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Keywords

transmedia storytelling, middle school engineering, imaginative education

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This paper describes the development of two versions of an NGSS-aligned principles of engineering design unit for use in middle schools. By employing a narrative framework that can help students to connect more deeply with the human contexts and consequences of the engineering design process, our goal was to enhance students' cognitive and emotional engagement in the learning of engineering design concepts. We first detail the design of an initial version of the unit, titled The Survivorama, which used narrative to enrich a primarily traditional, in-person teaching approach. We then describe the adapted version of the unit, titled the Molasses Disaster, and the modifications we made to the stories and transmedia story elements that facilitated the creation of a fully remote version of the unit. To investigate questions related to the effectiveness of the remote curriculum in sustaining student engagement in the remote context, we carried out a mixed-methods study that looked at (1) teachers' characterizations of the effect of the curriculum on student engagement and (2) student learning outcomes as measured by performance assessment tasks. Qualitative analysis of teacher interviews supported the notion that teachers found both versions of the curriculum to be highly engaging for their students, though with some important caveats regarding younger students and students who were less literate. Quantitative analysis comparing 2019 and 2020 student response data for students in the 2019 nontreatment, 2019 treatment, and 2020 treatment groups found statistically significant differences in the pattern of responses for both problem-solving and conceptual drawing performance assessment tasks. The pattern of responses supported the inference that student engagement was similar for students in both the 2019 in-person context and the 2020 remote context, and that both differed significantly from the 2019 nontreatment group.

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Introduction

There are several significant reasons for advancing engineering education in the pre-college setting. Among these are the need to improve general engineering and technical literacy (National Research Council [NRC], 2012), the need to develop a deeper, more interconnected understanding between engineering and other science, technology, engineering, and mathematics (STEM) areas (Chase et al., 2018), and the need to provide a critical platform for early engineering learning that can promote equity and inclusivity (Charmaine Spruill et al., 2021; Holly, 2021).

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However, the history of implementing educational frameworks to meaningfully meet these needs in classrooms in the United States has been rocky. Initial efforts by individual states to promote an agenda for pre-college engineering education produced conditions that were uneven across areas of teaching, learning, and assessment (Chandler et al., 2011). More recent attention has shifted toward cohesive national-level efforts like those of the Next Generation Science Standards (NGSS) (NRC, 2013) as the basis of a unified curriculum. And yet, as researchers and curriculum designers are learning to better articulate a systematic approach to engineering through the NGSS framework, we are also discovering a broad need for methods that can support teachers in this area, especially by improving the self-efficacy of, and content knowledge available to, pre-college engineering education instructors in K-12 classrooms (Purzer et al., 2014).

These concerns are only magnified when we consider the additional needs that have surfaced as we come to understand the historical impacts of COVID-19 on teaching, learning, and assessment. Evidence from in-process reports and first-year studies of remote learning during the pandemic has demonstrated that STEM education is suffering from a decrease in student engagement resulting from instruction in remote settings. This is an effect detected at the elementary (Soucy, 2021), middle (Ozdemir, 2021), and high school (Garbe et al., 2020) levels, as well as in post-secondary settings (Castro & George, 2021). Early studies further suggest that this decrease in engagement may disproportionally and more persistently affect disadvantaged students (Lucas et al., 2020), and, in particular, low-income, Black, and Hispanic students (Dorn et al., 2020).

For many observers, including our project team, this decline in student engagement has underscored the need for STEM educators not only to provide area-specific content for students to work with, but also to better engage with the affective needs of students (Roman et al., 2022). Therefore, our team shifted priorities to accommodate this new normal. As Brown (1992) noted a generation ago, “an effective intervention should be able to migrate from our experimental classroom to average classrooms operated by and for average students and teachers, supported by realistic technological and personal support” (p. 143). If the average pre-college engineering classroom in the ongoing COVID-19 era will include at least some remote instruction, with all the implications thereof, then researchers and curriculum developers must anticipate and adapt to the cognitive and affective needs that come with such a shift.

Adapting to Remote Learning

Prior to 2020, the Transforming Engineering Education in Middle Schools (TEEMS) project team had developed an in-person curriculum based on the theory of imaginative education (IE) (Egan, 2005) that provided a means of sustaining students’ cognitive and emotional engagement in the learning of engineering design concepts. The IE teaching approach had been previously demonstrated to be an effective way to engage learners in developing deeper conceptual understandings of engineering design, both by connecting to students’ emotions and by facilitating the conceptual transfer of key engineering design concepts (Li & Chua, 2021; McAuliffe et al., 2011).

Broadly, we sought to utilize IE as a means by which to engage students by offering a story-based approach to learning engineering concepts that consisted of three elements: (a) a coherent narrative framework that made use of developmentally appropriate cognitive tools, (b) an immersive set of interactions conveyed through transmedia elements, and (c) an integrated approach to engineering and science that aligned with the core principles of the NGSS.

The TEEMS curriculum had been originally designed to be offered to teachers in the traditional, in-person classroom setting. Activities and interactions often called on teachers to make use of in-class, hands-on activities and assessments. In response to the COVID-19 pandemic, however, we set out to strategically adapt our *principles of engineering design* unit to uphold the strengths of our curriculum and to meet the emergent need of creating a method of sustaining engagement in the remote learning context.

Early feedback from participating instructors suggested that many aspects of the initial in-person curriculum—working with physical artifacts related to the engineering story and interactive whole-class activities, for example—were key strengths of the design. Therefore, we had concerns about transitioning to a remote version without compromising student engagement. To meet these concerns, we sought to emphasize the degree to which the curriculum would capitalize on more coherent narratives and richer stories to maintain students’ engagement in the remote learning context.

Engaging Through the Imagination

A central feature of the IE teaching approach is an intense focus on using elements of story in such a way as to support both cognitive and emotional engagement in the learning process (Egan, 1997, 2005, 2010). IE provides a method of humanizing complex topics that might otherwise disinterest or disengage students (Hagen, 2013). It helps students to observe and connect to important features in the world around them (Judson, 2017). More generally, it is a teaching practice that has shown promise in engaging students in a variety of primary and secondary education settings, ranging from inquiry science (Hadzigeorgiou et al., 2012) and math education (James, 2006) to the informal study of literature (Stewart, 2014).

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The capacity of the IE teaching approach for maintaining students' cognitive and emotional engagement provided our project with a rationale for crediting that a remote version of the *principles of engineering design* unit may effectively mitigate a potential decrease in engagement through the use of narrative. However, as the use of IE in the pre-college engineering education setting is still in its infancy, there yet remain a number of open questions about its application in situations outside of the traditional classroom setting.

As such, little is currently known about the relative effectiveness of IE in asynchronous or remote settings as opposed to use in the traditional classroom setting. The lack of research on this topic is likely due to an inherent challenge of modifying traditional IE-based lessons to new formats that would take them beyond their initial, in-person, storytelling context. This is a challenge that the TEEMS project team has in the past sought to minimize by employing a transmedia approach to storytelling (see, for instance, Jenkins, 2007). Specifically, transmedia narratives are used to create multimodal variations of story-centered engineering units that can take learning beyond the in-person, synchronous, learning context.

Research Questions

Drawing comparisons between the in-person and remote versions of the *principles of engineering design* unit created by the TEEMS project team, we explored the degree to which the remote version of the unit appeared to sustain engagement. We defined this broad research goal by framing outcomes in terms of two research questions:

1. How did participating teachers characterize the effect of the curriculum on student engagement in traditional and remote implementation contexts?
2. To what extent did student learning outcomes differ between traditional and remote settings on performance assessment tasks?

Conceptual Framework

IE is a theory of teaching and learning developed by Kieran Egan (Centre for Imagination in Research, Culture & Education, 2021; Egan, 1997, 2005). The IE approach is designed to facilitate learning by building students' cognitive and emotional engagement with—and a sense of wonder about (Judson, 2017)—ideas, knowledge, and people and the world around them.

The primary means by which this is accomplished is through the use of cognitive tools which are ordered into a set of toolkits based on the type of understanding that is most salient for learners depending on their stage of cognitive development (Egan, 1997).

Cognitive tools represent individual story tropes or themes that help build student engagement with a topic and act as a mediational tool to facilitate learning. Some cognitive tools include, for example, incorporating the perspectives of heroes, using vivid images and details, and findings extremes of reality that help build a sense of wonder in students (Egan, 2005).

These cognitive tools are designed to be developmentally appropriate, such that younger students are taught using techniques that match the way in which they use their imaginations (Egan, 1997). Sets of cognitive tools are thus ordered into toolkits that help match students with their most developmentally appropriate cognitive tools (Imaginative Education Research Group, 2018).

Prior toolkits remain available from previous developmental stages, and so it is that the number and variety of cognitive tools available to teachers grow expansively across stages of cognitive development. Thus, it would be reasonable within the IE framework for a teacher to utilize tools in combination with one another, such as "vivid images" along with tools like looking to "extremes of reality" (Judson, 2017).

Our approach differs somewhat from traditional IE instruction because it centers on narrative as its principal cognitive tool, embedding a universal set of themes and ideals into our curriculum in addition to employing other cognitive tools within an individual story. As such, we make use of a methodology that stratifies the use of cognitive tools into layers of detail and specificity.

To provide a generalized formal structure, we use an encompassing thematic narrative that frames the development of both story and instruction. Within this overarching narrative construct, we then employ one or more *stories* that capitalize on multiple cognitive tools. Because middle schoolers are developing from a mythic understanding toward a romantic understanding (see, for instance, Egan, 2005), our team favors tools like "extremes of experience and limits of reality," "heroic qualities," and "dramatic oppositions." Finally, at the level of individual daily lessons or experiences, we make use of transmedia *elements* that convey the cognitive tools directly to students through a variety of interactions throughout the story. These are summarized in Table 1.

Table 1
Terms, descriptions, and examples of a narrative IE approach.

Term	Description	Examples
Narrative	A universal set of themes that form the foundation of the learning experience. The narrative contains one or more *stories*.	Engineers help others; the NGSS Engineering Design Cycle can be used to solve important problems; engineers use many kinds of approaches and tools
Story	An emotionally engaging set of circumstances that illustrate some aspect of the *narrative*. Stories are more directly guided by several *cognitive tools* and contain many *elements*.	A girl's home is devastated by a natural disaster, and she wants to help rebuild with her community; a boy's dog is blind, and the boy wants to find a way to help him
Elements	Specific details within the *story* that convey some part of the *narrative* and embody, at most, the intersection of a few *cognitive tools.*	A heroic engineer named Isaac who tries to save a doomed neighborhood; an evil corporation called Collusia that uses advanced technology to hurt people

Transmedia Story Elements

A useful consequence of the narrative-first approach to IE is that successive layers of abstraction promote a fluid relationship between the ideas within a narrative framework and their ultimate expression as story elements. Existing as they do within the bigger universe of the narrative, whole stories can be written to express the constants embedded in a universal framework, each one having a slightly different take on the underlying themes. Similarly, individual elements can be constellated to encompass essential characteristics of the story in generative and diverse combinations, no two being exactly alike.

Such dynamism in the potential of expressions also creates flexibility in the modes of storytelling by permitting combinations of elements that can easily cross among diverse media. This fluid approach is deeply informed by the notion of *transmedia storytelling*, whereby "a story unfolds across multiple media platforms, with each new text making a distinctive and valuable contribution to the whole" (Jenkins, 2006, pp. 95–96) and by which "integral elements of a fiction are systematically dispersed through multiple distribution channels with the aim of creating a unified and coordinated experience" (Contreras Espinosa & Eguia Gomez, 2017, p. 27).

And so, for example, a story element like "a heroic engineer named Isaac" can be experienced by students in documentary form as courtroom testimony (a text element), he can show up as a figure in a YouTube clip (a video element), and his artifacts can be interacted with in the classroom through a website (as graphical elements). Our hero Isaac is expressed in a range of media through different story elements, and the greater the number of elements there are of Isaac for students to interact with—and the greater the number of means by which to interact—the more fully realized the character can become. It is by weaving together many elements using a transmedia approach to storytelling that a sense of fullness and completion of story elements can be expressed to participants in the learning environment.

Study Context

The TEEMS project, funded through the NSF DRK-12 program from 2018 to 2022, investigated the use of transmedia narrative IE to develop conceptual understanding among middle school engineering students.

The curriculum was designed to align with the content standards and core disciplinary ideas of the NGSS (NRC, 2013). In summary form, the four middle school engineering design content standards were MS-ETS1-1: Defining the criteria and constraints of a design problem; MS-ETS1-2: Evaluating design solutions using a systematic process; MS-ETS1-3: Analyzing data to compare design solutions; and MS-ETS1-4: Developing a model for iterative testing of design solutions. These content standards were complemented by three NGSS disciplinary core ideas (ETS1.A, ETS1.B, and ETS1.C) that related to the three-step NGSS engineering design process.

There are two types of units in the full TEEMS curriculum. Two units, the first and final ones, are larger multi-week (two-to-three week) experiences that present engineering design concepts to students. Four smaller multi-day (two-to-three day) units occur throughout the school year and present an engineering perspective on science concepts, providing an interdisciplinary engineering/science approach to the middle school science topics of "Earth's Systems," "Biological Evolution," "the Human Body," and "Matter and Its Interactions."

Implementing Two Versions of the Unit

The focus of this paper is the initial multi-week unit that was adapted from the in-class version to a remote version. The original story for this unit was titled *The Survivorama* and the revised story is titled *The Molasses Disaster*. These stories were

Table 2
Implementation features of the two versions of the principles of engineering design unit.

Year	Story	Mode of presentation	Participation	Grades represented
2019	The Survivorama	In-person	Treatment and nontreatment	Sixth grade
2020	The Boston Molasses Disaster (2020 unit)	Remote	Treatment only	Sixth grade, seventh grade, eighth grade

meant to facilitate the teaching and learning of the *principles of engineering design* unit. Both versions of the unit were aligned with the NGSS and were designed to express concepts within the NGSS standard MS-ETS1-1 most directly. Additionally, both made use of the three NGSS disciplinary core ideas ETS1.A, ETS1.B, and ETS1.C and were created to articulate the narrative themes of "engineers help others" and "the engineering design cycle can be used to solve important problems."

Although the two versions of the unit started from the same blueprint, they diverged in the manner in which they were implemented. In 2019, *The Survivorama* was implemented in classrooms in our partner school system (described more fully in the Methods section, below) as part of a quasi-experimental study wherein both treatment and nontreatment classrooms were recruited. In treatment classrooms, *The Survivorama* unit was taught. In nontreatment classrooms, teachers delivered the standard engineering curriculum employed in our partner school district. As a response to the concerns of teachers in 2020, the project recruited participants solely into a treatment group; as such, all participating teachers used *The Boston Molasses Disaster* that year. Finally, and again in response to teacher concerns resulting from COVID-19, our team expanded from seeking participation with sixth-grade classrooms in 2019 to offering the curriculum to all middle school grades (sixth, seventh, and eighth grades).

The major differences between the 2019 and 2020 implementation of the curriculum are summarized in Table 2.

The Survivorama

The Survivorama unit introduces students to the principles of engineering design by telling the story of Monet, an adventuresome and skilled 17-year-old engineer, who faces off against the machinations of an evil corporation bent on destroying the world's climate to fuel a profit motive. Throughout the unit students will learn about:

- The overall form of the NGSS engineering design cycle.
- The use of the engineering design cycle in creating prototypes of solutions to a problem.
- To identify and consider the consequences of failures in the design process.
- To apply their understanding by engaging in a design challenge.

The overall structure and flow of the unit are illustrated in Figure 1.

Monet's Story. Video, audio, and written documents introduce the story of Monet, which frames the unit. In this section, we learn about our protagonist and how she initially was a precocious engineer who worked at the Survivorama—an artificial environment where extreme climates can be emulated—to help with the development of a SuperSuit. One day, Monet loses her access to the Survivorama. She learns from Hunter, a friend and colleague who has since hacked the Survivorama's computers, that all of the work they were doing was being repurposed to evil ends. Hunter later disappears into the Survivorama, and Monet realizes that she is in a race against time to rescue him.

Create a Class Design Cycle. A whole-class mini-activity prepares students to become active participants in helping Monet to save Hunter. Using Hunter's logbook and an old video detailing the process of engineering design, Monet calls upon students to help her use engineering methods to help her get to Hunter by designing a new, more powerful, SuperSuit.

Define, Develop, and Optimize. Across multiple day-long lessons, students work to apply what they have learned about the engineering design process to create a SuperSuit that can survive the zones of the Survivorama using different types of resources. These resources include voicemails, hacked emails, and maps (Figure 2) that allow students to better define the problem. In subsequent lessons, students use lists of resources in a "materials toolbox," as well as a SuperSuit template and prototype sketches to develop and then optimize their SuperSuit.

Monet's Story Ends. A closing video wraps up Monet's story and students transition from the Survivorama story and into the other lessons and activities of the unit.

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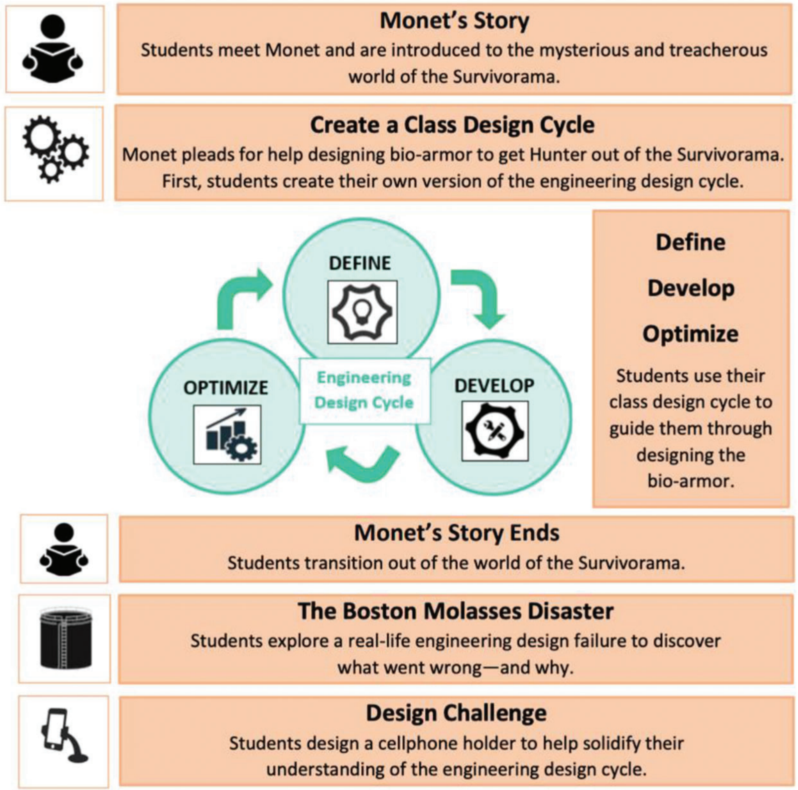

Figure 1. The Survivorama unit structure.

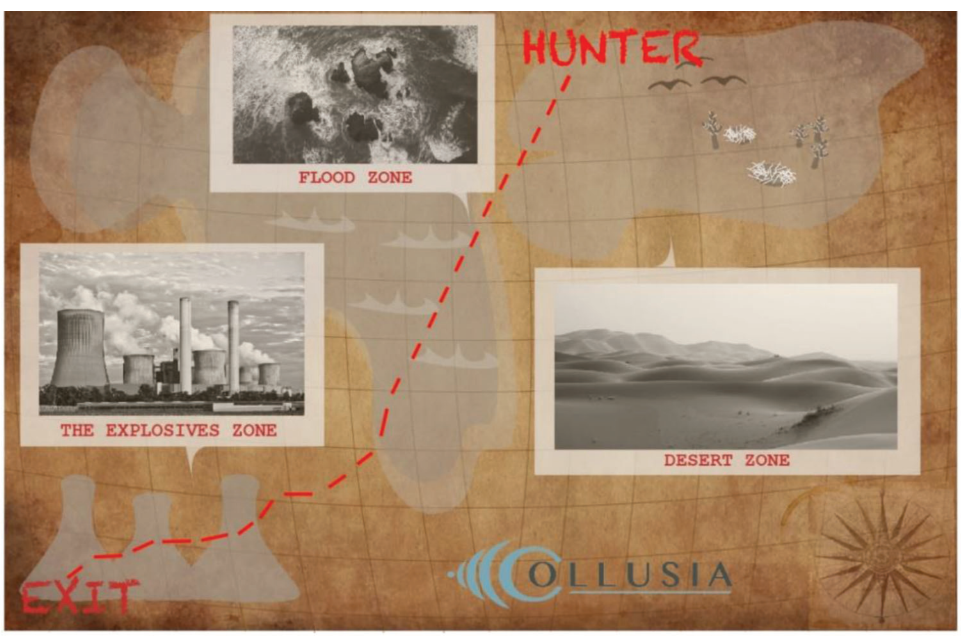

Figure 2. A map of the lethal environments within the Survivorama.

The Boston Molasses Disaster (2019 Short Story)

This second story complements the themes of the Survivorama by shifting the perspective from "What happens when we use the engineering design cycle correctly?" to "What happens if the engineering design cycle fails?"

Here, students experience the unusual tale of the 1919 Boston Molasses Disaster and are introduced to the real-life hero Isaac Gonzales, an immigrant engineer who made multiple attempts to mitigate the disaster. Ultimately, Isaac was unsuccessful, and a massively overloaded tank of molasses failed, sending a surge of over two million gallons of the substance into the streets of Boston's North End.

Students are shown the ways in which this disaster resulted from a failure to properly employ the engineering design cycle: ignoring a problem (a failure to define the problem), rushed construction of the tank (a failure to adequately develop the solution), and the materials of the tank being left untested (a failure of optimization).

Design Challenge. Recapitulating all of the prior lessons about the steps of defining, developing, and optimizing through the NGSS engineering design cycle, students are provided an in-class activity whereby they create a cellphone holder. This story is presented as a problem to students about turning cellphone use into a way to benefit learning.

Lessons Learned. As our design team began the process of transitioning the *principles of engineering design* unit to a new story for use in the remote setting, feedback from teachers who had implemented *The Survivorama* throughout the fall of 2019 helped to inform the revisions. Among these were the insights that:

- Students responded better to deeper, more realistic motives and character interactions.
- Students preferred believable settings, favoring realistic tropes over the fantastical.
- Teachers preferred a more coherent system of stories and activities, seeing the transition among multiple unconnected stories as being more challenging.

This feedback would help guide the decision to center the story on the Boston Molasses Disaster of 1919 and to build a more cohesive and complete framing story based on a realistic setting.

The Molasses Disaster (2020 Full Unit)

As with *The Survivorama*, *The Molasses Disaster* introduces students to the principles of engineering design. In this version, our story starts with the tale of Marielle and Leo, who discover artifacts related to the 1919 Boston Molasses Disaster among their grandmother's things. As they sort through the artifacts, they come to learn more about Isaac Gonzales and his role in trying to stop the disaster. Through their experiences across these interwoven stories, students will learn about the three-step NGSS engineering design process, its uses, and the consequences of its failures. The structure of the 2020 full implementation of the unit is detailed in Figure 3.

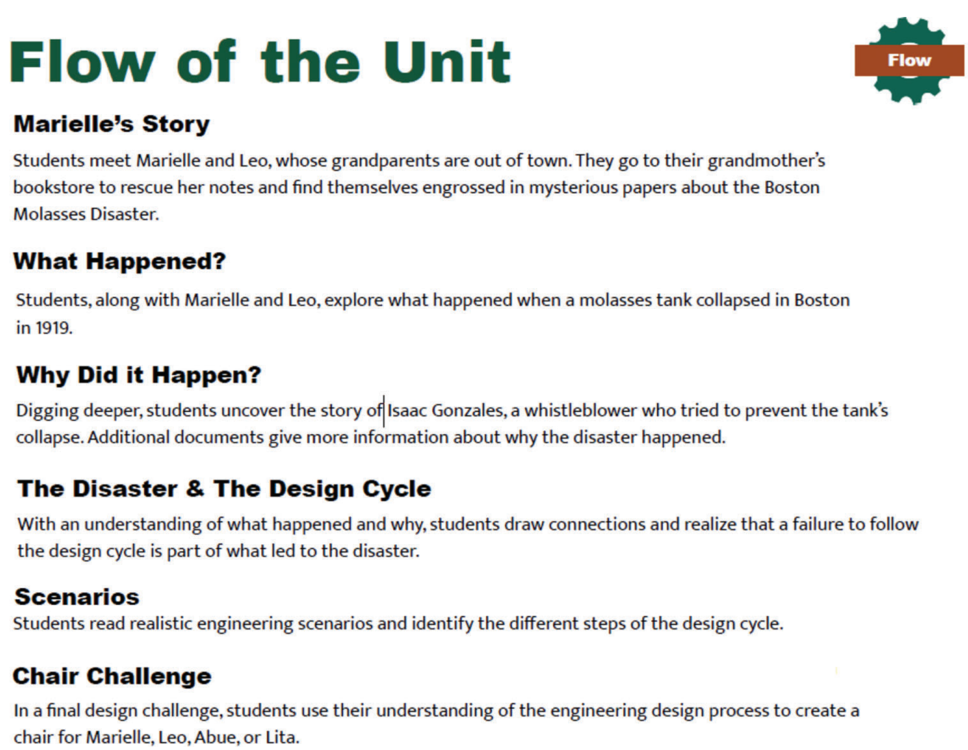

Figure 3. The Molasses Disaster unit.

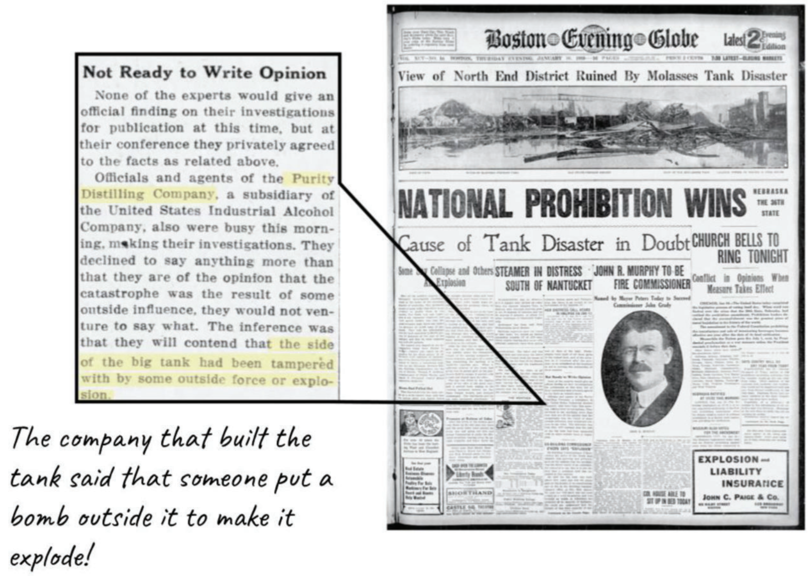

Figure 4. Annotated historical document used in the Molasses Disaster unit.

Marielle's Story. Through digital diary entries, photographs, maps, and other documents students get to know teenage Marielle and her little brother Leo. While their grandparents are away, a storm breaks out a window and threatens to destroy some of their grandmother's important documents. They learn that these documents were part of their grandmother's research into the 1919 Boston Molasses Disaster for a book she has been writing. Because the notes are all scattered from the storm, Marielle and Leo resolve to puzzle through the pieces to assemble them for her.

What Happened? Video, audio, diagrams, news articles, and other documents provide details of the 1919 Boston Molasses Disaster and tell the story of Isaac Gonzales. This version of the story is, in essence, a form of the prior "Boston Molasses Disaster" story told as part of *The Survivorama* unit (see above), but greatly expanded. It is also more strongly grounded in reality, as the digital artifacts presented for students to explore include a greater number of historical and period-specific documents that detail the response to the disaster as in Figure 4.

Why Did It Happen? This section provides a more documentary explanation of the causes and consequences of the Boston Molasses Disaster and incorporates Martin's story, which is a real-life account of how one man's life was permanently changed by the disaster. Through these documents, Marielle and Leo come to understand the human consequences that can occur when the engineering design process fails.

The Disaster and the Design Cycle. Across multiple lessons, students are guided from the failed engineering design process of the 1919 Boston Molasses Disaster and back into the world of Marielle and Leo's framing story to better understand the engineering design process and how it can work in the world around them. Videos and a teacher-led sorting activity allow students to explore the relationships among the steps of the engineering design process and the logic behind the process as a whole.

Scenarios. Using real-world problems as the basis, students explore a variety of different applications of the engineering design cycle. Each scenario provides a small story framework that introduces a problem.

Chair Challenge. Finally, returning to a story element strongly featured in Marielle and Leo's story—the joy of a comfortable chair—students are presented with an opportunity to use the engineering design process, from start to finish, to design an ideal chair that matches the needs of a particular person.

Method

To address our two research questions, we made use of a multi-method research design to gather evidence on the topic of student engagement in the different versions of the curriculum. By utilizing parallel qualitative and quantitative investigations targeting different levels of interaction with the curriculum (teachers and students, respectively), a consensus among the findings can enrich our ability to draw inferences about the phenomenon that neither in isolation would allow individually.

This approach was also, to some extent, driven by practical considerations of the project as it unfolded. Qualitative methods were more effective for gaining insight into teacher understanding of the various ways in which the curriculum would be used, and quantitative methods allowed us to model statistical comparisons between treatment and nontreatment conditions in terms of student learning as measured by summative performance assessment tasks.

To provide more contextualizing information about the study, the following subsections will describe the *participants*, *data sources*, and *procedures* employed.

Participants

School Sites

The findings for this paper are drawn from the implementation of the TEEMS curriculum in eight of the 12 middle schools in our partner school system. This school system is an urban public P-12 school district in a Northeastern state that serves more than 25,000 students. In addition to 12 middle schools, the district supports 32 elementary schools, three secondary schools (grades six to 12), and eight alternative schools. A majority of the district's students are Hispanic (67%) or African American (19%). A sizeable majority (83%) of the district's students are designated as "high needs" students—a designation that describes factors related to language needs, economic disadvantages, and/or disability status.

Data reported in this study were gathered in the first and second implementation years of a four-year, NSF-funded DRK-12 project. In the first year of project implementation, occurring in 2019, participation in the project was divided into treatment and nontreatment schools following a quasi-experimental design that prioritized balancing the population characteristics of the schools, most especially to equally represent high-needs populations in both groups. Three middle schools were assigned to treatment, and two to nontreatment conditions in 2019, each having one teacher per school participating in that condition.

In 2020, six middle schools were recruited for the project and no nontreatment condition was assigned. This decision was supported by a confluence of factors: (a) we had prior evidence of the curriculum's effectiveness as a tool for teaching engineering that might be useful for teachers during the COVID-19 pandemic, (b) we had believed that the curriculum would transition better than other alternatives into a remote version, and (c) given the enormous impact of the COVID-19 pandemic, we wanted all teachers to have the opportunity to make use of the curriculum. As such, within the six participating middle schools, there were three middle schools wherein two teachers requested to participate and were offered the TEEMS curriculum. A total of nine teachers participated that year.

The duration of implementation for the *principles of engineering design* unit was roughly the same in 2019 and 2020, ranging from a little more than two weeks of daily instruction at the minimum to slightly less than three weeks at the maximum, allowing time for students to work with various activities and to build additional background knowledge in some classrooms. The average instructional period was between 40 and 50 minutes per day.

One noteworthy difference in instruction between the 2019 and 2020 years was the grade levels represented in the study. In 2019, all six participant classrooms were sixth grade only. In 2020, there were 2 sixth grade classrooms, 6 seventh grade classrooms, and 1 eighth grade classroom across the six schools. Overall, implementation of engineering instruction across years of middle school in the state where our project is based is known to be incomplete and spotty (Chandler et al., 2011). This was an insight supported by our own experience across several years in our partner school system. For those reasons, we had cause to infer that there would be no grade-based, cumulative effect of prior experience with engineering for seventh and eighth grade students. However, to rule out this possibility, we carried out by-grade comparative analyses of the 2020 treatment data (comparing the performance assessment task scores among the sixth, seventh, and eighth grades within that treatment year, reported in the Findings section below).

Teacher Participants

Participating teachers represented a broad range of backgrounds and experiences. Our participants ranged from first-year teachers to seasoned educators closing in on their third decade of service. They worked at some of the most under-resourced schools in the district and some of the most well-resourced schools. Two teachers work in specialized educational settings—one with a focus on science and technology and one that emphasized the visual and performing arts.

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Teachers' beliefs about their own efficacy are key to instructional effectiveness (Armor et al., 1976; Ashton & Webb, 1986). At the outset of each school year, we asked teachers to self-report their engineering self-efficacy using three of the four subscales of the Teaching Engineering Self-Efficacy Scale (Yoon et al., 2014). On average, teachers reported high levels of self-efficacy on that instrument in the domains of content knowledge self-efficacy, engagement self-efficacy, and outcome expectancy (the disciplinary self-efficacy subscale was not used).

However, in interviews, teachers reported a wide range of comfort with engineering. One said, "Engineering is not my forte…it's not even something that really interests me. Whenever I'm given a choice, I don't teach engineering." Another echoed that feeling of slight dread, if not quite as stridently:

> Engineering is usually not my responsibility, but when I have done it, I've felt that there was a lack of engaging resources. A lot of what I could find was too advanced [for my students.] The district's unit…was lacking in comparison to other units they provide us with resources for.

Others, however, reported feeling comfortable teaching engineering. One recalled positive experiences teaching Project Lead the Way and the STEMScopes engineering lessons, and another talked about leading after-school engineering experiences for elementary students.

Student Participants

This study reports an analysis of summative performance assessment task data for middle school students in both the treatment and nontreatment groups in 2019, as well as the treatment group in 2020. In 2019, a total of 724 students participated in the study—410 students from three treatment schools and 314 students from two comparison schools. In 2020, a total of 391 students participated in the study from six treatment schools. The demographic characteristics of the student sample are representative of the district-level demographics, described earlier.

Data Sources and Procedures

This study drew on three data sources for our analyses: (a) *2019 teacher interviews*, (b) *2020 teacher interviews*, and (c) student responses to a *problem-solving scenario* and a *conceptual drawing* performance assessment task.

2019 Teacher Interviews

All three teachers in the treatment group participated in a focus group interview in November of 2019, following the implementation of *The Survivorama*. (The 2019 focus group was designed to be formative in nature and was therefore conducted with the treatment teachers.) Utilizing a questioning route that had been established through prior classroom observations and responses to feedback forms, a 90-minute semi-structured interview was carried out focusing on the topics of the potential added value and costs of teaching engineering through stories, strong positive or negative experiences, and overall level of student engagement in the unit. This group interview was audio recorded and transcribed for analysis. Qualitative data were analyzed using Dedoose software and basic descriptive coding followed by a pattern coding process, from which initial themes emerged (Saldaña, 2013).

2020 Teacher Interviews

During the second implementation year, sensitivities to teachers' time, schedules, and workload during the pandemic necessitated changes to our approach to gathering qualitative data. These interviews were initiated with individual treatment teachers because during COVID-19 a focus group was not possible. In late 2020, nine teachers who had implemented *The Molasses Disaster* participated in individual interviews via Zoom. Interviews were guided by a semi-structured interview protocol and lasted about 30–40 minutes each. These interviews were guided by several key questions intended to surface insights about teachers' perceptions of the overall value of the curriculum, the effectiveness of some elements of the unit, and suggested improvements. The interviews were recorded and transcribed, then analyzed using the process described above.

Performance Assessment Tasks

Subsequent to the completion of instruction of their *principles of engineering design* unit—a period ranging from October to November in 2019 and 2020—a performance assessment instrument was administered to students in classrooms participating in the 2019 treatment, 2019 nontreatment, and 2020 treatment groups. This assessment included both a *problem-solving scenario* and a *conceptual drawing* task. In general, students were requested to provide short-answer constructed responses to the prompts and were allowed a class period to complete the assessment tasks as a whole.

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The performance assessment our team used was adapted for use in the pre-college context from a prior performance assessment instrument created by Atman et al. (2008). It is detailed in Piña et al. (2021), wherein we discuss the theoretical framework for the assessment, the interrater reliability of the scoring procedure, as well as validity evidence addressing the standards of: (a) content representativeness, (b) meaningfulness, and (c) instructional sensitivity for the tasks described in this article.

The *problem-solving scenario* task consisted of a short story to orient students to a problem that could be occurring in their neighborhood and priming them to "think like an engineer." It then asked students to respond with the question: "What would you say to your neighbors about their first step in figuring out how to use the land?" Students' responses were analyzed using a rubric that focused on four aspects of engineering design thinking in student responses, scoring a point for each indication of students' use of language and ideas related to: (a) measuring, (b) modeling, (c) strategizing, and (d) collaborating. An ideational fluency score for each student was then generated by summing across all four categories.

The *conceptual drawing* task consisted of a prompt that reminded students of the value of drawing ideas in engineering and asked students to "Create your own drawing that shows your understanding of the engineering design process. Remember to include as many details as you can think of." Students' responses were scored using a five-category graduated rubric that ranked the characteristics of their drawing first by type and then by elaboration of details. A score for each student would then be assigned ranging from one (basic) to five (advanced) based on these criteria.

Instructions for how to administer the assessment, along with copies of the assessment (pen-and-paper in 2019; digital links in 2020) and an explanation of the rationale of the performance tasks and how students would be scored were provided to teachers in advance. Follow-up questions that teachers had about administering the assessment were fielded by the project's instructional specialist.

In the first implementation year, pen-and-paper assessments were received by an analysis team in the spring of 2020. For the second implementation year, a digital version of the assessment was hosted in Qualtrics, and teachers worked with the instructional specialist and employed a multitude of technical solutions to return student responses to the drawing task. Student response data were then scored by a team of trained scorers at the project's host university in the late spring of 2020 and 2021, respectively. The data were then analyzed using R software (R Core Team, 2020).

Findings

Research Question 1: Teachers' Characterizations of the Effect of the Curriculum on Student Engagement

The Importance of Real-World Stories

Across both implementation years, the TEEMS narrative appeared to effectively engage many students, but not all. During the first year, teachers suggested that students responded well to the narrative nature of the curriculum and appeared to be more engaged by narratives grounded in real scenarios than by those set in a fantasy world. Teachers strongly agreed that the Boston Molasses Disaster story was particularly captivating for students because of the local connection and because of the story's ties to Puerto Rico, which was relevant to many students' identities. On the other hand, teachers agreed that, as one put it, "students weren't as invested in the bio-armor project because it was not a real simulation… The project was not as engaging because it was not based in real life."

The narrative aspect of TEEMS appeared to become more important during the second year of the project when students were learning remotely, and the stories had been rewritten in response to year-one findings. One teacher said that TEEMS was:

> the first time I saw some of their brains and hearts turn on and start to engage in the work…It was really cool. It was like, this was the first time you've turned your camera on in the entire year so far. It was really powerful to me. It was incredible.

Another noted,

> at first they said, "this isn't real, Miss, you made this up," but once they got to dive into the court transcript, and looked at the case debrief, they had a great time just talking about the [Boston molasses] disaster. At the time, we were still working out how to have good discussions online, and that discussion is when the authenticity kind of kicked off for us.

The Importance of Relatable Characters

Especially in the project's second year, the importance of relatable characters came through as a theme from teachers. They noted that the story at the heart of the curriculum, and the characters in the story, were relatable to their students.

As one teacher expressed, students "could see themselves in the characters." Another surmised that students had developed "an identity connection, an emotional connection" with the unit because of the characters. One teacher reported that one of his favorite moments of the year came during a discussion of the story when students were inspired to share stories about their own families, backgrounds, and cultures. Another was pleased that her students got "emotionally invested" in the characters. Another said, "We spent too long talking about the characters and the story, but it was such a good discussion, you couldn't stop it." She said that, in part because school was remote, it was the first time that discussion in her class had really gotten going. Yet another reported that the unit helped some of her most disengaged students finally begin to get involved in learning:

> A number of students who had not been very engaged in the lessons prior to that point, and it was late in the year, it was the first time I saw some of their brains and hearts turn on and start to engage in the work. I noticed that many of those people who would be on zoom, but not answering questions, not doing the work, they were the ones who really connected with some of the characters in the story. It brought out that empathy in them. It was really cool. It was like, this is the first time I've had a conversation with you, and the first time you've turned your camera on in the entire year so far. It was really powerful to me, I was like, oh my god, this is incredible.

At the same time, teachers in both years also noted limitations to the narrative approach. During the first year (when the curriculum was taught in person), teachers emphasized the importance of allowing students to work with physical objects, even if that meant simply printing elements of the curriculum out on paper rather than showing them on screen. Though teachers and students enjoyed the TEEMS videos and stories, it was also noted that it is important to "bring things from the screen to right in front of [the students]." Examples of this included the need to copy/print some materials so that students could see them close up rather than on the screen, the need to create additional worksheets/graphic organizers, and one teacher bringing a jar of molasses to class because "just seeing it on the screen wasn't enough for them." Initial plans to address and understand the importance of tactile objects in the context of narrative curriculum were halted at the onset of the pandemic and remote learning; however, further investigation of this is warranted.

During the second year (and after significant changes to the stories themselves) teachers raised new cautions about the possible limits of the curriculum. Some students perceived the characters' dialogue as inauthentic. As one teacher reported, "in one of my classes they were like, 'no child talks like this, no child sounds like this.' But other classes were like yeah, that's me."

Also, teachers suggested that the narrative may have been received differently by different students. One noted, "My honors kids really resonated with it, my more special ed students were like, this isn't realistic." Another said, "There was one class, slower readers, and they were falling behind. I skipped a section [of the story], and no one noticed." Another asked if there was a way that the story could be condensed into more manageable chunks so that students with less well-developed reading and comprehension skills would be able to engage with the story without having to confront as much text. While this concern did not emerge as a major theme from teachers, the accessibility of narrative curriculum to various subpopulations of students—particularly those with learning differences—is an important consideration that merits increased scrutiny.

As a whole, emerging findings from this project suggest engaging middle-grade students with story is most effective when it is: (a) grounded in real-world scenarios and (b) made relatable by the inclusion of culturally relevant characters.

Research Question 2: Student Learning Outcomes Measured by Performance Assessment Tasks

A known feature of the distribution of responses to performance assessment tasks is that the scores most often do not tend to follow a normal distribution (Davey et al., 2015, p. 12). As such, as a first step in the analysis of student responses to the performance assessment, a preliminary Shapiro–Wilk test of normality was carried out for the *problem-solving scenario* task student response data and the *conceptual drawing* task data. In both cases, it was found that the data were not normally distributed ($p < 0.05$) for both.

However, there is a growing consensus that group-comparative statistical analyses (t-tests and F-tests) are sufficiently robust with large enough sample sizes that the violation of the normality constraint does not significantly affect the rate of type I errors (Blanca Mena et al., 2017; le Cessie et al., 2020).

We analyzed the data using both parametric comparative analyses and their nonparametric equivalents. Neither the overall outcomes nor the pattern of *post hoc* analyses differed based on the type of analysis, and so we have chosen to report the parametric analyses with the caveat that the data were found to be non-normally distributed.

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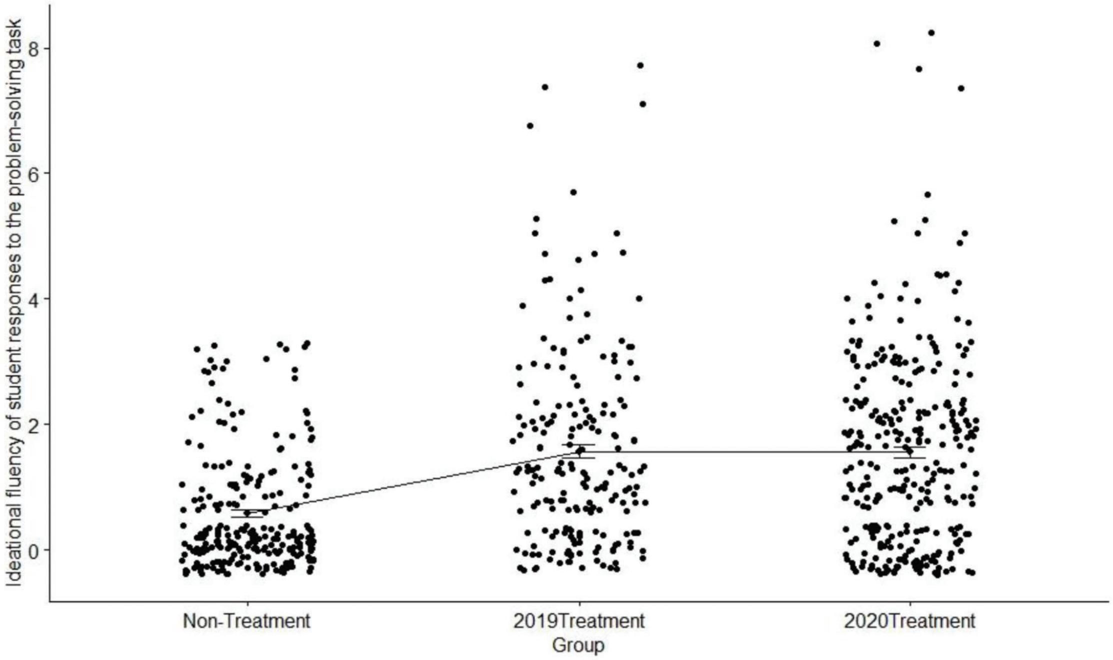

Figure 5. Mean plot of student responses to the problem-solving scenario task.

Responses to the Problem-Solving Scenario Task

The first analysis of the problem-solving scenario task student response data was carried out to address an initial concern (identified in the School Sites section, above) about the possibility of a grade-related difference in student learning outcomes in the 2020 treatment group data. A by-grade analysis comparing the sixth grade ($n = 57$), seventh grade ($n = 146$), and eighth grade ($n = 105$) responses—a one-way ANOVA—found no statistically significant differences in the overall pattern of scores.

In by-group comparisons, analyzing the student responses of 2019 nontreatment, 2019 treatment, and 2020 treatment groups to the problem-solving scenario task, there were noteworthy differences in the overall pattern. When scored for ideational fluency as described earlier (see Data Sources and Procedures), a majority of student responses for both the treatment 2019 group ($n = 194$) and treatment 2020 group ($n = 308$) to the problem-solving task had at least one response making use of engineering language and ideas (2019 = 72.1%, 2020 = 68.2%). This contrasted with the nontreatment 2019 group ($n = 236$) wherein only 36.4% of students were able to do so.

This inference was further supported by a group comparative analysis of the student response data (a one-way ANOVA) that demonstrated statistically significant differences (F [2, 735] = 40.73, $p < 0.001$, $\eta^2_p = 0.0997$) in the pattern of responses of the three groups. *Post hoc* comparisons—Bonferroni-corrected t-tests—showed statistically significant differences between the 2019 treatment and 2019 nontreatment groups, $p < 0.001$, and the 2020 treatment and 2019 nontreatment groups, $p < 0.001$. There was no difference between the 2019 treatment and 2020 treatment groups.

This pattern in the student responses to the problem-solving task can further be demonstrated in a by-group mean plot of the student response data, wherein similarities between the 2019 and 2020 treatment groups are observable, along with their shared contrast to the 2019 nontreatment group (Figure 5).

Responses to the Conceptual Drawing Task

A similar pattern was found in an analysis of student responses to the conceptual drawing task. Initial analysis of a potential by-grade effect in the 2020 treatment group data comparing the sixth grade ($n = 32$), seventh grade ($n = 106$), and eighth grade ($n = 94$) responses—again, a one-way ANOVA—found no statistically significant differences in the overall pattern of scores for this item.

In by-group comparisons, student responses from the 2019 treatment group ($n = 185$) and the 2020 treatment group ($n = 232$) showed a relatively high number of responses (2019 = 87%, 2020 = 77.2%) in which students were able to produce engineering design process diagrams at a level at or above the basic level. This stood in contrast with the nontreatment 2019 group ($n = 188$) wherein only 46.2% of students were able to produce responses at those levels.

Figure 6. Mean plot of student responses to the conceptual drawing task.

Statistical analysis provided evidence to show that there were group differences, as well. A one-way ANOVA demonstrated statistically significant differences in the pattern of responses of the three groups, F (2, 602) = 39.33, $p < 0.001$, $\eta^2_p = 0.116$. Bonferroni-corrected t-tests showed statistically significant differences between the 2019 treatment and 2019 nontreatment groups, $p < 0.001$, and the 2020 treatment and 2019 nontreatment groups, $p < 0.001$. There was no difference between the 2019 treatment and 2020 treatment groups.

As with the earlier analysis, a visual inspection of by-group mean plots of the student response data to the drawing task can illustrate both similarities between the 2019 and 2020 treatment groups, and their difference from the 2019 nontreatment group seen in Figure 6.

Summary Quantitative Inferences

Performance assessment tasks were identified early in the project's history as a means by which to capture salient indicators of cognitive and emotional engagement in the unit. Indeed, student engagement in well-designed performance assessment tasks has been identified as a benefit of this form of assessment (Potter et al., 2017) and as a necessary consideration from the standard of task fidelity (Davey et al., 2015, pp. 22–23). Student responses to performance assessment tasks can tell us more about students' ability to think with the ideas of engineering design (Schwartz et al., 2005), but only in the condition that students are willing and able to deeply engage with underlying concepts (Harrison, 2002).

If the processes of cognitive and emotional engagement were to be disrupted or obstructed by the changing conditions of the mode of instruction (as by going to remote modes of instruction), decreases in the pattern of student responses would be evidence of a negative influence on student scores resulting from the change in instructional mode. However, this is not what our findings have demonstrated. For both the *problem-solving scenario* and *conceptual drawing* tasks, the performance of students in both treatment groups was highly similar, and both performed at a level well above that of students in the nontreatment condition.

Discussion

Taken as a whole, the teacher interviews and performance assessments provided useful insights into the possibilities of sustaining student engagement across different instructional formats using the IE teaching approach in the remote setting. Our analyses provided complementary evidence to indicate that centering story is an effective way to engage students, even as we adapted our mode of instruction in response to the COVID-19 pandemic—our quantitative comparisons helped to demonstrate *that* the story was engaging in both in-person and remote formats, and our qualitative data helped to frame *why* the story was engaging in these formats.

However, there were key limitations in our approach that these analyses revealed, as well. There was some evidence to suggest that perhaps not all students responded to the stories in the curriculum equally well. Some teachers indicated that students with learning differences (i.e., students with IEPs) and less literate students (i.e., slower readers and English language learners) appeared to struggle with following the narrative as it unfolded. This inference, however, was not supported by evidence drawn from student performance on the assessment tasks.

These conflicting findings may indicate that more scrutiny must be paid to the effectiveness of this curriculum with diverse student populations. Throughout the design process, curriculum developers were sensitive to the challenge of developing a story that would engage a broad range of students. The team discussed ways of differentiating the narrative, many of which were infeasible (especially as we adapted to remote teaching) such as having multiple different versions of the story targeted at different reading levels. Others were overly complex, such as creating an adaptive narrative for the curriculum offering a variety of story pathways.

Typical remediation strategies for differentiating the curriculum would suggest providing content in new forms, such as through websites and simulations (Milman, 2014) and redesigning elements of the content to vary in terms of challenge, complexity, and readability levels (Tomlinson, 2000). These solutions, in essence, call for extensive modifications to be made to the stories and the elements they contain, which are beyond the scope of this project in its current incarnation.

Another important, and often overlooked, aspect of creating narratives for instruction is the difficulty posed in developing stories that students will find genuinely meaningful and engaging while, at the same time, instructionally useful. A good story—one that successfully balances these opposing needs—is not produced in an afternoon. It requires a novelist's skill and attention to detail, and a willingness to abandon ideas when they no longer work. In the context of curriculum design, *stories* (a type of narrative with a setting, characters, drama, etc.) also need to relate to a content-related *narrative* (the overarching connection of ideas).

Throughout this process of developing and redeveloping the *principles of engineering design* unit, our curriculum development team reflected on the nature of these challenges. One clear struggle was the development of stories that strongly resonated with students. As a project team member noted: "we had to constantly iterate, abandon stories that didn't work, even if we thought they were good stories" and how this was "an incredible process of evolution." They indicated that this was not always easy because:

> We couldn't be too attached to anything. We had to abandon a lot of good ideas, even once they were completely worked into the curriculum, usually based on feedback from teachers. You have to put your ego and investment aside.

When asked what constituted a story that successfully engaged students in engineering, our design team reported that:

> A story has to be realistic enough that kids buy into it, but not mundane. The best stories are those where we pull out universal themes that kids have experienced—like friendship, loneliness, conflict…A good story is stand-alone—our stories don't exist just to support the curriculum. Our stories could stand alone without any attached curriculum.

At the same time though, a key question that guided the curriculum's development was: Why would this kind of engineering matter to students? Here, the interplay between narrative and story was seen as essential. One of our curriculum team members summed up the overall narrative of the project as:

> Engineers are people who help people, help the community. They solve problems to make the world a better place… In TEEMS, stories are connected to that narrative, videos are connected to it, activities are connected to it; it is all helping students deepen their understanding of this narrative.

The COVID-19 pandemic was a challenge to educators and researchers in the pre-college engineering education context and beyond. However, it created a unique opportunity to explore questions about remote instruction that would have otherwise been impossible. Based on our experiences creating two versions of the *principles of engineering design* unit, it seems to be the case that narrative instructional approaches that carefully leverage good story can be effective in both in-person and remote settings. Future work is necessary to support the tentative findings that we have presented here, especially given the limitations of the study wherein so many simultaneous modifications were made to the curriculum as a response to the conditions of the pandemic. Furthermore, given the time- and resource-intensive nature of this type of curriculum development, future research will help determine if the extent of students' academic and affective gains warrants the substantial investment required.

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