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Failure as an active agent in the development of creative and inventive mindsets

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A R T I C L E I N F O

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A B S T R A C T

This study explores the ways in which high school student inventors define the terms *failure* and *learning from failure* as well as what they learn about creative failure while inventing that may be applicable to other contexts. A 14-year-old grants program for high school inventors served as the site of study. Findings from this study make visible participants' emic understandings of creative failure. Discourse analysis revealed students' preference for use of *high points* and *low points* to characterize creative failure as a part of a larger process of inventing instead of the notion of failure as an end point. This finding demonstrated student take-up of one of several ways of thinking as an inventor. It also added the transdisciplinary work of invention to previous studies in other disciplines such as mathematics in which creative failure was used by educators and taken up by students as a productive part of learning. This study goes a step further by uncovering ways two inventors selected as telling cases (Mitchell, 1984) describe their understandings of how what was learned from failure may transfer to other experiences.

The epistemological and ontological frames guiding this study, and the interactional ethnographic methods used to analyze interview data, offer an approach to assess ways of thinking among individual students as well as the collective group of participants. Findings frame the change(s) in thinking about creative failure in words used by students to describe their understandings, as they reflect on their personal experiences to invent solutions to real-world problems.

1. Introduction of interactional ethnography: an approach to discovering students' notions of creative failure in the context of an invention education program

Notions of failure as an outcome and as a trigger for negative emotions by students (Covington & Teel, 1996) who may perceive themselves as having not met expectations stands in stark contrast to the term's portrayal within particular academic disciplines, such as engineering, in which failure is used to test a design or type of material as part of an inquiry based approach to learning (Mehalik, Doppelt, & Schunn, 2006). Conflicts between these alternate ways of thinking about failure represent a frame clash (Agar, 1994) rooted in differences between ways of thinking and knowing within different academic disciplines and fields of study. Physicist William Shockley is one of the early scholars who have written about creative failure in a positive light (Shockley, 1976). He characterized failed attempts to develop a tubeless radio as opportunities for learning and as steps on the path to success. Shockley was awarded the 1956 Nobel Prize in Phyiscs for his inventive work on semiconductors and the transitor effect.

Positive descriptions of failure and its linkages to what Shockley referred to as trial and error can be found in accounts of interdisciplinary work by innovators and in particular disciplines such as mathematics and the arts. Perez-Breva (2017) reported that

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innovators start with hunches and then generate knowledge and important understandings from failures. Kapur (2008), in his work in mathematics, documented the productive role of failure within groups of students solving ill-structured problems. Kapur and Bielaczyc (2012) reported that the few groups that had managed to solve ill-defined problems successfully relied on trial and error (p. 60). Choreographer Twyla Tharp (2003) described the role of failure in the performing arts, and a corresponding "repertoire of tweak, and cut and add and replace and reposition" (p. 221). These findings make visible ways in which learners from different disciplines, at different stages of development, use something they name as failure or creative failure to uncover underlying concepts and principles needed for work being undertaken (Sitkin, 1992; Kapur & Bielaczyc, 2012; Trueman, 2014; Thomke & Nimgade, 2017).

Getting young people to take up the notion of creative failure as a positive occurrence and an important part of learning and discovery is one of many types of thinking identified as being important to their development as inventors (Flemings, 2004) and creative problem solvers. Curriculum and instruction aimed at teaching ways of thinking (such as learning from failure), as opposed to teaching for memorization of facts and events, represents another frame clash (Agar, 1994). The turn toward teaching ways of thinking in schools across the United States has been accelerated by the adoption of national science and engineering standards (NRC, 2013). Prior to the issuance of Next Generation Science Standards, the majority of elementary and secondary schools were not required to teach engineering or design thinking. Today, a growing number of U.S. classrooms are now teaching engineering design. Some go beyond engineering design by engaging students in transdisciplinary work known as *invention* (though few call it out by this label).

Teaching young people to invent and to think in ways that are common to inventors, including ways of drawing on knowledge and ways of doing things from different disciplines, often leads invention educators to explore new ways of assessing learning. Changes in ways individual students come to know and internalize particular ways of thinking, such as creative failure, can be more difficult to measure than knowledge of discrete facts. We demonstrate in this study one way of examining the development of thinking skills (i.e., learning from creative failure) high school students acquired while inventing.

We have chosen the national InvenTeams program as a site of study, given its fourteen-year history of helping young people from diverse backgrounds to develop working prototypes of their inventions. One of the repeated themes from the program's post-experience surveys has been agreement by students that they learned from failure as they invented. The survey data, however, offers few insights into students' conceptions of failure and what is meant by learning from failure. Survey data also provided limited insights into how failure influenced students' work on their team projects and how they viewed the applicability of their experiences to other parts of their life world. The unanswered questions led the two interactional ethnographic researchers—who are also program administrators—to step back from ethnocentrism (Heath & Street, 2008) to answer two research questions:

- How and in what ways do high school students who have conceptualized, designed, and built an invention as InvenTeam members define failure and learning from failure?
- How and in what ways (if any) do students describe what was learned about creative failure and problem solving in the InvenTeam context that they view as potentially being applicable to other contexts?

To address the first research question, all students in the most recent year (2016-17) were given an opportunity to respond to a post-experience survey; 73% of the students responded. Students were asked to rank their response to the statement, "Working on an InvenTeam taught me to learn from failure," according to a 5-point Likert scale (with 1 being "strongly disagree" and 5 being "strongly agree"). The question had been asked in the survey for more than a decade. Students were also asked to respond to two open-ended questions, the first of which was added in 2016-17: 1) "In your own words, define failure," and 2) "In your own words, describe your experience with InvenTeams." These open-ended questions became the focus of a domain analysis (Spradley, 1980) to begin to uncover how and in what ways students inscribed their developing understandings of failure. Responses were examined for inferences as to how failure may (or may not) have been a productive part of what students said they learned from the InvenTeam experience.

To address the second research question, we created a purposeful sample of six students who were asked to participate in a semi-structured interview to discuss their InvenTeam experience, and we conducted an in-depth analysis of interview transcripts. Students interviewed were asked to recount instances in which something did not go as planned and they had to step back, reformulate, and renegotiate new directions to achieve the team's goal. The further tracing of perspectives and experiences of two of the six students constituted the third step of the study, and allowed for the creation of two telling cases that sought to generate theoretical inferences to inform broader understandings of particular phenomenon (Mitchell, 1984).

In the next section, we take a step back to present the epistemological and ontological theories that are foundational to our emphasis on discourse in this study.

2. Sociocultural theory, dialogic theory, and social constructionism as ways of examining creative failure

Three major theories guide this research and our developing understandings of how students construct new knowledge and ways of thinking while participating in InvenTeams (Green & Bloome, 2014). The first theory builds on the work of interactional ethnographers in education studying classroom interaction and the social and cultural aspects of learning. From this ontological framework and logic of inquiry (Green, Skukauskaite, & Baker, 2012; Birdwhistell, 1977; Gee & Green, 1998, Ch. 4), we embrace four principles originally framed by Heath and Street (2008):

- Suspending known categories to construct understandings of local and situated categories and referential meanings of actions being developed by participants;
- Acknowledging differences between what they as ethnographers know and what the actor(s) in the context know;
- Constructing new ways of knowing that are grounded in local and situated ways of knowing, being, and doing the processes and practices of everyday life within a social group or configuration of actors;
- Developing ways of representing what is known by local actors and what the ethnographers learn from the analysis at different levels of analytic scale.

Our study and efforts to develop understandings through discourse analysis offered ways of identifying how new concepts and new ways of thinking, knowing, and being were constructed and taken up by the collective group, as well as by individual participants on InvenTeams (Putney, Green, Dixon, Duran, & Yeager, 2000; Lima, 1995). The emphasis on dialogic discourse and language as a core part of teaching and learning, which traces its roots to anthropology and sociology, aligns with research perspectives advanced by dialogic theorists. Wegerif (2015) stated that the "process of thinking is dialogic in form and has both a social external and visible aspect as well as an individual internal and invisible aspect" (p. 428). Littleton and Mercer (2013), building on the work of Barnes (1992), use the term *exploratory talk* (one of three types of talk) to refer to students' use of talk for reasoning together. These perspectives suggest that students who engage in exploratory talk as they work together on a task situated within a group (such as an InvenTeam) "think aloud" and are "simultaneously reasoning together and co-regulating their activity using the cultural and cognitive tool of spoken language" (Littleton & Mercer, 2013, p. 102). Littleton and Mercer (2013) argued that this type of talk is most productive for problem solving and collaborative learning (p. 72). The culturally based social use of language within the group is taken up by individual students and then leads to new ways of thinking (i.e., psychological development). As the student learns and develops, and actively contributes to the dialogues in his/her community, the student adds to the community's shared knowledge and the change of its social practices.

Social constructionism constitutes another perspective guiding our theory-building and theory-dependent research efforts (Heath & Street, 2008). Students' and the teams' reasoning and thinking in the InvenTeam initiative is focused on constructing a prototype of a product that solves a problem identified in their local community. This type of learning activity combines the need to develop new knowledge and understandings with designing and building; these encompass both minds-on and hands-on approaches to learning, which constitute a form of social constructionism. Harel and Papert (1991) used this term to refer to building knowledge structures through what is being constructed, as opposed to knowledge that is merely transmitted from one person to another. The *learning while doing* approach embraced by social constructionism is at the core of InvenTeams in the sense that students' new and novel designs of a solution to a problem must also be reduced to practice through their co-construction of a working prototype of an invention. However, as noted by Wegerif (2015), Harel and Papert did not focus on social interaction, whereas discourse is core to our ontological and epistemological stance as interactional ethnographers of InvenTeams.

In the next section, we return to our exploration of what is interactionally accomplished by students as they invent. We begin by presenting an overview of what is meant by the term *creative failure* from our perspectives as researchers and program administrators within the context of the InvenTeam initiative.

3. Creative failure and learning in the context of designing and developing an invention

Efforts by individuals or teams working to produce novel ideas and solutions to problems stand in stark contrast to routine problem solving, according to Flemings (2004). Flemings, an inventor, engineer, and educator, argued that "invention rests at one end of the spectrum of design, and at the other end rests routine problem solving…" (p. 12). The literature describing ways inventors approach non-routine problem solving references four types of actions or phases of activity, including: 1) identifying and defining a problem; 2) conducting inquiries and identifying, listening, and learning about what matters to end users; 3) designing solutions; and 4) building and testing physical prototypes (Aulet, 2013; Middendorf, 1981; Shavinina & Seeratan, 2003; Wagner, 2012). The sequential nature of this characterization of inventors' work does not account for failure and the inevitable need to revisit assumptions and decisions at different phases, which contributes to representations of inventing as being iterative, recursive, and non-linear (Frigotto, 2018). Failure is not an end unto itself in this context, but rather a step along the way as inventors work to advance their understanding of a problem and to develop a solution to that problem. Creativity and failure often appear together in the literature, alongside claims that creative thinking generates solutions to the problems that arise when something does not work out as planned. Inventors consider these situations to be opportunities for "learning while designing" (Crismond & Adams, 2012, p. 744) and a normal event that occurs as one engages in "learning by iteration and from feedback and failure" (Crismond & Adams, 2012, p. 744). Thus, from an inventor's perspective, failure is an active agent in creative activities, and the notion of learning from failure is an important aspect of thinking as an inventor.

Our review of studies, focused on youths' experiences with failure, found that it has been studied in relation to tinkering, making, and engineering (Ryoo, Bulalacao, Kekelis, McLeod, & Henriquez, 2015; Wagner, 2012; Lottero-Perdue & Parry, 2017; Martinez & Stager, 2013). Ryoo et al. (2015) focused on an equity-oriented approach of iterative, continuous improvement that celebrates students' processes over the products they create. Wagner (2012) expounded on youths' capacity to make action-oriented change through iteration that is not considered as failure. Lottero-Perdue and Parry (2017) examined elementary school teachers' ways of communicating and reacting to engineering design failures and noted that elementary school students were accepting of failure when they had a chance to modify and test designs again. Martinez and Stager (2013) explored learning theories of making, tinkering, and engineering with a view that tinkering is informed and iterative, thereby allowing for answers to be derived from mistakes. All researchers and authors noted the importance of collaboration. Few studies report findings related specifically to high school students' experiences with creative failure in the context of inventing technological solutions to problems they identify in their local communities.

Table 1
Summary of the Phases of an InvenTeam Grant Cycle.

Phase	Phase description	Months	Duration in weeks	Activities	Milestone
Teacher-focused phases					
1	Recruitment for and submissions of initial applications for Excite Award	Oct.–Apr.	24	Application requires invention proposal, information on school, resumes of teachers, letter of support from administrator, and statement of interest for invention projects	April deadline
2	Finalists' selection by LMIT staff	Mid-Apr.	2	LMIT evaluation of educators' applications utilizing rubric	35 educators receive Excite Award to attend EurekaFest
3	Professional development	Mid-June	1	Excite Award recipients attend professional development during EurekaFest at MIT, view current year's projects, receive feedback on proposed projects, and review guidelines for the final application	Invitation to Excite Awardees to submit final application if they attended EurekaFest
4	Summer work with students	July–Sept.	8	Excite Award recipients work with students to form teams and complete final InvenTeams application.	Final applications submitted
5	Judging	Sept.	4	National jury review and ranking of applications, recommendations to LMIT for staff to make final selection	15 teams selected for $10,000 InvenTeam grants and notified
Team-focused phases with teachers, mentors, and students					
6	Invention project launch	Oct.–Feb.	20	Grant agreements signed, procurement cards released, communications and financial training for teams, on-site visits from LMIT while teams iteratively build, test, and refine invention prototypes based on results and feedback, beginning of year survey	Mid-grant technical review with community in Feb.
7	Post-technical review	Mar.–June	12	Final invention modifications and prototype building, raise travel funds to attend EurekaFest at MIT, end of year survey	Working prototype shipped to MIT
8	Capstone event	Mid-June	1	Teams travel to MIT, showcase inventions, present to peers, meet collegiate inventors, and attend seminars	EurekaFest

Our selection of the Lemelson-MIT (LMIT) Program's 14-year-old InvenTeam grants initiative as a site of study addresses the need for greater insights into young people's experiences with creative failure and the ways in which students interpret such experiences for self. The program is a sponsored program within the School of Engineering at the Massachusetts Institute of Technology (MIT). It has successfully recruited and worked with 229 teams of high school students across the United States that received grants of up to $10,000 to produce a working prototype, ultimately showcased at MIT during a multiday event called EurekaFest. Almost all teams have produced working prototypes of their inventions at the end of the grant period. Seven teams have secured U.S. design or utility patents for their work, although that is not an expectation of the program. It can be expected that youth engaged as inventors on InvenTeams will encounter struggles and failure as part of the iterative design process. Thus, the InvenTeam initiative offers a telling case (Mitchell, 1984) for developing understandings of ways young people engaged in the creative aspect of inventing conceptualize failure, and ways in which creative failure can be a productive learning experience (Littleton & Mercer, 2013).

Initial documentation of the program, conducted as part of an ongoing ethnographic study, found that the program consists of eight phases of work, as shown in Table 1. A proposal for an invention is submitted to LMIT by educators within a seven-month window, and 35 applicants are given Excite Awards that fund travel to attend free professional development sessions held concurrently with EurekaFest. Afterward, Excite Awardees have three months to work with their students to generate a final InvenTeam application. Fifteen InvenTeam grantees ($10,000 per team) are identified after a national jury panel reviews applications in September. Grant agreements are signed and teams commence work within a month. A mid-grant technical review is held by each team with their community partners four months after the team's work commences. Prototype building takes place in the four months that follow and a culminating event, known as EurekaFest, is held at MIT with all teams in attendance.

Post-experience survey results collected for program evaluation purposes offer glimpses into InvenTeam students' experiences with creative failure. Results from the voluntary surveys collected from students at a total of 61 high schools at the end of each grant year between 2013 and 2016 indicate that students consistently agree that working on an InvenTeam project taught them to learn from failure. Table 2 shows that students' responses to "working on our InvenTeam project taught me to learn from failure" ranged from a mean of 4.362–4.398 on a 5-point Likert scale, with 4 being "agree" and 5 being "strongly agree."

As program administrators, we recognized that the online survey did not allow for examining ways in which respondents were defining failure and learning from failure. The inability to connect individual student responses to the context of the student's prior knowledge and experiences, experiences within the InvenTeam project, and experiences at the moment responses were given to the survey raised questions about how to interpret the data. Additional insights into the meanings students attribute to their experiences were needed to generate warranted claims of the program's impact on students and their views regarding creative failure.

We describe in the next section the steps taken as part of this study to supplement the survey data in order to answer our research questions.

4. Exploratory study of creative failure through the "Lens" of interactional ethnography

Transcripts were not available for the day-to-day interactions between students who are on InvenTeams, their teachers, technical mentors in the local context, and LMIT staff. Our preliminary analysis of the talk between students and the program administrators in what follows represents the initial stages of a larger ethnographic study. It represents the progressive uncovering of the meaning making and emic understandings of the collective group as well as individuals within the collective.

4.1. Data collection and analysis

Table 1 presented a summary of an event map depicting the eight phases of an InvenTeam cycle constructed from headnotes of our knowledge of events as program administrators during the 2016–17 year. The data collection for this study began near the end of the 2016–17 school year in May, with the administration of a voluntary online post-experience survey administered by LMIT staff during Phase 7. The survey release date coincided with the teams' efforts at the end of the school year to complete their work prior to shipping their prototype to MIT. The survey was administered after LMIT had worked with students' teachers for as long as six months during Phases 1 through 4, prior to the teams' receipt of a grant from LMIT, and after LMIT had worked with both the teachers and students throughout the school year as they developed their prototypes. Survey question formats varied and included open-ended, matrix, multiple choice, and Likert scale agree/disagree questions. The online survey results were supplemented by transcriptions of one-hour in-person interviews of six students. The interviews were conducted by a program administrator during EurekaFest (Phase 8 in Table 1). EurekaFest is a multi-day capstone event for InvenTeams; it is hosted by the program every June at MIT to celebrate teams' work and prepare them for next steps in the invention pathway. There are other concurrent events during EurekaFest; namely,

Table 2
Descriptive Statistics for "My InvenTeam Experience Taught Me to Learn from Failure".

Year	# Student responses	% Agree response	*M*	*SD*	Min.	Max.
2016	86	87	4.395	0.937	1	5
2015	128	88	4.398	0.767	1	5
2014	116	90	4.362	0.838	1	5
2013	113	86	4.381	0.816	2	5

Table 3
Classifications and Characterizations of U.S. Secondary/High Schools.

School classification[a]	% of high schools in the U.S.[b]	Funding sources	Special program emphasis[c]	Career, technical, and vocational (CTE)	Federal free or reduced-price lunch program available[d]	Number of study participants
Private	0.1%	Tuition and endowments	Yes	No	No	1
Traditional Public	93.1%	Federal, state, and local	Yes	Yes	Yes	4
Charter	6.9%	Federal, state, and local	Yes	Yes	Yes	1

Note. Percent of high schools in the United States by school classification were calculated from U.S. Department of Education's NCES, 2016a and NCES, 2016b data; school classifications are from NCES, 2017.

[a] National Center for Education Statistics (NCES) uses both *high* and *secondary* as terms to define students in grades 9–12.

[b] NCES data includes all secondary schools, including those combined with elementary schools (beginning with grades 6 or below and ending with grade 9 or above).

[c] Special programs include magnet programs, gifted programs, disciplinary programs, Advanced Placement classes, and International Baccalaureate classes.

[d] The Federal free or reduced-price lunch program participation is a proxy for poverty; all InvenTeam applicants provide free lunch enrollments as a percentage of school enrollment.

professional development for the finalists (i.e. Excite Award recipients) vying for the next year's InvenTeam grants and participation by the program's prize-winning collegiate inventors.

The program administrator's written records indicated that a stratified purposeful sampling strategy (Creswell, 2013) was used to select the six students from post-experience survey respondents. This type of sampling was utilized to be at the "extreme of a continuum" (Rubin & Rubin, 2012, p. 56). The sampling produced six interviewees, three male and three female students. One student attended a private high school, four students attended traditional public high schools (two of whom were in a special magnet program within their traditional public high school), and one attended a public charter school. Table 3 provides characteristics on private, public, public magnet, and public charter schools. The students' race and ethnicity were diverse and included those underrepresented in STEM. Half of the interviewees held leadership roles on their InvenTeams. The other half were team members occupying roles that were not labeled as leadership roles. Half of the students joined an InvenTeam to learn new things, while the others joined an InvenTeam to demonstrate what they could do. The six inventors were from five different InvenTeams; two female inventors were on the same team to allow for both inter-team and cross-team comparisons.

The researchers utilized a semi-structured interview script, which allowed for responsive interviews (Rubin & Rubin, 2012) and discussions that could inform the meaning of words and language from students' perspectives (Frank, 2011, p. 49). The approach to interviewing "allowed for gathering rich, detailed data directly" (Heyl, 2001, p. 369) from InvenTeam students to help us genuinely discern what students meant when agreeing to "working on my InvenTeam project helped me to learn from failure." Students were invited to select their own pseudonym. Interviews were video recorded and transcribed.

The teams' technological inventions were conceptualized, designed, and built to solve a problem that each team had identified and agreed upon. The inventions were presented and displayed as an early prototype in each community midway through the grant year in February 2017 (Phase 6 in Table 1). Final versions were presented and publicly showcased at MIT in June 2017 (Phase 8 in Table 1). Accounts of the teams' work publicly accessible on the LMIT website indicate that inventions developed by the five teams with interviewees included solutions that addressed: a societal problem with health implications in their community, a public safety problem involving bicycling in automobile traffic, automobile driving challenges for persons with a physical disability, alerting persons to life-threatening conditions in a closed environment, and facilitated cleaning of public venues. All of the technological inventions included an electronic component and involved integrating several subsystems into a working prototype.

The next phase of our exploratory study consisted of a domain analysis (Spradley, 1980) of the interview transcripts, which provided a systematic approach to categorizing definitions of failure offered by the six students. Intertextual and intercontextual references in the transcripts across time and events—capable of revealing what students report as having been learned from failing—required a more focused analysis of the information students conveyed as they spoke to the program administrator, who, as interviewer, is considered to be an implicated listener (Bakhtin, 1986). Due to space limitations, we limit our presentation of findings to in-depth analyses of responses from two of the six students. The two students were selected for reporting purposes given the contrast in their definitions of failure and the possibilities this presented for gaining different insights into the types of productive learning that can be generated by failure. The focused analysis involved locating a key event (Gumperz & Hymes, 1972) within each student's interview transcript to anchor all subsequent analysis. The interviewer's direct question about the student's experience with failure served as the key event in both instances; that is, it provided an anchor (Forsey, 2008; Bloome & Bailey, 1992; Bloome & Egan-Robertson, 1993) for subsequent analysis of other questions and answers within the transcript with ties to failure.

4.2. Results and discussion of online survey and interview findings

The 2017 InvenTeam initiative comprised 201 student participants. The voluntary post-experience survey received 147 unduplicated responses, including 128 respondents that reached the end of the survey. Survey respondents were 57% male and 43%

Table 4
Descriptive Statistics for "My InvenTeam Experience Taught Me to Learn from Failure".

Variable	# Student responses	% Agree response	*M*	*SD*	Min.	Max.
Learn from failure	120	86	4.242	0.926	1	5

female. Table 4 shows that 86% of the 120 students reported, "working on our InvenTeam project taught me to learn from failure." The mean was 4.2 on a 5-point scale with 4 being "agree" and 5 being "strongly agree."

All students were asked to define failure in their own words directly after responding to the "learn from failure" statement. A domain analysis (Spradley, 1980) of students' written words yielded seven categories of student definitions of failure. The seven categories, as shown in Table 5, are: 1) personal failure (including feelings of not succeeding); 2) quitting or giving up; 3) not achieving the results or goal; 4) a course correction, setback, or process that one goes through; 5) a learning opportunity or a learning experience; 6) part of getting closer to success; and 7) did not experience failure. Forty-nine percent of responses define failure as quitting or not achieving the desired results, whereas thirty-four percent define failure as part of a process, a learning experience, or getting closer to success.

The last question on the post-experience survey asked students to describe their experience with InvenTeams in their own words. The question was asked at a later point in the survey, after answering non-failure-related questions. Failure appeared in only three of the 119 responses, suggesting that it was not the topic of greatest focus for students when describing their experience. The three responses related to failure were:

- It was fun until there was failure. After failure, it just feels extremely stressful.
- I experienced moments of triumph, and moments of failure. But it was a great experience that I will never forget.
- It was very fun. I met with a bunch of my friends and worked on something we all felt passionate about. There was failure and frustration, but a feeling of success at the end.

We sought to gain further insights into the emic meanings of students' definitions of failure, so we extracted the six students' responses to the online survey question from the larger set of data. Table 6 shows that four of the six students defined failure as a learning process.

The next phase of our analysis involved examining the transcripts of in-person interviews with the six students—and their accounts of high and low points in their work—to develop a prototype. Our analysis revealed that when students were asked by the interviewer to offer other descriptive words for high and low points, such as success or failure, failure was not a top-of-mind descriptive substitute for a low point. Alec, who identifies as an engineer, stated:

> A failure can be a low point. But it isn't always a low point, so I would be cautious of equating those two to each other. Definitely from working with robotics and anyone that builds stuff or does anything, in fact, knows that you have to fail a bunch in order to reach a final solution or a final product. When the team is prototyping something, and we kind of feel like we reach a dead end, that's not always a low point. The only times what I would describe as a low point is when I start to question whether or not something that … Like when I start to regret something, that's a low point. I think that the only regret that I had in this entire process was trying to do epoxy [to aluminum] for too long.

Alec described his team's lowest point, yet he did not refer to it as failure. He continued to discuss how things worked or did not work technically. His concluding comment was how the team "had a lot of different failures and dead ends, but again those are to be expected. Those are normal. I don't think I or anyone else on the team would consider those low points."

A subsequent domain analysis (Spradley, 1980) of portions of each student's interview—in which they were asked to describe high points, low points, and then asked directly about experiences with failure—demonstrated that Alec's reference to his team's technical work was typical of all but two responses. Table 7 shows that all students described a type of technical failure, but one exception was Magdalena, who described failure from a human interaction perspective. Failure, from her perspective, occurred when

Table 5
Domain Analysis of Student Definitions of Failure.

Categories of students' definitions of failure	# Student responses	% of responses in all domains (n = 147)
Personal failure/feeling of not succeeding	21	14
Quitting/giving up	26	18
Not achieving results/goal	46	31
Course correction/setback/going through a process	27	18
Learning opportunity/experience	18	12
Getting closer to success	6	4
Did not experience failure	3	2
Total of all domains	147	100
Total respondents	123	100

Table 6
Students' Definitions of Failure in Post-Experience Survey, Based on Reason for Joining Team.

Respondent (pseudonyms)	Phrases that defined failure
Reason for joining: Learn new things	
Magdalena	Failure is something that you were unable to accomplish THAT time, but also something you can learn from to accomplish next time.
George	An (sic) setback that can be learned from.
Chelly	Failure is allowing something to stop you from pursuing and accomplishing something great. In essence, giving up and not persisting.
Reason for joining: Demonstrate what I can do	
Alec	An educational opportunity.
Jacob	Failure is when you give up on something importan (sic) without putting forth the effort to fix the change she (sic) needed for you to be successful.
Celaena	Failure is a success without the sugar coating, it's something that needs to always be redefined and learned from.

she "didn't feel as though I was pulling my team together the way I needed to be." "How to work and organize better with other people" was mentioned by one other student during the interviews in the context of what was learned from the InvenTeam experience, but was not cited in the discussion portion of the interview focused on failure.

Jacob offered the second non-technical response to the question probing definitions of failure. He referred to his team's fear that they could not raise enough funds locally to attend EurekaFest since the teams must engage in fundraising activities to cover travel costs. Jacob was the only student to mention this topic and it is not a topic that appeared in students' responses in the online survey.

We chose to focus in and further analyze the transcripts for two of the six students in order to go beyond merely defining failure, and to generate emic understandings of how InvenTeam students think about learning from failure. Magdalena and Chelly were selected as tracer units for this layer of the analysis because the type of failure Chelly described was typical of four other students in that it related to learning from a technical failure. We selected Magdalena as she was the only student to describe failure from a human interaction perspective. We also selected the two for their similarities on other traits that might influence differences in definitions of failure. Both young women joined InvenTeams to learn new things, and both are underrepresented in STEM by race, ethnicity, and gender. We could not control for differences in their roles on their respective teams. Magdalena was "lead on team management and a member of the business and branding team." Chelly was "part of the solar panel team, which deals with the technology aspect of our invention."

Focusing in on the two young women makes visible the differences in the students' accounts of what was learned from failure and the ways learning was constructed through dialogue and other interactions with individuals. Chelly's example of a technical failure makes visible the learning(s) taking place at the individual level as the individual participates in the collective, with the collective being other students on the team who were also learning how to do new things such as coding. The example of the failure that occurred in the case of Magdalena—with her interaction with another team member—makes visible the learning taking place at the individual level and between two individuals who are subsets of the collective. Building on Bakhtin's notion that we speak with an implicated listener in mind, we traced the intertextual (Bloome & Bailey, 1992; Bloome & Egan-Robertson, 1993) and intercontextual (Floriani, 1993) references across different phases of activity offered by the students' accounts of their experiences. This created an empirical account of the ties across time, texts, and events in students' responses to interview questions, and a means for understanding what the students considered as being socially significant in their local context.

Excerpts from the analysis of Chelly's transcript shown in Rows 1 and 2 of Table 8 demonstrate that she agreed with the interviewer's use of the term *low point* as a definition of failure. Rows 3 through 8 show that Chelly arrived at this definition after having discussed a challenge with coding as a time when she "hit a block in the road." She went on to discuss another challenge with coding that took place further into the InvenTeam project, and cited both instances when asked to define failure. After confirming the definition of failure as a low point, in Rows 9 through 12 she cited learning to work as a team, both in her subgroup and with the larger group as a whole, as what was learned from failure. Chelly then proceeded to make visible her negative emotions and feelings associated with failure (Rows 13–16). Chelly, who recently graduated from a large public high school located on the West Coast of the

Table 7
Definitions of Failure by Six Students from Interviews.

X is a type of failure…	…that is Y	Described by…
Lot of different holes you have to jump through in order to get it sealed tight… Lot of things that we hadn't looked at or even thought about… We kind of got into a slump at some point… Hit the wall.	A technical failure	Celaena
We'd do a couple parts and none would fit or the electronics wouldn't work and that would set us back.	A technical failure	George
Coding … lights wouldn't turn on … fix that, oh the sensor doesn't work.	A technical failure	Chelly
Trying to super glue and epoxy and JB Weld [a type of epoxy adhesive] the aluminum because that really just doesn't work well.	A technical failure	Alec
We weren't going to have enough money to come here [EurekaFest] … [and] something wrong with the wiring of the device … had to rewire each sensor because it wasn't working.	A technical failure	Jacob
Didn't feel as though I was pulling my team together the way I needed to be … because there's a member in my team who has a very negative outlook. Him and I would butt heads a lot.	A humanistic failure	Magdalena

Table 8
Analytical Steps in the Reconstructed Interview with Program Administrator (PA) and Chelly (C).

Row	Actor	Dialogue	Textual/intertextual and intercontextual reference
Step 1: Agreement on definition of failure as a starting point for transcript analysis			
1	PA	…used the terms *high point* and *low point*, are there better terms or different terms that you would use to describe those moments in the project? In other words, would you consider them successes and failures?	• PA's talk to examine what counts as failure. • Reference to previous discussion of high points and low points.
2	C	Yes, I'd say I would.	• Acknowledging that low points constitute failure. • Acknowledging discussion of high and low points.
Step 2: Tracing backward to locate intertextual & intercontextual ties to low points earlier in the transcript			
3	PA	Can you tell me about one specific time where you hit that block on the road?	• PA probing failure without naming it for student.
4	C	… It was with the coding… we could have it all working just in one with our sensor, and lights, oh and our LCD display because that's you know what we were going to use as one of our safety features, and we just couldn't get it to work… And that's how it was for a while, and we were just so frustrated because we couldn't you know understand or solve the problem… It just really intensified that negative feeling.	• Offering example of a block in the road with coding. • Acknowledging negative emotions and negative feelings associated with failure.
5	PA	So, would that have been one of the low points in the project then?	• PA probing failure without naming it for student. • Confirming coding example as a low point.
6	C	Yes. Definitely that was one of the low points.	• Confirming coding example as a low point.
7	PA	…were there other low points?	• Exploring other low points.
8	C	Yes… It was also with coding. Surprise, surprise. And we were starting out with our sensor and lights, so just those two. Having the lights on and then making the sensor… we just couldn't get it. It was again, just frustrating … were just really tired and just you know wanting to get it done.	• Offering second example of a low point, also involving coding, • Acknowledging negative emotions and negative feelings associated with failure.
Step 3: Tracing forward in the transcript to uncover emic understandings of failure and learning from failure			
9	PA	So, talk to me a little bit about failures and learning from failures, and how that may have happened either during the InvenTeam project or another situation that you've come through.	• PA's talk to examine what counts as learning from failure. • PA exploring in context of InvenTeam or broader context.
10	C	Well for failures … I'm thinking… like we said of those [reference to coding], like I would consider those failures even though you know we ended up fixing. I would say that those were failures at least in the beginning.	• Referencing coding examples as failures.
11	PA	Yeah, what you learned from your successes or your failures during the InvenTeam project or in another project that you may have worked on.	• PA's talk to examine what counts as learning from failure. • PA exploring in context of InvenTeam or broader context.
12	C	Well as I guess … You can as cliché as it may seem from our failures I think we really just learned how to you know work as like a team, and how this as a team effort, and I mean overall not just within like my subgroup.	• Learned how to work as a team. • Team effort at the subgroup and whole-group level.
Step 4: Tracing forward to examine other discussions of failure			
13	PA	What about those low points? What made them memorable?	• Exploring significance of failure and learning from failure.
14	C	The feeling I say because that really impacted us. The frustration, anxiety, and stress we felt about those low points or you know I mean going those low points affected our confidence in this invention, and it affected how… We ended up doubting ourselves in a lot of the cases you know because of these feelings that the low points you know produced, and like I said I kind of… When you're reminiscing or like thinking about it, going back to those times, that's where you really kind of feel again.	• Acknowledging negative emotions and negative feelings associated with failure.
15	PA	Is there some great learning that you can take from this experience and hopefully apply to some of the things that you might experience in the future?	• Exploring transferability of learning from failure.
16	C	Definitely. Because, like I said you know, through this process we went through a lot of high and low points, and I feel… Thinking about you know those low moments that I will have in college… I know that I'm going to have low points in college and I think that you know I can take the experiences I've had here like with the inventing, and I could apply there.	• Expressing potential of InvenTeam experience with highs and lows to transfer to college experiences.

United States, stated (Row 16), "I know that I'm going to have low points in college and I think that you know I can take the experiences I've had here like with the inventing, and I could apply there." This statement suggests Chelly perceives that her experiences with her InvenTeam—and the way she learned to deal with failure and the negative emotions around failure as a result of participation—will transfer to other experiences she is anticipating in college.

Table 9
Analytical Steps in the Reconstructed Interview with Program Administrator (PA) and Magdalena (M).

Row	Actor	Dialogue	Textual/intertextual and intercontextual reference
Step 1: Agreement on definition of failure as a starting point for transcript analysis			
1	PA	Talking about the high points and the low points again, are the terms *high points* and *low points* appropriate for what you were going through, versus other words like successes and failures?	• Program Administrator's (PA's) talk to examine what counts as failure. • Reference to previous discussion of high points and low points.
2	M	Maybe. I guess the reason I have a harder time saying high point versus low point what would be because the team … would work on what they needed to work on, okay?… They wouldn't feel the same amount of stress I would feel because I was always the one talking to our mentors, I was the main point of contact or with Tony Perry or Lemelson, whatever. I feel like they didn't feel the same amount of stress that I did. And so, every point was always a stressful point for me throughout the whole thing. Was I happy at times? Of course it was. And yeah, it was a fun project. But I know for a fact that I was the most stressed out of everybody. I would joke that I was a mom with eight kids.	• Acknowledging stress of role on the team throughout the entire project. • Lack of resonance with a particular high or low point or term *failure*.
Step 2: Tracing backward to locate intertextual & intercontextual ties to low points earlier in the transcript			
3	PA	I'm sure that during the InvenTeam project, there were some high points and some low points.	• PA probing failure without naming it for student.
4	M	Yeah. Absolutely.	• Acknowledging low points.
5	PA	Can you share with me some of those high points and some of those low points?	• PA probing failure without naming it for student.
6	M	I can. I guess some low points would be when I didn't feel as though I was pulling my team together the way I needed to be and that would be because … there's a member in my team who has a very negative outlook. Him and I would butt heads a lot and I think it was because, it's just I was trying to set this mindset of we can do it, but he always had a reason why we couldn't. And so, I would have to butt heads with him a lot. And so that would cause some low points.	• Offering example of not feeling like she was pulling her team together and butting heads with another student as a low point.
Step 3: Tracing forward in the transcript to uncover emic understandings of failure and learning from failure			
7	PA	But you came out of the experience as team members. I mean, he [referencing student she butted heads with] didn't quit.	• PA probing failure without naming it for student.
8	M	No, he didn't. And we managed well. I learned how to speak in a way that he would understand and he learned to understand myself as well. We learned how to understand each other.	• Learned how to speak in a way that the other team member would understand…learned how to understand each other.
Step 4: Tracing forward to examine other discussions of failure			
9	PA	On other projects that you had worked on or other things in your life, had you experienced some of these types of high points and low points?	• PA probing failure without naming it for student.
10	M	I would say every PBL I've been in.	• Acknowledging prior experiences with low points.
11	PA	Okay. Every PBL. Yeah. How about the stress level? Had you experienced a similar type of stress level on other PBLs?	• PA probing failure without naming it for student.
12	M	Yeah. I mean, I wouldn't say on the same level, maybe. The way it works at STEM, they have you doing PBLs at ninth grade and its sort of something you're sort of thrown into. And they expect you to fail the entire ninth grade. That's an expectation of them. But you don't realize that and so you're just really stressed, especially for your first ever presentation because most schools don't start you out public speaking until maybe senior year. But we started doing it in ninth grade, eight times that year.	• Acknowledging past experiences with expectations of failure in school environment and related stress.
Step 5: Examine entire transcript for intertextual ties to accounts of learning from failure			
13	PA	Okay. In moving through the InvenTeam project, has the project impacted your self-confidence today?	• PA probing self-confidence.
14	M	My self-confidence? I actually feel after being part of the InvenTeam, that I can do a lot more. I didn't feel as though I could do as much before but with the work I've done with them, I have a new look at myself, I suppose.	• Acknowledging new view of self as a result of InvenTeam experience.
15	PA	So, what do you see?	• PA probing new view of self.
16	M	Well, I always had people tell me that I would be a leader when I was younger, but I didn't really believe it. But now I do because I did it. I led. I see myself now as someone who can just do anything if they put their minds to it. I truly now cannot see why I can't do anything if I just do it.	• Acknowledging new belief in self as a leader from having led.

Magdalena, who recently completed the 11th grade at a STEM magnet school located in the southern region of the United States, used the term *low point* in her description of challenges with another team member who made her feel as if she could not pull her team together in her role as the lead on team management (Row 6 of Table 9). She did not use the term *failure* in connection with her InvenTeam experience, but later in the interview she described another experience of a low point and used the term *failure* in the context of the other project-based learning experiences at her school that could be considered a low point (Rows 9–12). Learning how to speak in a way that would be understood by the team member with whom she butted heads, and learning how to understand each other (Row 8) were cited as what was learned from her low point on the InvenTeam. Like Chelly, she mentioned the stress of her InvenTeam work several times (Row 2) and described it as "ever present." She also characterized her prior experiences with project-based learning and expectations of failure among ninth graders entering the school she attends as having been stressful (Row 12). Her responses to interview questions regarding failure within the InvenTeam context do not refer directly to ways her experiences may be applied in other contexts. However, the experience she cited as a low point had to do with her relationship with another teammate in the context of her role as the team leader and project manager. Thus, we returned to the transcript (Step 5 in Table 9) to examine Magdalena's references to self as a leader that may be tied through references to the butting of heads with her teammate (a low point or failure). This revealed an exchange with the interviewer in which Magdalena described a new view of self as a leader, which grew out of having led during her InvenTeam experience and gave rise to a new belief that she "can do anything" (Row 16).

5. General discussion and conclusion

Our analysis confirmed that young inventors, like more mature inventors, learn through creative failure as part of the iterative and recursive nature of the invention process. The two telling cases informed us about the ways the new knowledge will be used in future contexts outside of inventing. Students preferred to use the terms *high points* and *low points* to characterize failure as just one step within a larger process, rather than the term *failure* itself, which can be interpreted as a final outcome. In most instances, the conceptualizations of failure by the six interviewees referred to experiences with a technical challenge, but instances of human conflict within the team and challenges with raising the funds needed to attend the EurekaFest capstone event at MIT were also mentioned. The definitions of failure offered in response to a question in the online survey of all students on InvenTeams varied, but could be classified as falling within seven categories: 1) personal failure (including feelings of not succeeding); 2) quitting or giving up; 3) not achieving the results or goal; 4) a course correction, setback, or process that one goes through; 5) a learning opportunity or a learning experience; 6) part of getting closer to success; and 7) did not experience failure.

The examination of the ways in which two students, Chelly and Magdalena, conceptualized what they learned from failure revealed two very different accounts of what was taken up and ways in which what was learned may apply in contexts that extend beyond InvenTeams. Chelly learned to deal with failure through her attempts at coding. She verbalized the negative emotions she experienced around failure, and expressed her belief that what she learned about how to deal with failure and the negative emotions it evokes will transfer to other experiences she is anticipating in college. Magdalena learned that she was a leader because "I did it"—a statement that was tied to the next portion of her transcript, in which she described overcoming an initial failure with the human interactions with a team member in her role as the project manager. This experience led her to state that she now sees herself as someone who can do anything, implying that what she learned about herself as a leader, will apply in other contexts. Further research into the other students' accounts of what was learned from failure may make visible other ways in which students are conceptualizing what they learn from failure, and their thinking as to how what they have learned applies in other contexts.

Students' definitions of failure reflect the ways more experienced inventors talk and write about failure as being an occurrence or active agent within an ongoing process as opposed to a negative outcome. How InvenTeam students' understandings of failure developed, or were talked into being (by whom, when, and where), was beyond the scope of this study. We also do not know if the definitions students within the context of carrying out the interdisciplinary work of inventing influences their views of performance within specific disciplines such as English Language Arts. However, these are important topics for future research. Given the limitations of this study, we do not know whether InvenTeam students' definitions of failure pre-dated their time on an InvenTeam, nor do we know the extent to which their conceptions of failure were altered by their experiences as members of the team or by the broader ways of thinking and cultural conditions present within their local schools and/or other social groups to which they belong.

Unanticipated accounts of the emotional aspects of learning from failure, uncovered during the analyses of our telling cases, point to the need for further research into the pedagogy that supports learning through iteration (including invention education), especially given concerns raised by some researchers on behalf of students from underrepresented backgrounds who may experience failure in ways that are different from other students (Ryoo et al., 2015; Vossoughi, Escudé, Kong, & Hooper, 2013). Additionally, data in the 2017 online post-experience survey regarding participants' experiences in areas such as learning persistence and developing self-confidence in the ability to solve problems represent other types of thinking skills that may be intertwined with students' experiences of high and low points while inventing. Examining these other ways of thinking was beyond the scope of this study, yet they warrant further research.

Bakhtin (1986) says that sooner or later what is heard and actively understood will find its way into subsequent exchanges. This suggests the need for longitudinal studies that go beyond the individuals' success in developing the prototype and, in some instances the award of a patent, to examine how individuals personally take up the notion of creative failure for future action (or not). These types of studies would show how and in what ways students' work in teams to identify real world problems and create novel inventions designed to solve the identified problems becomes a resource (or an active agent) for learning ways of thinking as an inventor. It would allow researchers to examine the extent to which the ways of thinking become a resource for students (or not) in other contexts.

The "thick descriptions" (Geertz, 1973) of life within InvenTeams as a social group that our research seeks to uncover are not yet possible given the early stages of collecting and triangulating multiple forms of data (Atkinson & Coffey, 2003). The many layers of work, such as the work done by InvenTeam leaders, mentors and school administrators in each local context, and the ways each of the layers of work supported the development of students' internalization of 'creative failure' as a positive experience, are not yet visible. Longitudinal studies would allow for extended studies of these layers so that ways cultural conditions in particular settings form, develop and support students' understanding of creative failure and other ways of thinking as an inventor can be seen and understood.

The broader implications of our study lie in its approach of combining survey data with semi-structured interviews and the use of an interactional ethnographic 'lens' for analysis in order to gain insights into students' emic accounts of changes in their ways of thinking after engaging in experiential learning activities. The approach to developing understandings and ways of talking about outcomes that reflect words students use—as opposed to those of adult educators or program administrators—can be used across a wide range of disciplines or fields of study. Adoption of the epistemological and ontological frameworks and research methodologies described herein also offer opportunities to generate new theories regarding the learning lives of students when teaching and learning emphasizes processes and ways of thinking that go beyond the boundaries of a single discipline.

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