surface in scientific study, in one way or anther. Here, we mention two loci in which we expect difficulties to surface.

The spatial metaphor presumes a collection of "places," and a sense of "nearby." Implicitly one should be able to visit the same places on multiple occasions. In contrast, "going back to identical places" in an activity is at least implausible, if not impossible. For example, once students have thought about other things, the context for a revisited thought will be different, and "being back there" will have different consequences. Furthermore, if a student tries literally to make the same move again, its repetition will be interpreted as a message, making the repeated move distinct from its original. So, ironically, the spatial metaphor may work best when one does not attempt to return to the same place, but only to nearby places.

"Nearby," of course, is subject to the same contextual variation. Having learned and experienced other things, returning to the vicinity of a certain place may find different moves selected as "easy to make." Thus, "nearby" will be different the second time.

Moving to our second locus of difficulty, the spatial metaphor works well in part because we have vivid imaginations and descriptive capabilities for the three-dimensional landscapes that populate our physical world. In principle, even if the spatial metaphor were perfect, we have no reason to believe engagement dynamics can be adequately described in only two or three dimensions. If it takes many dimensions to capture regularities in activities, then as a practical matter we may need other metaphors to help us think about these regularities.

Future Work

What do we take to be the most profitable and interesting future developments in a theory of exploration zones? First, we need to be more articulate about our methodology. What are the criteria by which one determines whether one or another analysis of the structure of an exploration zone is better or more accurate? Our exposition here has been suggestive, but how would we fend off truly competing analyses? Along similar lines, at what grain size should we describe pockets and pathways?

One way to operationalize good or bad exploration zone analyses might be to ask whether our analyses help teachers conduct effective, engaging explorations. However, we must be careful to recognize that science and practical help do not necessarily align. Still, it will probably be productive for us to see this enterprise as, in part, guided by a desire to give relatively practical help to teachers.

Theoretically, we would like to be clearer on what elements of what is happening in an activity at a particular time define its "place," and how they do so. So far, we have been somewhat vague and inclusive, taking essentially any "move" (proposal, comment, critique, etc.) as an element whose properties define (by principles about which we have been fairly mute) "where we are." In this vein, it is very likely that the perceptions of participants are critical to the definition of places and pockets. For example, ideas that are perceived as different will provoke surprise and the energy of novelty, even if they are not objectively very different from what has come before.

A major issue is the relation of exploration zones to a more fine-grained theory of activities. We broached this transition in several places. For example, we suggested that (1) ideas that involve similar descriptive terms, (2) ideas that fit into a common framework (such as all temporal sequences) and (3) ideas that follow regular rhetorical patterns (like justifications and explanations) frequently go together, thus helping to define pockets. Of course, one could try to remain at a purely empirical level, using, for example, statistical correlations of kinds of happenings across editions of an activity. But speculations about underlying mechanisms are at least heuristically helpful in identifying pockets. The danger, as we mentioned early on, is that a careful and accountable consideration of the dynamics of activities might blow apart the spatial metaphor and the tractable simplicity of an exploration zone analysis, and throw us into an arena that we are, as yet, not ready to pursue responsibly.

To what extent do exploration zone analyses cover different kinds of activities? Our main examples have been about design, which has different properties compared to other activities, like scientific investigation, or purely artistic activities. We have no reason to be deeply suspicious that the framework will fail in other arenas, and yet, creativity and "design proposals" play such a central role in design and in our analyses of example exploration zones that their ubiquity begs the display of equivalent features in different activities. Quite possibly this could turn into a cogent argument about the ways in which design and scientific activity are closely related.[9]

Finally, we believe our treatment of interest and engagement is still relatively crude. It bears a lot of empirical and analytical scrutiny. This we feel reflects the state of the art in the study of these features of activity, rather than a particular lack of exploration zone theory.

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[9] In this regard, consider the arguments about the relation of design to learning science in diSessa (1992).

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