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The Role of Students’ Previous Understandings in Reasoning Across Contexts

By

Janet Marie Casperson

A dissertation submitted in partial satisfaction of the requirements for the degree of

Doctor of Philosophy

in

Science and Mathematics Education

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

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The Role of Students’ Previous Understandings in Reasoning Across Contexts

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by

Janet Marie Casperson
Learning is typically thought of as a change in a student’s understanding within a single context. The term context is used here to describe a domain or subdomain of knowledge. Students’ previous understandings of the context are known to play a considerable role in such learning. Another important kind of learning is reasoning across contexts. Through reasoning across contexts, students’ understanding of one context influences understanding of another context. This dissertation investigated the role of students’ previous understandings in this reasoning process.

Psychology research has employed one type of experimental design to investigate reasoning across contexts. This has resulted in focus on a particular way of reasoning across contexts, called analogical transfer, in which participants’ previous understandings play a minimal role. In contrast, this dissertation employed a case study design for the purpose of investigating the role of participants’ previous understandings in reasoning across contexts.

Participants’ previous understandings of contexts were discovered to play a considerable role in their reasoning across contexts. Three categories of ways of reasoning across contexts in which students’ previous understandings play a role were identified. In the first of these, a participant’s new understanding of a context is a combination of ideas used previously to understand the same context and ideas used to understand another context. In the second, an idea from either the participant’s previous understanding or from the participant’s understanding of another context is modified to contribute to a new understanding. In the third, an idea from the participant’s previous understanding is brought into different focus through comparison with a corresponding idea from another context. These three are termed combining, modifying, and refocusing interactions, respectively.

Understanding of these different possible roles for students’ previous understandings in reasoning across contexts can inform instruction in which a general concept is instructed through particular contexts. An example of such a general concept is the concept of equilibration considered here.
To my family
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Chapter 1

Introduction

1.1 PURPOSE

Understanding the nature of learning is essential to the goal of effective instructional practice. The work described in this dissertation focuses on one important aspect of learning: the way in which people reason across contexts, or in other words, the way understanding of one context influences understanding of another context. The term context is used here to refer to a distinct knowledge domain (e.g., algebra or physics) or subdomain (e.g., projectile or orbital motion in physics). Reasoning across contexts is important to education because it is fundamental to the paradigm of the instruction of general concepts (e.g., gravitational acceleration) through particular contexts (e.g., projectile or orbital motion). Following such instruction, students are expected to be able to reason from their understanding in another context. This dissertation examines reasoning across contexts for the purpose of informing instructional practice.

Psychology research has examined a particular way of reasoning across contexts, called analogical transfer (Gentner & Holyoak, 1997). In analogical transfer, a person gives a new understanding of a context that is independent of any previous understanding of that context she might have had. The person instead derives her new understanding wholly from her understanding of another similar context. Education research has documented the considerable role (typically considered interfering) that students’ previous understanding can play in learning within a single context (e.g., inquiry into the nature of gravitational acceleration). This dissertation demonstrates that students’ previous understanding can also play a role in their reasoning across contexts. The term context interaction is introduced in this dissertation to describe a way of reasoning across contexts in which a person’s previous understanding of a context can play a role. This dissertation therefore considers analogical transfer, in which a person’s previous understanding plays a minimal role in reasoning across contexts, to be a special case of a context interaction.


1.2 BACKGROUND

Analogical transfer is one particular way of reasoning across contexts that has gained considerable attention in both psychology (Holyoak, 2005) and education (Bransford, Brown, & Cocking, 1999). Some terminology will be helpful in illustrating this way of reasoning across contexts. Recall that the term context is used here to refer to a domain or subdomain of knowledge. Some examples of contexts between which analogical transfer might take place are given in Figure 1. These contexts are taken from the Bassok and Holyoak (1989) study of interdomain analogical transfer. Context X and Context Y present problems from the domains of algebra and physics, respectively.

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Domain:</strong></td>
<td>Algebra</td>
<td>Physics</td>
</tr>
<tr>
<td><strong>Context:</strong></td>
<td>A boy was given an allowance of 50 cents a week beginning on his 6th birthday. On each birthday following this, the weekly allowance was increased 25 cents. What is the weekly allowance for the year beginning on his 15th birthday?</td>
<td>An express train traveling at 30 meters per second (30 m/s) at the beginning of the 3rd second of its travel, uniformly accelerates increasing in speed 5 m/s each successive second. What is its final speed at the end of the 9th second?</td>
</tr>
<tr>
<td><strong>Understanding:</strong></td>
<td><strong>Idea 1:</strong> The new allowance is the initial allowance plus the total change in allowance. <strong>Idea 2:</strong> The total change in allowance is the rate of change in allowance multiplied by the time over which the allowance changes. <strong>Idea 3:</strong> The time over which the allowance changes is the final time minus the initial time.</td>
<td><strong>Idea 1:</strong> The new speed is the initial speed plus the total change in speed. <strong>Idea 2:</strong> The total change in speed is the rate of change in speed (i.e., the acceleration) multiplied by the time over which the speed changes. <strong>Idea 3:</strong> The time over which the speed changes is the final time minus the initial time.</td>
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Figure 1. Examples of contexts taken from Bassok and Holyoak (1989) between which analogical transfer might take place. The contexts are from the domains of algebra and physics. Normative understandings of the contexts are given.

Also given in Figure 1 are the normative understandings of Contexts X and Y and the ideas of which they are composed. The word idea is used here to describe an inference that a person makes between the features presented by a context. These ideas together
will be considered to comprise the person’s understanding of a context. The normative understandings of Contexts X and Y are the solutions to the contexts’ problems that are agreed to be correct by the contexts’ respective domains. Participants may alternatively have nonnormative or partial understandings of the contexts.¹

The contexts considered in analogical transfer are said to be analogically similar because they can be understood in the same way. In other words there is a shared understanding that can be used to describe the contexts.² For the contexts given in Figure 1, the normative shared understanding is the following solution: the product of the rate of change and elapsed time added to the initial value. The analogical similarity is what makes analogical transfer possible.

During analogical transfer, a participant’s understanding of one context is derived entirely from her understanding of another context. A schematic of this process is given in Figure 2. This schematic illustrates the derivation of understanding of one context (understanding of Context Y, labeled $U_{\text{new}}$) from understanding of another context (understanding of Context X, labeled $U_{\text{other}}$). Through the process of analogical transfer, ideas that are used to explain Context X come to be used to explain Context Y. The process by which this happens is called mapping and will be discussed below. Research on analogical transfer calls Context X the source and Context Y the target to indicate the direction of the mapping process. In analogical transfer, the participant’s previous understanding of a context does not play a role in her new understanding of the same context (i.e., previous understanding of Context Y does not act as a source for $U_{\text{new}}$). The resulting shared understanding of the contexts is comprised only of the ideas that the participant transfers.

Psychology research seeks to understand the process by which students reason across contexts. The research methods of this discipline focus on the design of controlled experiments. The experimental conditions are designed to differ only by a feature, called a design feature, that is anticipated to affect the participants’ reasoning process. Aspects of the investigated reasoning processes are then inferred from the results. Using this research method, psychology research has been successful in elaborating detailed models of analogical transfer (Gentner & Forbus, 2011). These models assume that participants

¹ Such nonnormative and partial understandings are typically not considered by research on analogical transfer. They are mentioned here because they are considered in this dissertation.

² The shared understanding of contexts may also be called an abstract schema or general concept. The term abstract schema is used in psychology research to describe what is shared by the preferred or normative understandings of the contexts, rather than what is shared by the participants’ understandings of the contexts. As mentioned above, unlike research on analogical transfer, this dissertation considers participants’ understandings of the contexts, regardless of whether they are normative. What is shared by the participants’ understandings, called the shared understanding, may therefore be different from that described by an abstract schema. The use of the term general concept in education is similar to that of abstract schema in its focus on what is shared by normative understandings of multiple contexts.
Figure 2. Schematization of analogical transfer, in which understanding of Context Y is derived from Context X. Context X is called the source of the influence while Context Y is called the target. Understandings of these contexts are represented as labeled boxes: the understanding of the source is labeled $U_{\text{other}}$ and the understanding of the target is labeled $U_{\text{new}}$. The large arrow in the background indicates the progression of time: $U_{\text{new}}$ comes after $U_{\text{other}}$. The small arrow connecting $U_{\text{other}}$ and $U_{\text{new}}$ represents the influence of $U_{\text{other}}$ on $U_{\text{new}}$.

To use an idea from Context X to explain Context Y via a process called mapping. This process associates ideas from one context with equivalent features of the other context, where the term equivalent is used to indicate that the features with which the idea is associated in the different contexts reflect the analogical similarity of the contexts. For example, consider Idea 1 from the normative understanding of Context X ($U_{\text{other}}$) in Figure 1. This idea is associated with the context features “initial allowance,” “change in allowance,” and “new allowance.” Before this idea is used to understand Context Y ($U_{\text{new}}$), it must be associated with corresponding features of that context (“initial speed,” “change in speed,” and “new speed”). Figure 3 gives a schematic of the mapping process that does this work.

Figure 3. Schematization of mapping Idea 1 in Figure 1 from Context X to Context Y. The addition of “initial allowance” and “total change in allowance” is mapped to “initial speed” and “total change in speed.” The equality of this addition with “new allowance” is mapped to “new speed.”
The results of investigations of analogical transfer illustrate that the controlled experiment methodology can be very effective in elaborating aspects of the process of reasoning across contexts. However, the results of this methodology must be understood as limited to the constrained experimental conditions in which they are discovered. In investigations of analogical transfer, the constraints of experimental design led psychology researchers to focus on contexts about which participants have no useful previous understanding. This dissertation contends that this focus has excluded investigation of innumerable other ways of reasoning across contexts in which participants’ previous understanding does play a role.

Education research on reasoning within a single context has revealed a significant role for a students’ previous understanding. The reasoning process in which a student’s previous understanding of a context plays a role in their later understanding of the same context is called constructivist learning (Smith, diSessa, & Roschelle, 1993). A schematic of this process is given in Figure 4.

![Figure 4. Schematization of constructivist learning](image)

For example, a student could have the following nonnormative understanding of Context Y in Figure 1: “The new speed is the initial speed plus the time over which the speed changes.” Although nonnormative understandings are typically thought of as interfering with instruction, research has revealed that such nonnormative understandings are often composed of ideas and can play a productive role in learning of a normative

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3 The relationship between the design constraints of an experimental design and the focus of psychology research on analogical transfer will be elaborated in Chapter 2 through a review of the methods used to investigate analogical transfer.
understanding. For example, the idea that the new speed is increased by an amount that is proportional to time is correct. The productive role of such intuitions in learning is investigated by the research tradition called knowledge in pieces (diSessa, 1993). Following on such research on the role of previous understanding in reasoning within a single context, this dissertation investigates the role that participants’ previous understandings play in their reasoning across contexts.

1.3 THIS DISSERTATION

In contrast to research on analogical transfer, this dissertation investigates the role of participants’ previous understanding of a target context in reasoning across contexts. This role of prior knowledge is illustrated in Figure 5.

Figure 5. Schematization of a context interaction, in which the participant’s new understanding of Context Y (labeled $U_{\text{new}}$) is derived in part from both her previous understanding of Context Y (labeled $U_{\text{prior}}$) and her understanding of Context X (labeled $U_{\text{other}}$). Both $U_{\text{prior}}$ and $U_{\text{other}}$ act as sources for $U_{\text{new}}$. The large arrow in the background indicates the progression of time: $U_{\text{new}}$ comes after $U_{\text{prior}}$ and $U_{\text{other}}$. The small arrows connecting $U_{\text{prior}}$ and $U_{\text{other}}$ to $U_{\text{new}}$ represent the interaction between these context understandings.

This dissertation adopts the term context interaction to describe the influence on a participant’s new understanding of a context ($U_{\text{new}}$) of both her previous understanding of the same context ($U_{\text{prior}}$) and her understanding of another context ($U_{\text{other}}$). In a context interaction, both $U_{\text{prior}}$ and $U_{\text{other}}$ act as sources for $U_{\text{new}}$. This dissertation will therefore
use this U-notation instead of the source/target terminology to refer to the context understandings.

Education research has often observed students express a new understanding of a context (U\textsubscript{new}), following instruction in another context (U\textsubscript{other}), that is comprised of both normative ideas from the instructed understanding of the other context (U\textsubscript{other}) and nonnormative ideas from their previous understanding of the same context (U\textsubscript{prior}) (Linn & Eylon, 2006). It has also been noted that ideas may appear in the student’s new understanding (U\textsubscript{new}) that are transitional between the instructed normative ideas (U\textsubscript{other}) and students’ nonnormative ideas (U\textsubscript{prior}) (Clark, 2006). These observations indicate some of the variation in understandings that result from context interactions.

A context interaction has three defining properties that specify the relationship of U\textsubscript{new} to U\textsubscript{prior} and U\textsubscript{other}. While context interactions share the first of these properties with both analogical transfer and constructivist learning, the second is shared with only analogical transfer, and the third is shared with only constructivist learning.

- First, a context interaction causes a change in understanding of Context Y: i.e., U\textsubscript{new} is different from U\textsubscript{prior}. Whereas analogical transfer ensures by design that this property can be assumed, this dissertation will demonstrate this property through analysis of collected data.

- Second, the new understanding of Context Y that results from a context interaction reflects the influence of the student’s understanding of Context X: i.e., U\textsubscript{new} is similar in some way to U\textsubscript{other}. Whereas analogical transfer considers only what the normative understandings of the contexts share, this dissertation considers instead what is shared by the students’ understandings of the contexts, which can be normative or nonnormative.

- Third, the new understanding of Context Y reflects the influence of the participant’s previous understanding of Context Y: i.e., U\textsubscript{new} is similar in some way to U\textsubscript{prior}. As in investigations of constructivist learning, this dissertation considers the role of students’ previous understandings.

The second and third defining properties address the relationship of U\textsubscript{new} with U\textsubscript{other} and U\textsubscript{prior} that is established by a context interaction. As mentioned above, unlike research on analogical transfer, this dissertation considers the variety of understandings of contexts that are possible, beyond just the normative understanding. This allows discovery of variety in the relationship of U\textsubscript{new} with U\textsubscript{other} and U\textsubscript{prior} that is used in this dissertation to infer variety in the kinds of context interactions that are possible.

To illustrate an example of a context interaction, consider the three understandings of the previously discussed examples of Contexts X and Y given in Figure 6. U\textsubscript{new} is not simply composed of ideas from U\textsubscript{other}. Instead, an idea from U\textsubscript{new} (Idea 2) that relates a context feature (rate of change of allowance) to time by multiplication is associated with a feature (initial speed) that was related by addition to time in U\textsubscript{prior}. Both the participants’ understanding of Context X (U\textsubscript{other}) and her previous understanding of Context Y (U\textsubscript{prior}) play a role in her new understanding of Context Y (U\textsubscript{new}). The particular relationships between U\textsubscript{new} and U\textsubscript{prior}, and U\textsubscript{new} and U\textsubscript{other}, facilitate inference of the nature of the process of the kind of context interaction underlying the
<table>
<thead>
<tr>
<th>(U_{\text{prior}})</th>
<th>The new speed is the initial speed plus the time over which the speed changes.</th>
</tr>
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</table>
| \(U_{\text{other}}\) | *Idea 1:* The new allowance is the initial allowance plus the total change in allowance.  
*Idea 2:* The total change in allowance is the rate of change in allowance multiplied by the time over which the allowance changes. |
| \(U_{\text{new}}\) | The new speed is the initial speed multiplied by the time over which the speed changes. |

**Figure 6.** Three understandings of the contexts presented in Figure 1. While \(U_{\text{other}}\) is the normative understanding of Context X, \(U_{\text{prior}}\) and \(U_{\text{new}}\) are both nonnormative understandings of Context Y. \(U_{\text{prior}}\) reflects the correct idea that the new speed increases with time, but does not take into account the rate of change of speed (the acceleration). Although \(U_{\text{new}}\) is nonnormative, it nonetheless reflects the influence of both \(U_{\text{prior}}\) and \(U_{\text{other}}\). Note that Idea 3 from Figure 1 is not included because it is shared by all three understandings.

expression of \(U_{\text{new}}\) in this example. Specifically, in this example the context interaction associates an idea (that “time over which the speed changes” should be multiplied) from \(U_{\text{other}}\) with a nonequivalent feature of Context Y (“initial speed” rather than “rate of change of speed”) that is selected by an idea from \(U_{\text{prior}}\) (that “initial speed” should be operated on). The understanding that results from such a context interaction is in terms of an idea that is transitional between the normative idea learned in the other context \((U_{\text{other}})\) and the nonnormative idea from the student’s previous understanding \((U_{\text{prior}})\) (Clark, 2006).

This dissertation has the goal of examining the variety of ways in which a participant’s previous understandings can play a role in reasoning across contexts. The methods needed here to investigate the role of previous understandings are different from those used to investigate the process of analogical transfer. For example, contexts are needed about which participants have a previous understanding (everyday contexts are considered in which the general concept of equilibration\(^4\) can be observed) and data must be collected that will facilitate identification of similarity between both \(U_{\text{new}}\) and \(U_{\text{prior}}\) and \(U_{\text{new}}\) and \(U_{\text{other}}\) (process data\(^5\) are collected). Such methodological differences will be discussed in Chapter 2.

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\(^4\) As will be discussed in Chapter 2, in equilibration contexts, two quantities change progressively less with time and eventually become the same.  
\(^5\) As will be discussed in Chapter 2, process data are data generated by semi-structured clinical interviews designed to expose how students’ understandings change.
The dissertation reveals a considerable role for participants’ previous understandings in reasoning across contexts. Chapter 3 presents the analysis of nine identified kinds of context interaction. In addition to illustrating the employed analytical method, each participant’s context interactions serve to illustrate their overall approaches to reasoning across contexts. While one participant’s previous understandings result in a sense that the considered contexts are similar, another participant’s previous understandings result in a sense that the contexts are different. These participants’ subsequent context interactions reflect the participants’ efforts to maintain these perceived relationships. A third participant’s context interactions are instead guided by a preference for her understanding of one context that interacts with her previous understandings of different contexts.

Chapter 4 presents a comparative analysis of the nine interactions introduced in Chapter 3. The interactions are considered in groups according to the kinds of relationships they establish. This provides insight into the role that the previous understandings play in the establishment of those relationships. The three groups of interactions examined are called combining, modifying, and refocusing interactions. The significance of these categories is elaborated through examination of the relationships of context interactions both within and across these categories. The three categories of context interaction are summarized as follows:

- **Combining Interactions**: This category of context interactions results in a new understanding of a context (U<sub>new</sub>) that is comprised of ideas that were seen previously either in the participant’s previous understanding (U<sub>prior</sub>) or in the participant’s understanding of another context (U<sub>other</sub>). The new understanding (U<sub>new</sub>) will therefore be described as a combination of ideas from U<sub>prior</sub> and U<sub>other</sub>. As in analogical transfer, the ideas are associated with features that are equivalent to (or the same as) those with which they were associated in their original context. In contrast to analogical transfer, the participant has two sources (U<sub>prior</sub> and U<sub>other</sub>) for the ideas that compose her new understanding (U<sub>new</sub>). The different context interactions that belong to this category represent the different proportions in which the ideas from previous understandings are combined. Analogical transfer, in which a participant’s new understanding (U<sub>new</sub>) is composed entirely of ideas that were seen previously in the participant’s understanding of another context (U<sub>other</sub>), is therefore a special case of a combining interaction.

- **Modifying Interactions**: This category of context interactions results in a new understanding of a context (U<sub>new</sub>) that is in terms of an idea that is similar to but not the same as, an idea used previously to understand another context. In contrast to analogical transfer, the idea is associated with features that are not equivalent to those with which they were associated in their original context. The idea that results from this association is different from that used previously. This idea will therefore be said to be modified.\(^6\) The different context interactions that

\(^6\) A modification of a normative idea could result in transitional ideas like those observed in Clark (2006).
belong to this category represent different origins of and relationships between the understandings.

- **Refocusing Interactions:** This category of context interactions results in a new understanding of a context \(U_{\text{new}}\) that is in terms of an abstraction of an idea from the participant’s previous understanding \(U_{\text{prior}}\) that corresponds with (or is the same as) an idea from her understanding of another context \(U_{\text{other}}\). The interaction therefore refocuses the student’s previous understanding of the context. The term correspond is used here to indicate that a difference in understandings is accounted for by a difference in the inferred relationship between equivalent context features (e.g., equivalent features being perceived as being opposites instead of the same). The different context interactions that belong to this category represent different relationships between the understandings.

The final chapter concludes this dissertation with a summary of the dissertation’s findings and consideration of future work that can be done both to examine the completeness of the context interactions identified by this dissertation and to gain additional insight into the reasoning processes underlying these context interactions. Implications of this work for pedagogy are also considered.
Chapter 2

Methods Employed To Investigate Reasoning Across Contexts

2.1 INTRODUCTION

Recall that investigations of analogical transfer focus on a particular way of reasoning across contexts in which a participant’s previous understanding of contexts plays a minimal role. In contrast to investigations of analogical transfer, this dissertation has the goal of investigating the role of participants’ previous understandings in reasoning across contexts. This chapter demonstrates that different methods are needed to achieve this different goal. Section 2.2 briefly describes characteristics typical of the methods used to investigate analogical transfer. In Section 2.3, these characteristics are contrasted with those used to accomplish the goal of this dissertation study.

2.2 METHODS USED TO INVESTIGATE ANALOGICAL TRANSFER

2.2.1 Introduction

Psychology research has focused on investigation of one particular way of reasoning across contexts, called analogical transfer. In this way of reasoning across contexts, a participant derives a new understanding of a context ($U_{\text{new}}$) entirely from her understanding of another context ($U_{\text{other}}$); the participant’s previous understanding of the context ($U_{\text{prior}}$) plays a minimal role in her new understanding. As discussed in Chapter 1, this focus is a consequence of the research methods employed by the discipline of psychology research, in which the effect of individual design features\(^7\) on the reasoning process is investigated through controlled experiments. The relationship between analogical transfer as a reasoning process and the methods that have facilitated its investigation will be discussed in more detail in the four following sections: selection of

\(^7\) Recall that a design feature is a designed difference between experimental conditions.
contexts, design of the intervention, implementation of the intervention, and analysis of collected data. These same aspects of methodology will be used in Section 2.3 to discuss the methodological differences that are needed to facilitate investigation of the role of participants’ previous understandings in reasoning across contexts.

2.2.2 Selection of Contexts

A key part of an investigation of reasoning across contexts is the selection of contexts across which the participant will reason. Following are two criteria for the selection of contexts for this general purpose: (1) the participant must be able to perceive some similarity between the contexts and (2) the participant must perceive some need for new insight for understanding the contexts. The participant will be unable or see no need to reason across contexts if these criteria are not met.

The design of an experiment for investigation of reasoning across contexts requires further specification of these criteria, because the design must exclude the possibility that a participant’s new understanding could be derived from any other reasoning process (e.g., constructivist learning). Psychology research has employed a particular version of these criteria for this more specific purpose: (1) the contexts can be described by a normative understanding that is shared by the contexts and are therefore analogically similar and (2) the participants’ understanding of one context (U\text{prior}) must be very different from (i.e., essentially unrelated to) the normative understanding that is shared by the contexts. These two criteria together ensure that if after instruction\(^8\) of the normative understanding in one context (making U\text{other} the instructed understanding), the participant is able to provide the instructed understanding in another context (making U\text{new} the instructed understanding), it can be concluded that this understanding was derived from the participant’s understanding of the instructed context (U\text{other}). In other words, these criteria ensure that the participant’s previous understanding of the context (U\text{prior}) does not play a role in her new understanding (U\text{new}), and inferences from the effect of design features are therefore limited to informing the more specific reasoning process of analogical transfer rather than the process of reasoning across contexts in general.

The contexts selected for investigation of analogical transfer can be described by a shared normative understanding. This will be illustrated through examination of the contexts used in two different investigations of analogical transfer: those described in Bassok and Holyoak (1989) and those described in Loewenstein and Gentner (2001).

Bassok and Holyoak (1989) examined ninth-graders’ analogical transfer between analogically similar problems from algebra and physics. Two of the problems used in this study were given in Figure 1 and are shown again in Figure 7 below. While the algebra context is about the increase in a child’s allowance, the physics context is about

\(^8\) The term instruction is used here in a sense that is somewhat unusual. As will be discussed in Section 2.2.3 below, this instruction has the general goal of ensuring that U\text{other} is different from U\text{prior}.  

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the increase in speed of a train. However, in both contexts, the value (allowance and speed, respectively) increases linearly with time. This means that the problem in each context can be solved in the same way. The shared understanding of these two contexts adds to an initial value an amount that is equal to the rate of increase in that value times the duration of increase.

<table>
<thead>
<tr>
<th>Algebra Problem</th>
<th>Physics Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>A boy was given an allowance of 50 cents a week beginning on his 6th birthday. On each birthday following this, the weekly allowance was increased 25 cents. What is the weekly allowance for the year beginning on his 15th birthday?</td>
<td>An express train traveling at 30 meters per second (30 m/s) at the beginning of the 3rd second of its travel, uniformly accelerates increasing in speed 5 m/s each successive second. What is its final speed at the end of the 9th second?</td>
</tr>
</tbody>
</table>

Figure 7. Example of analogically similar problem solving contexts. Both of these contexts can be described by an understanding that determines the quantity value by adding an initial value to an amount that is equal to the rate of increase times the duration of increase. It is this shared understanding that defines the contexts as analogically similar.

Loewenstein and Gentner (2001) examined preschoolers’ analogical transfer between analogically similar rooms. Two such rooms, called the Hiding and Finding rooms, are shown in Figure 8.

Figure 8. Example of analogically similar spatial identification contexts. Both of these contexts can be described by an understanding that identifies the location of the toy relative to the spatial location of the objects in the room. It is this shared understanding that defines the contexts as analogically similar.

Each room is filled with five objects, but although the corresponding objects in each room are of the same type, they have different shapes, sizes, and colors. The participant is told that the rooms belong to different characters that like to hide a toy in the same
place, so that if one character hides his toy under his bed, the other character’s toy can be found under his bed. The shared understanding of these two contexts is the location of the toy relative to the spatial location of the objects in the room.

The contexts are additionally chosen so that participants’ understanding of one context is very different from the shared normative understanding of the contexts. In Bassok and Holyoak (1989), this was accomplished by ensuring that the participants had not yet studied this type of problem in their algebra and physics classes. Instruction of the normative understanding in algebra would therefore establish a difference between participants’ understanding of the algebra ($U_{other}$) and physics ($U_{prior}$) problems. This difference in understandings was achieved in Loewenstein and Gentner (2001) by designing the contexts such that the toy must first be hidden in the Hiding room before it can be found in the Finding room. In other words, $U_{prior}$ cannot be known before instruction of $U_{other}$ (hiding of the toy). In both cases, either by selection of the participants or by design of the contexts, participants are unable to give the shared understanding in the second context prior to instruction in the first context.

Investigations of reasoning across contexts select contexts that meet the following two criteria: (1) the participant must be able to perceive some similarity between the contexts, and (2) the participant must perceive some need for new insight for understanding the contexts. Unlike investigations of analogical transfer, this dissertation does not employ an experimental design. Different specific versions of these criteria are employed by this dissertation because of its different goal to investigate the role of previous understandings in reasoning across contexts. The specific versions of these criteria employed by this dissertation will be discussed in Section 2.3.2.

2.2.3 Design of Intervention

Investigations of reasoning across contexts present contexts to the participants in the form of an intervention. This intervention has two general goals: (1) to establish a difference between the participants’ context understandings (if one does not already exist) through instruction in one context, and (2) to give participants the opportunity to eliminate this difference by reasoning across contexts.

Recall that the second criterion for selection of contexts for investigation of analogical transfer ensures that participants’ understandings of the contexts are very different from the normative understanding. The intervention employed by an investigation of analogical transfer can therefore guarantee that a difference is established between participants’ context understandings by instruction of the normative understanding in one context. Following instruction of the normative understanding in one context ($U_{other}$), participants are prompted to consider the second context. If the participant then gives the normative understanding in the second context ($U_{new}$), it can be

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$^9$ Note that the usual meaning of instruction as “giving the participant the normative understanding” is included in this meaning if students do not previously have the normative understanding in the other context.
concluded that analogical transfer has taken place. The instruction employed by Bassok and Holyoak (1989) took the form of a general tutorial in one problem domain (algebra or physics) before presenting the participant with a problem from the other domain. In Loewenstein and Gentner (2001) this instruction took the form of the placement of the toy in a Hiding room before asking the participant to find the toy in the Finding room.

It has become well known that instruction of the normative understanding in one context is not always sufficient to ensure that the participant can apply this understanding in another context (e.g., Gick & Holyoak, 1983). The controlled experiments used to investigate analogical transfer have identified three design features that increase the likelihood of participants giving the instructed normative understanding in another context \( U_{\text{new}} \). The three design features include instruction of the shared understanding in more than one context, instruction of contexts that are very similar to one another, and comparison of the instructed contexts. These design features are thought to help facilitate participants’ recognition of the normative understanding as shared across contexts. Such recognition of the normative understanding as shared is in turn expected to facilitate use of this understanding in another context \( U_{\text{new}} \). These three design features have become common in interventions used to investigate analogical transfer.

The design of an intervention has the goal of facilitating participants’ reasoning across contexts. Unlike investigations of analogical transfer, this dissertation does not employ an experimental design; therefore it does not require such tight constraints on \( U_{\text{prior}} \) and \( U_{\text{other}} \). Any difference in understanding will suffice and instruction will be aimed at establishing such a difference. This will be discussed in more detail in Section 2.3.3.

### 2.2.4 Implementation of Intervention

The implementation of an intervention determines the way in which the researcher engages participants in the intervention. Aspects of implementation include the mode of participants’ engagement, the number of participants, the duration of the intervention, and the kind of data collected. Investigating a reasoning process through a controlled experiment imposes constraints on each of these aspects of implementation. As mentioned previously, a controlled experiment tests the effect of a design feature on participants’ reasoning process. Such a test is accomplished by comparing the effect of experimental conditions that differ by this design feature. The comparative nature of experiments requires that the experience of subjects assigned to each condition be as similar as possible but for the designed feature of difference. The intervention is therefore primarily conducted either in a one-on-one clinical setting in which the researcher’s prompts and responses are tightly scripted or with multiple participants working independently through written materials.

The participants assigned to each experimental condition can be expected to exhibit some degree of individual difference in their reasoning. A large number of participants is therefore typically assigned to each condition to facilitate seeing beyond the effect of the individual differences to the effect of the condition to which participants
have been assigned. The goal is to achieve statistically significant evidence of the effect of the design feature by which the experimental conditions differ.

The duration and kind of data collected can be understood as being primarily determined by the practical constraints imposed by conducting an intervention with a large number of participants. To make implementation with a large number of participants feasible, the intervention is designed to be of short duration. In investigations of analogical transfer, the intervention is typically conducted in a single session lasting less than an hour. To make analysis of the large quantity of data generated by the participants feasible, the intervention is additionally designed to produce data that can be analyzed simply. In investigations of analogical transfer, the goal of data collection is primarily to document whether the participant succeeds in giving the normative understanding in another context, and the simplest means of documentation is usually preferred. Field notes of participant responses or written solutions typically suffice.

The implementation of the intervention specifies the mode of participants’ engagement, the number of participants, the duration of the intervention, and the kind of data collected. In investigations of analogical transfer, the implementation of the intervention is constrained by the goal of investigating reasoning across contexts through a controlled experiment. This dissertation is not conducted as an experiment and will therefore not be subject to the same constraints. As will be discussed in Section 2.3.4, the primary constraint on implementation of this dissertation is the need to collect data that can reveal relationships between participants’ understandings that indicate a context interaction.

2.2.5 Analysis of the Collected Data

The analysis of the collected data has the goal of inferring a participant’s reasoning process from the relationships established by her new understanding (\(U_{\text{new}}\)) with her previous understanding of the same context (\(U_{\text{prior}}\)) and her understanding of another context (\(U_{\text{other}}\)). The other aspects of the employed methodology can contribute to the relative ease or difficulty of accomplishing this goal.

The use of a controlled experiment to investigate reasoning across contexts has the effect of greatly simplifying the data analysis. Recall in investigations of analogical transfer, the participant is known to not have a normative understanding of the context prior to the intervention (\(U_{\text{prior}}\)) and that the intervention instructs the normative understanding in an analogically similar context (\(U_{\text{other}}\)). The analysis employed in investigations of analogical transfer therefore needs only to document that the participant now has the normative understanding of the context (\(U_{\text{new}}\)) to be able to infer the relationships between understandings (\(U_{\text{new}}\) is different from \(U_{\text{prior}}\) and the same as \(U_{\text{other}}\)) that indicate that analogical transfer has taken place. Investigations of analogical transfer typically accomplish this documentation of participants’ new normative understanding.
(U_{new}) by scoring the expression of their understanding\textsuperscript{10} against a schema that represents the normative understanding of the context. In Bassok and Holyoak (1989), the participant’s expressed understanding is a written solution to the problem presented by the context. In Loewenstein and Gentner (2001), the expressed understanding is the choice of the object under which the second character has hidden his toy. A threshold score is imposed to identify solutions that indicate successful transfer. The analysis rarely examines participants’ nonnormative solutions. However, some studies (e.g., Gick & Holyoak, 1987; Gentner, et al., 2003) also score unsuccessful solutions against anticipated alternate schemas for the purpose of demonstrating their decreased frequency following the intervention.

An experimental design greatly simplifies the analysis needed to infer that the investigated reasoning process has taken place. This dissertation will employ a methodology that is minimally constrained to allow investigation of the role of participants’ previous understandings in reasoning across contexts. As Section 2.3.5 will demonstrate, this has the effect of making the analysis of the collected data much more complex.

2.2.6 Summary

Psychology research employs an experimental design to investigate reasoning across contexts. This affects the following four aspects of methodology: selection of contexts, design of the intervention, implementation of the intervention, and analysis of the collected data. The use of an experimental design results in the relevance of the inferred reasoning process being limited to the constrained conditions under which it was investigated. Specifically, experimental investigation of reasoning across contexts has resulted in the focus of psychology research on one particular way of reasoning across contexts, called analogical transfer, in which participants’ previous understandings play a minimal role.

In contrast to investigations of analogical transfer, this dissertation has the goal of investigating the role of participants’ previous understandings in reasoning across contexts. Rather than employing an experimental design, this dissertation investigates reasoning across contexts through a series of case studies. This has a different effect on the four aspects of methodology. Recall that this dissertation uses the term context interaction to describe a general category of ways of reasoning across contexts in which a participant’s previous understanding of a context can play a role. The methodological differences that are needed to facilitate investigation of context interactions will be discussed in Section 2.3.

\textsuperscript{10} For example, a participant’s expression of their understanding may be in the form of a written solution to a problem.
2.3 METHODS USED TO INVESTIGATE CONTEXT INTERACTIONS

2.3.1 Introduction

This dissertation has the goal of investigating the role of participants’ previous understandings in reasoning across contexts. Unlike investigations of analogical transfer, this dissertation does not employ an experimental design. It instead employs a case study design. This different goal and research design require different methods. The following four sections will contrast the methods used in this study with those used to investigate analogical transfer in the areas identified in Section 2.2: selection of contexts, design of the intervention, implementation of the intervention, and analysis of collected data.

2.3.2 Selection of Contexts

Recall the following two general criteria given in Section 2.2.2: (1) the participant must be able to perceive some similarity between contexts, and (2) the participant must perceive some need for new insight for understanding the contexts. Section 2.2.2 demonstrated that a more specific version of these criteria is needed to investigate reasoning across contexts using an experimental design, as in investigations of analogical transfer.

This dissertation does not employ an experimental design. Specific versions of the criteria are instead specified by the goals of this dissertation. This dissertation has the goal of investigating the role of previous understandings in reasoning across contexts. It additionally has the goal of preserving the possibility of observing analogical transfer (i.e., a context interaction in which the participant’s previous understanding plays a minimal role) to enable communication with the findings of psychology research. Recall that in analogical transfer a participant’s new understanding ($U_{\text{new}}$) is composed completely of ideas previously used in her understanding of another context ($U_{\text{other}}$). This specific way of reasoning across contexts is facilitated by the shared normative understanding of contexts. For this reason the specific version of the first criterion employed in this dissertation will be the same as that used in investigations of analogical transfer: (1) the contexts can be described by a normative understanding that is shared by the contexts and are therefore analogically similar.\textsuperscript{11}

\textsuperscript{11} As the other aspects of methodology discussed in the following sections will demonstrate, although the contexts are designed to have a normative shared understanding, this dissertation will make no effort to instruct this normative understanding and the data analysis will exhibit no preference for participants having learned this normative understanding. The other aspects of methodology employed by
The second general criterion requires that students perceive some need for new insight for understanding the contexts. Investigations of analogical transfer constrained context selection to ensure that participants’ understandings of the contexts are very different from the normative understanding. This was done to ensure that instruction of the normative understanding of one context would establish a known difference between the participants’ context understandings that could then be eliminated by reasoning across contexts. As was discussed in Section 2.2.2, this criterion eliminates the possibility of participants’ previous understandings playing a role in reasoning across contexts. This dissertation therefore employs a different specific version of the second criterion: the participant must have previous understanding of the contexts that is nonnormative. This ensures that the participant can be directed by the intervention design to perceive some need for insight for understanding the contexts. The way in which the contexts selected for this dissertation meet these specific versions of the general criteria are discussed below.

The contexts selected for this study are physical contexts that exhibit a shared scientific phenomenon called *equilibration*. Equilibration is a general phenomenon that can be seen in a variety of contexts. In all equilibration contexts, a quantity with two distinct initial values changes more slowly with the decreasing difference between these values. This specific phenomenon can be understood as having two general characteristics: (1) that initial values of a quantity that are distinct come to have the same equilibrium value, and (2) that this happens at a rate that decreases with the difference of the value of the quantity from its equilibrium value. While the first of these characteristics describes a more general phenomenon, called *equalization*, the second characteristic is what distinguishes equilibration from equalization. The equilibration behavior is represented in Figure 9.

![Equilibration Behavior](image)

**Figure 9.** Representation of equilibration behavior. The top curve represents the decrease in the value of a quantity, while the bottom curve represents the corresponding increase in the other value of the quantity.

This dissertation will instead be focused on students’ understandings of the contexts, whether normative or nonnormative.
Gas and dye equilibration are both examples of the general phenomenon of equilibration. Schematic illustrations of these contexts and their behavior are given in Figure 10. In both contexts, a divided container is filled on both sides with different colors of the same substance: in the gas context, the left is filled with colored gas, while the right is filled with regular air; in the dye context, the left is filled with dyed water, while the right is filled with ordinary water. In both contexts, the slowing rate behavior emerges from the behavior of particles. The particles comprising the substances move randomly. When the divider is removed, particles move from the left to the right, as others move from the right to the left, mixing the two substances. The proportion of the particles that move from the left that are colored will decrease as the left becomes more mixed. Similarly, the proportion of the particles that move from the right that are uncolored will decrease as the right becomes more mixed. As a result of these decreasing proportions, the rate of change of the concentrations decreases, until the concentrations on the two sides of the container are equal.

![Figure 10](image1.png)

Another example of the general equilibration phenomenon is temperature equilibration. A schematic illustration of temperature equilibration is given in Figure 11. Initially, the left piece of metal is hot and the right piece of metal is cold. This means that the particles in the left piece of metal have high average kinetic energy, while the average kinetic energy of the particles on the right is low. In temperature equilibration, the slowing rate behavior emerges from interactions between particles, rather than from their movement. Interactions between particles with different kinetic energies reduce the

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12 These schematized illustrations employ a simplification that the sides of the container are well mixed and can therefore be represented by a uniform color. A more accurate representation would depict color near the middle changing more quickly than at the edges. The employed simplification can alternatively be interpreted as representing the average of the quantity values on each side of the container. These illustrations were used to present the equilibration phenomena to the participants in this dissertation study. The participants did not remark on this simplification being unrealistic.
difference between the particles’ average kinetic energies. Temperature is a measure of the particles’ average kinetic energy. Particle interactions therefore result in a decrease in the temperature of the left, and a corresponding increase in the temperature of the right. As the temperatures of the left and right become more nearly equal, the rate of change decreases, until they are equal.

![Figure 11. Schematic illustration of temperature equilibration. The heat context is represented as two identical pieces of the metal with different temperatures that are placed in contact side by side. The different temperatures of the pieces of metal are represented by different uniform colors. The arrow indicates the progression of time. The changing values of the temperatures are represented by changing colors.](image)

As examples of the same general phenomenon, gas, dye, and temperature equilibration are analogically similar and therefore meet the first criteria for selection of contexts for this dissertation. In all three contexts the two values of a quantity (concentration or temperature) change at a rate that decreases continually with the decreasing difference in quantity values. The similarity of such equilibration contexts means that understanding of one context can provide productive insight into others (Narasimhan, 1999; Vogl, 2005).

Participants have initial understandings of the gas, dye, and heat contexts from their everyday experiences. For example, they have experienced that the smell of food cooking will spread throughout the house (gas context); that if juice concentrate is added to a container of water a homogeneous drink will result (dye context); and that if a hot drink is left in a cold room it will cool down (heat context). Education research confirms that students find the overall equalization behavior of such contexts to be relatively intuitive (diSessa, 1993). Students know that differences in concentration of gas or liquid tend to equalize over time (Odom & Barrow, 1995; Westbrook & Marek, 1991), and that objects with different temperatures that are in contact will become the same temperature over time (Kesidou & Duit, 1993; Linn & Hsi, 2000; Clark, 2006). In a pilot study that was conducted prior to this research, three middle-school participants were able to correctly predict equalization behavior in the gas, dye, and heat contexts.

Research indicates that participants know considerably less about the rate of change of this equalizing behavior. Undergraduate students don’t know whether the rate of gas and dye equilibration increases or decreases with the difference in concentrations (Odom & Barrow, 1995), and few eighth grade students believe that heating and cooling happen at a decreasing rate of change rather than a constant or increasing rate of change (Linn, Layman & Nachmias, 1987). The middle-school participants interviewed for the pilot study demonstrated similar difficulties in considering the rate of the gas, dye, and temperature equilibration.
For instance, one participant from the pilot study explained slowing rate behavior in the gas context in terms of an idea about resistance. She said,

“Because in the beginning there’s nothing stopping the ones (particles) that are coming over from coming over, but once there’s a lot of particles over there they can hit each other and bounce back.”

The same participant explains the heat context instead in terms of an idea about how much change can be made. She said,

“Because as the colder one gets warmer, it’s not trying to make the hotter one as cold, because they’re starting to equalize, so there’s not much of a difference between them, so they can’t really change the other one that much.”

These results indicate that middle-school students have a variety of nonnormative understandings of equilibration contexts. Such contexts therefore meet the second criterion for selection of contexts. As the results of this dissertation will illustrate, interactions between these nonnormative understandings can result in participants changing their understandings of the contexts.

Equilibration contexts, like the gas, dye, and heat contexts, meet both selection criteria for investigation of context interactions. These contexts can be described by a shared normative understanding. In addition, participants have previous understandings of these contexts. This dissertation examines participants’ reasoning across the gas, dye, and heat contexts for evidence of context interactions.

2.3.3 Design of Intervention

The primary goal of this dissertation is to investigate the role of previous understandings in reasoning across contexts. The fundamental result of reasoning across contexts is a change in understanding of a context. As discussed in Section 2.3.2, participants have a variety of previous understandings about the contexts selected for this investigation. A change in understanding must therefore be documented relative to its initial state. For this reason, the intervention will begin by eliciting participant’s initial understandings of the three contexts.

During the intervention, the participant is introduced to the gas, dye, and heat contexts. The participant is told that although the contexts are about different things (gas, liquid, and heat), they are similar in that they share a general behavior: that their two sides come to be the same. The representations used to present this shared equalizing behavior of the different contexts are given in Figure 12.
AMOUNT OF GAS
The amount of colored gas on each side becomes equal.

AMOUNT OF DYE
The amount of dye on each side becomes equal.

AMOUNT OF HEAT
The amount of heat on each side becomes equal.

Figure 12. Representations of the equalizing behavior of the gas, dye, and heat contexts. The distinct initial quantity values are represented as different colors. The arrows indicate the progression of time. That the quantity values become equal later is represented by the two colors being the same.

The participant is told that although the two sides of each context come to be the same, they might do this in one of two different ways: constant rate or slowing rate. These different behaviors are illustrated in Figure 13. Following introduction of the behaviors, the participant is prompted to predict which behavior happens in each context, and to explain why that behavior would happen. As will be discussed in Section 2.3.5, the data analysis for this dissertation has the goal of characterizing relationships between participants’ expressed understandings. Constraining participants to choosing between two behaviors facilitates characterization of relationships between participants’ statements of behavior. Participants’ statements of explanation for why this behavior happens are not similarly constrained to reflect the realistic variety in participants’ understandings. Prompts from the interviewer have only the goal of clarifying the understanding that participants express. As will be discussed in Section 2.3.5, this has the effect of complicating analysis of the relationships between expressed understandings. The representations used to illustrate these different behaviors in the gas context are given in Figure 13. The participant’s initial predictions and explanations are derived from their prior knowledge of the nature and physical interaction between the substances in the gas, dye, and heat contexts. This phase of the interview will be called the prediction phase.

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13 This use of the word interaction in “physical interaction” is different from how the word is used in the bulk of this dissertation. The interaction here is physical between substances: i.e., between the particles of gas and air, dye and water, and hot and cold pieces of metal.
CONSTANT RATE:
Changes the same amount each second.

SLOWING RATE:
Changes by a lot and then less.

Figure 13. Representations of two possible rates of equalization in the gas context. The arrows represent the progression of time. The difference in quantity values is represented in two ways: by a difference in color in a representation of the container (above the arrow) and by a difference in values on a graph (below the arrow). In the representation of slowing rate behavior, the difference decreases more at first (the colors become more similar; the graphed values become more nearly equal) than in the representation of constant rate behavior.

Following documentation of the participant’s initial understandings of the contexts, the intervention provides opportunities for the participant’s understandings of the contexts to interact and result in a new understanding of a context. Designed opportunities for interaction need not result in changed understanding. Three design features were introduced in Section 2.2.3 that have been found to facilitate participants’ derivation of the shared understanding of the contexts during investigations of analogical transfer: instruction of the shared understanding in more than one context, instruction of contexts that are very similar to one another, and comparison of the instructed contexts. To increase the likelihood of opportunities for interaction resulting in change, these same features have been implemented in the design of the intervention for this study. Three contexts are included instead of just two because consideration of multiple contexts is thought to facilitate change in understanding. Consideration of contexts that are very similar to one another before consideration of a different context is thought to additionally facilitate change in understanding. The gas and dye contexts are typically considered to be more similar than either of these contexts is to the heat context: While slowing rate behavior happens in the gas and dye contexts because of the motion of particles, this behavior happens in the heat context because of the interaction of particles. For this reason, the gas and dye contexts are investigated first before investigation of the heat context is considered. Comparison of the considered contexts is thought to facilitate change in understanding as well. For this reason, each opportunity for change implemented in the design of this study takes the form of a comparison.

Participants’ initial understandings can interact even before instruction. Following the prediction phase, participants are prompted to compare their understandings of the different contexts. This prompt to compare is the first designed opportunity for the participants’ understandings of the contexts to interact, and participants may choose to revise their understandings in response. This phase of the interview will be called the comparison phase.
Participants then investigate each context in turn. The investigation plays the role of instruction in this intervention. Its primary goal is to introduce a potential new source of insight for understanding the other contexts. While the investigation introduces the normative understanding of what behavior the contexts have, it does not make an effort to communicate the normative understanding of why that behavior happens. The normative understanding of what behavior happens in the context is communicated through observation of a simulation of the behavior of the context. Consideration of five suggested explanatory ideas derived from participant responses during the pilot study has the goal of providing the opportunity for participants to change their understanding of the investigated context. An understanding that is expressed following an investigation will be called a learned understanding. Although the participant’s learned understanding of the behavior of the context following investigation will be normative, her understanding of why this behavior occurs may not be. Screenshots from the observed simulation are given in Figure 14 along with the five explanatory ideas.

![Figure 14](image1.png)

(a) Screenshots from the computer simulation of the gas context (a), and the five suggested explanatory ideas (b). Note that the fourth suggested explanatory idea, about resistance, plays a significant role in the episodes selected for presentation in this dissertation. Analogous simulations and ideas are presented during the dye and heat investigations.

At the conclusion of each investigation, the participant summarizes her new understanding of the context and is then prompted to consider whether her new understanding affects her understanding of the subsequent context. These prompts to compare comprise the second, third, and fourth designed opportunities for the participant’s understandings of the contexts to interact, and participants may choose to revise their understanding of the subsequent context in response.
2.3.4 Implementation of Intervention

Investigations of analogical transfer typically make use of static evaluations of participants’ understandings. Such evaluations elicit statements that can be evaluated against what is predetermined to be shared by the contexts. Such static evaluations do not capture participants’ full understanding. Flexible probing that responds to a participant’s statements of understanding can provide greater insight. However, such variation in implementation is typically not tolerated by investigations of analogical transfer, because they seek to make statistical claims about the effect of design features on participants’ reasoning.

This dissertation study seeks relationships between understandings that will indicate the result of an interaction. These relationships will be discussed in more detail in Section 2.3.5. Between which understandings there will be relationships, or what ideas will indicate those relationships is not predetermined by the design. It is therefore necessary that participants’ various understandings, both across contexts and across time, be captured in as much detail as possible to facilitate the identification of relationships during analysis. For this reason, the design detailed in the previous section is implemented as a semi-structured interview, in which the interviewer clarifies the participant’s understanding as much as possible while maintaining the natural flow of conversation.

This dissertation seeks to investigate the role of previous understandings in reasoning across contexts. Large numbers of participants are not needed, provided that interaction with previous understandings is reasonably common. Six sixth grade participants (11 or 12 years old) were interviewed for this study. The interviews were both audio and video recorded in their entirety. The audio recordings from the interviews were transcribed in full and supplemented with annotations of gestures from the video recording. As will be discussed in the remainder of this dissertation, multiple kinds of context interactions were discovered in the transcript of the interviews of just three of these participants. These participants are given the pseudonyms Hanna, Greta, and Sandra.

2.3.5 Analysis of Collected Data

The methods employed for analysis of the data collected from an investigation of reasoning across contexts have the goal of demonstrating that participation in the intervention results in a change in understanding that reflects the influence of the participant’s understanding of another context. As discussed in Section 2.2, investigations of analogical transfer employ an experimental design that imposes considerable constraints on the design and implementation of the intervention but has the effect of greatly simplifying the analysis of the collected data. As discussed above, this dissertation has removed a number of these constraints to facilitate investigation of the role of the participant’s previous understanding of a context in reasoning across contexts. This results in a much greater burden being placed on the data analysis.
The analysis employed by this dissertation has the goal of examining the transcript of the conducted interviews to determine whether a participant’s expressed understanding of a context has changed in a way that indicates that it is due to the role of her previous understanding in reasoning across contexts. In other words, to determine whether the participant’s expressed understanding establishes the relationships that are the defining properties of a context interaction discussed in Chapter 1: that \( U_{\text{new}} \) is different from \( U_{\text{prior}} \), that \( U_{\text{new}} \) is similar in some way to \( U_{\text{other}} \), and that \( U_{\text{new}} \) is also similar in some way to \( U_{\text{prior}} \).

Participants’ expressions of understanding of the equilibration contexts have two parts: their statements of a context’s behavior (indicated by the capital letter B) and their explanations of the behavior’s cause (indicated by the capital letter E). Such statements will be considered as the primary window on participants’ understanding of the contexts.

As discussed in Section 2.3.3, the intervention limits participants’ statements of behavior to prediction of either constant or slowing rate behavior to simplify the identification of relationships in this aspect of the participant’s understandings. The expressed behavior is either the same as a previous expression of behavior or it is different.

Participants’ explanations of the behavior’s cause are not limited in order to reflect the realistic variety in students’ understandings of why these behaviors happen. However, this complicates identification of the relationships needed to identify an expressed understanding as the result of a context interaction: both difference and similarity. Not all differences in explanation reflect a change in understanding; Participants can express the same understanding in different ways. This analysis is interested only in changes in explanation that correspond to changes in understanding. The analysis therefore looks beyond the details of expression to identify differences in understanding indicated by participants’ explanations. Similarity between a participant’s explanations of different contexts can be disguised by the different context details in which a participant’s explanations are embedded. To detect similarity in a participant’s explanations of different contexts, the analysis must look beyond details of the context in which the understanding is expressed. Establishment of any degree of similarity between explanations in different contexts may indicate an instance of interaction.

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\(^{14}\) Note that the role of the interviewer in prompting the establishment of these relationships is considered during the analysis. For example, explanations given following consideration of the suggested explanatory ideas are considered to be most likely due to those ideas than to an interaction with the understanding of another context.
Three relationships between expressed explanations are considered by the analysis in the identification of context interactions. These are listed following:

- The new explanation is in terms of an idea that is the same as an idea used in a previous explanation: i.e., the idea is associated with features of the context that are equivalent to (or the same as)\(^{15}\) the features with which it was associated previously.
- The new explanation is in terms of a modification of an idea used in a previous explanation: i.e., the idea is associated with features of the context that are not equivalent to the features with which it was associated previously.
- The new explanation is in terms of an abstraction of an idea used in a previous explanation: i.e., the idea is associated with a generalization of the features of the context with which it was associated previously (e.g., with features described as opposites, rather than as full and empty).

The approximate number of ideas for which these relationships apply will also be considered. In particular, an explanation that is in terms of many of the same ideas will be said to be very similar, an explanation that is in terms of some of the same ideas will be said to be somewhat similar, and an explanation that is in terms of only a few of the same ideas will be said to be minimally similar, where the approximate number is judged relative to the total number of expressed ideas. This provides a finer grain of resolution on the kind of relationship that is established. For example, an instance of analogical transfer would result in a new understanding that is both very similar to \(U_{\text{other}}\) and minimally similar to \(U_{\text{prior}}\).

Identification of the relationships between a participant’s understandings is aided by representation in a schematic chart like that given in Figure 15. Such a schematic summarizes abstractions of the participant’s understandings.

Each numbered box represents a different state of the participant’s understanding. The order in which these understandings are expressed during the interview is indicated both by the number in the upper left of each box and the large arrow pointing downward in the background of the schematic. The behavior (predicted or observed) is represented by a large capital letter S or C in the background of each box, for slowing or constant rate, respectively. The explanation is represented by abbreviated statements of ideas. For explanations of slowing rate behavior, those statements recorded above the central line explain why more change happens at first, and those below the line explain why less change happens later. The ideas found in these schematics are different from codes in

\(^{15}\) Recall that the term equivalent is used to indicate that the features with which an idea is associated in different contexts reflect the analogical similarity of the contexts. In other words they are the same at the relevant level of abstraction (e.g., in the equilibration contexts considered here, the difference between concentrations in the dye context is equivalent to the difference between temperatures in the heat context). Where the relationship between two understandings of the same context is considered, the features with which the idea is associated are literally the same.
that they were developed only for the purpose of identifying relationships between understandings, not to characterize the participant’s understandings of equilibration apart from this comparison.

Figure 15. Representation of participant understandings that indicate an interaction. The large arrow in the background represents the progression of time. The numbered boxes represent different states of the participant’s understanding in the order in which they are expressed. The large capital letter S or C in the background of each box indicates the participant’s understanding of behavior. The abbreviated statements in each box represent the participant’s understanding of why the behavior happens. Those above the central line in boxes labeled with the letter S address why more change happens at first, while those below the line address why less change happens later. The frames surrounding some boxes indicate the influence of the investigation on the expressed understanding. A frame labeled with the letters “obs” indicates that the understanding follows observation of the simulation. A frame labeled with the letters “sug” indicates that the understanding follows consideration of the suggested explanatory ideas. The small arrows connecting U1 and U3, and U2 and U3, represent the interaction between these context understandings.

The frames surrounding the boxes indicate the influence of the context investigations on the expressed understandings. The first understanding (U1) is a prediction in the dye context. This understanding originates from the participant’s prior knowledge of the nature and physical interaction of dye and water, not from instruction. This is indicated by the absence of a frame surrounding the understanding in the chart. The second understanding (U2) follows the gas investigation. The frame surrounding this understanding in the schematic, labeled “obs + sug,” indicates that the participant’s expression of the context’s behavior follows observation of the simulation and that the explanation follows consideration of the suggested explanatory ideas. The third understanding (U3) is a new explanation given during the dye investigation. The frame
surrounding this understanding in the schematic, labeled “obs,” indicates that the participant’s expression of the context’s behavior follows observation of the simulation but precedes consideration of the suggested explanatory ideas.

The three understandings represented in Figure 15 together indicate an interaction discovered in the transcript of Greta’s interview. Following is a selection taken from this transcript to illustrate Greta’s new understanding of the dye context. Greta expresses this understanding following the gas investigation and confirmation of her prediction of slowing rate behavior (through observation of the simulation) during the dye investigation.

G-U3 Greta: Because a lot goes at first, and then there’s not that much left, so it resists whatever wants to come towards where the other one has gone, so when it resists, there’s not much room (on the right side) for the other one to come in. So it slows it down from going completely there. /…/ Once you lift the divider up, there’s a lot of dye, so it’s looking for somewhere else to go, and then once it’s settled, and there’s still a bit more, it resists the other dye and it slows it down from getting perfectly even.

This understanding is represented in Figure 15 as U3. The observed slowing rate behavior is indicated by the large capital S in the background of the box. This behavior was both predicted previously and observed during the dye investigation. Greta has one idea about why there is more change at first. She says, “there’s a lot of dye, so it’s looking for somewhere else to go.” This idea is represented in the schematic by the abbreviations “full/empty urgency.” The schematic indicates that this idea was also seen in the gas context (U2). Greta has two ideas about why there is less change later. She says, “there’s not much [dye] left” and there’s “not much room” for additional dye. These ideas are represented by the abbreviations “less remaining” and “less space - more resistance,” respectively. The schematic indicates that the first of these ideas was seen previously in the dye context (U1), while the second was seen in the gas context (U2).

Examination of the identified results of interactions reveals significant variety that cannot be explained by analogical transfer. This variety will be discussed further in both Chapters 3 and 4.

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16 This interaction is the first discovered in the transcript of Greta’s interview (G1) and will be discussed further in Chapters 3 and 4.

17 An ellipsis flanked by slashes (/…/) is used to indicate an omission of transcript that is nonessential to the illustration of the student’s understanding. Another transcription convention that will be used in this dissertation includes the use of a double slash (//) to denote the speaker abruptly breaking off and starting a new utterance, as well as to denote an interruption by another speaker. An ellipsis (...) will be used to denote the speaker’s utterance trailing off.
2.3.6 Summary

Unlike investigations of analogical transfer, this dissertation has the goal of investigating the role of participants’ previous understanding in context interactions through a series of case studies. The methods used to investigate context interactions will therefore be different from those used to investigate analogical transfer. Two of the most significant differences in methodology are the selection of contexts about which participants have previous understandings and collection of process data that capture changes in students understanding.

2.4 SUMMARY

Investigations of analogical transfer have different goals from those of this dissertation study. Investigations of analogical transfer seek to understand the conditions under which someone can give a particular understanding of a context that was learned in another context that is similar. In contrast, this dissertation study seeks to understand the role of participants’ previous understandings in context interactions. This difference in research goals is reflected in the four aspects of the research methods used: selection of contexts, design of the intervention, implementation of the intervention, and analysis of the collected data.
3.1 INTRODUCTION

The participants interviewed for this dissertation exhibited different overall approaches to reasoning across contexts. This chapter examines a selection of the context interactions identified in the transcript of three of these participants: Hanna, Greta, and Sandra.

Recall that a context interaction has three defining properties: (1) it causes a change in understanding of a context, and the new understanding that results (2) reflects the influence of the understanding of another context (3) and reflects the influence of the previous understanding of the same context. As discussed in 2.3.5, the data analysis for this dissertation uses these properties to identify new understandings that are the result of context interactions.

This chapter presents the analysis of nine identified kinds of context interaction: three from each of the three participants. In addition to illustrating the employed analytical method, each participant’s context interactions serve to illustrate their different overall approaches to reasoning across contexts. While Hanna’s context interactions reflect her sense that the gas, dye, and heat contexts are similar to one another, Sandra’s context interactions reflect her sense that the dye context is different from the gas and heat contexts. In contrast to both Greta and Sandra, Greta’s context interactions reflect her learned understanding of slowing rate behavior. The identified nine kinds of context interaction will be considered in more detail in Chapter 4.

3.2 HANNA’S APPROACH TO REASONING ACROSS CONTEXTS

Hanna’s three context interactions demonstrate an approach to reasoning across the gas, dye, and heat contexts that is strongly influenced by a sense that the contexts are similar to one another. These context interactions are illustrated schematically in Figure 16 as H1, H2, and H3. In this discussion of each context interaction, specific understandings (e.g., U1, U2, U3) illustrated in Figure 16 will be identified as U_{new}, U_{prior}, and U_{other}.
Figure 16. Schematic of Hanna’s three context interactions. These context interactions are indicated with different colored arrows, numbered sequentially, and labeled with the first initial of Hanna’s name. Also identified is each context interaction’s kind (replacing, cueing, and guiding). Additional details about the way in which participants’ understandings are represented in schematics like this are described in the caption of Figure 15.
Recall that $U_{\text{new}}$, $U_{\text{prior}}$, and $U_{\text{other}}$ correspond to a new understanding of a context, a previous understanding of the same context, and an understanding of another context, respectively.

Hanna develops her sense of similarity during her first interaction (H1). During the comparison phase, Hanna is directed to compare her initial understandings of the gas, dye, and heat contexts. Hanna initially predicted constant rate behavior in both the gas and heat contexts and slowing rate behavior in the dye context. However, during comparison, she revises her prediction of behavior in the dye context to slowing rate behavior, making her predictions in all three contexts the same. When asked why she has changed her mind, she says, “it just sounds more reasonable to me that they would all do the same thing, even though they’re different.” This revision and its accompanying justification reflect the establishment of Hanna’s sense of the similarity of the contexts.

Hanna learns that the gas context has slowing rate behavior through observation of a simulation during the gas investigation. The interviewer then directs Hanna to revisit the dye and heat contexts. In response, Hanna revises her predictions of behavior in the dye (H2) and in the heat (H3) contexts to be the same as the behavior she observed during the gas investigation. These revisions reflect the tacit influence of the sense of similarity that Hanna established during H1.

The following numbered sections illustrate each of Hanna’s three context interactions. Recall from Chapter 2 that interactions result in a change in understanding that establishes some similarity with other understandings. The relationships established by Hanna’s three context interactions are used to define the replacing, cueing, and guiding interactions.

3.2.1 Hanna’s First Interaction (H1): *Example of Replacing Interaction*

Hanna initially predicted slowing rate behavior in the dye context (U2). However, when Hanna is directed to compare this understanding with her understandings of the other contexts (U1 and U3), she expresses a different understanding of the dye context (U4) that is similar to both her initial understanding in the same context (U2) and her initial understandings in the gas and heat contexts (U1 and U3). This section illustrates that this change in Hanna’s understanding is the result of a context interaction in which $U_{\text{prior}}$ is U2 and $U_{\text{new}}$ is U4.

Hanna’s new understanding of the dye context establishes relationships both with her initial understandings of the gas and heat contexts and with her previous understanding of the dye context. That Hanna’s new understanding is similar to her initial understandings of the gas and heat contexts indicate that U1 and U3 are both $U_{\text{other}}$ for this interaction.

The following sections identify the relationships established by Hanna’s change in understanding during H1 that define characteristics of a particular kind of context interaction, called a *replacing interaction*. In this kind of interaction, the prediction and explanation of $U_{\text{other}}$ replaces the prediction and explanation of $U_{\text{prior}}$. 
Previous understandings that are relevant to H1.

This section introduces the understandings (i.e., U1, U2, and U3) that are relevant to the new understanding of the dye context (U4) that results from H1. The relationships (both differences and similarities) that Hanna’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Hanna initially predicted constant rate behavior in the gas context (U1). In explanation of this prediction, Hanna said,

\[ H-U1 \]

Hanna: Because the gas would be moving every second to cover up all the space. And the space would keep moving until it covered every bit of the room.

Hanna’s explanation for her prediction of constant rate behavior in the gas context was in terms of a spreading process (the gas “moves” to “cover” the space) that happens the same way “every second.”

Hanna initially predicted slowing rate behavior in the dye context (U2). In explanation of this prediction, Hanna said,

\[ H-U2 \]

Hanna: I think this one (the dye context) will be slowing rate. Because they would both (the dye and water) go at each other, and then that would change a lot. And then it would change a little bit, because it’s already been mixed together. And then it would do it a little bit less, because there’s a lot of it combined already and it’ll be equal in the end.

Hanna’s explanation for her prediction of slowing rate behavior in the dye context was in terms of a process of physical interaction\(^\text{18}\) that “mixes” and “combines” the dye and water and happens more at first than it does later. She explained that the dye and water mix a lot at first because the mixing process begins abruptly when the dye and water “go at each other.” She explained that the dye and water mix less later, because a lot of mixing has happened already (“it’s already been mixed together” and “there’s a lot of it combined already”).

Hanna initially predicted constant rate behavior in the heat context (U3). In explanation of this prediction, Hanna said,

\[ H-U3 \]

Hanna: Because the temperature would be combining with another temperature and would be mixing every second. It wouldn’t be just combined right away. It would be changing every second.

Hanna’s explanation for her prediction of constant rate behavior in the heat context was in terms of a process of physical interaction that “combines” and “mixes” the temperatures and happens the same way “every second.”

\(^{18}\) The term “physical interaction” will be used to distinguish this interaction between particles of substances from an interaction between understandings of contexts.
*Changed understanding of dye context during H1.*

During the comparison phase, the interviewer asks Hanna why she predicted different behavior in the dye context (U2) than in the gas and heat contexts (U1 and U3, respectively). In response, Hanna revises her prediction in the dye context to constant rate behavior (U4), eliminating the difference in her predictions. In explanation of this revised prediction, Hanna says,

\[ H-U4 \] Hanna: Because the amount of the dye and the amount of the water would be changing every second. Because it’s combining and …\[19\]

Hanna’s explanation for her new prediction of constant rate behavior in the dye context is in terms of a process of physical interaction that “combines” the dye and water and happens the same way “every second.”

This new understanding of the dye context (U4) is different from her initial understanding (U2). While Hanna initially predicted slowing rate behavior in the dye context, during comparison, she revises her prediction to constant rate behavior. Hanna explains both predictions in terms of a process of physical interaction that “combines” the dye and water. However, while her explanation for her initial prediction of slowing rate behavior described the process happening more at first (as the dye and water “go at each other”) than it does later (when “there’s a lot of it combined already”), her explanation for her new prediction of constant rate behavior describes the process happening the same way “every second.”

As shown above, there is a clear change in Hanna’s understanding of the heat context during the comparison phase: she predicts different behavior than she did previously and she explains this behavior in terms of a new idea about the process of physical interaction between dye and water happening the same way “every second.” The following section examines the similarities that this new understanding establishes with Hanna’s previous understandings to gain insight into the origins of this change in Hanna’s understanding.

*Similarities with previous understandings that are established by H1.*

Hanna’s new understanding of the dye context establishes similarities with her previous understandings. This section illustrates these similarities between Hanna’s new prediction of behavior in the dye context, her previous prediction of behavior in the same context, and her initial predictions of behavior in the gas and heat contexts (i.e., between U4, U2, U1, and U3); and between Hanna’s explanation for her new prediction, her previous explanation of a different behavior in the dye context, and her explanations for her initial predictions of the same behavior in the gas and heat contexts (i.e., between U4 and U2 and between U4, U1, and U3).

Hanna’s new prediction of constant rate behavior in the dye context is the same as the behavior she initially predicted in the gas and heat contexts. Hanna’s explanation for

\[19\] Hanna trails off at the end of this quote. Rather than following up on her explanation, the interviewer instead asks Hanna why she has changed her mind.
her new prediction also establishes similarities with her previous explanations of behavior.

Hanna’s explanation for her new prediction (U4) is *minimally similar* to her explanation for her initial prediction of a different behavior in the heat context (U2). As the previous section illustrated, the explanation in U4 is in terms of different ideas than the explanation in U2. The explanations are only similar in that they both describe the same mixing process of physical interaction. It is for these reasons that the explanations are interpreted to be *minimally similar*.

In contrast, Hanna’s explanation for her new prediction (U4) is *very similar* to her explanations for her initial predictions of constant rate behavior in the gas and heat contexts (U1 and U3). Like her explanation for constant rate behavior in the gas and heat contexts, Hanna’s explanation for her new prediction of constant rate behavior in the dye context is in terms of a process that happens the same way “every second.” In the heat context, Hanna additionally described this process as a physical interaction between two substances (the temperatures “mix” and “combine”). These explanations are interpreted to be *very similar* because they are in terms of the same ideas.

As shown above, Hanna’s new understanding of the dye context establishes similarities with her previous understandings: she predicts the same constant rate behavior as in the gas and heat contexts, and her explanation for this behavior is in terms of the ideas used to explain constant rate behavior in these other contexts. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by Hanna’s first context interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

*Nature of the replacing interaction in H1.*

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Hanna’s first context interaction. These relationships define the characteristics of a particular kind of interaction, called a *replacing interaction*.

- The behavior in \( U_{\text{new}} \) is different from the behavior in \( U_{\text{prior}} \) but the same as the behavior in \( U_{\text{other}} \) (e.g., in H1, Hanna’s new prediction of constant rate behavior in U4 is different from her previous prediction in U2, but the same as her predictions in U1 and U3).
- The explanation in \( U_{\text{new}} \) is minimally similar to the explanation of the different behavior \( U_{\text{prior}} \) (e.g., in H1, the explanation of constant rate behavior in U4 is in terms of different ideas than the explanation of slowing rate behavior in U2).
- The explanation in \( U_{\text{new}} \) is very similar to the explanation of the same behavior in \( U_{\text{other}} \) (e.g., in H1, the explanation of constant rate behavior in U4 is in terms of the same ideas used to explain the same behavior in U1 and U3).
These relationships suggest that the behavior and explanation in $U_{\text{other}}$ replace the behavior and explanation in $U_{\text{prior}}$. This replacing is the source of the name for this kind of context interaction.

A context interaction may be engaged either consciously or unconsciously. When the interviewer asks Hanna following her revision of prediction in the dye context why she has changed her mind, Hanna says,

Hanna: It just sounds more reasonable to me that they would all do the same thing, even though they are different.

This justification indicates that Hanna engages the replacing interaction both consciously and deliberately in order to establish a sense that she has that the contexts should all have the same behavior (“do the same thing”). The replacing interaction and its relationship with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

3.2.2 Hanna’s Second Interaction (H2): Example of Cueing Interaction

Recall that Hanna initially predicted slowing rate behavior in the dye context (U2), but revised her prediction to constant rate behavior during H1 (U4). During the subsequent gas investigation, Hanna learns that the gas context has slowing rate behavior (U5) rather than the constant rate behavior she initially predicted. Hanna then goes on to express a new understanding of the dye context (U6). This section illustrates that this change in Hanna’s understanding is the result of a context interaction. That this change in understanding is between U4 and U6 identifies U4 as $U_{\text{prior}}$ and U6 as $U_{\text{new}}$.

Hanna’s new understanding (U6) establishes relationships both with her learned understanding of the gas context (U5) and with her initial understanding of the same behavior in the dye context (U2). Hanna’s new prediction of behavior in the dye context is the same as the behavior she learned in the gas context. This indicates that U5 is $U_{\text{other}}$ for this interaction. Hanna’s new explanation is similar to her explanation for her initial prediction of slowing rate behavior in the dye context. This indicates that although Hanna revised her understanding during H1, her initial understanding of the dye context was not forgotten, and that U2 is also $U_{\text{prior}}$ for this interaction.

The following sections identify the relationships established by Hanna’s change in understanding during H2 that define characteristics of a particular kind of context interaction, called a cueing interaction. In this kind of interaction, prediction of a new

\[20\] Note that the term learned understanding is used to refer to participants’ understanding of a context following its investigation. As discussed in Chapter 2, during the investigation, participants observe a simulation of the slowing rate behavior of the context and consider suggested explanatory ideas. Although the participant’s learned understanding of the behavior of the context following investigation will be normative, her understanding of why this behavior may not be.
behavior that is the same as the behavior of $U_{other}$ cues recall of the explanation used previously to explain the same behavior in $U_{prior}$.

Previous understandings that are relevant to H2.

This section introduces the previous understandings (i.e., U2, U4, U5) that are relevant to the new understanding of the dye context (U6) that results from H2. The relationships (both differences and similarities) that Hanna’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Recall that Hanna initially predicted slowing rate behavior in the dye context (U2). As discussed previously, Hanna explained this prediction in terms of a process of physical interaction that “mixes” and “combines” the dye and water and happens more at first than it does later. She explained that the dye and water mix a lot at first because the mixing process begins abruptly when the dye and water “go at each other.” Further, she explained that the dye and water mix less later because a lot of mixing has happened already (“it’s already been mixed together”).

Following her initial predictions in the gas, dye, and heat context, Hanna was asked to compare her understandings of these contexts. Recall that during this comparison, Hanna revised her prediction of behavior in the dye context to constant rate behavior (U4). As discussed previously, Hanna explained this prediction in terms of a process of physical interaction that “combines” the dye and water and happens the same way “every second.”

During the gas investigation, Hanna observed that in contrast to her prediction of constant rate behavior, the gas context has slowing rate behavior (U5). Following consideration of the suggested explanatory ideas discussed in Section 2.3.3, Hanna gave an explanation for why this behavior happens. She said,

\[ H-U5 \]

Hanna: It (the gas) would be moving all around the room, and then as it fills the whole room, there would be less space to take up, so there would be less space to go around and cover /…/ [It goes a lot at first] because there’s nothing on one side, and there is something filled with gas on the other side.

Hanna’s explanation for the observed slowing rate behavior of the gas context was in terms of a spreading process (the gas “moves” to “cover” the space) that happens more at first than it does later. She explained these different parts of the behavior in terms of the decreasing amount of empty space in the container: she explained that the gas spreads more at first because there is more space available for the gas to move and spread out (“there’s nothing on the other side”); she explained that the gas spreads less later because the amount of space remaining decreases as it becomes filled with gas (“there would be less space to take up”).

Changed understanding of the dye context during H2.

Following the gas investigation, Hanna revises her prediction of behavior (U4) to slowing rate behavior (U6). In explanation of this revised prediction, Hanna says,
Hanna: Because they (the dye and water) are both really different, and if you put them together then they’ll probably change a lot. Over time, it’ll mix by itself, and it’ll have to change less and less /…/ because there’s not much of the two left to mix together. It would change a lot at first, because they’ll be smashing at each other, and it’ll mix by itself.

Hanna’s explanation for her new prediction of slowing rate behavior in the dye context is in terms of a mixing process of physical interaction and happens more at first than it does later. She explains these two parts of the behavior in terms of the decreasing difference between the concentrations on each side of the container: she explains that the dye and water mix a lot at first because “they are both really different,” and she explains that the dye and water mix less later because a lot of mixing has happened already (“there’s not much of the two left to mix”). She also explains that more change happens at first because the mixing process begins abruptly when the dye and water are “smashing at each other.”

This new understanding of the dye context is different from the understanding of the dye context she expressed just prior to the gas investigation (U4). While Hanna predicted constant rate behavior in the dye context prior to the gas investigation, she revises her prediction to slowing rate behavior afterward. Hanna explains both predictions in terms of a process of physical interaction that “mixes” and “combines” the dye and water. However, while her explanation for her prediction of constant rate behavior described the process happening the same way “every second,” her explanation for her new prediction of slowing rate behavior describes the process happening more at first (as the dye and water are “smashing at each other”) than it does later (when there’s not much of the two left to mix”).

As shown above, there is a clear change in Hanna’s understanding of the dye context following the gas investigation: she predicts different behavior than she did just prior and in explanation of this behavior she says that the process of physical interaction happens more at first than it does later instead of the same way “every second.” The following section examines the similarities that this new understanding establishes with Hanna’s previous understandings to gain insight into the origins of this change in Hanna’s understanding.

**Similarities with previous understandings that are established by H2.**

Hanna’s new understanding of the dye context establishes similarities with her previous understandings. This section illustrates these similarities between Hanna’s new prediction of behavior in the dye context, her previous predictions of behavior in the same context, and the learned behavior of the gas context (i.e., between U6, U2, U4, and U5); and between Hanna’s explanation for her new prediction, her previous explanations for both behaviors in the dye context, and her explanation for the learned behavior of the gas context (i.e., between U6, U2, and U4 and between U6 and U5).

Although Hanna’s new prediction in the dye context is different from her prediction just prior to the gas investigation, it is the same as the behavior she observed
during the gas investigation: slowing rate behavior. Hanna’s explanation for her new prediction establishes similarities with her previous explanations of behavior:

Hanna’s explanation for her new prediction of slowing rate behavior in the dye context (U6) is minimally similar to her explanation for her previous prediction of constant rate behavior in the dye context (U4). As the previous section illustrated, the explanation in U6 is in terms of different ideas than the explanation in U4. The explanations are only similar in that they both describe the same mixing process of physical interaction. It is for these reasons that the explanations are interpreted to be minimally similar.

Hanna’s explanation for her new prediction of slowing rate behavior in the dye context is also minimally similar to her explanation for the learned slowing rate behavior of the gas context. Hanna’s new explanation is similar to her explanation of slowing rate behavior in the gas context only in that it describes a process that happens more at first than it does later. The explanations of these two parts of the behavior are explained differently in the different contexts (in terms of the decreasing amount of space for gas; in terms of the decreasing difference between the concentrations on either side of the container). It is for these reasons that the explanations are interpreted to be minimally similar.

However, Hanna’s new prediction of slowing rate behavior in the dye context is very similar to her explanation for her initial prediction of slowing rate behavior in the dye context. Like her initial explanation for slowing rate behavior, Hanna’s new explanation for this behavior is in terms of a mixing process of physical interaction that happens more at first than it does later. These explanations additionally explain the two parts of the behavior similarly: in both explanations she explains that more change happens at first because the mixing process begins abruptly (the dye and water “go at each other”; the dye and water are “smashing at each other”); she explains that less change happens later because a lot of mixing has happened already (“it’s already been mixed together”; “there’s not much of the two left to mix together”). These explanations are interpreted to be very similar because they are in terms of the same ideas.

As shown above, Hanna’s new understanding of the dye context establishes similarities with her previous understandings: she predicts the same slowing rate behavior she observed in the gas context and her explanation for this behavior is in terms of the same ideas used to explain her initial prediction of the same behavior in the dye context. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by Hanna’s second interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

*Nature of the cueing interaction in H2.*

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Hanna’s second context interaction. These relationships define the characteristics of a particular kind of interaction, called a cueing interaction.
• The behavior in $U_{\text{new}}$ is different from the behavior in the same context just prior but the same as the behavior in $U_{\text{other}}$ (e.g., in H2, Hanna’s new prediction of slowing rate behavior in U6 is different from her previous prediction in U4, but the same as the behavior she learned in U5; this prediction of behavior is also the same as her initial prediction in U2).

• The explanation in $U_{\text{new}}$ is minimally similar to the explanation of the different behavior in the same context just prior (e.g., in H2, the explanation of slowing rate behavior in U6 is in terms of different ideas than the explanation of constant rate behavior in U4).

• The explanation in $U_{\text{new}}$ is minimally similar to the explanation of the same behavior in $U_{\text{other}}$ (e.g., in H2, the explanation of slowing rate behavior in U6 is in terms of different ideas than the explanation of the same behavior in U5).

• The explanation in $U_{\text{new}}$ is very similar to a previous explanation of the same behavior in the same context (e.g., in H2, the explanation of slowing rate behavior in U6 is in terms of the same ideas used to explain the same behavior U2).

These relationships suggest that the behavior in $U_{\text{other}}$ cues recall of a previous explanation of the same behavior in the same context. This cueing is the source of the name for this kind of interaction. The cueing interaction and its relationship with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

3.2.3 Hanna’s Third Interaction (H3): Example of Guiding Interaction

Recall that Hanna initially predicted constant rate behavior in the heat context (U3). After learning during the gas investigation that slowing rate behavior happens in the gas context (U5), and revising her prediction of behavior in the dye context to the same slowing rate behavior (U6), Hanna expresses a new understanding of the heat context as well (U7). This section illustrates that this change in Hanna’s understanding is the result of a context interaction in which $U_{\text{prior}}$ is U3 and $U_{\text{new}}$ is U7.

Hanna’s new understanding establishes relationships with her learned understanding of the gas context, revised understanding of the dye context, and with her initial understanding of different behavior in the heat context. That Hanna’s new understanding is similar to her learned understandings of the gas and dye contexts indicates that U5 and U6 are both $U_{\text{other}}$ for this interaction. That Hanna’s new understanding is also similar to her previous understanding of the heat context reinforces the identification of U3 as $U_{\text{prior}}$.

The following sections identify the relationships established by Hanna’s change in understanding during H3 that define characteristics of a particular kind of context interaction, called a guiding interaction. In this kind of interaction, the modification of
an idea from $U_{\text{prior}}$ to explain prediction of a new behavior is *guided* by the explanation in $U_{\text{other}}$ of the behavior in terms of the modified idea.

*Previous understandings that are relevant to $H_3$.*

This section introduces the previous understandings (i.e., $U_3$, $U_5$, and $U_6$) that are relevant to the new understanding of the heat context ($U_6$) that results from $H_3$. The relationships (both differences and similarities) that Hanna’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Recall that Hanna initially predicted constant rate behavior in the heat context ($U_3$). As discussed previously, Hanna explained this prediction in terms of a process of physical interaction that “combines” the temperatures and happens the same way “every second.”

After observing the slowing rate behavior of the gas context during the gas investigation ($U_5$), Hanna revised her prediction of behavior in the dye context to be slowing rate behavior ($U_6$). As discussed previously, Hanna explained the observed slowing rate behavior of the gas context in terms of a spreading process (the gas “moves” to “cover” the space) that happens more at first than it does later. She explained these different parts of the behavior in terms of the decreasing amount of empty space in the container: she explained that the gas spreads more at first because there is more space available for the gas to move and spread out (“there’s nothing on the other side”); she explained that the gas spreads less later because the amount of space remaining decreases as it becomes filled with gas (“there would be less space to take up”).

As discussed previously, Hanna explained her revised prediction of slowing rate behavior in the dye context in terms of a process of physical interaction that “mixes” the dye and water and happens more at first than it does later. She explained these two parts of the behavior in terms of the decreasing difference between the concentrations on each side of the container: she explained that the dye and water mix a lot at first because “they are both really different,” and that the dye and water mix less later because a lot of mixing has happened already (“there’s not much of the two left to mix”).

*Changed understanding of the heat context during $H_3$.*

Following the gas investigation ($U_5$) and revision of her understanding in the dye context ($U_6$), Hanna revises her prediction of behavior ($U_3$) to slowing rate behavior ($U_7$). In explanation of this revised prediction, Hanna says,

\begin{quote}
$H-U_7$ Hanna: If two totally different things are put together, then the temperatures would probably mix together. They would be so different that they would change a lot, and then in the end it would take longer for those two temperatures to become equal because they mixed a lot already.
\end{quote}

Hanna’s explanation for her new prediction of slowing rate behavior in the heat context is in terms of a process of physical interaction that “mixes” the temperatures and happens differently at first than it does later. She explains these two parts of the behavior in terms of the decreasing difference between the temperatures of the two pieces of metal. She
explains that the temperatures mix a lot at first because they are “two totally different things” and mix less later because the temperatures have “mixed a lot already.”

This new understanding of the heat context (U7) is different from her initial understanding (U3). While Hanna initially predicted constant rate behavior in the heat context, following the gas investigation and her dye revision, she predicts slowing rate behavior instead. Hanna explains both predictions in terms of a process of physical interaction that “mixes” the temperatures. However, while her explanation for her initial prediction of constant rate behavior described the process happening the same way “every second,” her new explanation of slowing rate behavior describes the mixing process happening more at first (when the temperatures “are both really different”) than it does later (when “there’s not much of the two left to mix”).

As shown above, there is a clear change in Hanna’s understanding of the heat context following the gas investigation and dye revision: she predicts different behavior than she did previously and in explanation of this behavior she says that the mixing process happens more at first than it does later, instead of the same way every second. The following section examines the similarities that this new understanding establishes with Hanna’s previous understandings to gain insight into the origins of this change in Hanna’s understanding.

**Similarities with previous understandings that are established by H3.**

Hanna’s new understanding of the heat context establishes similarities with her previous understandings. This section will illustrate these similarities between Hanna’s new prediction of behavior in the heat context, her previous prediction of behavior in the same context, the learned behavior of the gas context, and her revised prediction of behavior in the dye context (i.e., between U7, U3, U5, and U6). It also shows similarities between Hanna’s explanation for her new prediction, her previous explanation of a different behavior in the heat context, her explanation for the learned behavior of the gas context, and her explanation for her revised prediction in the dye context (i.e., between U7 and U3 and between U7, U5 and U6).

Although Hanna’s new prediction of slowing rate behavior is different from the behavior she predicted previously in the heat context, it is the same as both the learned behavior of the gas context and her revised prediction of behavior in the dye context. Hanna’s explanation for her new prediction establishes similarities with her previous explanations of behavior:

Although Hanna’s explanation for her new prediction of slowing rate behavior in the heat context (U7) is minimally similar to her learned explanation for the same behavior in the gas context (U5), it is very similar to her explanation for her revised prediction of the same behavior in the dye context (U6). All three explanations describe a process that happens more at first than it does later.

Unlike her learned explanation for slowing rate behavior in the gas context (U5), her revised prediction of slowing rate behavior in the heat context (U7) is in terms of a process of physical interaction between two substances (the dye and water “mix”), rather than the spreading of just one substance (the gas “moves” to cover” the space). In addition, she explains the two parts of the behavior differently in the different contexts: in
the gas context she explains this behavior in terms of the decreasing amount of space for gas; in the heat context she explains this behavior in terms of the decreasing difference between the temperatures of the two pieces of metal. It is for these reasons that the explanations are interpreted to be minimally similar.

Like her explanation for her revised prediction of slowing rate behavior in the dye context (U6), her explanation for her revised prediction of slowing rate behavior in the heat context is in terms of a “mixing” process of physical interaction. In addition, she explains the two parts of the behavior similarly. She explains the behavior in both contexts in terms of the decreasing difference between the two sides of the container: in both contexts she explains that more change happens at first because each pair of substances are really different (“they (the dye and water) are both really different”; the temperatures are “two totally different things”); she explains that less change happens later because a lot of mixing has happened already (“there’s not much of the two (dye and water) left to mix together”; “they (the temperatures) mixed a lot already”). These explanations are interpreted to be very similar because they are in terms of the same ideas.

Hanna’s explanation for her new prediction of slowing rate behavior in the heat context is in terms of a modification of an idea from her explanation for her previous prediction of constant rate behavior in the heat context (U3). Like her previous explanation of constant rate behavior in the heat context, Hanna’s explanation for her new prediction of slowing rate behavior is in terms of an idea about a “mixing” process of physical interaction between the temperatures. However, in her new explanation, this idea about the process of physical interaction is newly associated with the difference between the temperatures. This association enables explanation of why the heat context would instead have slowing rate behavior (the temperatures “mix” a lot at first because they are two “totally different things”). This explanation is interpreted to be in terms of a modification of an idea because of this new association. Note that this modified idea is the same as an idea that Hanna used to explain her revised prediction of slowing rate behavior: that more mixing happens at first when each pair of substances are really different.

As shown above, Hanna’s new understanding of the heat context establishes similarities with her previous understandings: her prediction of behavior is the same as the learned behavior of the gas context and her revised prediction of behavior in the dye context; in addition, her explanation for this behavior is in terms of a modification of an idea from her previous prediction of constant rate behavior in the same context that is the same as an idea used to explain slowing rate behavior in the dye context. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by Hanna’s third interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

Nature of the guiding interaction in H3.
This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Hanna’s third context interaction. These
relationships define the characteristics of a particular kind of interaction, called a *guiding interaction*.

- The behavior in $U_{\text{new}}$ is different from the behavior in $U_{\text{prior}}$ but the same as the behavior in $U_{\text{other}}$.
- An idea used to explain the behavior of $U_{\text{new}}$ is related to but not the same as an idea that was used to explain the different behavior of $U_{\text{prior}}$.
- The idea is modified to explain different behavior in $U_{\text{new}}$.
- The explanation for the behavior in $U_{\text{other}}$ is very similar to the explanation for the behavior in $U_{\text{new}}$.

These relationships suggest that the modification of an idea from $U_{\text{prior}}$ to explain a different behavior in $U_{\text{new}}$ is *guided* by the explanation of the behavior in $U_{\text{other}}$. This guiding is the source of the name for this kind of interaction.

The process data provides additional insight into the process by which a modification is guided. Hanna’s revision of her understanding of the heat context during her third interaction is not immediate. Following the gas investigation and dye revision, Hanna hesitates. When asked to share what she is thinking, she says,

Hanna: I’m thinking about the particles of the plates (pieces of metal), and the temperatures and how they could be mixing together, but they could be doing something else too. So I’m just thinking about how they could be mixing or just touching and then becoming different.

This illustrates that Hanna reconsiders the nature and physical interaction of the temperatures before she expresses her new understanding of the heat context. Settling on the mixing process of physical interaction may establish a similarity with her understanding of the dye context that then guides the modification of this idea to support prediction of the same behavior. The guiding interaction and its relationship with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

### 3.2.4 Summary of Hanna’s Three Interactions

All three of Hanna’s context interactions result in prediction of behavior that is the same as the behavior of another context. This indicates that Hanna’s three context interactions are strongly influenced by a sense that the contexts are similar to one another.

Hanna’s three context interactions each establish a different set of relationships between her understandings. These sets of relationships define the interactions as different kinds of context interactions with particular characteristics. Hanna’s three contexts interactions are called replacing, cueing, and guiding interactions, respectively. These interactions and their relationships with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.
3.3 GRETA’S APPROACH TO REASONING ACROSS CONTEXTS

Greta’s three context interactions demonstrate an approach to reasoning across the gas, dye, and heat contexts that is strongly influenced by her learned understanding of slowing rate behavior. These context interactions are illustrated schematically in Figure 17 as G1, G2, and G3.

Greta gives a new explanation for slowing rate behavior in the dye context during her first context interaction (G1). Greta predicted slowing rate behavior in the dye context prior to the gas investigation. During the gas investigation through consideration of the suggested explanatory ideas, Greta learns a new explanation for why slowing rate behavior happens. After confirming her prediction of slowing rate behavior through observation of a simulation during the subsequent dye investigation, Greta gives a new explanation for why this behavior happens. This revision of explanation is given prior to consideration of the suggested explanatory ideas in the dye context. Greta’s new explanation is in terms of ideas from both her previous explanation in the same context and her learned explanation for slowing rate behavior in the gas context.

Following the gas and dye investigations, Greta is directed to reconsider her understanding of the heat context. Greta previously predicted constant rate behavior in the heat context. However, she now revises her prediction of behavior to the same slowing rate behavior she observed during the gas and dye investigations (G2).

Greta’s explanation for her new prediction of slowing rate behavior in the heat context is different from her learned explanation of slowing rate behavior. Greta is directed to consider whether her explanations for slowing rate behavior in the gas and dye contexts can help explain her new prediction of slowing rate behavior in the heat context. In response, she revises her explanation in the heat context to be in terms of an idea that is similar but not the same as an idea she used to explain these other contexts (G3).

The following numbered sections illustrate each of Greta’s three context interactions. The relationships established by Greta’s three context interactions are used to define the supplementing, prompting, and reinterpreting interactions.
Figure 17. Schematic of Greta’s three context interactions. These context interactions are indicated with different colored arrows, numbered sequentially, and labeled with the first initial of Greta’s name. Also indicated is each context interaction’s kind (supplementing, prompting, and reinterpreting). Additional details about the way in which participants’ understandings are represented in schematics like this are described in the caption of Figure 15.
3.3.1 Greta’s First Interaction (G1): Example of Supplementing Interaction

Prior to the gas investigation, Greta predicted slowing rate behavior in the dye context and gave an explanation for why this behavior happens (U2). However, following the gas investigation, Greta gives a different explanation for this behavior (U4) that is similar to both her previous understanding in the same context (U2) and her learned understanding of the gas context (U4). This section illustrates that this change in Greta’s understanding is the result of a context interaction in which U\textsubscript{prior} is U2 and U\textsubscript{new} is U4.

Greta’s new understanding of the dye context establishes relationships both with her learned understanding of the gas context and with her previous understanding of the dye context. That Greta’s new understanding is similar to her learned understanding of the gas context indicates that U4 is U\textsubscript{other} for this interaction. That Greta’s new understanding is also similar to her previous understanding in the same context reinforces the identification of U2 as U\textsubscript{prior}.

The following sections identify the relationships established by Greta’s change in understanding during G1 that define characteristics of a particular kind of context interaction, called a supplementing interaction. In this kind of interaction, ideas from U\textsubscript{other} are added to U\textsubscript{prior} to supplement the explanation of the same behavior.

Previous understandings that are relevant to G1.

This section introduces the previous understandings (i.e., U2 and U4) that are relevant to the new understanding of the dye context (U5) that results from G1. Following this introduction to the relevant understandings, the relationships (both differences and similarities) that Greta’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Prior to the gas investigation, Greta predicted slowing rate behavior in the dye context (U2). In explanation of this prediction, Greta said,

\[\text{G-U2} \quad \text{Greta: If you take the divider up really fast, there’s particles in the red water, so the particles might rush forward, and that’s going to be a lot and leave a little left (on the left side). So then it’s going to be a slowing rate, because it’ll go a little by a little, and it’ll finally be mixed together.}\]

Greta’s explanation for her prediction of slowing rate behavior was in terms of movement of the dye (it “rushes” and “goes”) that happens more at first than it does later. She explained that the dye and water go more at first because the movement begins abruptly (the dye and water “rush forward”) when the divider is removed quickly. Further, she explained that the dye and water go less later because the amount of dye remaining decreases (the movement only “leave[s] a little left”).

During the gas investigation, Greta observed that slowing rate behavior happens in the gas context (U4). Following consideration of the suggested explanatory ideas, Greta gave an explanation for why this behavior happens. She said,
Greta: It’s open space and it needs somewhere to go, so it basically just goes over there. And there’s not as much space left over there, so basically it just has to slowly go in. /…/ There’s resistance because there’s other particles [of gas] that are trying to get in, but there’s not as much room for them to fit.

Greta’s explanation for the slowing rate behavior of the gas context was in terms of movement of the gas (it “goes”) that happens more at first than it does later. She explained these different parts of the behavior in terms of an increased “resistance” to movement that is due to the decreasing amount of empty space in the container: she explained that the gas goes more at first because there is more space available (“it’s open space”); she explained that the gas goes less later because the amount of space remaining decreases (“there’s not as much space left”; “there’s not as much room for them to fit”). She also explained that more change happens at first because there is urgency for the gas to move (“it needs somewhere to go”).

Changed understanding of dye context during G1.

During the dye investigation, Greta confirms her prediction of slowing rate behavior in the dye context (U2) through observation of a simulation, and gives a new explanation for this behavior before consideration of the explanatory ideas (U5).21 She says,

Greta: Because a lot goes at first, and then there’s not that much left, so it resists whatever wants to come towards where the other one has gone, so when it resists, there’s not much room (on the right side) for the other one to come in. So it slows it down from going completely there. /…/ Once you lift the divider up, there’s a lot of dye, so it’s looking for somewhere else to go, and then once it’s settled, and there’s still a bit more, it resists the other dye and it slows it down from getting perfectly even.

Greta’s new explanation for slowing rate behavior in the dye context is in terms of movement of the dye (it “goes”) that happens more at first than it does later. She explains that more change happens at first because there is urgency for the dye to move (“it’s looking for somewhere else to go”). She gives three reasons for why less change happens later: that the amount of dye remaining decreases (“there’s not that much left”; “there’s still a bit more”); that the amount of space remaining for dye decreases (“there’s not much room”); and that there is an increased resistance to movement (“it resists”).

This new explanation of slowing rate behavior in the dye context (U5) is different from the explanation Greta gave for this behavior in the dye context prior to the gas investigation (U2). In both explanations, Greta describes movement of the dye that

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21 If the explanation were given following consideration of the explanatory ideas, it would be unclear whether it was derived from those ideas or from her previous understandings. Because the explanation is given before consideration of these ideas, it is clear that it must have been derived from her previous understandings and is therefore a context interaction.
happens more at first than it does later. However, her explanations for these two parts of the behavior are different.

Prior to the gas investigation (U2), Greta explained that more change happens at first in the dye context because it begins abruptly (the dye and water “rush forward”) when the divider is removed. In contrast, following the gas investigation (U5), Greta explains that this part of the behavior happens because there is urgency for the dye to move (“it’s looking for somewhere else to go”).

In both U2 and U5 Greta explains that less change happens later because the amount of dye remaining decreases (the movement only “leave[s] a little left”; “there’s not that much left”). However, following the gas investigation (U5), Greta also gives two additional reasons for why less change happens later: that the amount of space remaining for dye decreases (“there’s not much room”) and that there is an increased resistance to movement (“it resists”).

As shown above, there is a clear change in Greta’s explanation of slowing rate behavior in the dye context following the gas investigation: she has a new explanation for why more change happens at first and two additional reasons for why less change happens later. The following section examines the similarities that this new understanding establishes with Greta’s previous understandings to gain insight into the origins of this change in Greta’s explanation.

**Similarities with previous understandings that are established by G1.**

Greta’s new understanding of the dye context establishes similarities with her previous understandings. This section illustrates these similarities between Greta’s new explanation of slowing rate behavior in the dye context, her previous explanation of the same behavior in the same context, and her learned explanation of slowing rate behavior in the gas context (i.e., between U5, U2, and U4).

Greta’s new explanation for slowing rate behavior in the dye context following the gas investigation (U5) is somewhat similar to her explanation prior to the gas investigation (U2). As the previous section illustrated, there are a number of ways in which Greta’s explanations in U2 and U5 are different, but there is one way in which they are similar. In both U2 and U5, Greta explains that less change happens later in terms of an idea about the decreasing amount of dye remaining (the movement only “leave[s] a little left”; “there’s not that much left”). These explanations are interpreted to be only somewhat similar because they share only one idea.

Greta’s new explanation for slowing rate behavior (U5) is also somewhat similar to her explanation in the gas context following the gas investigation (U4). In both U4 and U5, Greta explains that more change happens at first in terms of an idea about there being urgency for movement (“it needs somewhere to go”; “it’s looking for somewhere else to go”). Greta also explains in both U4 and U5 that less change happens later in terms of an idea about the increased resistance to movement (“resistance”; “it resists”) that is due to the decreasing amount of empty space in the container (“there’s not as much
space left”; “there’s not much room”). However, there are also ideas used in U4 that are not used in U5 (that more change happens at first because there’s more space available), and vice versa (that the amount of dye remaining decreases). These explanations are interpreted to be only somewhat similar because they share only some ideas.

As shown above, Greta’s new understanding of the dye context establishes similarities with her previous understandings: her new explanation for slowing rate behavior in the dye context is in terms of ideas both from her previous explanation of the same behavior in the same context and from her learned explanation for the same behavior in the gas context. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by Greta’s first interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

Nature of the supplementing interaction in G1.

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Greta’s first context interaction. These relationships define the characteristics of a particular kind of interaction, called a supplementing interaction.

- The behavior in $U_{\text{new}}$ is the same as the behavior in $U_{\text{prior}}$ and the behavior in $U_{\text{other}}$ (e.g., in G1, the slowing rate behavior that Greta explains in U5 is the same behavior she predicted in U2 and learned in U4).
- The explanation in $U_{\text{new}}$ is somewhat similar to the explanation of the same behavior in $U_{\text{prior}}$ (e.g., in G1, an idea that was used to explain slowing rate behavior in U2 is used to explain the same behavior in U5).
- The explanation in $U_{\text{new}}$ is somewhat similar to the explanation of the same behavior in $U_{\text{other}}$ (e.g., in G1, ideas that were used to explain slowing rate behavior in U4 are used to explain the same behavior in U5).

These relationships suggest that ideas from $U_{\text{prior}}$ supplement ideas from $U_{\text{other}}$ to explain the same behavior in $U_{\text{new}}$. This supplementing is the source of the name for this kind of interaction. The supplementing interaction and its relationship with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

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22 While Greta is explicit that this her association between resistance and space is causal in the gas context (“there’s resistance because /…/ there’s not as much room”), in the dye context such causality can only be inferred (“when it resists, there’s not that much room”).
3.3.2 Greta’s Second Interaction (G2): Example of Prompting Interaction

Following the gas and dye investigations, the interviewer directs Greta to reconsider her understanding of the heat context. Prior to the gas and dye investigations, Greta predicted constant rate behavior in the heat context (U3). This prediction is different from the learned slowing rate behavior of the gas and dye context (U4 and U5). In response to this observation, Greta expresses a new understanding of the heat context (U6). This section illustrates that this change in Greta’s understanding is the result of a context interaction in which $U_{\text{prior}}$ is U3 and $U_{\text{new}}$ is U6.

Greta’s new understanding establishes relationships both with her learned understandings of the gas and dye contexts and with her previous understanding of the heat context. That Greta’s new understanding is similar to her learned understandings of the gas and dye contexts indicates that U4 and U5 are both $U_{\text{other}}$ for this interaction. That Greta’s new understanding is also similar to her previous understanding in the same context reinforces the identification of U3 as $U_{\text{prior}}$.

The following sections identify the relationships established by Greta’s change in understanding during G2 that define characteristics of a particular kind of context interaction, called a **prompting interaction**. In this kind of interaction, the difference between the behavior in $U_{\text{other}}$ and $U_{\text{prior}}$ prompts modification of an idea from $U_{\text{prior}}$ to explain prediction of a new behavior in $U_{\text{new}}$ that is the same as the behavior in $U_{\text{other}}$.

*Previous understandings that are relevant to G2.*

This section introduces the previous understandings (i.e., U3, U4, and U5) that are relevant to the new understanding of the heat context (U6) that results from G2. Following this introduction to the relevant understandings, the relationships (both differences and similarities) that Greta’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Prior to the gas and dye investigations, Greta predicted constant rate behavior in the heat context (U3). In explanation of this prediction, Greta said,

\textit{G-U3 Greta: It could be gradual, so that it (the hot piece of metal) heats it (the cold piece of metal) up section by section. \ldots [The heat] goes gradually into each little section.}

Greta’s explanation for her prediction of constant rate behavior in the heat context was in terms of a heating process (“it (the hot piece of metal) heats it (the cold piece of metal) up”) that happens “gradually” “section by section.”

After observing the slowing rate behavior of the gas context during the gas investigation (U4), Greta revised her explanation for slowing rate behavior in the dye context (U5). As discussed previously, Greta’s explanations of slowing rate behavior during the gas and dye investigations were both in terms of a movement that happens more at first than it does later. In addition, she explained the two parts of the behavior in terms of a number of the same ideas: she explained that more change happens at first in terms of an idea about there being urgency for movement (“it needs somewhere to go”; “it’s looking for somewhere else to go”); she explained that less change happens later in
terms of ideas about the “resistance” to movement increasing, and the amount of space remaining decreasing (“there’s not as much space left”; “there’s not much room”).

*Changed understanding of the heat context during G2.*

Following the gas and dye investigations, the interviewer directs Greta to reconsider her understanding of the heat context (U3). In response, Greta revises her prediction of behavior to slowing rate behavior (U6). In explanation of this revised prediction, Greta says,

\[ G-U6 \]

Greta: It could go really fast at first, but then /.../ once it got towards the end, it would slow down a lot because the source of heat or cold is way at the front of the piece of metal and the particles that are at the very back, it’s going to take a while for them to heat up or cool down. [It would change more at the beginning] because it is right near the source // It’s right next to the hot piece, right next to the cold piece, so that when it gets all the way to the end // It’s all the way up here, so it’s going to take a while for it to get to the back.

Greta’s explanation for her new prediction of slowing rate behavior in the heat context is in terms of a process of heating and cooling (they “heat up or cool down”) that happens more at first than it does later. She explains these two parts of the behavior in terms of the increasing distance between the source and recipient of heat or cold (between “the source of heat or cold” and “the particles” that remain to be heated): she explains that the temperatures change more at first because the particles “right near the source” need to be heated; she explains that the temperatures change less later because the particles that remain to be heated are “at the very back.”

This new understanding of the heat context is different from her previous understanding (U3). While Greta initially predicted constant rate behavior in the heat context, following the gas and dye investigations, she predicts slowing rate behavior instead. Greta explains both predictions in terms of a process of heating and cooling (“it (the hot piece of metal) heats it (the cold piece of metal) up”; they “heat up or cool down”). However, while her explanation for her initial prediction of constant rate behavior described the process happening “gradually” “section by section,” her new explanation of slowing rate behavior describes the process happening more at first (when particles “right near the source” need to be heated) than it does later (when the particles that remain to be heated are “at the very back”).

As shown above, there is a clear change in Greta’s understanding of the heat context following the gas and dye investigations: she predicts different behavior than she did previously and in explanation of this behavior she says that the process of heating and cooling happens more at first than it does later instead of gradually section by section. The following section examines the similarities that this new understanding establishes with Greta’s previous understandings to gain insight into the origins of this change in Greta’s understanding.
Greta’s new understanding of the heat context establishes similarities with her previous understandings. This section illustrates these similarities between Greta’s new prediction of behavior in the heat context, her previous prediction of behavior in the heat context, and the learned behaviors of the gas and dye contexts (i.e., between U6, U3, U4, and U5); and between Greta’s explanation for her new prediction, her previous explanation of a different behavior in the heat context, and her explanations for the same behavior that she learned during the gas and dye investigations (i.e., between U6 and U3, and between U6, U4, and U5):

Although Greta’s new prediction of slowing rate behavior is different from the behavior she predicted previously in the heat context, it is the same as the behavior she observed in the gas and dye contexts: slowing rate behavior. Greta’s explanation for her new prediction also establishes similarities with her previous explanations of behavior.

Greta’s explanation for her new prediction of slowing rate behavior in the heat context (U6) is in terms of a modification of an idea from her explanation for her previous prediction of constant rate behavior in the heat context (U3). Like her previous explanation of constant rate behavior in the heat context, Greta’s explanation for her new prediction of slowing rate behavior is in terms of an idea about a heating process. However, in her new explanation, this idea about a heating process is newly associated with an increasing distance (between “the source of heat or cold” and “the particles” that remain to be heated). This association enables explanation of why the heat context would instead have slowing rate behavior (more heating happens at first because the particles that are receiving heat are “right near the source” and less later because the particles that remain to be heated are “at the very back”). This explanation is interpreted to be in terms of a modification of an idea because of this new association.

Greta’s explanation for her new prediction (U6) is minimally similar to her explanations for the same behavior that she learned during the gas and dye investigations (U4 and U5). Like her explanations of slowing rate behavior in the gas and dye contexts, Greta’s explanation for her new prediction of slowing rate behavior in the heat context is in terms of an idea about a process that happens more at first than it does later. However, Greta explains these two parts of the behavior differently in the heat context than she did in the gas and dye contexts: recall that her explanations in the gas and dye contexts (U4 and U5) were in terms of ideas about there being an initial urgency for movement, increasing resistance to movement, and decreasing space remaining. In contrast, her explanation in the heat context (U6) is instead in terms of an idea about there being increasing distance between the source and recipient of heat (the particles that are receiving heat are “right near the source” at first and “at the very back” later). These explanations are interpreted to be minimally similar because they are in terms of these different ideas.

As shown above, Greta’s new understanding of the heat context establishes similarities with her previous understandings: she predicts the same slowing rate behavior she observed in the gas and dye contexts and her explanation for this behavior is in terms of a modification of an idea from her explanation for her previous prediction of constant rate behavior in the same context. Together with the differences discussed in the
previous section, these similarities comprise the relationships between understandings established by Greta’s second interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

Nature of the prompting interaction in G2.

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Greta’s second context interaction. These relationships define the characteristics of a particular kind of interaction, called a prompting interaction.

- The behavior in $U_{\text{new}}$ is different from the behavior in $U_{\text{prior}}$ but the same as the behavior in $U_{\text{other}}$ (e.g., in G2, Greta’s new prediction of slowing rate behavior in U6 is different from her previous prediction in U3, but the same as the behavior she learned in U4 and U5).

- The explanation in $U_{\text{new}}$ is in terms of a modification of an idea from her previous explanation of different behavior in $U_{\text{prior}}$ (e.g., in G2, an idea that was used to explain constant rate behavior in U3 is modified to explain a different behavior in U6).

- The explanation in $U_{\text{new}}$ is minimally similar to the explanation of the same behavior in $U_{\text{other}}$ (e.g., in G2, the explanation of slowing rate behavior in U6 is in terms of different ideas than the explanation of the same behavior in U4 and U5).

These relationships suggested that an idea from $U_{\text{prior}}$ is modified to explain a different behavior that is prompted by the behavior in $U_{\text{other}}$. This prompting is the source of the name for this kind of interaction.

The process data provide additional insight into the process by which a modification is prompted. Greta’s revision of her understanding of the heat context is not immediate. Just prior to her revision of prediction, Greta said,

Greta: This time, I actually think it’s a constant rate. /.../ [It goes the same pace the whole time] because of the particles being next to each other. They can heat each other up // Actually, hold on, I just contradicted myself and changed my mind …

This illustrates that on returning to consideration of the heat context after the gas and dye investigations, Greta at first reiterates her prediction of constant rate behavior in the heat context. She prefixes this prediction by saying “this time, I actually think.” This indicates that her reiteration of this prediction is made consciously to contrast with the slowing rate behavior that she knows happens in the gas and dye contexts. She then begins to explain this prediction in terms of an idea that the heating and cooling process happens at a constant rate because of the small distance between particles (the particles are “right next to each other”) before she says that she’s changed her mind. This indicates that Greta’s prompting interaction resulted from her explicit consideration of an idea from her explanation for her prediction of a different behavior, and that this consideration led Greta to realize a way that slowing rate behavior could happen instead: that the heating and cooling process could happen at a slowing rate if the distance
between particles increased. The prompting interaction and its relationship with other interactions identified in this dissertation will be considered in greater detail in Chapter 4.

3.3.3 Greta’s Third Interaction (G3): Example of Reinterpreting Interaction

Recall that following the gas and dye investigations, Greta revised her prediction of behavior in the heat context to slowing rate behavior and gave an explanation for why this behavior happens. As discussed above, Greta’s explanation for her new prediction of slowing rate behavior in the heat context (U6) was different from the explanations she gave for this behavior during the gas and dye investigations (U4 and U5). The interviewer now points out to Greta that her explanation for her new prediction of slowing rate behavior is different from the explanations she gave for this behavior in the gas and heat contexts, and asks Greta whether these other explanations for slowing rate behavior can help her explain why slowing rate behavior happens in the heat context. In response, Greta revises her explanation for why this behavior happens (U7). This section illustrates that this change in Greta’s understanding is the result of a context interaction in which \( U_{\text{prior}} \) is U6 and \( U_{\text{new}} \) is U7.

Greta’s new understanding establishes relationships both with her learned understandings of the gas and dye contexts and with the understanding of the heat context she expressed just prior. That Greta’s new understanding is similar to her learned understandings of the gas and dye contexts indicates that U4 and U5 are both \( U_{\text{other}} \) for this interaction. That Greta’s new understanding is also similar to the understanding of the heat context that she expressed just prior reinforces the identification of U6 as \( U_{\text{prior}} \).

The following sections identify the relationships established by Greta’s change in understanding during G3 that define characteristics of a particular kind of context interaction, called a **reinterpreting interaction**. In this kind of interaction, an idea from \( U_{\text{other}} \) is modified to explain continued prediction of the same behavior in \( U_{\text{new}} \).

**Previous understandings that are relevant to G3.**

This section introduces the previous understandings (i.e., U4, U5, U6) that are relevant to the new understanding of the heat context (U7) that results from G3. Following this introduction to relevant understandings, the relationships (both differences and similarities) that Greta’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Greta observed slowing rate behavior during the gas and dye investigations (U4 and U5). As discussed previously, her explanations for this behavior were both in terms of movement that happens more at first than it does later. She explained these different parts of the behavior in terms of an increasing “resistance” to movement that is due to the decreasing amount of remaining space (“there’s not as much space left”; “there’s not much room”).

Following the gas and dye investigations, Greta predicted slowing rate behavior in the heat context (U6). As discussed previously, her explanation for this behavior was in
terms of a process of physical interaction between the pieces of metal by which they are heated and cooled (they “heat up or cool down”) that happens more at first than it does later. She explained these different parts of behavior in terms of the increasing distance between the source and recipient of the heat: she explains that at first the particles that need to be heated are “right near the source,” but later the particles that remain to be heated are “at the very back”.

**Changed understanding of the heat context during G3.**

Following prediction of slowing rate behavior in the heat context (U6), Greta considers whether her explanations for this behavior in the gas and dye contexts (U4 and U5) can help her explain why slowing rate behavior happens in the heat context. In response, Greta revises her explanation for why this behavior happens (U7). She says,

\[G-U7\] Greta: There might be too much heat already on one of the particles, and it’s trying to pass it back, but it’s way too hot for it to receive any more. /…/ The front particles are really hot because they’re right next to the heat, and then it might try to resist it, but the heat might need to keep pushing back because there’s still particles that are still cold. /…/ [It changes less] because the resistance of the particles. They (the particles) might be trying to resist the heat, but the heat might try and keep forcing, which if there’s resistance and force at the same time, it’s not going to go very far.

Greta’s new explanation for slowing rate behavior in the heat context is in terms of a heating process (the heat is “passed” from particle to particle) that happens more at first than it does later. Greta’s explanation for this behavior is in terms of two different ideas about why this happens.

Greta explains this behavior in terms of an idea about the increasing distance between the source and recipient of heat: she explains that the front particles heat fast “because they’re right next to the source” but the “particles (at the back) that are still cold” heat more slowly.

Greta also explains this behavior in terms of an idea about increasing “resistance” to heating that is due to the particles approaching their capacity for heat: she explains that the temperatures change more at first because the particles are below their capacity for heat (there are “particles that are still cold”) and less later because the particles have reached this capacity (there is “too much heat already on one of the particles”; “it’s way too hot for it to receive any more”).

Greta’s new explanation for slowing rate behavior in the heat context (U7) is different from the explanation she gave for this behavior just prior (U6). In both explanations, Greta describes a heating process that happens more at first than it does later. While her previous explanation for this behavior was in terms of only an idea about the increasing distance between source and recipient of heat, Greta’s new explanation for this behavior is additionally in terms of an idea about increasing resistance to heating that is due to the particles approaching their capacity for heat.
As shown above, there is a clear change in Greta’s explanation of slowing rate behavior in the heat context during consideration of whether her explanations for the same behavior in the gas and dye contexts can help explain why slowing rate behavior happens in the heat context: she newly attributes the decreasing rate of change to a resistance to heating that increases as the particles approach their capacity for heat. The following section examines the similarities that this new understanding establishes with Greta’s previous understandings to gain insight into the origins of this change in Greta’s explanation.

**Similarities with previous understandings that are established by G3.**

Greta’s new understanding of the heat context establishes similarities with her previous understandings. This section illustrates these similarities between Greta’s new explanation of slowing rate behavior in the heat context, her previous explanation of the same behavior in the same context, and her learned explanations for slowing rate behavior in the gas and dye contexts (i.e., between U7 and U6, and between U7, U4, and U5).

Greta’s new explanation for slowing rate behavior in the heat context (U7) is *somewhat similar* to her previous explanation for this behavior in the same context (U6). As the previous section illustrated, although Greta’s explanation in U7 is in terms of an idea that was not used to explain U6, it is also in terms of an idea that these explanations share. In both U6 and U7, Greta explains the decreasing rate of the heating process in terms of an idea about the increasing distance between the source and recipient of heat (the particles that are “right near the source” heat fast, while the “particles (at the back) that are still cold” heat more slowly). These explanations are interpreted to be only *somewhat similar* because they share only some ideas.

Greta’s new explanation for slowing rate behavior (U7) is *in terms of a modification of an idea* from her explanations for the same behavior in the gas and dye contexts (U4 and U5). Like her explanations in U4 and U5, Greta’s explanation in U7 is in terms of an idea about resistance. However, while this idea was associated with the decreasing amount of remaining space in U4 and U5 (“there’s not as much space left”; “there’s not much room”), in U7, it is associated with how far the particles are from reaching their capacity for heat (there is “too much heat already on one of the particles”; “it’s way too hot for it to receive any more”).

As shown above, Greta’s new understanding of the heat context establishes similarities with her previous understandings: her new explanation for slowing rate behavior in the heat context is in terms of both an idea from her previous explanation for the same behavior in the same context, and a modification of an idea from her explanation for the same behavior in the other contexts. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

**Nature of the reinterpreting interaction in G3.**

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Greta’s third context interaction. These
relationships define the characteristics of a particular kind of interaction, called a *reinterpreting interaction*.

- The behavior in $U_{\text{new}}$ is the same as the behavior in $U_{\text{prior}}$ and the behavior in $U_{\text{other}}$ (e.g., in G3, the slowing rate behavior that Greta explains in U7 is the same behavior she predicted in U6 and learned in U4).
- The explanation in $U_{\text{new}}$ is somewhat similar to the explanation of the same behavior in $U_{\text{prior}}$ (e.g., in G3, the explanation of slowing rate behavior in U7 is in terms of ideas that were used to explain the same behavior in U6).
- The explanation in $U_{\text{new}}$ is in terms of a modification of an idea from her explanation in $U_{\text{other}}$ (e.g., in G3, an idea that was used to explain slowing rate behavior in U4 and U5 is modified to explain the same behavior in U7).

These relationships suggest that an idea from $U_{\text{other}}$ is *reinterpreted* to explain the same behavior in a different context ($U_{\text{new}}$). This reinterpreting is the source of the name for this kind of interaction. The reinterpreting interaction and its relationship with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

### 3.3.4 Summary of Greta’s Approach to Reasoning Across Contexts

All three of Greta’s context interactions reflect the strong influence of her learned understanding of slowing rate behavior: in G1, ideas from the learned explanation ($U_{\text{4}}$) supplement explanation of the same behavior in another context ($U_{\text{5}}$); in G2, the shared behavior learned in the other contexts ($U_{\text{4}}$ and $U_{\text{5}}$) prompts revision of understanding of another context ($U_{\text{6}}$); in G3, an idea from the learned explanation in other contexts ($U_{\text{4}}$ and $U_{\text{5}}$) is reinterpreted to support explanation of the same behavior in another context ($U_{\text{7}}$).

Greta’s three context interactions each establish a different set of relationships between her understandings. These sets of relationships define the interactions as different kinds of context interactions with particular characteristics. Greta’s three context interactions are called supplementing, prompting, and reinterpreting. These interactions and their relationships with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.
3.4 SANDRA’S APPROACH TO REASONING ACROSS CONTEXTS

Sandra’s three context interactions demonstrate an approach to reasoning across the gas, dye, and heat contexts that is strongly influenced by a sense that the dye context is different from the gas and heat contexts. These context interactions are illustrated schematically in Figure 18 as S1, S2, and S3. Note that the revisions that result during Sandra’s first interaction happen in two parts, labeled S1a and S1b, that will be considered separately.

During the comparison phase, Sandra is directed to compare her initial understandings of the gas, dye, and heat contexts. Sandra initially predicted slowing rate behavior in the gas and heat contexts and constant rate behavior in the dye context. During comparison, Sandra first revises her explanations for her prediction of slowing rate behavior in the gas and heat contexts; these revisions make up the first part of Sandra’s first interaction (S1a). Sandra then goes on to revise her explanation for her prediction of constant rate behavior in the dye context; this revision makes up the second part of Sandra’s first interaction (S1b). That Sandra’s revisions preserve the difference in her prediction and explanation in the dye context indicates that they reflect the influence of her sense that the dye context is different from the gas and heat contexts.

Sandra confirms her prediction of slowing rate behavior in the gas context through observation of a simulation during the gas investigation. In addition, through consideration of the suggested explanatory ideas Sandra learns a new explanation for why this behavior happens. Following the gas investigation, Sandra revises her explanation for her continued prediction of constant rate behavior in the dye context (S2). That Sandra’s revision preserves the difference in her prediction and explanation in the dye context indicates that they reflect the continued influence of her sense that the dye context is different from the gas and heat contexts.

During the dye investigation, Sandra learns that the dye context has slowing rate behavior instead of the constant rate behavior she predicted (S3). Prior to consideration of the explanatory ideas in the dye context, Sandra gives an explanation for why this behavior happens that is the same as her initial explanation for the same behavior in the gas and heat contexts. This indicates that Sandra has overcome her sense of the contexts’ difference.

The following numbered sections illustrate each of Sandra’s three context interactions. The relationships established by Sandra’s three context interactions are used to define the highlighting, reframing, and extending interactions, and to further elaborate the reframing interaction identified previously by H1.
Figure 18. Schematic of Sandra’s three context interactions. These context interactions are indicated with different colored arrows, numbered sequentially, and labeled with the first initial of Sandra’s name. Also indicated is each context interaction’s kind (highlighting and reframing, extending, and replacing). Additional details about the way in which participants’ understandings are represented in schematics like this are described in the caption of Figure 15.
3.4.1 Sandra’s First Interaction (S1a & S1b): Example of Highlighting and Reframing Interactions

Sandra initially predicted slowing rate behavior in the gas and heat contexts (U1 and U3, respectively) and constant rate behavior in the dye context (U2). Directing Sandra to compare her understandings of the different contexts does not affect her predictions of behavior. However, it does affect her explanations for her predictions: Sandra first gives a new shared explanation for her prediction of slowing rate behavior in the gas (U4a) and heat contexts (U4b), and then gives a new explanation for her prediction of the different constant rate behavior of the dye context (U4c). This section illustrates that these changes in Sandra’s explanations are the result of two distinct context interactions: S1a and S1b.

In S1a, Sandra simultaneously revises her explanations for her predictions of slowing rate behavior in the gas and heat contexts. Schematics of the simultaneous revisions that result from S1a are given in Figure 19. Because Sandra changes her understanding of two contexts simultaneously, in S1a U\textsubscript{prior} and U\textsubscript{new} are simultaneously U1 and U4a, respectively; and also U3 and U4b, respectively (i.e., where U\textsubscript{new} is U4a, U\textsubscript{prior} is U1; where U\textsubscript{new} is U4b, U\textsubscript{prior} is U3).

Sandra’s new understandings of the gas and heat contexts (U4a and U4b, respectively) establish relationships both with her initial understanding of the other context and with her previous understanding of the same context. That both Sandra’s new understandings are similar to her initial understanding of another context indicates that U1 and U3 are simultaneously U\textsubscript{other} (i.e., where U\textsubscript{new} is U4a, U\textsubscript{other} is U3; where U\textsubscript{new} is U4b, U\textsubscript{other} is U1) in S1a. That both Sandra’s new understandings are also similar to her initial understanding of the same context reinforces the identification of U1 and U3 as U\textsubscript{prior} in S1a.

In S1b, Sandra revises her explanation for her prediction of constant rate behavior in the dye context. A schematic of this revision is given in Figure 20. This revision indicates that in S1b, U\textsubscript{prior} is U2 and U\textsubscript{new} is U4c.
Figure 20. Schematic isolating Sandra’s revision of explanation in the dye context in S1b following her revision of explanations for the shared behavior of the gas and heat contexts. The full schematic for Sandra’s three interactions is given in Figure 18.

Sandra’s new understanding of the dye context (U4c) establishes relationships both with her revised understanding of the other contexts and with her previous understanding of the same context. That Sandra’s new understanding in the dye context is similar to her revised understandings of both the gas and heat contexts indicates that U4a and U4b are both U_other in S1b. That Sandra’s new understanding of the dye context is also similar to her previous understanding of the same context reinforces the identification of U2 as U_prior in S1b.

The following sections identify the relationships established by Sandra’s changes in understanding during S1a and S1b that define characteristics of distinct kinds of context interaction, called highlighting and reframing interactions. In the highlighting interaction, U_new is in terms of an abstraction of an idea that is shared by explanations of the shared behavior of U_prior and U_other. In the reframing interaction, U_new is in terms of an abstraction of an idea from the explanation in U_prior that corresponds with an idea from the explanation of the different behavior of U_other, where the term correspond is used here to indicate that, where only two behaviors are possible, one behavior is explained in terms of a feature that is the opposite of the feature used to explain the other behavior.

Previous understandings that are relevant to S1a & S1b.

This section introduces the understandings (i.e., U1, U2, and U3) that are relevant to the new understandings of the gas, dye, and heat contexts (U4a, U4b, and U4c, respectively) that result from S1a & S1b. The relationships (both differences and similarities) that Sandra’s new understandings establish with these previous understandings are discussed in subsequent sections.
Sandra initially predicted slowing rate behavior in the gas context (U1). In explanation of this prediction, Sandra said,

\[ S-U1 \]
Sandra: First they want to see what it is (on the other side of the container). To get some to the other side // Then once there’s some over there, it’s not a big rush, so they just go slower. /…/ [It rushes at first] because there’s too much empty space, so some particles go to the right.

Sandra’s explanation for her initial prediction of slowing rate behavior in the gas context was in terms of the decreasing difference between the amount of gas on each side of the container: she explains that the gas goes more at first because there is no gas on the right (“there’s too much empty space”) and that less gas goes later because the amount of gas on the right has increased (“there’s some over there”).

Sandra initially predicted constant rate behavior in the dye context (U2). In explanation of this prediction, Sandra said,

\[ S-U2 \]
Sandra: Because there’s the same amount of liquid in each side, so the same amount will go to the opposite side every second. /…/ Because it’s the same amount of dye and the same amount of water. /…/ Since it’s the same amount of water and the same amount of dye, they want to switch, and share.

Sandra’s explanation for her initial prediction of constant rate behavior in the dye context was in terms of the relative amount of liquid on each side of the container: she explains that the same amount of dye will go “every second” because the amount of liquid on each side is the same (there is “the same amount of liquid in each side”; “it’s the same amount of dye and the same amount of water”). Sandra also explains that because the amount of liquid is the same on each side, the dye and water have to “switch” and “share” to change sides (i.e., dye can’t be added to the water without a corresponding amount of water being added to the dye). This indicates that beyond having the same amount of liquid on each side, Sandra thinks of the two sides of the container as being both full.

Sandra initially predicted slowing rate behavior in the heat context (U3). In explanation of this prediction, Sandra said,

\[ S-U3 \]
Sandra: The hot wants to get to the cold side, because it’s cold, and so first it goes fast, and then it goes slow, because there’s already some on the cold side /…/ There’s no hot in the cold and no cold in the hot and they want to get even.

Sandra’s explanation for her initial prediction of slowing rate behavior in the heat context was in terms of the decreasing difference between the amount of hot on the cold side, and cold on the hot side: she explains that the hot and cold go more at first because at first “there’s no hot in the cold and no cold in the hot” and that less goes later because there is then “already some (hot) on the cold side.”
Changed understanding of the gas, dye, and heat contexts during S1a & S1b.

Directing Sandra to compare her initial understandings of the contexts results in her revision of her explanations for her predictions: Sandra first gives a new shared explanation for her predictions of slowing rate behavior of the gas (U4a) and heat contexts (U4b), and then gives a new explanation for her prediction of different constant rate behavior of the dye context (U4c). Sandra says,

\textit{S-U4} Sandra: I think it’s these two (gas and heat contexts), that the two things that are involved are kind of opposites. /…/ Like cold and hot, and then full and empty. And then this one (the dye context), they’re both liquids, [it’s] just that one has dye and one doesn’t.

Sandra first explains that slowing rate behavior happens in both the gas and heat contexts because the two sides are “opposites:” she explains that in the heat context the two sides are “cold and hot” and in the gas context they are “full and empty.” She then explains that constant rate behavior happens in the dye context because the two sides are the same: she explains that the substances on each side are “both liquids,” and dismisses the potential difference that “one has dye and one doesn’t” as insignificant.

This new explanation indicates a change in Sandra’s explanations of the gas, dye, and heat contexts, i.e., \(U_{\text{new}}\) is different from \(U_{\text{prior}}\). Recall that in S1a, where \(U_{\text{new}}\) is U4a, \(U_{\text{prior}}\) is U1. While Sandra previously explained that more gas goes at first in the gas context because there is no gas on the right (“there’s too much empty space”) (U1), she now explains this behavior by simply saying that the two sides are “opposites” (U4a). Recall that in S1a, where \(U_{\text{new}}\) is U4b, \(U_{\text{prior}}\) is U3. While Sandra previously explained that more hot goes at first because “there’s no hot in the cold” (U3), she now explains this behavior by simply saying that the two sides are “opposites” (U4b). In addition, her shared explanation for both contexts only addresses why less change happens later implicitly (because they become the same). These differences indicate that S1a results in a change in Sandra’s understanding of the gas and heat contexts: she now explains slowing rate behavior in these contexts by addressing only why more change happens at first, and explains that this part of the behavior in terms of an abstraction of her previous explanation (full and empty are simply opposites; cold and hot are simply opposites).

Recall that in S1b, \(U_{\text{prior}}\) is U2 and \(U_{\text{new}}\) is U4c. While Sandra previously explained that the same amount of dye will go “every second” because the amount of liquid on each side is the same (there is “the same amount of liquid in each side”) (U2), she now explains this behavior by simply indicating that the two sides are the same (“they’re both liquids, [it’s] just that one has dye and one doesn’t”) (U4c). She no longer mentions the significance of the sides having the same amount (i.e., their both being full). This difference indicates that S1b results in a change in Sandra’s understanding of the dye context: she now explains that the same amount of dye goes every second in terms of an abstraction of her previous explanation (the same amount is simply the same).

The following section examines the similarities that these new understandings establish with Sandra’s previous understandings to gain insight into the origins of these changes in Sandra’s understandings.
Similarities with previous understandings that are established by S1a & S1b.

Sandra’s new understandings of the gas, dye, and heat contexts establish similarities with her previous understandings. This section illustrates these similarities. In S1a, \( U_{\text{new}} \) is in terms of an abstraction of an idea that is shared by the explanations of slowing rate behavior in \( U_{\text{prior}} \) and \( U_{\text{other}} \).\(^{23}\) Therefore the explanation shared by U4a and U4b is in terms of an abstracted idea that is shared by the explanations in U1 and U3. As the previous section illustrated, the explanation shared by U4a and U4b is in terms of an idea that slowing rate behavior happens because the two sides are “opposites.” The previous section also illustrated that this idea is an abstraction of ideas from U1 (that more gas goes at first because there is no gas on the right) and U3 (that more hot goes at first because there no hot in the cold).

In S1b, \( U_{\text{new}} \) is in terms of an abstraction of an idea from the explanation for constant rate behavior in \( U_{\text{prior}} \) that corresponds with an idea from the explanation for slowing rate behavior in \( U_{\text{other}} \).\(^{24}\) Therefore the explanation in U4c is in terms of an abstracted idea that corresponds with an idea from the explanation that is shared by U4a and U4b. As the previous section illustrated, the explanation in U4c is in terms of an idea that constant rate behavior happens because the two sides are the same. This idea corresponds with the idea that slowing rate behavior happens because the two sides are opposite that is shared by the explanations in U4a and U4b.

As shown above, Sandra’s new understandings establish similarities with her previous understandings: her new explanations of the predicted behavior are in terms of abstractions of ideas that were used in previous explanations. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by S1a and S1b. These relationships will be examined in the following section to gain insight into the nature of the underlying interactions.

Nature of the highlighting and reframing interactions in S1a & S1b.

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by the two parts of Hanna’s first context interaction: S1a and S1b.

The relationships established by S1a define the characteristics of a particular kind of interaction, called a highlighting interaction.

- The behavior in \( U_{\text{new}} \) is the same as the behavior in both \( U_{\text{prior}} \) and \( U_{\text{other}} \) (e.g., in S1a, the slowing rate behavior that Sandra explains in U4a and U4b is the same as the behavior she predicted in U1 and U3).

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\(^{23}\) Recall that in S1a, where \( U_{\text{new}} \) is U4a, \( U_{\text{prior}} \) is U1, and \( U_{\text{other}} \) is U3 and where \( U_{\text{new}} \) is U4b, \( U_{\text{prior}} \) is U3, and \( U_{\text{other}} \) is U1.

\(^{24}\) Recall that in S1b, \( U_{\text{new}} \) is U4c, \( U_{\text{prior}} \) is U2, and \( U_{\text{other}} \) is both U4a and U4b.
The explanation in $U_{\text{new}}$ is in terms of an abstraction of an idea that is shared by the explanations of the same behavior of $U_{\text{prior}}$ and $U_{\text{other}}$ (e.g., in S1a, the explanation shared by U4a and U4b is in terms of an abstracted idea that is shared by the explanations in U1 and U3).

These relationships suggest that an idea from the explanation in $U_{\text{prior}}$ that is shared with the explanation in $U_{\text{other}}$ is highlighted. This highlighting is the source of the name for this kind of interaction.

The relationships established by S1b define the characteristics of a distinct kind of interaction, called a reframing interaction.

- The behavior in $U_{\text{new}}$ is the same as the behavior in $U_{\text{prior}}$ but different from the behavior in $U_{\text{other}}$ (e.g., in S1b, the constant rate behavior that Sandra explains in U4c is the same as the behavior she predicted in U2, but different from the behavior she explained in U4a and U4b).

- The explanation in $U_{\text{new}}$ is in terms of an abstraction of an idea from the explanation in $U_{\text{prior}}$ that corresponds with an idea from the explanation for the different behavior of $U_{\text{other}}$ (e.g., in S1b, the explanation in U4c is in terms of an abstracted idea from U2 that corresponds with an idea from the explanation that is shared by U4a and U4b).

These relationships suggest that an idea in $U_{\text{prior}}$ is reframed by the explanation of different behavior in $U_{\text{other}}$. This reframing is the source of the name for this kind of interaction. The highlighting and reframing interactions and their relationships with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

3.4.2 Sandra’s Second Interaction (S2): Example of Extending Interaction

Sandra previously predicted constant rate behavior in the dye context (U4c), but slowing rate behavior in the gas and heat contexts (U4a and U4b, respectively). After confirming her prediction of slowing rate behavior in the gas context during the gas investigation (U5), Sandra is directed to reconsider her understanding of the dye context. Although this has no affect on her prediction of behavior in the dye context, it does affect her explanation for her continued prediction of constant rate behavior in the dye context (U6). This section illustrates that this change in Sandra’s understanding is the result of a context interaction. That this change in understanding is between U4c and U6 identifies both U2 and U4c as $U_{\text{prior}}$ and U6 as $U_{\text{new}}$.

Sandra’s new understanding (U6) establishes relationships with her learned understanding of the gas context (U5) and with her previous understanding of the same behavior in the dye context (U2 and U4c). Sandra’s new explanation for her prediction of constant rate behavior in the dye context (U6) is similar to her learned understanding of slowing rate behavior in the gas context (U5). This indicates that U5 is $U_{\text{other}}$ for this interaction. Sandra’s new explanation for her prediction of constant rate behavior in the
dye context (U6) is also similar to her previous explanations for this behavior in the same context (U2 and U4c). This reinforces the identification of both U2 and U4c as U\textsubscript{prior}.

The following sections identify the relationships established by Sandra’s change in understanding during S2 that define characteristics of a particular kind of context interaction, called an extending interaction. In this kind of interaction, an idea from U\textsubscript{other} is modified to explain continued prediction of different behavior in U\textsubscript{new}.

**Previous understandings that are relevant to S2.**

This section introduces the previous understandings (i.e., U2, U4c, and U5) that are relevant to the new understanding of the dye context (U6) that results from S2. The relationships (both differences and similarities) that Sandra’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Recall that Sandra predicts constant rate behavior during the prediction phase (U2) and revises her explanation for this behavior during the comparison phase (U4c). As discussed previously, Sandra explained that the same amount of dye will go “every second” because the two sides are filled up with the same amount of liquid (there is “the same amount of liquid in each side”) and so the dye and water have to “switch” and “share.”

Sandra confirmed her prediction of slowing rate behavior in the gas context during the gas investigation by observing a simulation of the gas context. Greta gave a new explanation for this behavior following consideration of the suggested explanatory ideas. She said,

**S-U5** Sandra: If you take the barrier out, there’s more space // they have more freedom to go to the right side. So they can go to the right side, and they want to get it equal because there’s more space. /…/ At first, the molecules have more space to move around, but then as the molecules on the left go to the right, there’s less and less space so it goes slower and slower.

Sandra’s new explanation for slowing rate behavior in the gas context was in terms of the increasing resistance to the movement of the gas: she explained that the gas goes more at first because there is a lot of empty space (there is “more space to move around”) and that less goes later because the amount of empty space decreases (“there’s less and less space”).

**Changed understanding of the dye context during S2.**

Following confirmation of her prediction of slowing rate behavior in the gas context (U5), Sandra is directed to reconsider her understanding of the dye context (U2 and U4c). In response, Sandra gives a new explanation for why constant rate behavior happens in the dye context (U6). Sandra says,

**S-U6** Sandra: Because in the gas one, there’s nothing on the other side, so there’s nothing to stop it or keep it in control. And in this one (the dye context), they’re both liquids. It’s just that one has a different color
than the other one, so they both stop each other, so they’re both
going at a constant rate.

Sandra’s new explanation for constant rate behavior in the dye context is in terms of a mutual resistance to movement between the dye and water (“they both stop each other”) that happens because both sides are filled up with liquids.

Sandra’s new explanation for constant rate behavior in the dye context (U6) is different from her previous explanations (U2 and U4c). In both explanations Sandra describes that the behavior happens because the two sides are filled up with liquids. However, Sandra now attributes to this property a different physical interaction between the dye and water than she did previously. While Sandra previously explained that because the sides were full, the dye and water would have to “switch” and “share” (U2), she now explains that this results instead in the dye and water resisting one another’s movement (“they both stop each other”) (U6). This indicates that Sandra’s explanation for constant rate behavior in the dye context has changed. The following section examines the similarities that this new understanding establishes with Sandra’s previous understandings to gain insight into the origins of this change in Sandra’s explanation.

**Similarities with previous understandings that are established by S2.**

Sandra’s new explanation for her prediction of constant rate behavior in the dye context establishes similarities with her previous understandings. This section illustrates these similarities between Sandra’s new explanation for constant rate behavior in the dye context, her previous explanations of the same behavior in the dye context, and her learned explanation for slowing rate behavior in the gas context (i.e., between U6, U2, and U4c, and between U6 and U5).

Sandra’s new explanation for constant rate behavior in the dye context (U6) is minimally similar to her previous explanations for this behavior in the dye context (U2 and U4c). As the previous section illustrated, Sandra describes in both explanations that both sides of the dye context are filled up with liquid. However the physical interaction that Sandra attributes to this property in her new explanation (that they will “stop each other”) to explain the predicted behavior is different from the one she attributes in her previous explanation (that they have to “switch” and “share”). These explanations for constant rate behavior are interpreted to be minimally similar because they are in terms of such different physical interactions.

Sandra’s new explanation for constant rate behavior in the dye context (U6) is also in terms of a modification of an idea from her learned explanation of slowing rate behavior in the gas context (U5). Like her explanation for slowing rate behavior in the gas context, Sandra’s new explanation for constant rate behavior in the dye context is in terms of an idea about resistance. However, in her new explanation, this idea about resistance is newly associated with a container in which both sides are full, instead of with a container in which one of the sides is empty. Prior to giving her new explanation in the dye context (G-U6), Greta says that in the gas context “there’s nothing on the other side, so there’s nothing to stop it or keep it in control,” in contrast with the dye context where “they’re both liquids /…/ so they both stop each other.” This explanation is interpreted to be in terms of a modification of an idea because of this new association.
As shown above, Sandra’s new understanding of the dye context establishes similarities with her previous understandings: although she continues to predict different (constant rate) behavior in the dye context than she learned (slowing rate behavior) in the gas context, her explanation for this behavior is now in terms of a modification of an idea from her explanation for that learned behavior. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by Sandra’s second context interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying interaction.

**Nature of the extending interaction in S2.**

This section summarizes the relationships (both differences and similarities) between understandings that are established by Sandra’s second context interaction. These relationships define the characteristics of a particular kind of interaction, called an extending interaction.

- The behavior in \( U_{\text{new}} \) is the same as the behavior in \( U_{\text{prior}} \) but different from the behavior in \( U_{\text{other}} \) (e.g., in S2, the constant rate behavior that Sandra explains in U6 is the same as the behavior she predicted in U2 and U4c, but different from the behavior she learned in U5).
- The explanation in \( U_{\text{new}} \) is minimally similar to the explanation of the same behavior in \( U_{\text{prior}} \) (e.g., in S2, the explanation in U6 is in terms of a different idea than the explanation in U2).
- The explanation in \( U_{\text{new}} \) is in terms of a modification of an idea from the explanation of the different behavior of \( U_{\text{other}} \) (e.g., in S2, an idea that was used to explain the learned slowing rate behavior of U5 is modified to explain the different behavior of U6).

These relationships suggest that an idea from \( U_{\text{other}} \) is extended to explain the different behavior of \( U_{\text{new}} \). This extending is the source of the name for this kind of interaction. The extending interaction and its relationship with other context interactions will be considered in greater detail in Chapter 4.

### 3.4.3 Sandra’s Third Interaction (S3): Example of Replacing Interaction

During the dye investigation, Sandra learns that the dye context has slowing rate behavior (U7) instead of the constant rate behavior she predicted previously (U2, U4c, and U6). Prior to consideration of the explanatory ideas, Sandra gives an explanation for why this behavior happens (U7). This section illustrates that this change in Sandra’s understanding is the result of a context interaction in which \( U_{\text{prior}} \) is U2, U4c, and U6, and \( U_{\text{new}} \) is U7.

The slowing rate behavior that Sandra learns in the dye context is the same as the behavior she initially predicted in the gas and heat context. Sandra’s new understanding of the dye context establishes relationships both with these initial understandings of the
gas and heat contexts and with her previous understandings of the dye context. That Sandra’s new understanding is similar to her initial understandings of the gas and heat contexts indicate that U1, U3, U4a, U4b, and U5 are $U_{\text{other}}$ for this interaction.

The following sections identify the relationships established by Sandra’s change in understanding during S3. These relationships are shown to be the same as those identified by H1 in Section 3.2.1, indicating that S3 is an additional example of the replacing interaction.

**Previous understandings that are relevant to S3.**

This section introduces the understandings (i.e., U1, U2, U4a, b, and c, U5, U6, and U7) that are relevant to the new understanding of the dye context (U7) that results from S3. The relationships (both differences and similarities) that Sandra’s new understanding establishes with these previous understandings are discussed in subsequent sections.

Recall that Sandra initially predicted slowing rate behavior in the gas context (U1). As discussed previously, Sandra explained this prediction in terms of the decreasing difference in the amount of gas on each side of the container. Although she revised this explanation twice (U4a and U5), each revision was similarly in terms of this idea.

Recall that Sandra initially predicted constant rate behavior in the dye context (U2). As discussed previously, Sandra explained this prediction in terms of the amount of liquid on each side of the container being the same. Although she revised this explanation twice (U4c and U6), each revision was similarly in terms of this idea.

Recall that Sandra initially predicted slowing rate behavior in the heat context (U3). As discussed previously, Sandra explained this prediction in terms of the decreasing difference in the amount of hot on the cold side and the amount of cold on the hot side. Sandra revised this explanation only once prior to the dye investigation (U4b) and this revision was also in terms of this idea.

**Changed understanding of the dye context during S3.**

After observing slowing rate behavior in the dye context instead of the constant rate behavior she predicted, Sandra gives an explanation for why this behavior happens (U7). This explanation is given before she considers the suggested explanatory ideas. She says,

\[ S-U7 \quad \text{Sandra: They (the dye and water) will go // Because the colors want to mix and because they’re different, they will go fast at first, then slow // at a slowing rate. /.../ Because there’s already some // they’re already almost equal, so it has no rush to make it all the way equal.} \]

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25 Recall that if the explanation were given following consideration of the explanatory ideas, it would be unclear whether it was derived from those ideas or from her previous understandings.
Sandra’s explanation for the learned behavior of slowing rate behavior in the dye context is in terms of the decreasing difference between the color of each side of the container: she explains that the dye and water go more at first because “they’re different” and that less goes later because “they’re already almost equal.”

This new understanding of the dye context is different from her previous understandings (U2, U4c, and U6). While Sandra’s previous explanations were for prediction of constant rate behavior, this new explanation is instead for the learned slowing rate behavior. Sandra explains both behaviors in terms of the movement of dye and water. However, while her explanations for her predictions of constant rate behavior were in terms of an idea about the liquids on each side of the container being the same, her explanation for the learned slowing rate behavior of the dye context is in terms of their difference.

As shown above, there is a clear change in Sandra’s understanding of the dye context during the dye investigation: she explains the different learned behavior in terms of a different relationship between the liquids on each side of the container. The following section examines the similarities that this new understanding establishes with Sandra’s previous understandings to gain insight into the origins of this change in Sandra’s understanding.

_Similarities with previous understandings that are established by S3._

Sandra’s new understanding of the dye context establishes similarities with her previous understandings. This section illustrates these similarities between Sandra’s new explanation of slowing rate behavior in the dye context, her previous explanations of different behavior in the dye context, and her previous explanations of the same behavior in the gas and heat contexts (i.e., between U7 and U2, U4c, and U6; between U7 and U1, U4a, and U5; and between U7 and U3 and U4b).

Sandra’s explanation for the observed slowing rate behavior of the dye context (U7) is _minimally similar_ to her explanations for her previous prediction of constant rate behavior in the dye context (U2, U4c, and U6). As the previous section illustrated, Sandra’s explanation for slowing rate behavior is only similar to her previous explanations for constant rate behavior in that they are in terms of the relationship between the liquids filling each side of the container. It is for this reason that the explanations are interpreted to be _minimally similar._

However, Sandra’s explanation for slowing rate behavior in the dye context (U7) is _very similar_ to her explanations for slowing rate behavior in the gas and heat contexts (U1, U4a, and U5; and U3 and U4b). Like her explanations for slowing rate behavior in these contexts, Sandra’s new explanation for this behavior in the dye context is in terms of the decreasing difference between the contexts’ sides: she describes this difference in terms of a difference in the amount of gas on each side of the gas context, a difference in the amount of hot and cold in each side of the heat context, and a difference in the colors of each side of the dye context. These explanations are interpreted to be very similar because they are in terms of this same idea.

As shown above, Sandra’s new understanding of the dye context establishes similarities with her previous understandings: she explains the same slowing rate
behavior she predicted in the gas and heat contexts, and her explanation for this behavior is in terms of an idea that she used to explain slowing rate behavior in these other contexts. Together with the differences discussed in the previous section, these similarities comprise the relationships between understandings established by Sandra’s third interaction. These relationships will be examined in the following section to gain insight into the nature of the underlying context interaction.

**Nature of the replacing interaction in S3.**

This section summarizes the set of relationships (both differences and similarities) between understandings that are established by Sandra’s third context interaction. These relationships are the same as those identified by H1 to define the replacing interaction.

- The behavior in $U_{\text{new}}$ is different from the behavior in $U_{\text{prior}}$ but the same as the behavior in $U_{\text{other}}$ (e.g., in S3, the slowing rate behavior that Sandra explains in U7 is different from the behavior she explained in U6, but the same behavior she learned in U5 and predicted in U3).

- The explanation in $U_{\text{new}}$ is minimally similar to the explanation of the different behavior $U_{\text{prior}}$ (e.g., in S3, the explanation of slowing rate behavior in U7 is in terms of different ideas than Sandra’s previous explanation of constant rate behavior in U6).

- The explanation in $U_{\text{new}}$ is very similar to the explanation of the same behavior in $U_{\text{other}}$ (e.g., in S3, the explanation of slowing rate behavior in U7 is in terms of the same ideas used to explain the same behavior in U1 and U3).

However, unlike in H1, in S3 the similarity between the behavior in $U_{\text{new}}$ and $U_{\text{other}}$ is established by observation of the behavior during an investigation. This suggests that this similarity could instigate the replacement of the explanation in $U_{\text{prior}}$ with the explanation in $U_{\text{other}}$.

The process data provide additional insight into the process by which a replacement is instigated. Sandra’s revision of her explanation in the dye context is not immediate. Following observation of slowing rate behavior in the dye context, Sandra said,

Sandra: Maybe [slowing rate behavior happens] because it’s the same thing (on each side). It’s so similar that it wants // No, maybe it (the colors) is different so it wants to get similar.

This illustrates that Sandra at first tries to explain her observation of slowing rate behavior of the dye context with an idea from her previous explanation for constant rate behavior (that the same amount goes every second because the context’s sides are the same). That she then stops and gives the same explanation she gave previously for slowing rate behavior in the gas and heat contexts (that more goes at first than it does later because the context’s sides are different) indicates that Sandra’s replacing interaction resulted from her realization that the idea from her previous explanation of different behavior in the dye context cannot explain the observed behavior, and that ideas from explanations of the same behavior could be more productive. The replacing
interaction and its relationship with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

3.4.4 Summary of Sandra’s Approach to Reasoning Across Contexts

Sandra’s first two context interactions result in changes in understanding that preserve the different behavior of the dye context. This indicates that these two context interactions are strongly influenced by a sense that the contexts are different from one another. Sandra’s third context interaction results in a change in explanation after learning that a different behavior happens in the dye context. That Sandra’s new understanding is the same as her initial understandings of the gas and heat contexts indicates that Sandra overcomes her sense of the contexts’ difference during her third interaction.

Sandra’s three context interactions each establish different sets of relationships between her understandings. Recall that Sandra’s first context interaction happened in two parts that established two distinct sets of relationships between understandings. Sandra’s second and third context interactions established an additional two sets of relationships between understandings. These four sets of relationships define four different kinds of context interactions with particular characteristics. Sandra’s four context interactions are called highlighting, reframing, extending, and replacing. The fourth kind of context interaction, the replacing interaction, was also identified by Hanna’s first context interaction. Sandra’s three context interactions will therefore be considered to identify only three new kinds of interaction: the highlighting, reframing, and extending interactions. These context interactions and their relationships with other context interactions identified in this dissertation will be considered in greater detail in Chapter 4.

3.5 SUMMARY

This chapter examined a selection of context interactions identified in the transcript of three of the participants interviewed for this dissertation. In addition to illustrating the analytical method employed in this dissertation, this chapter presents three different overall approaches to reasoning across contexts, and nine different kinds of context interaction.

The three participants discussed in this chapter exhibited three different overall approaches to reasoning across contexts: Hanna’s context interactions reflect her sense that the gas, dye, and heat contexts are similar to one another; Greta’s context interactions reflect the influence of her learned understanding of slowing rate behavior; and Sandra’s context interactions reflect her sense that the dye context is different from the gas and heat contexts.
The nine different kinds of context interaction discussed in this chapter were called replacing, cueing, guiding, supplementing, prompting, reinterpreting, highlighting, reframing, and extending interactions. The analysis in this chapter demonstrated that each kind of context interaction establishes a different set of relationships between understandings. These sets of relationships were used to define the characteristics of each kind of context interaction. The nine kinds of context interaction will be considered in greater detail in Chapter 4.
4.1 INTRODUCTION

This chapter presents a comparative analysis of the kinds of interaction introduced in the previous chapter. Recall that the new understanding that results from an interaction establishes relationships with previous understandings. This chapter examines the interactions in three groups that are defined by the kinds of relationships they establish:

- **Combining interactions**: result in a new understanding that is in terms of an idea that is the same as an idea used in a previous explanation.
- **Modifying interactions**: result in a new understanding that is in terms of a modification of an idea used in a previous explanation.
- **Refocusing interactions**: result in a new understanding that is in terms of an abstraction of an idea used in a previous explanation.

Comparison of the interactions in each group provides insight into the way in which the kinds of relationships are established. Each group will additionally be compared with analogical transfer.

4.2 COMBINING INTERACTIONS

4.2.1 Relationship Between Replacing, Supplementing, and Cueing Interactions

This section will discuss the relationship between the replacing, supplementing, and cueing interactions. These interactions will be called *combining interactions* because they combine ideas from the participant’s previous understanding of one context with ideas from her understanding of another context in different proportions. This combination can be thought of in terms of the following qualitative equation:

\[ U_{\text{new}} = a U_{\text{prior}} + b U_{\text{other}}, \]

where the lowercase letters \( a \) and \( b \) are weights on the participant’s previous understanding of the context and on her understanding of another context, respectively.
With combining interactions, the ideas that comprise the participant’s new explanation of the context are not new to the participant. They were present in either the participant’s previous understanding of the same context or in the participant’s understanding of another context. As a result, the weights on these understandings can be thought of as having fractional values that add to one.

The expression of an idea in different contexts cannot be literally the same, because the idea must be associated with features of the contexts in which it is expressed. However, in combining interactions, the features with which the ideas are associated in the different contexts are equivalent, i.e., the association preserves as much as possible about the original feature while accounting for the difference in context. For example, consider a participant whose new understanding of the dye context is in terms of an idea about resistance that she expressed in the gas context. She associates the resistance idea with the perceived empty space on the right side of the gas context and with the perceived remaining space for additional dye on the right side of the dye context. These spaces are equivalent. This example of combining was taken from the example of the supplementing interaction introduced in Chapter 3 and will be discussed in more detail below.

The values for the weights on the participant’s previous understanding of a context and her understanding of another context indicate the participant’s relative preference for reasoning from her previous understanding of the context and her understanding of another context. Such a preference may be based on the participant’s perceived “authority” of one of these understandings. The participant’s previous understanding of a context could be lent authority by its origins in the participant’s previous understanding of the nature and physical interaction of the substances filling the context (e.g., the participant may have a relative preference for reasoning in the dye context from her previous understanding of that context, because it is consistent with her prior knowledge and experience with the nature of liquids and their interactions). In contrast, the participant’s understanding of another context may be lent authority by its similarity with her understanding of still another context (e.g., the participant may have a relative preference for reasoning in the dye context from her understanding of the gas context, because it is additionally similar to her understanding of the heat context), or its origins in suggested explanatory ideas during the investigation of that context (e.g., the participant may have a relative preference for reasoning in the dye context from her understanding of the gas context, because that understanding is derived from the explanatory ideas suggested to her by the interviewer).

The participant’s preference may instead be based in her perception of the difficulty of reasoning from one of these understandings. The participant may perceive it to be difficult to derive an explanation from her understanding of another context (e.g., the participant may have a relative preference for reasoning in the dye context from her previous understanding of that context, because she may find it to be difficult to reason from her understanding of another context). In contrast, the participant may perceive it to be difficult to derive an explanation for an unpredicted behavior from her previous understanding of the nature and physical interaction of the substance filling the context (e.g., the participant may have a relative preference for reasoning in the dye context from her understanding of the gas context, because she finds it to be difficult to explain why
that behavior happens from her prior knowledge and experience with the nature of liquids and their interactions).

In the replacing interaction, the weight on her previous understanding of the context is zero ($a = 0$) while in the cueing interaction the weight on her understanding of the other context is zero ($b = 0$). This indicates that the participant chooses between reasoning from her previous understanding of the context and reasoning instead from her understanding of another context. In the supplementing interaction, both weights have nonzero values. This indicates that the participant has a preference for ideas from both her previous understanding of the context and her understanding of another context. The examples of these interactions introduced in Chapter 3 will be discussed below to illustrate this relationship.

Examples of Replacing Interaction

Both Hanna’s first interaction (H1; described in Section 3.2.1) and Sandra’s third interaction (S3; described in Section 3.4.3) are examples of a replacing interaction. In both examples, the participant’s new explanation ($E_{new}$) is in terms only of ideas that are used to explain the same behavior in another context ($E_{other}$). The participant’s previous explanation in the same context ($E_{prior}$) does not contribute to her new explanation ($E_{new}$).

In H1, Hanna revises her prediction of behavior from slowing to constant rate behavior during comparison. This revised prediction of constant rate behavior in the dye is the same as her predictions of constant rate behavior in both the gas and heat contexts (i.e., $B_{new}$ and $B_{other}$ are the same). In addition, her explanation for this behavior ($E_{new}$) is in terms of an idea that she used to explain the behavior in the gas and heat contexts ($E_{other}$). She explains this behavior in all three contexts in terms of a process (spreading, combining, or mixing) that happens in the same way “every second.” The identified process in each context is equivalent.

The ideas used to explain her previous prediction of slowing rate behavior do not contribute to this explanation of her new prediction of constant rate behavior in the dye context (i.e., $a = 0$). This indicates that Hanna chooses her shared understanding of the other contexts over her previous understanding of the same context. This choice may reflect the authority that is lent to this understanding by being shared by both the gas and heat contexts.

In S3, Sandra observes slowing rate behavior in the dye context instead of the constant rate behavior she predicted. The slowing rate behavior that Sandra observes in the dye context is the same as the behavior she observed in the gas context (i.e., $B_{new}$ and $B_{other}$ are the same). In addition, her explanation for this behavior ($E_{new}$) is in terms of an idea that she used to explain the behavior in the gas and heat contexts ($E_{other}$). She explains this behavior in all three contexts by saying that the substance (gas, dye, or heat) goes more at first because of an initial difference between the sides and less later because the difference decreases. The identified difference in each context is equivalent.

The ideas used to explain her prediction of constant rate behavior do not contribute to this explanation of the observed slowing rate behavior of the dye context (i.e., $a = 0$). This indicates that Sandra chooses her shared understanding of the other contexts over her previous understanding of the same context. This choice may reflect
both a perceived difficulty of deriving an understanding for the observed slowing rate
behavior from her prior knowledge of the nature and physical interaction of dye, and the
authority that is lent to this understanding by being shared by both the gas and heat
contexts.

In both H1 and S3, the participant’s new understanding of the behavior of the dye
context is comprised entirely of ideas from her understanding of the behavior of other
contexts; her previous understanding of the dye context does not contribute. These ideas
are associated with equivalent features of the new context.

Example of Supplementing Interaction

Greta’s first interaction (G1; described in Section 3.3.1) is an example of a supplementing
interaction. Prior to the gas investigation, Greta predicted slowing rate behavior in the
dye context. During the dye investigation, Greta confirms that the dye context has the
same slowing rate behavior that she observed in the gas context during the gas
investigation (i.e., B_p, B_o, and B_n are the same). Although Greta’s understanding
of the behavior does not change, her explanation for why this behavior happens does: On
observing slowing rate behavior in the dye context, Greta revises her explanation for why
this behavior happens. Greta’s new explanation for slowing rate behavior in the dye
context (E_n) is comprised of both ideas from her previous explanation of this behavior
in the same context (E_p), and ideas from her learned understanding of this behavior in
the gas context (E_o).

Greta’s new explanation for slowing rate behavior (E_n) explains that more
change happens at first because the dye has a sense of urgency: “there’s a lot of dye, so
it’s looking for somewhere else to go.” She used this idea to explain the behavior in the
gas context (E_o): “it’s open space and it (the gas) needs somewhere to go.” The
available space identified in the dye context is equivalent to the empty space in the gas
context. Greta’s new explanation for slowing rate behavior (E_n) explains that less
change happens later because there isn’t much dye left (“there’s not that much left”) and
because the remaining dye is resisted (“it resists the other dye”). She used the first of
these ideas previously to explain the behavior in the dye context (E_p): “it’ll leave a
little left so then /.../ it’s going to go a little.” The identified amount of remaining dye is
equivalent to that identified previously in the same context. She used the second of these
ideas to explain the behavior in the gas context (E_o): “there’s resistance /.../ [because]
there’s not as much room.” The remaining space in the dye context is equivalent to that
identified in the gas context.

Both ideas from Greta’s previous explanation in the dye context (E_p) and ideas
from her explanation in the gas context (E_o) contribute to her new explanation of the
observed slowing rate behavior in the dye context (E_n). This indicates that Greta has a
preference for both her previous understanding of the context and her understanding of
another context (i.e., a and b are nonzero). Greta’s preference for her previous
understanding of the dye context may reflect authority that is lent to an understanding
that originates from prior knowledge of the nature and physical interaction of dye.
Greta’s preference for ideas from her understanding of the gas context may reflect the
authority that is lent by their having been learned during the gas investigation.
**Example of Cueing Interaction**

Hanna’s second interaction (H2; described in Section 3.2.2) is an example of a cueing interaction. Hanna initially predicted slowing rate behavior in the dye context, but changed her prediction during the comparison phase. Following the gas investigation, she changes her prediction again back to slowing rate behavior. For the purposes of this discussion, Hanna’s previous understanding of slowing rate behavior (not her intermediate understanding of constant rate behavior) in the dye context will be called $U_{prior}$. The slowing rate behavior Hanna again predicts in the dye context is the same behavior she observed in the gas context (i.e., $B_{prior}$, $B_{other}$, and $B_{new}$ are the same).

Hanna’s new explanation for slowing rate behavior in the dye context ($E_{new}$) is in terms only of ideas she used previously to explain the same behavior in the same context ($E_{prior}$). At both times, Hanna explains slowing rate behavior by saying that the dye goes more at first because the dye and water collide (“go at each other”; “smash at each other”), and less later because the dye and water have already changed a lot (“a lot combined already”; “there’s not much left to mix”). Both the identified physical interaction and the identified amount remaining are equivalent to those identified previously. That Hanna’s new understanding is given after observing the same behavior in the gas context indicates that this observation likely cues her recall of her previous understanding.

Hanna’s explanation of the observed slowing rate behavior in the gas context ($E_{other}$) does not contribute to her explanation for her new prediction in the dye context ($E_{new}$) (i.e., $b = 0$). This indicates that Hanna chooses her previous understanding of the dye context over her understanding of another context. This choice may reflect both a perceived difficulty of deriving an understanding for the dye context from her understanding of the gas context (that overcomes the authority otherwise expected to be lent to ideas learned during an investigation), and the authority that is lent to an understanding that originates from prior knowledge of the nature and physical interaction of dye.

**Summary of Examples of Combining Interactions**

As these examples illustrate, the replacing, supplementing, and cueing interactions indicate a spectrum of combinations of a participant’s previous understanding with her understanding of another context. The ideas that comprise the participant’s new understanding are from either the participant’s previous understanding of the same context, or from her understanding of another context. These ideas are associated with equivalent features in the new explanation. In the replacing interaction, only the participant’s understanding of another context contributes to her new understanding; in the cueing interaction, only the participant’s previous understanding contributes to her new understanding; and in the supplementing interaction, both the participant’s previous understanding and understanding of another context contribute to her new understanding.
4.2.2 Relationship of Combining Interactions with Analogical Transfer

Combining interactions result in a new understanding of a context that is comprised, in different proportions, of ideas from the participants’ previous understanding of the same context, and ideas from her understanding of another context. This section will discuss the relationship between such interactions and analogical transfer. The first part of the discussion will address the relationship between the results of analogical transfer and the results of the three combining interactions. The second part will discuss the relationship between the reasoning processes underlying these results.

Relationship Between Results of Interactions

Analogical transfer describes an interaction that has a particular result: an understanding of a context that is comprised only of ideas from her understanding of another context. Of the combining interactions, the replacing interaction is most like analogical transfer. In the replacing interaction, the participant’s previous understanding of the context does not reflect a role in her new understanding of the same context. The result is an understanding that is derived entirely from her understanding of another context. This result is identical to that of analogical transfer.

In the supplementing interaction, the participant registers a relative preference for her previous understanding of the context and her understanding of another context without making a choice (i.e., both $a$ and $b$ are nonzero). The result is only a partial contribution from her understanding of another context. This result is like that of analogical transfer, in that the participant’s understanding of another context plays a role in her new understanding. However, in contrast to analogical transfer, her new understanding also reflects the role of her previous understanding of the same context.

At the far end of the combining spectrum, the cueing interaction, is least like analogical transfer. In the cueing interaction the participant’s new understanding does not reflect the contribution of her understanding of another context. The result of this choice is that the participant’s understanding is derived exclusively from her previous understanding of the same context. This result is least like that of analogical transfer.

Relationship Between Reasoning Processes of Interactions

Analogical transfer describes a reasoning process in which a participant “maps” an idea from her understanding of one context onto her understanding of another context, i.e., she associates an idea with equivalent features of the other context.

The results of both the replacing and supplementing interactions reflect the influence of the participant’s understanding of another context. Those ideas that originate in her understanding of the other context (all of the ideas in the replacing interaction; some in the supplementing interaction) are associated with features that are equivalent to those in the other context. This result is consistent with the effect of the mapping process described by analogical transfer.

However, analogical transfer cannot account for ideas that originate instead from the participant’s previous understanding of the same context (all of the ideas in the cueing interaction).
interaction; some in the supplementing interaction). The results of the supplementing interaction reflect the relative preference of the participant for both her previous understanding of the context and her understanding of another context. The results of the replacing and cueing interaction instead reflect her choice between these understandings. Analogical transfer cannot explain the reasoning process that derives such a relative preference. Such a preference would be irrelevant to analogical transfer in which the participant has no previous understanding of the context.

Summary of Relationship with Analogical Transfer.

Of the three combining interactions, the replacing interaction is most like analogical transfer. The mapping process described by analogical transfer can account for the contribution of the participant’s understanding of another context in the replacing and supplementing interactions. However, it cannot account for the contribution of the participant’s previous understanding of the same context in the supplementing and cueing interactions.

4.3 MODIFYING INTERACTIONS

This section will discuss the relationship between the reinterpreting, extending, prompting, and guiding interactions. These interactions will be called modifying interactions because they result in an explanation that is in terms of an idea that has been modified from another expressed understanding. The modified idea was not present in either the participant’s previous understanding of the context or the participant’s understanding of another context. A modified idea is one that is associated with something about the context that is not equivalent to what it was associated with before. For example, consider a participant whose new understanding of the heat context is in terms of an idea about resistance that is modified from her expression of understanding in the gas context. The resistance idea is associated with a perceived empty space on the right side of the gas context, but it is associated with a perceived capacity of individual particles for heat in the heat context. The features of space and capacity are not equivalent. This example of modification was taken from the example of the reinterpreting interaction introduced in Chapter 3 and will be discussed in more detail in Section 4.3.1.

The four modifying interactions will be discussed in pairs. The reinterpreting and extending interactions make up the first pair, in which an idea from the participant’s previous understanding of another context is modified. This pair of interactions will be discussed in Section 4.3.1. The prompting and guiding interactions make up the second pair, in which an idea from the participant’s understanding of the same context is modified. This pair of interactions will be discussed in Section 4.3.2. Each pair illustrates results of these modifications of understanding that are complementary to one another.
4.3.1 Relationship Between Reinterpreting and Extending Interactions

This section will discuss the relationship between the reinterpreting and extending interactions. The reinterpreting and extending interactions both result in the participant maintaining her prediction of behavior but revising her explanation for why it happens (i.e., $B_{\text{new}}$ and $B_{\text{prior}}$ are the same, but $E_{\text{new}}$ and $E_{\text{prior}}$ are different). This revised explanation is in terms of an idea that has been modified from her understanding of the behavior of another context (i.e., the modified idea in $E_{\text{new}}$ originates from $E_{\text{other}}$).

The results of the modifications in the reinterpreting and extending interactions are complementary to one another. In the reinterpreting interaction, the behavior of the context that is explained is the same as the behavior of the context from which the idea originates (i.e., $B_{\text{new}}$ and $B_{\text{other}}$ are the same). In contrast, in the extending interaction, the behavior of the context that is explained is different from the behavior of the context from which the idea originates (i.e., $B_{\text{new}}$ and $B_{\text{other}}$ are different). Examples of these interactions that were introduced in Chapter 3 will be discussed below.

**Example of Reinterpreting Interaction**

Greta’s third interaction (G3; described in Section 3.3.3) is an example of a reinterpreting interaction. In this interaction, following the gas investigation, Greta revises her explanation for her prediction of slowing rate behavior in the heat context (i.e., $B_{\text{new}}$ and $B_{\text{prior}}$ are the same, but $E_{\text{new}}$ and $E_{\text{prior}}$ are different). Greta’s prediction of slowing rate behavior in the heat context is the same as the behavior she observed in the gas and dye contexts (i.e., $B_{\text{new}}$ and $B_{\text{other}}$ are the same).

The reinterpreting interaction modifies an idea from her shared explanation for slowing rate behavior in the gas and dye contexts to explain why the same behavior happens in the heat context (i.e., the modified idea in $E_{\text{new}}$ originates from $E_{\text{other}}$). Like her explanation of slowing rate behavior in the gas and dye contexts, Greta’s new explanation for slowing rate behavior in the heat context is in terms of an idea about resistance. However, in her new explanation, this idea is associated with a nonequivalent feature of the heat context. Greta explains this behavior in the gas and dye contexts by saying that the rate slows, because “there’s not as much room,” and in the heat context by saying that the rate slows, because “the particles have too much heat on them.” During this modification, Greta associates her idea about resistance from the gas and dye contexts with a feature of the heat context that is nonequivalent: with the capacity of particles for heat instead of with the capacity of a container’s side for particles.

**Example of Extending Interaction**

Sandra’s second interaction (S2; described in Section 3.4.2) is an example of an extending interaction. In this interaction, following the gas investigation, Sandra revises her explanation for her continued prediction of constant rate behavior in the dye context (i.e., $B_{\text{new}}$ and $B_{\text{prior}}$ are the same, but $E_{\text{new}}$ and $E_{\text{prior}}$ are different). Sandra’s prediction of constant rate behavior in the dye context is different from the behavior she observed in the gas context (i.e., $B_{\text{new}}$ and $B_{\text{other}}$ are different).
The extending interaction modifies an idea from her explanation of slowing rate behavior in the gas context to explain why different behavior happens in the dye context (i.e., the modified idea in $E_{\text{new}}$ originates from $E_{\text{other}}$). Like her explanation of slowing rate behavior in the gas context, Sandra’s new explanation for slowing rate behavior in the dye context is in terms of an idea about resistance. However, in her new explanation, this idea is associated with a nonequivalent feature of the heat context. Sandra explains slowing rate behavior in the gas context by saying that the gas goes more at first, because there’s “nothing to stop” it and less later, because there’s less space left. She then explains constant rate behavior in the dye context by saying that the dye and water “stop each other.” During this modification, Sandra associates her idea about resistance from the gas context with a feature of the dye context that is nonequivalent: with a container that is full on both sides instead of with a container that is full on only one side.

**Summary of Examples of Reinterpreting and Extending Interactions**

As these examples illustrate, both kinds of interaction modify an idea from the participant’s understanding of another context. The modified idea is different from ideas in both the participant’s previous understanding of the same context and in her understanding of another context. While in the reinterpreting interaction the modification is used to support explanation of the same behavior, in the extending interaction this modification is used to support explanation of a different behavior.

### 4.3.2 Relationship Between Prompting and Guiding Interactions

This section will discuss the relationship between the prompting and guiding interactions. The prompting and guiding interactions both result in the participant revising her prediction of the behavior in a context to be the same as the behavior of another context (i.e., $B_{\text{new}}$ is different from $B_{\text{prior}}$, but the same as $B_{\text{other}}$). The participant’s explanation for this revised prediction is in terms of an idea that has been modified from her explanation for her previous prediction of behavior in the same context (i.e., the modified idea in $E_{\text{new}}$ originates from $E_{\text{prior}}$).

The results of the modifications in the extending and reinterpreting interactions are complementary to one another. The **prompting interaction** results in an explanation that is different from the participant’s explanation for the behavior in another context (i.e., $E_{\text{new}}$ is different from $E_{\text{other}}$). In contrast, the **guiding interaction** results in an explanation that is similar to the participant’s explanation for the behavior in another context (i.e., $E_{\text{new}}$ is similar to $E_{\text{other}}$). Examples of these interactions that were introduced in Chapter 3 will be discussed below.

**Example of Prompting Interaction**

Greta’s second interaction (G2; described in Section 3.3.2) is an example of a **prompting interaction**. In this interaction, following the gas and dye investigations, Greta revises her prediction of behavior from constant to slowing rate behavior (i.e., $B_{\text{new}}$ and $B_{\text{prior}}$ are
different). This behavior is the same behavior she observed in the gas and dye contexts (i.e., \( B_{\text{new}} \) and \( B_{\text{other}} \) are the same).

The prompting interaction modifies an idea from her explanation of constant rate behavior to explain why slowing rate behavior happens instead (i.e., the modified idea in \( E_{\text{new}} \) originates from \( E_{\text{prior}} \)). Like her explanation of constant rate behavior in the heat context, Greta’s explanation for her new prediction of slowing rate behavior is in terms of an idea about distance. However, in her new explanation, this idea is associated with a nonequivalent feature of the heat context. Greta explains constant rate behavior in the heat context by saying that the particles are “next to each other.” She then explains slowing rate behavior in the same context by saying that the heat goes more at first, because the cold is “right next to the source,” and less later, because “the source is way at the front.” During this modification, Greta associates her idea about distance with a feature that is nonequivalent: with the increasing space between the source and recipient of heat instead of with the constant space between particles. This association is prompted by her observation of the same behavior in the gas and dye contexts.

Example of Guiding Interaction

Hanna’s third interaction (H3; described in Section 3.2.3) is an example of a guiding interaction. In this interaction, following the gas investigation and dye revision, Hanna revises her prediction of behavior from constant to slowing rate behavior (i.e., \( B_{\text{new}} \) and \( B_{\text{prior}} \) are different). This behavior is the same behavior she observed in the gas context and predicted in the dye context (i.e., \( B_{\text{new}} \) and \( B_{\text{other}} \) are the same).

The guiding interaction modifies an idea from her explanation of constant rate behavior to explain why slowing rate behavior happens instead (i.e., the modified idea in \( E_{\text{new}} \) originates from \( E_{\text{prior}} \)). Like her explanation of constant rate behavior in the heat context, Hanna’s explanation for her new prediction of slowing rate behavior is in terms of an idea about mixing. However, in her new explanation, this idea is associated with a nonequivalent feature of the heat context. Hanna explains constant rate behavior in the heat context by saying that the temperatures would be “mixing every second.” She then explains slowing rate behavior in the same context by saying that the heat goes more at first, because the temperatures are “totally different,” and less later, because “they mixed a lot already.” During this modification, Hanna associates her idea about mixing with a feature from the heat context that is nonequivalent: her idea about mixing was initially not associated with the difference between the temperatures. This association is guided by her similar understanding of the dye context.

The resulting explanation for slowing rate behavior is similar to Hanna’s explanation for slowing rate behavior in the dye context (i.e., \( E_{\text{new}} \) and \( E_{\text{other}} \) are similar). Hanna explains slowing rate behavior in the dye context by saying that the dye goes more at first, because the dye and water are “really different,” and less later, because “a lot of mixing has happened already.”

Summary of Examples of Prompting and Guiding Interactions

As these examples illustrate, both kinds of interaction modify an idea from the participant’s explanation of different behavior in the same context. The modified idea is
not equivalent to ideas in either the participant’s previous understanding of the same context, or in her understanding of another context. While the prompting interaction results in an explanation that is different from the participant’s explanation in another context, the guiding interaction results in an explanation that is similar to the participant’s explanation in another context.

4.3.3 Relationship of Modifying Interactions with Analogical Transfer

Modifying interactions result in an explanation that is in terms of an idea that has been modified from another expressed understanding. This section will discuss the relationship between such interactions and analogical transfer. The first part of the discussion will address the relationship between the results of analogical transfer and the results of the four modifying interactions. The second part will discuss the relationship between the reasoning processes underlying these results.

Relationship Between Results of Interactions

Analogical transfer results in an understanding that is comprised only of ideas from her understanding of another context. These ideas are associated with equivalent features of the new context. In contrast, the understanding that results from the modifying interactions is in terms of an idea that originates from either the participant’s understanding of another context or from her previous understanding of the same context. This idea is associated with nonequivalent features.

The reinterpreting and extending interactions are like analogical transfer in that the understanding that results is in terms of an idea that originates from the participant’s understanding of another context. In contrast, the understanding that results from the prompting and extending interactions is in terms of an idea that originates from the participant’s previous understanding of the same context. The results of the prompting and guiding interactions nonetheless reflect a role for the participant’s understanding of another context: in both the prompting and guiding interaction, the resulting prediction of behavior is the same as the behavior of another context; in the guiding interaction, the explanation for that behavior is additionally in terms of ideas that were used to explain the behavior in another context. Although the result of the guiding interaction is identical to that of analogical transfer, the process underlying this result is very different: the ideas that comprise the participant’s explanation are modified from her previous understanding of the same context to be the same as those used to explain the behavior in another context.

In analogical transfer, the ideas that comprise the participant’s new explanation originate from her explanation of the same behavior. This is true also of the reinterpreting interaction: the modified idea is used to explain the same behavior. An idea that has been associated with nonequivalent features can also be used to explain a different behavior. This is the result of the extending, prompting, and guiding interactions.
Relationship Between Reasoning Processes of Interactions

Analogical transfer describes a “mapping” reasoning process in which ideas are associated with equivalent features of another context. Modifying interactions instead associate ideas with nonequivalent features. Analogical transfer does not address a process by which such an association might happen. A participant may modify rather than map an idea if she is unable to explain the context’s behavior without modification.

Like the combining interactions, the results of the modification interactions reflect the relative preference of the participant for both her previous understanding of the context and her understanding of another context. This relative preference determines what ideas will be modified to play a role in the participant’s new understanding. As with the combining interactions, such a preference may be based on either the participant’s perceived “authority” of an idea from one of these understandings, or on her perception of the difficulty of reasoning from one of these understandings.

Summary of Relationship with Analogical Transfer

The modifying interactions may reflect an inability of the participant to support explanation of a behavior with ideas from other understandings. The participant associates an idea from another understanding with nonequivalent features of the context. The result is an explanation in terms of ideas that have not been expressed before. This is unlike the mapping process described by analogical transfer.

4.4 REFOCUSING INTERACTIONS

4.4.1 Relationship Between Highlighting and Reframing Interactions

This section will discuss the relationship between the highlighting and reframing interactions. These interactions will be called refocusing interactions because they refocus the participant’s perception of her previous understanding of a context. Refocusing interactions result in a new explanation for the same behavior in a context (i.e., B_{new} and B_{prior} are the same, but E_{new} and E_{prior} are different). The new explanation (E_{new}) is comprised of ideas from her prior explanation (E_{prior}) that have been abstracted to correspond with ideas used to explain the other behavior (E_{other}).

An abstracted idea is one that is associated with a generalization of the features with which it was originally associated. For example, consider a participant who has an idea about the relationship between the two sides of the gas context being “full and empty.” An abstraction of this idea might identify the relationship between sides of the gas context instead as being “opposite.” This abstraction captures the essence of the relationship between sides of the context in terms that are independent of the context being about gas.
The features with which ideas are associated determine whether or not they correspond. In the highlighting interaction, the behaviors of the two contexts are the same. The new explanation that results is in terms of an abstracted idea that corresponds with an idea used to explain the same behavior in another context. The abstracted idea is associated with a generalization of features of the context that are the same as features used to describe the other context. In the example of the highlighting interaction introduced in Chapter 3, the participant identifies the relationship between the sides of the context as being “opposite” in both contexts. This example will be discussed in more detail below.

In the reframing interaction, the behaviors of the two contexts are different. The new explanation that results is in terms of an abstracted idea that corresponds with an idea used to explain the different behavior in another context. The abstracted idea is associated with a generalization of features of the context that are the opposite of the features used to describe the other context. In the example of the reframing interaction introduced in Chapter 3, the participant identifies the relationship between sides of the contexts as being “opposite” as opposed to identifying it as being “the same.” This example will be discussed in more detail below.

Example of Highlighting Interaction

The first part of Sandra’s first interaction (S1a; described in Section 3.4.1) is an example of a highlighting interaction. In this interaction, during the comparison phase, Sandra revises her explanations for her prediction of slowing rate behavior in both the gas and heat contexts (i.e., B\text{prior}, B\text{other}, and B\text{new} are the same; E\text{new} and E\text{prior} are different).

Sandra’s new explanation for her prediction of slowing rate behavior in the gas context is in terms of an idea that is abstracted from an idea she previously used to explain this behavior. Sandra previously explained the slowing rate behavior in this context in terms of an idea about the relationship between the sides of the context: the sides are “full and empty.” She now explains the behavior by associating the same idea with a generalization of these features: the sides are “opposites.” This abstracted idea corresponds with the idea Sandra used to explain slowing rate behavior in the heat contexts: the sides are “hot and cold.”

Sandra simultaneously gives a new explanation for her prediction of slowing rate behavior in the heat context. This explanation is in terms of the same abstracted idea about the opposite relationship between the sides of a context.

Example of Reframing Interaction

The second part of Sandra’s first interaction (S1b; described in Section 3.4.1) is an example of a reframing interaction. In this interaction, during the comparison phase, Sandra revises her explanation for her prediction of constant rate behavior in the dye context (i.e., B\text{prior}, B\text{other}, and B\text{new} are the same; E\text{new} and E\text{prior} are different). This behavior is different from the behavior she predicts in the gas and heat contexts (i.e., B\text{new} and B\text{prior} are different from B\text{other}).
Sandra’s new explanation for her prediction of constant rate behavior in the dye context is in terms of an idea that is abstracted from an idea she previously used to explain this behavior. Sandra previously explained the constant rate behavior in terms of an idea about the relationship between the sides of the context: the sides are “both liquids.” She now explains the behavior by associating the same idea with a generalization of these features: the two sides are “the same.” This abstracted idea corresponds with the abstracted idea Sandra used to explain slowing rate behavior in both the gas and heat contexts: the two sides are “opposite.”

Summary of Examples of Interactions
As these examples illustrate, both kinds of interaction refocus the participant’s perception of her previous understandings of contexts’ behavior. While in the highlighting interaction this refocusing associated an idea with generalized features that describe both contexts, in the reframing interaction it associates an idea with generalized features of the contexts that are opposites.

4.4.2 Relationship of Refocusing Interactions with Analogical Transfer

Refocusing interactions result in a new explanation for the behavior of a context that is comprised of ideas that are abstracted from the participant’s previous explanation of the behavior. The abstracted ideas correspond with ideas used to explain the behavior of another context. This section will discuss the relationship between such interactions and analogical transfer. The first part of the discussion will address the relationship between the results of analogical transfer and the results of the two refocusing interactions. The second part will discuss the relationship between the reasoning processes underlying these results.

Relationship Between Results of Interactions
Recall that analogical transfer describes an interaction that results in an understanding of a context that is comprised only of ideas from her understanding of another context. Of the refocusing interactions, the highlighting interaction has a result most like that of analogical transfer. While the result of analogical transfer is comprised of ideas that are associated with features that are equivalent to those in another context, the result of the highlighting interaction is instead in terms of abstractions of these ideas. However, unlike in analogical transfer, these ideas were also present in the participant’s previous understanding of the context.

The understanding that results from the reframing interaction is in terms of abstractions of ideas that correspond with but are not the same as ideas from her understanding of another context. This result is least like that of analogical transfer. These ideas were also present in the participant’s previous understanding of the context.
Relationship Between Reasoning Processes of Interactions

Analogical transfer describes a reasoning process in which a participant “maps” ideas from her understanding of one context onto her understanding of another context: i.e., she associates the ideas with equivalent features of the other context. The new explanations that result from the highlighting and reframing interactions are in terms of ideas that are associated with generalizations of features of the context. These ideas are related to ideas used to explain the behavior of another context and to ideas from her previous explanation of the same context. This indicates that the interaction is due to a different reasoning process than mapping. The refocusing interactions do not associate ideas from one context with the features of another context. Instead they select ideas from the participant’s previous explanation of the context that correspond with those used to explain the other context and disassociate the idea from the particular features of the context. The result is an understanding in terms of abstractions of ideas used previously in the same context.

Summary of Relationship with Analogical Transfer

Unlike analogical transfer, the ideas that make up the understanding that results from the refocusing interactions do not originate from another context. These ideas are instead abstractions of ideas from the participant’s previous understanding. The refocusing interactions select and abstract ideas from the participant’s previous understanding that correspond with the ideas used to explain another context. This is a different reasoning process than the mapping process described by analogical transfer.

4.5 SUMMARY

This chapter discussed three groups of interactions called the combining, modifying, and refocusing interactions. The combining interactions all result in new understanding that is a combination of ideas from the participant’s previous understanding of the same context and ideas from her understanding of another context. The modifying interactions all result in a new understanding that is in terms of ideas that are modified from another expressed understanding. The refocusing interactions result in an understanding that is in terms of an abstraction of ideas from her previously expressed understanding of the same context.

The relationship of each group of interactions to analogical transfer was additionally considered. Combining interactions were found to be most like analogical transfer, because as in analogical transfer, those ideas that originate in the participant’s understanding of another context are associated with equivalent features of the context. However analogical transfer cannot explain the contribution of the participant’s previous understanding of the context. Unlike analogical transfer, modifying interactions result in the association of ideas with nonequivalent features of a context. Such modified ideas
can be used to explain different behavior than they were used to explain originally. Refocusing interactions result in the abstraction of ideas from the participant’s previous understanding that correspond with ideas from the participant’s understanding of another context. Analogical transfer cannot explain such an abstraction process. The significance of these differences both for future research and curriculum development will be considered in Chapter 5.
Chapter 5

Conclusion

Learning results in a person having a new understanding of a context. The way a person understands one context can influence what they come to understand about another context. The process by which this kind of learning happens has been of great interest to psychology research. Research has elaborated the process in detail through the design and implementation of controlled experiments, and the development of computational models to simulate their results. The process elaborated by this research is called analogical transfer. Research on analogical transfer has not investigated the role that a person’s previous understanding of context can play in the process they have elaborated. For practical purposes it has assumed that a person’s previous understanding plays a minimal role. Other research on learning has demonstrated the significant role that previous understandings can play in learning within a single context. This dissertation has sought to explore whether a person’s previous understanding can play a similarly significant role in their reasoning across contexts.

This dissertation employed a different methodology than that used in psychology research. This dissertation adopted a case study design to capture participants’ changes in understanding that result during reasoning across contexts. The analysis sought to identify relationships between the participant’s new understanding of a context and both their previous understanding of the same context and their understanding of another context. Such instances of changed understanding were said to result from a context interaction. This dissertation identified nine instances of context interaction in the transcripts of interviews with three students.

Characterization of the relationships established by the identified context interactions revealed the variety of roles that previous understandings can play in reasoning across contexts. Like in analogical transfer, three of the context interactions, called combining interactions, result in a new understanding that is in terms of ideas that are the same as ideas used in another understanding. Unlike analogical transfer, the combining interactions describe two sources for these ideas: the participant’s previous understanding of the same context and the participant’s understanding of another context. While the replacing interaction resulted in a new understanding of a context that was primarily comprised of ideas from the participant’s understanding of another context, the new understanding that resulted from the cueing interaction was primarily comprised of ideas from the participant’s previous understanding of the same context. The supplementing interaction resulted in support of the participant’s previous explanation with ideas from her understanding of another context. That there are two sources for ideas used in the understanding that results from combining interactions indicates that the participant must decide between her ideas from her previous understanding and her ideas from her understanding of another context. Models of analogical transfer do not address this decision process.
The remaining two groups of interactions, called modifying and refocusing interactions, result in a new understanding that is in terms of an idea that is not the same as any of the ideas used in either the participant’s previous understanding of the same context or her understanding of another context. Four of the context interactions were identified as modifying interactions. These modifying interactions resulted in a new understanding of a context that was in terms of a modification of an idea from either the participant’s previous understanding of the same context or from the participant’s understanding of another context. However, both of these understandings play a role in this modification. In the prompting and guiding interactions, the participant’s understanding of another context influenced the modification of an idea from the participant’s previous understanding of the same context. In the reinterpreting and extending interactions, the participant’s previous understanding of the same context influenced the modification of an idea from the participant’s understanding of another context. Two of the context interactions were identified as refocusing interactions, which resulted in a new understanding of a context that was in terms of an abstraction of an idea from the participant’s previous understanding of the context. However, the participant’s understanding of another context played a role in this abstraction. In the highlighting interaction, the idea that was abstracted was shared with the understanding of another context, while in the reframing interaction the idea that was abstracted instead corresponded with an idea used in the understanding of another context. Models of analogical transfer do not address the process by which a participant’s new understanding can come to be in terms of such new ideas.

The nine kinds of context interactions indicate some of the ways that a person’s previous understanding can play a significant role in their reasoning across contexts. Additional kinds of interaction would likely be revealed by interviews with additional students about either the same contexts or about different contexts of which students are similarly known to have significant previous understanding. In addition, an experimental design, like those used to investigate analogical transfer, could provide additional insight to the different reasoning processes underlying any of the discovered kinds of context interaction.

The significant role that a person’s previous understanding can play in reasoning across contexts is of great interest to education. It is not unusual for students to have considerable prior knowledge about contexts presented during science instruction. Understanding the role that this prior knowledge can play in the application of a general concept instructed in another context should be a priority for design of effective science instruction. In addition, the different context interactions could be legitimate targets of instruction in their own right. The discovered context interactions are fundamentally productive reasoning processes that can result in new ways to approach understanding an unfamiliar context. Fostering such productive reasoning processes could empower students to leverage their previous understandings during inquiry activities.
References


