Title: Design Principles that Guide Co-Design Activities in Partnership Toward New Possibilities of Science Learning at Schools

Abstract

Despite the decades of reform efforts, the ways in which minoritized students experience science at schools remain mostly unchanged. There is an increasing consensus among researchers that transforming classroom practices necessitates collaborative efforts among researchers and practitioners through a long-term, meaningful partnership. This study presents a set of design principles (DPs) emerging from several years of design work with high school science teachers and university researchers towards providing engaging and empowering science learning experiences for Latinx, multilingual students, and students from socioeconomically disadvantaged communities. We posit that e*ngaging and empowering experiences* not only facilitate minoritized students to expand their ways of making sense of the world, but also develop identities as people who enjoy, value, and use science to make a difference. We propose a conceptual argument that design principles are a form of principled practical knowledge (Bereiter, 2014) providing practical guidance and mediating professional interactions in a complex partnership setting. We illustrate and unpack how the principles guide successful transformation of teaching practices with examples from a co-designed high school physics unit about momentum. This study is significant in that it sheds light on important, and often invisible, processes of co-constructing student experiences mediated by teachers' principled and intentional pedagogical actions. In addition, the characteristics of design principles that facilitate transformative collaborative activities in a partnership are theorized.

key words: design principles, research-practice partnership, participatory design research, co-designing

Introduction

With the call for addressing the inequity and injustice experienced by minoritized students at schools, there is increasing attention to participatory design research where researchers and practitioners formulate a long-term, democratic partnership and work together toward transformative changes in disciplinary classrooms (Bang & Vossoughi, 2016; Fishman et al., 2013; Gutiérrez & Jurow, 2016; Penuel & Gallagher, 2017). This paper presents a set of design principles that advance theoretical knowledge in design research and provides practical guidance for researchers and practitioners working together to transform teaching and learning in science classrooms. As a form of principled practical knowledge that communicates know-how combined with know-why (Bereiter, 2014), the design principles support the co-design of meaningful science learning experiences for students from non-dominant communities by mediating professional interactions in a complex partnership setting.

The principles presented in this article emerged from several years of design work between high school science teachers and university researchers to solve practical problems in a local context. The focus was on supporting the academic success and well-being of Latinx, immigrant, multilingual, and female students from low-income families in secondary science classrooms, in particular in physics and chemistry courses--gateway courses to the STEM fields where women, Black and Latinx are the most disproportionately underrepresented (National Center for Science and Engineering Statistics, 2020). In this project, a group of high school science teachers and university researchers co-designed and implemented curricula and assessments to provide students with engaging and empowering learning experiences. The team conceptualized that e*ngaging and empowering experiences* not only facilitated minoritized students to expand their ways of making sense of the world, but also developed identities as people who enjoy, value, and use science to make a difference. With this aim, the team engaged in a “pedagogical imaginary” (Gutiérrez & Calabrese Barton, 2015) to provide transformative science learning experiences for students (see the details of the collaborative design processes in Author & other, 2021). The analysis of professional interactions revealed the centrality of the design principles of in setting and working toward pedagogical goals. Specifically, the design principles mediated the team to develop shared pedagogical goals and language, facilitated the teachers to connect their own personal concerns to the goals, and supported teachers’ collective reflection on the ‘why’ of their practices (Author & other, 2021). The analysis of student performances in the co-designed unit provided evidence of the expansion of meaningful learning opportunities for Latinx and female students in high school physics classrooms (see the detail in Author & others, under review). Building upon these research findings, we intend to further advance the knowledge base in design research by unpacking one form of generalizable knowledge produced through the design work. In our view, this set of design principles can function as a ‘ladder’ (Bereiter, 2014) leading to potentially radical design improvement by providing practical guidance toward transforming science teaching and learning at schools. One important question in the field of design research is how design work might contribute to more generalizable knowledge about learning (Bereiter, 2014, Brown, 1992, Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). This article presents a set of design principles as a form of generalizable knowledge that can be used across different disciplines of sciences, grade levels, and schools demonstrating that local design work can contribute to the advancement of the knowledge base in the learning.

This article is organized in the following way. First, we discuss the challenges in transforming science teaching and learning at schools toward social transformation, and how design principles might help to address the challenges. Next, building upon the decades of research on science teaching, learning, and equity, we present a set of design principles as a conceptual tool for guiding the co-design of transformative science learning through partnership. We present one co-designed physics unit to illustrate how the design principles guide teachers' pedagogical actions which eventually come alive in the form of student experiences. The article concludes with the discussion about theoretical and practical significance of the work.

Research questions:

1. How do these design principles guide teachers' intentional pedagogical actions?
2. How are students' experiences mediated by teachers' pedagogical decision-making?

Literature Review: Challenges for Transforming Disciplinary Teaching at Schools for Equity

Our proposition of using design principles in partnership is informed by three challenges facing the educational community. The first two challenges have to do with the disconnect between the knowledge produced by researchers and practitioners. The third one is associated with the complexity of transforming classroom practices in local contexts.

#1: Using the knowledge produced by research in practice

The first challenge is ***facilitating the use of the knowledge produced by research into practice***. Despite implementation challenges, over the last few decades, research on science teaching and learning has made substantial progress in shedding light on the persistent inequities in science learning opportunities across different student groups. For one, significant gaps in science learning opportunities among students of color in communities with high concentrations of families living in poverty are associated with historically persistent and systemic racism, classism, sexism, and heterosexism (Calabrese Barton, 2001; Hand et al., 2012; Ladson-Billings, 2006; Rodriguez, 1998). Therefore, promoting equity in classrooms necessitates a multifaceted approach that attends to power, teaching, and opportunities to learn (Hand et al., 2012). It is necessary to attend to and directly address historical inequities, what Ladson-Billings (2006) calls "educational debt." Researchers even provide some examples of promising approaches, such as expanding who participates in designing policies and programs in science education (e.g., Bang & Medin, 2010; Birmingham et al., 2017), broadening the notions of what counts as science learning (e.g., Bang et al., 2012, Warren at al., 2020), attending to the organizational processes that limit opportunities to learn (Hoadley et al., 2017), and connecting curriculum to students' interests and experiences (Penuel, 2017).

From an instructional point of view, there are several promising research-based frameworks or pedagogical approaches developed by scholars to help teachers to address inequities through the work of teaching. They include culturally relevant pedagogy (Ladson-Billings, 1995), culturally sustaining pedagogy (Paris & Alim, 2017), culturally responsive teaching (Gay, 2010), community cultural wealth (Yosso, 2014), culturally congruent teaching (Au & Kawakami, 1994), leveraging funds of knowledge (González et al., 2006; Moje et al., 2004), and rightful presence (Calabrese-Barton & Tan, 2020). And the list continues to grow. Each framework provides important insights into the type and nature of challenges facing minoritized students at school, offering promising instructional approaches for supporting the students. For example, González and his colleagues argue that the key to promoting equity in science classrooms is to leverage marginalized youths' funds of knowledge to create a hybrid space in classrooms (González et al., 2006; Moje et al., 2004). Leveraging funds of knowledge is different from the generic notion of "building on prior knowledge" or "connecting to everyday experiences." This necessitates teachers making two critical shifts that profoundly affect their curriculum design and enactment with students. One is developing a dynamic, practice-oriented view about culture as the ways in which people organize and make sense of all experiences. The other is debunking the pervasive idea of racially and economically marginalized households as lacking worthwhile knowledge and experiences (Gonzalez et al., 2006).

Despite the increasing volume of research, such knowledge is rarely used by practitioners to transform actual classroom practices in ways that promote equity and justice. For example, the research-based idea of culturally responsive teaching is well-received by practitioners and yet poses challenges. In one survey of almost a hundred teachers across the U.S., researchers found that 86% of teachers felt favorably about the impact of culturally responsive science teaching (Harris et al., 2018). However, they also found that implementation was a significant concern. Educators struggle with designing and implementing lessons that go beyond student-driven inquiry or constructivist teaching practices (Patchen & Cox-Petersen, 2008). Researchers found that teachers need more guidance on what culturally responsive science lessons look like (Brown, 2017), and integrating culturally relevant pedagogy with the new science standards moves the field into "new frontiers that require substantial input from in-service teachers" (Harris et al., 2018, p. 193). One important challenge facing the education community is facilitating practitioners to use the knowledge produced by the researchers to make a real difference in minoritized student learning (Bryk, 2015; Coburn & Penuel, 2016; Penuel, 2017).

#2: Leveraging practitioners' rich knowledge about students and communities

The other related challenge is ***leveraging practitioners' rich knowledge about students and their communities*** to support minoritized students' meaningful disciplinary learning in classrooms. The advancement of the scholarship on teaching reveals the context-specificity of instruction and the need for flexibility and principled adaptation in design and implementation to support minoritized students in local contexts (Carter & Darling-Hammond, 2016; Gitomer & Bell, 2016; Hatano & Inagaki, 1986; Penuel at al., 2007). Providing engaging and empowering science learning experiences for minoritized students requires a teacher's deep contextual knowledge as well as trusting relationships (Author, in press; Ladson-Billings, 2009). Expert-developed, prescribed curricula are fundamentally limited since they are developed without knowing the students they serve, therefore not connecting with the students' cultural experiences, interests, and concerns situated in a particular time and place. Teachers' rich knowledge about students and communities is an invaluable resource for designing powerful learning experiences with a particular group of students (Gay, 2010; Ladson-Billings, 2009).

In addition to the necessity of leveraging practitioners' deep knowledge, researchers draw our attention to the ways in which such knowledge is leveraged in partnership, pointing out that the *process* of partnering shapes the possible forms of learning that emerge in and through collaborative efforts (Bang & Vossoughi, 2016; Vakil et al., 2016). Bang and Voussoughi (2016) identify three key features of partnering that affect both the process and outcomes of partnership: critical historicity, power, and relational dynamics. In traditional education research, for example, power dynamics are typically manifested through the relationship between the researcher and "the researched" (i.e., subject-object relationship). Disrupting these power hierarchies is foundational to create equitable and justice-oriented learning experiences for students. Accordingly, an equitable partnership needs to elevate practitioners' deep knowledge of the communities they work with and the contexts they work within, placing this expertise on equal footing with knowledge provided by researchers in the processes of studying, designing, implementing, and innovating educational programs (Bang & Vossoughi, 2016; Bryk et al., 2015; Coburn & Penuel, 2016; Gutiérrez & Jurow, 2016).

#3: Working on the classroom activity system

The last challenge we intend to address within partnership activities is ***working on the classroom activity system, beyond working with individual teachers***. Historically, reform efforts have attempted to address one or at most two elements of the classroom activity system that are known to affect unequal science learning opportunities in classrooms (e.g., teacher, curriculum, assessment, policy). For example, numerous reform efforts in the field of science education focus on providing expert-developed curricula that supposedly support minoritized students' learning (e.g., culturally relevant curriculum) via one-shot professional development.

Recently, there is a growing awareness among researchers that working on multiple components of a classroom activity system, instead of trying to fix only one factor, is necessary for providing meaningful science learning experiences for minoritized students (Author & other, 2021; Bryk et al., 2015; Penuel, 2017). The multiple components of a classroom activity system, including teachers, students, curriculum, practices, norms and relationships, work together to shape students' experiences in classrooms. Improving a classroom activity system necessitates concerted, purposeful, and ongoing pedagogical actions across planning, teaching, and assessment toward community-valued goals. For example, teachers need to carefully select curricula that are culturally relevant to their minoritized students. Teachers also need to skillfully facilitate classroom interactions while attending to, leveraging, and responding to students' diverse ways of thinking, talking, and doing based on deep respect for the knowledge and experiences of students (Author, in press). In addition, creating multiple ways of being 'successful' with the careful design of a classroom assessment system is crucial to support minoritized students' meaningful disciplinary learning (Author & other, 2021; Author & other, under review). A set of design principles that provide practical guidance can help educators to work on/with the *system,* instead of tackling just one component of the classroom activity system (e.g., curriculum) in a flexible and principled way.

Summary. The recent attention to research+practice partnership in the educational community has to do with the prospect of such research programs in creating a context for addressing the three challenges outlined above. In our view, the key to a successful partnership is to create 'a point of contact' where both researchers and practitioners can bring their expertise, formulate a democratic relationship, and work together to engineer engaging and empowering learning experiences for minoritized students in local contexts. In such partnerships, it is crucial to mediate the interactions among multiple people who bring diverse individual concerns, values, experiences, and different priorities for transformative and consequential learning. Design principles, as a conceptual tool, can help to mediate such professional interactions in a complex partnership setting.

Conceptual Framework: Design Principles as a Conceptual Tool for Guiding Principled and Collective Pedagogical Decision-making in Partnership

As concise phrases, the proposed design principles (DPs) communicate key lessons from prior studies on how and under which conditions students from non-dominant communities engage in science meaningfully. For example, numerous prior studies report that students from non-dominant communities are more likely to engage in science meaningfully when they feel the topic of the study matters to them or people whom they care about (Birmingham et al., 2017; Calabrese Barton & Tan, 2010). This key idea and other implications of prior studies is synthesized into our design principle of 'make it matter.' One important feature is that DPs specify pedagogical goals ("why" of practice), rather than describing actions, activities or strategies ("what" of practice). By specifying *goals*, teachers are positioned to leverage their rich contextual knowledge about the communities and students to make their own professional decisions about pedagogical actions when tailoring to their own classroom contexts. In this way, DPs empower teachers as active designers and engineers of student experiences, instead of passive consumers of expert-developed curricula (Author & other, 2021).

In the focal partnership project, a group of high school science teachers and researchers worked together to transform science teaching and learning toward the expansion of minoritized students' opportunity to learn. A set of five design principles were used throughout the partnership to mediate their professional interactions. The design principles were: (a) make it matter, (b) support sensemaking, (c) attend to race, language, and identities, (d) build a welcoming community, and (e) disrupt power hierarchies. Each of the principles drew teachers' attention to an aspect of the classroom activity *system* that shaped minoritized students' learning experiences, and then motivated teachers to take deliberate pedagogical actions to create a better context for students' engagement. The proposed five DPs are not mutually exclusive; rather, they are tightly related to each other. Additionally, the DPs are not static, inflexible tenets but instead an evolving framework that is meant to be modified through partnership activities with teachers over time. The following unpacks each of the DPs.

Make it matter. The first DP is grounded in the literature that studies minoritized students' science learning in and out of school settings. Historically, the science that minoritized students encounter at schools has been disconnected from their lives. These students are more likely to be tracked into low-level courses, which are off-putting due to their focus on rote memorization and completing worksheets rather than inquiry-based exploration (Parker, 2014).

Latinx students have pushed back against curriculum that they find “unhelpful for their economic future and, simply, boring” (Villenas & Deyhle, 1999, p. 427). Not surprisingly, research shows that youths, especially those from economically and racially non-dominant communities, are more likely to engage and learn science at schools when they feel what they do in classrooms matters, whether to them or to the people they care about (Birmingham et al., 2017; Calabrese Barton & Tan, 2010). This sense of mattering refers to establishing a personal connection and seeing a real impact of their work on the condition of students’ lives and their communities, either in the present or in the future. From our perspective, this construct of mattering is different from other motivational constructs, such as interest or relevance. Things that are interesting or personally relevant do not necessarily matter (Stuckey et al., 2013). For example, a video that shows a ‘magical event’ (e.g., a singer shattering a wine glass without touching it) can spark interest and curiosity for most students in the moment, but students don’t necessarily feel that understanding the science behind this phenomenon matters to them, especially for those who have difficult life situations (see Tan & Calabrese-Barton, 2017 for example). Instead, making it matter is related to altruistic consequentiality, where students find phenomena meaningful when their investigations have a positive influence on the lives of people whom they care about. This sense of mattering is deeply personal and dependent heavily upon historical, social, geographical, and political contexts where one’s lives are situated.

Support sense-making. The second principle is directly related to the goal of science education in the recent reform documents (NGSS Lead State, 2014; NRC, 2013). The discipline of science fundamentally concerns deepening one’s understanding of how the world works (TSTS, 2007; NRC, 2013). Different from the generative work that scientists do, historically, students tend to experience science as the final form of answer at schools (Duschl, 1990). The instruction often focuses on delivering canonical scientific knowledge or skills while positioning students as passive receivers or someone who has 'wrong' ideas that need to be fixed. The principle of supporting sense-making calls for re-framing the relationships among knowledge, learning and learners in science classrooms. It involves positioning students as capable sense-makers who exert their epistemic agency to deepen their understanding about the world while expanding their ways of thinking, talking, and doing (Herrenkohl & Mertl, 2010; Schwarz, Passmore, & Reiser, 2017).

Supporting students' sense-making has been a major focus of science education research. There are several promising frameworks, tools, and strategies suggested by researchers that can be leveraged to design student experiences toward this goal (e.g., Windschitl et al., 2012; Reiser, 2014). Some examples of the research-based strategies are framing a unit around a phenomenon or problem; beginning the sequence by eliciting students' ideas and organizing activities in a way that supports ongoing changes in student thinking; and developing a cohesive unit storyline where each lesson is driven by students' questions. At the stage of enactment, students should be guided to engage in scientific and engineering practices to expand their sense-making repertoires (ways of thinking, talking, and doing). Researchers highlight the important role of classroom discourses facilitated by teachers in expanding students' understanding about the world (e.g., McDonald & Kelly, 2012; McNeill & Pimentel, 2010; Kelly, 2007; Michaels et al., 2002).

Attend to race, language, and identities. The third principle is grounded in the critical scholarship that reveals the role of race, language, and identities in shaping students' learning experiences at schools (Bang et al., 2012; Calabrese Barton, 2001; Hand et al., 2012; Kelly, 2007; Villenas & Deyhle, 1999). Researchers have documented the struggles of students of color and multilingual students in navigating the spaces across home, community, and schools in a highly racialized and deeply unjust society that has been constructed through the history of colonization (Villenas & Deyhle, 1999). Students from non-dominant communities constantly have social encounters that undermine their rightful presence as members of the scientific and classroom community (Calabrese-Barton & Tan, 2019). For example, during one of our student interviews, a Latinx boy shared his experiences of being accused as a 'stealer' when the adults at school were "racially profiling" him. He didn't feel like he belonged on school grounds and although he had maintained a love for science, he didn't share it with most teachers or peers. The principle of *attending to race, language, and identities* intends to draw teachers' attention to students' racialized experiences that they encounter every day, both inside and outside the classroom. This principle also draws teachers' attention to structural inequities that create differential access to resources and opportunities across students along with racial, linguistic, cultural, and socioeconomic lines in historical and political contexts. Researchers note that this 'thick' perspective on equity is foundational for teachers to make complex interpretations about students' academic performances and behaviors in classrooms (Author & other, 2019). This principle points to the importance of creating a space where students feel comfortable to be who they are; where students use their home languages and practices to *do* science and students think of themselves as valuable members of a classroom learning community. Since minoritized students' identities are multifaceted, it's important to not essentialize or stereotype, and bring in dimensions beyond ethnicity and race. For example, leveraging local youth culture or interests and hobbies such as music or sports (Irizarry, 2007). Additionally, students can leverage forms of expression not typical in science class including informal language, drawings, and sense of humor.

Building a welcoming community. This principle is closely linked to the third one, *attending to race, language, and identity* in that it aims to support the rightful presence of students who have been historically marginalized in science classrooms. Whereas the third principle facilitates teachers to design academic tasks where students leverage students' everyday experiences, practices, languages, and identities to do science at schools, the principle of *building a welcoming community* draws teachers' attention to a non-academic aspect of teaching, that is the classroom culture or atmosphere built around cumulative interactions and relational work. A recent study about teachers' responsiveness that promotes equity shows how brief non-academic interactions between the teacher and minoritized students can be consequential in students' opportunity to learn (see Author, in press). For example, a teacher's friendly introduction of a recently immigrated Vietnamese student to the other peers helped the students to form new social relations, and support the students to intellectually contribute to the group task despite the linguistic challenge. Through the detailed analysis of 658 events from six lessons, Author found that a responsive teacher continuously attended and addressed minoritized students' relational challenges--their difficulties of relating themselves to people (i.e., peers and the teacher), the space, and discipline--in addition to supporting their disciplinary engagement. The classroom culture is co-constructed by both the teacher and students who bring their own life histories (Milner et al., 2018). Creating a space where minoritized students feel welcomed, valued, and socially and emotionally connected with people is foundational for the students to engage in deep intellectual work (Milner et al, 2018).

In our partnership, high school science teachers noted that this principle attended to a broader issue beyond the development of a storyline, curriculum, and assessment of a unit. The teachers also agreed that it was unlikely that students from non-dominant communities would engage in science meaningfully without building such a welcoming culture grounded in teachers' intentional, cumulative, and ongoing relational work. Therefore, they needed to work on this from day one because equity could not be achieved simply by having a well-designed curriculum. This principle serves as a frequent reminder that facilitates teachers to be intentional about the relational work that they do on a daily basis, including when they enact the co-designed curriculum and assessments.

Disrupt power hierarchies. There is an increasing awareness among science education researchers that addressing inequity in disciplinary learning necessitates careful attention to the power dynamics in classroom settings (Hand et al., 2012; Agarwal & Sengupta-Irving, 2019). Research shows how learning in schools has traditionally been racially coded and cultured in oppressive ways for historically marginalized groups (Bang & Medin, 2010; Mensah & Jackson, 2018). The power is systematically distributed in classrooms along racial or linguistic lines while norming particular ways of doing, talking or being as appropriate or better but not the others. Critical scholars point out the "Whiteness" of school science, as it privileges a Eurocentric knowledge frame over others (Mensah & Jackson, 2018). The prevalent forms of school sciences put students, particularly those from racially, linguistically, and socioeconomically non-dominant communities, in "untenable epistemological positions that work against engagement in meaningful science learning" (Bang & Medin, 2010, p. 302). Accordingly, critical scholars point to de-settling the settled expectations of what it means to do science or be good at science at schools as a key for addressing inequity. The principle of disrupting power hierarchies aims to create expansive learning experiences where various ways of thinking, talking, and doing are leveraged, recognized, legitimized, and valued toward collective construction of knowledge in a classroom learning community.

Researchers note that disrupting power hierarchies involves teachers' sensitivities to 'multiplicity' (Warren et al., 2020)--multiplicity of doing sciences in the professional science communities as well as multiplicity of students' diverse ways of thinking, talking, doing and being. This sensitivity facilitates teachers and researchers to ask critical questions of what is counted as 'science' at schools, what it means to be good at sciences at schools, who is positioned and recognized as 'be good at science' and who is not, and why. It is necessary to problematize simplistic dichotomies that set the hierarchy, such as right or wrong, good or bad in order to disrupt power hierarchies and create learning experiences that are equitably consequential.

Design Principles in Action: Teaching a Physics Unit, Momentum

We present one co-designed physics unit to illustrate teachers' pedagogical actions guided by the design principles and how the design principles came alive in the form of student experiences in classrooms. The co-designed unit was enacted in the 11th grade physics classrooms at one high school in the fall semester in 2019. The students were mostly from Latinx, low-income families. The overall unit storyline as well as analysis of student performance in this unit was presented elsewhere (Author & others, under review). Table 1 presents teachers' *intentional* pedagogical actions guided by each of the design principles. Due to limited space, here we highlight only a few pedagogical actions with respect to each design principle.

--Insert Table 1 about here--

Make it matter

The teachers were committed to making their physics content truly matter to students, and purposefully employed numerous pedagogical actions toward this aim as they designed the curriculum, facilitated classroom interactions, and designed and enacted assessment (see Table 1). Due to space limitations, we highlight two of these actions. One notable pedagogical action observed during the co-design activities was humanizing the learning of physics. The teachers developed the unit storyline focusing not on the principles of momentum but instead on how students could make the world a better place for someone they cared about. Enacting this humanized design depended heavily on how the teachers framed the unit's focal problem and overarching question and kept the framing throughout. Accordingly, for the second pedagogical action, we highlight how the teachers launched the unit on the first day in a way that fostered deep personal connections.

#1: Humanize the design of physics learning by focusing on how students could make the world a better place for someone they cared about. Redesigning the unit storyline was key to the teachers' commitment to making their classroom investigations impactful for students. Throughout the unit, students learned more in order to answer the essential question the teachers devised,"How are modern cars designed to keep you and your loved ones safe in a collision?" This shift was intentional on the part of the teachers, and they reported that in the previous year the "momentum unit" focused more on math, learning formulas and definitions, and solving problems such as conservation of momentum. In the beginning of the design process for the updated version of the curriculum, the teachers discussed what they felt mattered to students, including spending time with their family and friends, becoming adults, and learning how to drive. While they initially considered designing a dream car, they shifted the focus to protecting a loved one to put others at the center of the learning experience. The topic extends beyond personal relevance and their identities as new drivers, because by protecting their loved ones, they are solving a problem that affects people they care about and forming more deeply personal connections within historical, geographical, and social contexts.

The teachers kept the same general activities as the prior year, but framed them differently to connect the physics content with students' interests and home lives. One of the teachers, Ms. Davis reflected on the previous year explaining:

> "We still talked about car collisions, but we didn't make a personal connection, or give them the chance to make that more meaningful for them. We had hands-on labs, just like before in experiences but to have them connect it back to their community, their families, the people they care about, that was probably the biggest difference and that set up a lot of the buy-in when we were early on in the unit."

While the activities such as the egg drop lab or collision carts contained the same physics content, students related in very different ways due to the overarching framing of the unit and the teachers' explanations of how each activity fit within the bigger picture of protecting students' loved ones in a collision. In addition to reframing existing labs, teachers added new activities such as drawing and sharing about their dream car, designing a car for their loved one, and writing a letter explaining the car's personalized details and safety features. The focus on making it matter guided teachers to shift their material and focus, generating new forms of learning that put people at the center of learning physics.

#2 Facilitate students to make deep personal connections to the activities. Not only did the 'make it matter' principle guide the teachers' design of curriculum and assessment, but also their enactment with students in classrooms. On the first day of the unit, students started by envisioning their loved one and a car for them, rather than learning the definition of momentum or seeing the equation for Newton's second law on the board. To introduce the essential question that would drive the unit, Ms. D. invited students to visualize someone they cared about:

> I want you to think about **someone in your life, who you care about**, someone who has cared about you, who was taking care of you when you were sick, when you were down on your luck, or just down in general...Do you have someone in mind? Now I want you to fast forward, 20 years from now. You guys have been all successful in your lives...Now you have extra money to share. And this person, who you care about and who cares about you, comes to mind. **I want you to think about, what kind of car would you design for this person?**

After this introduction, students created personalized car designs, forming new attachments with both peers and the physics content. But beyond personalization, the cars were designed as an act of gratitude and connection to someone "who you care about and who cares about you." Students were asked to draw their car designs, list important design features, and write a note to their person describing their car. When they shared their designs with other classmates, students showed how they included GPS in Spanish to help their parents navigate, back-up cameras to protect their siblings with learner's permits, and four wheel drive for their friend who enjoyed camping and off-roading. From the first day, students saw how physics related to everyday life, with a direct connection to the people and things that mattered to them. The launch was not used as a "hook" to make them interested before launching into the science content. Instead, all the activities that followed this first day were organized within the central question of "How are modern cars designed to keep you and your loved ones safe in a collision?

Throughout the unit, students shared their designs with peers and the teacher and learned more about the people, places, and things students cherished. At the end of the unit, students explained how their car followed physics principles to decrease the impact in a collision, but connected these ideas to memories and stories when explaining to their loved ones how it worked and how it was designed especially for them.

The teachers reframed previous activities, included new personalized activities like the letter and car design, and communicated to students that they were not learning about momentum for the sake of developing abstract physics content knowledge but to understand and impact the world around them. Although students engaged in standard physics labs such as collision carts and the egg drop lab, they watched dash cam footage, received collision incident report forms for real car crashes, and envisioned the egg as a passenger to investigate how materials impact a collision. The unit included everyday relevance for these young people learning how to drive, while also protecting their loved ones.

Support sensemaking

Here, we describe three intentional pedagogical actions the teachers took while designing and enacting curriculum and assessments to support students in making sense of the world around them (see Table 1 for the other actions). The key to supporting sense-making was drawing students' attention to observable changes, supporting students to notice important patterns in the focal phenomenon, and providing new experiences that expanded the ways in which students thought about the processes of the phenomenon using unobservable or theoretical ideas.

#1: Highlight key observations or patterns, and formulate questions that focus on how and why. The teachers selected the problem of safety in a car collision to create a context for students to engage in sense-making while addressing the ideas of momentum and impulse. The teachers first drew students' attention to the things happening in their local community over the past 100 years in terms of car collisions. Specifically, students were presented with information about the changing car crash fatalities in the state of California (CA) from 1918 to 2018 using the graph and numbers (from 24.09 to 1.02). Next, they were informed that the most popular car in CA in 1918 was Ford Model-T and it was Toyota Camry in 2018. They looked at the graphs and schematics of the cars (see Figure 1).

--Insert Figure 1: making observations and noticing important changes, patterns, or relationship--

While noticing the dramatic decrease in car crash fatalities over time along with the changes in car design features, the following question was posed on the second day of the unit: *How do the design features present in modern cars contribute to fewer car crash fatalities over the past 100 years?* In the initial assessment conducted on that day, students were tasked to draw and explain *what* might happen to Model-T vs. Camry during and after a collision, *how* different design features might relate to safety and *why*. The classroom discussion as well as students' written responses to the initial assessment revealed a range of students' ideas and ways of making sense of car collision and safety. Many students thought "sturdy" or "strong" materials would make passengers safe compared to "soft" or "fragile" materials. Most students also thought a car that got damaged in a collision would be less safe for passengers than one that resisted crumpling. Students noted the presence of safety features in modern cars such as an airbag, but did not explain how and why the airbag decreases the damage to the passenger.

#2: Draw students' attention to key observations or patterns, then help them to notice "changes", and explain by pressing 'why.' The other action taken by the teachers to support students' sense-making was formulating daily essential questions using students' responses and wonderings elicited from prior activities. Building upon the initial assessment, the teacher invited students to explore, "*How can we predict the outcome of a collision*?" Students watched dash cam footage of car crashes and engaged in chat stations to predict what would happen in scenarios such as a hockey player and figure skater crashing into each other. From this activity, students were left wondering, "*Why do some collisions cause more damage than others?*" They figured out some answers from simulations where they adjusted the initial velocity and mass of two colliding carts but asked, "*How does the material influence the damage in a collision?"* They tested out the compressibility of materials and damage during an egg drop lab, and also recorded and reviewed slow motion video footage to observe the moment of impact and consider *why* there was a difference between the egg hitting cotton balls versus paper. In their final set of activities, students conducted research in small groups and made connections between their labs and car designs, answering the question of "*How do safety features reduce injury during a collision?"*

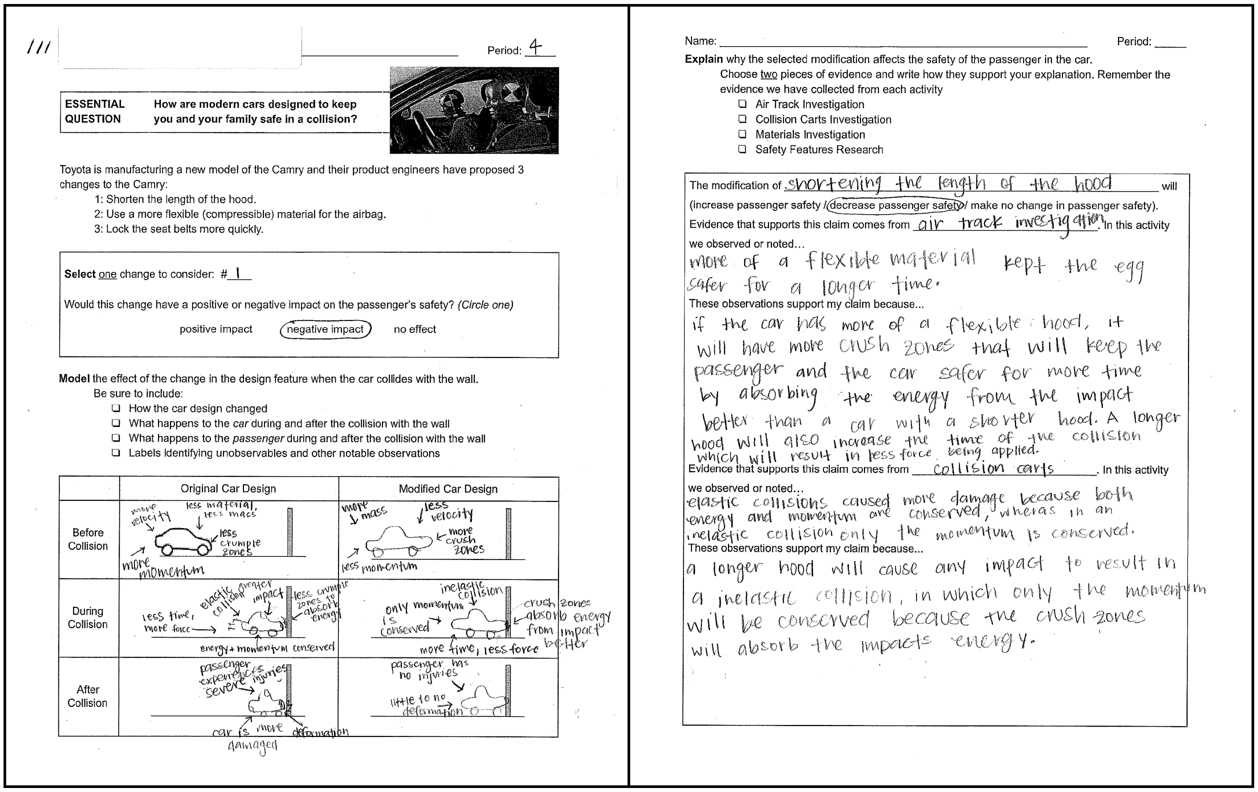
In addition to formulating daily essential questions using students' language and wonderings, the teachers made a deliberate effort to "let students figure it out," instead of giving 'answers' quickly in order to support students' sense-making. Throughout the five-weeks-long unit, students were guided to expand their initial thinking while engaging in various activities. Students predicted and tested their ideas and wonderings, and had conversations with their peers and the teacher both individually and collectively. The teachers continuously guided students to notice what they needed to in the activity, and pressed students to explain why. For example, students explored how the material would influence the damage in a collision through the egg drop activity. In this activity, students first predicted the outcome of various collisions between eggs ('passengers') and a variety of materials (flexible vs. less flexible), before gathering and analyzing data on the resulting collisions. Next, students made observations while dropping the egg onto different materials and discussed the patterns. The teacher facilitated small group discussions and drew attention to what students missed while they were talking and drawing the model. The teacher directed students to the *changes* happening when the egg hit the material and helped students become more aware of how they were describing what was happening in order to translate it into the model. In the transcript below Ms. D. helps students focus in on and describe what happens when the egg hits the sponge:

> Ms. D.: When you guys are going back and replaying the footage, what do you notice is happening to the sponge as the egg makes contact? [gestures egg hitting into hands]
> Student: It's adjusting [moves hands down, motions downward]
> Ms. D: Adjusting in what way?
> Student: Elastically.
> Ms. D: Uh, in which direction? What do you mean by adjust?
> Student: In itself [motions downward]
> Ms. D: Into itself? [copies student's downward motion] I see you're using your hands to push down.
> Student: Yah.
> Ms. D: So you mean downwards? Okay. Can we actually show that kind of adjustments in our model? [points to other student's paper]
> Studnet: In them?
> Ms. D: Yes, in the model.

Ms. D repeated the student's wording of "adjustment" and his downward motion to communicate the change in the sponge when the egg hit. The teacher helped students to focus on the essential question of the day of how materials reacted differently and came to *their* own conclusions informed by *their* data about how differences in material made a difference. Students reached the conclusion that, in fact, a flexible material was best for protecting the egg ('passengers'), in the event of a crash.

#3: Use curriculum-embedded assessments that help both the teacher and students to see changes in students' thinking. Lastly, the teachers purposefully designed and enacted assessments that enabled both the teacher and students to see any changes in student thinking throughout the unit. Toward the end of the unit, students were tasked to evaluate three proposed design changes of a new Camry from the safety standpoint. Specifically, they were tasked to pick one of the proposed design changes (e.g., shorten the length of hood), draw the modified car, and explain the effect of changes in design feature when the car collided with the wall. Students were expected to choose two pieces of evidence from the class activities and explain how the evidence supported their argument (see Figure 2). Students' responses to the two assessment tasks (initial and final assessments) provided evidence of the expansion of students' thinking and talking throughout the unit. For example, one student initially thought that the Model T experienced more damage than the Camry because "there was less coverage and the material was most likely more fragile than a modern car, so the damage it faced was much more severe." Toward the end of the unit, this student talked about the safety in a car collision in a far more complex way while connecting observable features (e.g., the length of the hood) to unobservable, theoretical science ideas (e.g., more time by absorbing the energy). Drawing upon the observation from the egg drop activity ("more of a flexible material kept the egg safer for a longer time"), the student stated, "if the car has more of a flexible hood, it will have more crush zones that will keep the passenger and the car safer for more time by absorbing the energy from the impact better than a car with a shorter hood. A longer hood will also increase the time of the collision which will result in less force being applied." The analysis of student learning, as measured by the quality of student explanation using 152 copies of student assessments, showed the statistically significant improvement of the quality of student explanations throughout the unit (see Author & other, under review).

--Insert Figure 2 about here--



Period: 4

ESSENTIAL QUESTION How are modern cars designed to keep you and your family safe in a collision?

Toyota is manufacturing a new model of the Camry and their product engineers have proposed 3 changes to the Camry:

1: Shorten the length of the hood.

2: Use a more flexible (compressible) material for the airbag.

3: Lock the seat belts more quickly.

Select one change to consider: # 1

Would this change have a positive or negative impact on the passenger's safety? (Circle one)

positive impact negative impact no effect

Model the effect of the change in the design feature when the car collides with the wall.

Be sure to include:

- How the car design changed
- What happens to the car during and after the collision with the wall
- What happens to the passenger during and after the collision with the wall
- Labels identifying unobservables and other notable observations

	Original Car Design	Modified Car Design
Before Collision	more velocity; less material, less mass; less crumple zones; more momentum	more mass; less velocity; more crush zones; less momentum
During Collision	less time, more force; elastic collision; greater impact; less crumple zones to absorb energy; energy + momentum conserved	inelastic collision; only momentum is conserved; crush zones absorb energy from impact better; more time, less force
After Collision	passenger experiences severe injuries; car is more damaged; more deformation	passenger has no injuries; little to no deformation

Name: Period:

Explain why the selected modification affects the safety of the passenger in the car.

Choose two pieces of evidence and write how they support your explanation. Remember the evidence we have collected from each activity

- Air Track Investigation
- Collision Carts Investigation
- Materials Investigation
- Safety Features Research

The modification of shortening the length of the hood will (increase passenger safety / decrease passenger safety / make no change in passenger safety).

Evidence that supports this claim comes from air track investigation. In this activity we observed or noted... more of a flexible material kept the egg safer for a longer time.

These observations support my claim because... if the car has more of a flexible hood, it will have more crush zones that will keep the passenger and the car safer for more time by absorbing the energy from the impact better than a car with a shorter hood. A longer hood will also increase the time of the collision which will result in less force being applied.

Evidence that supports this claim comes from collision carts. In this activity we observed or noted... elastic collisions caused more damage because both energy and momentum are conserved, whereas in an inelastic collision only the momentum is conserved.

These observations support my claim because... a longer hood will cause any impact to result in a inelastic collision, in which only the momentum will be conserved because the crush zones will absorb the impacts energy.

Attend to race, language, and identities

Teachers were committed to recognizing and validating their students' identities and language in ways that extended beyond the science classroom. We highlight two pedagogical actions teachers took to attend to racial and linguistic identities. First, the teachers purposefully designed and enacted assessment tasks that integrated students' experiences and stories into their scientific explanations. The activities and discussions surrounding the tasks created space for students to do identity work (Author & others, 2013), sharing personal stories, concerns, and experiences with their peers, teachers, and community members. Second, the teachers designed tasks that prompted students to use their home language to do science.

#1: Creating a space for identity work: Designing tasks where students share stories with others and leverage their assets. When teaching this unit previously, the teachers relied on a more conventional assessment that prompted students to construct scientific explanations using a format of claim-evidence-reasoning ('CER assessment') to assess students' understanding of momentum, impulse, and inelastic and elastic collisions. Inspired by the principle of attending to race, language, and identities, the teachers included a few non-traditional forms of assessment tasks, such as writing a letter ('Letter assessment') and giving a sales pitch about the cars that they designed. These tasks created spaces for students to share their stories with peers and the teachers while leveraging their assets, talents, or interests that were typically invisible in science classrooms.

For their final project, students created a car design and wrote a letter to their loved one detailing the safety features and why they designed it for that person. Students connected safety features to physics core ideas about energy transfer in a collision, but also wrote about their loved ones' preferences, needs, routines, and interests. In their letters, students described the crumple zone, explained the relationship between force and time in a collision, and how certain features like seatbelts and airbags keep a passenger from continuing to move forward with their car. In addition, they addressed their loved one's particular needs to see at night, drive long hours for their job, or transport people, equipment, and groceries for trips, work, and errands. One student mentioned specific modifications that would allow his uncle to operate the car from his wheelchair, writing that "El carro tiene asientos para soportarlo y también el carro está modificado para que puedas manejar." ("The car has seats which support [the wheelchair] and the car is also modified so that you're able to drive it"). Students shared personal concerns, family struggles, and joyful moments, foregrounding race, youth culture, and other components of their identity through storytelling. Students referred to their ages and geographical location, family relationships and values, physical features like being short or large, interests and hobbies, their personalities and job requirements like working the nightshift. Students did not explicitly refer to their racial identities, however their values, ideas, and concerns were tied to their racial and ethnic backgrounds as primarily low-income first generation Latinx families. Due to the way the unit was launched, many students saw this envisioned "dream car" gift as a way of giving back to someone who had cared for them in the past and deserved more luxury in their life. For example, one student wrote, "I believe you deserve something that will take care of you just as well as you have with me." The Letter assessments provided opportunities for students to reflect on their relationships, tell stories, and develop a deeper connection to their loved ones, all within the broader context of learning and communicating about momentum and impulse.

In addition, the activity of giving a "sales pitch" created space for identity work through story-sharing, positioning, and social recognition. Near the end of the unit, each student wrote a script for a "sales pitch" to describe the car they designed for their loved one and the associated aesthetic and safety features. The teachers included time in class to practice, and group members supported each other through their nerves with public speaking. During the final sales pitch, the groups approached as a team, and listened to each other's speeches. The teachers and community members served as panelists, providing a real audience and legitimacy to the sales pitch task. Students integrated their scientific understanding with everyday experiences as they shared about their car designed for daredevils like their dad or for people who have a big family and need a lot of room. The panelists asked follow up questions about the design and physics content, but also clarifying questions about the loved one and the drawing. During the panel presentations, students told stories about driving around or completing everyday tasks with loved ones and also shared about their hobbies. Additionally, presenting the drawing provided space for conversations about the design style, creativity, and artistic abilities. For example, one student created a digital drawing of his car and the panelist asked, "Do you like to do that sort of thing, or did you start doing that with this [drawing]?" This led to a conversation about him learning to use a new computer program and preferring the cleaner lines in comparison to hand drawing. Each of these small moments helped students express their intersecting identities within the context of learning physics. Due to the way the activities were designed, the students formed new relationships, expressed care for each other, and recognized each other as capable sensemakers and as individuals. Overall, both non-traditional assessments provided rich opportunities for students to leverage their identities while forming new relations with both physics and people in the classroom.

#2: Design tasks for students to integrate home language into science learning. Throughout the curriculum, students' home languages were legitimized and leveraged as valuable resources for relating more deeply with the science content. On the first day when sharing their dream cars, students voiced concerns about their loved ones' safety in relation to language use. Some students shared that they would appreciate a computerized infotainment system in Spanish or built in maps with GPS directions voiced in Spanish to ensure their parents could communicate and navigate comfortably. The majority of their parents were immigrants from Mexico, and there was heightened anxiety in the community about their immigrant status at this time associated with heated debates around the Trump administration's immigrant policy. Ms. D. commented on family members' insecurity about and understandable challenges with learning a second language in these circumstances and encouraged students to further pursue these features as legitimate safety concerns.

Initially, students discussed how language could factor into car safety, foregrounding their linguistic identities as a *topic* in the science classroom. By the end of the unit, their home language became the *medium* for some students in expressing their scientific understanding, due to the format of the non-traditional form of assessment. The teachers attended to linguistic identities by asking students to write in the language their loved one would be most comfortable with, as well as share the design with the person in that language. Students shared deeply personal stories as well as explained the scientific principles in their car design, all in the language of their choice.

The way the task was framed led students to adjust for their audience and communicate in ways not typically seen in a science classroom. A large part of this was writing in other languages, but students also demonstrated various linguistic repertoires. Many letters included poetic or expressive language such as “You never fail to hold my hands in times of need, and make me feel safe and warm when fear overcomes my body but for now, rest easy, it's now my turn to keep you safe when you're on the road and taking on a new adventure.” Others included playful language or slang such as “haha Bopp! Thanks gee” or “you gon be safe as frizk.” Some students explicitly addressed this informal register, with one student apologizing to their teacher for being “unprofessional” while another student turned in two letters, one labeled “professional” and the other “personal.” Ms. D. told students she appreciated the opportunity to learn more about their lives and relationships, as well as practice her Spanish when reading the letters and seeing their videos explaining the design. In these videos, students shared their designs with their loved ones, communicating in their home languages about how and why the car was designed for this person.

Building a welcoming community

We observed a wide range of pedagogical actions taken by different teachers that contributed to building a welcoming community before, during, and after the lessons (see Table 1). Those actions facilitated some form of relational work among the teacher and students, while surfacing and legitimizing various emotions, feelings, or struggles that young learners had. For example, Ms. D always stood next to the front door before the bell rang. She called on every single student's name as they came in ("Good morning, Jose!"). Mr. L told jokes, stories, and shared school news as students trailed into class, and many students would stay and continue chatting with him during lunch or study hour. Mr. T started each day with a "mindful minute" meditation, breathing exercise, or stretch to help the students quiet their nervous systems, reflect on their thoughts and feelings, and get ready to learn physics. He also asked students every Friday to "share out good things." He responded enthusiastically, validated their non-physics experiences, and followed up on comments from the previous week. For example, asking about last weekend's visit with an out-of-town brother, or soliciting a round of applause for the girls dance team for making regionals. All of the teachers engaged in deep relational work that created a legitimate presence, therefore the students felt that people cared about them in this space and that they belonged in the classroom community. While the teachers worked to build a welcoming community regardless of the unit, below we present one intentional pedagogical work observed on the first day of this unit--creating a space for students to get to know each other in the classroom learning community.

#1: Create a space for students to get to know each other and the teacher. As usual, students had a new seating chart as they transitioned into a new unit. As illustrated above, the main task of the first day of the co-designed unit was to draw a dream car for themselves and for the loved one and think of the important design features as an engineer. After quietly drawing a dream car for themselves, Ms. D asked all students to stand up and share their car with two people (one with the same colored shirt, and the other with the same height). Students walked around the room, found someone with the same or similar colored shirt, introduced themselves to each other, and talked about *their* dream car. Students shared about their friend who had gotten into an accident and needed a backup camera, their sibling who loved to go camping and would appreciate a four-wheel drive, their mother who needed extra storage for her work materials, or room for a cooler when taking their cousins on trips. Mr. D brought students back to their seats, and gave the next task. At this time, students were prompted to draw a dream car for their loved one and describe essential features for them, including the top three "must have" features. After quiet individual drawing, Ms. D asked students to stand up once again and share their dream car with their peers, saying "I'd like you to take a little bit of time, get to know each other, share your work….find one more person that you haven't talked to yet." Students found someone they did not know well, introduced themselves, and excitedly shared their dream car and essential features. Before turning into the next whole group activity after students' sharing, Ms. D asked, "How many of you have learned something new about someone else in our classroom?" Several students, including Mr. D, raised their hands. With a big smile, Ms. D told her students, "I certainly did. I heard a lot of passion about cars out there. Some people have adventurous spirits but I didn't know about them. There are some students who have dogs or pets that they want to take on road trips. I didn't know about this. Thank you for sharing."

Sharing about their experiences in relation to the dream car was not the initial hook to pique their interest, but instead remained central throughout the unit. Throughout the co-designed unit, we observed multiple times that the teachers created a space for students to get to know each other and build social relations with one another as part of doing academic work. Students connected with the material through their loved one, but also connected with peers in the classroom learning community while sharing about their designs for that person. In addition, students stayed in the same small group of four students throughout the unit, working together to solve the physics problems but also learning about each other in the process. When they conducted their own research on various safety features and reported back to their small group, one student added details he knew from fixing cars with his dad and uncle and another student talked about modified safety features for babies like his younger cousin. Throughout the unit, the teachers implemented activities that encouraged students to formulate relationships not only with the teacher but with their peers.

Disrupting power hierarchies

There were two notable intentional pedagogical actions guided by this principle. One was creating multiple ways of being good at science by using multiple forms of assessments, including non-traditional ones. The other was deliberately facilitating the classroom interactions in a way that students felt everyone's voice mattered in the classroom.

#1: Create multiple ways of being good at science. Historically, students in this community had engaged in Claim-Evidence-Reasoning (CER) assessments across science classes from the middle to high school level. CER assessment was recommended by the school district, with the goal of supporting students to develop a way of thinking, talking, and doing sciences as expected by the Next Generation Science Standards. During the exit interview, we learned that many students in this school struggled with the CER assessment. For example, one Mexican-American male student, Luca (pseudonym), shared his experience as the following:

> "Just cause I didn't have my CER, [my science teacher] kind of doubted me cause she thought I didn't know anything. But I had to prove her wrong and I went all out on my CER...I feel like CER is more work and it doesn't really get - get you to express your feelings, like your thought process...All the way, I rather have full umm power over my

creativity and what I'm allowed to say. Not just a claim, evidence, and reasoning. I just don't like CERs, they're really (long) and boring."

With the goal of disrupting the settled norms, expectations, and practices of doing science at schools, in this co-designed unit, teachers and researchers intentionally designed multiple forms of curriculum-embedded assessments. The non-traditional assessments, such as drawing a dream car, writing a letter to the loved ones, giving a sales pitch, were meant to facilitate students to leverage their personal concerns, assets, home practices and languages. Whereas CER assessment signified the valued ways of doing science by the NGSS, Letter assessment facilitated students to use their personal concerns, relationships, interests, and home languages to do physics while explaining how the design features of the car would protect their loved ones from a collision (see detailed analysis in Author & other, under review). Non-traditional forms of assessments were received highly positively by both teachers and students. The teachers learned more about students and their families, which opened up the door to deepen their relationships. Students, in particular those who have been marginalized in physics and chemistry classes, expressed their excitement about non-traditional forms of assessment tasks. For example, Luca said, "I'm very glad that [my science teacher] didn't pick CER. I didn't even know that she had the option to do it."

#2: Deliberately facilitate classroom interactions that make students feel everyone's voice matters. With the principle of disrupting power hierarchies, the teachers in this project paid particular attention to the power hierarchy between the teacher and the students in a classroom learning community. Accordingly, one intentional pedagogical work that the teachers did was positioning all students as capable sense-makers by publicly validating everyone's presence, voices and contributions in a classroom learning community. Whenever Ms. D started a class discussion, she explicitly and publicly communicated that everyone's voice should be heard, and everyone had valuable ideas (e.g., "We would like to hear each other's voices today, hearing each other's ideas"). Instead of giving the floor to students who raise their hands--those who were likely to have a positive perception toward science through historically positive relationships with sciences, Ms. D rolled a dice to randomly call on a student and distribute the opportunity to share ideas. Ms. D affirmed students' presence by providing positive and encouraging words to students when sharing their ideas regardless of scientific accuracy (e.g., "Thank you, David! Great to hear your voice."), in particular when the students who tended to be 'shy' or 'quiet' shared their ideas.

In addition to valuing individual contributions, Ms. D leveraged the collective ideas and wonderings of the class in a way that shifted power dynamics. For example, Ms. D compiled students' ideas about what they should study next and displayed their responses at various points in the unit. One time Ms. D created a wordcloud of their ideas and brought to the students' attention that the word "materials" was written in large text because it was a common response, and explained how subsequently they would explore the effects of materials on collisions. Moving in a new direction based on students' feedback and ideas altered the typical power hierarchy where the teacher explains their reasoning or plan for the unit sequence.

Students also exerted agency in small but meaningful ways during activities. In the egg drop lab, Ms. D led a whole group conversation about how to make individual measures "compatible" so they could compare and compile different people's data. She prompted students to define their variables, such as determining the break point for the egg. She asked, "What would you say is a 'broken enough' egg? Is a crack enough to say that you're done?...At what point should we establish with uniformity when we can say that the egg is 'broken'?" After they decided that it was broken once “there’s yolk coming out” Ms D clarified, “What if we see the egg whites coming out? Do we still keep going?” When a student hesitantly answered, “No? Yes?”, trying to guess the “correct” answer, and Ms D explained “It’s your choice.” Students appeared surprised they were asked to define variables in a lab. After they decided to only focus on the yolk as a criteria for breaking, Ms D concluded with, “Just so we’re all on the same page. We are going until the yolk comes out of the egg.” As in other activities, Ms. D. positioned students as capable sense-makers who exerted their epistemic agency to understand the world, but she went a step further by inviting students to be authentic contributors in the lab design. They decided the “rules of the game” in a way which is not typical in many science classes and especially not in physics labs. By asking the class to come to a consensus on how they were defining what counted as a “collision” or when the egg was “broken enough”, Ms. D. reformulated the participation structure of a conventional physics lab which includes a fixed set of materials, variables, and outcomes.

Additionally, students’ findings from the lab were compiled to create a class set of “data” rather than individuals submitting a lab write up with one correct solution. There were many times throughout the unit when students’ ideas were valued collectively and used to inform their sensemaking, shifting traditional power dynamics. For example, after students predicted what would happen in various collision scenarios, Ms. D asked the class to vote thumbs up or down on which player would “dominate” or feel less damage. The effect was a poll to visualize the class’s predictions and range of answers, putting student thinking at the center of their discussion. Ms. D. noted the diversity of students' opinions and asked students with opposing views to share to make visible each side’s reasoning. However, she only responded with more questions or said "interesting" rather than evaluating ideas as right or wrong. Students were given the space to share their ideas and saw how it informed the day's activities and the overall class thinking.

Summary

In summary, we presented examples of the five design principles in use, emphasizing the interaction between pedagogical actions guided by these principles and the resulting student experience. Our intention is not to extol the virtues of this one unit but rather to illustrate and unpack how the principles can guide successful enactment. We supplement the existing examples of what culturally responsive instruction looks like on both the design and instructional sides, but beyond this contribution, we highlight the value of the design principles in working towards equitable enactment. We address the disconnect between research and practitioner knowledge and acknowledge the complexity in transforming classroom practices. In the next section, we delve deeper into *how* the design principles work toward transformative and consequential learning by examining what characteristics make them a useful tool for mediating the collaborative design process between teachers and researchers.

Discussion: Three Characteristics of Design Principles That Make Them a Useful Mediating Tool in Co-designing Activity

Despite decades of reform efforts, the ways in which minoritized students experience science at school remain largely unchanged. There is a growing consensus among researchers that changing classroom practices necessitates collective, ongoing, sustainable and concerted efforts of reimagining new forms of learning at schools between researchers and practitioners through partnership. Our proposition of using design principles as mediating tools is grounded in participatory design research (Bang & Vossoughi, 2016) but calls attention to both the complexity of transforming disciplinary teaching practices in local contexts and the importance of coordinating professional interactions in a partnership. A key challenge in such a partnership is to create *conditions* for teachers and researchers working together to break away from normalized modes of disciplinary teaching and learning, thereby reimagining and bringing about new forms of activity in schools. We posit that the design principles emerging from our design work is one form of principled practical knowledge (Bereiter, 2014) that functions to provide practical guidance, rather than explanation or prediction. Expanding the conception of principled practical knowledge, we theorize three characteristics that make design principles useful as a tool for mediating collaborative design when people from diverse backgrounds work together.

The first characteristic that makes design principles useful is their *built-in uncertainty*. The design principles conceptualized in this study had an intermediate level of abstraction in that they were not higher level phrases that communicate ideological, theoretical orientation or commitment (e.g., 'promoting equity and justice', 'implementing culturally relevant pedagogy') nor concrete descriptions of teaching behaviors that provide instructions (e.g., 'five best practices', 'eliciting students' initial ideas'). It appeared that this 'in-between' level of abstraction opens up a space of collective meaning-making of pedagogical goals communicated with design principles during the co-designing activity. Take an example of the design principle, *attend to race, language, and identities*. Teachers and researchers in this project unpacked why they should attend to race, language, and identities in order to create engaging and empowering science learning experiences for the students in local contexts. They also had to unpack what '*attend to race, language, and identities*' meant and how it might look like in classrooms. The built-in uncertainty of the design principles facilitated the team to engage in collective meaning-makings of the principle, therefore guided their collective and principled actions (see details about the meaning-making conversation in Author & other, 2021). We speculate that the collective meaning-making, facilitated by the uncertainty of design principles, has a transformative impact on student experiences, instead of the DPs themselves. Furthermore, the built-in uncertainty of design principles allows teachers to connect their own problems of practice to a lofty goal or commitment in the community. Many science teachers struggle with enacting culturally relevant pedagogy while addressing content in the state standards, such as 'momentum' or 'Newton's Laws.' The principles, such as *make it matter, support sense-making* and *attend to race, language, and identities*, provide practical guidelines of how to set up and facilitate learning experiences in a culturally congruent and sustainable way while addressing problems of practice grounded in daily work of teaching.

Another characteristic that makes design principles useful is *generalizability*. In this project, we worked with two teams of high school science teachers (chemistry and physics) to co-design four units throughout the year. Although the forms of learning looked different across the units, disciplines, and classrooms, all four units were framed around problems or phenomena that mattered to the students at the moment in their contexts. With the principle of *make it matter*, the teachers and researchers intentionally centered students' science learning experiences on a phenomenon that had consequences for the people whom students cared about. While we have talked extensively about the momentum unit and its meaning for students, it is worth noting that the other units also positioned students as someone who made a difference in people's lives. For example, in a chemistry unit about stoichiometry, students designed a chemically powered heating or cooling device for people who did not have access to electricity. The flexibility and generalizability of the design principles means they can be utilized in a variety of subject areas and classrooms to affect practice, while also making contributions on a theoretical level. Design researchers have asked how design work that takes place in a unique local context might contribute to more generalizable knowledge about learning (Bereiter, 2014, Brown, 1992, Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). Design principles as conceptual tools provide possibilities for local design work contributing to the advancement of knowledge base in learning.

The third characteristic that makes design principles useful is their *provisionality*. In order to mediate the processes of co-designing toward transformative learning, design principles ought to be a subject of ongoing critique, refinement and revision by the members in the partnership, rather than a complete set provided by an inventor. In this project, for example, the principle of *disrupt power hierarchies* was originally framed as *disrupt <u>the</u> power hierarchy* when it was first introduced to the teachers. During the co-designing process, this principle was interpreted as a call for creating student-centered instruction, while attending mainly to the epistemic power hierarchy between the teacher and students. Although this was one important aspect of power dynamics that shaped students' opportunities to learn in a classroom community, there were other forms of power dynamics that were not addressed. For example, attending to power dynamics that transpire in daily interactions along the lines of race, gender, and language as well as power dynamics operationalized through the schooling system. This awareness, inspired by critical scholars, led the team to revise the design principle from 'disrupting *the* power hierarchy' into 'disrupting power hierarch*ies*.' We speculate that the process of creating, critiquing and revising the design principles provide powerful opportunities for the members in the partnership to make progress toward transformative and consequential learning.

Summary and Significance

This study presented a set of design principles (DPs) emerging from several years of design work with high school science teachers towards providing engaging and empowering science learning experiences for Latinx, multilingual students, and students from socioeconomically disadvantaged communities. We identified teachers' purposeful pedagogical actions guided by each design principle when they designed and enacted curriculum and assessments. We also illustrated students' experiences mediated by the purposeful pedagogical actions in one co-designed high school physics unit.

This study is significant for practitioners and researchers who seek to transform teaching and learning at schools through participatory design research. First, the five design principles along with the images of student experiences illustrated in this study would be useful resources for teachers and researchers who engage in co-design activities in various contexts. Numerous prior studies highlight the need for having more concrete images of 'what it looks like' in order to support teachers' reimagination. Not only does this study provide a concrete image of student experiences in one co-designed physics unit, we explicate 'the links' among: (a) pedagogical goals communicated with each design principle, (b) teachers' intentional actions guided by the principles, and (c) students' experiences mediated by curriculum and assessment. To be clear, we do not argue or consider that the presented image of student experiences in the co-designed unit is *the* ideal or finalized one. Although the form of learning observed in the co-designed unit was radically different from the typical mode of learning physics normalized in the school community, we view the image of student learning reported in this study as a subject of critique, revision, and discussion for continuing improvement toward transformative and consequential learning.

In addition, this study advances the theoretical knowledge base in design research by further articulating the characteristics of principled pedagogical knowledge (Bereiter, 2014) that mediates co-designing processes in a complex partnership setting. With the awareness about the limitations of the top-down reform movement, researchers increasingly seek out ways to create a collaborative design space where multiple stakeholders work together to create new forms of learning. There are growing efforts to understand the processes of creating such conditions, in particular that results in consequential and transformative learning. In a recent study that explored the utility of cultural-historical activity theory (CHAT) in designing such spaces, for example, Severance and his colleagues (2016) highlighted the need to bring in specific concepts and tools developed as part of design-based research to create such conditions (Severance et al., 2016). Not only does this study provide one form of tools to create such conditions, it begins to shed light on the process of creating conditions for emergence of what is called "transformative agency" (Engerström et al., 2014; Virkkunen, 2006). Working together with people from widely different backgrounds is necessary for making transformative changes in any setting, but incredibly challenging. Design principles, with built-in uncertainty, generalizability, and provisionality, can be modified across different contexts to powerfully mediate complex human interactions toward transformative and consequential ends.

Reference (Link)

REMOVED TEXT:

This unit lasted five weeks and covered the key concepts of momentum and impulse. The co-designed unit began by inviting students to draw a dream car for their loved one, and consider safety features that they wanted to include in order to protect the loved one in a collision. While positioning students as car designers or engineers, students were asked to brainstorm what information they needed to build a safe car. Students learned that the most popular car in 1920s, Model-T, and the one in 2000, Toyota Camry, showed different fatality rates per drive. While noticing the changes of car design over time, they were invited to theorize the reason why the two cars showed different fatality rates in collisions. Various student ideas, experiences, and languages were surfaced through these initial assessments and conversations. For example, the majority of students thought that a 'stiff material' would make the car safer in a collision than a 'soft material.' The majority of students also thought that having a lot of damage in the car as the result of the collision meant that the car was not safe. Throughout the unit, students engaged in various activities, such as chat stations, online simulation of elastic vs. inelastic collisions, egg drop lab etc., to predict and test their ideas about factors that affect the momentum and impulse, therefore to figure out how they could build a safe dream car for their loved ones. Students also met and talked to the invited speakers, undergraduate students majoring in engineering who were members of the auto club of a nearby university. Toward the end of the unit, students revised their car designs to make them safer using new information, disciplinary languages and new understanding. Students then prepared and delivered a 2 minutes 'sales pitch' to 'judges' (e.g., administrators, teachers, graduate students from a nearby university who studied physics, university professors). During this sales pitch, each student showed the revised model of his or her dream car, told the stories of their loved one, and explained how and why the proposed design features might make the loved one safe in a collision. Students completed a final performance assessment where they engaged in various scientific practices, such as developing and using models, constructing explanations, and developing arguments using evidence. The assessment task prompted students to evaluate the proposed design change of a Toyota Camry from a safety standpoint. In addition, students wrote a letter to their loved ones in either English or Spanish. Students were encouraged to deliver the letter to their loved one, mostly mom or dad, and shared short video clips with the teachers. The clips captured students reading the letter in Spanish or English at home and their families' emotional reactions.

Video #1: draw a dream car for the loved one and identify three features

Video #2: How can we predict the outcome of a collision?

Video #3: how does the material influence the damage in a collision.

- From the curriculum standpoint, teachers support students to form a sense of mattering in two ways. One is setting up a learning context centering an issue that a particular group of students in their classroom care about. It involves selecting the topic or focus of inquiry in a lesson or unit by leveraging students' everyday experiences, concerns, or interests. For example, in the focal project, teachers designed a chemistry unit where students addressed concerns about homeless people through designing heating and cooling devices for them. In this unit, students learn about stoichiometry and exothermic and endothermic reactions in high school chemistry. The other way teachers make it matter is through facilitating conversations that help students establish their personal connection during the instruction (i.e., enactment). Teachers typically work with over 20 students simultaneously. It is unlikely that every student feels connected to the selected topic at the onset of the instruction. By inviting students to share their personal experiences and stories, such as about people impacted by a recent wildfire caused by climate change, students as a collective can formulate a sense of mattering over time. We theorize that this process of formulating a sense of mattering is an important aspect of what Dewey (1906) referred to as the work of 'psychologizing' that is essential to support meaningful learning for students.

personal connection and seeing a real impact of their work on the condition of students' lives and their communities, either in the present or in the future.

- Humanize the learning of physics; bringing the experiences of people that students care at the center of learning physics & positioning students who can make the world a better place for the people whom they care (e.g., engineers who improve the safety of car in a collision)

OLD STORYLINE

Over the course of five weeks, students in Ms. Davis' class learned about momentum and impulse, through designing a car to keep a loved one safe in a collision. To introduce the essential question that would drive the unit, Ms. Davis asked students to visualize someone they cared about:

> I want you to think about **someone in your life, who you care about**, someone who has cared about you, who was taking care of you when you were sick, when you were down on your luck, or just down in general...Do you have someone in mind? Now I want you to fast forward, 20 years from now. You guys have been all successful in your lives...Now you have extra money to share. And this person, who you care about and who cares about you comes to mind. **I want you to think about, what kind of car would you design for this person?**

Students drew their car designs, listed important design features, and wrote a note to the person they cared about describing their car. When they shared their designs with other classmates, students showed how they included GPS in Spanish to help their parents navigate, back-up cameras to protect their siblings just learning how to drive, and four wheel drive for their friend who enjoyed camping and off-roading. Ms. Davis told the class she enjoyed learning about their lives. From the first day, students saw how physics related to everyday life, with a direct connection to the people and things that mattered to them.

Students then took on the role of designers and engineers as they brainstormed what information they needed to build a safe car, and compared the different fatality rates of the 1920s Model T versus the 2000 Toyota Camry. In this non-conventional form of initial assessment, students drew what would happen to the cars before, during, and after a collision, and theorized why the earlier car had a higher fatality rate in collisions. The majority of students thought that a 'stiff material' would make the car safer in a collision than a 'soft material', and that a car heavily damaged by a collision would be less safe for passengers. While these initial ideas were scientifically inaccurate, they were not corrected by the teacher, but rather engaged with and modified throughout the following labs, discussions, and activities.

Each set of activities helped answer a mini essential question of the unit, starting with, "*How can we predict the outcome of a collision*?" While handing out collision incident report forms for real car crashes, Ms. Davis explained that it might not be possible to prevent all car crashes, but they can predict and prepare. Students watched dash cam footage of car crashes and engaged in chat stations to predict what would happen in various scenarios such as a hockey player and figure skater crashing into each other. From this activity, students were left wondering, "Why do some collisions cause more damage than others?" They received some answers from simulations where they adjusted the initial velocity and mass of two colliding carts and learned about inelastic and elastic collisions. When asked to reflect on future directions for their inquiry, many students mentioned the importance of materials, and Ms. Davis brought this to their attention by displaying a word cloud with their top answers in large text. An egg drop lab helped them test out the compressibility of materials and damage, answering the question, "*How does the material influence the damage in a collision?"* They recorded and reviewed slow motion video footage to observe the moment of impact and consider *why* there was a difference between the egg hitting cotton balls versus paper.

In their final set of activities, students made connections between their labs and car designs, answering the question of "*How do safety features reduce injury during a collision?"* They conducted research in their small groups and listened to a presentation by undergraduate students majoring in engineering who were members of the auto club of a nearby university. Toward the end of the unit, students revised their car designs to make them safer using new information, disciplinary languages and new understanding.

Students then prepared and delivered a 2 minutes 'sales pitch' to 'judges' (e.g., administrators, teachers, graduate students from a nearby university who studied physics, university professors). During this sales pitch, each student showed the revised model of his or her dream car, told the stories of their loved one, and explained how and why the proposed design features might make the loved one safe in a collision. Students completed a final performance assessment where they engaged in various scientific practices, such as developing and using models, constructing explanations, and developing arguments using evidence. The assessment task prompted students to evaluate the proposed design change of a Toyota Camry from a safety standpoint. In addition, students wrote a letter to their loved ones in either English or Spanish. Students were encouraged to deliver the letter to their loved one, mostly mom or dad, and shared short video clips with the teachers. The clips captured students reading the letter in Spanish or English at home and their families' emotional reactions.

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