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REVIEW ARTICLE

Enriching Students' Scientific Thinking Through Relational Reasoning: Seeking Evidence in Texts, Tasks, and Talk

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Abstract As reflected in the Next Generation Science Standards, concerns about the adequacy of education and career preparation in science, technology, engineering, and mathematics (STEM) fields have led to fundamental shifts in the focus of K-12 science education. Such shifts are also highlighted in many of the articles within this special issue, and the issue focus on the role of relational reasoning in learning in STEM domains. Within this commentary, we reflect upon how the articles within this special issue align with, and shed new light on, the Next Generation Science Standards (NGSS), specifically with respect to relational reasoning. We then describe a novel pedagogical approach designed to augment students' acquisition of NGSS practices and core ideas (i.e., Quality Talk Science (QT_s)) and how evidence from our research on QT_s has shown increases in relational reasoning. In this section, we also provide multiple discourse excerpts that serve as exemplars for each of the four types of relational reasoning (i.e., analogy, anomaly, antinomy, and antithesis). Finally, we present specific exemplars from QT_s that reinforce the ideas and findings forwarded by the authors of each of the papers within this special issue and propose some thoughts regarding future directions for research.

Keywords Relational reasoning · Classroom discussions · Critical-analytic thinking · Next Generation Science Standards

Concerns about the insufficient number of US students prepared to succeed in science, technology, engineering, and mathematics (STEM) careers, as well as intransigent low performance on

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assessments of basic scientific knowledge, skills, and perspectives, have led to calls for fundamental shifts in K-12 science education (National Assessment of Educational Progress 2009). The Next Generation Science Standards (NGSS; National Research Council 2012) reflect a fundamental rethinking of desired educational outcomes in STEM, with a move away from the acquisition of discrete facts and concepts toward a three-dimensional focus on helping students (a) engage in scientific and engineering practices, (b) understand the crosscutting concepts that unite STEM disciplines, and (c) delve deeply into a small but critically important set of core ideas in each discipline. The articles in this special issue on relational reasoning directly inform science education research and practice on how to achieve three-dimensional STEM education outcomes. Specifically, relational reasoning is a fundamental aspect of several NGSS core scientific and engineering practices, including developing and using models, analyzing and interpreting data, engaging in mathematical and computational thinking, and engaging in argument from evidence.

Here, we reflect upon how the articles within this special issue shed new light on NGSS practices. We provide evidence of relational reasoning through *tasks* and *text*, while also demonstrating evidence of relational reasoning gathered from students' *talk* in small-group discussions in science classrooms aimed at promoting critical-analytic thinking. We also present exemplars from our own work to reinforce the contentions forwarded by the authors of each of the papers within this special issue. We end our reflections on this special issue by identifying promising future directions for relational reasoning in STEM research in order to facilitate students' acquisition of a three-dimensional understanding in STEM.

Relational Reasoning as a Component of Core Science and Engineering Practices

Developing and Using Models

Models serve a number of important purposes in scientific inquiry, including making it "possible to go beyond observables and imagine a world not yet seen" (National Research Council 2012, p. 50). Resnick et al. (2016) adeptly connected models of the unobservable with relational reasoning. In particular, they identified a number of barriers to productive relational reasoning about models through their work on people's challenges understanding extreme scales (e.g., time in geology, distances in nanoscience). For example, they identified both productive and unproductive analogical reasoning between the geologic time scale and a 24-h clock. The lack of salient cues regarding which aspects of the base and target concepts are analogous and which are not can lead to flawed mental models of geologic time and undermine the use of such models to understand other scientific phenomena (Gentner & Namy 2006; Resnick et al. 2016). Despite showing powerful remediation effects using corrective feedback, Resnick et al.'s work suggests from the outset that it would be more beneficial to choose base concepts that have a high likelihood of invoking productive analogical reasoning. Their work highlights the challenges of finding such base concepts, and curriculum developers and educators would be wise to thoroughly probe the kinds of analogical reasoning that various models invoke in students.

Analyzing and Interpreting Data

The NGSS for the practice of analyzing and interpreting data specifically mentions graphical interpretation, because many data representations in science involve the coordination of plotted data and described analyses. The Danielson and Sinatra (2016) article, with its focus on relational reasoning between text and graphics, directly informs research and practice on helping students analyze and interpret data. For example, the authors identified a number of different ways that graphics can relate to text beyond analogy, including instances where the graphics showed anomalous data (i.e., deaths from cholera over time, by location) and instances of antitheses using refutation graphics (i.e., visuals of the Earth's orbit). Unfortunately, students often assume that they should be looking for analogous relations between the description of an analysis and a graphical representation of the data, even in instances where other relations were intended. Therefore, as Danielson and Sinatra argued, representational graphics should be intentionally designed to make clear which of the four aspects of relational reasoning is necessary for interpretation. In addition, Danielson and Sinatra posed interesting questions regarding research showing that graphics can cause extraneous load (Segers et al. 2008): were the graphics indeed extraneous, or did the students simply not know which type of relational reasoning to enact?

Engaging in Mathematical and Computational Thinking

Mathematical thinking, beyond the mechanical use of algorithms, requires students to consider and compare multiple methods of solving problems and identify relations among those methods. Richland et al. (2016) made a compelling case that such thinking is challenging to learn and enact and therefore requires efficient and effective pedagogy (Stein et al. 2008). Mathematical thinking is indeed a core practice in STEM, but its foundational nature makes it no less demanding upon working memory (Begolli et al. 2015). Students must be taught how to compare and contrast mathematical procedures and solutions, and Richland et al. capitalized upon the relational reasoning literature to show how the cognitive load of that process can be decreased through more explicit instruction on which kinds of relations are most important for a particular comparison. This suggests that the initial investment in teaching students to engage in relational reasoning will reap dividends when students are asked to compare and contrast mathematical procedures and solutions because they will be more facile with not only the analogous aspects of those procedures and solutions but also the other relevant relations among them as well. This theme of the benefits of a broader view of relational reasoning, beyond analogical reasoning (Alexander & the DRLRL 2012), is one that was reinforced throughout this special issue.

Engaging in Argument from Evidence

The contribution by Kendeou et al. (2016) demonstrated how the expanded conceptualization of relational reasoning by Alexander and colleagues (Alexander & the DRLRL 2012; Dumas et al. 2013) can productively inform research on engaging in argument from evidence in STEM. Kendeou et al. showed how relational reasoning can focus students' attention on the nature of the critical relations between the normative and nonnormative knowledge claims, which in turn can lead to knowledge revision (i.e., co-activation, integration, and competing activation; Kendeou & O'Brien 2014). Such attention is necessary if students are to learn how to "defend their explanations, formulate evidence based on a solid foundation of data, [and] examine their own understanding in light of the evidence" (National Research Council 2012, p. 52). These STEM practices necessarily involve attending to what is analogous, anomalous, antinomous, and antithetical among various models. Kendeou et al. have shown how knowledge revision depends upon relational reasoning and provided directions for future research in teaching and supporting students' relational reasoning as they engage in argument from evidence.

Relational Reasoning Evidenced in Quality Talk Discussions

Although the NGSS provide meaningful ways to think about and organize important scientific information and knowledge, we now need a more comprehensive understanding of the pedagogical approaches or mechanisms likely to promote students' engagement of and learning about the well-defined cross-cutting concepts and disciplinary core ideas. As a result, we are among a number of researchers who have begun to explore the extent to which various pedagogical approaches augment students' acquisition of NGSS practices and core ideas (e.g., Roseman et al. 2015; Ryu & Sandoval 2012; Sandoval & Reiser 2004; Schwarz et al. 2009). Specifically, we have spent the last several years refining and implementing an intervention called Quality Talk (Wilkinson et al. 2010) for use in high school chemistry and physics classrooms (i.e., Quality Talk Science (QT_S)), because we believe that it will enhance students' knowledge of scientific practices and content in ways that complement the NGSS.

Rooted in social constructivist and sociocognitive theory (Vygotsky 1978) as well as meta-analytic and discourse analysis findings (Murphy et al. 2009), QT_s incorporates the best features of existing discussion approaches into one unified, innovative, teacher-facilitated discussion approach aimed at promoting students' critical-analytic thinking and reasoning about, around, and with text and content (Murphy et al. 2016). In alignment with the NGSS, the multifaceted intervention approach facilitates students' development and use of models, analysis and interpretation of data, and engagement in argumentation using reasoning and evidence. In addition, through the discussions, students are provided with opportunities to communicate scientific and technical information.

Implementation of QT_s begins with teachers participating in a comprehensive professional development workshop and coaching where teachers learn about the components of QT_s including the instructional frame (i.e., optimal instructional parameters for discussion, like using small, heterogeneous groups, and the inclusion of a prediscussion activity, like the catalyst worksheet), discourse elements (i.e., types of authentic questions and responses linked to critical-analytic thinking and reasoning; see Fig. 1), pedagogical principles (e.g., gradual release of responsibility and interpretive authority to students), and teacher moves (i.e., discourse moves by teacher intended to promote thinking and reasoning). Optimal implementation of QT_s generally includes (a) teacher-led Quality Talk lessons for learners focused on types of authentic questions (e.g., high-level thinking questions that prompt students to analyze, generalize, or speculate about the content, connection questions that lead students to make connections between content and other texts, or personal experience questions) and responses (e.g., elaborated explanations or co-construction of reasoning through exploratory talk) that enhance students' participation in regular (i.e., bi-weekly) small-group discussions; (b) incorporation of science lessons pertaining to core disciplinary ideas (e.g., nuclear fission, thin films) into the curriculum; and (c) students' use of a catalyst worksheet before, during, and after discussions. Students in various levels of high school physics and chemistry have shown improved oral and written argumentation and reasoning about scientific phenomena, models, and data after participating in the QT_s intervention (Murphy et al. 2015, 2016).

Turn	Speaker	Discourse	QT Codes	RR Codes
1.	Teacher	What, what is it in terms of the molecules of the substance, like, if you could shrink yourself down and look at them, what would you notice the difference between, like, a liquid and a solid? 'Cause we're talking about going from a liquid to a solid, so what, what literally happens to the molecules in that?	**AQ/HLT**	**RRP**
2.	Student 3	**They become closer together when they're in a solid, but they're more spread apart when they're in a liquid, and even further apart when they're in a gas, but then when they're a solid they come closer together.**		**Antithesis**
3.	Student 1	**And I think when we're talking about things like water and sodium acetate, they, they also crystalize, so they go into a lattice structure, which is order, so I guess that would be entropy.**		**Analogy**
4.	Teacher	So you said a lattice structure; in other words, they're becoming what together?	**TQ**	
5.	Student 1	Like bonded.		
6.	Teacher	OK.		
7.	Student 1	**Uh, OK, so if something bonds, then it needs... Well, no, that doesn't explain giving off energy. Because to bond, it needs energy and that doesn't fit the pattern.**		**Anomaly**

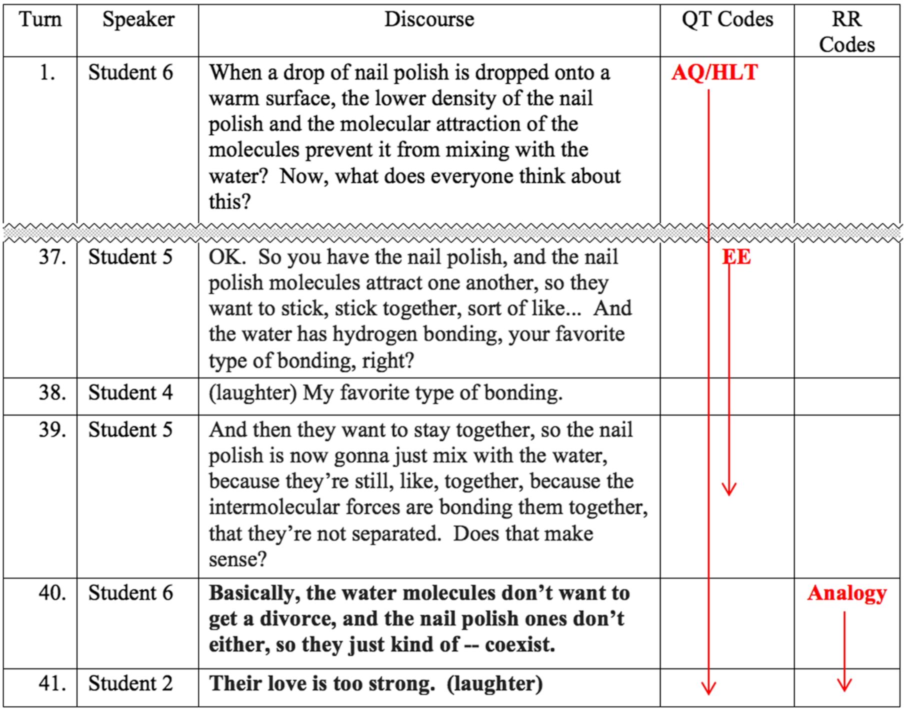
Fig. 1 Excerpt from a QT_s discussion on hot packs with three forms of relational reasoning. The excerpt was initiated with a relational reasoning prompt (RRP) in the form of an authentic, high-level thinking question (AQ/HLT), and responses to the question included relational reasoning with antithesis, analogy, and anomaly

Of particular interest to this special issue, however, is the nature of the relational reasoning evidenced by those participating in the QT_s intervention, as well as how such reasoning may change over time as they participate in QT_s discussions. To explore these questions, we closely examined data, spanning an academic year, from groups of high school students participating in the larger QT_s study (Greene et al. 2016). Specifically, we coded our data for evidence of the various forms of relational reasoning (i.e., analogy, anomaly, antinomy, and antithesis) as well as for the various QT_s discourse elements (e.g., authentic questions [AQs], test questions [TQs], elaborated explanations [EEs], and exploratory talk [ET]).

As can be seen in Fig. 1 example, we found evidence of relational reasoning in the questions asked by teachers and students, which we refer to as relational reasoning prompts, as well as in students' responses to the various kinds of AQs. In this excerpt, taken from a larger discussion in which the students are considering various models for explaining hot packs, the teacher asked an AQ that elicited student analysis to describe the differences between two very different states of matter (i.e., liquid and solid), so we have labeled this a high-level thinking (HLT) question. Of importance is that while many AQs may lead to students enacting relational reasoning, this particular question specifically called for relational reasoning in that the teacher asked students to consider the properties of two antithetical states of matter (i.e., liquid and solid).

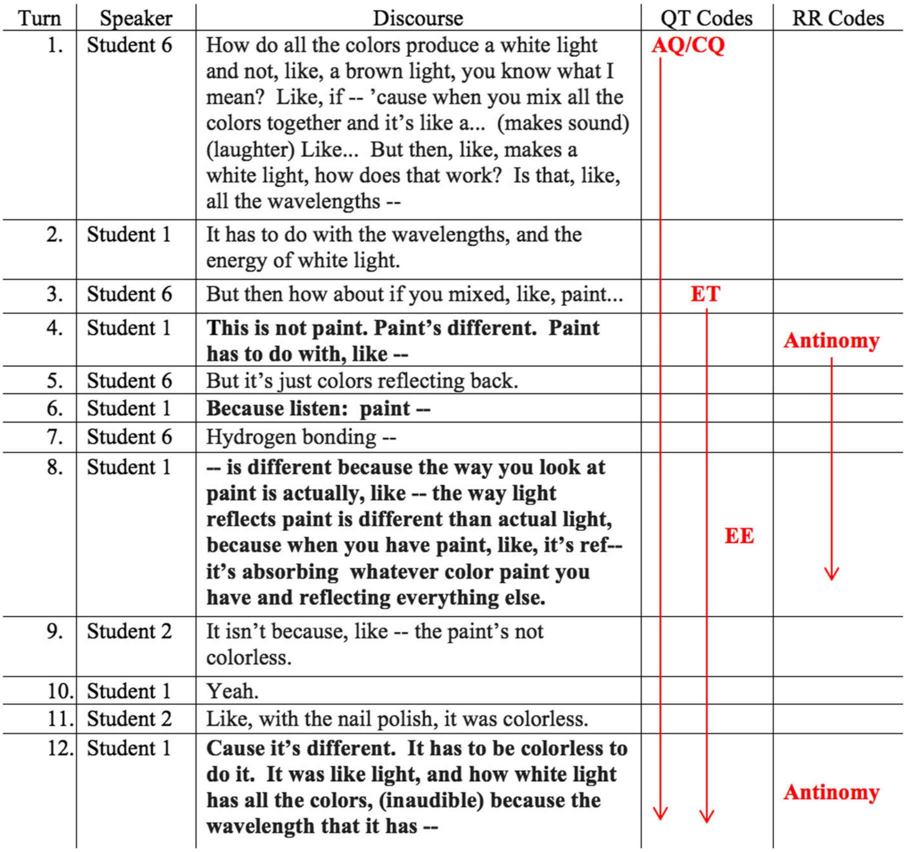
In our data, of the various forms of relational reasoning, analogy was the most frequently used form (56 %). Examples of analogical reasoning appear in Figs. 1 and 2. In the excerpt, students were discussing water and sodium acetate when one student drew the analogy between the order needed for a crystallized lattice and the order effects on the degree of entropy. By comparison, in the excerpt of the discussion in Fig. 2, high school students were trying to explain how and why a drop of clear nail polish forms a multicolored, thin film when dropped in a container of water. Within the excerpt, student 6 asked an AQ that elicited HLT from group members, in the form of an EE (i.e., claim with two or more reasons and/or evidence). The explanation appeared to give way to analogical reasoning in which students drew similarities between molecules wanting to stay together and not wanting a "divorce" because the molecules were "in love" as one might do with a human couple who wanted to stay together.

Interestingly, antinomous reasoning (23 %) was the second most frequently occurring form of analogical reasoning in the Quality Talk discussions. Indeed, these high school students showed some facility in identifying cases and noncases of phenomena. No doubt, this particular type of reasoning is extremely important in science domains. For example, in Fig. 3, students were attempting to understand the nature of light and how different colors of light occur. Several students participated in what we refer to as ET, where they were co-constructing an understanding of a phenomenon with an element of disagreement. It is this element of disagreement that offered strong evidence of antinomous reasoning. During turn 4, student 1 proclaimed: "This is not paint. Paint's different." This particular turn represents both the element of disagreement within the



Turn	Speaker	Discourse	QT Codes	RR Codes
1.	Student 6	When a drop of nail polish is dropped onto a warm surface, the lower density of the nail polish and the molecular attraction of the molecules prevent it from mixing with the water? Now, what does everyone think about this?	**AQ/HLT**	
37.	Student 5	OK. So you have the nail polish, and the nail polish molecules attract one another, so they want to stick, stick together, sort of like... And the water has hydrogen bonding, your favorite type of bonding, right?	**EE**	
38.	Student 4	(laughter) My favorite type of bonding.		
39.	Student 5	And then they want to stay together, so the nail polish is now gonna just mix with the water, because they're still, like, together, because the intermolecular forces are bonding them together, that they're not separated. Does that make sense?		
40.	Student 6	**Basically, the water molecules don't want to get a divorce, and the nail polish ones don't either, so they just kind of -- coexist.**		**Analogy**
41.	Student 2	**Their love is too strong. (laughter)**		

Fig. 2 Excerpt from a QT$_s$ discussion on molecular attraction with analogical reasoning. The excerpt was initiated with an authentic, high-level thinking question (AQ/HLT), and responses to the question included an elaborated explanation (EE) and analogical reasoning



Turn	Speaker	Discourse	QT Codes	RR Codes
1.	Student 6	How do all the colors produce a white light and not, like, a brown light, you know what I mean? Like, if -- 'cause when you mix all the colors together and it's like a... (makes sound) (laughter) Like... But then, like, makes a white light, how does that work? Is that, like, all the wavelengths --	AQ/CQ	
2.	Student 1	It has to do with the wavelengths, and the energy of white light.		
3.	Student 6	But then how about if you mixed, like, paint...	ET	
4.	Student 1	**This is not paint. Paint's different. Paint has to do with, like --**		Antinomy
5.	Student 6	But it's just colors reflecting back.		
6.	Student 1	**Because listen: paint --**		
7.	Student 6	Hydrogen bonding --		
8.	Student 1	**-- is different because the way you look at paint is actually, like -- the way light reflects paint is different than actual light, because when you have paint, like, it's ref-- it's absorbing whatever color paint you have and reflecting everything else.**	EE	
9.	Student 2	It isn't because, like -- the paint's not colorless.		
10.	Student 1	Yeah.		
11.	Student 2	Like, with the nail polish, it was colorless.		
12.	Student 1	**Cause it's different. It has to be colorless to do it. It was like light, and how white light has all the colors, (inaudible) because the wavelength that it has --**		Antinomy

Fig. 3 Excerpt from a QT_s discussion on color in light with antinomous reasoning. The excerpt was initiated with an authentic, connection question (AQ/CQ), and responses to the question included an episode of exploratory talk (ET), an elaborated explanation (EE), and antinomous reasoning

episode of ET *and* the beginning of antinomous reasoning. In essence, student 1 was reasoning that the color that makes up light is unique and different than the color that makes up paint. That is, paint color is not a case of light color. What makes this example so poignant is that this series of turns offers a co-occurrence between Quality Talk discourse elements and one of the more cognitively difficult forms of relational reasoning (Dumas 2016).

Finally, anomalous reasoning (12 %) and antithetical reasoning (9 %) occurred the least frequently in the examined discourse. Exemplars of both forms of reasoning by students appear in the previously highlighted discussion of hot packs in Fig. 1. Specifically, when considering the relation between bonding, energy, and states of matter, one student tried to make sense of the hot pack changing from a liquid to a solid and giving off heat. Although the student did not resolve the conceptual challenge in this brief excerpt, what is clear is that the student recognized that the hot pack did not seem to follow the expected pattern associated with changes in states of matter. Within this same discussion, student 3 described the antithetical properties of the various states of matter. What is fascinating is that the student chose to expand the antithetical reasoning voiced by the teacher in her AQ. That is, although the student acknowledged the teacher's juxtaposition of the properties of liquids and solids, the student purposefully clarified that the antithetical properties between solids and gases were even more extreme.

Although many of the authors in the present volume have speculated about which type of reasoning may be more useful or frequent within a given domain or scientific task, we would contend that our data raise speculation about the extent to which relational reasoning is task- or context-specific. Arguably, there are any numbers of reasons why some forms of reasoning may occur more frequently than others. For one, it may be a prior knowledge issue in that some forms of reasoning may be more difficult and require somewhat more formal instruction to acquire. Or, it may be the case that the models under discussion provided fewer opportunities for students to reason in these ways (i.e., a task issue). For example, our lessons were about models of scientific phenomena but contained only minimal amounts of raw data. Perhaps, lessons requiring students to consider data would give way to increases in anomalous or antithetical reasoning. Our discourse data do, however, shed some light on the extent to which various forms of AQs elicit relational reasoning.

Specifically, Poisson regression revealed that connection questions (i.e., shared knowledge or intertextual questions) and personal experience questions were more likely than other kinds of questions to elicit relational reasoning in students' responses (Greene et al. 2016). Similar analyses on students' responses revealed that episodes of ET, where students co-construct understandings, were more likely to include relational reasoning than other types of responses. It is possible that the element of disagreement required for ET promotes students' engagement of the relations among scientific phenomena, models, arguments, or explanations as was the case in the excerpt in Fig. 3.

There was also some evidence of changes in the nature of students' verbal relational reasoning over time as they participated in the intervention over the course of the school year (Greene et al. 2016). Descriptively, the frequency of relational reasoning events doubled from the time 1 discussion in September to the time 5 discussion in April, and the Poisson regression revealed time as a statistically significant predictor of relational reasoning. When we explored descriptive changes in the various types of relational reasoning over time, we found that the frequency of all types of relational reasoning increased with the notable exception of anomalous reasoning. As mentioned, this may be attributable to the nature of the task, but further research, involving multiple tasks, would be necessary to explore this. The aforementioned caveat regarding the nature of our data notwithstanding, our exploration does provide an initial foray into the potential of QT_s as a mechanism for enhancing students' understandings of the scientific practices and content of the NGSS while, at the same time, augmenting their ability to reason relationally about complex scientific phenomena, models, arguments, and explanations.

Relational Reasoning and Evidence from Quality Talk Science

As mentioned, QT_s has been implemented in both chemistry and physics classrooms with students of varying ability levels (e.g., noncollege bound, English language learners, or advanced). This has resulted in an accumulation of a rich library of discourse data from many different students engaging in QT_s discussions on a wide variety of topics. Within this section, we draw on this rich library of discourse data to provide classroom-based evidentiary support for some of the primary contentions forwarded by the authors in this special issue. Thus, in the sections that follow, we will review some of the salient aspects of the different papers within this special issue while also providing representative exemplars of relational reasoning from QT_s discourse.

Evidence for the Use of Talk as a Tool to Promote Relational Reasoning

Of the articles included within this special issue, the Richland et al. (2016) paper shares the most surface similarities to QT_s. Indeed, the central argument in Richland et al. is that talk can "provide a powerful opportunity for students to engage in relational reasoning". While differences are noted with respect to content area (i.e., mathematics vs. science), we believe that there are clear parallels between the notion of students talking about *the multiple pathways to solving a mathematics problem* and students talking about *the multiple models from which one may conceptualize a scientific phenomenon*. Students in Richland et al.'s research consider and discuss the various ways that one may solve a mathematics problem, whereas students in QT_s consider and discuss different models or claims related to a scientific phenomenon. In the QT_s excerpt below, one of the students provided an EE examining each of the four potential models in an attempt to understand which model best explained "how the inflation and deflation an airbag prevents injury."

> Student 4: [Looks down at handout.] I felt like one of the strongest discrepancies throughout all the models is the actual velocity of the driver after the impact and the inflation of the airbag. Uh, I think one and two…[no,] one and four might say... Yeah, one and four say that the driver has an equal ~ and it's an equal and opposite reaction that cancel each other out, and, uh, two and three say that the…the driver's velocity is slowed. [Looks up to peers] Do we have any feelings on that?

As evident in the example, student 4 considered each of the four models and examined inconsistencies among them so as to inform his explanatory understandings of the phenomenon. Specifically, he used antinomous reasoning as he examined various characteristics of the possible scientific models. Thus, the scientific discourse that students in QT_s engage in, like the mathematical discourse described by Richland et al., provides rich opportunities for students to engage in relational reasoning.

Evidence for Text-Graphic Relational Reasoning

Like authentic scientific texts read by STEM experts, the information that high school students read prior to QT_s discussions contains both text and graphics, with the texts and graphics having partial overlap (i.e., "representational graphic" Carney & Levin 2002). Reading and discussing such texts may serve to prompt students' relational reasoning (Danielson and Sinatra 2016). In the discussion excerpt below, student 1 explicitly referenced a graphic representation from one of the texts while examining a claim about the energy released when clicking a disk in a reusable hot pack. In doing so, she also engaged in relational reasoning. Specifically, student 1 was responding to a claim articulated by her peer that "all the energy in the reaction was released in heat energy."

> Student 1: Yeah, I mean, it's…what are we considering? That all of the potential energy in the system, which would be chemical potential energy as well as the elastic potential energy of that little disk…then you push the disk, right? You change that potential energy into kinetic energy. That kinetic energy changes a couple of the molecules into

> the solid state, and off of the solid state then everything can ~ all of the chemical bonds all snap, change it to solid, and give off the heat. But the thing that I was wondering is that, *if it [the claim] said all of the energy that was released in the reaction was released as heat energy, I would agree with that. But if you look at the little picture here... Yeah, I mean, the final thing that...the thing at the end, it has energy in it. So, there's always gonna be a final energy. And the difference between the initial energy and the final energy is going to be our energy that's released as heat.* But it's not all of the energy. There's still some final energy left. That's why I said no.

One of the unique aspects about this excerpt is that student 1 used the picture as evidence against the claim posed by her peer. In doing so, she engaged in antinomous reasoning. In essence, while grappling with the amount of heat energy released, she was discerning "what something [energy] *is*, by ascertaining what it *is not*" (Alexander & the DRLRL 2010, pp. 35–36). As Danielson and Sinatra (2016) suggested, processing such representations provides the potential for students to engage in relational reasoning, resulting in a learning advantage. Indeed, the opportunities for students to process and discuss both text and graphics may be a contributing factor to the increases in relational reasoning and learning outcomes evidenced in students who participate in QT_s (Greene et al. 2016).

Evidence for Conceptualizing Magnitude and Scale Through Relational Reasoning

Resnick et al.'s (2016) central argument was that relational reasoning, specifically analogical reasoning, can facilitate students' conceptualizations of extreme magnitude. As a case in point, in one of the texts read by students in QT_s, an analogy was provided to help them conceptualize the massive the amount of energy produced during uranium-235 fission. Indeed, this analogy was so salient to one of the students, student 4, that she chose to reference this example during their discussion as she built upon the response from another student who referred to the amount of energy produced by fission somewhat generically as "a lot of energy."

> Student 9: And that, for one molecule [of uranium-235], lets off…it was like a really small number of joules, but if you think, that's only for one atom of uranium. So if you have a lot of atoms of uranium, if you even have one mole of uranium…actually that'd be a lot…if you had a little bit of uranium [makes gesture pinching fingers close together] that'd be a lot of energy.
> Student 4: *I liked the comparison that [the text] made to the gasoline. That was kind of cool. It was like if you used one thing of, one atom of uranium, it could keep your car going for 19,000 years.*
> Student 1: No, it was like if you use one atom in place of each gasoline.
> Student 9: Of each gasoline atom. So you'd fill your tank with uranium-235 and a bunch of neutrons.
> Student 4: That's a good way to think about it, like, compare them.
> Teacher: Put the energy into perspective?
> Student 4: Yeah.

Two aspects of the preceding excerpt are worthy of note. First, the exchange shows a group of students discussing an analogy of the energy contained in a tank of gasoline in a car (i.e., a familiar concept) to the magnitude of energy released during fission (i.e., an unfamiliar concept on a much larger scale) as they were trying to better comprehend the magnitude of energy. Second, the excerpt also showed that the students explicitly acknowledged the function of the analogy; that is, the purpose of the analogy was to put the magnitude "into perspective." Thus, an analogy initially presented in the science text was later referred to by students in their discussion. As Resnick et al. might suggest, analogical reasoning may have helped the group of students better conceptualize the magnitude of energy released through their relational reasoning.

Evidence for Knowledge Revision and Misconception Correction Through Relational Reasoning

As mentioned, one of the QT_s lessons, and concomitant discussion, pertained to thin film formed on water by clear nail polish. During the discussion, students in one group talked about the experiment and drew comparisons between the nail polish, prisms, and rainbows. Through the course of the discussion, one of the students used relational reasoning as she tried to explain to another student *why you can see a rainbow* by drawing an analogy to previously learned content about prisms. Importantly, at the end of the excerpt, one of the students admitted that his prior understanding of how a rainbow was formed was wrong.

> Student 5: I think the only reason you can actually see rainbows is because of all the water in the air, so it intercepts. Like water in the air.
> Student 2: But water is below the nail polish.
> Student 5: I'm not talking about the nail polish. I'm talking about rainbows.
> Student 7: *No, she's talking about this. Like when the white light hits this prism, the way that you can see the rainbow is because all of the water molecules in the air.*
> Student 5: So that's the only reason we can see those rainbows, but you can't see these ones.
> Student 2: Okay, to be honest, the reason why I though you could see the rainbow on the ground was because part of the rainbow was coming down from the raindrops. That's honestly what I thought. But okay.

As student 7 explained the role of raindrops in rainbows by drawing an analogy to shared knowledge about prisms, student 2 was able to correct his misconception about how rainbows are formed. Thus, the conflicting information presented by student 7 through her relational reasoning provided student 2 with the evidence necessary to restructure his knowledge framework (Kendeou et al. 2016). Indeed, as Kendeou et al. articulated, the presentation of conflicting information afforded the "learning conditions" necessary to "facilitate the encoding and activation of the correct information" while simultaneously lessening "the reactivation of such incorrect information". In this way, QT_s may afford students the opportunity to deeply consider their understandings as well as those held by others and, potentially, to co-activate correct information.

Concluding Considerations and Future Directions

Throughout our commentary, we have described the research that we have conducted on QT_s and how initial findings suggest that our approach to enhancing high school students' high-level comprehension and STEM literacy may also support students' relational reasoning capabilities in line with the NGSS (Greene et al. 2016). Toward this end, we have offered exemplar discourse from our research in support of relational reasoning through the themes and arguments forwarded in each of the papers within this special issue. However, there is one article that we have yet to address. As we bring this commentary to a close, we will situate QT_s within the framework forwarded by Dumas (2016) while also considering a future direction for relational reasoning research.

Dumas organizes much of the extant relational reasoning literature into each of four measurement paradigms (i.e., in vivo, in vitro, in recordo, and in silico) and concludes by forwarding five principles gleaned from the review. Of the measurement paradigms, readers may identify our QT_s research as most in line with the in vivo paradigm. However, the in vivo measurement paradigm was defined as “naturalistic” and “without any manipulation”. As such, as a consideration for future research, we contend that the category for in vivo research be extended to include other research methodologies that are conducted in authentic classroom settings (Murphy and Cromley 2015). This direction is in line with one of Dumas’ principal findings—if *relational reasoning is malleable and teachable*, we believe a promising direction for future research would be to use experimental designs or design-based research to test the efficacy of intervention approaches on relational reasoning in STEM using the in vivo measurement paradigm. In doing so, students will benefit from enhanced instructional approaches designed to enrich relational reasoning in line with the aforementioned three-dimensional focus on STEM learning.

Coda

For each of the articles in this special issue, ours included, the authors have situated relational reasoning within their programs of research in order to advance the ways in which we think about preparing students for STEM careers. In doing so, the authors, themselves, engaged in analogical reasoning by mapping their respective research contexts onto the emerging research in relational reasoning. The result was a thorough examination of how students’ scientific thinking can be enriched through relational reasoning via the lenses of varied established literatures. As these literatures and lines of research grow and endure, we can look forward to continued strengthening of students’ scientific thinking and reasoning and illumination of mechanisms through which the desired educational outcomes of the NGSS may be achieved through relational reasoning with varied tasks, complex texts, and purposeful, Quality Talk.

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