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Engineering Cognitive Intervention: Leveraging “Productive Failure” in pH Process Control to Catalyze Conceptual Change and Development of Pedagogical Content Knowledge (PCK)

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Abstract

In the teaching of chemistry and chemical engineering experiments, operational deviations in the process control dimension are often regarded as procedural failures that urgently need to be minimized or eliminated in traditional teaching. This study challenges the epistemological assumption of avoiding errors and explores how chemistry teacher trainees can achieve core concept transformation and construct subject specific teaching knowledge (PCK) in carefully designed pH regulated "trial and error" scenarios. This study applied the theoretical frameworks of "Productive Failure" and "Cognitive Engineering" to design a "Strategic Cognitive Conflict" intervention plan using the refining of crude copper sulfate pentahydrate - a classic chemical separation unit that requires selective precipitation of $Fe(OH)_3$ within an extremely narrow process window (pH 3.5-4.0) - as the experimental framework. 90 chemistry teacher education students were randomly divided into an experimental group (actively encountering predetermined cognitive conflicts by limiting initial pH physical measurements and supplemented with structured diagnostic reasoning) and a control group (following the traditional "nanny style" error avoidance operating procedures). The quantitative results confirmed that although the two groups achieved statistical equivalence in the final product purity ($p = 0.862$, indicating that the macroscopic engineering output was not compromised by intervention), the experimental group showed overwhelming advantages in understanding the competitive dissolution equilibrium mechanism ($p < 0.01$, Cohen's $d = 2.65$), the underlying principles of precise pH process control ($p <0.01$, Cohen's $d = 3.01$), and the ability to transfer knowledge to unknown acid-base engineering systems ($p < 0.01$, Cohen's $d = 2.93$). Qualitative analysis revealed three hierarchical paths of cognitive repair: surface instrument calibration, deep equilibrium reasoning, and systemic integration. Research has shown that strategic process parameter tuning is not a system engineering disaster, but rather a core cognitive catalyst that triggers a deep conceptual shift; Through appropriate cognitive scaffolding guidance, such "failure" experiences can effectively incubate the essential system diagnostic abilities of future educators in complex engineering management and inquiry based teaching.

Keywords

Cognitive Engineering; Productive Failure; Pedagogical Content Knowledge (PCK); Chemical Engineering Education; Systems Engineering Thinking.

1. Introduction

1.1 The Epistemological Dilemma of "Error Elimination" in Chemistry Process Laboratories

In traditional chemistry and chemical engineering laboratory instruction, deviations in process control are often regarded as direct threats to experimental efficacy. To this end, standard laboratory manuals typically provide highly scaffolded protocols to eliminate process ambiguity and strictly prevent students from deviating from the prescribed process route. Under this paradigm, students' academic performance is heavily attached to macroscopic engineering indicators such as yield and purity, rather than to their diagnostic reasoning abilities regarding system anomalies. This "error-free" laboratory culture reinforces a highly misleading epistemological stance: that correct and mechanical procedural execution is equivalent to deep internalization of the underlying thermodynamic and engineering principles.

However, cognitive science and engineering education research consistently demonstrate that the core competence of expert engineers and excellent teachers is forged precisely through repeated diagnosis and remediation of anomalies in complex systems. Such systematic diagnostic ability is indispensable for pre-service chemistry teachers who will be expected to guide secondary school students in inquiry-based experiments. If future educators experience chemical engineering processes only as flawless assembly lines, they will inevitably lack the pedagogical content knowledge (PCK) (John Loughran et al., 2012)[1] required to identify, explain, and transform students' procedural cognitive misconceptions (Kurt VanLehn et al., 1992)[2].

1.2 Theoretical Elevation of the Research Perspective: From Macro-Process Optimization to Micro-Cognitive Engineering

Refining crude copper sulfate through oxidation reaction and sequential precipitation is the cornerstone of global inorganic chemistry and basic chemical engineering courses. In previous studies (Qu et al., 2026)[3], we optimized the process of this system from the perspective of macro process engineering, improved green chemistry parameters (including reagent substitution, mother liquor circulation, and yield maximization strategy), aiming to ensure the physical efficiency of the separation and purification process.

On the basis of the macro process optimization mentioned above, this study has achieved an upgrade to "Micro cognitive Engineering" in academic significance. We have reexamined the most easily uncontrollable process node in this experiment: pH adjustment, which achieves selective precipitation of $Fe(OH)_3$ within a very narrow tolerance window of 3.5-4.0, while avoiding co precipitation of $Cu(OH)_2$ or $Cu_2(OH)_2SO_4$. This study no longer regards this pH threshold as a rigid engineering instruction, but reconstructs it as a "cognitive trap" that is highly prone to inducing "productive failure". This leap in research focus - from pursuing frictionless operation of physical processes to utilizing 'Desirable Difficulties' to promote thinking leaps - provides cutting-edge complementary contributions to the innovation of engineering education paradigms.

1.3 Theoretical Framework: Productive Failure and the Error-Based Cognitive Repair Loop

This study conceptualizes operational error as a highly productive engineering learning resource and implements two complementary theoretical frameworks (Figure 1):

Productive Failure: Proposed by Manu Kapur (2008, 2025)[4,5], this framework suggests that in the absence of clear initial guidance for learners to handle complex challenges, their inevitable experiences of frustration can effectively activate prior knowledge and expose cognitive system gaps. Recent meta-analyses confirm that problem-solving prior to instruction (productive failure) yields significantly higher conceptual transfer compared to direct instruction (Engelmann, 1966&1982, and Padilah 2025) [6-8]. This "trial and error first, guidance later" mechanism enables learners to have an absorption depth that traditional "cramming" teaching cannot match when receiving concept explanations in the future. In the pH control experiment, students are allowed to make mistakes before

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obtaining precise intervention, aiming to lay a cognitive anchor for their subsequent in-depth analysis of multiphase thermodynamic principles.

Error based Cognitive Repair: As a supplement to the former, this theory emphasizes the implicit cycle of learner detection, diagnosis, and correction. This closed loop consists of four progressive stages: (1) Noticing the deviation between expected process parameters and actual phenomena; (2) The mechanism and causes of hypothetical bias; (3) Testing physical or chemical characterization; (4) Reconstructing mental models. When this framework is applied to pre service teachers, individual level cognitive repair is directly transformed into the accumulation of PCK - empowering them to transform their own "system failure" experience into a teaching scaffold that guides students to break through conceptual bottlenecks in the future.

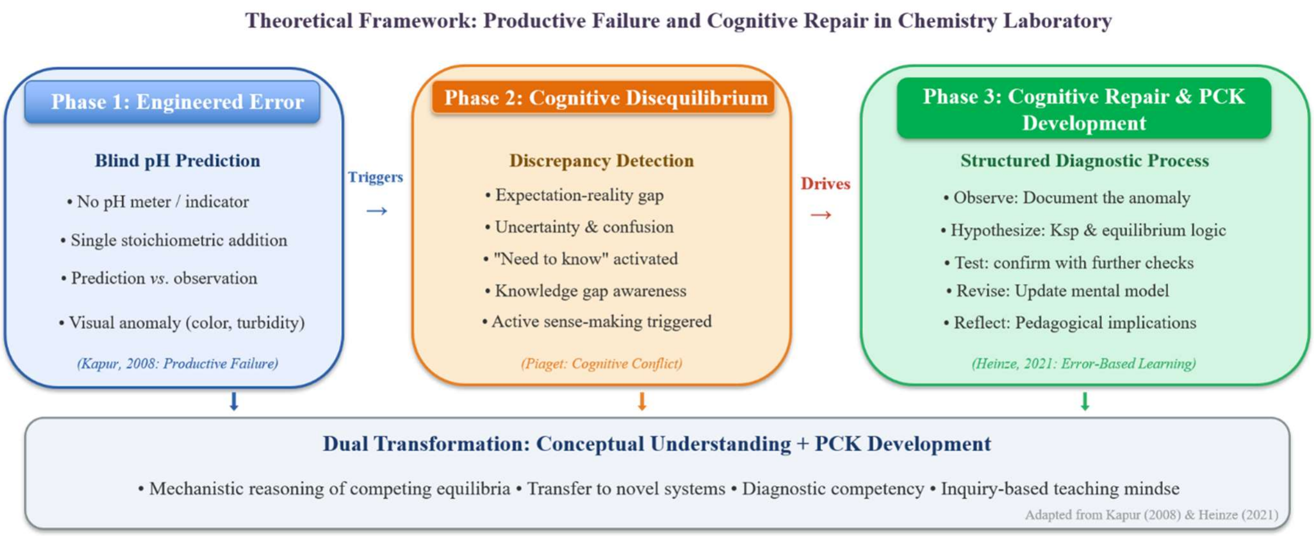

Figure 1. Theoretical Framework: Cognitive Engineering of Productive Failure

1.4 Research Questions

This study focuses on the following three core issues:

1) Does the intervention of pH cognitive conflict through engineering design deepen the understanding of competitive dissolution equilibrium among normal university students more effectively than the traditional error avoidance teaching model?

2) What cognitive repair pathways emerge when students diagnose pH process mismatches, and how do these pathways map conceptual changes at different levels?

3) How do these strategic failure experiences promote the development of PCK and System Engineering Thinking among teacher trainees?

2. Intervention Design: A Cognitive Engineering Approach

2.1 Engineering Taxonomy of pH Process Control Errors

Based on previous pilot observations and teaching experience, we have classified three common pH control failure modes in the copper sulfate refining process for students into typological categories (Figure 2):

Category 1: Instrumental Errors. Improper physical operation involving sensors or measuring tools, such as failure to calibrate pH meters, neglect of temperature compensation, or misreading of color charts. This type of error can be corrected and resolved through standard operating procedures (SOP), without necessarily involving underlying theoretical knowledge.

The second type: Equilibrium Misconceptions. There is a substantial cognitive dissonance among students regarding the relationship between pH threshold, solubility, and co precipitation kinetics. For example, adhering to the linear naive concept of "the lower the pH or the more alkali added, the

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more thorough the impurity removal", but failing to thoroughly grasp the solubility product constant (Ksp) boundary that dominates multi-component systems.

The third category: System Integration Failures. It occurs when students are able to perform thermodynamic calculations in isolation but are unable to place them in macroscopic chemical pipelines for dynamic evaluation. For example, it is possible to calculate the target pH, but it cannot predict the pH thermal drift caused by downstream evaporation and concentration units, or the interference of residual H_2O_2 on crystallization kinetics. This type of failure exposes a lack of 'global systems thinking', rather than simply isolated conceptual gaps or understanding issues.

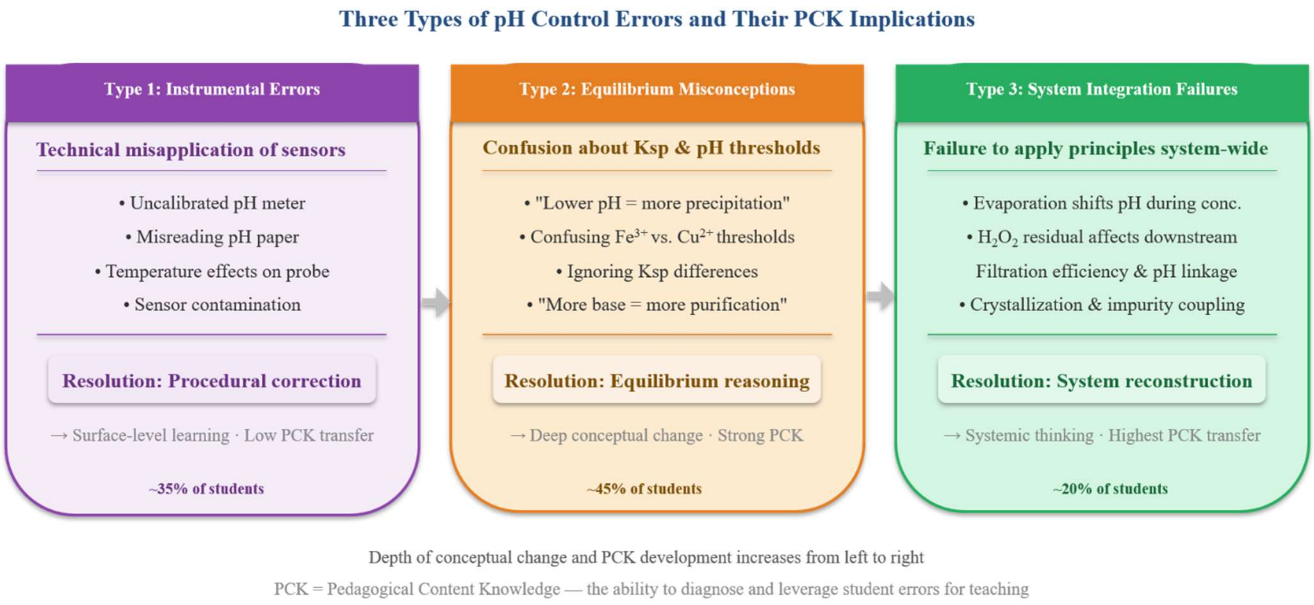

Figure 2. Three Types of pH Control Errors and Their PCK Implications

2.2 Four-Stage Cognitive Conflict Induction and Repair Protocol

The experimental group underwent a closed-loop engineering scheme aimed at maximizing the value of trial and error teaching (ensuring safety and information saturation) as shown in Figure 3:

Phase 1: Blind prediction (inducing cognitive imbalance). During the initial alkaline addition process, students were deprived of access to real-time pH monitoring equipment. They must calculate the single addition of alkaline solution based solely on stoichiometric calculations under ideal conditions. Due to the buffering effect of residual acids and the nonideality of activity coefficients in real multiphase systems, this' paper talk 'inevitably leads to pH overshoot or overshoot, thereby successfully triggering' productive failure 'under controlled conditions.

Phase 2: Anomaly detection and perception. Students can visually observe the sudden changes in physical properties caused by parameter loss of control, such as yellowing/greening of the solution or premature precipitation of blue-green copper salt flocs. Subsequently, permission was granted to measure the true pH value, and the strong conflict between theoretical assumptions and objective data officially activated the "perception" mechanism of cognitive repair.

Phase Three: Structured Diagnostic Reasoning. Students need to use a diagnostic scaffold similar to the "Engineering Troubleshooting Table" for systematic analysis:

Observation: The deviation between theoretical expected parameters and actual measured states.

Mechanism Hypothesis: Explaining the causes of bias based on multiple chemical equilibria and Ksp differences.

Evidence Testing: What macro representations within the system support the hypothesis.

Strategy Correction: Develop a reverse compensation or process repair plan.

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Stage 4: System repair and meta reflection. Return the precision monitoring tool, and the student will callback the system to the target tolerance range (3.5-4.0) and complete the entire process. Write a reflection log after the experiment, analyze the cognitive benefits of system failures and their PCK mapping for future coaching careers.

The control group, under the strong support of "real-time sensor monitoring and teacher intervention", performed traditional assembly line operations that pursued "zero failures".

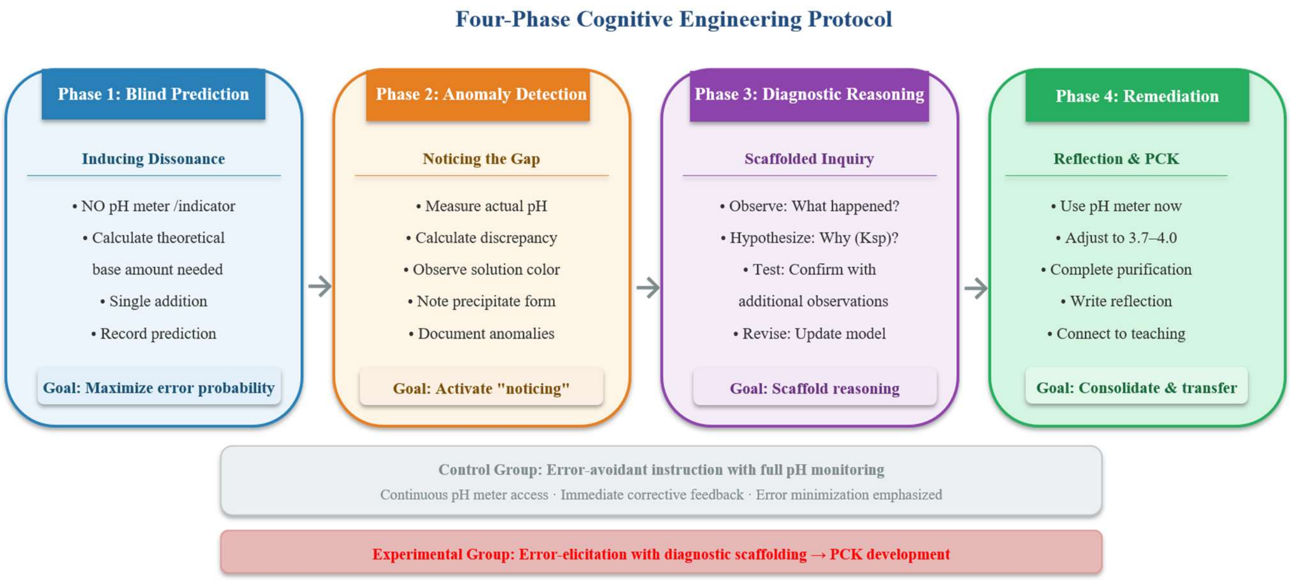

Figure 3. Four-Phase Cognitive Engineering Protocol - Experimental vs. Control Design

2.3 Theoretical Rationale for the Cognitive Engineering Design

This plan implements "productive failure" through three mechanisms: firstly, strategically delaying the provision of measurement tools by temporarily not providing pH measurement tools during the initial addition stage, artificially creating a high probability of process fluctuations. Secondly, mandatory pre action feedforward prediction exposes gaps in the mental model; Finally, the structured worksheet reconstructs the potentially frustrating "experiment mess up" into a rigorous "engineering system troubleshooting" without revealing standard answers.

3. Methodology

3.1 Participants and Context

90 chemistry teacher education students from the 2024 cohort of Lingnan Normal University participated in the research. All students have completed one semester of inorganic chemistry and one semester of inorganic laboratory training, ensuring a comparable baseline knowledge level. Students were randomly assigned to either the experimental group (N = 45) or the control group (N = 45). Two groups shared teaching teachers, reagent batches, and hardware equipment to ensure the internal validity of randomized controlled trials (RCTs).

3.2 Experimental Operating Procedures

The refined object is 10g of crude copper sulfate containing iron (2-3%). Standard unit operations include: (1) weighing, hydration and dissolution; (2) Add 3% H_2O_2 oxidized Fe^{2+}; (3) PH adjustment (experimental group: single addition based on stoichiometric prediction, followed by diagnostic inference and repair; control group: gradual adjustment under closed-loop feedback); (4) Hot filtration separation; (5) Evaporation concentration; (6) Cooling crystallization.

3.3 Data Collection Matrix

Quantitative data dimensions:

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1) Conceptual Understanding Assessment (CUA): administered post-intervention (double-blind scoring, Cronbach's α = 0.87), examining in depth pH-dependent thermodynamic principles and parameter transfer abilities to novel chemical engineering scenarios.

2) Macroscopic engineering output: visual inspection of crystal morphology including color and form, together with quantitative spectrophotometric determination of residual iron using the 1,10-phenanthroline method at 510 nm, providing an objective hard indicator of product purity.

3) Diagnostic reasoning quality (experimental group only): assessing precision of error identification, depth of mechanistic explanation, and engineering rationality of remediation strategies.

Qualitative data dimensions: reflective journals and semi-structured interviews (N = 12) were employed. Thematic analysis was used to extract cognitive repair pathways and PCK evolution trajectories by examining students' conceptual understanding, views on pedagogical methods, and reflective application to future teaching practice.

3.4 Data Analysis Strategy

Use independent sample t-test to analyze quantitative data and compare the mean values between the experimental group and the control group. Use Cohen's d to calculate the effect size to quantify the magnitude of differences and intuitively quantify the power of cognitive interventions. Using thematic analysis to analyze qualitative data, iterative development of coding was achieved through multiple rounds of open coding and consensus discussions among research teams to reach consensus among researchers. Identify error repair paths through system analysis of diagnostic worksheets and interview records.

4. Results and Analysis

4.1 Quantitative Findings: Equivalent Engineering Output, Explosive Micro-Cognitive Gains

As shown in Table 1 and Figure 4, the artificially embedded cognitive conflict did not erode the engineering performance of the system; the two groups showed no statistically significant difference in final product purity ($p = 0.862$). This hard indicator strongly refutes the traditional pedagogical bias that "trial-and-error will inevitably ruin experimental output." It also confirms that the cognitive engineering intervention did not impair students' ability to successfully complete the separation process.

Table 1. Comparison of conceptual understanding outcomes and macroscopic engineering output

Assessment dimension (1–10 scale)	Control group (Mean ± SD)	Experimental group (Mean ± SD)	p value	Cohen's d
Product purity (hard engineering indicator)	8.21 ± 0.7	8.18 ± 0.8	0.862 (ns)	0.04
Depth of mechanistic understanding of pH-dependent equilibria	5.45 ± 1.4	8.62 ± 0.9	<0.01*	2.65
Underlying principles of precise pH process control	5.12 ± 1.5	8.78 ± 0.8	<0.01*	3.01
Knowledge transfer to novel acid–base engineering systems	4.88 ± 1.3	8.45 ± 1.1	<0.01*	2.93
Structured diagnostic reasoning (experimental group only)	—	8.71 ± 0.9	—	—

Note. ns = not significant; * $p < 0.01$.

What is truly transformative is the overwhelming advantage of the experimental group in underlying conceptual understanding and engineering transfer, with effect sizes (Cohen's d) all exceeding 2.5. The control group merely memorized parameter ranges mechanically, whereas the experimental

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group truly internalized the thermodynamic logic governing the window. The largest gap, observed in "knowledge transfer," indicates that "productive failure" not only resists rote memorization but also forges flexible engineering thinking capable of responding to complex and novel process conditions.

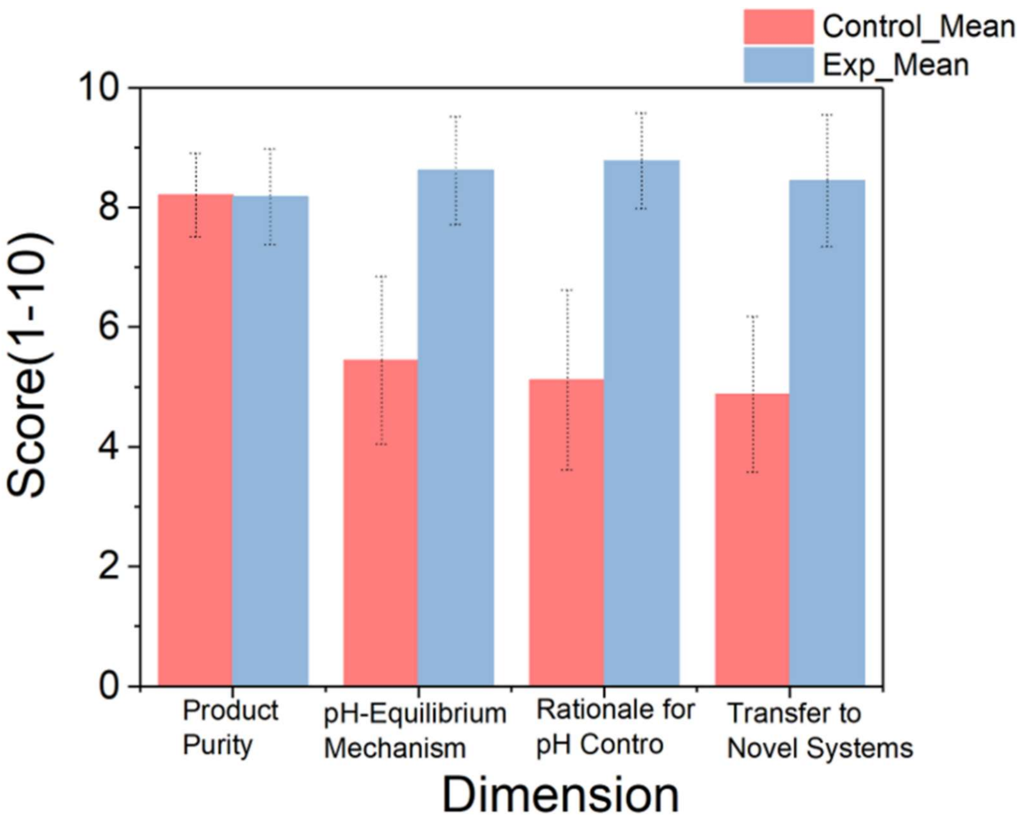

Figure 4. Quantitative Results: Process Equivalence vs. Conceptual Superiority

4.2 Three Stepped Cognitive Evolution Pathways in Error Repair

Qualitative triangulation revealed three repair pathways when students confronted parameter loss of control, directly mapping onto the depth of conceptual change:

Pathway 1: Surface-Level Instrument Calibration (35%, CUA mean = 7.2). Students attributed the failure to physical operations ("misread the test paper" or "no temperature compensation"). Their remediation remained at the level of SOP reset, lacking interrogation of the internal mechanisms of the system. Conceptual change was limited.

Pathway 2: Deep Equilibrium Restructuring (45%, CUA mean = 8.9). These students demonstrated substantive conceptual transformation. When witnessing the precipitation of blue-green flocculent $Cu_2(OH)_2SO_4$ caused by pH overshoot, their original linear belief that "the more base, the cleaner the impurity removal" collapsed. As one reflection stated: "After checking the Ksp values, I suddenly realized that excessive base addition was not only removing impurities but also 'killing' copper. pH regulation is essentially walking a tightrope between two solubility cliffs." Such students successfully upgraded their mental models from "unidirectional reaction" to "competitive phase equilibrium control."

One student explained in a reflective summary:

"I thought if a small amount of base could precipitate iron, more base would precipitate even more iron. But when the solution turned turbid blue-green, I realized something else was happening. I looked up the Ksp values and saw that $Cu(OH)_2$ precipitates at a higher pH than $Fe(OH)_3$. So adding too much base was actually precipitating copper as well. That was when I understood why the pH range was so specific-it is a thermodynamic window between two solubility thresholds."

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These students demonstrated significant conceptual gains, averaging 8.9 on the CUA. Their reasoning showed clear evidence of conceptual change: they revised their mental model of precipitation from “the more the better” to “precise process control is essential.”

Pathway 3: Global System Integration (20%, CUA mean = 9.4). This was the highest manifestation of cognitive elevation. These students transcended the confines of a single reactor and exhibited outstanding systems engineering thinking. They keenly detected the butterfly effect triggered by pH fluctuation: “Colloidal precipitates not only contaminate the product but also worsen downstream filtration kinetics by clogging the filter paper, and residual acidity even alters the final crystal morphology. " They recognized that in a real chemical engineering pipeline, pulling one hair moves the whole body, and loss of control of a micro-parameter requires system-level comprehensive evaluation and compensation. Their diagnostic reasoning integrated multiple process variables into a coherent systemic understanding. One student commented in an interview:

"The pH error was not just about pH-it affected the entire process. The precipitate was harder to filter, the solution took longer to evaporate, and the crystals were smaller. I realized that in a real chemical engineering process, we cannot fix just one variable in isolation-everything in the process is interconnected and mutually influential. " Figure 5 summarizes these three hierarchical pathways and their associated CUA scores.

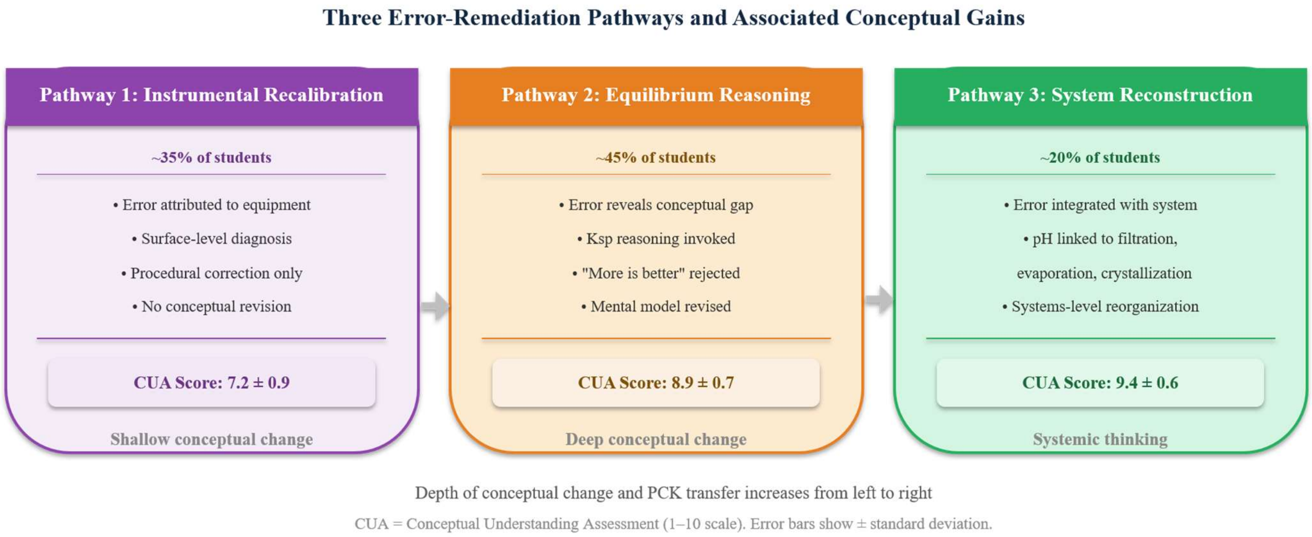

Figure 5. Three Error-Remediation Pathways and Associated Conceptual Gains (CUA)

4.3 Qualitative Themes: The Catalytic Role of Trial-and-Error Experience in Shaping Pre-Service Teachers' PCK

The analysis of reflection summaries and interview records reveals three dominant themes in students' perceptions of incorrect learning experiences, which have special significance for the development of PCK:

Topic 1: From "Loss of Control Anxiety" to "Cognitive Insight". Chemistry teacher trainees who are accustomed to strong scaffolds generally feel anxious in the early stages of blind testing, as this goes against their expectations for a highly guided laboratory experience. A student wrote, 'I'm worried that I might' mess up 'the experiment and get a low score.' However, after breaking through with the engineering diagnostic table, anxiety quickly transformed into a sense of control. Another student reflected, 'At first, I thought it was completely destroyed, but now I am extremely grateful for taking a wrong turn. I will never forget the pH range of copper sulfate refining - more importantly, I understand why it is important and thoroughly understand the reasons why it cannot be surpassed.' This transition from anxiety to cognitive insight highlights the importance of appropriate scaffolding in error based learning interventions.

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Topic 2: Awakening from the PCK Perspective - From "Error Sentinel" to "Cognitive Physician". The respondents explicitly linked their experience of failure to their future teaching career. The experimental group no longer sees student errors as troubles that need to be corrected, but instead begins to elaborate on the strategy of using errors as a window to diagnose students' conceptual understanding - this is the core component of PCK. A student pointed out, "Before this experiment, I thought good teaching meant giving clear instructions, so that students could avoid detours and never make mistakes. Now I realize that mistakes are where real learning happens. As a teacher, my job is not to prevent mistakes, but to give them 'productivity'

Topic 3: Establishing Macro Process Engineering Thinking. Intervention forces students to view the laboratory as an interconnected chemical engineering system rather than a series of isolated steps. A student explained this transformation: 'I realized that in real chemical processes, you can't just fix one thing - you must understand how micro variables like pH create ripple effects throughout the macro system.'. This systematic thinking (Anderson, 1972)[9] orientation is precisely the way of thinking that chemical engineering education aims to cultivate. Students deeply realize that "pH is not an isolated number, it is the key neural node that determines the efficiency of the entire process line (reaction filtration evaporation crystallization). 'This global perspective that transcends the boundaries of micro reactions and macro processes is the core demand of contemporary engineering education.

5. Discussion

5.1 Cognitive Imbalance: The Engine Driving the Reconstruction of Deep Concepts and Engineering Literacy

The data from this study confirms that in specific contexts, the teaching dividends of "engineering trial and error" far outweigh those of "smooth sailing". The underlying mechanism lies in Piaget's cognitive disequilibrium. When objective engineering parameters mercilessly shatter students' linear assumptions, the sharp cognitive gap forces them out of their comfort zone of thinking. The step-by-step evolution of paths 1 to 3 essentially reflects the differences in the depth of students' resolution of "system anomalies". Only by guiding students to attribute faults to "insufficient understanding of mechanisms" rather than simply "equipment failure", can true engineering thinking be reshaped.

5.2 Dual Empowerment of Pre Service Chemistry Teachers by the Trial and Error Paradigm

This study reveals the unique premium of 'productive failure' in teacher education. Teachers who have not experienced cognitive pain often lack the ability to design effective exploration activities; Normal students who have experienced the entire process from collapse to enlightenment internalize the embodied experience of designing cognitive conflict traps. In addition, it reshapes students' epistemology of science and engineering - knowledge is no longer a static dogma, but a dynamic system that approaches truth through engineering iterations of hypothesis, testing, and correction.

Qualitative interviews revealed a profound shift in how these pre service teachers perceive incorrect teaching effectiveness. Initially, the experimental group students reported high levels of anxiety, reflecting their cultural adaptation to the traditional avoidance error paradigm. However, the revised reflection revealed the emergence of PCK.

By experiencing productive failures firsthand, these pre service teachers have transformed from passive followers of experimental plans to active designers of cognitive conflicts. They realized that 'misalignment' was not a failure of laboratory management, but a highly effective teaching tool that anchored abstract thermodynamic concepts to tangible visual anomalies. Pre service teachers who have personally experienced productive failures are more capable of designing productive failure experiences for their students. They understand what it feels like to be confused from within, what it feels like to struggle with problems, and what it feels like to achieve understanding through the construction of meaning through effort. This experiential knowledge is a key component of PCK and cannot be obtained solely through lectures or readings.

Learning experiences based on errors can help pre service teachers develop more refined scientific and engineering epistemology. They no longer view scientific knowledge as a set of fixed facts to be transmitted, but as a dynamic process of hypothesis testing, correction, and refinement - in which errors are not anomalies but essential features. This epistemological understanding is the foundation of inquiry based science and engineering teaching.

5.3 Consistency with Macro-engineering Research: From "Material Closed Loop" to "Mind Closed Loop"

In response to Section 1.2, this study forms a perfect puzzle with the previous macro process optimization research (Qu et al., 2026). Previous research has delved deeply into the "closed-loop of materials and energy", elevating the physical ceiling of hardware technology; This study focuses on the "closed loop of cognition and logic". The combination of dual perspectives provides an innovative model for international engineering education reform that is more three-dimensional and operational than a single dimension.

5.4 Limitations and Prospects

Due to the limitation of a single institutional sample and the lack of long-term tracking, future research should focus on extending such "cognitive engineering" mechanisms to more complex chemical unit operations (such as distillation and extraction), and quantitatively evaluating their conversion rates in real micro teaching for teacher trainees.

6. Conclusion

This study provides strong empirical evidence that the introduction of "engineered productive failure" in chemistry and process engineering laboratories can significantly deepen the understanding of underlying concepts, systems engineering thinking, and PCK among teacher trainees. Quantitative verification shows that students who actively experience and diagnose pH process fluctuations, without sacrificing macroscopic product purity (engineering effectiveness), have a "dimensionality reduction blow" to the traditional teaching mode of avoiding errors in terms of their control over multiphase thermodynamic principles and new situational transfer.

The study distills the following three core engineering education implications:

1) “Process fluctuation” does not equal “system disaster.” Scientifically embedded process barriers such as blind parameter adjustment not only fail to destroy final output but can effectively dismantle the “operational proficiency illusion” of high scores with low competence.

2) Cognitive repair maps the progression of engineering competency. From surface-level instrument correction, to deep phase equilibrium restructuring, to global system integration, the most valuable “failures” are those that can trigger system-level cognitive reorganization.

3) PCK grows through engineering troubleshooting. Overcoming the experience of “cognitive conflict” is an essential path for pre-service teachers to transform from “passive assembly-line executors” into “engineering educators with keen system diagnostic capabilities.”

For modern chemical engineering and teacher education, avoiding errors is not only tactical laziness but also strategic shortsightedness. The core mission of educators is by no means to pave a frictionless slide leading to standard answers; rather, it is to carefully calculate “desirable difficulties” and transform mechanical, protocol-driven laboratories into cognitive engineering forging grounds full of dynamic challenges and profound epiphanies.

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