ABSTRACT

Title of Dissertation	A Study Of Social Interaction And Teamwork In Reformed Physics Laboratories
	Paul Gresser, Doctor of Philosophy, 2005
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It is widely accepted that, for many students, learning can be accomplished most effectively through social interaction with peers, and there have been many successes in using the group environment to improve learning in a variety of classroom settings. What is not well understood, however, are the dynamics of student groups, specifically how the students collectively apprehend the subject matter and share the mental workload.

This research examines recent developments of theoretical tools for describing the cognitive states of individual students: associational patterns such as epistemic games and cultural structures such as epistemological framing. Observing small group interaction in authentic classroom situations (labs, tutorials, problem solving) suggests that these tools could be effective in describing these interactions.

Though conventional wisdom tells us that groups may succeed where individuals fail, there are many reasons why group work may also run into difficulties, such as a lack or imbalance of knowledge, an inappropriate mix of learning styles, or a destructive power arrangement. This research explores whether or not inconsistent epistemological framing among group members can also be a cause of group failure. Case studies of group interaction in the laboratory reveal evidence of successful groups employing common framing, and unsuccessful groups failing from lack of a shared frame.

This study was conducted in a large introductory algebra-based physics course at the University of Maryland, College Park, in a laboratory designed specifically to foster increased student interaction and cooperation. Videotape studies of this environment reveal that productive lab groups coordinate their efforts through a number of locally coherent knowledge-building activities, which are described through the framework of epistemic games. The existence of these epistemic games makes it possible for many students to participate in cognitive activities without a complete shared understanding of the specific activity's goal. Also examined is the role that social interaction plays in initiating, negotiating, and carrying out these epistemic games. This behavior is illustrated through the model of distributed cognition.

An attempt is made to analyze this group activity using Tuckman's stage model, which is a prominent description of group development within educational psychology. However, the shortcomings of this model in dealing with specific cognitive tasks lead us to seek another explanation. The model used in this research seeks to expand existing cognitive tools into the realm of social interaction. In doing so, we can see that successful groups approach tasks in the lab by negotiating a shared frame of understanding. Using the findings from these case studies, recommendations are made concerning the teaching of introductory physics laboratory courses.

A STUDY OF SOCIAL INTERACTION AND TEAMWORK IN REFORMED PHYSICS LABORATORIES

By

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Dedication

For the late Paul Henry Gresser.

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Chapter 1: What Are the Students Doing?

None of us is as smart as all of us.

Ken Blanchard

None of us is as dumb as all of us.

Anonymous laboratory graffiti

Introduction

Recently I attended a piano recital that featured an exciting rendition of the William Tell Overture, played by a quartet of fourteen year-old children. There were two pianos set up side-by-side, with two children to a piano. I had never seen such an arrangement, and was surprised by both the richness of sound resulting from eight hands playing the keys in unison and by the tight coordination between the pianists. Their eyes darted rapidly from the sheet music to the keyboard to their teammates' hands and faces and back again. Subtle signals were exchanged. I was fascinated by the complexity of this arrangement. There was no conductor for this quartet, just a shared sense of purpose and a coordination of action so tight that it made more sense to speak of how "the group" had played, rather than how each individual pianist had played.

After the performance, I spoke with the teacher of these performers. The coordination was impressive, I told her, but why go through all the trouble to train them to play in such a configuration, if they were unlikely to need that kind of skill? After all, there are no serious piano quartets. She replied that, in addition to the interesting musical effect, the piano quartet had a pedagogical purpose. Playing the piano cooperatively with a group of peers forces one to pay attention to one's own rhythm in a way that would not happen by playing alone.

Music instruction is just one of many disciplines that has begun to utilize cooperative learning. Students are now working in peer groups in every level of schooling. It has become almost conventional wisdom that students have the potential to learn a great deal through social interactions with their peers, perhaps even more efficiently than they would in traditional lecture environments. We know that peer interaction helps in the classroom. It behooves us now to attempt to understand *why* this is so, and to do this we must develop tools that allow us to explicate and discuss *what students are doing* when they work in groups and how it relates to their individual processes of thinking and learning. Many researchers are doing precisely this.

Group work in introductory physics laboratories

The introductory physics laboratory is a classic example of an environment in which students are expected to learn through a cooperative activity. They are given a task that is normally too complicated and time-consuming to be accomplished by students working individually. Students seem quite capable of establishing a division of physical labor necessary to accomplish a task in the time allotted. On the other hand, it is rare to see genuine cooperation in *cognitive* labor. All too frequently we see lab groups in which one dominant personality takes charge of all the important processes, such as planning an approach to the problem or evaluating a procedure, while others are perfectly content to retrieve materials, read gauges, and perform other tasks which, though essential to the experiment itself, do very little in assisting the participants in learning the essential cognitive tasks of experimentation. In such an arrangement, group-work can actually be detrimental to student learning, since students can be constantly involved in the activity and yet not understand how this division of labor fits into the general experimental plan. In this study we are primarily interested in finding and analyzing cases when students interact intellectually and productively in achieving a cognitive goal.

Reformed Laboratories as a Data Set

This dissertation was carried out as part of a project conducted by the Physics Education Research Group at the University of Maryland, College Park, to reform an introductory algebra-based physics course for biology and pre-med majors. As part of this project, the laboratory portion of the class was radically redesigned with a new environment, set of activities, and goals. As a result of the changes made, we observed a considerable increase in productive student interaction. Rather than engaging in mainly logistical discussions on how to divide up the physical labor (Lippmann, 2003), the students were frequently engaged in meaningful discussions about physics. Cognitive activities that were previously accomplished non-verbally by the group's leader (or not engaged in at all) were now being accomplished by several students through complex discussions and sometimes heated arguments.

These laboratory sections provide an excellent source of information on how students coordinate their efforts when confronted with a task that requires cooperative thinking. We will examine these groups in action via transcriptions of videotapes taken during normal lab time. By doing this, we see what is it students actually *do* during group-work, when not guided by detailed instructions on what to do. This is our glimpse into the natural cooperation of students, rather than cooperation of the type that can be forced upon them.

Research Objectives

In this work, I attempt to answer the following questions:

- How might one describe the moment-to-moment activity of a small group of students and their shared interpretation of this activity?
- How does a group go about negotiating this shared interpretation?
- What sorts of shared interpretation lead to productive group work, and what sorts hinder it?

Before one can answer these questions, it must be decided what we mean by "the students." Shall we regard them as individuals and answer this question separately for each student, or regard the group as a single entity and speak about what the "group" is doing? Shall we take an individualist perspective, or a social perspective? I intend to do both.

Clearly there is merit to taking this dualist view of group activity. Consider how one would answer the question, "What are the musicians doing?" in reference to our piano quartet. On one hand, we can describe a single pianist's hand movements across the keyboard. On the other hand, we might also want to describe the group's coordinated actions as if it were a single entity, as in, "the group fell out of sync." Both descriptions shed light on what is happening. In order to accurately and meaningfully describe what "the students" are doing in lab, it may sometimes be necessary to discuss what the individuals are doing, but sometimes it may be more helpful to treat them as a single unit.

Using this dualist approach, I extend existing theoretical approaches, such as epistemological framing and epistemic games, to describe what the students are doing, both individually and as a group. I also explore how individual action *guides* the behavior of the group (if and when the group is acting as a unit). Once we have a vocabulary with which to describe student action, it can be ascertained what kinds of behavior are productive and which are not.

It should be noted that I seek first and foremost a *descriptive* view of group activity, rather than a *normative* view. Much attention in education research has been given to how students *should* behave in the classroom, rather than how they *actually* behave. It is not my goal in this paper to propose an optimal method for groups to work in problem-solving, but rather to identify what methods *are* used. Therefore, we will need to understand what sorts of team knowledge-building techniques students bring into the classroom before assessing how they should put these skills to work. Then, as we learn to describe the variety of behaviors students engage in, we can begin to think about how to facilitate student learning in lab.

An Example of Group-Work

Let us examine a short excerpt from one of these labs. The purpose of this lab activity is to determine how the force between two magnets depends on the distance between them. This transcript is from the first few minutes of the laboratory period.[1]

BELINDA: We can measure the area of the magnet.
DORIA: But how do we measure...
BELINDA: Pressure...
ANGIE: But it's not... pressure times area...
CONSUELA: It's magnetic force...
BELINDA: Oh yeah, it's E Q.
DORIA: No, but that's electric. Force of a magnet is just F equals Q V B sine theta. There's no distance in it.
BELINDA: Where are you coming up with that?
DORIA: It's in the book. And it's in... haven't you learned it for MCATs yet?
BELINDA: No.
DORIA: Really?
BELINDA: Really.
DORIA: That's the hardest stuff.
CONSUELA: Oh gosh.
BELINDA: Hey when do you get your scores back?
CONSUELA: I know, that's what you guys just said, and I was like oh yeah...
BELINDA: All right so F equals Q V B sine theta. What is this? Equal to M V squared over R. What's your R? Your radius?
DORIA: That's like the... because... well you see… not

[1] All names in the transcripts reported in this thesis are gender indicative pseudonyms.

between two magnets. That's like... magnetic field caused by centripetal...
BELINDA: What is... what is B?
DORIA: B is the field strength of the magnet.
BELINDA: But how are we going to measure any of that?
DORIA: Yeah, I know. So I don't know how it depends on distance.

What is this group doing? Is there an understood purpose to this activity, or are they just blindly brainstorming equations? Are they working towards a specific goal, or are they just muddling through, expecting something to become obvious later? Do the students share an understanding of a specific strategy that is being implemented here, or perhaps does one student have this understanding while the rest of the students are just playing along? To what extent do these students agree on what they are doing? If you asked this group what they are doing, how are they likely to respond?

I argue that this group is engaged in a highly coherent activity, one which includes a specific goal and, a set of appropriate (and inappropriate) moves, and a shared understanding among most of the group members of how the activity is to be played out. This type of activity is known as an *epistemic game,* and can be immensely helpful for students in progressing through laboratory activity as a way of apprehending the situation and aligning their behavior accordingly. It allows a group of students to recognize the *kind* of activity that is being proposed, if not the minute details of that particular instance of the activity. Through epistemic games, we see the emergence of group activity that utilizes the network of individual minds in a unique and productive manner. Also, because these games are ubiquitous and identifiable, they provide a powerful tool for a lab instructor to diagnose what a group is doing, what their goal is, and even how they are interpreting the activity itself.

Research Claims

As we examine students engaged in these laboratory activities, we will operate under the basic assumption that student action is nearly always *purposeful* rather than random, and that it may even be possible for a group of students to share at least part of this sense of purpose. By assuming the existence of intention, we can identify patterns in student behavior based on what this intention might be. In this dissertation, I demonstrate the following points:

1. Use of the vocabulary of epistemic games and epistemological framing makes it possible to identify common patterns of behavior in these reformed laboratories.

2. A small number of regularly appearing strategies can be classified by explicitly stated motives and those inferred through characteristic statements. They can also help identify what the groups are not doing that might be useful.

3. A group might come to share an understanding of these strategies, and therefore work towards a common goal, through appropriate social interaction.

4. Groups that make use of these shared strategies operate more productively than those that do not.

By identifying and understanding the nature of these strategies, we can have a better understanding what the students are really doing in the laboratory.

Overview of Dissertation

Chapter 2 provides an overview of the chief research disciplines that concern the dynamics of group-work. It describes relevant works from cognitive science, sociology, education research, and social psychology that have inspired my particular take on group interaction in the laboratory. Here I present research that explores human activity both from the perspective of individual cognition and from the perspective of social interaction, as well as research that attempts to join the two disciplines.

Chapter 3 describes the laboratory course in which this study took place. These labs were specifically designed to be dramatically different from the so-called "traditional labs" that physics students traditionally take. These labs are sources of rich and complicated social interaction, which makes for a rich and interesting data set.

In Chapter 4, the concept of epistemic games is explored. We see several examples of students engaged in coherent, purposeful activities that last typically for a few minutes per instance. Epistemic games will be our unit of analysis for further considerations.

Chapter 5 deals with epistemic games as social activities. *Distributed cognition* will be introduced as a point-of-view from which we can regard epistemic games as a distinctly social manifestation of a cognitive activity.

In Chapter 6 we observe in detail two groups of students engaged in the same activity. One group successfully aligns their behavior and engages in shared epistemic games, leading to productive activity and meaningful discussion, while the other group fails to connect in this way, and therefore flounders, incapable of operating as more than the sum of its parts.

Chapter 7 consists of advice on how one can, as an instructor, use the framework of epistemic games and distributed cognition to understand the behavior of laboratory groups and foster more productive teamwork.

Chapter 2: Literature Review

Introduction

In this dissertation, I focus on groups of individuals in the introductory physics laboratory, where activities typically require a sophisticated level of cooperation among the group members in carrying out cognitive tasks and linking them together. But to understand group work, we need to consider many different disciplinary angles of approach. Group work is a phenomenon that exists through the interaction between individual cognition, group behavior, and cultural influences and artifacts. This section provides an overview of the previous research that is relevant for the approach I set forth.

First I discuss the working model of the mind, which has been explored by cognitive scientists in various fields. Then I will discuss some of the schools of thought concerned with the social aspect of learning, known collectively as the *socio-cultural approach.* Next, I give an overview of research in "framing," which can be used to describe how people interpret and find meaning in the events they experience. Finally I outline some of the empirical studies on group behavior that are particularly relevant to this study because of their focus on learning environments.

Each of these disciplines has something to offer in the exploration of student interaction, from the small-scale point of view of individual human action to the observation of large-scale emergent phenomena in the social setting. Though some researchers choose to focus on either individual phenomena or social phenomena, for this study, pieces from both will be necessary to understand what groups of students are doing in the lab.

The Cognitive Model

In studying groups, it is helpful to consider emergent phenomena. We often speak of "the roar of the crowd", "the spirit of the nation", or "the team's persistence" as if groups of individuals had qualities normally attributed to individuals. But the metaphorical nature of these anthropomorphisms is understood. At the end of the day, group behavior can in theory be traced back to the workings of the human mind. For a half a century, scientists from a number of fields have come together in an attempt to describe the workings of the mind through complex representations and computational procedures. This field is known as cognitive science.

Cognition as a science

The term "cognitive" describes "any kind of mental operation or structure that can be studied in precise terms." (Lakoff & Johnson, 1999) Cognitive science, therefore, is considered the scientific study of thought, as compared to other sorts of inquiry into the subject. This is a relatively new field, blossoming in the 1950's with the decline of behaviorism as the prominent approach to studying human behavior. Behaviorism was an approach to psychology based on the idea that only observable actions of individuals were legitimate variables to consider when constructing a model of human behavior. Cognitive science takes another route. Recognizing that we are a long ways away from being able to directly link our thoughts to specific neural pathways in the brain, cognitive science seeks to build mesoscopic models of thought that is based on what is known about the physiology of the nervous system, yet is large enough to explain the complicated manifestations of cognition that we observe directly. Mental structures are hypothesized in order to account for cognitive activities.

Cognitive science is an interdisciplinary endeavor that synthesizes work from a number of fields, including philosophy (Russell, 1945, 1948; Fodor,1974), experimental psychology (Pinker, 1999, 2002; Miller, 1956), linguistics (Chomsky, 1957; Fauconnier & Turner, 1999), artificial intelligence (Minsky, 1985; Penrose,1989), and anthropology (d'Andrade, 1989, 1995). The history of how these fields came together is presented in Howard Gardner's *The Mind's New Science* (1988); and some of the basic cognitive models are discussed in Paul Thagard's *Introduction to Cognitive Science* (1996). The validity of a particular cognitive model is determined by to what extent it is based on legitimate neuroscience, what kind of explanatory power it has, and when simulated by a computer, how closely the results resemble human behavior.

Relevant principles

Cognitive science is an enormous, thriving field, with applications in a great number of disciplines. I will not attempt to review this vast quantity of literature here, but rather will begin from a synthesis constructed for the purpose of applications to education. This synthesis focuses on the properties of the individual. I will consider the implications of these ideas from an individual functioning in the context of a group.

In E. F. Redish's "A theoretical framework for physics education research: Modeling student thinking,"(2003) he enumerates principles from neuroscience that have implications for understanding how students learn:

> *Principle 1: All phenomena are describable as arising from the fundamental physical objects and laws that we know.*

and

> *Principle 2: All cognition takes place as a result of the functioning of neurons in the individual's brain*

We can take this to mean that cognition should be considered a biological process situated in the central nervous systems of individuals. Though we can sometimes speak metaphorically about aggregates of individuals performing acts of cognition (i.e. "our class couldn't calculate integrals" or "the group knew all about magnets"), it is important to keep in mind that these emergent phenomena are the result of individual cognitive action. In my analysis of group work, for example, group action will sometimes be described using terminology that is typically used in reference to individual cognition. When these concepts are applied to groups, they mean something different.

Now consider:

> *Principle 4: There is a real world out there and every individual creates his or her own internal interpretation of that world based on sensory input.*

This is an important idea to keep in mind whenever studying a group of individuals engaged in a joint activity, to understand that each individual has his or her own interpretation of what is going on. The extent to which a group can have a "shared experience" is limited, and we may perceive that we are having a shared experience but we may be wrong.

Then we have the concept of constructivism:

Principle 5: New knowledge is built on a base of existing knowledge by building new links and suppressing old ones.

This further illustrates the problem of considering a group of students as a unit. It is not usually helpful to consider knowledge to be a material substance that can be shared by a group of people or directly transferred from one person to another.[2] On the other hand, constructivism gives us a way to understand why students seem to learn a great deal from working together with peers. While students may not have identical sets of resources from which to learn (i.e. real-world experiences and formal training), resources they do have in common constitute an important element of how we define a group's productive ability.

Fundamental to this model of knowledge structure are the concepts of *associational patterns* and *control structures*. When one posits the existence of knowledge as actively constructed resources, it becomes important to consider how these resources are connected, or what resources may be activated in what sorts of contexts. In order to process the abundance of sensory input to the brain, the mind must be able to select relevant pieces and ignore others. We call this selection process is called *framing*. In other disciplines, essentially the same phenomenon is described as “registers”, “scripts”, or “schemas.” (Schank & Abelson, 1977; Rumelhart, 1975; Kant, 1998; Bartlett, 1935) Additionally, in order to pare down the abundance of existing knowledge elements, the mind groups together certain resources (and excludes others) to deal with similar situations. This process is the basis of epistemic games, which will be discussed in detail later.

The Socio-Cultural Approach

So far, the issues we have discussed focus on activities situated in the mind of an individual. Since cognition is defined as a biological process, one might be tempted to study the individual in isolation and to extrapolate what is known about individual behavior in order to understand collections of individuals.

However, what this generalization misses is that the mind cannot act in isolation, and in fact its functioning depends highly on the nature of its environment and the other minds it comes into contact with. Even though we construct our own personal realities, the materials we use are signals from the objective reality outside. Some of these signals, such as light and sound, arrive at our senses unprocessed, ready to be interpreted and operated upon in the way our minds see fit. On the other hand, the most important signals we receive are often the products of the cognition of others. A simple sentence, for example, and the means by which to comprehend it, is the product of thousands of years of cognitive cooperation. The shared method of cognition and framing and the tools constructed to aid it, such as language, number systems, and traditions, are what we call *culture*. There can be many levels of culture relevant to an individual. One level can be the culture of human civilization, so all-encompassing that it requires a powerful imagination to think outside of it. On the other hand, a strong culture can also exist between two

[2] Hammer and Elby (2002) refer to this epistemological concept as “knowledge as propagated stuff”.

or three people, and this culture may include private jokes, shared points-of-view, specific methods of communication, and temporary shared frames.

In this study, we examine small groups of individuals engaged in the process of learning physics. In addition to the large-scale culture that allows them to communicate with each other, we observe the development of a small-scale culture within the group, which may or may not lead to productivity towards this goal. A great deal of literature exists that stresses the importance of culture in cognition, and warns against treating the individual mind in isolation. Some of this research even goes as far as to suggest that the definition of cognition be expanded to include social activities. The general attitude that an individual's development is a product of culture is known as the *socio-cultural approach.*

Lev Vygotsky and the Zone of Proximal Development

By far the most influential contributor to the socio-cultural literature is early-20th century Russian psychologist Lev Vygotsky, whose work on child development (Vygotsky, 1978, 1986) was rediscovered and celebrated in the 1960's. Vygotsky proposes that intellectual development is primarily a function of social interaction, rather than, as Jean Piaget argues, a product of epigenesis[3]. Vygotsky's ideas inspired a generation of education researchers seeking to understand the effect of culture and social factors in student learning.

Vygotsky's work focused mainly on child development theory, specifically the development of mental faculties, such as language, thought, and reasoning. These abilities, he argues, are social in nature, meaning that they developed socially first and only later became internalized as a tool one might use on one's own. He refers to these as *higher mental functions*, as opposed to *lower mental functions,* which are entirely innate. This dichotomy quite elegantly places nature and nurture side-by-side, though with more emphasis placed on the latter. Vygotsky's framework provides a way of understanding how the learning of higher mental functions is accomplished socially.

One of the most important concepts proposed by Vygotsky that has proven to be productive for socio-cultural researchers, is that of the *zone of proximal development,* which he describes as "the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers." (Vygotsky, 1978) There is a collection of knowledge that an individual does not yet possess, but has the ability to learn on his own. Knowledge that exists outside this area, the learner does not yet possess the ability to understand without developing a stronger cognitive framework. This is in agreement with the principle of constructivism, which states that new knowledge must be build on the foundation of prior knowledge.

Vygotsky suggests that with the guidance of a more experienced individual, one's potential to learn increases. The expanded learning potential between one's *actual level of development,* or what one can do alone, and one's *potential level of development,* or what can be accomplished socially, is the zone of proximal development. Vygotsky suggests that one's potential level of development is more indicative of one's abilities than one's actual level of development.

Few teachers will deny the main implication of this theory, that one's ability to learn is improved by the presence of a guide. But Vygotsky's idea of development zones is much deeper

[3] Or, how the environment interacts with pre-wired tendencies.

than that. Vygotskian scholar Annemarie Palincsar (1998) explains that the theory states that one's learning ability is more dependent on the social environment in which one interacts than on one's innate abilities. Education researchers find this egalitarian implication to be appealing and optimistic.

Vygotsky introduces the term *scaffolding* to describe the process by which an experienced individual can assist someone in the process of learning. How this takes place determines whether or not a student is able to learn more under the tutelage of an experienced other. We naturally think of the student-teacher relationship as being the primary arrangement for learning, however, peers can also help each other learn. In this study, we will be examining not only how students' abilities are augmented by the presence of the teacher and teaching materials, but how certain types of peer interaction can do the same thing. Research on cooperative learning suggests that learning in peer groups can be tremendously effective (Johnson & Johnson, 1989). Vygotsky's theoretical framework gives us a way to think about how this is happening.

Alexei Leont'ev and Activity Theory

The idea of a zone of proximal development suggests that, by examining student learning in isolation, one would miss a vitally important factor, that of the social environment. To Vygotsky, the perceptual input fueling cognition is not a concept to be ignored or swept under the rug. The importance of social interaction, as influenced by cultures of various grain sizes, was further explored in the science of *activity theory,* spearheaded by Vygotsky and continued by Alexander Luria and Alexei Leont'ev (1981, 1978).

Activity theory expands upon Vygotsky's framework by suggesting that the development of higher mental functions is assisted through the use of cultural artifacts, such as language, numbers, and tools. Focusing on the importance of learning being mediated through these tools, he described human activity as lying "not in its reduction to single elements but rather in its inclusion in a rich net of essential relations," between the individual, the environment, and the tools used by the individual to interact with the environment.

Activity theory is an attempt to explain cognition through interactions between the human nervous system and the material world outside, interactions that are defined and guided by culture. Leont'ev discusses the use of tools as evidence of cognition outside the explanation of Pavlovian behaviorism. The presence of tools, and of the cultural meaning tied to them, mediates the transfer of knowledge. Activity theory can be useful for describing the interactions that take place in the laboratory, as students use both physical tools, such as computers and calculators, and cultural tools, such as the scientific method, to explore the physical world.

Situated Cognition

After the Western world discovered the works of Vygotsky and his peers, the socio-cultural approach gradually began to influence educational psychology. One school of thought associated with these ideas is known as *situated cognition,* which posits that all knowledge is *situated*, or, exists within a specific context. Suchman (1987) coined the term *situated action* to "(underscore) he view that every course of action depends in essential ways upon its material and social circumstances."

The context dependency of knowledge explains why students may be capable of certain feats in the classroom, but not in real-life (or vice versa). For example, a student can be quite capable of applying physics knowledge to homework problems, but incapable of activating that knowledge in the laboratory with actual equipment. Another student may be extremely handy in the laboratory but not particularly good at applying their skills to abstract problems. This is a problem for any cognitive model that regards the individual mind as simply a collection of knowledge elements – one either "knows" how a circuit works or doesn't. By expanding the cognitive view to include context, we can understand why knowledge is sometimes activated, and sometimes not.

Researchers in this field generally propose the expansion of cognition to include socio-cultural factors. This would include not only the specific context, but social interactions as well. Brown and Duguid make an excellent case for the importance of social arrangement in *The Social Life of Information* (2002). They demonstrate within the everyday work environment of a corporate office those ways in which the social environment can dramatically affect individual cognition, and ultimately the product of a group's work. Lave and Wenger (1991) discuss the situated nature of knowledge through the portrayal of apprenticeships in a variety of cultures, arguing that skills may be effectively taught though active participation, as opposed to direct instruction. They use the term *know how* to describe knowledge deeply-situated within a context, such as one's ability to cut produce correctly, as opposed to *know what*, or knowledge that can be explicitly stated and exchanged sans context. Researchers have used situated cognition to describe a number of other phenomena (Clancey, 1997; Brown et al, 1989; Brighton et al, 2003).

Distributed Cognition

Another socio-cultural school of thought known as *distributed cognition* was developed by Edwin Hutchins and explored in his book *Cognition in the Wild* (1995). Hutchins takes as one example the process of navigating a navy ship, and he describes how the necessary information for this process is spread out among the crew and the artifacts they use. Hutchins stresses that no one person possessed the knowledge to navigate the ship on his own, but that this knowledge was arranged in a unique social environment. This is an example of a process, not unlike that of doing science, in which an immense cognitive task is carried out not by a single mind, but by many minds interacting with both each other and with the environment and certain tools. It is just as difficult to pin down the knowledge of ship navigation to a single mind as it is to argue that the ability to navigate a ship exists outside of the ship context.

Chapter Five of this thesis explores the physics laboratory group as a system of distributed cognition, encompassing the minds of the individual group members, physical tools, and cultural artifacts, into a single entity capable of complex computations.

The Intersection of Cognition and Culture

Neither cognitive science nor the socio-cultural approach can, by itself, provide a satisfactory view of group learning. While cognitive science has given us several useful models of the human mind, its scope generally excludes the influence of culture. The socio-cultural approach places culture and human interaction at the center of importance to human thought. Although focusing on the output of a group, rather than the workings of individual minds, may be perfectly sufficient for someone concerned exclusively with that output (like a project manager working with the ideas presented in Duguid and Brown), however, it is not sufficient for an educator whose primary concern is the state of individual minds. The study of group lab-work requires that we give attention to both cognitive and social factors. We seek to understand both how individual minds contribute to the construction of a social unit and how social interaction affects individual thought.

Donald Brown (1989) provides an extensive list of *human universals*, or activities that exist independently of culture. This includes methods of classification, artistic expression, and ways of making sense of the world. Steven Pinker (2002) argues that these universals may have come about as the result of psychological evolution over the millennia, which, like physical evolution, has resulted in much more overt similarity between human beings than differences. Our brains, having developed according to the dictates of the genes, are pre-wired to facilitate the learning of certain types of behavior and ways of thinking. Regardless of one's upbringing and perspective of the world, one's mind will develop in certain ways for purely epigenetic reasons. Child psychologist Jean Piaget (1983) studied these cases extensively and his results illustrate quite a few early cognitive developments that are inevitable, and quite independent of current cultures.

As important as these epigenetic factors are, they do not account for everything we learn. In fact, Vygotsky adamantly insisted that the important elements of mind, such as our reasoning strategies and language, are developed through socio-cultural interaction. It is quite obvious that our worldviews are heavily influenced by cultural artifacts. It is not by coincidence that most people in France communicate using the French language. We come into this world and adopt pre-existing strategies of apprehending our environments, communicating with others, and dealing with the problems we encounter. It is no surprise that our culture, or our community's established "way of doing things" influences how we think.

There are two types of culture that are pertinent to the study of group behavior. First there is the *macroscopic* culture in which we are immersed (and may be, for the most part, unconscious). It is from this culture that we inherit our language, our general sense of manners, our numerical system, and the tools we use to operate on the environment, such as our calculators, computers, pencils, and paper. A group of scientists could accomplish very little together without this kind of shared common culture. Secondly there is a *microscopic* culture that can emerge in a group. Small groups can develop their own ways of doing things and a common understanding of procedure and purpose. These microscopic cultures differ from macroscopic cultures in that a single person can easily interact within many microscopic cultures, but may find it tremendously difficult to interact in another macroscopic culture. It is the existence of these microscopic cultures that, as we will see in the next few chapters, boost a group's productivity.

Frames and Framing

Because we are confronted with an enormous number of signals from our environment every second, it is necessary for us, as individuals, to have a cognitive tool for parsing and interpreting signals in a way that creates meaning. We need a method of organizing what we see, hear, and feel in a way that we can understand "what's going on." This activity is known as *framing*. Framing is an example of an individual cognitive activity that is heavily influenced by our respective cultures, microscopic and macroscopic, and that allows us to interact within these cultures.

Gregory Bateson: Framing as Interpretation

Framing builds on the development of the Gestalt theory in psychology in the first half of the 20th century (Wertheimer, 1922). These researchers demonstrated the importance of the individual's organization of their perceptions and their response to contexts.

Gregory Bateson used the idea of context dependence to show the importance of considering not just behavior via stimulus and response, but mental states that affect the individual's interpretation of a stimulus. The first important piece on frames is Bateson's "A Theory of Play and Fantasy"(1955). In this essay Bateson suggests that "human verbal communication can operate and always does operate at many contrasting levels of abstraction." He describes *metacommunicative messages* as parts of communication that contain information about how to interpret the message, and demonstrates several levels of abstraction in which people can communicate, where the necessary means of interpretation is supplied as part of the message.

As an example, Bateson describes a pair of monkeys he observed at the zoo engaging in an activity we would call "play." Play resembles actual combat in terms of action; however, messages seem to be exchanged between the participants that clarify that these actions are to be taken as moves in a game of amusement, rather than deliberate attempts at bodily harm. The messages that convey the understanding that "this is play" establish a "psychological frame", which Bateson describes as that which "is involved in the evaluation of the messages which it contains" or "assists the mind in understanding the contained messages by reminding the thinker that these messages are mutually relevant and the messages outside the frame may be ignored."

Bateson's concept of framing was a serious challenge to behaviorist doctrine, which suggested that all psychology could be reduced to stimuli provoking responses. The fact that animals engage in a process of interpretation meant that something important was happening inside the mind that could not be accounted for with the dominant psychological model of the early 20th century.

Erving Goffman: Framing as Organization

The concept of "framing" in communication theory was extensively elaborated by sociologist Erving Goffman, who presented an expansion upon Bateson's ideas in a book entitled *Frame Analysis: An Essay on the Organization of Experience* (1974). Goffman describes *primary frameworks* as ways in which people interpret their experience, or, the means by which one would answer the question, "What's going on here?" He helps explain Bateson's example by illustrating play activity as:

> *"...closely patterned after something that already has a meaning in its own terms - in this case fighting, a well-known type of guided doing . . . Bitinglike behavior occurs, but no one is seriously bitten. In brief, there is a transcription or transposition… of a strip of fighting behavior into a strip of play."*

To Goffman, framing is the active use of cognitive schemas through which people interpret and describe the world around them. Answering the question "What's going on here?"

is framing, while the “frame” can be thought of as the answer. For example, when one sees two men fighting to the death with swords, one might draw the conclusion that this is a Shakespearean play and enjoy the action in a “play frame.” Alternatively, one might frame this situation as a genuine altercation, and react quite differently.

Deborah Tannen: Framing as Communication

Frames are explored further by Deborah Tannen (1999) and other researchers in socio-linguistics (Lakoff, 2004). One of Tannen’s ideas that is useful for us is that framing is a social activity that allows the communication of meta-messages, or messages that are communicated through one’s prior knowledge and expectations rather than through actual spoken words. Framing, then, is how a single phrase, such as “How are you?” can be interpreted as having completely different meanings, depending on who is saying it to whom, what their past history is, and other information not included in the sentence itself. Though framing, language takes on a richness and versatility that could not exist through “face value” communication.

An example Tannen gives of framing is the joking that takes place between boys and young men. When a group shares a “joking” frame, insults about one’s mother are not taken personally, but rather interpreted as moves in a friendly game. Someone who has not framed this situation appropriate might interpret these comments much differently, become offended, and start a fight.

Types of Framing

An excellent review and synthesis on framing is provided by Gale MacLachlan and Ian Reid (1994). They present as a simple example of the use of framing the act of “interpreting” a book. The text itself is not the whole of the book’s message. One looks for clues within and outside of the text to determine how to interpret that text. The same text will be interpreted differently if it is sandwiched between a pink paperback binding, sold at the local grocery store, and written in internet *leetspeak*, than it would if it were found at a university science library, written with careful, precise language. In one frame, I would skim and try to enjoy myself, while in the other I would read it very carefully.

Redish defines an *epistemological frame* as “the set of epistemic resources the individual assumes is appropriate to carry out the task at hand” (2004). Just as one can read a book in different frames, students can interpret a classroom exercise in a number of different ways, and how the activity is framed will affect what sorts of cognitive tools they bring to bear in the exercise. And just as a misframing of a joke can lead to insult, a mutual misframing of a laboratory activity between students can lead to ineffective work. Other researchers have studied epistemological framing in different contexts (Shaffer, 2005; Schwartz & Sherin, 2002).

Framing is both an individual cognitive activity, as described by Goffman, and a social activity, as described by Tannen, and is therefore an important concept to keep in mind when observing social discourse. In a group, each individual frames what is going on in his own way. It is possible and desirable for a group of individuals to have some level of consensus as to how they choose to interpret events and communications, and to reach this level, they engage in what Redish refers to as "frame negotiation." But just as a group's strength can come from sharing a common frame, it can also come from the combination of different methods of interpretation.

Group Interaction

Another branch of social science, known as *group dynamics*, claims that individual behavior is highly dependent on the group context, and deals with the nature of groups. In this section I outline some of the contributions made by researchers in this field that are relevant to our discussions. Although it is useful to examine what has been learned about group interaction, much of this research is too general to be of use in answering the question of how students interactively deal with conceptual physics.

Social psychologist Kurt Lewin, the proclaimed "father of organizational development, published a number of works (1935; 1948; 1951) in the early 20th century on group dynamics that have had a profound impact on the field. One of his primary research objectives was to determine the causes of ineffectiveness in groups. This led to Lewin's *force field analysis,* which provides a graphical method for groups to analyze the various factors influencing their productivity. In this analysis, there are *driving forces* and *restraining forces* that respectively boost and hinder group productivity. *Equilibrium* is reached when these forces equal. The purpose of force field analysis is to assign scalar quantities to physical events, and consequently to be able to determine what effects certain changes will have on the group's productivity.

Many researchers on group dynamics propose that groups pass through certain predictable stages in their development. One of the most frequently-cited works is Bruce Tuckman's stage model (1965, 1977), which posits that a group passes through four distinct stages in its evolution from a collection of individuals to an effective team. These stages are: forming*, storming, norming*, and *performing*. *Forming* is characterized primarily by the establishment of boundaries through testing and the establishment of dependency on group leaders. *Storming* is characterized by conflict and interpersonal polarization. *Norming* is characterized by the establishment of roles and a growing inter-group cohesiveness. And *performing* describes the phase in which the group utilizes these new roles in the accomplishment of tasks. Though Tuckman's model is linear, other researchers have made use of it by adding stages or creating a non-linear representation of how a group can progress (Bales, 1965; Schon, 1983). Tuckman's original model, nevertheless, is still frequently used in management research (Rickards & Moger, 2000; McGrath, 1997).

Tuckman's model is a Piaget-style stage model for epistemology. However, as I demonstrate in Chapter Six, this model is too simplistic to accurately describe how lab groups develop, owing to the transitive nature of group characteristics. A resources model (Elby & Hammer) would be more appropriate. The Tuckman model proposes phases of activity that last for a considerable length of time, while lab groups seem to be able to shift from a "well-oiled machine" to a "rusty heap" and back again several times during a class period. What can be learned from the phase model, however, is that the formation of a "good" group requires certain social processes that take time. Nevertheless, this model only provides a general understanding of groups, and treats the task at hand as a static component. Laboratory activities require much interpretation and manipulation on the part of the group; therefore we require a theory that includes interaction between it and the participants.

Another attempt to describe the evolution of a group is the *Johari window*, named after its creators, Joseph Luft and Harry Ingram (1955). They describe the window as "a graphical model of awareness in interpersonal relations." As shown in Figure 1, the window encompasses the group's behaviors and motivations, which can be separated into four quadrants:

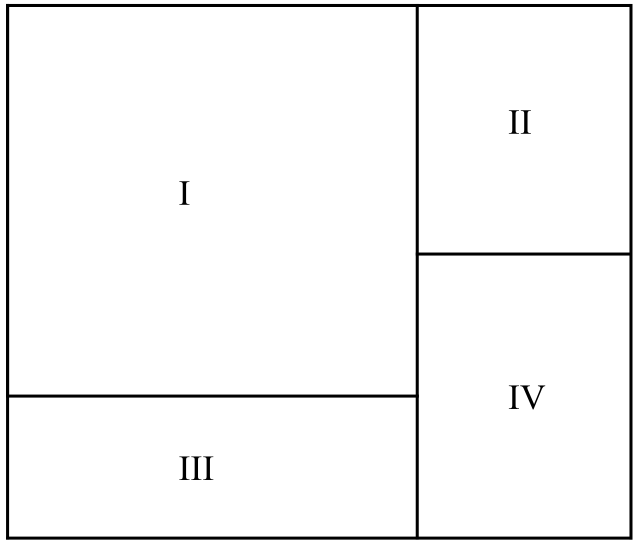


Figure 1. The Johari Window

Quadrant I, the "open" quadrant, refers to that which is known both to self and to others. Quadrant II, the "blind" quadrant, refers to that which the individual cannot see in one's self, but which others can observe. Quadrant III, the "hidden" quadrant, refers to that which is known to the individual but not to others. Quadrant IV, the "unknown" quadrant, refers to that which nobody is aware of.

According to this model, a change in one quadrant will result in a change in other quadrants. Group evolution typically involves an increase in Quadrant I, with more behavior becoming "shared", accompanied by a decrease in Quadrant III. This model presents a more dynamic view of groups than the Tuckman stage model; however, it shares a few of its shortcomings. The window is context independent, and therefore is assumed to be evolving without regard to contextual changes that happen on a short time scale. This means that its resolution is insufficient to describe the transitions observed in our laboratories.

Another method for group analysis known as *sociometry* was created by Jacob Levy Moreno (1950, 1951). He describes it as "the mathematical study of psychological properties of populations, the experimental technique of and the results obtained by application of quantitative methods". It is intended to reduce conflict and increase communication within a group by measuring the degree of relationship between the group participants.

Sociometry involves surveying the group members about their feelings towards the other members. This information is put together in a *sociomatrix*, a graphical representation from which various conclusions can be drawn about the group as a whole. A variety of studies have shown that group productivity is correlated with the level of sociometric cohesiveness between the members, and that using this technique can increase productivity, safety, and harmony within many different group settings (Val Zelst, 1952; Hoffman et al, 1992) As I explain in the next chapter, it was our intention to use some sort of metric to arrange laboratory groups, but due to various constraints, no such method was ever implemented.

Team roles

A common endeavor in group research is the attempt to classify various team roles, and using these, to hypothesize what sorts of combinations make up an ideal group. On such study done by Meredith Belbin (1981) places people into nine categories known as *team roles,* which are defined as "A tendency to behave, contribute and interrelate with others in a particular way":

Action oriented team roles: Shaper, Implementer, Completer Finisher
People oriented team roles: Coordinator, Teamworker, Resource Investigator

Cerebral oriented team roles: Plant, Monitor Evaluator, Specialist

These team roles are defined by both the skills and weaknesses these personalities bring to bear in a group situation.

Richmond and Striley (1996), in their study of 10th graders engaged in science laboratory activities, provide another classification of individual behavior, this one in terms of participation style. Most important to the working of the group is the emergence of a group "leader" and the style in which this person interacts with the rest of the group. They identify three types of leadership: *inclusive*, *persuasive*, and *threatening*. Preferable of the three is the inclusive leadership, under which the leader actively tries to establish cooperation in the group, rather than competition. We will see in video transcript later on that the emergence of a team leader is quite typical of our laboratory environment as well, and that the behavior of this individual can make or break the group as a working unit.

Rather than focus merely on types of individual behavior, Shepardson (1996) insists that the important feature in scientific inquiry is the negotiations that take place between the participants. He identifies four types of negotiations that take place during this activity. A *negotiation of materials* involves the distribution of the physical materials at the students' disposal. A *negotiation of actions* is done to bring about some kind of physical manipulation, such as setting up equipment or drawing a picture. A *negotiation of status* refers to an interchange that results in the designation of leadership or some other individual role. Finally, a negotiation of meaning brings about a shared understanding of the task concepts.

There is merit to understanding the nature of exchanges, just as it might help us to understand the sorts of personality types that emerge in a group setting. Unfortunately, neither of these formulations is specific enough to help in the present study. Categorizing students in terms of a scheme fails to describe what I demonstrate as happening during the labs: that roles can change, and sometimes quite frequently. Categorizing exchanges ignores what is learned from the literature on framing, that a particular negotiation can be construed different by each member of a group. I will show that these classification schemes are too static for our purposes.

Researchers David and Roger Johnson are two of education's most enthusiastic advocates of group learning. Their studies (1989; 1993) on how to effectively implement group learning environments in the classroom heavily influenced the laboratory reforms we examine in the next chapter. According to them, "any assignment in any curriculum for any age student can be done cooperatively." Central to the implementation of cooperative learning is the *theory of social interdependence*, inspired by both Piaget and Vygotsky, which claims that during the act of cooperative learning, skills are developed through the *cognitive disequilibrium* brought about through the social interaction. Interaction with peers exposes students to many different perspectives, and can inspire thought in a way that traditional classroom environments may not be able to do.

Discussion

As previously mentioned, the focus of this research is on the interplay between individual cognition and social interaction. The chief concepts that will be taken from this research are those of epistemological framing, distributed cognition, and Tuckman's stage model.

Epistemological framing is not only a useful tool for describing an individual's interpretation of reality, but can also be a tremendously powerful tool for dealing with groups. I will demonstrate that how effectively a group works can depend highly on whether or not there is a shared framing of the type of problem before them, and what cognitive tools are appropriate to handle this particular problem. Distributed cognition is a socio-cultural concept that nevertheless places importance on the cognition of individual minds. This concept is used to describe how groups can appear to take on "a mind of their own", or at least operate in a way that is difficult to reduce to the actions of individual minds. Tuckman's stage model is presented as a dominant model of group evolution, and will be used in contrast to the model constructed in this work.

This chapter presents two distinct types of research, cognitive and socio-cultural, which can be combined in order to explain the workings of a lab group both collectively and with respect to individuals. In the next chapter, I present research specific to science labs, which inspired the reform project that resulted in the labs that we will be observing.

Chapter 3: Laboratory Reforms and Social Context

This study was conducted as part of the Learning to Learn Science (LLS) project, which proposed to reform an algebra-based introductory physics course at the University of Maryland, taken mainly by pre-med students, biology and life-science majors, and architecture students. The class consisted mainly of juniors and seniors. This course included a laboratory much like those conducted at most physics departments – a two hour activity supervised by a graduate-level teaching assistant. Between twenty and thirty students, working in pairs, make up a class. Typically, the lab activities were scheduled to roughly coincide with the corresponding topics in lecture, so that the instructor would have covered any new material that might be relevant to the lab activity. Occasionally, this was not the case, forcing students to encounter certain concepts in laboratory for the first time.

Videotaped studies of these classes (Lippmann, 2003) revealed that the students were not accomplishing certain important learning goals. Although the students were dividing up labor, they were not engaging in a great deal of productive teamwork. Meaningful discussions about the physics concepts being explored were rare. Students spent most of their time following directions and trying to get through the lab manual, and not much time making use of peer interaction as professional scientists do.

Over the course of several semesters, my colleagues and I at the University of Maryland implemented many reforms to the introductory physics labs. Some of the goals of this reform project were (a) to inspire more productive and meaningful teamwork, (b) to present open-ended exploratory-based activities, rather than those heavily-guided by a lab manual, and (c) to present the topics of uncertainty and measurement analysis in a novel way. In this chapter, first I present some of the relevant research on lab reform and pedagogy that inspired this project, and then I illustrate the end result of these reforms, the laboratory class which we will be studying in detail.

Research on Science Laboratories

Much recent research on science laboratories is inspired by an early work by Fred Reif and Mark St. John (1979). In this, they enumerate the goals of the laboratory as a learning environment, differentiating between “basic skills”, such as estimating quantities, determining errors, and applying useful measuring techniques, and “higher-level skills”, such as effectively describing experiments and using the resulting knowledge in different situations. They note that after taking a traditional laboratory course, students are generally incapable of explaining what they have done in a way that makes sense to others.

We have observed a similar trend in our introductory laboratories. Even students who appeared quite competent in manipulating the equipment had difficulties articulating what they were doing and why. On the other hand, the SCL labs, in which inter-group discussion is more frequent and whole-class discussions are held each week, students were observed to be far more capable of explaining the details and meaning of the experiment, as shown in lab reports of increasing lucidity.

Further inadequacies of the laboratory class are explored by Séré (1993, 1998). Séré showed students in an introductory physics lab having woefully incompetent conceptions of measurement uncertainty and how to deal with it. Rather than accepting uncertainty and spread in a data set as vital components of the experimental results, they used the concept to apologize for what they deem to be poor experimental skills, or "human error." Lippmann made a point of banning "human error" from the SCL labs, consistently sending the message to the students that spread in a data set is a feature of the answer, rather than a flaw of it.

These studies suggest that the students' view of the nature of measurement is much different from that which one would seek to teach them. Buffler et al (2001) did a study to determine what exactly the students think about measurement. By administering and analyzing a questionnaire, they concluded that students' beliefs about measurement fall into two categories: the *point paradigm*, which centers on the idea that the goal of measurement is to approach a single value, and the *set paradigm*, which understands measurements as establishing intervals, or spreads. The researchers' view is that students holding the former view must be brought around to accept the latter view. Hans Niedderer and Dimitris Psillos (1998), through extensive case studies of laboratory work, came to the conclusion that two types of assessment were necessary to determine the effectiveness of the course. First, a comparison must be made between what the students are doing during the lab activity and the intended activities. Secondly, the learning outcomes as assessed after the lab must be compared to what was intended.

The research cited in this chapter provided a background for the various types of problems with the laboratories that other researchers have explored. It influenced the reform project in its early stages, and led to a set of lab activities that we feel addresses many of these problems, particularly with making sense of the nature measurement-making in general.

Physics Education Research at the University of Maryland

Finally, my research is most directly inspired by the works of two of my colleagues, Rebecca Lippmann and Jonathan Tuminaro. As graduate students, Lippmann and Tuminaro both wrote dissertations concerning the very population of students we will be examining later in this work.

It was initially Lippmann's idea to initiate a campaign to reform the traditional labs. This task was nothing to take lightly. Few people in a physics department are anxious to tamper with the undergraduate laboratory, an ancient institution which, though not exactly the proudest feature of our department, has managed to exist for a long time without causing crisis.

Lippmann introduced a reformed set of labs in the fall of 2001 and directed them for three semesters. These labs focused intensely on measurement issues, such as the treatment of uncertainty, error bars, and function fitting. Lippmann had observed that, in traditional labs, students spent a great deal of time discussing logistics of setting up equipment and very little time in "sense-making mode." One of the goals of this project was to reverse this trend by removing the lab manual and carefully engineering the activities so that these measurement issues would need to be seriously addressed.

Her dissertation (2003) explores how students spend their time in these new reformed labs. To me, this project was of vital importance in that it demonstrated that radical reforms in the laboratory were possible with the resources at our disposal. My set of labs, which will be discussed in the next chapter, were only possible because of Lippmann's groundbreaking work.

My immediate predecessor, Jonathan Tuminaro, also conducted interesting research that is carried on the present work. Tuminaro took Collins and Ferguson's concept of epistemic games and used them to describe the problem-solving attempts of our introductory physics students. We will be discussing Tuminaro's version of epistemic games in detail in chapter four.

“Traditional” Laboratories

As a first step in this research, my colleagues and I made several major reforms to this laboratory course. Among the many goals guiding these reforms was our desire to design a laboratory environment in which there was a great deal of social interaction fostering cognitive sharing and increasing the fraction of time students spend in sense making about physics and measurement. In addition to this being beneficial for the students, this would also happen to yield rich activities that are easily studied in real time through video and audio recorders. The result of this reform effort was a set of activities we call *scientific community labs*, which foster much richer social interactions and teamwork than traditional labs.

The term *traditional labs*, which is typically used to describe those labs that existed prior to this study, is somewhat misleading, since they by no means are the same activities as the *Harvard forty* (Menzie, 1970), the original set of laboratory standards proposed in 1886 when laboratory courses began to proliferate in the United States. However, despite modernization and reform, not only in response to improved technology but to the expansion of physics itself, several of the Harvard forty experiments are still found in today’s undergraduate laboratories.

The idea of modernizing the introductory physics labs is not new; Robert Millikan (1903) suggested more than a century ago that laboratory work “often degenerates into a servile following of directions, and thus loses all save a purely manipulative value.” He laments the fact that too little of a connection is drawn between theory an experiment in physics courses. The fact that labs are still taught separately from lectures, often with different instructors and separate grades, suggests that some of Millikan’s problems with the laboratory are still waiting to be solved.

In a typical lab, students are given a short description of a physical phenomenon they are to investigate, followed by detailed instructions on how to perform every portion of the activity. As if being asked to ignore the literal meaning of the word “experiment,” students are expected not to stray from the activity they are intended to complete, and are generally expected to be able to acquire results that demonstrate the relevant physical concept. They are then required to write up a report of what they have done. This sort of activity is what I will refer to here on in as a “traditional lab,” though the details of how they are conducted can vary from college to college, especially those in which faculty have made deliberate attempts to reform them.

I have observed not only a general dissatisfaction among physical faculty with the state of traditional labs, but also a wide of divergence of opinion on what these activities are intended to do. My discussions with faculty and teaching assistants revealed a variety of opinions on the subject. Suffice to say, laboratory courses *can in principle* be used to:

- demonstrate the physical phenomena introduced in lecture
- verify physical laws
- simulate experiments with certain historical or technical significance
- familiarize students with laboratory equipment
- present topics concerning measurement and uncertainty
- teach students proper laboratory protocol
- simulate certain features of *real-life* lab work

It is generally understood, both by the students and by the instructors, that the laboratory is, in fact, a simulation, and sometimes a very artificial one. A simulation chooses a few features of the real experience to emphasize, while ignoring the rest.

Unfortunately, traditional labs tend to downplay the entire social dimension of doing science. Research on traditional labs has shown that a majority of a student's time in a traditional lab is spent dealing with logistical issues, such as interpreting and carrying out the instructions in the lab manual (Lippmann, 2003). Very little teamwork is required and meaningful discussions about the nature of the activity rarely take place. When lab groups interact, it is typically to divide up the tasks. They do not usually function as a team, as a unit that is more than the sum of its parts. Nor are the students expected to interact with other groups. A laboratory activity can be performed by individual students working in isolation (and they frequently are, during lab makeup week).

It is rather unfortunate that, due to the constraints of the classroom, laboratories reduce the social dimensions of science. A student performing an experiment in social isolation is lacking exposure to two vitally important features of science work: the experience of observing the work of others and the experience of passing on one's work to others. In real scientific research, there are no detailed instructions, and there is not always an accepted answer to work towards. Rather than having the rigid, authoritarian presence of instructors and lab manuals, real experimentation is done in the company of a scientific community. While potential scientists must learn to interact in such a culture, traditional labs do not address this issue. So we designed a new set of labs that would.

Scientific Community Laboratories

SCL-1

Reforming this laboratory course was part of a four-year research project funded by the National Science Foundation. The original reforms were made by Rebecca Lippmann and Dr. Edward F. Redish, and produced a first-semester set of scientific community labs (SCL-1). Though their primary goal was to create a set of lab activities that placed emphasis on the nature of measurement and uncertainty, they also succeeded in dramatically increasing the amount of social interaction that took place. A chief goal was to get the students to address how making measurements leads to a result, or how it can answer a question.

During the course of this research project, we collected several hundred hours of videotape of students working in the laboratory, in problem-solving tutorials, doing homework problems, and participating in lecture demonstrations. It was through the observation of these videos that we recognized noteworthy student behavior in the laboratories. These videos made up the bulk of our observational data for many studies henceforth.

Lippmann's dissertation parsed student discourse in the laboratory into three main categories: logistics, sense-making, and off-task. *Logistics* refers to the management of the smaller details, such as figuring out how to put the apparatus together and manipulating equations. *Sense-making* refers to activity associated with understanding the physics, reconciling what is observed with intuition, etc. Lippmann demonstrates that *meta-cognitive* statements, or those that specifically address what they are doing and thinking about, that inspire frame shifts into sense-making. Shown below in Figure 2 is a time-line of these activities in a traditional lab, and Figure 3 shows a similar time-line for an SCL-1 lab.

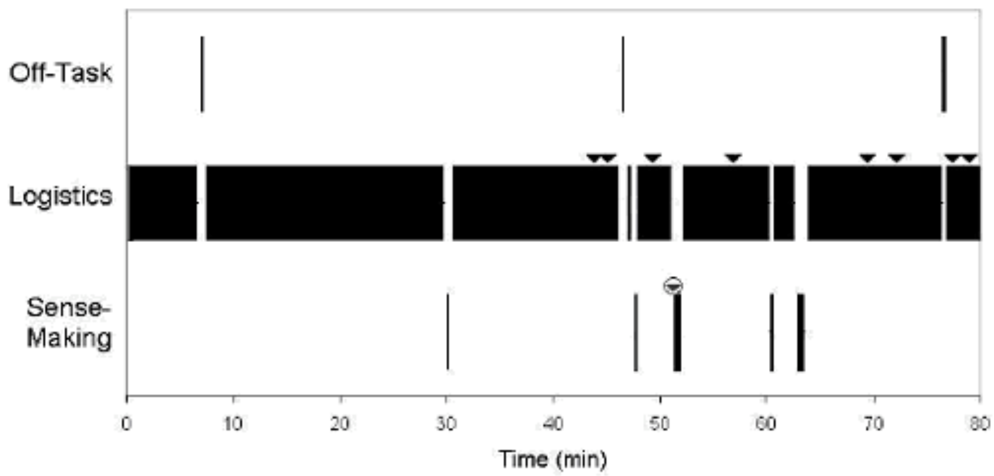


Figure 2. Lippmann plot of student activity in a traditional lab.

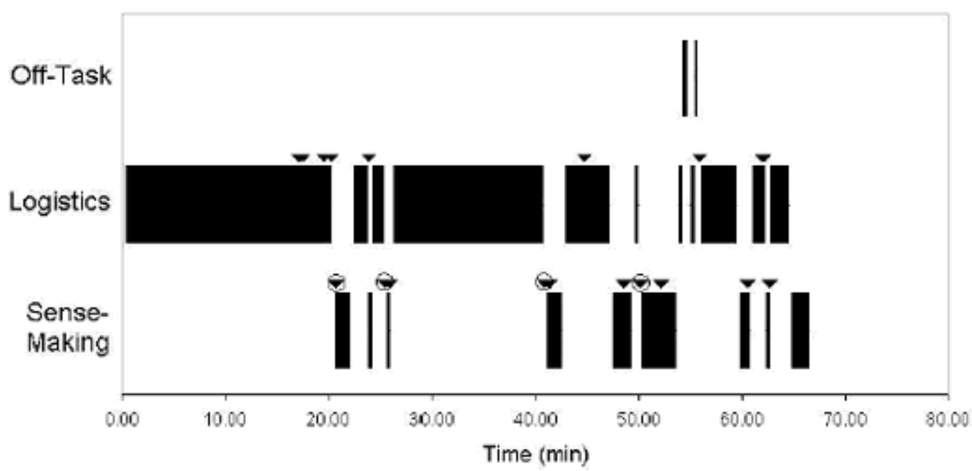


Figure 3.

Lippmann plot of student activity in a SCL-1 lab.

Lippmann found that the SCL-1 labs were significantly better than traditional laboratories in inspiring sense-making behavior. It is this kind of discussion that I am referring to when I talk about "meaningful conversations about physics."

SCL-2

When the task of directing these labs fell into my hands, my colleagues and I continued to make small modifications to them. Inspired by the success of the SCL-1 set, we designed a second semester set, SCL-2 (see Appendix B), to tackle topics of electricity and magnetism, waves and light, and radioactivity. As SCL-1 had focused on topics of uncertainty and measurement, SCL-2 took on the task of data analysis using computer spreadsheet software. For each lab, in addition to the experimental issue, a question is posed about the data that requires the students to invent their own method of data analysis.

The course sequence in which the SCL-1 and SCL-2 labs were embedded was offered once a year for two semesters. Between six and eight lab sections were held each semester from fall of 2001 to spring of 2004, with the exception of spring 2003, in which twenty sections were held. Some were taught by graduate students specializing in physics education research, and the rest by graduate students in other fields of physics. Each semester, four sections were chosen to be videotaped with the students' permission (see Appendix D). Cameras were installed where they could record groups of four, but also so that they could zoom back and record a whole-class discussion. Microphones were strategically placed to capture the discussion of the target groups in detail. Nearly five hundred hours of videotape was taken.

One suggested limitation of using videotape analysis to study students was the possibility that students would tend to act differently from normal while under observation. We have no reason to believe this phenomenon appreciably altered the data. Sudden moments of self-consciousness, brought on by the fact that the camera loomed twenty feet away, are rare. More often than not, the students would refer to the cameras jokingly. Although a camera is zoomed in a particular group, it is difficult for the subjects to tell who exactly is being filmed. On the other hand, there is ample evidence that students are generally forgetful of the fact that they're being filmed. Students regularly reveal intimate details of their personal lives, speak boastfully of cheating on tests, and sometimes share rude comments about the instructor.

Reforming the Laboratory

The major goal of the LLS project was *epistemological development* – exploring the nature of the knowledge the student were learning and what they had to do to learn it. The project tried to build the idea that physics was about "sense-making" and tried help students reconcile their physical intuition with the physics concepts they were learning. A chief goal of the lab reform was to have the lab not contradict the message sent in the rest of the class: to make sense of the physics for yourself and not rely on the pronouncements of authority.

In addition to this, Redish and Lippmann interviewed two biology researchers who hired undergraduates to work in their research labs to determine what sorts of skills would be desirable for their incoming undergraduates to possess. They expressed two needs for the students:

- A broader understanding of what an experiment entails, rather than in-depth training in the minutiae of specific experiments.
- Ability to use a basic data analysis computer program (especially Microsoft Excel©).

With these epistemological goals and practical goals, we formulated a mission statement for the SCL-2 labs (see below) that guided our reform attempts. This statement was made available in the opening pages of the laboratory manual, and we repeatedly pointed the students towards it whenever questions arose concerning what would be required to get a good grade on the lab reports and lab practicals.

Mission Statement

You are going to learn three basic things this semester:

1. **How to recognize *relationships***. All the complicated stuff that goes on in a physics lab can be boiled down to a simple premise: if you change one thing, another thing changes too. First we identify *what* changes. Then we try and decide *in what way* it changes. This is what we call "functional dependence." That's all physics equations are, really, a precise statement about how changing one thing will affect another thing. In this lab, we will explore many different kinds of physical phenomena and try to figure out *what affects what and how.*

2. **How to make a persuasive case for your data.** In physics, answers don't just pop up out of the ground, ready to be printed in a textbook. Data from an experiment doesn't make much sense at a first glance. First you must be able to understand what data *means.* Then you need to be able to *present* this data to others in such a way that it will persuade them that the *conclusions* you've drawn from this data are correct. In order to do these things, you must have a good understanding of the limitations of your observations and *how precise your data is* and *how well you can trust it.* For this, we will try to develop quantitative estimates of how accurate our results are.

3. **How to make a computer do the hard stuff.** We will be using the *Microsoft Excel* spreadsheet to tabulate data, crunch numbers, and construct graphical representations of our data. Not that we can't do these things by hand, it's just that a computer can do it a lot faster, relieving us of a lot of busy-work and leaving us more time for more interesting activities. If you plan on going into research, it is essential to know how to use a computer spreadsheet.

Figure 4. Mission Statement

The following is a list of specific changes made to the labs in order to pursue these goals. They were implemented incrementally over the four years, and corrected as needed.

- Eliminating the lab manuals
- Changing the classroom architecture
- Assigning roles
- Including class interaction
- Encouraging the lab instructors to give the students some space

Eliminating the Lab Manuals

Having a lab manual can be like having an additional member in your group – at times a threatening leader, rather than an inclusive one. While this "member" may be difficult to understand, it is nevertheless understood by the students that it has the answers in it somewhere. In a traditional lab, the lab manual dominates the conversation at every turn. Students can spend the entire lab period trying to figure out what it's trying to say, rather than thinking about what they themselves know. Ideally, students are expected to develop a level of autonomy and to interact as a group. The intervening presence of the lab manual can prevent this from happening.

I experienced an interesting event early in the reform effort in one of my own laboratories. The experiment involved lenses, and required the students to go through a number of procedures in order to produce real images, virtual images, etc. Frustrated with the lab manuals for taking all the fun out of what is otherwise an interesting phenomenon to observe (and guided by a whim that only first-year graduate students are reckless enough to act on), I told the students at the beginning of lab to put their lab manuals on the floor – we wouldn't be needing them. Instead, I gave them a short list of questions on the chalkboard for them to answer, and encouraged them to go about it their own way. Having taken away their main crutch, I half-expected a mutiny. Instead, the students were delighted to be rid of the cumbersome thing. They began to pay serious attention to the equipment they were using, held interesting conversations about the physics, and generally acted in a way that convinced both me and the LLS project leaders that eliminating the lab manual could be a serious step in the right direction of reforming the lab.

In the following semester, when the SCL-1 labs were first conducted, the lab manual was not included. No longer was this silent member going to do all the hard work for the group. No longer was the manual going to determine *what kind* of experiment to conduct, how to solve the problem, how to plan the experiment, and what to make of the data. These are tasks that the students, as a group, need to learn how to do, and having the manual was robbing them of this experience. Consequently, the first major reform was to banish the manual from the laboratory.

Without a lab manual to guide them, the students find themselves in an awkward and unfamiliar position. The clues needed to complete the lab can no longer be found somewhere in the text. So where are they? What we wanted was for the students to cease looking for answers from authority, and to start attempting to find the answers themselves. A community of peers, for example, is a tool far more useful than a lab manual, though it takes time and effort to figure out how to operate it. But the question remained: how much guidance should the students be given?

A new list of lab activities was drawn up (see Appendix B). A typical lab activity consists of a short expository passage to provide a physical context and motivation for the task presented. They are often humorous, and intended to send the meta-message that laboratory ought to be fun. Then there is a short question or pair of questions that comprises the goal of the lab. Finally, they are given an activity timetable[4]. Over the course of two hours, the students are expected to design an experiment, collect data, draw conclusions based on this data, and finally to present their conclusions to the rest of the class. An example of such an activity is shown below.

The students are not told what kind of experiment would be best, how to design it, or how to construct a convincing argument for their results. The assignment is two-fold: they must do the experiment *and* determine a way to go about doing the experiment. In order to do all of this in the time allotted, a certain level of productive teamwork is necessary.

[4] We expected student's biggest problem would be managing their time. Rather than risk having a significant number of students not complete the laboratory, general time guidelines were given, though one could argue this went against our general philosophy of allowing students to think things through themselves.

Lab 5: Magnetic Force, Part One

When you hold two magnets close to one another, they feel either an attraction or a repulsive force between them, depending on their orientation. It appears that the magnitude of this force depends on the distance between the two magnets. But how?

Question: How does the force between two magnets change if you change the distance between them?

Pre-lab discussion	Whole Class	10 minutes
Planning the experiment	Groups of 4	20 minutes
Data collection	Groups of 4	20 minutes
Class discussion	Whole Class	20 minutes
More data collection	Groups of 4	30 minutes
Writing the report	Groups of 4	10 minutes

Figure 5. Sample SCL-2 laboratory handout

Changing the Classroom Architecture

Shown in Figure 6 is a representation of the architectural setup of a traditional Physics 121/122 lab at the University of Maryland. Students work side-by-side with their partners, constantly facing the authoritarian presence of the lab instructor and/or written instructions on the blackboard in front of them. This setup most strongly resembles a Roman slave galley[5], and is not the best environment for students to interact in any meaningful way. One must crane one's neck just to see one's lab partner. One sees nothing but other students' backs. We decided to change this setup.

[5] This is not necessarily an association the students will make for themselves. I, on the other hand, cannot see a traditional laboratory without being reminded of *Ben-Hur*.

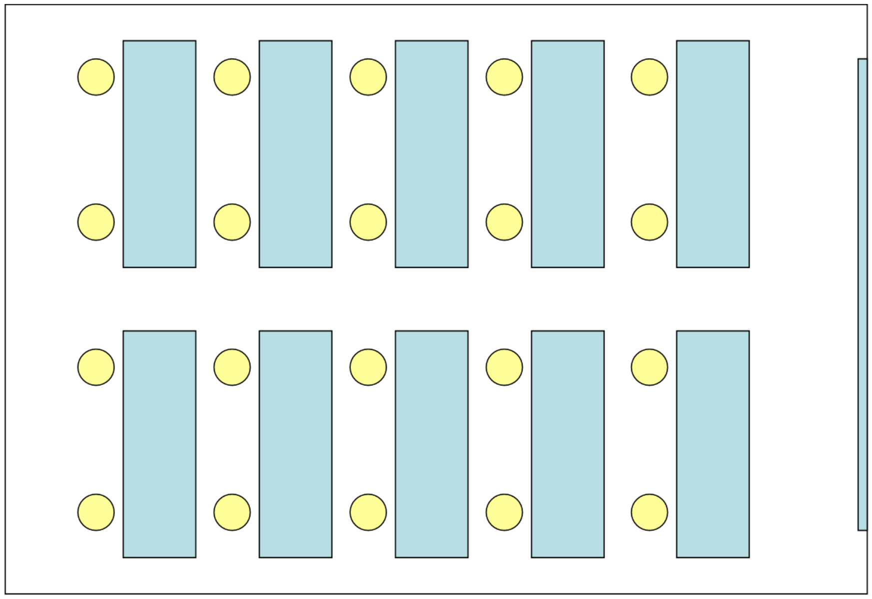


Figure 6. Traditional laboratory architecture

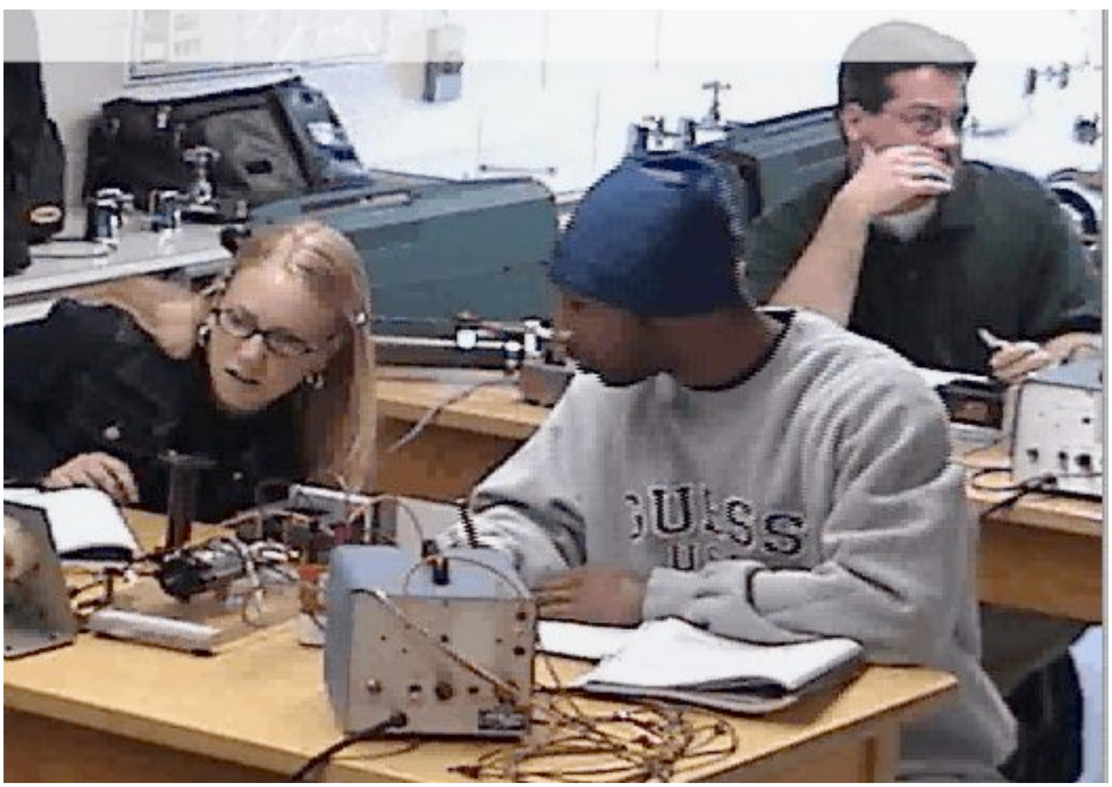


Figure 7. Students in a traditional lab.

Shown below is the setup of a reformed lab. Students work together in groups of four, at a desk small enough for everyone to get in everyone else's face. It is no surprise that a lot more intra-group conversation occurs when you turn them towards each other, or that much more interesting social interactions occur in larger groups. This was demonstrated in Lippmann (ibid.) after this change was made.

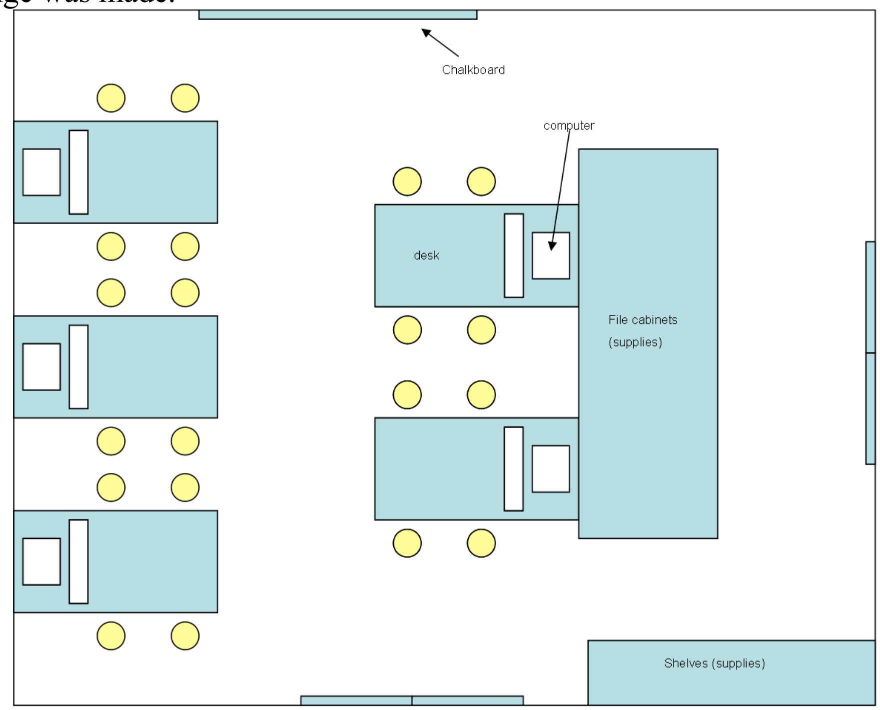


Figure 8. Scientific community laboratory architecture

Assigning Roles

As a consequence of the previous reforms, the groups found themselves with a great deal of work to do. Unfortunately, much time can be wasted when students aren't sure how to divide up the tasks. I observed, as a TA teaching traditional labs, that what frequently occurs is that one student will, for whatever reason, take over the lion's share of the work, with his or her partner doing next to nothing. Even in our reformed labs, with four members to a group, one student sometimes tended to dominate. We decided that it would be necessary to intervene for the sake of guiding the students towards a clearer and fairer division of labor. Inspired by the work of Johnson & Johnson (1993), rotating "roles" were assigned to the four group members:

Roles

The Journalist: Keeps notes throughout the lab, writes the "Journal" section of the lab report.
The Data Interpreter: Deals specifically with the illustration and interpretation of data.
The Critic: Acts as liaison with other groups, suggests improvements, writes "Evaluation".
The Checker: Checks the lab report as a whole at the

Figure 9.

Scientific community laboratory roles

It was not our intention to rigidly control the behavior of each student, nor is it our assumption that students are able to operate purely within the confines of such a classification system and produce anything of value. The purpose of assigning roles was to make the cooperative process a bit easier by eliminating the need to spend much time deciding who does what, and, by making the roles rotate, to be sure the students learn all aspects of the lab, rather than choosing to simplify their tasks by becoming specialists. Beginning a large and involved activity with little guidance is extremely difficult. Giving the students a very general idea of what is expected of each individual prevents much awkwardness, and can hasten the natural process by which the members themselves decide how to divvy up the labor.

Another goal of assigning roles was to achieve what Johnson & Johnson (ibid.) refer to as *group interdependence*. While the group is judged by their collective performance, it is best for the students to understand what they are primarily responsible for *individually,* so that they have a better idea where they fit into the group. As a member of a group, one not only has responsibility for one's own performance, but also a degree of responsibility for the performance of others. This point was articulated to the students early and frequently. Assigning roles also helps clarify what is expected of each group member. The uncertainty of not knowing what one is supposed to be doing can completely hinder creative thought. A brief guideline of where to start can help avoid awkward silences and get them started thinking.

Including Class Interaction

A scientist must be able to interact in a number of different communities. We wanted our students not only to be able to interact constructively with their collaborators, but with the other groups as well. With this in mind, we arranged for a "Class Discussion" segment at the end of the lab period, in which each group presents its data and conclusions, and then is expected to deal with criticisms from the rest of the "community." The class as a whole, like the group as a whole, can be a valuable tool in the laboratory, a source of information, ideas, and constructive criticism. But like the group, the class also takes effort to figure out how to operate. After all, what does a student have to gain from criticizing his peers, other than to earn their distrust and ire?

The message we wanted to send to the students was that the purpose of interacting in a larger community is not necessary only for the larger community's sake, but because doing so can help you, or your group, individually. Constructive criticism, after all, should construct something. Plus, if the class as a whole can develop its own dynamics, the way good teamwork can develop in a group of four, students can "use" the class community in the same way that they use the group community and the other resources at their disposal.

In order to create the need for a vibrant and effective class discussion, we set forth a requirement in the lab report that each group must, by talking to and listening to their peers, develop some concrete ideas about how they could improve their experiment if they were to do it again. Part of the lab report was an evaluation in which the students had to discuss these improvements and how they came to their attention. The underlying message is that they are all in this together. If no constructive class discussion takes place, nobody gets the points. If it does take place, everyone prospers. This, we feel, was an appropriate simulation of a "real" scientific community. Students come to learn that the measure of their work's quality is not just the judgment of the instructor, but that of their peers. If they are to learn anything from the other groups, they must figure out how to communicate with them as well. Also, a scientific community does not just accept results. Its job is to challenge and refine in order to produce a communal result that is right, stable, and better than any individual or single group can produce for themselves.

Encouraging the Lab Instructors to Give the Students Some Space

Another major reform of this laboratory was in how the lab instructors themselves were trained to handle these reformed labs. We instructed the lab TAs to give the students more space and autonomy then perhaps they may have been accustomed to giving. This meant perhaps not giving students ideas when they were stuck, not directing the class discussion when nobody seems to have anything to say, or not approving of or disapproving of a weak experimental design a group may not be sure about. The goal was to take those tasks that students naturally associate with the instructor and to give those back to the students themselves. One way of looking at it is that we refrain from doing for the students what the individual students cannot do, in the hopes that they might construct a well-functioning group that *can* do these things. On the other hand, it is not desirable to remove the TA from the class entirely. Their function as a guide is to raise questions in a way that, hopefully, the students will learn to develop their own "inner TA" and begin asking those questions themselves.

The Reformed Labs in Action

The result of these various reforms was a new class that resembled traditional labs in only superficial ways. The students in these labs spent a great deal of time engaging in lively discussion about the topics most relevant to experimental physics: what the best way to design an experiment is, how to minimize error, how to interpret data, and how to build a convincing case for your argument. These labs required a wide spectrum of different activities - so many of them, that no single person could finish a lab in the allotted time. Developing a well-functioning group is necessary for these tasks.

Naturally, the students were typically quite overwhelmed at first with the new class structure. For the first few weeks, they were frustrated with the lack of guidance. However, after a few weeks, most groups tended to "get it" and become comfortable with not knowing the results ahead of time. When enough of the groups learned to function as units, one could see interesting social dynamics develop in the class as a whole. In a few cases, the students were able to conduct the end-of-lab discussions and debates on their own, with a minimum of instructor interference. Getting the students to this point was not an easy process.

Conclusion

What we accomplished over the course of the four year project was a radical transformation of the traditional labs. The reformed labs tackle different issues than those of traditional labs, but they have the advantage that the activities, rather than being quasi-individual activities, have a strong social element to them. Cooperation at the group level is necessary, as is cooperation as a class.

What was remarkable was the amount of genuine student interaction that took place in these labs. After a few weeks, many of the groups were engaging in a number of different strategies to tackle the difficult goals we set before them. It was this kind of activity that allowed a group to act as more than the sum of its parts, and generally this led to these students accomplishing the goal of the lab and producing remarkable lab reports. This kind of teamwork, I determined, was worth a detailed study.

Chapter 4: Introduction to Epistemic Games in the Laboratory

Introduction

The laboratory activities included in the SCL-1 and SCL-2 labs are more difficult for students than they seem to faculty. In order for a group to complete the lab, a sequence of sub-goals must be accomplished. Initially, the students must determine exactly what the question is asking and what constitutes the answer. Next, they need to formulate a plan of action. Then, they need to construct an experimental apparatus and collect a certain amount of data. Finally, they need to build a persuasive explanation of their data. Each of these steps can consist of a sequence of sub-steps.

Because this activity consists of so many different goals, which typically need to be accomplished in a particular order, the concept of *goal-oriented action* will be important to our analysis of their behavior. Doing a laboratory activity is not supposed to be like cleaning a house, wherein many contributors can "pitch in" and accomplish the task without a sophisticated sense of purpose, cooperation, and synchronization. Rather, they are *sequentially constrained*, in that accomplishing one part of the task will affect what needs to be done next. In the presence of sequential constraints, it is necessary to have a certain amount of central control over what the members do. Productive laboratory group work is characterized by a shared sense of purpose, which can change, as needed, in response to what is accomplished. Understanding how a group functions requires one to consider both what the individuals believe is occurring, and then on a different level, what elements are shared among the group.

In the previous chapter, I discussed various means of describing and understanding group activity. Since group activity consists of many dimensions of complexity, a researcher has many different lenses with which to view the same occurrences. In this chapter, I discuss the concept of *epistemic games,* which are coherent activities engaged in for the purpose of accomplishing a specific goal. I define and discuss five epistemic games that characterize most of the behavior observed in my data set, and give examples of them from the video transcriptions. These will provide the unit of analysis for considering purposeful activity in the laboratory.

Previous Research on Epistemic Games

In this section, I present two distinct approaches to the subject of epistemic games: the formulation of Collins and Ferguson, which identifies epistemic games as expert strategies for the construction of knowledge, and the formulation of Tuminaro and Redish, which uses epistemic games to describe locally coherent strategies created by students, which are sometimes tacit and unarticulated. By "locally coherent", I am referring to strategies that consist of a finite set of associated moves, while excluding other moves on the basis of relevance.

Collins & Ferguson: Epistemic Games as Expert Strategies

Collins and Ferguson (1993) introduced the concept of epistemic games to describe strategies used in science and social studies for the purpose of guiding inquiry. According to them, the knowledge base used by researchers, i.e. the facts, equations, and concepts accumulated by the community, are not the only resources necessary to perform in the field. Equally important as these components is the means by which they are organized and processed. They describe *epistemic forms* as target structures that guide inquiry, and *epistemic games* as the rules and strategies used in pursuit of these structures.

A simple example of an epistemic game is list-making. In this task, the epistemic form, or the end-product of the activity, is the list itself. Although everyone knows right away how to make a list, up close we can see that this simple activity is governed by implicit constraints and allows the participant to engage in a limited set of sub-activities. As an epistemic game, it has the following components: *entry conditions, ending conditions,* and *moves.* The entry conditions are that which signals the need for this particular game. Examples of such conditions would be sending out wedding invitations, planning a trip to the grocery store, or simply bringing several similar objects out of long-term memory into working memory. The ending conditions are that which signals that the game has been completed, or "won." In making a list, one has completed the game when the target quantity (the list) is acquired, it is complete, no item is repeated, and no item can be divided into a number of items. The moves in list-making would include adding items, deleting items, combining items, splitting an item into pieces, or changing the specifications of the list itself.

An epistemic game is "epistemic" in the sense that it builds new knowledge. In making a list, one can draw upon a variety of sources. If I were to construct a list, for example, of presidents who served one term in office, I might draw from my recollection of events I myself witnessed (George Bush) or my memory of historical facts (John Adams, Jimmy Carter), and I might have to go hunting in a book for the rest of them. In this case, the epistemic game is a means of collecting information from different sources and constructing a new (for me) piece of knowledge. But it is not necessary for this information to be collected from an outside source. In constructing a grocery list, I can say that each item on that list, and the fact that I need such a thing, was a piece of knowledge I already possessed. Nevertheless, the list itself is considered new knowledge, even though it consists of old knowledge; the organization is new.

Collins and Ferguson describe many such epistemic games used in professional research for the organization of old knowledge into new knowledge such as cost-benefit analysis, stage models, multicausal analysis, and constraint systems. The purpose of illuminating the existence of these games is to demonstrate the importance of the methods, as opposed to the knowledge base, in the acquisition of knowledge, and to suggest that schools place more focus on the teaching of epistemic games, instead of merely drilling students in memorization of the facts themselves, which in many cases can be easily looked up. For instance, students of physics should be instructed in how discipline-specific epistemic forms, such as equations, graphs, Feynman diagrams etc. fit into grander schemes of physics knowledge construction, rather than merely ends in themselves.

Tuminaro: Epistemic Games as Strategies per Se

Tuminaro and Redish (2005) use the concept of epistemic games to describe the activities of students engaged in mathematical problem-solving in an introductory algebra-based physics course. Whereas Collins and Ferguson's epistemic games are expert strategies, used by professional researchers and consequently are well thought-out and typically successful, Tuminaro expanded the definition to include *any* coherent strategy. The definition he uses comes from Redish (2004):

A coherent activity that uses particular kinds of knowledge and processes associated with that knowledge to create knowledge or solve a problem.

Like Collins and Ferguson's epistemic games, Tuminaro's epistemic games are purposeful, coherent activities. However, since Tuminaro uses these games descriptively, rather than normatively, he includes all emergent strategies, even those that may be unproductive or damaging. He demonstrates the existence of several specific epistemic games being played by students engaged in solving homework problems. While the use of an appropriate epistemic game can lead to new knowledge and a solution to the problem, he also shows how certain games, motivated by incorrect expectations or poor epistemologies, can lead to commonly-made mistakes and endless loops of non-productive behavior.

An important characteristic of the epistemic games proposed by Tuminaro is not just the entry conditions, ending conditions, and allowed moves; Tuminaro observed that games tended to be *exclusionary.* Often a student playing a particular epistemic game would consistently ignore (or even actively resist in response to an instructor's suggestion) certain moves that an expert might consider appropriate for solving that problem, even though data taken in other contexts showed the student perfectly capable of carrying it out.

Epistemic Games as Group Activities

As previously mentioned, I seek to describe laboratory group-work with a focus on the intended goals of the various activities associated with it. I use epistemic games for this purpose, as they can be defined by these intended goals and by the set of allowed moves, both of which can be observed or inferred through analysis of student conversation. Epistemic games provide a means by which one can make sense of group work. They allow us to address "what the students are playing at" and "what the students are working towards."

Like Tuminaro, I use epistemic games to describe what students actually do, rather than using them normatively to describe preferred methods. Students in our SCL labs in general do not behave as directed by the instructor, even when a well-defined method is specifically suggested. Simple suggestions to "change their mode of thinking" tend not to be effective. In these laboratory activities, they are given few instructions, and therefore have to rely on their own devices, logic, and methods to apprehend and accomplish the activity. It is this intuitive activity I am most interested in; a judgment of what students should do needs to take these activities into account.

As I mentioned in chapter two, researchers in situated cognition seek to expand the definition of cognition to include group activities. I do not imply that a group can play an epistemic game in the same way that an individual plays an epistemic game. For example, a necessary component of an epistemic game is the intended goal, or ending conditions. When a group is "playing" an epistemic game, we have no reason to assume *a priori* that each member shares a common goal. Games can be identified by the characteristic moves, even if the intended goal is not understood. Nevertheless, I use the phrase "playing a game" to imply an understanding of the intended goal, while it is possible for one to "participate" in a game without such an understanding.

I should also mention that epistemic games need to be differentiated from games *per se.* What makes epistemic games epistemic is that they are involved in construction of knowledge.

Since a necessary component of an epistemic game is the ending conditions and epistemic form, i.e. the intended goal, we can also say that epistemic games are *purposeful* activities. One may argue that people are *always* engaged in purposeful activities, unless they are acting randomly, and in which case the randomness is most likely the intended goal. Indeed, just about any activity can be described in terms of intention. However, not every activity has as its goal the building of knowledge. Hence, epistemic games are differentiated from other activities in that they are *epistemically purposeful.*

In the following section, I propose five epistemic games that describe the observed behavior of groups of students in the laboratory. They were formulated through a process of closely examining video footage in order to ascertain the overarching goal of the activity, and to identify the set of activities and knowledge elements being used and the general strategy being applied to use these tools in the pursuit of their goal.

Collins & Ferguson Epistemic games (1993)	**Tuminaro Epistemic Games (2004)**	**Gresser Epistemic Games (2005)**
• List-making • Compare and contrast • Cost-benefit analysis • Primitive elements • Cross-product or table • Tree-structure or hierarchy • Axiom systems	• Mapping Meaning to Mathematics • Mapping Mathematics to Meaning • Physical Mechanism Game • Pictorial Analysis • Recursive Plug-and-Chug • Transliteration to Mathematics	• Evaluative and Concretizing Plan-Making • Equation Bridging • Recursive Equation Bridging • Strategic Mapping • Exploration

Table 1. List of epistemic games across three contexts.

On the Process of Constructing Epistemic Games

Over the course of this research project, around 400 hours of laboratory activity was captured on videotape. For this particular project, 35 hours were selected for viewing, and they depicted a number of groups engaged in three specific laboratory activities. The lab instructors had recommended these specific groups on the basis of their relative articulateness; the lab activities were chosen because we felt that they represented the biggest challenge for planning, designing, and making sense of the physics involved.

Initially I had hypothesized that the productivity of the groups depended most heavily on the students' individual personalities, and that success in a lab group depended on complementary *combinations* of such personalities. Four laboratories were viewed several times and transcribed, and with this data, I attempted to categorize the students using a number of classification frameworks, including those of Shepardson (1996), Richmond & Striley (1996), and Belbin (1981). The goal was two-fold: determine whether or not the group was operating in a productive way, and identify what roles were being played out by the participants.

The main difficulty facing this analysis was an observed lack of stability within the groups. A group of students that appeared to be cooperating constructively one minute might all of a sudden start spinning their wheels in an unproductive activity. Students who appeared to be leading during one clip would be found, several minutes later, taking orders or not participating at all. And in one case, the incessant banter of one pair of students seemed to be distracting and intimidating to the rest of the group was observed later, in another context, to be helping keep a vital discussion alive. How does one go about categorizing this kind of behavior, when the context seems to be the determining whether it is helping or hurting the group? It became clear, as more and more videos were watched, that the context itself might be the component of group work worth closer analysis.

One thing, however, was certain: the roles we had assigned to the students, inspired by Johnson & Johnson (1989, 1993) were not being assumed in any meaningful way. The chief goal of these roles was to assist the students during the getting-to-know-you phase, so that each student would have something specific to do. But a secondary goal was to nudge them into a group configuration that we believed would be productive. A good group, we theorized, must have at least one member consistently bringing the discussion around to address what data would be collected, while another member must be responsible for coordinating the various members' work. But we did not observe, for example, a "data-interpreter" consistently dealing with data, nor did we observe the other members refraining from data-specific issues. Rather, the groups seemed to, at times, go into "data mode", wherein each member would assume some of this role's responsibilities. Modes seemed to be a powerful influence on the groups' activities.

It was frustrating, not being able to identify these patterns in individual student behavior. But this led us to question, if observable personality traits and interactions are transitory, what exactly does remain constant? Reviewing the same laboratories led to me to hypothesize that the students operated within "modes" lasting on the order of a few minutes at a time, and that these modes could be the way in which the students were apprehending and dealing with the laboratory task at hand.

Epistemological framing describes how a student might "interpret" a task, and how this interpretation leads to the activation of specific sets of knowledge, skills, and behavior appropriate to that context. This is a productive tool with which to describe these observed modes and why shifts in focus and behavior were so common. But the activity observed was even more structured than just that. These modes, when observed closely, appeared to be characterized by systems of unspoken rules and the pursuit of a common goal, which was sometimes unspoken as well. This is what led to the decision to use epistemic games to describe laboratory group work as locally coherent behavior.

The task of forumulating epistemic games began with determining what the goals, or perceived end-games, of the students were. In rare instances, the students explicitly state what they are attempting to do, but in most cases this must be inferred from the conversation. Another obstacle was in the fact that many games do not play out to conclusion. Nevertheless, observing what the students are trying to determine and what sorts of events lead them to "move on" give strong evidence as to what the goals of the games are. When a block of activity is identified and a goal is determined, the next step is to figure out what moves are being used and what moves are not. Through this process, many potential epistemic games were constructed to describe what was being observed.

But epistemic games can not be of much use to us if we must invent a new one to describe every instance of locally coherent behavior. It is only useful if a finite number of games can be used to describe most of what is seen in the laboratory. After watching many laboratories, some games were modified and some were determined to be the same game and combined. After five well-defined epistemic games were identified, those we will explore in this chapter, most of the locally coherent behavior we observed in lab could be described by one of these games. This convergence suggests that the students have a limited range of games at their disposal[6], that they do not merely play a new game every time a new situation rears its head. In this thesis, we have taken as our goal to identify a few important and frequently recurring games and to explore their characteristics and effects on the group behavior.

Evaluative and Concretizing Plan-Making

The first game we will examine I call *Evaluative and Concretizing Plan-Making*. This is typically a very productive game for students choosing an experiment that answers the lab question, and it serves as a standard to which other games can be compared.

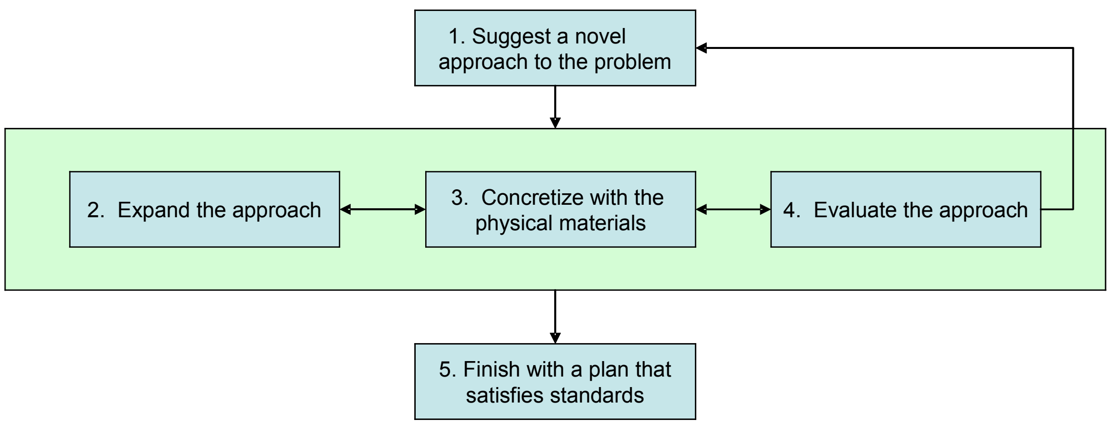


Figure 10. Schematic diagram of students' moves with *Evaluative and Concretizing Plan-Making*

This game begins when a suggestion of a novel approach to the problem is made by one of the students. The goal of this activity is to construct a plan on how to proceed through the experiment, using this suggestion as the central idea. We can say that a *round* of this game lasts as long as this suggestion is *in play*, or as long as the suggestion is being acted upon.

The initial idea which starts the game is typically a quick suggestion, rather than a complete plan. It serves to focus the conversation and thought onto the same issues. We can identify this opening move when a student makes a statement that begins with, "What if we did…" or "Let's try…" This is how one signals to the group that one wants to play this particular game.

[6] At least insofar as they can be observed using the methodology described herein.

We can tell that this game is an example of "locally coherent behavior" not just by the actions engaged in, but by those actions excluded from the activity. When a round of Evaluative and Concretizing Plan-Making begins, the game includes discussion about the idea put forth. Statements that are not concerned with the idea in play are interpreted by the other group members as moves to end the game. If these statements are not ignored, they initiate another round of the game focusing on another idea, or signal the end of the game.

There are three classes of moves appropriate for this game. The first is labeled on Figure 9 as "Expand the approach." These are moves that, in general, add to the idea in play. This would include fleshing the idea out and adding detail to it. The second class of moves is labeled "Concretize with the physical materials." These moves are attempts to make the idea realistic by applying it to the materials they have available. The importance of this class of moves is most obvious when a group *isn't* considering how to practically apply their idea. Concretization suggests an implicit goal that the plan they are working towards cannot be merely a theoretical solution to the problem, but it must be physically realized. The third class of moves is labeled "Evaluate the approach." Evaluating involves testing the idea against the group's sense of what constitutes a good, complete plan. Examples of this kind of move would be questioning whether or not the plan is doable, realistic, or easy, or able to yield the data necessary for the assignment. The extent to which an idea is evaluated varies from group to group, as does and the character of these evaluations. The evaluative moves also suggest a more subtle dimension to the intended goal of the game. The idea is to construct a plan that not only is physically realized, but satisfies certain standards the group members consider essential before moving to the next step or game.

The epistemic form of this game is the plan of the experiment. That which makes this game unique, however, are the features of this plan, specifically that it is a plan that both satisfies certain criteria as set by the group members and has been demonstrated with the physical materials as realistic. This plan is technically not a complete and detailed plan of an experiment, since the students frequently follow up this game with further tests, such as appealing to the lab instructor for approval or the physical implementation of the plan. We can think of a group's plan as having several levels of completeness, and within Evaluative and Concretizing Plan-Making, the goal is to construct a plan that satisfies a certain collection of tests. In short, the idea must be complete enough, realistic enough, and devoid of problems to the extent that the group is ready to commit to the idea and move on to the next stage (and game).

Two examples of Evaluative and Concretizing Plan-Making

We can observe an instance of *Evaluative and Concretizing Plan-Making* in the following transcript of a group of students (labeled as "Group 1" in Appendix A) engaged in laboratory activity #5 (see Appendix B). The goal of this activity is to determine how the force between two magnets depends on the distance between them. The group has at its disposal a spring, a force probe, and various other materials. Magnets are provided to the group after they check in with the instructor with a plan on how to proceed.

Lab 5: Magnetic Force, Part One

When you hold two magnets close to one another, they feel either an attraction or a repulsive force between them, depending on their orientation. It appears that the magnitude of this force depends on the distance between the two magnets. But how?

Question: How does the force between two magnets change if you change the distance between them?

Pre-lab discussion	Whole Class	10 minutes
Planning the experiment	Groups of 4	20 minutes
Data collection	Groups of 4	20 minutes
Class discussion	Whole Class	20 minutes
More data collection	Groups of 4	30 minutes
Writing the report	Groups of 4	10 minutes

Figure 11. SCL-2 “magnet lab”

In the following excerpts, the statements are coded to correspond to the boxes in the game diagram.

1	**BELINDA:** But if you can measure... if you can do the spring the first one, and then put a second one... and then you can look at how much the spring changes, the length of the spring, and come up with a force that way.

She is suggesting they attach one magnet to the spring and hold the other magnet a distance away, allowing the group to measure the displacement of the spring.

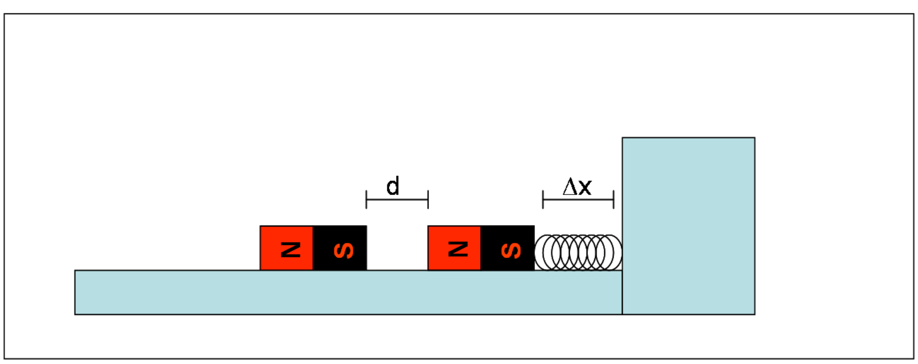


Figure 12. Idea setup

This is a novel approach that has not been discussed before by this group in the lab period. Her statement begins this round of Evaluative and Concretizing Plan-Making.

2	**DORIA:** And just say like, force is X K.
4	**BELINDA:** But, yeah, cause K is constant.
4?	**DORIA:** Right.
4	**ANGIE:** He said we're looking at relative[7]. So we don't have to know exactly what it is, we're just looking for relative.
2 or 1 **3**	**BELINDA:** So, force equals delta K... delta C... K is going to be constant anyway, so and we're relatively speaking. Hook up your spring, and at the bottom you have a magnet. Then you hold the magnet at different lengths... away.. from whatever...
	DORIA: Whatever the change...
3	**BELINDA:** This'll be measured... oh no, this'll be measured.
	DORIA: Right.

Doria and Angie are now working within Belinda's idea-space. They explicitly validate the idea ("Yeah"), add to the idea ("And just say like, force is K X"), and describe the benefits of the idea ("So we don't have to know exactly what it is, we're just looking for relative.") Belinda also takes the idea forward further.

3/4	**BELINDA:** The change in spring. How easy will that be though? We need a pretty pliable spring. Not something taut, cause if it's real taut you won't be able to see a difference.
	DORIA: Right.
	(Angie leaves)
3	**CONSUELA:** Are we going to hang it... hang it down...?
4	**BELINDA:** Yeah, I think it needs to be. Because the spring will... will have a bigger change when it's hanging.
4	**DORIA:** But the magnet's pretty heavy. We're going to have to... we can't have a too flimsy spring, because then it won't have anywhere to go.
3	**BELINDA:** That's the only thing... can we hang it from like... can we hang it from higher? Because, otherwise how are you going to...

[7] This refers to an earlier comment by the lab instructor that they need only to determine functional dependence, not the absolute force value.

3	**DORIA:** Suck. Well we need to feel how heavy the frickin' magnets are.

Now the group is making attempts to concretize, or see how this idea will work with the actual equipment. They also are beginning to ask evaluative questions, such as "How easy will that be though?" and clarifying questions, such as "Can we hang it from higher?" and "Are we going to hang it… hang it down?" Notice that the group's idea is going from a general abstract idea to a very specific, concrete one, as the members attempt to define precisely how it will be implemented.

CONSUELA: That's what I mean.
DORIA: Are we not allowed to take it?
CONSUELA: We just need an idea, and then he'll give us the magnets, he said.
ANGIE: This one doesn't require a lot of force.
DORIA: Oh [TA]... can we have a magnet?
BELINDA: Well can we talk to him about our thing?
DORIA: Yes. It sucks. But I mean...
BELINDA: Oh yeah, we have a question...

Here the group is negotiating the end-game. According to the instructions of the lab, before the group is allowed to receive the magnets they need to present a plan to the lab instructor. Consuela articulates these terms to the group when she says, "We just need an idea, and then he'll give us the magnets, he said." This external constraint has shaped this group's understanding of how one "wins" the Evaluative and Concretizing Plan-Making Game, or more specifically how developed the plan must be before their work at this stage is done. "We just need an idea" implies that the group has an understanding that their plan does not need to be a complete procedure. However, their moves within this game suggest a shared concept of just how developed it must be before they have an idea ready to present to the instructor. It must be fleshed out, concretized, doable, and not too difficult. These are the standards that define an idea that is good enough for them at this stage. In the next stage, the idea is brought before the instructor, who may have different standards by which to judge this idea. The tacit approval of the idea and the sentiment that it is ready to be sent to the next judge is evidence that this game has been "won."

Another example of Evaluative and Concretizing Plan-Making can be seen in this clip of Group 2, also engaged in this magnet experiment. In this class, the magnets are available to the groups along with the rest of the equipment. However, a check-in with the instructor is still required before they can proceed with data collection.

4 **3**	**DAPHNE:** So we need to think if this is going to work. I don't see why that wouldn't work. Cause what would be changing is like, make… we'd have this magnet at this distance, this distance, and this distance, and measure how far it would...
4	**BONNIE:** What are we measuring exactly?

2	**DAPHNE:** If we change the distance then we're finding the force. I think what he said was, you have to vary one of the two... to figure it out. And I have no idea how you vary the force. I guess by changing the different magnets or something? You can't change the charge of the magnets. So if we measure the distance, then if this force is proportional to this force, then we're measuring the force.

Daphne is referring to an idea that they had been whispering about during the TA's instructions. The idea is to hold one magnet fixed and attach the other magnet to a spring. With this setup, they can vary and measure the distance between the two magnets. When she says "if this force is proportional to this force," she means that the force between the magnets is equal to the force applied to the spring. How they can measure the force on the spring has not been determined or discussed.

3	**CATHY:** So how would we get the spring first of all to lay like... straight?
2	**DAPHNE:** We can do it with the one we did last semester.
2	**CATHY:** And so we would measure how far it... like we would measure the distance of the spring at like...
2	**DAPHNE:** The change of the spring. The change in distance of the spring.
2	**CATHY:** All right. It's worth a try.
3	**DAPHNE:** We can try and see what... let me get the magnets.
3	**ASHLEY:** I'll get the spring.
3	**CATHY:** And maybe some silly putty too.

We know from the explicit instructions of the lab that an idea must satisfy the instructor in order for the group to take data, and therefore that an idea must satisfy the group's standards before it will be brought before the instructor. We can think of these as two levels of commitment to the idea. Here we can see a third level. The idea has been suggested by Daphne. Cathy makes an attempt to concretize the idea. Daphne appears to have an idea of how to measure the force. Cathy remarks that this idea is "worth a try," and the group members demonstrate agreement with this by going to get the specific materials. Apparently there is a level of approval they have reached on the idea so far, that it is worth investing the time and effort necessary to collect the materials, presumably so that they may further concretize the idea and determine whether it is doable, appropriate, and easy.

	BONNIE: Okay, I don't quite understand what we're doing. Which is not good, cause I'm the journal person.

2	**CATHY:** We have to measure both of these, though.
2	**BONNIE:** Right, but we vary one. Yeah, we have to find some way of measuring force based on the spring. I'm not sure how it works.
	CATHY: Ummm...
3	**BONNIE:** Those are strong magnets.
4	**CATHY:** See, I don't think they're so... look... like, I really don't think they're gonna... move a spring.
3	**BONNIE:** Yeah, once the distance...
3	**CATHY:** Cause, in order to get the...
3	**BONNIE:** The other thing is, there aren't going to be a lot of distances, cause one you get it like two inches away or so, it stops...
3	**CATHY:** Then I guess maybe it moves... So we would have to keep... we would have to keep one of them... in place, right? It would have to be like... that doesn't do anything... that doesn't do anything.
3	**BONNIE:** So we do the other side too, the attraction side (**CATHY:** Yeah) So like, turn one around... see how close they can get to...
3	**CATHY:** It's gonna be really hard because... it's not gonna pull back... it's gonna get to a point and automatically it's just gonna go this way.
	BONNIE: Yeah. So we I guess find this point, like, if you, can you hold it back so far... and it won't do anything...

In this dialogue, Bonnie admits to not understanding the idea in play, while Cathy does seem to understand it so far. At first, Cathy's moves generally describe or expand the idea ("We have to measure both of these, though."), while Bonnie's moves, at first requesting clarification, are generally evaluative ("The other thing is, there aren't going to be a lot of distances, cause one you get it like two inches away or so, it stops...") Eventually, however, Cathy starts making evaluative moves as well.

3	**DAPHNE:** See, the idea is you tape this on and hold it like... I guess we'd have to hold the other side of the spring fixed, wouldn't we?
	BONNIE: *laughs* That spring is...
3	DAPHNE: We wanted a stretchier one cause it's gonna be... it won't... if the spring isn't stretchy enough then these probably won't even come together.
	BONNIE: Oh, yeah, I know.
3	**DAPHNE:** But we have to hold this side fixed, don't we?

	BONNIE: Yeah.

As the other groups return with the equipment, we see more attempts at concretization.

As in the previous example, this group is operating within a narrow idea-space representing the idea Daphne has put into play. What they do with this idea can be classified as pushing the idea forward through explanation and expansion, determining how to physically realize the idea, or evaluating the idea against certain standards. The game of Evaluative and Concretizing Plan-Making proceeds with these moves until either the idea satisfies the group, at which they can commit to this idea and move on to another activity, or the idea is abandoned. This is what we hoped they would be doing at this particular point in time: thinking about how an experiment produces a result.

Equation Bridging

In general, the epistemic form that guides behavior through a complex activity such as a laboratory experiment, which requires the organization of many different ideas and actions, will be a plan of how to design the experiment and organize information. In general it will be a collection of things that the group is able to do, and a general understanding of how those things might lead to the goal of the experiment. In the previous game, students begin with a general idea, and proceed to build a detailed plan around it. It is a game by which the players attempt to navigate from what they know to what they need, and in the process, accumulate the list of actions and concepts necessary. But this is not the only approach available to the students.

Equation Bridging represents a method of solving a problem that is much simpler than Evaluative and Concretizing Plan-Making. In this game, the intended goal is to find a single equation that will yield the target quantity or quantities. It suggests an expectation much like the "plug and chug" approach to problem-solving (Tuminaro, 2003), in which the goal of the exercise is to find that particular equation into which obvious things can be put in and the "answer" drops out. Unlike plug and chug, equation bridging includes experimentation as a source of information, rather than relying exclusively on what's present within the equations. This equation is the epistemic form, an artifact that acts as a "bridge" between what the students already know or can determine easily and the target quantity.

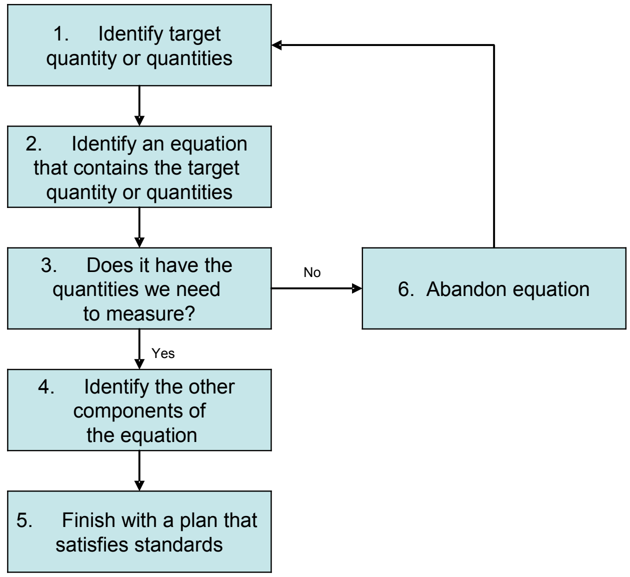


Figure 13. Schematic diagram of students' moves with *Equation Bridging*

In order for this game to begin, the target quantity or quantities must be identified. Equations are then suggested on the grounds that they contain the target quantity, rather than how closely they seem to relate to what's going on physically. "Getting" the target quantity, then, is a game of determining the other components of the equation. If they cannot be determined, or if the equation turns out to be inappropriate for the task, it is abandoned. In this event, the game is played again with another equation until what they believe to be the correct equation is discovered, or until the game is abandoned.

An example of Equation Bridging

Here we see Group #1 playing Equation Bridging in the magnetic force experiment. This example occurs before the previous clip in which this group utilizes Concretizing and Evaluative Plan-Making.

	BELINDA: We can measure the area of the magnet.
	DORIA: But how do we measure...
	BELINDA: Pressure...
2	**ANGIE:** But it's not... pressure times area...
3	**CONSUELA:** It's magnetic force...
2	**BELINDA:** Oh yeah, it's E Q.
3 **2**	**DORIA:** No, but that's electric. Force of a magnet is just F equals Q V B sine theta. There's no distance in it.
	BELINDA: Where are you coming up with that?
	DORIA: It's in the book. And it's in... haven't you learned it for MCATs yet?
	BELINDA: No.
	DORIA: Really?

	BELINDA: Really.
	DORIA: That's the hardest stuff.
	CONSUELA: Oh gosh.
	BELINDA: Hey when do you get your scores back?
	CONSUELA: I know, that's what you guys just said, and I was like oh yeah...
2 3 4	**BELINDA:** All right so F equals Q V B sine theta. What is this? Equal to M V squared over R. What's your R? Your radius?
3	**DORIA:** That's like the... because... well you see… not between two magnets. That's like... magnetic field caused by centripetal...
4	**BELINDA:** What is... what is B?
4	**DORIA:** B is the field strength of the magnet.
	BELINDA: But how are we going to measure any of that?
	DORIA: Yeah, I know. So I don't know how it depends on distance.
	CONSUELA: How the hell are we supposed to do this?
	BELINDA: All right. If you like...
	DORIA: I feel like it should be the same as like...

This group has attempted this game with four separate equations:

1. $F=PA$
2. $F=Eq$
3. $F=qvB\ sin(\theta)$
4. $F=(1/r)\ mv^2$

Angie suggests the first equation, F=PA (force equals pressure times area), and it is abandoned quickly on the grounds that the F in it doesn't apply to magnetic force. It seems to have been activated as a result of Belinda pointing out that it is possible to measure the area of the magnet. With force as the target quantity and area as an acquirable quantity, this equation, which had been used in a previous semester, is activated, and then quickly thrown out. This equation had been used in the previous semester, and the students quickly judge that it isn't the right *kind* of force.

Belinda proposes the second equation, F=Eq (force equals electric field times charge), which had been introduced recently in the course. It too is judged inappropriate on the grounds that it applies to "electric force" rather than "magnetic force."

The third equation, F=qvB sinθ (force equals charge times velocity times magnetic field times the sine of the angle between the velocity vector and the magnetic field vector), is suggested by Doria, who implies that she had discovered it through studying for the MCAT's, which are standardized tests that potential medical school students take during their junior year. I should point out again that this laboratory activity had been purposely assigned prior to the introduction of magnetism in lecture. The students were intended to explore magnetic force phenomenologically, using prior physics knowledge and skills. The students were not expected to have any knowledge about magnetism at their disposal. Doria brings in this equation, which the other students are unfamiliar with, and it is accepted as valid, for the time being.

Belinda suggests the fourth equation, $F=(1/r)mv^2$ (force equals mass times velocity squared divided by radius) seemingly as a response to the third equation. It is plausible that she is familiar with a problem in which a charged particle moves in a circle under the influence of a centripetal magnetic force (we will later examine games in which a problem is mapped onto a previous problem.) Whether this is the case or not, this fourth equation is put on the table and the group members set up about trying to determine what the various components are and how they can be measured.

Compared to Evaluative and Concretizing Plan-Making, the rules of Equation Bridging are simple. The goal is to find an appropriate equation that transforms *knowns* (such as the area of the magnet) into the target quantity, which is unknown. One starts a round of this game through the suggestion of an equation, which at the very least must contain the target quantity. If the equation is appropriate, i.e. it gives them the "right kind" of target quantity, the equation stays in play. If the other components of the equation are known, or the methods by which they can be determined are known, the game is won. If the equation fails their test of appropriateness, or contains unknown variables, either the group abandons the equation and begins a round with a new equation, or the game itself is abandoned for a different one, which is what we will see in the next section.

One hypothesis of what is going on here is that the equation bridge could be seen as "the answer;" that is, the students are still viewing the lab as trying to demonstrate a known result, and they are trying to decide what that result is. Since this result is given to them by authority, they tend to use authoritative resources rather than their own sense-making. Another, and more appropriate, equation that students might seek is an equation that would allow them to measure one of the two quantities they are trying to relate. Thus, "$F=-kx$" in the previous discussion allowed them to see that measuring the stretch of a spring might permit them to infer the force that the second magnet was exerting on the first.

Unfortunately, the goal of this epistemic game is inappropriate for the activity. They are attempting to find an equation that essentially answers the lab question for them, one that states the relationship between force and distance, while perhaps reducing the experimental goals to something trivial, like calculating a constant. The purpose of the lab, however, is to construct this relationship using experimental data. Even if this game were won, the most it would do for them is give them a theoretical answer that they could work towards. It would not avoid the necessity of designing an experiment. It is plausible that the students may have been playing this game in order to determine the "right" answer before starting.

Equally damaging to the students in this instance is that Equation Bridging, as an epistemic game, excludes certain activities as viable moves. The knowledge base they are accessing is the equations that can be found in the textbook, the students' notes, class materials, or from memory. They are *not* trying to make sense of the relationship between distance and force by intuition or through sense-making. They are not, as in Concretizing and Evaluative Plan-Making, thinking about how an experiment might yield the information they need. A basic idea that students may come up with is, just by thinking about the magnets themselves, that the force must be the strongest when they are right next to each other and diminishingly smaller as they get further away. This obvious fact says quite a bit about what sort of equations might relate force and distance. But since the students are stuck in a well-defined game of brainstorming equations and manipulating them, they do not access the common sense ideas that would help them. It is the *goal* guiding the behavior, rather than the behavior itself, that is inappropriate. This supports the idea of using epistemic games to describe and explain what students are doing.

It should be noted that this is the same group that engaged in Evaluative and Concretizing Plan-Making earlier in this chapter. It is interesting to note that, although this group is capable of interpretive and sense-making moves, they are choosing not to do this here. This group's choice of games is discussed in more detail in chapter six.

Another example of Equation Bridging:

CHUCK: Wasn't force mass times velocity?
BRANDON: Mass times acceleration.
ALLISON: We can see when at.. like at what height it... flipped over.
BRANDON: That's good.
ALLISON: Like here, feel it. Where exactly... does it go over. And then for here... oops, sorry. For here, like, where... it comes out.
(enter Django with spring)
BRANDON: There's K X squared. You just brought K X squared to the table. Thanks.
DJANGO: Hooray, but we don't know the spring constant!

This group has identified force as the target quantity. Chuck recalls force being "mass times velocity" (a common error), and is corrected by Brandon. Now, they do not discuss how one might go about measuring acceleration. Rather, Allison, who is clearly not merely looking for relevant equations (and hence not participating in the game), distracts Brandon momentarily with a physically realizable idea. Then Django arrives with a heavy duty spring, causing Brandon to identify it as "K X squared." It is possible that Brandon has recalled the equation of energy stored in a spring ($E = kx^2$), but more likely, since they are looking for equations with force, that he has made another common error, thinking that $F = kx^2$. Django is quick to note that this equation contains an unknown (and perhaps unknowable) quantity, k, the spring constant. Brandon believes they do not need this piece of information. As far as he is concerned, this game is over.

Recursive Equation Bridging

Equation Bridging is intended to be an easy solution to the problem of determining unknowns. Rarely in these labs will there be an activity for which thinking up the correct equation accomplishes a significant part of the task. They were designed to avoid such easy solutions. Nevertheless, a mathematical equation is frequently such a solution in standard homework assignments (see *Plug and Chug* in Tuminaro). While a single equation may not be the solution for the entire task, it frequently constitutes part of the solution, in conjunction with other equations, reasoning elements, and ideas.

Recursive Equation Bridging resembles Equation Bridging in many ways. As shown in Figure 13 below, the moves and move structures are nearly identical. One feature, however, is unique to Recursive Equation Bridging. In the event that an appropriate equation has been found but not all of the components of this equation, aside from the target quantity, are known, the possibility exists to continue the game by choosing a new target quantity, among the quantities which are unknown, and repeating the process.

The reason I classify this as a different game lies in the fact that it implies different intentions on the part of the players. Equation Bridging is intended as a one-step solution. Recursive Equation Bridging may require many steps, some sophisticated mathematical calculations, and a more complicated conceptual understanding of their solution. In Equation Bridging, the equation itself *is* the solution, while in Recursive Equation Bridging, the solution is an organization of different equations. The latter requires a much higher degree of active participation on the part of the players.

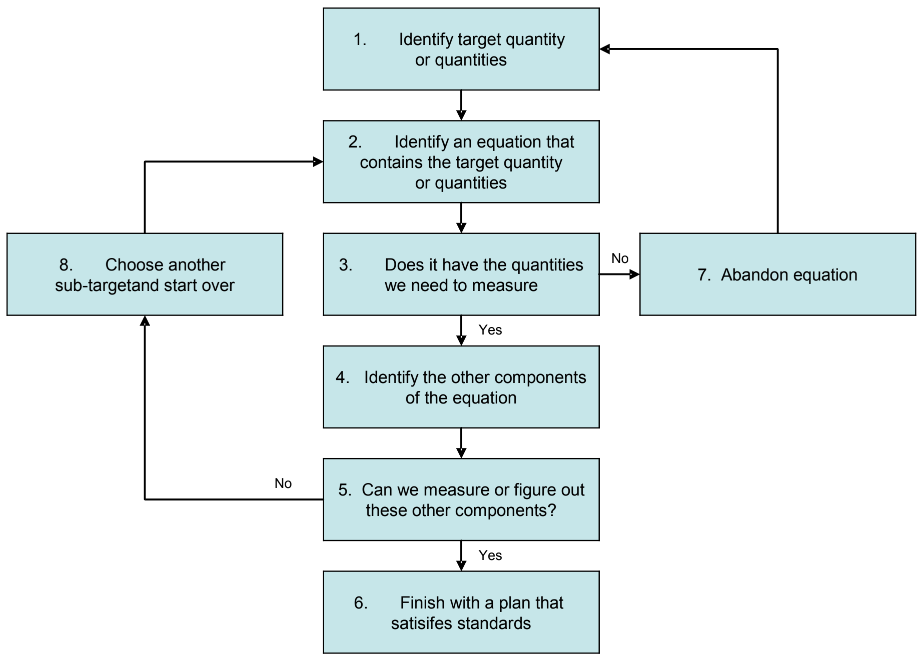


Figure 14. Schematic diagram of students' moves with *Recursive Equation Bridging*

An example of Recursive Equation Bridging

After four rounds of Equation Bridging, our Group #1 is going to make an attempt at Recursive Equation Bridging:

4	**DORIA:** B equals...
4	**BELINDA:** What is mu right there?
4	**DORIA:** Mu... is that thing... what is it called?! (slaps book) Mu is the permeability of free space, and we don't really have to know what it is.
5	**BELINDA:** Oh, so it's a constant.
5	**DORIA:** Right.
4	**BELINDA:** So good. So we know constant times what, current?
	DORIA: Yeah.

5	**BELINDA:** We don't know... how are we gonna measure current?! This is bad.

In a previous excerpt the group had identified F, or force, as the target quantity (see Figure 14 below, step 1). With Equation Bridging they were able to relate F to other things by using the magnetic force equation in SI units (step 2). This being the fourth unsuccessful attempt to relate F to terms they can measure or know, they identify a new target quantity (B) within that equation and attempt to play Recursive Equation Bridging (step 3), which yields the Biot-Savart Law. When they determine that this game has neither revealed F in terms of what they can measure or find out, the game ends unsuccessfully.

Goal: **Target quantity =** *In terms of quantities we know or can find out*

1) Target quantity $\mathbf{F} = ?$
2) Result of Equation Bridging $\mathbf{F} = q\, v\, \mathbf{B}\, sin(\theta)$
3) Result of Recursive Equation Bridging $\mathbf{B} = \mu\, \mathbf{I}$
4) What was not determined $\mathbf{I} = ?$

Figure 15. Two attempts to solve a problem using game strategies.

Strategic Mapping

In the previous examples of games, students attempted to formulate an approach to a problem presented to them. They use both internal resources, such as memorized formulae and intuition, and external resources, such as textbooks, notes, and instructions from the TA. These games are similar in structure, the idea being to *build* a plan from an initial idea. Sometimes, however, it is not necessary to build a new plan when a plan previously encountered will suffice.

Tuminaro (ibid.) proposes a game entitled *Transliteration to Mathematics.* The theory behind this game is based on research on problem-solving that suggests students attempt to apply previously used techniques to a new problem, even without a conceptual understanding of these techniques (Ben-Zeev, 1998). Indeed it is easy to recognize that a problem *looks like* something familiar based on shared features. The act of "transliterating" involves only the mapping of quantities from the current problem to the problem one is already familiar with, as opposed to "translating," which involves consideration of meaning.

Students play a similar game in the laboratory that I call *Strategic Mapping*. This game has a structure that looks like the reverse of the games we have already discussed. Rather than building up a plan from small ideas and pieces, the structure of the plan is suggested as an initial idea, and this is borrowed from an example that the players have seen previously. As in previous games, the epistemic form is the plan itself. The game begins with the recognition of a target quantity, followed by a suggestion of a previous solution pattern. With this pattern as a guide, certain features of the plan are already assumed. If they have gone through a similar problem, at the very least they know that the mathematics and computational tasks are within their grasp. The goal is to successfully map the current problem onto the previous pattern. The moves within Strategic Mapping can be seen in Figure 15.

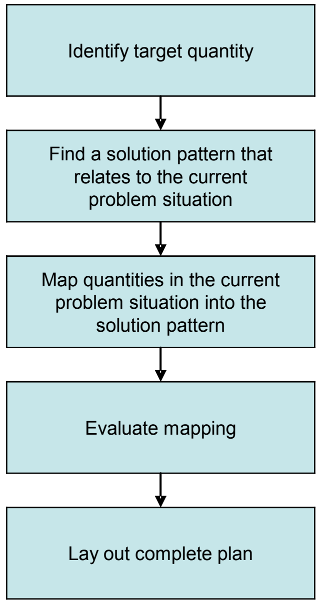


Figure 16. Schematic diagram of students' moves with *Strategic Mapping*

An example of Strategic Mapping

Strategic Mapping can be extremely difficult to identify if the moves are not made explicit by the players. The feature of this game that differentiates it from other games is in the nature of the idea suggested. A student playing this game may not necessarily come out and say that the idea he has put in play is part of a solution pattern he has already dealt with. Unless the intentions are verbalized, one cannot be entirely certain that this is the case. Nevertheless, with enough understanding of the previous problems the students have dealt with, one can sometimes infer that this is the nature of the student's activity. In the following two examples, students suggest approaches that are strongly analogous to a homework problem that had been assigned recently. I posit that these students have this example in mind, and are actively trying to map the current problem onto this familiar example.

Two hard rubber spheres of mass ~10 g are rubbed vigorously with fur on a dry day. They are then suspended from a rod with two insulating strings. They are observed to hang at equilibrium as shown in the figure on the right, which is drawn approximately to scale. Estimate the amount of charge that is found on each sphere.

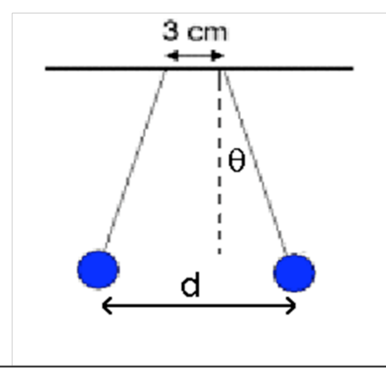


Figure 17: Previously used homework problem

The following is the solution to this problem presented by the course instructor:

Let's estimate that the charges we have placed on each sphere is the same and equal to Q. They might be different, but the spheres are identical and we presume we have rubbed them the same way, so they are likely to have similar charges. How can we figure out how big the charges are? Let's look first at the picture. The balls are not hanging straight down. Why not? Because there is an electric force between them pushing them outward. Presumably, the stronger the electric push, the farther out the balls would hang, so the angle must tell us something about the strength of the electric force. If we knew the electric force and if we knew the distance between the balls, we could calculate the electric charge from the electric force law, $F = kQ^2/d^2$. We can estimate the angles and the distance from looking at the figure. Therefore, our chain of reasoning is as follows.

- Figure out the angles and distances from looking at the picture.
- Figure out the magnitude of the electric force by using a free-body diagram and the condition that the force on each ball must balance.

Figure out the magnitude of the charge from using Coulomb's law.

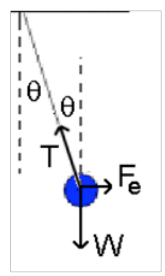
From the figure, we can estimate that the distance d is about 8 cm. This means that the sides of the triangle with the angle marked θ are about 2.5 cm [= (8 cm - 3 cm)/2] and 10 cm. (I did this by eye. Better estimates might be done by measuring with a ruler, but since we are only estimating -- that is, we only want accuracy to one significant figure – this should be OK.) This gives us that tan θ = opposite/adjacent = 2.5/10 = 0.25. We can get the hypotenuse by the Pythagorean theorem to be

$$c = \sqrt{a^2 + b^2} = \sqrt{(2.5\text{ cm})^2 + (10\text{ cm})^2} = \sqrt{106.25}\text{ cm} = 10.3\text{ cm}$$

.

From this we can get the sine and cosine of the angle as well (sin = 2.5/10.3 = 0.24 and cos = 10/10.3 = 0.97).

Now we need to create a free body diagram and balance the forces. This is shown in the figure at the right. We don't know either the tension nor the electric force, but by balancing the up forces against the down and the left forces against the right we get two equation for our two unknowns and can solve for everything. It works like this.



$$F_{up} = F_{down} \qquad F_{left} = F_{right}$$

$$T\cos\theta = mg \qquad T\sin\theta = F_e$$

$$T = \frac{mg}{\cos\theta}$$

$$F_e = T\sin\theta = mg\frac{\sin\theta}{\cos\theta} = mg\tan\theta$$

Since we know the mass of each sphere is 10 g = 0.01 kg, the weight is W = mg = 0.1 kg x 10 N/kg = 1 N. The tangent of the angle is about 0.25 so our electric force must be about 0.25 N. Assuming both charges are equal to Q, we get

$$F_e = \frac{k_C Q^2}{d^2} \qquad Q^2 = \frac{d^2 F_e}{k_C} = \frac{(0.1\text{ m})^2\, 0.25\text{ N}}{9\times 10^9\ (\text{N-m}^2)/\text{C}^2} \approx \frac{1}{4}\times 10^{-2-10}\ \frac{\text{N-m}^2}{(\text{N-m}^2)/\text{C}^2} = \frac{1}{4}\times 10^{-12}\ \text{C}^2$$

Taking the square root, we get that the charge is about 0.5 μC.

Figure 18: Solution to previously used homework problem

In this problem, the force between two charged objects is determined indirectly by observing the angles at which the strings hang. Students generally don't know how to measure force directly in the laboratory, however, measuring angles is straightforward.

In this clip, Group Three has been attempting to come up with ideas. A recurring problem for them has been the presence of friction. This is clearly an important part of this group's standards; several ideas have been dismissed so far due to their inability to eliminate the effects of friction. As you will see, a discussion about this topic leads to the suggestion of a setup that is extremely similar to the homework problem:

ALLISON: I think that... what we need to do is... mark a spot where one magnet is gonna start out at. And bring the other one closer...
BRANDON: What if you tape one to the thing...
DJANGO: We need something that...
BRANDON: Can't move.
DJANGO: No friction.
BRANDON: Space?! You want... space?
CHUCK: Let's ice the table over!
DJANGO: We should go to space...
ALLISON: We could... hang something... in the air. There's like... air friction, but that's not... if we hang them.
DJANGO: Yeah, like a... thing where they... like a pendulum kind of thing?
CHUCK: Yeah.
DJANGO: We need string! (leaves)
ALLISON: If we have like...
BRANDON: I don't understand this pendulum idea.
ALLISON: I'm trying to explain it to you now. It's so you have... two things like hanging, and then you bring them like... they're on a string, so there's no...
BRANDON: Oh, so M G will be the same on them.
ALLISON: What?
BRANDON: If they weigh the same, M G will be the same if they're both on the string... bring the strings closer together.
ALLISON: To weigh them?
CHUCK: Do we have anything to hang them to weigh them from though?
BRANDON: Bring the strings closer together.
ALLISON: To weigh them?
CHUCK: I mean, to hang them from.
BRANDON: We could make something.
ALLISON: Well, we'll make a little contraption.
BRANDON: We could make something using a box... cardboard box.

Allison's idea was immediately identified by Django and Chuck. Brandon seemed to understand the gist of it after a short discussion. Because there seems to be so much of an understanding of what this idea was about, in the absence of meaningful discussion of how it works and how it will yield the target quantity, is evidence that this homework problem prototype is a shared concept within the group. It did not need to be mentioned explicitly. Since they know they have done this problem before (or have been responsible for it) they seem to accept that it is a valid approach. What they focus on, rather than details of the calculation, is how to simulate this previous example, i.e. how to map the present problem, with the materials they have at their disposal, onto this pattern, which is understood to be valid. Consider the lines:

ALLISON: We could... hang something... in the air. There's like... air friction, but that's not... if we hang them.
DJANGO: Yeah, like a... thing where they... like a pendulum kind of thing?
CHUCK: Yeah.

"Yeah, like a..." suggests that this reminded Django *of something else.* He has seen this before.

Exploration

Some activities in the laboratory appear to lack the kind of structure seen in other games. Frequently a group will be observed playing around with the materials, without an apparent plan of action. However, this kind of behavior is far from random, even if an observer perceives it as being so. "Playing around" serves a very real and very important purpose: to aid in the brainstorming of ideas.

I propose *Exploration* as a game that describes activities contributing to the creation of ideas by investigating the features of the laboratory materials. While the group is not working from a blank slate (they may have some ideas about what long-term strategies they can marshal), this activity is not narrowly focused on a single idea as other games are. Students frequently engage in this game when they realize they lack the know-how to engage in more complicated games devoted to constructing a plan. Without an understanding of how the materials behave, students cannot imagine what the equipment will do when subjected to certain conditions. They also lack the ability to concretize. Exploration helps to build this set of information.

The moves associated with Exploration are shown in Figure 18. Entry conditions are merely that the players have equipment to work with. Participants explore the equipment, point out its relevant features, and hold short discussions about these features. What ends this cycle of exploration is when an idea emerges and the players are ready for the minimum level of commitment that will drive this idea into another game. From here, the idea is "in play."

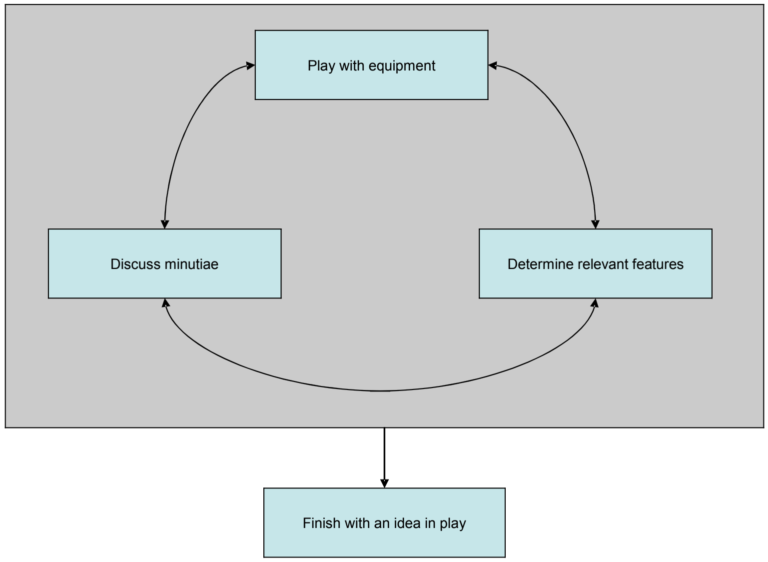


Figure 19: Schematic diagram of students' moves with *Exploration*

An example of Exploration

Here is a group at the very beginning of the lab period. As seen previously, they had an idea on how to proceed and acquired the magnets and materials. At some point, this previous idea was abandoned, and now they are engaged in Exploration:

CATHY: Then I guess maybe it moves... So we would have to keep... we would have to keep one of them... in place, right? It would have to be like... that doesn't do anything... that doesn't do anything.
BONNIE: So we do the other side too, the attraction side (CATHY: Yeah) So like, turn one around... see how close they can get to...
CATHY: It's gonna be really hard because... it's not gonna pull back... it's gonna get to a point and automatically it's just gonna go this way.
BONNIE: Yeah. So we I guess find this point, like, if you, can you hold it back so far... and it won't do anything...
DAPHNE: See, the idea is you tape this on and hold it like... I guess we'd have to hold the other side of the spring fixed, wouldn't we?
BONNIE: *laughs* That spring is...
DAPHNE: We wanted a stretchier one cause it's gonna be... it won't... if the spring isn't stretchy enough then these probably won't even come together.
BONNIE: Oh, yeah, I know.
DAPHNE: But we have to hold this side fixed, don't we?
BONNIE: Yeah.

DAPHNE:	We can tape it to the paper...
ASHLEY:	This is just trying out.
BONNIE:	Idea number one.

As you can see, the previous idea of how to arrange the magnets and spring has not been abandoned; yet, they are not exclusively focused on it. The line, "This is just trying out" suggests the shared frame of understanding in this group. They are not committed to any idea. They are merely seeing what the materials can do. Their discussion is not about the broad plan for acquiring the target quantity, but rather about details concerning the equipment: the stretchiness of the spring, the orientation of the magnets, etc.

Exploration differs from other games, particularly Evaluative and Concretizing Plan-Making, in the open-endedness of its goal. They are not working towards something specific. Rather, they engage in this game in the hopes that a goal will come to light in the process.

Discussion

These five epistemic games describe the coherent activity observed in our reformed laboratory sections, which is to say, in a specific socio-cultural environment. They are by no means an exhaustive list of such activities. Just as Collins and Ferguson illustrate epistemic games observed in expert settings and Tuminaro illustrated those manifested in physics problem-solving, these games represent an arsenal of coherent skills used for particular activities. The purpose of laying out these games as such is to have a vocabulary with which to talk about coherent activity in this environment. A game, which typically lasts on the order of two or three minutes, will be our unit of analysis for the treatment in chapter six. In general we are concerned with what factors guide group behavior in the learning environment of labs. Now that we have a way of classifying this behavior, let us now examine how these games are played, what inspires their use, and what they can accomplish for the students.

Chapter 5: Epistemic Games as Distributed Cognition

Introduction

In the previous chapter, we examined how student activity can be parsed into segments of coherent, purposeful behavior known as epistemic games. There is a clear advantage to considering these games as a unit of analysis when describing individual student behavior; they give us a means by which to answer the question, "What is this student doing?" that says something about the purpose and the procedure of the activity. As we have seen, a *group* of students can also engage cooperatively in these epistemic games. Therefore, it is desirable to use a similar analysis to describe what is going on *within the group,* so that we might be able to answer the question, "What are these students doing *as a group?"*

In chapter four, epistemic games were introduced as cognitive activities, while in chapter two, cognition was presented as a process occurring within the nervous systems of individual human beings. Consequently, one may conclude that epistemic games are *individual* activities that take place in the human mind. However, in many of the examples shown previously, we see games being played by groups of individuals. Group game-playing is not merely several individuals all engaged in the same cognitive game. One can participate in a game without having an understanding of its goal, or without having been present at the initiation of the game. The cognitive labor can even be distributed among the individuals in a group so that a long-term game might be played without each individual being aware of all its components.

But how can this be, if epistemic games are cognitive activities that take place inside the nervous systems of individuals? How can we attribute cognitive properties to a network of individual nervous systems? For many researchers, the social character of cognition is so powerful that they are inclined to expand the domain of *cognition* to include social activity of all kinds. Such a radical paradigm shift may not be necessary for our purposes.

In this chapter, I will review Hutchins' (1995) concept of *distributed cognition,* which regards the cognition of social networks separately but analogously to the cognition of individuals, without denying the existence of or deemphasizing the importance of the latter. By using the concept of distributed cognition, I will attempt to expand the domain of epistemic games to include the group activities observed in our reformed labs, but at the same time acknowledge the fundamental distinction between cognitive action centered in the nervous system and social activity distributed across a network of individuals and including cultural influences and artifacts. Epistemic game-play is not necessarily an isolated individual cognitive activity. In the physics laboratory, it can also be a tool situated within a larger system, one which includes individual minds, group interaction, and physical equipment.

Situated Cognition

Distributed cognition is one of several branches of the school of thought known collectively as *situated cognition* (Lave & Wenger, 1991; Lave, 1988; Brown & Duguid, 1992). The general claim of situated cognition is that cognition itself cannot be studied in isolation as a phenomenon bound by the human brain. Instead, knowledge is *situated* within a specific socio-cultural environment. In order to understand how people engage in learning, sense-making, and other cognitive processes, one has to take into account social interaction, cultural artifacts, and other features of the outside world.

One can think of socio-cultural effects doing for educational psychology what friction does for physics. One can understand a great deal by studying a mind in isolation, however, when that mind is placed in the real world, the effects of friction are enough to drastically affect its properties. Rather than merely correcting previously existing theories with socio-cultural effects, researchers in this field place them at the center of attention, stressing that the knowledge is context-dependent, rather than universal. From the perspective of situated cognition, an introductory physics laboratory is a specific, unique socio-cultural environment, with a myriad of real-world complications that one might be tempted to ignore, such as social hierarchies, time constraints, and personal agendas. In order for a study to have “ecological validity,” or to reflect a real-life situation, these effects must be considered relevant features of the socio-cultural context.

Edwin Hutchins and Distributed Cognition

Psychologist Edwin Hutchins, who was mentioned briefly in chapter two, founded the school of thought known as *distributed cognition.* This approach is Vygotskian in its attempt to emphasize the importance of the socio-cultural environment to cognition. Situated cognition attempts to reconcile the cognitive with the socio-cultural by asserting that knowledge can distributed amongst individual minds, interactions, and cultural artifacts in a way that this system can operate, in many ways, like a human mind, but with capabilities individual minds lack.

Like most advocates of the socio-cultural approach, Hutchins laments the trend in cognitive science to de-emphasize the importance of culture and the environment. “The computer was not made in the image of the person,” he says in his work *Cognition in the Wild,* “The computer was made in the image of the formal manipulations of abstract symbols. And the last 30 years of cognitive science can be seen as attempts to remake the person in the image of the computer.” (p. 363)

The field of artificial intelligence has indeed figured prominently in modern cognitive models. The metaphorical connection between the mind and the CPU is strong, and works both ways. Just as computer terminology is used generously to describe cognitive processes, researchers use computer programs to simulate cognitive models. D’Andrade (1995) demonstrates that the common thread in competing cognitive models is the concept of cognition as *computation,* or, the manipulation of symbols. Hutchins does not disagree with the premise that the human nervous system does indeed engage in computation. However, he points out that it does more than just that. Cognitive models deemphasize the importance of the *input,* the “stuff” upon which the nervous system computes. Unlike a computer, whose primary functions are generally pre-wired and can operate in isolation, the human mind requires constant contact with the so-called outside world, and while it comes pre-wired with a number of vital functions (like eating and breathing), more complicated functions, such as communication through language and mathematical skills, are learned through contact with socio-cultural influences. These functions are what Vygotsky called “higher mental functions,” which are social in nature, rather than strictly genetic. These skills are not intuitive (though as Steven Pinker points out in

The Language Instinct (1994), evolution has done a smashing job of preparing our bodies so that they can be easily adopted[8]), but rather internalized from our interactions with the outside world.

Rather than refute the concept of cognition as computation, Hutchins runs the ball the other way. If, he argues, we can describe a human nervous system as cognitive on the grounds that it can compute, why not expand our definition of "cognition" to include other systems that can also compute? He makes a strong biological argument for the loosening of this definition. There is no unitary entity in the human body to which we can attribute individual cognition. Cognition is made up of a massive network of neurons, from the mysterious matter in the brain to the sensory nerves criss-crossing the body. But where is the boundary that defines what this system *is* and *isn't*? Hutchins quotes Gregory Bateson (1972) to illustrate this problem:

> *Suppose I am a blind man and I use a stick. I go tap, tap, tap. Where do I start? Is my mental system bounded at the handle of the stick? Is it bounded by the skin? Does it start halfway up the stick? But these are nonsense questions. The stick is a pathway along which transforms of difference are being transmitted. The way to delineate the system is to draw the limiting line in such a way that you do not cut any of these pathways in ways which leave things inexplicable.*

Unfortunately, this argument blurs a traditional line separating the science of the body from the science of the rest of the world. Perhaps this separation truly is made only out of convenience. I argue that there is still considerable merit to regarding the "mind" and the "environment" as separate, if only for the reason that the study of hands and the study of sticks require vastly different tools and models. Perhaps when this is no longer the case, we can disregard the boundary. Until that time, let us use it.

So why use the cognitive model to describe extra-corporeal events? Here is where Hutchins makes his strongest points. We in fact live in a world in which there exist networks of human beings engaged in joint computational tasks. Says Hutchins:

> *Thus, a particular kind of social organization permits individuals to combine their efforts in ways that produces results…that could not be produced by any individual …working alone. This kind of effect is ubiquitous in modern life, but it is largely invisible… The skeptical reader may wish to look around right now and see whether there is anything in the current environment that was not either produced or delivered to its present location by the cooperative efforts of individuals working in socially organized groups.*

The first half of *Cognition in the Wild* describes two such systems: the system of navigation aboard an amphibious helicopter transport in the United States Navy, and the system of navigation wielded by canoe sailors in a non-literate Micronesian society. As Hutchins explains, "in a computational sense, all systems of navigation answer the question, 'Where am I?' in fundamentally the same way." As individuals, we engage in this computation continuously. The brain is pre-wired to be able to assess its own position by considering the direction of and distance to familiar objects. Navigation crews are engaged in basically the same computation, only the computational process is *distributed* amongst a broad system.

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[8] For example, vocal communication, and the physiological structures associated with it, evolved because it is a desirable trait. On the other hand, no human being will learn English (or any other language, for that matter) if raised in social isolation. The *physical ability* to speak is genetic, whereas the *cognitive ability* to speak a particular language depends on socio-cultural interaction.

A navigation crew consists of as many as a dozen men acting together to compute the ship's position. If we consider this computation to be a type of cognition, it is clear that it is not occurring strictly within the nervous system of any one individual. The cognitive process is distributed among many nervous systems. Also, a great deal of computation is being done by inanimate objects. For example, the chart from which the sailors work embodies information and facilitates computational processes. In theory, a human brain could store all the information that exists in a navigational chart, but why bother? One could, in theory, do all basic mathematics in our heads, but why bother? In this system, not only is cognition distributed amongst the human beings present, but amongst the cultural artifacts at the group's disposal.

A system of distributed cognition can engage in computations far more complicated than those done by individual brains in isolation. The idea of two people "putting their heads together" means more than doubling the computational power. Social-cultural interactions seem to give rise to a social "being" with outstanding computational power. Now we could, in theory, trace all the components of a system of distributed cognition back to biological cognitive processes. A navigational chart, for example, was constructed by combining many pieces of knowledge carried by individuals, just as language was compiled slowly by many contributors, all individual brains. But breaking down knowledge as a cultural artifact into its constituent pieces would be unnecessarily complicated, like studying the vibrations of individual atoms in order to understand which direction your car will go if you turn the steering wheel to the left.

A system of distributed cognition, as Hutchins describes it, consists of individual nervous systems (whose inner workings are complex and not entirely understood, but by no means ignorable), interactions between these individuals, the environment, and cultural artifacts, both abstract (like language and math) and concrete (like charts and compasses). The "cognition" engaged in by such a system is analogous to that engaged in by individual minds, though Hutchins takes care to point out how, for example, group memory and group learning can differ from individual memory and learning. I present an example in the quote from Otto von Bismarck: "Only fools learn from their mistakes. I'd rather learn from other people's mistakes." Through participation in a system of distributed cognition, von Bismarck might thus be able to expand his ability to learn from mistakes, just as he might make mistakes which benefit those around him. Though an individual acting in isolation might go through the slow process of learning by trial-and-error, Hutchins illustrates how mistakes made in the navigation environment frequently serve as learning experiences for the rest of the crew. Because of the spread of information, the system of distributed cognition is far more efficient at this type of "learning."

The Lab Group as a System of Distributed Cognition

The notion of distributed cognition perfectly describes the manifestation of epistemic games in the laboratory. These games can and are played by individuals. Tuminaro shows ample evidence of individuals engaged in these activities either in near isolation or by offloading some of the computational effort to a marker board or calculator. In chapter four, we saw that it is not so easily to distinguish between an individual playing a game and a game being played by a group. Also, as Bateson pointed out, the line between what's going on in the head and what's going on with the tools we use is not so distinct either. It would, of course, be tremendously difficult to describe every group action we observe in the laboratory in terms of the individuals engaged and the cognitive processes that are obscured behind their skulls. On the other hand, the "group behavior", though admittedly composed of individual behavior, is relatively easy to observe. Let us use Hutchins' concept of distributed cognition to consider the *system* consisting of the students, their interactions, their tools, and their environment, and by doing so, talk about epistemic games as *both* individual cognitive processes *and* group activities engaged in by the system of distributed cognition.

It should not be too much of a stretch to regard a group as an entity. In fact, we subconsciously do this every time we remark, "this group knows how to use the oscilloscope" or "my class didn't understand Newton's third law." But rather than use a strictly social formulation for understanding group activity, as many Vygotskian researchers do, let's keep cognition in the nervous system and just consider them to be part of a larger, more complicated network of nervous systems, made up of living, breathing organisms which are our colleagues, and the long-dead organisms that contributed to the tools we use to communicate and make computations.

The Scientific Community as a System of Distributed Cognition

Science itself is an example of a system of distributed cognition. We speak of the "scientific method" as a procedure that one can engage in; however, nobody really does science in isolation. At the very least, one uses cultural tools, such as language and logic, to make observations and describe the world around us. We may draw upon the observations and descriptions made by others.

Professional scientists, in fact, are far from isolated. They use tools and techniques constructed by scientists before them, and produce information that will be used by others. Modern research groups consist of many scientists working together, each doing a part of a larger computational process, perhaps not even fully aware of every detail of the whole plan. By engaging in scientific research, whether one is aware of it or not, one is acting within an enormous system of human beings, a system which collects observations and processes them *almost like* a sentient being with extraordinary computational ability. Redish (1998) refers to the "culture of science"- the set of processes by which communities of scientists build a *community consensus knowledge base* or *community map*. This refers to the collection of information that is distributed throughout the minds of individuals and embodied in cultural artifacts. It is understood that the knowledge within individual brains exists in different quantities and forms, but that the collection of all minds is an emergent phenomenon that evolves and grows, much like an individual mind.

By now it is conventional wisdom that students are able to learn quite efficiently when they are acting in a group of peers. The right kinds of social environments, in which certain nervous systems cooperate with other nervous systems and the appropriate cultural artifacts, give rise to an emergent phenomenon that strongly resembles an individual cognitive system. The introductory physics laboratory is an environment in which we expect for students to work together in configurations that allow the groups to accomplish more than the sum of their parts. We want for a lab group to function as a system of distributed cognition, not just as a collection of individuals. We want them to develop a community of interaction that plays a part in the process of doing science. And as part of this, we hope that these groups can play epistemic games, though somewhat differently than they might play them as individuals

It should be noted that the primary purpose of an introductory physics laboratory is *not* analogous to the primary purpose of a navigation team. The purpose of the latter is to determine where the ship is and where it is heading. The purpose of a laboratory group is *not* primarily to produce the experimental results, but to provide an environment in which the individual students can learn how to conduct experiments, and this includes having an understanding of the broad picture, something which an individual sailor may not have. Our lab groups differ from navigation groups in that the group-work is not an end in itself, but a means by which individual students can learn.

Individuals can engage in epistemic games. Systems of distributed cognition can also engage in epistemic games. Armed with this framework, let us now go back and reexamine the epistemic games as they occur in the laboratory, and observe the nature of these games when engaged in by a strong network of minds.

Chapter 6: How Epistemic Games are Played in the Laboratory

Introduction

I now have the tools to describe what groups of students are doing as they try to design and analyze their experiments in lab. I give examples in chapter four to show that students engage in blocks of coherent activity describable as epistemic games. In chapter five, I use the perspective of distributed cognition to suggest that epistemic games may describe not just a cognitive activity of an individual, but also one engaged in by groups of individuals working with a shared understanding of procedure, and ideally, of purpose as well.

In this chapter, I present case studies of two lab groups. The first lab group works extremely well as a team, in that they communicate productively and share a general sense of purpose. In another way of speaking, they align their individual behaviors in a way that it makes sense to describe their activities as "group epistemic game-playing." We will follow this group through a half hour of lab activity, identify the types of epistemic games and activities they engage in, and discuss the nature of these games, how they are initiated and negotiated among the group, and what these activities accomplish for the group.

The second group I observe does not appear to engage in these same kinds of activities, and consequently, is not able to progress through the activity the way the first group does. I examine this group and attempt to understand why this group cannot engage in gameplay, what sorts of social interaction are missing, and what social interactions perhaps hinder the ability of the group to work together effectively.

The goal of this analysis is to demonstrate what the students are *doing* in lab, and to distinguish between the components of productive activity and unproductive activity. Understanding the social interactions and individual actions that accompany productive teamwork will give allow us to make more informed judgments about what makes for a "good" lab group and what sorts of skills a poor lab group is not using.

Case Study: Group 1

Group 1 was observed previously in chapter four, engaging in Equation Bridging and Recursive Equation Bridging. Here I examine this group in more detail. The magnetic force lab (shown in full in Appendix A) is a four-hour activity; I explore the first half hour of this activity. This is an interesting portion of the lab, since it is the time in which the group first apprehends the task, interprets the question they must answer, examines the materials available, and constructs a plan on how to proceed.

Shown below in Table 1 is a timetable for 22 minutes of this group.

Time	Transcript	Game Playing	Outside Interaction	Other	Off-task
0:00	1-4				
0:15					
0:30		Equation			
0:45		Bridging			
1:00	1-27				
1:15					
1:30					
1:45			Discussion w/		
2:00	2-3		student from		
2:15			another group		
2:30			Assimilating		
2:45					
3:00	2-25	Recursive			
3:15		Equation			
3:30		Bridging			
3:45					
4:00	2-40				
4:15					
4:30					
4:45					
5:00	3-15	Evaluative and			
5:15		Concretizing			
5:30		Plan-Making			
5:45					
6:00	3-33				
6:15					
6:30					
6:45				Logistics	
7:00	3-47				
7:15		Evaluative and			
7:30		Concretizing			
7:45		Plan-Making			
8:00	4-25				Off-task
8:15					
8:30					
8:45					
9:00	4-39		Discussion		
9:15			with other		
9:30			groups (offscreen)		
9:45					
10:00	4-43		Assimilating		
10:15					
10:30					
10:45				Floundering	
11:00	5-16				
11:15					
11:30					
11:45					
12:00	5-31	Evaluative and			
12:15		Concretizing			
12:30		Plan-Making			
12:45					
13:00	6-8	Evaluative and			
13:15		Concretizing			
13:30		Plan-Making			
13:45					
14:00	6-28				
14:15					
14:30				Equipment	
14:45				Logistics	
15:00	6-46				
15:15					
15:30					
15:45					
16:00	7-15				
16:15					
16:30		Evaluative and			
16:45		Concretizing			
17:00	7-42	Plan-Making			
17:15					
17:30					
17:45					
18:00	8-14				
18:15					
18:30					
18:45					
19:00	8-45				
19:15					
19:30					
19:45			Discussion with		
20:00	9-13		TA		
20:15					
20:30					
20:45					
21:00	9-37				
21:15					
21:30					
21:45					
22:00	10-12				
22:15					

Table 2. Timetable of student activity in Group 1, Experiment 6

The activity has been divided into four types:

- **Game Playing** – These are segments of activity that are described using the epistemic game terminology provided in chapter four. Each segment is labeled with the type of game being played. Notice that time blocks associated with a game generally range from one minute to five minutes.
- **Outside Interaction** – This includes discussions between the group and the lab instructor (labeled 'TA' in the transcripts) or between the group and other students (labeled 'S' in the transcripts). This also includes what is labeled as *assimilation,* or discussion that is specifically geared towards considering or making sense of what has just transpired in a discussion with the instructor or other students.
- **Other** – This category describes other activity that is outside the framework of epistemic games.
- **Off-task –** Even the best groups go through periods of discussion that seem to have nothing to do with the topic at hand.

The chart scales by time, so that one can see the relative lengths of each block. I do not repeat large segments of text here in the chapter. The full transcript appears in Appendix B. The second column of Table 1 contains transcript references (e.g., 6-8 refers to page six, line eight).

Equation Bridging

This game, which lasts about a minute and a half, was detailed in chapter four. The goal of equation bridging is to find an equation that "bridges" quantities that are known with the target quantity required for the lab activity, in this case, the magnetic force. The students are observed searching through the notes, the textbook, and their own memories for equations that contain the quantity *F*. When one is suggested, they determine if this is an appropriate equation (i.e. does it refer to *magnetic* force) and whether it can actually bridge the target quantity to known quantities. These are the *allowed moves* of the game. We see this game played from *1-4* to *1-38*.

Of the four members of the group (Angie, Belinda, Consuela, and Doria, named alphabetically counter-clockwise from the front-left of the table, for those with access to video), we observe that at least three (Angie, Belinda, and Doria) are making moves characteristic of this epistemic game. They suggest equations and evaluate each others' equations when they are suggested. This is an excellent example of a *shared game,* shared in the sense that a majority of the members are aware of the basic structure of the game. The dialogue shows the students suggesting equations and then evaluating them in terms of whether or not it has the right ingredients, while the physical meaning of the equation is almost an afterthought. But the general structure of the game involves making suggestions, dissecting the equation, and evaluating it in terms of what it has and what it doesn't have. The students do little else. For example:

BELINDA: Pressure...
ANGIE: But it's not... pressure times area...
CONSUELA: It's magnetic force...

BELINDA: Oh yeah, it's E Q.	
DORIA: No, but that's electric. Force of a magnet is just F equals Q V B sine theta. There's no distance in it.	

Because this group began playing this game before the hour started (and therefore before the camera began rolling), we unfortunately don't observe the initiation of this game. Furthermore, there is no explicit discussion of the purpose of this game, suggesting that either (a) the goal of the game was stated or alluded to before the start of this transcript, (b) the game had been played before and its goal is unspoken, or (c) the understanding of the purpose of this game is not shared among all the group members. Explanations (a) and (b) seem most plausible; the fact that the dialogue is so focused towards the goal of finding the "right equation" makes (c) highly unlikely.

In this game we see a basic example of the group acting as a system of distributed cognition. Equation bridging is by no means being played entirely in the head of one individual. Moves are shared by at least three of the group members. Equations are suggested, evaluated, and dicussed by several members. Plus, the knowledge base of this game, being the body of equations from which they are brainstorming, is not entirely located inside the head of one member, or even in the heads of the members of the group. Rather, some of this information exists in the textbook (a cultural artifact, written by physicists, encompassing information contributed for a large number of sources) and from the notes (a more localized cultural artifact, constructed by the students from the information assembled by the instructor of the course). Equation bridging, which seemed simple at a first glance, is actually quite complicated. It is being played by a distributed cognitive system, consisting of nervous systems and artifacts, but most importantly by the interactions between student and student, and between student and artifact. These interactions are the core elements of the epistemic game.

Discussion with student

This group's game of equation bridging is interrupted by the entrance of a student from another group, who asks, "What's acceleration? It's like one half… delta X… the one formula… like I know acceleration is delta V over delta T but…" It is common in these labs for a group that is stuck to consult another group for help. Partly in order to inspire this kind of interaction, the lab instructors are encouraged to be reluctant in giving away answers.

As observers, we lack the context to see how this question fits into what this other group is doing, and for that matter, the same is true of Group 1. It is not necessary for them to understand if this student has a particular epistemic game in mind. They have been asked a question and they know what kind of answer is being solicited. There is no evidence that Group 1 is aware of the purpose of this question. If this visiting student is playing an epistemic game, this exchange is evidence that one can participate in this game *without* an understanding of the purpose or procedure. Group 1 is *participating*, but not *playing*.

BELINDA: Oh V... It's D equals V oh T plus one half A T squared.
DORIA: That one?
S: D equals V oh T plus one half A T squared.

BELINDA: So like, you could get rid of, yeah, it's the V initial, so if V initial is zero you can get rid of that and D equals one half A T squared.	

This student draws our group into an activity, perhaps an epistemic game, and in doing so brings them into her system of distributed cognition.

This interaction lasts from *1-39* to *2-6*. After the student leaves, Belinda goes off-task. However, Consuela is inspired by this interaction to consider the ideas brought to the table, in this block of activity labeled *Assimilation*:

BELINDA: I was at the gym yesterday, and all of a sudden like right here started... like touch it and it really hurts...
CONSUELA: What are they doing? They're doing the... They're measuring the... that doesn't work though, right? They're measuring acceleration, but what is that gonna do? Force equals...
BELINDA: Well force is A… force equals M A.
CONSUELA: So they're using mass.

This activity could now lead directly into a new game inspired by the external interaction, but it doesn't do so right away.

Recursive Equation Bridging

The next block of activity we have also discussed in chapter four. The group continues to discuss equations, playing a variation on the Equation Bridging game that we have defined as Recursive Equation Bridging. Unable to "make something happen" with just one equation, they now attempt to string equations together. In this game, the magnetic force equation and the Biot-Savart Law are combined in order to bridge magnetic force with known quantities. They are unable to do this, being left at the end of the game with *I*, the current, which they do not know how to measure. These events suggest that there is a lack of conceptual underpinning here. Although the difficulty of measuring current is discussed, nobody seems to notice that such an equation must be inappropriate for the present situation, where there *is no current*[9]. This is evidence that the students are not strongly applying their sense-making skills to this game. That useful skills are not used during this time period (particularly skills we can see them doing at other times) suggests that epistemic game-play is not merely the selection of certain skills, but the suppression of others. When there is an epistemological framing of a situation, the decision that "this game is about *X*" unfortunately seems, in this instance, to also mean that "this game is not about *not X*". The upside of framing is that you don't have to consider everything at once; a downside of framing is that possibly useful components are left out of the frame.

Signs of frustration have begun to show, with Belinda's going off-task to talk about her day at the gym, and the following lines:

[9] The idea of an Amperian pseudo-current, which is discussed in some older texts, has not been considered in this class.

CONSUELA: How the hell are we supposed to do this?
BELINDA: We don't know... how are we gonna measure current?! This is bad.
BELINDA: But how are we going to measure any of that?
DORIA: Yeah, I know. So I don't know how it depends on distance.

These statements give more detail to the type of frame Belinda is in. Determining whether a component can be measured or not comes late in the Recursive Equation Bridging game. Belinda seems frustrated that they are led to consider equations based solely on whether they have *F* or not, only to determine later that the equation will not be helpful.

Evaluative and Concretizing Plan-Making

Until line *2-41*, the group has appeared to act with at least a shared sense of procedure. But here there is a sudden shift in activity. Belinda suddenly has a burst of inspiration that seems to be cued by the interaction with the student from the other group. The issue of motion and the relation to force has been raised and now recognized:

BELINDA: That one. And then you could do Vf squared equals Vo squared plus 2 A D. But if you're ooooooh...!

What is this "oooooh" all about? Rather than following up with the assimiliation, she appears to be suddenly inspired by another idea that has popped into her head:

BELINDA: What if we... okay... because if we're holding the magnets... like say we connect the one to a string... and we had them dangle *gasp* we had it dangle off this thing (motions to force probe).
DORIA: Can we look at that?
BELINDA: (brings force probe down) So, you tie up the string, right?

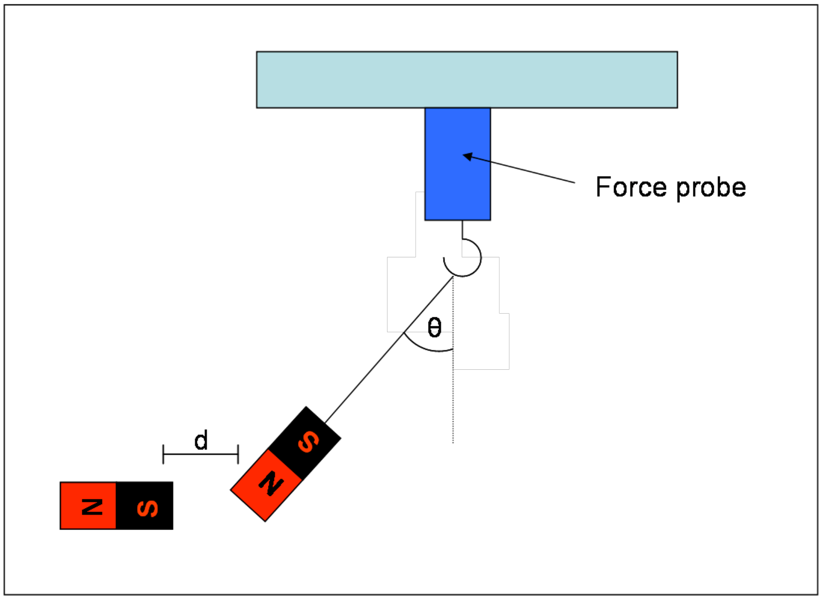

Figure 19. Belinda's idea

Suddenly everyone stops making moves associated with Equation Bridging and Recursive Equation Bridging. What ensues we have described as a round of Evaluative and Concretizing Plan-Making that lasts from *2-41* to *3-45*, or almost three minutes.

What is interesting about this shift is the almost seamless transition the students make *as a group* from one type of coherent behavior to another. Doria and Consuela go along with Belinda and proceed to make moves that add to, evaluate, and concretize the idea Belinda has set forth. I posit four reasons for this:

- Mutual frustration with equation-related games they failed to win.
- Realization that a one-equation or multi-equation solution to the whole problem does not exist.
- Trust in Belinda as the dominant personality of the group.
- Familiarity with the game of Evaluative and Concretizing Plan-Making.

Notice that there is no meta-cognitive discussion associated with this shift. Nobody comes out and says that what they are currently doing isn't working. Belinda doesn't explicitly suggest that they try another method. But clearly there is a change of some sort. Suddenly everyone is discussing the materials and how to accommodate Belinda's idea concerning the possibility of hanging the magnet from a string connected to the motion detector, and bringing the other magnet up next to it. They are no longer discussing possible candidates for equations. Physical realization, long ignored, is suddenly in the forefront.

One possibility, based on examples seen in other groups and Belinda's sudden "ooooooh" moment noted earlier, is that Belinda has recalled the pendulum homework problem (see Figure 16). Perhaps in her mind she is attempting to play the game of Strategic Mapping. Without an explicit statement, we cannot know for sure this is what she is doing. However, it raises an interesting possibility: that this group, while clearly playing Evaluative and Concretizing Plan-

Making as a unit, may consist of individual members who have different interpretation of their goal. To Belinda, the goal might be to map this situation onto the homework problem, while to Doria and Consuela, the goal may be to construct a plan from scratch using this idea, which, for all they know, Belinda has made up on her own.

Logistics

Unfortunately, the group does not manage to construct a plan around Belinda's idea. From line *3-34* on, we see the shared activity start to break down. They have gotten stuck. Angie suggests another shift:

ANGIE: Who's the critic? Who's critic?
BELINDA: You are! You're evaluation. That's critic.
CONSUELA: Oh yeah.
ANGIE: Am I supposed to ask other people?
BELINDA: If you have...
DORIA: Umm..

Angie then leaves to go consult another group for ideas. This is explicitly stated as one of the tasks of the person taking this role (see Appendix B).

The statement, "Am I supposed to ask other people?" implies that this is not merely an idea that Angie has produced out of the blue. "Supposed to" implies that *this is something they do* whenever they reach points like this. The behavior of the other group members suggests that consulting another group is an accepted move.

This exchange is interesting because up until now we have been regarding the group as sharing an understanding of localized events. They appear to have a strong shared understanding of what moves are associated with each game, and sometimes it appears that they have a shared understanding of the activity's goal. Angie's move to consult other groups, however, suggests that there might also be a strategy-of-strategies that could be shared by the group members, or an idea of where to go next if one game or activity should fail.

Game Conflict

From *4-6* to *4-25*, Belinda attempts to revive the game of Evaluative and Concretizing Plan-Making. The group follows suit and attempts to flesh out her idea and realize it with the physical materials. But this too falls apart. At *4-26*, Angie leaves to consult other groups, and Belinda goes off-topic again.

Here we can observe a bit of conflict regarding how to proceed. Angie believes that the next move should be to consult other groups. Doria, as evident in the video, is leafing through the textbook, commenting, "You know… this book just sucks. I don't get it!" The fact that she is consulting what was previously the source of equations suggests that Doria is inclined to return to one of the equation-related games. Belinda, on the other hand, remarks, "I wanna look at materials," and leaves the table. This suggests she is inclined to play Evaluative and

Concretizing Plan-Making, which begins normally through the discovery of some feature of the materials. It is unclear what Consuela thinks.

What is going on here? This group seems perfectly capable of game-playing with a shared procedure with a few different games. And yet, there is clearly a difference in opinion on what needs to be done next. The group members appear to be framing the situation differently. For Angie, the key to progressing forward is figuring out what to do from another group. For Belinda, an idea will present itself by examining the materials. Doria is still convinced there's a piece of the puzzle they need somewhere in the textbook or in the notes. Consequently, the group separates. Rather than working as a coherent unit, they become four individuals working in isolation. We should not assume *a priori* that this is a bad thing. A divergence may be exactly what is needed here.

Assimilation/Floundering

Upon Angie's return in line *4-45*, there is a brief discussion through which her experience is assimilated by the group. Angie points out that another group was going to measure the acceleration of a magnet as it is attracted towards the other one, but that it was decided it would be impossible to measure, it being such a small interval of time to measure.

Until line *5-23*, the group doesn't seem to be working together as a single unit at all. Statements are all over the place:

CONSUELA: So using a spring would be too messy because of those...
ANGIE: Yeah, I think it would be, I think would complicate it too much.
CONSUELA: How else are we supposed to like...
BELINDA: All I know is that we'll need a ruler of some sort. I came up with that.
ANGIE: All I know is that... we didn't have pre-lab discussion.
BELINDA: He said that we're gonna do a lot of thinking for this experiment.
CONSUELA: Can we at least have them... I feel like it would be easier... I want to see the magnets.
BELINDA: If we can control the distance...
ANGIE: They did give us the protractor.

Each group member seems to be thinking about something different. The conversation is unfocused and serves no observable purpose. And most importantly, it doesn't appear that anyone is really listening to anyone else. Ideas are mentioned, and rather than causing seamless transitions to coherent activity, they merely hang in the air, only to get swept away by the next utterance. This is not students working as a group. The system of distributed cognition has temporarily disintegrated.

Evaluative and Concretizing Plan-Making

This dry period does not last very long. Angie makes the statement: "What if we did it this way?" and manipulates the materials. Her idea is to lay the magnets on the table and to attach one to the force probe. Suddenly the group springs into action as a unit again. They are once again playing Evaluative and Concretizing Plan-Making. Angie's statement is understood by the group as an explicit initiation of this game. They are familiar with the activity.

Inspired by this return to a familiar game, Belinda, in line *6-9*, tries to start another round of this game: "What if we measured… all right… we have the thing hanging and we held it out for like five centimeters… see how fast they come together." Belinda wants to measure the time it takes for the magnets to snap together. The attention of the group is temporarily turned to this idea, which Angie and Doria proceed to dismiss on the grounds that it is not possible to measure this small of a time interval[10].

What is interesting about this segment of video is that it demonstrates just how productive a group can be when everyone recognizes a familiar epistemic game. Just before Angie's suggestion, the group was floundering with no shared sense of purpose or procedure, and accordingly, nothing was happening. Then, an explicit attempt is made by a group member to start a game everyone is familiar with, and suddenly there is genuine communication and the group can again be recognized as a single unit working within shared constraints. The video depicts a shift in attitude. They are doing the same things again, presumably with the same end-purpose in mind.

An Idea in Play

In line *6-16*, Angie makes the following request:

ANGIE: Turn the box off and turn it back on.

The "box" she is referring to is the piece of hardware that interfaces the force probe equipment and the desktop computer. This equipment was used during tutorial sessions in the previous semester, so we can assume that the group members are familiar with what the force probe can do. Until line *6-45*, the group attempts to get the force probe working. Something is wrong with the equipment (as you can see later on in the class hour, the wire just wasn't plugged in all of the way, resulting in no input) and by line 6-41, they have given up trying to make it work on their own, and are calling the instructor over for assistance.

This group has *partial knowledge* of how the force probe works. Why does it not seem to bother them that they cannot get the equipment working? One possibility is that the group has the understanding that, in matters of technical detail, their system of distributed cognition includes the lab instructor. Though the instructors have been consistently denying the groups their participation in more theoretical matters, like working through the mathematics or thinking of an idea, they typically help out when a piece of equipment does not work, since it was not our intention to make students spend significant amounts of time trying to figure out what's wrong with the equipment, the way we might force them to work out a kink in their idea, for example.

[10] This would be hard to implement. Since the force varies over the distance that the magnet travels, it requires an integral over the unknown varying force.

This is because the goal of the lab is to get them to think about how an experiment tells you something, not how to work particular equipment. It is interesting to note the sorts of things the students consider are appropriate to request assistance with. The have run into *many* problems in this lab already, but this is the first time they have asked the instructor for advice.

Also important to notice is that the moment Angie ordered Belinda to check out the box, the group begins to concretize almost exclusively. They run with Angie's suggestion. Belinda, being in front of the equipment, uses the equipment to show how the idea can be implemented. Not being able to understand how the box works, however, prevents them from going forward with the idea.

Game-shift

Something interesting happens in line *7-4*. The group suddenly becomes extremely interested in a conversation going on across the room (which the camera, unfortunately, was not able to capture). Belinda, as evident in her facial expression in this line, thinks she has just witnessed something important. She immediately asks about Hooke's Law, demonstrating that she has observed a group using a spring rather than the force probe, and has perhaps seen the instructor validating this idea.

BELINDA: (oooh face)
DORIA: What?
BELINDA: What's Hooke's Law?
DORIA: Force equals negative K X.
BELINDA: We probably wouldn't know the.. we wouldn't know the K of the spring.
DORIA: Right.
BELINDA: But if you can measure... if you can do the spring first one, and then put a second one... and then you can look at how much the spring changes, the length of the spring, and come up with a force that way.
DORIA: And just say like, force is X K.
BELINDA: But, yeah, cause K is constant.
DORIA: Right.

Belinda has proposed another round of Evaluative and Concretizing Plan-Making, with the idea of using a spring as a measurement of force (see Figure 11). Suddenly, the group is no longer discussing how to get the interface box to work, but rather, how to improve upon Belinda's idea. There was no explicit declaration that they were dropping the previous idea, though the frustration, due to not being able to get the interface box to work, was visible. The group, understanding perfectly well how to play this game, moves quickly into it. They play this game for nearly two minutes, with an emphasis on concretizing with the materials, until they decide to consult the instructor.

Discussion with TA

From line *8-13* to line *10-21*, the group has a discussion with the lab instructor. Belinda, the group's consistent spokesperson, proceeds to describe the group's plan to him, which is to hang one magnet from a spring and to bring another magnet near it at different distances, and through the displacement of the spring, they can determine the force between the magnets:

BELINDA: Well, this is what our idea is thus far. So, we're thinking that, we hang the spring... it's right here... we hang the spring. And at the bottom of this would be our magnet. Then we would control the distance that... we would take another spring and like put it five centimeters... within ten centimeters, twenty-five centimeters, and at each different distance, we can measure the distance of the spring, how much it goes down. Because according to Hooke's Law, which is this, if we use the same spring, relatively speaking, we don't need to know the spring constant.
ANGIE: (?)
BELINDA: I don't know. So we don't need to know this. So we can kind of verify that the change in the spring distance as the one magnet on the bottom is attracted to the other one we hold up against it would kind of approximate the force between the two?

As for the constant that appears in Hooke's Law, Belinda sweeps this under the rug on the grounds that they are "relatively speaking." She suggests that the force of the magnet on the spring would "approximate" the force between the magnets. The instructor replies that it does more than approximate. That's what it is. Perhaps by "approximate", Belinda meant that what was measured would be proportional to the force they are looking for, not necessarily equal to it. In this case she would be correct. It would be very difficult for the instructor to understand this double-meaning, even if it was understood by the other group members, leading to a potentially damaging miscommunication.

The instructor tacitly approves of the idea so far, but raises the issue of how the group might change the distance between the magnets. This group's plan is the most common approach to this particular lab problem, though the biggest problem with it is the inability to find forces at several different distances, since many data points are necessary to see a relationship between the magnet and the force. The instructor, concerned about time constraints, tells them that another group has faced this problem already, and solved it by placing the pages of a book between the magnets, and then varying the number of pages used. The instructor made this suggestion in order to encourage the group to use this method. The group understood it as a tacit approval.

How the experiment pans out

The group continues to run with the idea of measuring the force via Hooke's Law, but they reject the instructor's suggestion to use sheets of paper and, by the time the class discussion comes around, they have not been able to resolve this problem. This class discussion was conducted purposely to bring about the sharing of ideas, with the understanding that most groups did not yet have a complete plan on how to approach the experiment. This group listens to several plans, agrees that one in particular is a good approach, and then goes with that for the duration of the lab period. To see how this approach works out, see Appendix C.

Long-term strategy of strategies

In the first half hour of this laboratory activity, we see the group engaged in a three different epistemic games in the pursuit of their goal, namely Equation Bridging, Recursive Equation Bridging, and Evaluative and Concretizing Plan-Making. We have seen appeals to authority (textbook, notes, and instructor), appeals to peers (consulting other groups), the recall of previous information (homework problems), and sense-making (imagining what the magnets on strings will do). By examining these epistemic games, we can attempt to understand why the students chose certain games rather than others, and what may have guided the progression through these activities.

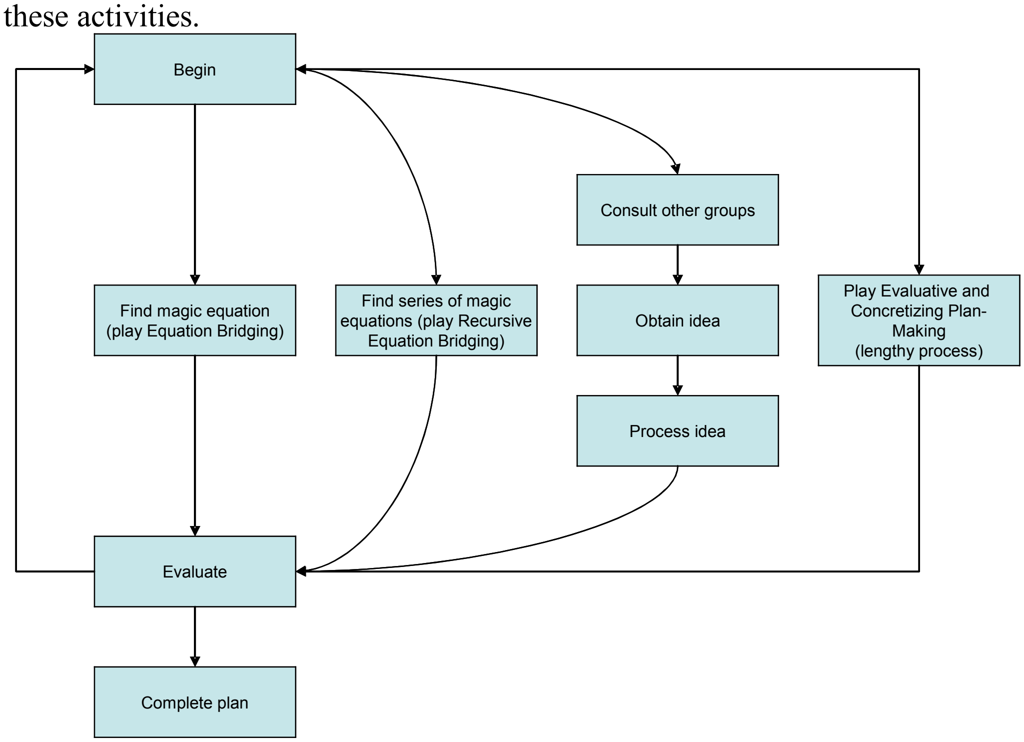

Figure 21. The evolution of group activity.

The activities that the students engage in, as shown in Figure 18 appear to increase in complexity over time. The first activity we see is the *Equation Bridging* epistemic game, the goal of which is to find one equation that connects what the students know with what they need to determine. Students engage in this activity frequently when doing homework problems, sometimes paradoxically spending hours on this simple activity, when a more complicated strategy (i.e. thinking about the problem) may take less time. Presumably that relevant equation, the key to everything, exists in the textbook, and finding it will be a quick one-step solution to the problem.

When Equation Bridging fails to produce the single equation they need, they then attempt to play Recursive Equation Bridging. This game involves more steps; one equation will not make everything fall into place. It involves a bit more mathematical manipulation, but like Equation Bridging, will not require sense-making or any serious thought about the materials they will be using.

The attempts at Equation Bridging and Recursive Equation Bridging both failed to move the group further towards their goal. Angie then suggests that the next step ought to be to consult other groups. On one hand, this is still looking for an easy solution, in that it will be someone else providing the creative effort. But unlike the previous epistemic games, consulting another group requires these students to engage in sense-making, not just to understand what the other groups might be doing, but to evaluate whether or not it is an approach worth trying. We observed this group reject one idea they got from another group, and then abandon this activity altogether. This is one of the reasons the lab is designed to encourage this kind of activity, rather than providing them with an instructor-approved solution.

What next, now that no shortcuts have been found? Here is where the group begins to investigate the materials at their disposal so that they might play Evaluative and Concretizing Plan-Making. They start small, suggesting very basic ideas that will require a great deal of concretization and elaboration before they can become full-fledged experimental plans. Since this is a lengthy process, it makes sense that the group would take a gamble on the easy solutions before deciding to participate in this game.

The general pattern seen is that the students move from activities requiring few steps and little sense-making to those requiring more steps and more sense-making. A group that has many strategies at its disposal may choose to exploit the easier options first. Therefore, if a group is observed engaging in an unproductive activity, it may mean they are taking a gamble that this approach will yield a quick solution, before going on to more sophisticated approaches. This is what I call the group's "strategy of strategies."

It should be noted that this strategy includes an "Evaluate" stage, in which the group evaluates the appropriateness and effectiveness of their method. This evaluation is not usually explicit, but we assume they have some reason for rejecting a method (which could be that they realize that they don't understand how to implement it.)

Tuckman stage model analysis of Group 1

The Tuckman model proposes that groups evolve by passing through four distinct stages: *forming, storming, norming*, and *performing*. Using this model, we can describe to first-order the general atmosphere of the group. However, there are two difficulties with this model: (1) the group appears to move in and out of phases within the course of this lab, rather than slow progressing linearly through each phase, and (2) the model tells us nothing specific about how the group is confronting the task at hand.

We could rightfully say that, for the most part, this group seems to be in the process of *performing*:

> Finally, the group attains the fourth and final stage in which interpersonal structure becomes the tool of task activities. Roles become flexible and functional, and group energy is channeled into the task. Structural issues have been resolved, and structure can now become supportive of task performance. This stage can be labeled as *performing*. (Tuckman 1965, p. 78)

The roles given to the students are certainly now flexible. No student seems to be concerned exclusively with the tasks assigned to them, though they seem aware of these tasks and comfortable with accomplishing them, whether they fall under their domain or not. Other non-spoken rules, such as leadership, also seem to have become flexible. Belinda remains the de facto spokesperson, but that doesn't stop other group members from taking the reins. And though Belinda does appear to take the lead quite often, the other members do so as well. For most of the laboratory, there seems to be little role-related conflict. The group seems quite capable of putting their skills together in the pursuit of a single task.

But then there is the period of time labeled "floundering" on the timeline. During this few minutes, the group cohesion breaks down. Each member has a different idea of what needs to be done at the moment. They do not discuss this divergence of opinion openly, nor do they agree to separate temporarily to pursue different objectives, as a *performing* group might be expected to do. Rather, they break off and do their own things. Following this is an unproductive conversation with each group member trying to get their ideas out, and simultaneously ignoring the others. From these few minutes, it seems more like they are storming:

> The second point in the sequence is characterized by conflict and polarization around interpersonal issues, with concomitant emotional responding in the task sphere. These behaviors serve as resistance to group influence and task requirements and may be labeled as *storming.* (Tuckman 1965, p. 78)

It could be that the obvious frustration on the part of the group members may be due to the breakdown of group cohesion. What is certain, however, is that the group is not *performing*.

Tuckman's original stage model is insufficient to explain how the group, normally in a performing stage, would suddenly revert to storming for several minutes. At the very least, a nonlinear model would be required. But the fact that this shift in group attitude took place on such a small time scale casts doubt on the practice of describing these behaviors as "stages." Rather, it could be said that the group has the ability to respond to a task in any of the ways described by the model, and that it is the tasks they are confronted with, and the social negotiation used to determine how to behave, that really matters. For this reason, the framework of epistemic games is better equipped to deal with these short-lived modes than a traditional stage model.

Case Study: Group 3

The previous example showed a group that engaged in a variety of activities and epistemic games. There were a few pitfalls and unproductive stretches, but in general there was a high level of coordination between the group members. They worked together, most of the time, as if with a shared sense of purpose of procedure. But this is not always how lab groups behave. Some groups fail to communicate in a way that activity can be well-coordinated. In this section, we will see another group (Group 3 in Appendix A) engaged in the SCL-2 magnet lab, and they do not engage in group epistemic game-play. Consequently, they do not progress towards a goal in the way we would hope they would.

In the opening moments of this lab, Allison shares an idea with the rest of the group:

ALLISON: All right. I was thinking... could we... have something in the middle, like... a paperclip or something, for instance? And measure, like the further... what?
CHUCK: I thought we were just doing two magnets.
ALLISON: We are doing two magnets but with the... like, with the distance it's going... to... what was I saying? I don't know, like, I feel like... you can feel the force... oh, no, I'm wrong. Never mind.

Allison's first statement looks a lot like the kinds of statements that students in Group 1 use to initiate a round of Evaluative and Concretizing Plan-Making. She has an idea of a possible physical setup, and is putting it on the table for the other students' feedback. The rest of the group does not follow suit. Chuck's comment suggests that he doesn't comprehend what Allison is suggesting, or that he has framed their present task in a completely different way.

In Evaluative and Concretizing Plan-Making, the group would respond with clarifying questions to determine exactly what is being suggested, followed by an attempt to flesh out the idea into a plan. Instead, Chuck's question shuts down Allison. For reasons unarticulated, she abandons this idea. What kind of epistemic game she might have been playing within her own mind is impossible for us to determine from this transcript. However, the conversation suggests that there was no understanding in the group of *what kind* of activity was going on. Allison seems to think that it is the time for making new suggestions. Chuck seems to think they've already decided on a general approach.

Now that we have seen successful attempts at Evaluative and Concretizing Plan-Making, one can imagine where this comment might have led a group with that strategy. Had they shared the understanding that the goal is to take an idea and mold it into a plan by asking clarifying questions, adding pieces, and constantly evaluating it, they could very well have devised a plan from this idea, using paperclips to vary the distance between the magnets[11]. However, the group does not share an understanding of purpose or procedure, so the comment falls on deaf ears.

After this exchange, Brandon suggests an idea that also fails to get the kind of productive response necessary:

BRANDON: I have an idea. We can put some kind of weight on the top of (them) and make 'em go in slow motion. It's harder, but then you'd have to know what the force of friction was.
CHUCK: No friction! (laughs)
BRANDON: Yeah. Why do you think that (?)
ALLISON: To see if...
CHUCK: Wasn't force mass times velocity?

[11] This could, however, modify the force if the clips were magnetizable.

BRANDON:	Mass times acceleration.

Brandon's suggestion is that they put the two magnets on the table top and put some kind of weight on top of them so that, rather than snapping together quickly, they will go slowly enough to be able to measure the velocity or acceleration. In theory, this is a plausible suggestion, though in practice it would be hard to implement. A group playing Evaluative and Concretizing Plan-Making might run with this idea for some time, before discovering, through concretization, that doing this will not slow the magnets down nearly enough to allow for a reasonable measurement of velocity or acceleration. But this group will never find that out, because they do not respond as if this is a specific strategy for making a plan. Rather than talking about how the idea might be implemented, the other students respond almost conversationally.

In fact, Chuck's comment reveals a bit about his epistemological framing. "No friction" comes off as a shared private joke. In introductory physics courses, word problems are frequently presented in a way that the student is instructed to ignore secondary effects, such as wind resistance and friction. Consequently, "no friction" has become synonymous with the contrived world of ideal, hypothetical problem situations, having little to do with the real world. By mentioning this, Chuck reveals how he is framing the present activity: that they are trying to treat a real-world problem with a physics-world scenario and rules. It is very likely that the humor Chuck sees in this statement implies an inconsistency between the two views in his mind. At any rate, this idea is not pursued by the group.

ALLISON:	We can see when at.. like at what height it... flipped over.
BRANDON:	That's good.
ALLISON:	Like here, feel it. Where exactly... does it go over. And then for here... oops, sorry. For here, like, where... it comes out.
BRANDON:	There's K X squared. You just brought K X squared to the table. Thanks.
DJANGO:	Hooray, but we don't know the spring constant!
BRANDON:	We don't need to.
ALLISON:	Is there any way to attach them to 'em?
DJANGO:	Tape.
BRANDON:	What's the idea?
DJANGO:	I don't really know.
BRANDON:	You just got the stuff. This is tough.
DJANGO:	I know.
ALLISON:	I think...
CHUCK:	We're trying to answer the question, "how does the force between two magnets.
DJANGO:	How about, this is attached to one side, and this is attached to another, and that magnet pulls it... till... there's not enough force... the spring...
BRANDON:	You don't want...
DJANGO:	Where's the other magnet?
CHUCK:	"How does the magnetic FORCE between 'em depend

on the distance?"	
DJANGO: (?)	
ALLISON: We could do... I don't think that we should use the springs.	
BRANDON: Springs don't make sense right now.	
CHUCK: "How does the magnetic force BETWEEN two magnets depend on the distance BETWEEN them?"	

We can see that there is a basic shared understanding that, at the present moment, it is appropriate to make suggestions; they are essentially starting from scratch. Allison puts forth another idea. She holds one magnet up on its side and brings the other magnet closer to it until the force is great enough to knock it over. This time, Brandon approves of the idea, though nobody seems to know what to do with it. It is possible that Allison herself is playing a game like Evaluative and Concretizing Plan-Making in her own mind. She wants to run with this idea, expand it, flesh it out, and concretize it with the materials. Or she could be engaging in Exploration, messing around until an idea surfaces. Without verbalization, it is hard to tell. The rest of the group does not do what she does, and their responses distract her. Without a common goal, they fail to communicate in a way necessary to use this idea, and rather than stick with it, they are distracted by another idea.

Django has been looking for equipment, which suggests that he frames this activity differently than Brandon. His purpose is to brainstorm ideas by considering the equipment one can use (or perhaps to play Exploration). When he brings over a spring, Brandon responds that Django has "just brought K X squared to the table." Neither Brandon nor Django understand "what's the idea." For the rest of this clip, each student seems to be doing his or her own thing. This is somewhat different from Group 1, which also went through a stage wherein each member went off to do her own thing. In Group 1's case, the members diverged for a few minutes, and eventually came back together. For Group 3, this divergence is the rule, rather than the exception.

It was noted previously in chapter four that this was an instance of Equation Bridging. The group briefly considers three equations:

$$F = mv$$
$$F = ma$$
$$F = kx^2$$

And though two of these equations are incorrect, the group did not see a way of physically realizing these equations, and took the ideas no further.

These students are interacting in a way that does not allow for true cooperative group-work. Allison has several ideas, but they are not acted upon. Brandon is generally responsive to the ideas of others, but does not share their sense of purpose. Chuck seems to purposely impede any progress they might make through his quips. Django seems to be content with the fact that he is the materials go-fer, and that other people will be responsible for the brain-work. This all would be fine if done for a short period of time (as we saw in Group 1), but in this case it goes on for a considerable chunk of the lab period. One could imagine different ways that a group might coordinate for these tasks. They might engage in Evaluative and Concretizing Plan-Making to deal with the ideas suggested by Allison and Brandon. Or they might engage in Exploration with the materials, as Django seems inclined to want to do. Either way, a coordinated team effort would accomplish more than the uncoordinated activity we see here. Without a shared sense of purpose, good and bad ideas alike are lost.

Later on, we see that the group continues to have trouble as a result of not being able to work with a common purpose:

BRANDON: I don't understand this pendulum idea.
ALLISON: I'm trying to explain it to you now. It's so you have... two things like hanging, and then you bring them like... they're on a string, so there's no...
BRANDON: Oh, so M G will be the same on them.
ALLISON: What?
BRANDON: If they weigh the same, M G will be the same if they're both on the string... bring the strings closer together.
ALLISON: To weigh them?
CHUCK: Do we have anything to hang them to weigh them from though?
BRANDON: Bring the strings closer together.
ALLISON: To weigh them?
CHUCK: I mean, to hang them from.
BRANDON: We could make something.
ALLISON: Well, we'll make a little contraption.
BRANDON: We could make something using a box... cardboard box.
ALLISON: So like...

The "pendulum idea" Brandon is referring to is the idea that they can hang both magnets from springs, thus eliminating surface friction. It is possible that Allison is trying to play something like Strategic Mapping by comparing the current situation to the homework problem discussed in chapter four. However, it is never articulated that this is the goal. And since the other group members are not in on this activity, even if it is an example of an epistemic game, it is not a shared game.

The group does not appear to have a shared understanding of what to do with this idea. Django, for example, continues to think about this activity in terms of getting materials. He hears the suggestion, and immediately runs off to get the string. Brandon is attempting to make sense of the suggestion in terms of the mathematics involved: "If they weigh the same, M G will be the same if they're both on the string…" This direction would be appropriate to take, since this idea is not yet in a form that it works out on paper. Chuck and Allison, unfortunately, are not discussing the math like Brandon is. They are more concerned with the physical implementation of the idea. Chuck asks, "Do we have anything to hang them, to weight them from though?" and then the rest of the group starts talking about how to design the actual apparatus.

In this example, we see that the group by no means has a shared goal. They seem to respond to each others' comments as they come along, the conversation shifting every few lines, rather than focusing on a single strategy. There seems to be no understanding of what specifically they are doing and no concept of what is appropriate right now and what is considered "changing the subject" or "shifting the frame."

Later on in the lab, this group does eventually develop a shared goal and coordination, but it takes a long time to happen. These clips were presented to demonstrate not that this group lacks the ability to work together, but that they accomplish little when they do not.

Tuckman stage model analysis of Group 3

This group is more difficult to describe using Tuckman's analysis. While Group 1 seemed to activate different stages in response to different contexts, Group 3 seems not even to follow a consistent stage for even a short amount of time. Instead, the lack of cohesion within the group has prevented these stages from manifesting at all; each member appears to have a different idea of what is going on and how to operate within the group.

Take, for example, the issue of group leadership. At a first glance, Brandon seems to be the *de facto* leader of the group. Conversation is constantly directed towards him, as if for his approval. His statements lead to new conversations, in contrast to those made by Allison, which are frequently ignored or shot down. But Brandon does not seem to be making any particular effort to assume leadership. His leadership is more like Richmond & Striley's (1996) *inclusive* type, rather than *persuasive* or *threatening*, as can be seen by his attention to, and approval of, Allison's ideas. Though one can only speculate as to whether or not Brandon is aware of his status as team leader, if there was a period of Forming, during which his dominance was established, or a period of *storming*, in which his leadership was challenged, this is no longer going on, as far as Chuck and Django are concerned. Allison, however, is not in the same place. She makes obvious and numerous attempts to take over temporary leadership of the group. As far as leadership is concerned, Allison appears to be *storming*, while the rest of the group is beyond that stage.

So while Brandon seems comfortable with his leadership role, and while Allison *storms* by herself, Chuck and Django play out their own roles as well. Chuck consistently acts as a comic relief; Django understands that his duty is to be the materials gofer, a role that absolves him of any need to think. So while one hand, there are elements of their roles that seem well-established and recurring, the "structural issues" mentioned in Tuckman's analysis are far from resolved. If Allison's comments are omitted from the transcript, this group appears to be Performing, albeit unproductively. Chuck, Django, and Brandon seem comfortable with their roles vis-à-vis each other. But throw Allison into the mix and there is role conflict and discord. This situation is not easily explained through the Tuckman model.

Group 3 illustrates further inadequacies of the stage model, which fails to accommodate a group wherein the members are acting non-uniformly. Epistemological framing, on the other hand, can describe this situation. There is a shared understanding between the male members of this group of what is the appropriate way to move forward, and Allison does not share this frame:

ALLISON: All right. I was thinking... could we... have something in the middle, like... a paperclip or something, for instance? And measure, like the further... what?
CHUCK: I thought we were just doing two magnets.
ALLISON: We are doing two magnets but with the... like, with the distance it's going... to... what was I saying? I don't know, like, I feel like... you can feel the

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force... oh, no, I'm wrong.  Never mind.
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We see here that the shared frame, so often an enabling tool, is in this case blocking a productive member from participating.

The Tuckman model also assumes that with the progression of a group through the four stages, the group's productivity increases. Group 3 is, in some ways, *performing* through flexible roles, however, rather than enabling them to efficiently tackle the task before them, it is hindering them by suppressing the challenges presented by Allison. But through epistemic games we can see that many locally-coherent activities are in fact unproductive and undesirable. Performing, as in working together towards a common goal, is not always going to lead to productivity.

Discussion

These two case studies demonstrate what a shared epistemological frame can do for a group – and what can result from the lack thereof. The chief difference between Group 1 and Group 3 is in the former's ability to share an understanding of the purpose of their activity. When this sharing occurs, the students are able to cooperatively make use of a small range of skills in a manner that is tacitly (or even explicitly) understood.

Group 1 was capable of coming together in the pursuit of a number of locally-coherent epistemic games. Within their shared frame was an understanding of the purpose of their activity and the types of moves appropriate to this activity. Shifts from one epistemic game to another occurred typically without explicit vocal direction, suggesting that these games were well-understood within that group. We see that Group 1 engaged in a sequence of games that generally increased in complexity with respect to cognitive steps. It is appropriate, then, to regard this group as a functioning system of distributed cognition, in which manipulations of ideas are carried out jointly by the group, and not within the head of any one member. This is made possible through the shared epistemological framing of the group and the epistemic games they have developed.

Group 3 was generally unproductive, and as we could observe, many good ideas failed to bloom because of their inability to work together in the way that Group 1 did. We do not see structured games taking place, nor do we see evidence of a shared perception of the task. Instead, we see a group wherein each member operates without meaningful mutual interaction. This cannot be regarded as a system of distributed cognition; it is little more than the sum of its parts. And consequently, the group was incapable of handling the task set before them, which was intended to be completed by a functioning group, not by individuals.

Chapter 7: Conclusion

Overview

The goal of this study was to determine how students cooperatively take on tasks in the physics laboratory. By including the cognitive and the social perspective, I have approached this topic with a net broad enough to catch both the contributions of individual students and the emergent phenomena within the group itself. We have seen that groups of students can engage in structured, locally coherent cooperative activities that can be extremely productive in the construction of knowledge in the lab environment. We have also seen that groups can engage in these activities, and frequently switch between them, without stating explicitly what they are doing.

Chapter four presents epistemic games, which are a powerful tool for categorizing and analyzing cognitive behavior geared towards the building of knowledge. A great deal of what happens in the laboratory can be illustrated through the terminology of epistemic games, and five frequently occurring games are presented. In order to expand the concept of epistemic games to describe not just individual cognitive activities, but shared group activities, we present in chapter five the framework of distributed cognition, which allows individuals to play a part in a larger cognitive system that includes not just minds but interactions, social factors, and cultural artifacts. Thinking about a laboratory group as a large computational system consisting of interacting minds allows us to talk about epistemic game-play as a social phenomenon, as well as a cognitive phenomenon. Finally in chapter six we see how the games are played in the laboratory and how successful game-play can assist a group's performance.

Research Findings

Now that we have determined how to parse student activity, we can see student activity from a new vantage point. From this perspective, we can see the social dynamics that can lead to a shared epistemological frame and productive group work, as well as social dynamics that can hinder cooperation. We also gain some insight concerning what might be going on in a group that is not articulated by the students or obvious from an observer.

We have learned that students engage in locally coherent epistemic games, with specific goals and specific sets of behavior appropriate for them. Through studying video transcript, we see that these epistemic games typically last on the order of a few minutes, and can be played either by an individual or by a group of individuals. Though it is not necessary for each group member to be entirely aware of the end goal of the activity, a shared understanding of the appropriate moves leads to an emergent phenomenon analogous to the epistemic games an individual might play, only tremendously more effective.

Students who share an understanding of the epistemic games at their disposal are capable of a high level of productivity, as we have seen with Group 1. They can approach the laboratory task in several different ways, without having to engage in lengthy discussions *about* what they are doing. In general, the conversations we observe in groups engaged in shared game-play are richer and more productive than those we observe in other groups.

As we have seen with Group 3, when a group does not engage in shared epistemic game-play, the students tend to work at cross-purposes. One can say that the group is only as productive as its most dominant member, who performs the cognitive labor on his or her own. This is not the kind of behavior we are seeking to promote.

We have seen that social interactions play an important role in the selection, negotiation, and carrying out of these epistemic games. Though detailed explanation is not necessary in order for a group to converge on an epistemic game, this occurrence requires a shared epistemological frame. It is necessary for the members to be able to understand what is going on when someone proposes a new game to play. Ignorance about what the other group members are doing will cause students to work as individuals, not as a unit.

Knowing that students engage in these games and understanding the nature of them can be helpful for a lab instructor. It is essential to know what sorts of strategies the lab groups might be attempting to use. Awareness of the existence of these strategies helps an instructor to answer the question "What are the students doing?" by observing certain verbal clues.

Finally, we have seen that it is useful to consider a laboratory group as a system of distributed cognition. Each student brings his or her own skills and ideas to the table, and a group that can communicate well will be able to function as a single computational unit that makes use of all of these resources. The virtues of teamwork come about not just through the summation of individual skills, but through the emergence of group behavior irreducible to the sum of individual minds.

With these labs, our research group had intended to get the students thinking about a number of things. We wanted them to learn to make connections between the physical concepts they were learning in lecture and the experiments in lab designed to probe them. We also wanted them to think about experiments in terms of design, specifically, having goals, proposing ways to reach those goals, and evaluating their proposals on the basis of how well it would work (and incidentally for this study on how certain it allowed them to be of their results.) Understanding the extent to which these particular goals are achieved, and also what needs to be focused on to make them achieved more effectively and more often, requires the kind of analysis demonstrated in this thesis. Group epistemic games gives us a method of identifying the goals towards which the students are working and the strategies they are employing in the pursuit of these goals.

Suggestions for Future Research

Our work is far from done. We have some tools with which we can make sense of group-work, and there is still more to be learned about epistemic game-play and distributed cognition. Hopefully the questions I raise here will be addressed in future research projects.

First of all, how do shared understandings develop? The path from four total strangers to one well-oiled laboratory group must be a rocky one, filled with trial-and-error. It would be helpful to make a lengthy case study of one group, starting with their first experience together, and tracing their progress throughout the year. Perhaps there are definite moments where the group comes to an explicit understanding about what these strategies are and how to execute them. Or perhaps the evolution is unspoken and gradual.

Next, we would like to determine which of these epistemic games should be encouraged, and which (if any) are unproductive enough to be discouraged. It has been our stance throughout this work that there is a time and place for any of these strategies. What may be productive in one context might be unproductive in another. A dead-end strategy might bring to light some fact that inspires another strategy or completes a piece of another abandoned idea. Many researchers mentioned in this thesis insist on an optimal way for laboratory groups to act. From our perspective, however, groups need to negotiate their strategies on their own. The strategies that do not yield the answer can be just as important as those that do. Nevertheless, it would be to an instructor's advantage to know if there are strategies that do nothing but harm, and to be able to identify it and discourage it.

Further research might examine epistemic games in other contexts. The laboratory activities studied in this dissertation were designed with a specific pedagogical and research agenda. But there exist many reformed laboratories, tutorials, and classroom activities that also attempt to foster an increased level of group work. It would be enlightening to see what sorts of group epistemic games emerge in those environments, and how they relate to those found in this study. It would also be possible to examine non-academic work environments, such as a corporate office or a town hall meeting, and see what sorts of group strategies emerge.

Piano Quartet Redux

We know instinctively that there is strength in numbers. I saw it in the eyes of the four young pianists, as they glanced at each other for encouragement, feedback, and signals. Comparing these faces to those of the terrified solo performers convinced me that something special was happening in the group that couldn't be done alone.

With this study, I set out to explore what makes a group different and what makes up this thing called "teamwork." Teachers know that students can learn a great deal from each other, and that teamwork, aside from being a means to an end, can be a powerful learning environment. Working together is not just about combining manpower. It is about learning how to interact with others, learning how other people think, and if you are lucky, learning more about yourself.

Chapter 8: Suggestions for Laboratory Instruction

Introduction

The things we have observed in these laboratories indicate that there is something unique about our reformed labs. Group learning may occur in other classes, but normally it is heavily guided. Students who are majoring in science will eventually get the chance to work in laboratory environments, but it will also be under the guidance of more experienced others. The SCL labs give students the opportunity during the school years to engage in mostly unguided scientific inquiry in a community of one's peers. It is intended to be a place where students can pick up some of the skills, both technical and social, necessary to do science.

During the four years in which my colleagues and I offered these labs, we have learned a great deal about how one can successfully implement major reforms to an ailing laboratory course. As I have demonstrated in this dissertation, it is indeed possible to create a laboratory environment in which students engage in meaningful discussions about physics, learn to work together as a team unit, and in doing so, tackle projects far larger in scope than those offered by traditional labs. In this chapter, I present details on our reform effort and suggestions for instructors who may wish to get involved in a similar reform project, based not only on what we see in our research, but on my own "teacher's instincts." These are conjectures and could serve as a framework for the development of future research.

Suggestions for Laboratory Reform

As mentioned previously in chapter three, the reforms that led to the development of the scientific community laboratory sets were inspired by specific needs of our class population and specific perceived failings of our traditional laboratory curriculum. I do not claim in general that what has worked for us will work for all physics departments. However, we have learned enough about the reform process to be able to provide general advice about what may and may not work. It should also be noted that our reforms progressed primarily through trial-and-error. We had eight semesters and over a hundred different sections to work with, and we were able not only to make incremental changes at the beginning of each semester, but we had the control to be able to make changes during the semester as well. Our experience was full of noble failures and unexpected successes. In the end, however, we were satisfied with the result, and hope that our experience may help others in reforming their own labs.

Class population concerns

There are many different ways to approach a laboratory section, just as there are many different topics to choose from. A guiding principle in any lab reform should be the specific needs of one's students. No one kind of lab is ideal for everyone, and the more relevant the labs are to the student population, the more effective they will be.

The target population for the scientific community labs was mainly pre-med students and biology majors. During our preliminary planning, we consulted with professors from the biology department and asked what sorts of laboratory skills they would like their students to have. A chief concern of theirs was students not being able to understand the broad picture of experimental research. This is what first opened my eyes to the idea that perhaps traditional laboratories, in their attempt to provide simulations of real experimental work, were focusing on the minutiae and ignoring the substance of experimentation. Indeed, when students engage in a dozen "experiments," but never have the opportunity to plan their own experiment or debate results with others, they run the risk of not understanding at all what scientists are really doing in the lab.

Deciding which components of experimentation should be simulated by the introductory lab, and which can be omitted, is important and should be done with an understanding of the needs of one's student population. These needs can change from year to year. The last thing a lab reformer wants to do is design a lab whose skills may not be at all relevant for the students. Right now it is typical for biology majors, engineering majors, architecture majors, and pre-meds to take an introductory physics laboratory. It is a mistake to take a narrow viewpoint that the physics lab exists solely to teach about physics experimentation. Rather, it is an opportunity (sometimes a student's only one) to learn about experimentation *per se.*

Significance of experiments

Traditional laboratories typically deal with topics that have just recently been introduced in lecture. The idea is that, after the students learn the theory behind a concept, then they get a chance to *see* it. This makes a lot of sense from a teacher's perspective, since it assists in the narrative flow of the course. However, this is entirely contrary to how research is done. If students are in the laboratory doing nothing besides verifying something they have already been told is true, they are missing out on the act of building knowledge *based on observation,* which is the chief significance of doing an experiment. They must have the opportunity to explore topics without an *a priori* understanding of what the answer is.

This formula need not be followed. It can be reversed with positive results. The scientific community laboratories were designed specifically so that "the answer" of the experiment was not known in advance. This meant either giving them topics that were not specifically covered in lecture, or introducing topics in laboratory first and in lecture afterwards.

The merit to this latter approach is that the students are doing experiments for the same reason real scientists would do them. There is some phenomenon that they don't understand and the purpose of the experiment is to explore this phenomenon, make sense of it, and attempt to model it. This approach is far more representative of "real research" than the traditional way. Furthermore, it can change the narrative structure of the lecture in a positive way. When a new concept is introduced, the instructor can point out that the class has already explored it in the real world. The experience gives the students something concrete upon which to apply the more theoretical and mathematical components of the concept.

Tackling a topic first in laboratory gives the students the impression that what they are doing *means something,* that this is the activity by which the concepts in the textbook were built. Giving them the punch-line first and the joke second, as in traditional courses, robs the experiment of its deeper significance.

Difficulty level of experiments

When considering the kind of laboratory activities to present, one must take care to aim for an appropriate level of difficulty. An experiment that is too difficult may cause widespread demoralization and the failure of students to *get* the purpose of the experiment, or it may result in one lab instructor having do to the experiment nine or ten times, resulting in nothing more than a lengthy demonstration. On the other hand, if laboratories are too easy, the students will be bored and will not find cause to engage in genuine discourse about what is going on. Ideally, one would seek activities that are well within the capabilities of the students, yet still present a genuine challenge.

At a first glance, the SCL labs seem to be quite difficult in terms of how much needs to be done within a small period of time. In just under four hours, a lab group must design an experiment, take data, formulate a conclusion, present results to their peers, evaluate the other students' experiments, and write up a lab report. Although we do not expect cutting-edge experimental techniques, the volume of work necessary to complete these labs is considerably higher than in a traditional lab, where the experiment is pre-designed and the instructions are provided. This is the chief reason we chose to give them labs spanning two weeks.

What makes these activities doable for the students is the enhanced productivity that results from social interaction. Students work in groups of four rather than in pairs. At the very least, physical and mental labor can be divided up amongst the members. But more importantly, having a larger group of students significantly increases what the students can accomplish. It means a larger pool of ideas. It can mean the emergence of more sophisticated epistemic games.

In traditional laboratories, it is quite common for students, when confronted with a difficult activity, to run out of time. Lab instructors normally grant the students extra time to finish. This can have extremely bad effects on the students' expectations. If they know they'll be given the time necessary to finish, students will never consider the practical decision of how to design an experiment *with specific constraints,* time being one of them. We have found it desirable to keep to a strict timetable with the labs, and to continuously remind the students that it is preferable to go with a design that isn't "perfect" than to go with a design that cannot be finished within the time allotted. This is how real science research is done. Nobody is given infinite time and infinite resources to do an experiment. While it is desirable to do the best experiment one can, it is of utmost importance to do something realistic.

A good rule-of-thumb would be that students working together in larger teams can do considerably more than they would working in pairs. A laboratory designed should not be afraid to present the students with difficult tasks and lengthy assignments, so long as the students are assured that they are not being graded on an all-or-nothing basis.

Negotiating reforms with the students

Not all of the changes made to our labs were done between semesters; some were implemented incrementally during the semester in order to address specific problems that emerged. Some were accepted easily by the students, while others took some effort to implement. But in general, we observed an interesting pattern over the semesters in the students' behavior as a result of the reforms.

Initially, the students were surprised at how difficult the laboratories seemed to be. Based on their previously laboratory experiences, they expected something entirely different. Being thrust into a new environment with unfamiliar rules can be distressing for students. It seemed that any radical change to the structure of the lab, even those which made the activities easier for the students, was initially met with fear and frustration. This phenomenon can be a major barrier for a serious course reformer. Student morale is important for an instructor, and widespread frustration can be construed as a failure, and perhaps discourage further attempts to reform and lead back to traditional ways that, while sometimes unproductive, the students are at least familiar with.

I do not suggest that a lab reformer ignore the plight of frustrated students. Quite the opposite in fact; nothing is more important to a curriculum reformer than honest feedback from the students. The challenge then, if one seeks to change the course in positive ways, is to negotiate these changes with the students.

First of all, it is desirable to be completely honest and up-front with the students about what is happening. Let them know that this laboratory is going to be different than those they are familiar with. This might be a challenge, since teachers have a tendency to exaggerate just how different things are going to be "with them." Nevertheless, the students must be reassured constantly that it is okay to feel a little bit "lost" during the first few weeks of a new type of course. Secondly, do not be afraid to make your intentions clear to the students. If the underlying purpose of the laboratory is to teach them how to deal with experimental error, remind them of this fact frequently. We published a "mission statement" (see Appendix B) in which the three main goals of the laboratory were stated explicitly for the lab instructor to point the students to in case the issue of "why are we doing this" is raised. Finally, from our experience, it took from three to five weeks for the students to get comfortable with our reformed labs. This may seem like a long time to suffer uncertainty (and we would love to figure out how to decrease this time), however, the patience pays off. The subsequent weeks of lab, after the students had grown accustomed to the new rules, were extremely productive. It doesn't hurt to let the students know that it might take a little while to get comfortable with your reforms, but that, in the end, they might enjoy these new labs far more than the traditional ones.

Feedback

The only thing worse than having students openly express hostility towards a reformed class is having them do it secretly. When trying out something new, it is vitally important to stay in touch with how the students think. In my experience, anonymous feedback, while potentially painful for the reformer, is the best method for assessing how the students are taking things. It helps for two reasons. First, if there is a widespread problem among the students with respect to the laboratory, one can rectify the problem before the students become frustrated to the point of not caring. Second, if the students get the impression that the designer of the labs genuinely cares about their opinion and will be responsive to their needs, they will be more willing to go along with the new setup. A laboratory reformer might find an honest and forthcoming class of students to be a valuable resource for ideas on how to improve the course.

Suggestions for Laboratory Design

Let us now take a look at some of the components of lab curriculum that one might decide to tinker with when designing or conducting a reformed lab.

Equipment

In a sense, the laboratory equipment is what makes a lab. It's what sets it apart from other courses. We found that in traditional labs, the *purpose* of the lab frequently seemed to be learning how to use specific equipment. One introductory lab sequence featured two labs in which the students mainly learned how to operate an oscilloscope. The actual physics being explored with the equipment was secondary. My general opinion is that laboratory can be an appropriate setting for the students to learn how to use lab equipment, but that the manipulation of these tools should in general take a backseat to the conceptual goal of the lab.

An example of this being an issue occurs in SCL-2. In this set of labs, the students are encouraged to use the Microsoft® Excel spreadsheet for the tabulation and manipulation of data. This program was selected specifically because of its similarity to many of the more sophisticated data analysis programs typically used in biological research. A show of hands proved that about half of my class had had previous experience with the program. In each section, lab instructors made sure that no single group of four students was without an experienced Excel user. We did not want the chief purpose of this lab to be learning how to use the features of this program. However, we did deem it important for every student to have laboratory experience with a spreadsheet program. The SCL-2 labs included lab practicals in which included a test of basic spreadsheet proficiency.

In each experiment, use of the spreadsheet was encouraged. We introduce sophisticated equipment not for its own sake, but to make tasks easier for the students. If the equipment does indeed make a task easier, the students will choose to use it on their own, and that is exactly what we observed.

Our general policy was to allow students to use sophisticated equipment if and only if they had a reasonable understanding of how it worked. Most of the equipment at their disposal was hardware store junk, everyday objects with no fancy technological function. More complicated equipment, such as force probes and motion detectors, were allowed only after the students had learned how to use them in another part of the course. Regular laboratory time was never devoted to the teaching of new equipment; rather, it was intended for the students to work with what they understood, and to seek new equipment on their own.

What it is important to avoid is a situation where the students are "doing" without "understanding." If, for example, students use a spreadsheet's curve-fitting algorithm to construct a best-fit line, chances are they have no idea how this is being done. We required that our students be able to explain how things were done, and encouraged them to stick with what they understood, rather than using tools whose significance was not understood. If students become accustomed to using equipment they don't truly understand, this shuts off their sense-making abilities, which we consider to be vitally important in doing laboratory work. From a design perspective, any equipment that the students are allowed to use should be either within their abilities to understand or very near that. This means not providing them with black boxes, which they need only to press this button or that button to get results. The idea is to give them access to equipment that expands their cognitive abilities and doesn't do the thinking for them.

Architecture

How the classroom is arranged can seriously affect student performance. Our traditional labs are typically arranged as in Figure 7, with the students arranged in rows. This arrangement is not ideal for communication between students. One might as the very least consider rearranging the classroom so that group members are facing each other. What you want is communication between the students, so that they might act together as a single unit. This cannot be done if they are not physically able to see each other and converse easily. The scientific community labs were conducted in a room arranged as in Figure 8, with groups of four. The seats were close enough together for students to be able to converse privately within a group, but close enough to other groups so that inter-group conversation could take place without anyone leaving their seat. We found this to be an excellent arrangement for maximum communication within and between groups.

Grouping

In theory, a laboratory instructor has the ability to assign groups however one pleases. We considered many different ideas for how to arrange groups. For instance, it seemed like a good idea to create diverse lab groups by matching "A" students with "D" students, separating friends, and mixing males with females. These noble intentions, however, were not executed for technical reasons. Gathering the necessary information to assign the groups for hundreds of students proved to be too difficult a task to be accomplished before the first lab. The students were allowed to form their own groups, as it is done in traditional labs.

This turned out to be a good way to group students. The most important factor in what makes a good group is how well they communicate. From my observation, students know better than the instructor who they might communicate best with, and will arrange themselves along those lines. I found that the best lab groups were those with members who had worked together before or were friends outside of class. Basically, it was students who already knew how to relate to each other who found it easiest to engage in sophisticated epistemic activities in the laboratory. Breaking these students up would force them to start all over in that respect.

An important issue facing any laboratory course designer is how one goes about arranging the students in the classroom in order to foster positive group-work. One is normally constrained by campus and department protocol when it comes to how many students total should make up a class, and possibly by other factors, both economical and social. Our particular conditions varied from semester to semester, and as a result we were able to observe a variety of arrangements to compare and contrast.

A team has to be of a size so that in most cases all students will be engaged with the work. Johnson & Johnson (1993) suggest groups of three or four. Our preferred number of students to a group is four. A group of four has enough students to encompass a broad collection of ideas and enough hands to be able to multitask when an activity requires many different things to be done at once. Groups of three frequently had more trouble with the division of labor and finishing the lab on time. Also, groups of three tended towards social arrangements by which one student took control and called all the shots. In foursomes it was more likely to see temporary leadership, rather than permanent. Groups of five seemed to be as productive as groups of four, though not more, leading one to believe that some cognitive power is wasted in this arrangement. Indeed, it seemed that shy students were less likely to participate in groups of five. It is easier to fade into the background in a larger group.

This is not to say that students cannot be productive in other numbers. I have observed quite a few diligent trios and efficient quintets, but these were atypical. Groups of four appeared to maximize participation and give the groups enough manpower to tackle a complicated multi-step experiment. Furthermore, consider a traditional laboratory section consisting of twenty-four students working in pairs. Having twelve groups, each at a different point in the activity, makes it tremendously difficult for the instructor to keep tabs on each group. Cutting this down to six allows the instructor to work more closely with each group. He or she is able to spend five or ten minutes with a single group should the need arise.

Timing

The scientific community laboratories (see Appendix B) provided a basic timeline for the students to follow. It is given not necessarily to dictate what the students do, but as scaffolding. We realize that students don't have a lot of experience in designing their own projects, and that allotting time for activities within certain constraints may not come naturally to them. With the timeline, they have a general idea of how much time should be devoted to each activity. We find that students typically don't follow them closely, but nevertheless appreciate the fact that they exist. Perhaps knowing that one is "on schedule" is important for students emotionally.

If there is a certain time for something to be due, this should be adhered to strictly. If the instructor caves in whenever students need extra time, it will be no coincidence that they'll need extra time *every time.* Designing a project means recognizing and planning around time constraints. So though it may seem draconian, dealing with time constraints is an important lab skill for the students to develop.

General Suggestions for Laboratory Instruction

Whether one is teaching a reformed lab or a traditional lab, one's role as a lab instructor is vital to student learning. However, what we have learned about how students behave in lab recommends instructor behavior that contradicts some conventional wisdom. Here are some suggestions that may improve one's performance in teaching labs.

Facilitation rather than lecturing

Is it important to take a step back and consider: what is the appropriate role of a lab instructor? Traditionally, the teaching assistants in charge of labs supplement the instructions in the lab manual with suggestions of their own on the blackboard. They make sure each lab group is making progress, and if they are not, they try to get the group on the right track. A lab instructor can find himself *doing* a lot of a group's experiment for them if they happen to be running out of time or hung up on something they don't understand. And of course, the instruction is there to answer whatever questions the students have.

My general attitude towards this kind of teaching is negative. The students should *never* be given a task so complicated that it requires a teacher to step in and do some parts of it. Anything an instructor does, whether it's validating a student's idea or hooking up the equipment properly, takes away from the student the opportunity the learn for himself. How can a student learn to perform an experiment if an instructor is always there to give her ideas, help her out when she's stuck, fix mistakes, and evaluate the students' actions? It is absolutely desirable for the students to do all these things for themselves.

The general approach I have taken, both as a lab instructor and as a coordinator of laboratory teaching assistants, is to regard the teacher's role in the lab as a *facilitator*, rather than a teacher. This means backing off considerably. Any time a student seeks the help of an instructor, it means, in addition to not knowing how to proceed, that the student doesn't know *how to think about* how to proceed. The proper role of an instructor in this case is not to tell the students how to proceed but to point them in the right direction of how to think about how to proceed. This can mean using some version of the Socratic Method. A few well-placed questions can lead the students to doing what needs to be done, rather than the instructor doing it for them. In a sense, this too is an intervention that "does something" for the students, but ideally we want for the students to develop an "internalized instructor." By this I mean that when the students grow accustomed to the instructor asking the same questions to them when they're stuck ("What are you doing?", "Why are you doing it" etc.) they begin asking these questions to themselves in anticipation of what they know the instructor would ask.

Encouragement of social interaction

Students come to the laboratory armed with a number of cognitive resources that pertain to social interaction. What they may not have is a good idea of how to implement these skills in this new context. Ultimately, we want them to get comfortable working in their groups and interacting with others. How does an instructor encourage this kind of behavior?

I have found that in the first few weeks of the reformed lab, when students are still getting to know each other and get comfortable working together, they often aren't communicating sufficiently to be able to engage in the kind of sophisticated game-play that we see later on. A lab instructor can encourage this in many ways. When a student asks the instructor a question, the proper tactic might be to pose this question directly to the other group members. They need to see that through mutual participation they can solve many of the problems they run into without resorting to the instructor's aid. Some scaffolding is required to get them accustomed to asking each other questions, brainstorming together, and conducting meaningful conversations in general.

Equally useful is opening a group's eyes to the potential for other groups to help them. If a group is stuck, an instructor can point them towards another group that may have already solved their problem. For social reasons, the students may not be comfortable with mingling in this way, so it behooves the instructor to remind them that this is perfectly appropriate behavior, and can help them considerably. It is far preferable for one group to make suggestions to another group, rather than for the instructor to provide these instructions, because typically students will not accept the word of their peers as gospel as readily as they do with the instructor. Some evaluation is required and a decision must be made whether or not to accept the advice. This requires a judgment, even if it is tacit. Through this kind of interaction, they begin to see the benefit to working within a social community.

Self-governing labs

Through scaffolding and facilitating rather than direct intervention, an instructor will see groups becoming more and more capable of doing things for themselves, as they learn to properly marshal the skills of the individual members through appropriate social interaction. The better they get at this, the less they need an instructor for detailed guidance.

It is customary in scientific community labs for there to be a half-hour at the end of the lab where each group presents their data, and then the class engages in a discussing about the best way to do this experiment. Normally the presence of a lab instructor is required to get the discussion going. Students are naturally shy in lab. They aren't quick to criticize others, and they dislike receiving criticism. Most of the hard-hitting questions have to be made by the instructor. What I have noticed, though, is that when the attitude of facilitating is maintained, the students need the instructor for this role less and less. By the end of the semester, my classes were able to conduct these end-of-class discussions entirely on their own, without my intervention. As their incentive, they had to write a section of the lab report based on what they learned from other groups. After many weeks of seeing what kind of behavior is appropriate during a class discussion, they are more than capable of engaging in this behavior by themselves. Critiquing the experiments of others ceases to be an emotionally charged action. Students are capable of doing these things by themselves, and it should be encouraged by the gradual withdrawal of help by the instructor.

Being aware of epistemic game-play

In this study, we see that students engage in coherent activities whose goal is to build knowledge as a group unit. An important feature of these epistemic games is that so much of what is going on is non-verbal. This can be very confusing for an instructor who is listening in on a group. It may not be easy to determine in a few minutes what the group is doing and what their goal is.

Instructors have a tendency to focus on correctness of specific activity, rather than on the character of activity and whether it can be expected by itself to produce a good result without need for intervention. Recognizing the existence of epistemic games is a good first step. When students are working together well, they may be engaged in a sophisticated activity that they might find it hard to articulate to you if you ask them what they're doing.

As we saw in chapter six, a group that is not making progress may be stuck in a particular game loop. Through lack of communication, they may not even realize that they are excluding certain reasoning strategies from their arsenal. An instructor can assist such a group by explicitly asking what the goal of their present behavior (if any) is, or more generally, what it is they are doing. Bringing this subject out into the open may help both instructor and student realize where they are and how to move forward. By recognizing recurring epistemic games, such as Equation Bridging, an instructor can see what sorts of things group *aren't* doing when they *are* doing one thing, and perhaps, with a quick question, they might inspire a game shift.

Conclusion

Through this study, we see the enormous potential for groups to tackle laboratory activities through sophisticated social interaction. An explicit goal of any attempt at laboratory reform can and should be to encourage and foster this kind of teamwork. Real science is conducted through social interaction, and students ought to be introduced to science through a community of their own. Learning how to work as a team is not easy for students. It can take several weeks, but it is worth the patience and effort.