Changing Student Performance and Perceptions through Productive Failure: 
Active Learning for Applied Chemistry in Pharmaceutics

Dan Cernusca, Ph.D.
North Dakota State University, College of Pharmacy

Sanku Mallik, Ph.D.
North Dakota State University, College of Pharmacy

Abstract

This paper will analyze the implementation of an active learning strategy built on productive failure in a foundational course in a pharmacy doctorate program. This strategy followed several non-graded tasks, aligned with effective strategies for failure-based activities. A quasi-experimental research design using one control and two treatment groups showed students in the treatment cohorts scored significantly higher than the control group. Students also perceived the productive failure activities as more valuable than lectures.

Motivation and Objective of the Study

Foundational courses in pharmacy doctorate programs help students build strong competencies to allow them to “integrate knowledge foundational sciences to explain how specific drug and drug classes work” and to apply these knowledge “to solve therapeutic problems and advance patient care” (Medina et al., 2013). The most common instructional strategy used in fundamental and applied sciences builds on a scaffolding approach that includes in class instructor-driven worked examples of well-structured problems followed by transfer problems set up as homework. While worked examples are useful for well-structured problems (Jonassen, 2011), this strategy has major shortcomings (Darabi, Nelson, & Palanki, 2007; van Gog et al., 2015).

First, the expert’s logical and systematic presentation of the problem-solving process tends to prompt learners to focus on the procedural aspects of the problem-solving mechanics. Consequently, learners often miss those problem-solving steps and insights that address the conceptual integration of foundational knowledge in the context of target topic exemplified through the worked example. Second, because the instructor assigns transfer problems outside the classroom learners often miss critical on-time feedback they might need when engaging in the problem-solving process. Since homework is intended to be a form of the learning-by-doing problem-solving task (e.g., Schank, Berman, & Macpherson, 2009), the lack of on-time feedback significantly hinders the effectiveness of this instructional task. The consequences of these two shortcomings become even more critical for topics that build on each other, as the gaps in knowledge and skills grow exponentially in time.

The major objective of the intervention presented in this study was to mitigate the above weaknesses of worked examples by including in the instructional process a strategy that merges worked examples, homework-like tasks, and active learning classroom environment (Pelley, 2014; Wolfe, 2006). Next section will provide details about this instructional intervention.

Instructional Context and Gap

Pharmaceutics I is a foundation course focused on helping first year students (P1) enrolled in the in the pharmacy doctorate (Pharm. D.) program to create integrative bridges between the foundational chemistry course in pre-pharm curriculum and clinical courses in the Pharm. D. curriculum. The main expectation of this course is that students will build strong analytical and problem-solving skills. The instructional process in Pharmaceutics I builds on lectures augmented with story problems (Jonassen, 2004, p. 10) presented as worked examples. These worked examples build on each other, exposing P1 students to topic-specific problem-solving strategies that evolve from simple to complex. During the lecture, students have the opportunity to engage in the problem-solving process as they solve in-class transfer problems with a complexity matching that of the worked examples presented by the instructor. To sustain students’ engagement with the transfer problems the instructor uses virtual clickers, ResponseWare from Turning Technologies® (Turning Technologies, 2017) to collect students’ answers and provide

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Productive failure focuses on the role errors and error acknowledgment by the learner play during problem-solving. The core elements of the implementation of this strategy are the intentional delay of scaffolding, that is, the support provided to the learners prior and during the problem-solving process (Kapur & Bielaczyc, 2012). We propose that the main consequence of the productive failure strategy is the exposure of learners to tasks for which we deny them the opportunity to work within their zone of proximal development. Vygotsky defined the zone of proximal development as “the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem under [expert] guidance or in collaboration with more capable peers” (Vygotsky, 1978). One of the outcomes of offering the learner all the potential solutions to address this issue.

As part of the needs analysis phase, the instructor identified three main potential constraints that can justify the identified gap in students’ performance. First, students learned the basic chemistry knowledge and skills needed for solving the problems associated with the focal topics above discussed two to three years before this course. Second, the level of complexity of the problems used in Pharmaceutics I course is higher than what students used to solve in basic chemistry courses, the time they started to build these knowledge and skills. Finally, students often failed to make the required connection between the conceptual aspects of chemical reactions and the algebraic equations used to model them.

These identified constraints indicated that an effective solution to the target issues should simultaneously address several factors. First, it needs to make students aware of their level of prior knowledge in basic chemistry, especially when students are behind the expected level of prior knowledge. Next, the identified solution should help students build a valid idea of the complexity of the problems in the course. Third, the instructor needs to provide on-time feedback to help student gradually master the required complexity of those problems. Finally, an effective solution should make students aware that they need to focus on the conceptual understanding rather than surface elements of the problem-solving process associated with buffered and isotonic solutions, respectively dispersed systems. The instructional strategies and tools used at the time of the analysis, mainly the lectures augmented with worked examples and virtual clickers, provided support for on-time feedback and awareness of one’s lagging prior knowledge. However, the most critical issues, a clear picture of problem complexity and the need to focus on conceptual understanding of the problem-solving process, lacked support in the existent instructional strategy. To address this issue, the redesign team decided to implement productive failure, a failure-based instructional strategy that proved to be effective in increasing students’ problem-solving skill in mathematics (Kapur, 2008, 2010, 2013).

**Instructional Intervention**

Productive failure focuses on the role errors and error acknowledgment by the learner play during problem-solving. The core elements of the implementation of this strategy are the intentional delay of scaffolding, that is, the support provided to the learners prior and during the problem-solving process (Kapur & Bielaczyc, 2012). We propose that the main consequence of the productive failure strategy is the exposure of learners to tasks for which we deny them the opportunity to work within their zone of proximal development. Vygotsky defined the zone of proximal development as “the distance between the actual development level as determined by independent problem solving and the level of potential development as determined through problem under [expert] guidance or in collaboration with more capable peers” (Vygotsky, 1978). One of the outcomes of offering the learner all the needed conditions to create a zone of proximal development is a relatively low level of anxiety that is engaging rather than paralyzing.

By forcing students to solve problems that are above their actual level of problem-solving knowledge and skills without any instructional support, the instructor denies them the opportunity to move into their zone of proximal development and forcing them to fail. However if students in the course will have a wide range of problem-solving knowledge and skills and the instructor allows students to collaborate, then the problems to solve need to be above the expected zone of proximal development of the peer group to force students to fail. If this failure would occur in a high-stake assessment context, more likely the level of anxiety will paralyze learners, preventing them from learning. However, since productive failure happens in low or no-stake situations, the level of anxiety during the failure phase will typically be at the engaging stage. This decreased level of anxiety create an instructional dynamics that brings the problem difficulty level closer to learners’ potential zone of proximal development making this strategy productive for the learning process. The main assumption behind the effectiveness of productive failure strategies is that when a learner is confronted with a task that is similar to a previously failed one, the previous failure will be referenced and act as a strong activation of prior knowledge and skills (Kapur, 2008).
The implementation of productive failure in Pharmaceutics I had, therefore, the potential to create awareness among students about the complexity of the problems in this course. The expectation was that once students became aware of the complexity of the problems they need to solve they will focus on the underlying conceptual aspects of the problem-solving process rather than searching for easy-out strategies to get the correct answer. The integration of productive failure strategy for the buffered and isotonic solutions section of Pharmaceutics I, the focus of this study, followed several steps, aligned with effective strategies for failure-based activities (Tawfik, Rong, & Choi, 2015).

Step 1. A short revision of fundamental chemistry knowledge that served as a base for these topics followed by an worked example for a simple, one concept buffer problem to determine the level of understanding of the students. The instructor started the productive failure session with a simple problem on the calculation of acetic acid and sodium acetate required to prepare a buffer solution of desired pH value (see Figure 1a). The problem directly targeted the topics discussed in class.

![Figure 1](image1.png)

**Problem – 1**

What is the molar ratio of sodium acetate to acetic acid required to prepare an acetate buffer of pH = 5.0? The pKₐ for AcOH is 4.76.

\[
pH = pKₐ + \log \left( \frac{\text{Salt}}{\text{Acid}} \right)\]

\[
\Rightarrow 5.0 = 4.76 + \log \left( \frac{\text{AcONO}}{\text{AcOH}} \right)
\]

\[
\Rightarrow \log \left( \frac{\text{AcONO}}{\text{AcOH}} \right) = 5.0 - 4.76 = 0.24 \Rightarrow \left[ \frac{\text{AcONO}}{\text{AcOH}} \right] = 10^{0.24} = 1.74
\]

*This solution was presented after results were collected with virtual clickers and posted!*

![Figure 2](image2.png)

**Problem – 2**

A buffer solution was prepared by first mixing 50 mL of 0.2 M KH₂PO₄ with 39.1 mL of 0.2 M KOH and then diluting the solution to 200 mL with water. Calculate the pH of this solution. The pKₐ for KH₂PO₄ is 7.21.

\[
\text{pH} = pKₐ + \log \left( \frac{\text{Salt}}{\text{Acid}} \right) = pKₐ + \log \left( \frac{[\text{HPO₄}^\text{2-}]}{[\text{H₂PO₄}^\text{2-}]} \right)
\]

\[
= 7.21 + \log \left( \frac{0.0391}{0.0169} \right) = 7.21 + 0.55 = 7.76
\]

![Figure 2](image3.png)

Students performed the calculation for this first problem and submitted the ratio (a number) using virtual clickers. The class response (98% correct) indicated that the students followed the application of the Henderson-Hasselbalch equation in performing the buffer calculations (Figure 1b).

Step 2. Failure problem. A more complex, two-concept buffer problem was then posted for students to solve without any prior worked example. Students were encouraged to collaborate while solving this problem and the results were collected with a clicker question. As part of this problem, the instructor included a two-part question with this problem (Figure 2a). In the first part, students needed to calculate the concentrations of the chemicals provided as aqueous solutions. In the second part, they needed to use the concentrations to calculate the pH of the buffer.

The instructor encouraged students to discuss the problem with their neighbors. The clicker responses indicated 21% correct answers (Figure 2b). The responses indicated that the students found the problem to be challenging. Discussions amongst themselves clearly did not produce a positive impact on the outcome. The
problem therefore achieved the proposed goal, to create a failure context for the buffer problem solving. Subsequently, the instructor discussed the steps required to analyze the information provided critically and to answer the question successfully.

Step 3. Once the instructor discussed the failure problem and the expected solving process he rechecked the comprehension with a similar, near-transfer problem. However, instead of providing the solution concentration of the chemicals, as it was in the failure problem, the instructor gave students the amounts of the chemicals and the volume of buffer required. This tweak in the problem statement intended to test students’ deep understanding of the conceptual aspects of the problem solving process. Again, the students discussed the solving strategies among themselves and responded through the clickers.

Figure 3. Near-transfer problem: (a) Modified buffer problem; (b) Answers collected with virtual clickers;

Once the clicker answers were collected and posted the instructor had some discussions with students and concluded that the pH values between 9.2 and 9.27 were acceptable as they emerged from significant digit rounding errors. Therefore, about 54% of the class responded correctly (Figure 3b). The instructor again explained the steps and the critical thinking needed to address the problem and emphasized the impossibility of a few calculated pH values (e.g., 0 and 4).

Step 4. The last buffer problem, a three-concept far-transfer problem, closed this productive failure cycle (Figure 4a). As shown in Figure 4a, in this final step the instructor challenged students with a buffer problem that used all the concepts discussed in the previous three steps.

Figure 4. Far-transfer problem: (a) Three-concept buffer problem; (b) Answers collected with virtual clickers;

The results were again collected with a clicker question. Following the posting of the results and after some discussions with the students, the instructor concluded that the pH values between 2.50 and 2.63 were acceptable as they emerged from significant digit rounding errors.
Since the goal of administering this problem was to validate the effectiveness of the productive failure cycle, the instructor was pleased to note that 74% students now responded with the correct answer (Figure 4b). This result confirmed that the expected impact of the innovative integration of productive failure in the design of the active learning instructional process addressed the major goal for this intervention. That is the integration of productive failure reduced the potential gap in student performance in solving buffered and isotonic solutions problems. We will discuss in more details the actual student exam performance on this category of problems in the results section.

Research Questions & Methodology

The exploratory questions in this study were: (1) Will the use of productive failure as an active learning instructional strategy increase students’ exam performance?; (2) Do students perceive productive failure as more valuable for their learning than the more traditional lecture part in the course?

Two cohorts of P1 PharmD students, 2015 and 2016, served as treatment groups for the productive failure intervention, while 2014 cohort served as the control group in a quasi-experimental research design. Cohorts had between 81 and 85 students and while instructional tasks were mandatory, the participation in this study was voluntary. We used the results of an entry knowledge test administered by the instructor during the first week of the semester to analyze the homogeneity of the groups at the entry point in the instructional process across semesters. The second exam that mainly covered the target type of problems, buffered and isotonic solutions, served as the main measure of student performance used to test the impact of the productive failure strategy. Finally, only for the last treatment cohort, fall 2016, we administered a perceptional construct, adapted from the published literature (Grasman & Cernusca, 2015), which measured students’ perceived value of productive failure on their learning (Table 1).

<table>
<thead>
<tr>
<th>The use of Productive Failure with ResponseWare (virtual clickers) in PSCI 368 helped me to:</th>
<th>Strongly Disagree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>… better retain the material taught in Buffered Solutions lectures</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>… better prepare for Exam 2</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>… develop a better understanding of the concepts introduced in Buffered Solutions lectures</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>… feel more confident in my ability to learn the material for Buffered Solutions</td>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>

The perceptional survey was administered online during the last week of the semester using Qualtrics®. The perceptional construct showed a strong internal reliability with Cronbach’s Alpha = .97, being above .70, the accepted value for a strong internal reliability.

Results

While the mean values of pretest scores decreased each year (see Figure 5), a one-way ANOVA showed no statistically significant differences between the three groups’ mean value of prior knowledge, F (2,235) = 2.56, p = 0.08. Tukey’s HSD test did not indicate any statistically significant differences between paired groups. Consequently, the three groups were homogenous at the entry point in the instructional process.

When students’ performance on Exam 2, buffered solutions, was analyzed, a one-way ANOVA revealed a significant effect for the semester, F (2,247) = 25.5, p < .001. Mean values for the three groups are presented in Figure 5. Tukey’s HSD test showed that students in the 2016 cohort scored significantly higher on the Exam 2.
buffering solutions, than both 2015 treatment cohort (p < .001) and the 2014 control cohort (p < .001). The 2016 treatment cohort also scored significantly higher than 2015 treatment cohort (p < .01) did.

![Figure 5. Mean score values for the control cohort (Fall 2014) and respectively productive failure treatment cohorts (fall 2015 and fall 2016) for both the entry knowledge and Exam 2, buffered solutions.](image)

When we analyzed the exit survey results, regarding the perceived value of productive failure for the Fall 2016 group, the mean value of the five items was 7.3, on an evaluation scale of 1 (strongly disagree) to 9 (strongly agree). Considering a value of “5”, the middle of the scale, a neutral opinion that will equate the value of the productive failure with the other instructional tasks during the lecture, we used a one-sample t-Test to test the significance of the mean value for the fall 2016 group. The one-sample t-Test indicated that students perceived the productive failure activities as statistically significant more valuable than other instructional tasks during the lectures, t (71) = 11.2, p < 0.001.

**Discussions**

Instructors often face rather asymmetrical results within the same course, even if they carefully designed and implemented what they assumed to be an effective instructional strategy. In Pharmaceutics I, the course that was the context for this innovation, the instructor found that the active learning strategy worked for about two-thirds of the course failed to produce same results for one section, the buffered and isotonic solutions and dispersed systems. More important, this issue proved to persist across semesters despite instructor’s continuous efforts to improve the instructional process by adding extra worked examples and trying to maximize the use of virtual clicker during the lectures. This outcome convinced the instructor to work with an instructional designer to bring an external perspective in the efforts to bring students’ performance for the somewhat troublesome section of the course. The success of the solution totally depended on the instructor’s willingness to implement it in the course and implement strategies to monitor the impact of that implementation. This aspect is critical since in for students heavily focused on high achievement, as is the case with Pharm. D. students, the implementation of the proposed failure-based strategy could easily fire back by stimulating students’ resistance to potential academic failure.
Form students’ perspective, the benefits of the proposed strategy, integration of productive failure into active learning classroom environment, is trifold. First, the productive failure cycles bring to the classroom problems with a level of difficulty that is typical for homework or exam preparation while adding a level of engagement in the problem-solving process that is hard to stimulate and control outside the classroom. As a result, after a cycle of productive failure, students leave the classroom with a level of problem-solving skills that allows them to be successful in solving additional transfer problems when assigned as homework or as preparation materials for an examination. Second, during the productive failure cycle students get multiple feedback opportunities at the time they need it the more, that is, they are working on building and improving their problem-solving skills. Finally, the use of technology-driven instructional tools such as virtual clickers encourages students’ participation in the problem-solving process, as their input of the solution for the problems used in the classroom is anonymous. The simultaneity of these three benefits resulted from the implementation of the proposed strategy provide a strong support for its innovative character.

Both by the increases in students’ performance as well as their perception of the value of productive failure in their learning process support the effectiveness of this strategy. As shown in the results section, students’ performance on the exam that previously lagged in terms of students’ performance continuously increased while despite the fact that students’ entry-level knowledge had a decreasing tendency. The fact that the second semester of productive failure implementation produced a mean performance that was statistically significantly higher than the first semester of its implementation also showed that this strategy requires time for the instructor to master the novelty of this strategy to the point to ensure its full integration into the instructional process.

The main adjustment in the application of productive failure from one semester to the next one was the complexity of the problems used in the classroom. That is, in the first semester the instructor tested the strategy to, first, get a sense of its potential negative impact due to its “failure” part and, second, to make sure this strategy has a measurable impact on students’ performance on the second exam that covered the target topics, the major objective of this effort. The expectation is that, as the instructor will implement the strategy in the future semesters students’ performance for this section of the course will level out, mapping students’ performance in the other assessments in the course.

Conclusions

While productive failure is a proven effective strategy for mathematics, this is, based on our knowledge, a first for Pharmaceutical Sciences in pharmacy education. What makes this implementation even more special is the integration of productive failure in an existing active learning environment without any major disruption to the instructional process but with significant improvement on students’ performance. The implementation of the productive failure strategy in the Pharmacology course confirmed its effectiveness when correctly transferred to this domain in pharmacy education. Further research will focus on the potential impact of this failure-based strategy for other topics in the course. More important, failure-based strategies have the potential to produce positive outcomes in other pharmaceutics and in the pharmacy practice courses that are driven by case-based instructional tasks.

References


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