LEARNING FROM DELIBERATE FAILURE: A HOLISTIC APPROACH USING THE CDIO FRAMEWORK

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ABSTRACT

This paper presents the outcomes from 2 runs of the Working Group on Learning from Deliberate Failure from 2 successive International CDIO Conferences: first in 2023 and another in 2024. This paper outlines a holistic approach based on the CDIO Framework to the development of failure-tolerant mindset among students. We believe this paper is the first of its' kind to offer a comprehensive set of design principles that provide guidance to faculty interested in engaging students in learning from Deliberate Failure. The purpose is to assist in the design of a series of learning tasks that had “failure elements” built-in (hence the term “deliberate failure”) so that students can become more receptive towards accepting failure as a way of learning. This paper first briefly summaries outcomes from earlier work where we highlighted that there exist 2 seemingly polar extremes of learning from failure: one that seeks to promote innovation (such as in product design) via frequent exposure to failure where frequent experimentations are encouraged so as to improve with every iteration; and another that strive to avoid failure at all costs, for example, in operating complex systems such as nuclear or chemical plants. For the latter, learning from failure is achieved through case studies of past failures or from simulation of known failure events. This is followed by a literature review on design principles. We then proposed a holistic approach that faculty can use to design learning tasks for learning from failure. The approach is holistic in 2 ways: First it comprehensively covers all aspects of students learning experiences, for a transformative change in their mindset on failure, from the initial appreciation of failure’s role in promoting learning to the eventual embrace of failure as an experience that is to be welcomed; to be achieved through a range of design principles appropriate for various stages of the transformative process. Secondly, the approach is holistic in that it also provides guidance on how faculty can facilitate the learning process, for example using autonomy supportive teaching, and role-modelling. This paper concludes with discussion on limitations of the approach, and possible future work notably in the areas of assessment of learning.

KEYWORDS

Deliberate Failure, Design Principles, CDIO Standards 1-12

BACKGROUND INFORMATION IN BRIEF

The work to investigate ways to better prepare students to learn from deliberate failure stemmed from efforts by the authors – from Singapore Polytechnic (SP) and Singapore University of Technology & Design (SUTD) – to understand the impact of digitalization on students' perception of mastery in their job roles. In the competitive and high-stakes educational system, fostering creativity and innovation requires a deliberate shift in pedagogical approaches to normalize and leverage failure. This is critical for equipping students to navigate the complexities of modern industries, where resilience and adaptability to setbacks are indispensable Subsequent studies by the authors and other colleagues in SP and SUTD, and via a Working Groups on Learning from Deliberate Failure at the 2023 International CDIO Conferences (Cheah & Willems, 2023) yielded the following insights:

(1) Learning from failure can largely be categorized into 2 different threads, based on the intended outcomes: (a) to promote product innovation, which is by far the common use of learning from failure, where one is encouraged to "fail fast, fail early" that leads to improvements in the next product iteration; and (b) to maintain operational stability in complex systems (such as chemical plants), by avoiding process upsets that leads to production issues, or worse in creating safety hazards.
(2) Learning from failure for case (b) remained an under-researched area. Failure in this regard is undesirable and is to be avoided at all costs. The dominant approach here is based on case studies of previous failures, and to a lesser extent, through simulation exercises based on typical (i.e. known) failure scenarios. This approach has its limitations in today's digitalized world (Cheah, 2023) but is beyond the scope of this paper.

The authors also noted the use of failure as an approach to engage students in learning still lacked a unifying approach (Tawfik, et al, 2015; Jackson, et al, 2022). Based on these findings, subsequent research in these areas was then split into 2 threads: Case (a) is led by SUTD to explore interventions that build up students' failure tolerance in product innovation, as they continue to learn from earlier mistakes to improve on the next product design cycle; and Case (b) is led by SP to explore how the CDIO Framework can be used to guide the redesign of existing integrated learning experiences or design new ones to better prepare students in dealing with process upsets in complex systems, to prevent operational failure. The focus on deliberate-learning-from-failure addresses the gap in preparing students not just for academic success but for real-world challenges, enhancing their ability to innovate within evolving digital and industrial landscapes.

Despite their markedly different approaches, both threads shared a common trait in that failure is inherent in both innovation activities (Baxter et al, 2023; Edmondson, 2011; McGrath, 2011) and in complex systems (Edmondson, 2011). Both strive to change students' mindset to move it away from fearing of failure to one that embraces failure. We introduce the term "unsuccess" to communicate to students they had not failed in their efforts – it is that they have "yet-to-succeed". This is similar to descriptions used by various authors, for example, embracing "constructive failure" (Clifford, 1984), "non-successes" (Covington, 1992), "small losses" (Sitkin, 1996), and "temporary failures" (Alif, et al, 2004). Our concept is shown in Figure 1, whereby with suitable interventions administered over several periods of study, the mindset will gradually migrate from "unsuccess" to "success".

At the 2024 International CDIO Conference, Willems et al (2024) presented work from SUTD for Case (a) while Cheah, et al (2024) presented work from SP for Case (b) using an approach he developed for learning from failure for chemical process plant operations using the CDIO Framework (Cheah, 2023).

At the same 2024 conference, the authors conducted the second Working Group for Learning from Deliberate Failure, which sought to synthesize a set of design principles to guide faculty in designing of learning tasks that engage students to learn from deliberate failure. This paper is the outcome of these works.

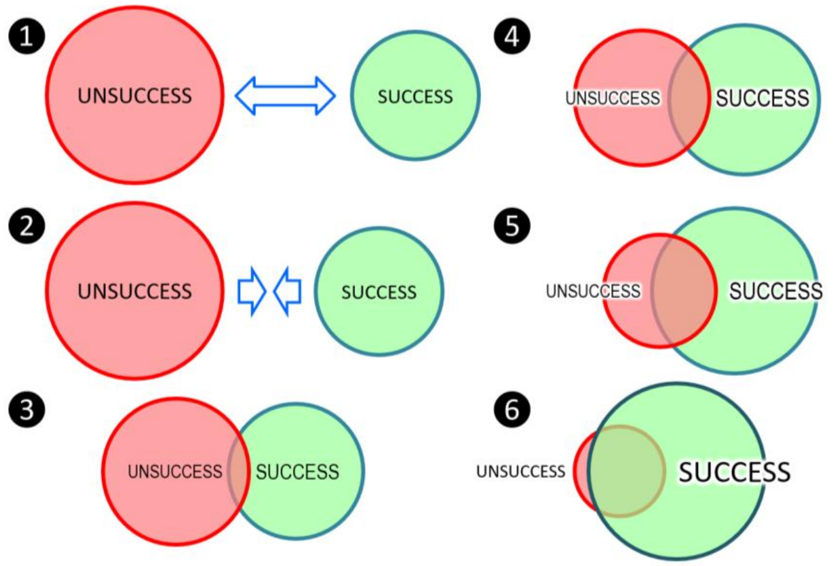

Figure 1. Changing of Mindset from "Unsuccess" to "Success"

SCOPE OF THIS PAPER

The relative pros and cons of learning from failure is still hotly contested (Eskreis-Winkler & Fishbach, 2022; Thiel & Semrau, 2022; Rhaiem & Amara, 2021; Madsen & Desai, 2010; Baumard & Starbuck, 2005; Van der Panne et al, 2003). This paper takes the position that it is beneficial to learn from failure, provided that the learning process is well-managed through a series of thoughtful design of learning interventions so that the desired change – i.e. acceptance of failure as a source of learning – can occur.

The needs to have a set of design principles is recognized when our efforts as reported above showed that there is a lack of research into the systematic design of interventions to better prepare students to embrace failures and see them as opportunities of learning especially in the case of operation of complex systems. By having a holistic and coherent approach, we hope to avoid what Feigenbaum (2021) called "Dissonant Paradigms of Failure in Higher Education" when we tell students it is acceptable to fail but our actions showed otherwise.

This paper presents an approach that we believe is a first of its kind to provide guidance on how to shift students' mindset from fearing failure to one that embraces it, through a series of CDIO integrated learning experiences, created based on various design principles depending on which aspect of change (see Table 1 later) is targeted. As changing students' mindset on failure is a complex, multi-faceted challenge, we suggest that using a design-based approach may be a viable way for faculty to iterate on the intervention efforts with "built-in" elements of deliberate failure to achieve the desired mindset change. In particular, VanLehn et al (2003) noted that learning did not take place despite instructor guidance of a concept if the students did not reach an impasse during the learning process.

“Deliberate Failure” in this context of this work means that educators can deliberately design learning activities with elements/difficulties that will lead to students encountering challenges to complete the prescribed task, i.e. “failure”. Such an approach would be equally applicable for both Cases (a) and (b) mentioned earlier. The differences lie in the choice of design principles to be used depending on the desired outcomes of the intervention, as some may be more suited for Case (a) as opposed to Case (b) and vice versa.

As such, this paper proposes a holistic approach in designing for deliberate failure using the CDIO framework as a basis. We thus synthesize prior work on learning from failure published within as well as beyond the CDIO tradition (e.g. Cheah, 2023; Foley et al., 2022; Huang et al., 2023; Willems et al., 2024). Below, we first expand on our choice for using design principles for this paper, after which we detail how these map onto the CDIO framework. We end the paper discussing the implications of our work.

WHAT ARE DESIGN PRINCIPLES?

Design principles are considerations that can be used to guide the design and development of learning environments in higher education that are based on sound practical and theoretical principles, and that can promote student engagement through innovative learning tasks. They exist in a range of different contexts, and they enable teachers and instructional designers to use well-researched ideas as guidelines for their own efforts to enhance student engagement and learning outcomes (Herrington & Reeves, 2011).

Van den Akker (1999) described design principles as heuristic statements in a format best illustrated as follows:

> *If you want to design intervention X [for the purpose/function Y in context Z], then you are best advised to give that intervention the characteristics A, B, and C [substantive emphasis], and to do that via procedures K, L, and M [procedural emphasis], because of arguments P, Q, and R. (pp.9)*

McKinney, et al (2006) cautioned that such design principles are not ”recipes for success” but are used principally ”to help others select and apply the most appropriate substantive and procedural knowledge for specific design and development tasks in their own settings”. Likewise, Herrington & Reeves (2011) reminded that it is unwise to consider design principles to be ”set in stone”. Instead, the authors suggested that they are best regarded as informed reusable guidelines for others wishing to create their own solutions to educational problems across sectors.

Table 1 shows a summary of design principles we proposed for designing integrated learning experiences for learning from deliberate failure. It expanded quite considerably the earlier work of Tawfik et al (2015). Following Carlson & Fishbach (2024) who noted that a key challenge of learning from failure is that extant research tended to be siloed to particular fields; hence our search covered a wide range of disciplines from education, psychology, organizational behavior, medicine, etc. The design principles are classified into various dimensions based on the type of outcomes each approach aims to achieve. Due to page limitations the respective design principles cannot be discussed in detail in this paper.

Table 1. Design Principles for Learning from Deliberate Failure

Design Principles	How it Work
Dimension: *Awareness of Failure*	
Define conditions for failure (Tawfik et al, 2015)	• Students are primed to investigate failure-states, through prompting to address the conditions for success and failure before problem-solving. • Use of failure-based question prompts, as learners may not fully understand the variables associated with a given failure scenario; hence a prompt can help in consideration of plausible scenarios and recognize potential misconceptions
Preparing the Mind: Visualization of Tasks (Cheah, 2023)	• In the context of the work of Cheah (2023), which concerns the process operation of chemical plants, this means getting students to study a given process (including the standard operating procedures) and identify areas where potential failure(s) can occur
Dimension: *Identify Consequences*	
"Learning from Disasters": Case Histories of Failures	• Cheah (2023): Traditional approach in the chemical processing industries – Learning from Disasters: making the connections between causes and consequences of an accident
Taxonomy of Failures (Young, 2019)	• Velikova et al (2018): Such taxonomy can help to establish the relationships between causes, failure symptoms and long-term consequences and improve understanding of failure • Narduzzo & Forrer (2024): A 2x2 typology of failure based on intentionality and the learning effect
Dimension: *Inquiry into Failure*	
Sense-making (Weick et al, 2005)	• Weick et al (2005): Sense-making is the process of determining how an event came about, an answer to the question "What is the story?" • Cheah (2023): Interactions between components, esp. for complex systems, with focus on relationships between process variables - Rumsfeld Matrix: Unknown Knowns
Trigger Thinking (Jackson et al, 2022)	• Theme 3 (*Failure as a mechanism to uncover key concepts*): Students first made aware of their failures, students to identify and reconcile their misconceptions… leading to: • Theme 4 (*Failure induce thoughtfulness in problem solving*)
Productive Failure (Kapur, 2015)	• It is an instructional approach that requires learners to struggle as they attempt to generate solutions to problems before, rather than after, receiving direct instruction on a targeted concept
Elaboration Prompts (Liobl & Leuders, 2019)	• Students explicitly prompted to make comparisons of correct and incorrect examples after problem solving (In general, prompts are questions or hints that aim to increase the likelihood that learners will engage in specific learning activities or give certain answers or self-explanations)
Desirable Complexity (Foley et al, 2016) based on Axiomatic Design (AD) Theory	• Using notion of "AD inverted" to "reverse engineer" selected elements of a learning task that were identified to offer opportunities for students to learn from failure. But need to be careful here though: not to make a task unnecessarily complex for the sake of making students make mistake!
Dimension: *Reflection on Learning*	
Different Perspectives on Failures	• Edmondson (2011): Blameworthy to Praiseworthy – Spectrum of Reasons for Failure • Jackson et al (2022) Theme 1 *Varied Meanings of Failure* – Process vs Solution-Oriented • Negative Knowledge (Gartmeier et al, 2008): Reflection on knowledge acquired experientially on what is wrong and what is to be avoided during performance in a given work situation • Dorland (2023): Use design thinking to reorient students' conceptions of failure as part of their creative problem-solving skill development process

Table 1. (cont'd)

Failure Stories	• Remove the Ego (Eskreis-Winkler & Fishbach, 2022): Cognitive Distancing, i.e. adopt a third-party perspective to think of one's own failure • Self-Talk (Kross et al, 2016): Small shifts in the language people use to refer to the self as they engage in this process consequentially influences their ability to regulate their thoughts, e.g. more receptive to learn from failures • Bledow et al (2017): Learning from others' failures
Systematic Reflection (Ellis et al, 2014)	• It is a learning procedure during which learners comprehensively analyze their behavior and evaluate the contribution of its components to performance outcomes; through a process of self-explanation, data verification and feedback
Dimension: *Accept/ Embrace Failure*	
Destigmatized Failure: Failure as Generative (Feiganbaun, 2021)	• Failure represented as temporary, healthy, and integral components of any learning process • Students learn more profoundly in the long term when they struggle more in the short term
Active Acceptance (Schwarz & Bouckenooghe, 2021)	• Organizations respond to failure by actively repositioning the failed outcome as success, by repositioning the criteria for what is success (e.g. by recasting what was achieved) in order to move forward, enabling organizational learning from failure
Intelligent Failure (Sitkin, 1996) as means to promote innovation	• Sitkin (1996): It results from thoughtfully planned actions that have uncertain outcomes and are of modest scale, are executed and responded to with alacrity, and take place in domains that are familiar enough to permit effective learning
Dimension: *Develop Confidence*	
Growth Mindset (Dweck, 2006)	• Eckstein et al (2023): Failure Pedagogy – Teach students about developing a growth mindset • Shahagun et al (2021): The Growth-Mindset Teaching (GMST) pedagogy as a learning opportunity and participants can feel safe to learn, re-learn, and explore knowledge without the fear of being wrong • Willems et al. (2024) on the role of encouraging an iterative mindset in stimulating innovation and design-thinking
Opportunities for Transfer	• Teaching Others – The Protégé Effect (attributed to Jean-Pol Martin in the 1980s) is a concept in learning suggesting we learn more effectively by teaching information to others, even if those others aren't necessarily any less knowledgeable
ACROSS ALL DIMENSIONS: *Teacher-Student Relationship*	
Student Reaction to Failure	• Henry et al (2019): Failure Mindset Coping Model – to help understand how students might approach challenges and respond to failures in undergraduate STEM learning contexts
Supportive Learning Environment	• Jackson et al (2022) Theme 2 *Student Reactions to Failure* and Theme 5 *Classroom Climate and Communications about Failure:* teachers need to foster a classroom culture that embraces failure and learning together • Eckstein et al (2023): Failure Pedagogy – Teacher Vulnerability: share your own failures with students • Narla (2022) Teaching to Fail: Create a vulnerable learning community • Foley et al (2022): Non-Violent Communication by Rosenberg (2015) • Bury & Masuzawa (2017): Non-Hierarchical Learning
Autonomy-Supportive Teaching (Reeve & Cheon, 2021)	• Adoption of a student-focused attitude and an understanding interpersonal tone that enables the skillful enactment of 7 autonomy-satisfying instructional behaviors (ASIBs)

Table 1. (cont'd)

ACROSS ALL DIMENSIONS: Faculty Professional Development	
Temporary Failure (Alfi, et al, 2004)	• Teacher education to address the difficulty of some teachers in allowing students to experience any kind of failure, not even temporarily; thus their willingness to challenge their students
Deliberate Reflection (Laksov & McGrath, 2020)	• Focuses on failure as catalyst to improve academic development work, through exploration and analysis of failure in one's practice, and discussion among peers • Vedder-Weiss et al (2018): Product framing of pedagogical failures – teacher sharing of learning experiences
Teacher Modelling (Wong & Cheah, 2022)	• Teacher demonstrating growth mindset, and other coping mechanisms, for example, arising from own failure • (The reference summarizes a literature review of teacher modelling using the context of developing self-directed learning competency in students)

PROPOSED HOLISTIC APPROACH TO LEARNING FROM DELIBERATE FAILURE

We argue that a holistic approach is needed so that students can most benefit from learning from deliberate failure. This is because the impact of failure can be so demoralizing that students may withdraw from the learning process altogether. Much has been written about the debilitating effects of failure that we will not repeat here (for a more recent discourse on this topic, see for example Edmondson, 2023; Eskreis-Winkler & Fishbach, 2022).

Based on the typical CDIO approach of progressively developing desired graduate attributes over a given program's duration, a similar way of inculcating failure-tolerant mindset among students can be articulated. An example used by Cheah (2023) is shown in Figure 2 below.

Figure 2. Pedagogy for Learning from Failure

Briefly, the 3 stages (each with 2 dimensions) can be explained as follows:

- *Awareness of Failure and Identify Consequences*: This means that students become aware of potential failure situation(s) before embarking on a given task. This is to be achieved via a deliberate process of getting them to visualize possible failure scenarios. They are then asked to explain plausible consequences. We are not looking for right or wrong answers at this stage. This is to "sensitize" them that "things can and will go wrong!".
- *Inquiry into Failure and Reflection on Learning*: This means that students are able to adopt an open mind and inquisitive stance to look into causes of failure and reflect on the learning. The main focus here is to let students see the possible learnings that can be gained; and metacognitive also think about how to improve on identifying plausible scenarios that were missed.
- *Embrace Failure and Develop Confidence*: This means that students recognize positive lessons that can be learnt from failure scenarios; and are able to derive key insights from such learning that they can apply the learnings gained in a given setting to other contexts.

Figure 3 represents our holistic approach towards developing failure-tolerant mindset among students. It shows how the integrated curriculum (CDIO Standard 3) can be used to progressively drive the desired transformation towards a failure-tolerant mindset, consistent with the pedagogy shown in Figure 2. This is shown as a series of learning outcomes (CDIO Standard 2). This is achieved through a series of design-implement experiences (CDIO Standard 5) and integrated learning experiences (CDIO Standard 7), focusing on real-world work environment for student engagement (CDIO Standard 1). The figure also highlights the importance of maintaining constructive alignment, where the attainment of desired outcomes via design-implement experiences and integrated learning experiences are checked using appropriate assessments (CDIO Standard 11). Lastly, faculty professional development is implied in the use of various design principles and teacher-student interactions (CDIO Standards 9 and 10).

DISCUSSIONS

The approach as shown in Figure 3 highlights that failing is a process, not an end point. We must allow for failure, and in order to learn from our failure, we must work on it (Litts & Ramirez, 2014). This paper introduces a repertoire of design principles at each stage of the transformative process, to aid the design of various learning interventions. The desired outcomes can be discerned from the CDIO Syllabus, most notably *Part 2.4 Attitudes, Thought and Learning*, as shown in Appendix 1.

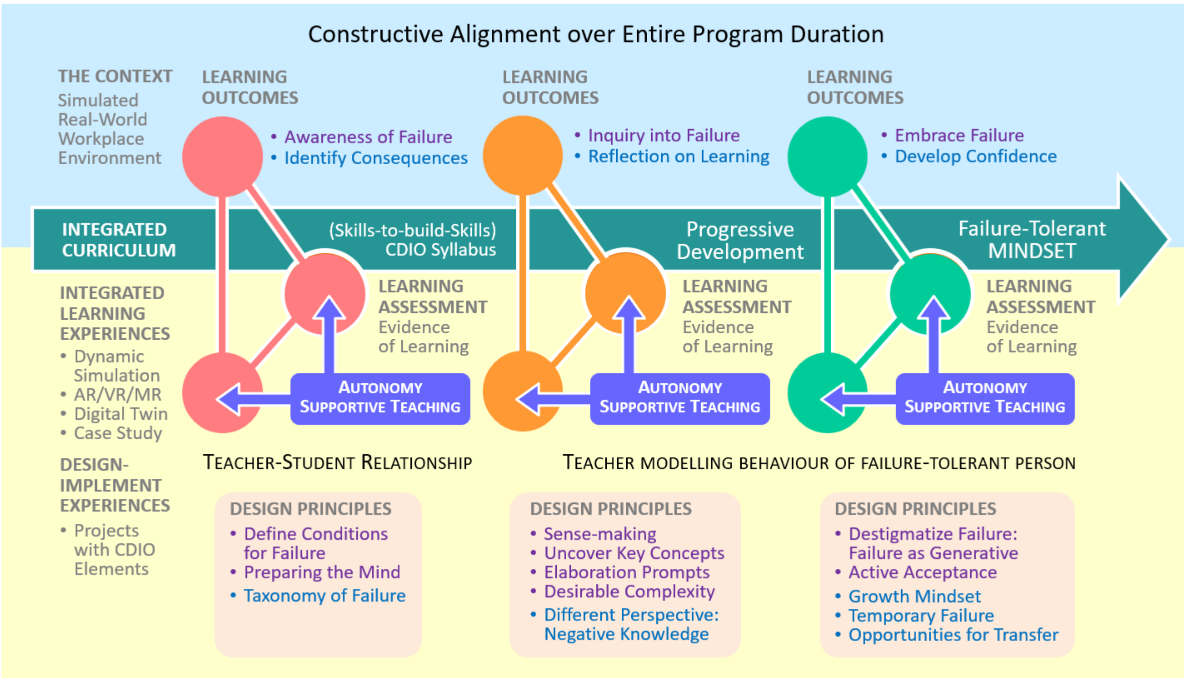

Figure 3. Approach to Develop Failure-Tolerant Mindset using CDIO

Our suggested approach is holistic in two ways. First, it comprehensively covers all aspects of students learning experiences, from firstly to initiate a mindset change to the development of failure-tolerant mindset. Second, it also provides guidance on how the desired mindset can be attained, through a range of tasks from the design and delivery of the curriculum, assessment and faculty professional development on how to facilitate the learning process, for example using autonomy supportive teaching, and role-modelling.

Table 1 is not meant to be a laundry list of all design principles that lecturers must use. There are certainly overlaps between some of the design principles, as different author(s) used a different terminology to describe one's proposed intervention. It is more like a toolbox where faculty pick the suitable design principles that match the desired aspect(s) of mindset change desired, in the design of appropriate learning interventions. It is also possible that using one design principle may have more than one effect on students learning. For example, systematic reflection can help in destigmatizing failure and promote growth mindset. Hence, it is reasonable to expect that a single learning intervention may concurrently employ several design principles within the same learning context.

We also deliberately omitted the use of game-based learning or gamification as design principles. The rationale for the omission is as follows: Usually the term "serious game" is used to describe games designed for educational outcomes as opposed to those designed for entertainment. For games to be of educational and aid students, they must focus on the content to emphasize theories to be learnt and should therefore be developed by scholars and teachers and be based on good academic philosophies (Adipat et al, 2021). However, often times the teachers' pedagogical expertise does not directly translate into game design, and it leaves educators puzzled regarding the effective ways to introduce learning games in a class and what elements of games and learning should be prioritized (Kucher, 2021). Studies by Chase et al (2021) showed that some common features can hinder students' failure tolerance, challenge-seeking and learning. Furthermore, recent research also highlighted that although there is agreement that games have educational potential, the assumption of blanket learner enthusiasm for game-based learning is not always accurate; and students have some resistance towards serious games, which are seen as less appealing than "real" video games (Persico et al, 2018). Other reasons include perception that serious games have lower production values (e.g. style, realism, color) than entertainment games; and that gaming as a voluntary, self-driven activity, is at odd with the structured nature of school (Passarrelli et al, 2019).

Limitation of This Study and Approach

While we tried to include in our coverage as many dimensions for the design principles as warranted, we acknowledge that Table 1 is not exhaustive. Many of the design principles are summarized from studies of organizational learning, which we believe are extendable and can be contextualized for promoting students' learning from failure. Such assumptions need to be tested out.

We also did not include analysis of factors that affect students' dispositions toward failure, although there is scholarly work reported in this area. For example, Thiel & Semaru (2022) suggested that effectiveness of failure feedback – i.e. feedback indicating that one's performance does not meet expectations – may be a matter of personality of the recipient of such feedback. In similar vein, De Castella et al (2013) wrote on the categorization of students into a 2 x 2 matrix based on their combined fear of failure and orientation toward success. The design principles suggested in Table 1 also did not explore possible synergistic effects of mechanisms through students collectively in groups, or for that matter, faculty – especially in organizational context learnt from failure. As noted by Dahlin et al (2018) who studies the effect of opportunity, motivation and ability to learn from failure is a complex interplay between the different mechanisms, and establishing a causal relation is not always consistent.

Another possible limitation is that the design principles in Table 1, are more applicable for learning from failure from product innovation than for process safety in complex systems. Many are derived from studies in the business and/or organizational contexts and may need to be adapted for educational use. Some, such as *intelligent failure*, may not be appropriate for complex systems. Also as noted earlier, study of interventions in complex systems is an under-researched area. The entries in Table 1 are largely based on the first author's personal endeavors in the classroom. An area in Table 1, notably *Preparing the Mind* is derived from the first author's teaching experience. So is Autonomy-Supportive Teaching which is used by the first author in managing students learning in flipped classrooms (Cheah & Sale, 2019). *Sense-making* had its origin in the business context and adapted by the first author for study of interaction between different parts of chemical plant operations in the form of *Relationship between Process Variables* (Unknown Knowns) in Rumsfeld's Matrix (Cheah, 2023). The design principles outlined here should be contextualized to respective engineering domains, and an assessment must be made as to what the ultimate purpose of learning from failure is (e.g. innovation versus safety, etc).

Lastly, some of the design principles can be applied in more than one stage of the transformative process of Figure 2. In actual applications, several design principles may be incorporated and applied simultaneously within the same learning interventions. Along the same line of argument of Dahlin et al (2018), we posit that in actual applications, we can expect complex interactions among the different mechanisms from different design principles.

However, that does not mean that the classification as shown in Table 1 is of no value. As noted by Edmondson (2023), the goal of a framework is simply to help us think differently, so we can take thoughtful action; and not to provide or insist on rigid classification (p.293).

Possible Future Works

Velikova et al (2018), in the study of accidents in the construction industry, noted that there is a general disagreement in the field of what constitutes failure. The authors suggested that developing a taxonomy can allow development of understanding of underlying definitions and links behind failure, hence leading to more effective communication about failure; and improving learning from failure. We believe that our approach can benefit from developing our own taxonomy of failure for more-generalized applications that are applicable for various investigations into failure between the 2 spectrums from product innovation to process safety. A preliminary idea is to base the taxonomy of failure on the 4 stages of conceiving, designing, implementing, and operating a product, process, system or service.

Another area that warrants further development work is the SP-CDIO Syllabus. The parts that are relevant to learning from failure are shown in Appendix 1. From our preliminary mapping (not included in this paper), there are outcomes that can be related to learning from failure, but the connections are not very explicit, and many need to be inferred from the generic statements in the syllabus. The authors do not advocate adding to the CDIO Syllabus. Instead, we opined that the use of taxonomy of failure may be more useful as this can provide more specific guidance on the type of learning outcomes expected.

This work may open up a range of studies to investigate, for examples: Which creative combinations of design principles work best for a given intervention scenario, with possible identification of task-specific characteristics that lend themselves to be more amenable to certain intervention? What is the role of context in influencing the choice of design principles or the learning outcomes?

How do cultural differences affect the reception of failure, or the willingness to develop a failure tolerant mindset? Early work conducted by the second author suggests that “failure” has a specific cultural meaning, and that this should be taken into account when developing deliberate learning from failure interventions.

Moreover, Willems et al (2024) and subsequent ongoing work shows that a range of interconnected interventions might be superior to one-off activities as changing students’ mindsets is a complex process that takes time.

In any case, given the complexity of the possible interactions involved, the test of hypothesis and design of experiments can be complicated. In this regard, some creative use of artificial intelligence may be useful to identify plausible correlations between e.g. failure tolerance and innovativeness. This is especially so because using Generative AI, with is low threshold of engagement, can allow for the experimentation of multiple iterations in a given learning activity. That is, if designed appropriately, it can lower barriers for failure, trial-and-error, etc. and even open up avenues for more personalized learning experiences (e.g. see Huang et al, 2024).

Lastly, an area that we had not covered is that of learning assessment, and the related challenge of transfer of learning. Dahlin et al (2018) noted that ability is the learning mechanism that is most difficult to investigate, and there is a large gap in understanding of how to improve such ability. Although there are case studies that conclude that learning is difficult, with many factors that are used to explain when learning will not occur, there are fewer studies that explain a better ability to learn from failure (Dahlin et al, 2018, p.268). Detailed discussions of transfer of learning are a huge topic in its own right and it is beyond the scope of this paper. There are various instruments that can be used in the investigation on learning from failure, beyond the somewhat dated Student Failure Tolerance Scale (Clifford, 1988). Examples include instrument to measure Higher Education Students’ Fear of Failure in Learning (Choi, 2020), and Performance Failure Appraisal Inventory (Conroy et al, 2002). De Castella et al (2013) provided in-depth discussion of the latter, along with other related measurements. Future work may involve evaluating these instruments to ascertain if we can administer several of them to calibrate students’ responses from various perspectives.

CONCLUSIONS

This work presents a holistic approach towards development of failure-tolerant mindset among students, using a pedagogy termed learning from deliberate failure, guided by the CDIO Framework. A model of progressive development towards failure-tolerant mindset over the duration of program of study is suggested; which is appropriate over a range of failure scenarios from that of product innovation to process safety. A wide-range of learning interventions based on design principles aimed at developing specific aspects of the failure-tolerant mindset is proposed. It is suggested that each program can use the model by adapting it to the program needs, using selected design principles matched to the intended learning needs. It is anticipated that a combination of design principles can be creatively combined in any intervention setting to maximize the impact. As this is an emerging area, a range of topics (not exhaustive) for future research is suggested.

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BIOGRAPHICAL INFORMATION

Sin-Moh Cheah is the Centre Director of the SP-CDIO Centre for Innovative Teaching and Learning; under the Department of Educational Development, Singapore Polytechnic. He has more than 17 years of experience implementing CDIO in various programs and had conducted many CDIO workshops for universities in Asia for a range of disciplinary programs.

Thijs Willems is a Research Fellow at the Lee Kuan Yew Centre for Innovative Cities at Singapore University of Technology and Design. He holds a PhD in organization sciences and primarily conducts ethnographic, qualitative research into the experiences of people at their workplace. Most of his current research focuses on the Future of Work, aiming to identify how organizations change with the advent of digital technology implementation. Thijs is interested in how companies and policymakers can help workers navigate these changes better. Learning, training, and workforce development initiatives appear to be key here; but these initiatives need to be designed in more innovative ways, so they better fit the disruptive changes happening in industry.

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APPENDIX 1. Selected SP-CDIO Syllabus Relevant for Outcomes of Learning from Failure: Part 2.4 Attitudes, Thought and Learning

Texts in bold italics are applicable to outcomes for learning from failure, although not showed strong matching. Some rephrasing or elaboration will be necessary.

2.4.1 Demonstrate Positive Attitude and Willingness to Make Decisions in Face of Uncertainty

Explain the meaning in a task assigned, e.g. using Intrinsic Motivation framework
Recognize the needs and opportunities for initiative, e.g. analyse the potential benefits, risks of an action or decision
Explain one's own belief about one's own abilities (i.e. growth mindset)
Respond proactively with appropriate action, e.g. make preliminary decisions based on information available at hand

2.4.2 Demonstrate Perseverance, Sense of Urgency and Will to Deliver

Display self-confidence, courage, enthusiasm and determination to accomplish objectives
Demonstrate a sense of responsibility for outcomes
Work independently or in teams with diverse compositions
Demonstrate openness in receiving feedback, criticism and willingness to reflect and respond
Identify root cause(s) of failure, and apply lessons learnt from failures

2.4.5 Demonstrate Critical Thinking

Explain the purpose and statement of a problem or issue
Identify and explain constraints within the problem or issue
Question assumptions, norms, practices or opinions
Use a range of critical thinking skills (e.g. analysis, compare and contrast, inference and interpretation, evaluation)
Analyse supporting evidence, facts and information
Identify fallacies, contradictory perspectives and underlying assumptions
Reframe and take a range of different perspectives
Explain different points of view and theories
Develop logical arguments and propose solutions
Summarise conclusions and explain key implications

2.4.6 Demonstrate Self-Awareness, Self-Reflection, Metacognition and Knowledge Integration

Identify one's skills, interests, strengths and weaknesses
Identify the strategies to overcome important weaknesses
Identify factors that promote effective thinking, e.g. motivation, openness, risk-taking, exposure to varied knowledge bases and ideas, etc
Identify barriers to effective thinking, e.g. traits, disposition, limitation of working memory, perception, lack of information, etc
Explain the role of emotion and feelings and the impact on decision-making
Explain need for well-being in a complex and changing world
Demonstrate metacognition in monitoring and evaluating one's quality of thinking
Reflect on one's own values, perceptions, etc;
Assimilate new knowledge into existing knowledge
Demonstrate transfer of knowledge to new context and/or applications

2.4.7 Demonstrate Learning Agility, Engage in Lifelong Learning and Educating

Identify key aspects of the learning process
Appraise one's own learning needs, set learning goals,
Use a range of learning strategies and skills (e.g. goal setting, learning plans, managing information, receiving feedback, etc)
Evaluate competence attainment in terms of goal(s) set and effectiveness of strategies employed
Explain how emotions and beliefs affect learning
Demonstrate self-directed learning in a range of contexts
Explain motivation for lifelong learning e.g. curiosity, remain relevant, professional development, etc
Identify strategies and skills for lifelong learning
Enable learning in and from others, e.g. share best practices
Establish good relationships with mentors and mentees
Demonstrate willingness to use advances in technology to aid learning