Development of an assessment for measuring knowledge transferred between the classroom and structural engineering practice.

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My name is Davis Ray. I am 21 years old, and a life-long resident of Arizona. I am a first year Mechanical Engineering graduate student at Northern Arizona University. My primary research project is sponsored by the Federal Highway Administration, and focuses on improving engineering education methods. I am also contributing to a research project sponsored by the US Department of Energy, in which I am assisting with the solid mechanics modeling of moisture swing polymers for use in low-energy carbon capture. For my senior capstone, I led the development of a theoretical offshore wind farm for the 2022 Collegiate Wind Competition, and helped our team earn second place at the competition. This experience led me to become the current president of NAU's Energy Club, where I now manage two interdisciplinary engineering teams who are working to complete the Collegiate Wind Competition and Hydropower Collegiate Competition. I am also the president of NAU Skate Club, which I founded this semester in order to provide enriching opportunities for community members, and share the benefits of skateboarding with others. I enjoy holding leadership roles, and apply myself entirely to the projects I am involved in.

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Introduction

It is well documented that humans are not adept at the process of transferring knowledge learned in one setting to another in which the underlying principles are the same, but the outward appearance is different from that in which the learning took place [1]-[7]. Knowledge transfer ("transfer"') is something that is often assumed in upper division structural engineering courses. For example, an instructor may assume that a student can apply fundamental principles of mechanics such as equilibrium, compatibility, and state of stress to practical engineering problems such as bridge design. Acknowledging that this assumption is faulty has led us to explore an *anchored* civil engineering curriculum in which these fundamental principles are situated (or anchored) in a specific practical engineering context. The goal of this broader investigation is to demonstrate that the process of anchoring will lead to better prepared bridge engineers and may lead to a positive shift in attitudes about careers in bridge engineering. This would, in turn, help address the need for more practice-ready bridge engineers. This goal is part of a study funded by the Federal Highway Administration (FHWA), entitled "Creating More Practice-Ready Bridge Engineers through Anchored Instruction". As part of the study, we identified a need for an assessment tool to measure student learning of fundamental engineering knowledge so that we can assess whether anchoring has an influence on the transfer of fundamental engineering knowledge to practical bridge engineering problem solutions. As no existing instrument was available to meet this need, we embarked upon the development of such an instrument which is the focus of this paper.

The purpose of this paper is to present the in-progress development of an assessment instrument, called the "Fundamental Engineering Knowledge (FEK) Assessment". This instrument is aimed at measuring undergraduate engineering students' ability to apply fundamental engineering knowledge to bridge engineering practice. To date, we have completed two iterations of instrument development and have achieved a Fleiss' Kappa inter-rater reliability, $\kappa = 0.445$ (95% CI, 0.415 to 0.475), $p < 0.001$, without reconciliation between the raters. The resulting instrument will be deployed through the end of the FHWA project (Summer 2025).

The study described in this paper will provide engineering educators with a descriptive road map of the assessment development process, which can be used towards refining and improving similar instruments and/or pedagogical interventions.

Background

FHWA Project: Creating more Practice-Ready Bridge Engineers through Anchored Instruction

The overarching objective of the FHWA project is to develop and install pedagogical interventions into an existing undergraduate civil engineering mechanics curriculum such that core principles are more likely to be transferred from the classroom to the bridge engineering profession.

This is expected to be accomplished by deeply contextualizing, or anchoring, fundamental engineering principles in bridge-centered case-studies throughout students' four-year course of study, beginning with sophomore-level mechanics courses. In these introductory-level courses, students are presented with the details of a local bridge and asked to perform simple analysis tasks. As students progress through statics, mechanics of materials, and structural analysis courses, they revisit this fully contextualized bridge analysis problem, giving them the opportunity to apply increasingly advanced skills. Important engineering concepts are therefore contextualized in terms of their application, thereby improving students' ability to grasp fundamental knowledge. Student progress is periodically measured via their performance on the FEK Assessment.

In this overarching study, we aim to produce a practical, adoptable, and validated framework for modifying existing civil engineering mechanics curriculum such that core principles are anchored within a contextualized case-study of a bridge analysis and design scenarios. This project has the potential to transform existing undergraduate engineering education by addressing the important issue of transfer between theory and practice. The research plan is guided by the research questions listed in **Table 1**. The focus of the present paper is the development of an instrument that can be used to help answer the first research question.

Table 1. Research Questions for Overarching FHWA Project

No.	Research Question
1.	Do students who experience the Anchored classroom interventions demonstrate an ability to transfer fundamental engineering knowledge to applied bridge design?
	a. If so, how many Anchored courses must a student have taken to demonstrate a significant positive correlation with their success in the Bridge Design course?
	b. If so, which interventions demonstrate a significant positive correlation with a students' success in the Bridge Design course?
2.	How are student attitudes towards careers in bridge design related to exposure to Anchored classroom interactions and a Bridge Design Course?
3.	How much extra effort is required to implement effective Anchored classroom interventions.

Anchored Learning

Anchored learning is based on the construct of "situated cognition" which also forms the basis for what is widely called "experiential learning". Anchored learning is founded on the notion that knowledge can be recalled when people are explicitly asked to use it as a "tool" for solving a problem [7]. The anchor is a highly contextualized scenario, or case study, that would realistically be solved in practice by a bridge designer. Thus, students apply theoretical concepts in the context of the anchor and its respective details. **Figure 1** conceptually illustrates how a model of anchored learning connects theoretical principals to practical application.

Anchored learning is a pedagogical model that has shown promise as an effective tool for developing knowledge transfer skills and increasing student performance [1]-[3],[5],[8]..

The FHWA project installs anchors into the civil engineering curriculum in the following courses: Statics, Mechanics of Materials, Structural Analysis, Reinforced Concrete Design, and Structural Steel Design. An additional Bridge Design and Construction technical elective course is provided as a means of measuring students' ability to transfer the theoretical knowledge attained in their foundational courses.

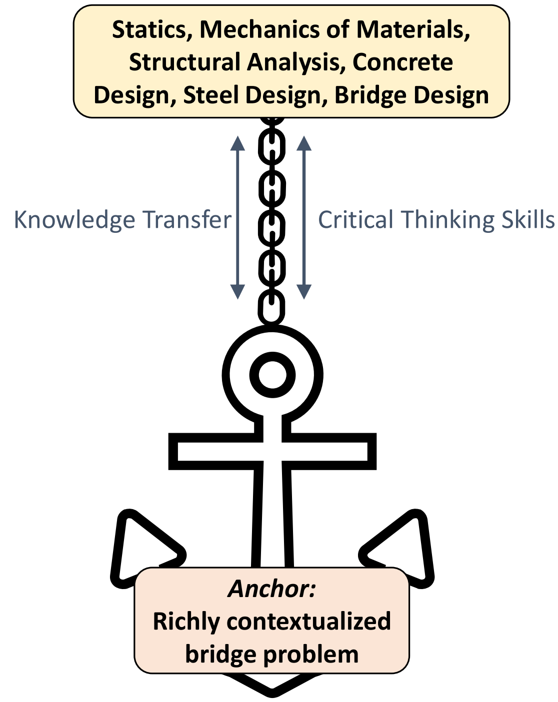


Figure 1. Conceptual model of an anchor.

<u>Knowledge Transfer</u>

Traditionally, undergraduate engineering students view their course work as a necessary means toward a degree. They do not view the theoretical and mathematical knowledge acquired in school as important to applied engineering practice. According to Bransford et al. [1], "it is left to the student to transfer theoretical knowledge to the solving of problems." Thus, there is a need for an engineering program that facilitates learning which promotes the transfer of fundamental engineering knowledge to engineering practice.

Knowledge transfer is defined in Gestalt psychology as "the use of the solution to one problem in solving a second problem that has elements in common with the first" [9]. Gestalt psychology focuses on the dynamic organization of experience into patterns or configurations.

In the context of engineering education, knowledge transfer is demonstrated by a student's ability to use understood information to solve new problems across time and contexts. For instance, given a problem in a new context, they must be able to interpret what is being asked, recall a previous experience in which pertinent information was used to solve a similar type of problem, identify how the information from the previous situation can be correctly applied to the new problem, and execute the results successfully. Students who exhibit an ability to transfer knowledge are better equipped to make meaningful contributions to their respective industry [6].

To improve students' knowledge transfer abilities, educators must first identify the factors that inhibit knowledge transfer, and then apply teaching strategies that improve upon these factors. Lockett et al. [6] present interview data from 53 participants who identify as academics, business owners and/or managers, and non-academics. According to Lockett, the profession prioritizes knowledge transfer more than the academy does. Some businesses have taken initiative to improve knowledge transfer by working closely with higher education institutions with defining the goals and learning outcomes of their programs, with a focus on application of engineering knowledge.

Fundamental Engineering Knowledge

To measure and evaluate whether students are transferring knowledge from one context to another, it is necessary to define what is meant by "knowledge". For a structural engineer who is practicing bridge engineering, Newtonian physics (statics) and mechanics of materials provides a foundational basis for what we are terming *fundamental engineering knowledge (*FEK). Using recommendations from Steif [10] for guidance, we define FEK within three categories. First are the conceptual basis for structural engineering which consist of relevant concepts (declarative knowledge). Secondly are the skills needed for implementing these concepts (procedural knowledge). Lastly are the common errors associated with conceptual lapses that will assist in evaluating student performance on the assessments.

Conceptual Basis for Structural Engineering

To identify relevant concepts, we began with a list of topics that are included in typical structural mechanics courses. We then proceeded to group these topically. Then, drawing from our collective years of structural engineering teaching and professional practice and informed by the Force Concept Inventory [11] and Statics Concept Inventory [12], we identified eleven common concepts, or fundamental categories of knowledge. For the purpose of this study, we defined "fundamental" as concepts that are required to perform a prerequisite level of structural analysis needed for a culminating bridge engineering course. (**Table 2**).

Table 2. Structural Engineering Concepts and Skills

Topic	Concept	Skill
a. Section Properties	the ability of an object to resist stress is proportional to its area, first moment of area, and second moment of area	Calculate centroid, area, first moment of area, and second moment of area.
b. Static Equilibrium	Sum of all forces on object, part, or particle is zero. Forces between two connecting parts are equal and opposite. Combinations or distributions of forces acting on a body are statically equivalent to a force and couple moment.	Draw FBD. Sum forces equal to zero.
c. Relationship between load, shear and moment	The change in internal shear in a beam is the integral of the externally applied transverse load and the change in internal moment is the integral of the shear.	Draw a V and M internal force diagram. Derive V and M from load.
d. Relationship between beam moment (M), curvature (θ), and deflection (Δ).	Based on the Bernoulli Beam assumption of plane sections remain plane, the slope of the 1st order deflection of a bending member is the integral of the internal curvature and the bending deflection the integral of the slope.	Determine deformation of structure including effects of bending, axial, and shear deformations.
e. Deformations by energy methods	Based on conservation of energy, the external work of loads applied to an object is stored as internal strain energy.	Determine deformation of structure including effects of bending, axial, and shear deformations.
f. Constitutive relationships	The normal and shear stress at any location within a member is related to the normal and shear strain according to the characteristic behavior of the material constituent from which the member is made.	Relate the strain on a cross-section to the subsequent stress, or vice versa.
g. Stress	A force normalized by the area it acts upon. Stress at a location is related to the differential force over the	Determine the normal stress, shear stress, or combination at

Topic	Concept	Skill
	differential area (*dF/dA*). The state of stress can be represented by the combination of normal and shear stresses on the orthogonal surfaces (e.g., X, Y, Z)	a location on a structural member. Determine the state of stress at a location on a structural member.
h. Stability	Equilibrium of a body in its deformed shape (i.e., "second order" deformation). If equilibrium is maintained the structure is stable, if it is not maintained the structure is unstable. For an object to be in static equilibrium, the sum of all forces of an object, part, and particle is zero - for the deformed shape (i.e., second order)	Identify and mitigate unstable conditions (e.g., potential brace locations, determine buckling load, calculate overturning and sliding forces.
i. Analytic Model	The boundaries of a structure can be represented as idealized rollers, pins, hinges, fixed supports, or springs. The loading on a structure can be represented as idealized concentrated point loads, point moments, or distributed loading	Model an actual structure as a representative idealized beam, frame, and/or truss, including boundary conditions that restrict movement in accordance with the actual constraints.
j. Superposition	The net response caused by two or more forces and/or displacements at the same location is the sum of the response that would have been caused by each action individually at that location.	Determine the actions of multiple loadings by applying each loading individually to the structure and combining the results at a specific location to represent the complete behavior of the originally loaded structure.
k. Limit States	Factor of safety. Strength. Serviceability. Demand vs capacity.	Identify all applicable design limit states and evaluate design criteria are satisfied (e.g., factor of safety, demand to capacity ratio

Common Errors Associated with Conceptual Lapses

To evaluate the assessments in a consistent and reliable manner, we categorized several common errors that students make by the activities performed when solving engineering mechanics problems. These common errors, listed in **Table 3**, are the basis of creating a reliable grading rubric in the FEK Assessment.

Table 3. Common Errors Associated with Conceptual Lapses

Error Type	Description
Formulation	Errors applying equations associated with conceptual misunderstanding of the phenomenon. Not using correct value for a variable or inconsistencies with the sign on terms.
Modeling	Errors associated with showing static equilibrium including: i) internal forces at a cut missing; ii) showing internal forces without cutting object; iii) not accounting for the sense and direction of the internal forces; iv) not showing internal forces in opposite directions on opposite sides of a section cut; v) and incorrectly showing resultant force.
Boundary Condition	Inappropriate assignment of reactive forces and moments at boundaries (i.e., supports). Missing reactions that should be present. Reactions that are not consistent with boundary condition.
Computing Equilibrium	Inconsistency between force direction and its sign. Multiplying a moment by a distance. Incorrect computation of the magnitude or location of resultant of distributed load. Incorrectly drawing the V and M diagram.
Math	Incorrect application of algebra, trigonometry, and/or calculus procedures.
Units	Not accounting for dimensional homogeneity, units inconsistent with variables, and unit conversion errors.

Development of Assessment and Grading Rubric

The purpose of the FEK Assessment is to provide data to answer the research question 1 (RQ1) listed in **Table 1**. For the FHWA project, students' ultimate ability to transfer fundamental engineering knowledge is measured using a traditional final examination in an optional Bridge Design and Construction course, taken in the senior year. Since this course is elective and only offered once per year, the number of students who enroll in it is modest. Therefore, to create a more robust data set, the FEK assessment instrument will be deployed in each of the following courses: Statics, Mechanics of Materials, Structural Analysis, Reinforced Concrete Design, Steel Design, and the Bridge Design courses.

The content of the FEK Assessment is mapped to two constructs: 1) core principles underlying structural engineering problemsTable 2; and 2) skills needed for implementing these concepts (**Table 2**). Students' ability to demonstrate these skills and explain these principles is assessed based upon common errors in structural engineering problems associated with conceptual lapses (**Table 3**).

Each problem assesses the students' ability to: 1) solve the problem; 2) identify the most applicable principle used to solve the problem; and 3) explain why they believe the principle they selected is most applicable.

<u>Development of the FEK Assessment</u>

To develop the FEK assessment, we established the following constraints.

1. Start with the 11 concepts and skills listed in **Table 2.**
2. Limit to 4-6 questions.
3. Focus on concepts with which students tend to struggle.

To improve the validity of the assessment, we included questions which require students to explain their thought process as a means of internally evaluating the intentionality of their answers. In addition, we wanted an assessment which would reliably attain the same results regardless of the rater. Thus, after defining our framework, we focused our development efforts on improving the reliability of the raters' scores. The first iteration of the FEK assessment was deployed in the Spring 2022 term. Four civil engineering faculty and one graduate student graded these assessments using a pilot rubric. The results of an inter-rater reliability (IRR) analysis indicated an average Fleiss' Kappa value of 0.285, or fair agreement amongst the raters [13]-[14].

Based on the results from the first iteration, the authors improved the assessment questions and rubric descriptions to more consistently quantify students' abilities. These revisions were based on discussions among the raters about how each interpreted the questions, with an aim to clarify any ambiguities. The second iteration was deployed in the Fall 2022 term and resulted in IRR Fleiss' Kappa of 0.445 which shows moderate agreement amongst the raters [13]-[14].

Development Process for Rubric

The current iteration of the FEK Assessment was developed over the course of six months by the authors. Two full iterations of the development process have been completed. We took a methodical approach to its development with a constant eye on consistency and the goal of being able to reliably measure the student's understanding of fundamental engineering knowledge.

Initial Development

We had an ultimate need to answer the question "did they transfer what they learned to bridge design." This led us to define what we meant by "what they learned." Our answer was that we wanted to know whether they learned the fundamentals of engineering mechanics within the domain of structural engineering.

Then we asked, "how do we know?'" whether they learned this fundamental engineering knowledge (FEK). This was needed to build a grading rubric which could reliably measure learning. The ability to "get the right answer" is the traditionally accepted method for assessing learning, however we know that a person can arrive at the right answer for the wrong reason (including guessing, especially if the assessment has a multiple-choice format). This led us to include an explanation component in the assessment to evaluate why the student answered the way that they did.

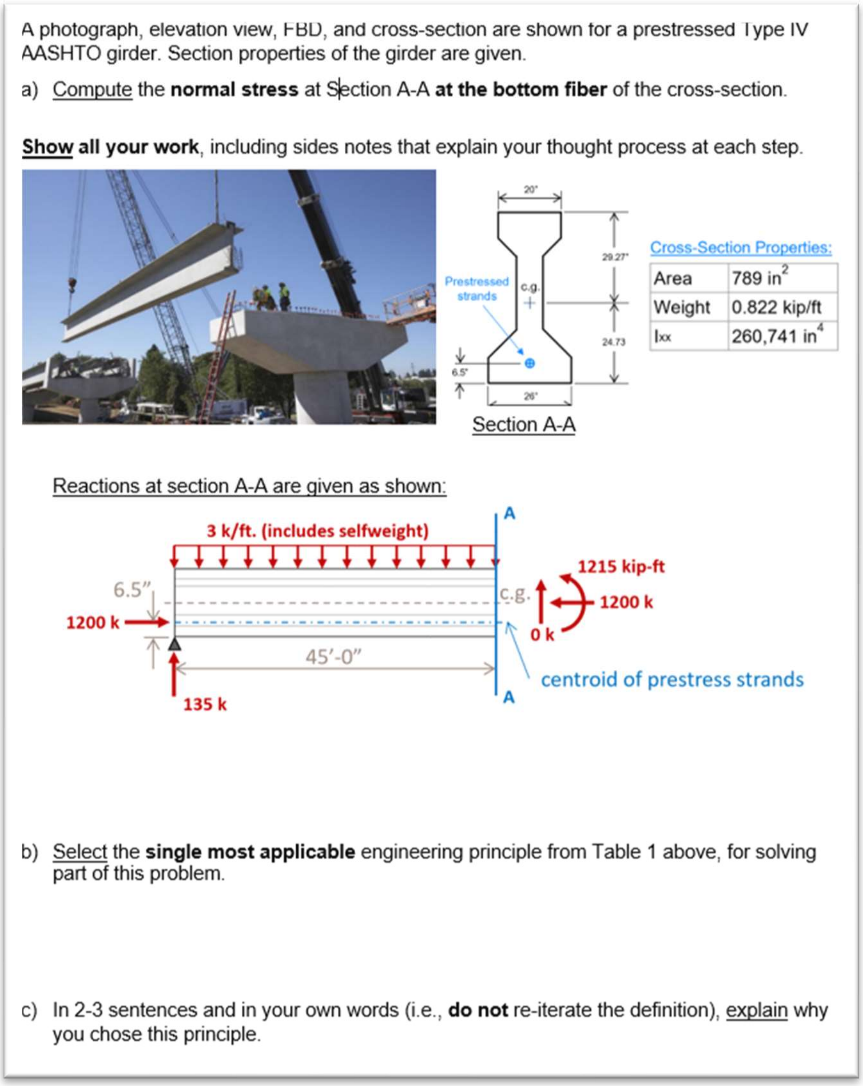
We wanted students to solve relatively simple engineering mechanics problems that were situated in a bridge engineering context. We knew that students could solve such problems using rote processes without really understanding the fundamental principles that they are using, so we added a component that asked them to describe which fundamental engineering principles they used in their solution.

This resulted in the first iteration (V1) of the FEK Assessment which consisted of four problems that each had various levels of difficulty. The difficulty levels were assigned to students from different classes (level 1 to statics students, level 3 to structural analysis students). This first version of the FEK Assessment was taken by the researchers themselves to identify potential problems. The team met to resolve any differences in interpretation of the assessment questions. This resulted in a second version (V2) which included a more focused 3-part rubric that assessed whether the student 1) gave the correct answer 2) selected the appropriate FEK associated with the solution and 3) explained their reasoning.

To evaluate the correct answer, we assigned the highest rubric score to students who showed work, had correct formulation, provided sketches, was well organized and resulted in the correct answer. Four faculty evaluated the students' work, and we compared our scores using Fleiss' Kappa inter-rater reliability index. We discussed the answers that the students gave and discussed ways to improve the problem statements, instructions, and grading rubric. As a result of the first set of evaluations, we made the following adjustments.

1. We were looking for students to explain their steps but didn't explicitly ask them to do so. So, we added that to the instructions.
2. We realized that as evaluators, we were looking at the "correct answer" and problem solution steps differently so we modified the rubric to better capture our shared understanding of what constituted the correct solution. As a result, we broke this into three categories: thoroughness, appropriateness of model, quality of answer. We collectively defined what the different point levels would mean.
3. We noticed that the FEK principles were difficult for us to categorize across the different questions. At this point, we had not yet organized the FEK to the level that would avoid confusion. So, we spent considerable time developing operational definitions of what we meant by FEK (see **Table 2.**). We decided to provide this table of concepts (column 2 in **Table 2.**) at the beginning of the assessment as the full set of options for all questions, replacing the multiple choice list within each problem.
4. In operationalizing the FEK, we decided that it would be useful to add a fifth problem to capture material constitutive behavior.

The resulting assessment (V3) is provided in Appendix A. For illustration purposes, an example of one of the problems is shown in **Figure 2** below.



A photograph, elevation view, FBD, and cross-section are shown for a prestressed Type IV AASHTO girder. Section properties of the girder are given.

a) Compute the **normal stress** at Section A-A **at the bottom fiber** of the cross-section.

Show all your work, including sides notes that explain your thought process at each step.

Cross-Section Properties:

Area	789 in^2
Weight	0.822 kip/ft
I_{xx}	260,741 in^4

Reactions at section A-A are given as shown:

b) Select the **single most applicable** engineering principle from Table 1 above, for solving part of this problem.

c) In 2-3 sentences and in your own words (i.e., **do not** re-iterate the definition), explain why you chose this principle.

Figure 2. Example of a FEK assessment problem.

The associated version (V3) of the rubric is provided in Appendix B. The portion of the rubric used to grade the above example problem (**Figure 2**) is shown in **Figure 3** below.

Question 2a				
Criteria	Proficient	Competent	Novice	Grade/Score
	5 points	*3 points*	*1 point*	
Thoroughness	All steps are shown with headers and logical flow. Clear and easy to follow. Includes annotations explaining their thoughts	Work is mostly complete and can be followed but thought process is not clear	Includes no indication of how that arrived at answer	
Appropriate process and model	Correct model, process, and equations were selected to set up and solve the problem	Mostly correct process with minimal errors/omissions setting up or showing equilibrium	Did not set up problem correctly including errors/omissions associated with showing equilibrium, using incorrect formula or incorrect variables	
Quality of answer	Got the correct answer	Setup was correct but there was an error with computing equilibrium, math error, and/or unit error	Multiple errors/omissions with math, units, or computing equilibrium.	
Question 2b				
Multiple Choice				**Grade/Score**
a - 3 pt. **f - 3 pt.** **g - 5 pt.**				
Question 2c				
Criteria	**Proficient**	**Competent**	**Novice**	**Grade/Score**
	5 points	*3 points*	*1 point*	
Explanation	In-depth explanation that accurately describes principle and relates it to their work, process, and model	Demonstrates a rationale for their answer but missing some key points	Appears to be a guess, reiterates the definition verbatim, and/or just plain wrong	

Figure 3. Rubric used to grade above FEK assessment problem.

Results

Sample

The FEK assessment was deployed during the Fall 2022 term in the following classes.

- Statics. Sophomore-level course which is required and a critical prerequisite for civil and mechanical engineering students.
- Mechanics of Materials. Sophomore-level course which is required and a critical prerequisite for civil and mechanical engineering students.

- Structural Analysis. Junior-level course which is required and a critical prerequisite for civil engineering students.
- Reinforced Concrete Design. Senior-level course which is required and a prerequisite for the senior capstone design course.

Because these courses are relatively dense with content, it was not feasible to consume an entire class period to deploy the assessment. However, we were able to have the instructors give the assessment as an extra-credit assignment. The instructors assured the students that they would receive full extra credit points simply for "trying their best". They asked the students to not work together, and to limit the use of external resources to textbook-like material. Thus, because the stakes were negligible, we expect to have collected an accurate representation of students' individual abilities – even though the assessments were not proctored. We do acknowledge that there is a possibility that students may not have followed our instructions. A description of the Fall 2022 sample is provided in **Table 4**.

Table 4. Fall 2022 Sample (N) of Students who Completed FEK Assessment and Gave Consent.

Course	Civil Eng.	Mechanical Eng.	Other	Total
Statics	4	11	4	19
Mechanics/Materials	0	0	0	0
Structural Analysis	4	7	0	11
Reinforced Concrete	22	0	0	22

Inter-rater Reliability

Reliability and Validity

Validity of an instrument is a measure of its ability to measure that which is intended. One common way to validate an instrument is to compare its results to another instrument that has already been validated. The lack of an existing instrument is what necessitated the development of the FEK assessment tool, so this was not an option. Another method of validation is termed "triangulation", in which other data is used to come to the same conclusion. In the case of this FEK Assessment tool, we have incorporated a qualitative explanation by which the student describes their rationale for selecting the answers that they chose. A rubric score associated with this explanation allows for internal validation that participants' answers are intentional. However, overall validation studies have not yet been completed on the data due to the early nature of the study.

Reliability of an instrument is a measure of its ability to measure the same results under repeated evaluations. In the case of the FEK Assessment, multiple experts evaluated the student responses using a rubric based on the common errors associated with conceptual topics. Agreement of scores among the various raters indicates that the instrument is reliable. This is termed "inter-rater reliability" In order to quantify this reliability, a Feiss' Kappa reliability index is used.

As a first step, the second author for this paper graded all the assessments. Then, based on his findings, he used a purposeful selection process to choose five assessments for the other authors to independently grade. These five assessments were selected to represent the bounds of possible scores in multiple rubric areas in order to represent a “worst-case scenario” for achieving agreement between raters. After grading, the inter-rater reliability results were computed from a Fleiss’ Kappa analysis [13]-[14]. These results are provided in **Table 5** and **Table 6** for V3 of the assessment and rubric.

Table 5. Overall Fleiss’ Kappa Agreement.

	Kappa	Standard Error	*Z*	*p* Value	Lower Bound 95%	Upper Bound 95%
Participant 1	0.421	0.039	10.9	< 0.001	0.345	0.497
Participant 2	0.550	0.036	15.5	< 0.001	0.480	0.619
Participant 3	0.346	0.035	9.9	< 0.001	0.278	0.414
Participant 4	0.443	0.046	9.7	< 0.001	0.354	0.532
Participant 5	0.335	0.033	10.2	< 0.001	0.271	0.400
Overall	**0.445**	**0.015**	**29.0**	**< 0.001**	**0.415**	**0.475**

Table 6. Fleiss’ Kappa Agreement on Individual Categories.

Rating	Conditional Probability	Kappa	Standard Error	*Z*	*p* Value	Lower Bound 95%	Upper Bound 95%
0	0.952	0.949	0.029	32.2	< 0.001	0.891	1.006
1	0.339	0.305	0.029	10.4	< 0.001	0.248	0.363
2	0.317	0.237	0.029	8.0	< 0.001	0.179	0.295
3	0.552	0.359	0.029	12.2	< 0.001	0.301	0.417
4	0.328	0.198	0.029	6.7	< 0.001	0.140	0.256
5	0.757	0.647	0.029	21.9	< 0.001	0.589	0.705

Results and Discussion

As shown above, a Fleiss’ Kappa analysis showed that there was moderate strength in agreement between the five raters, $\kappa = 0.445$ (95% CI, 0.415 to 0.475), $p < 0.001$. There was almost perfect agreement between raters for assessment problems which received a score of 0 ($\kappa = 0.952$, substantial agreement for problems which received a score of 5 ($\kappa = 0.647$), and fair agreement for problems which received a score between 1 and 4 ($0.198 \leq \kappa \leq 0.359$). The score on each element evaluated using the rubric had an average range equal to 1.2 (on a 0-5 scale) and an average covariance of 18%. Given the relative subjectivity of this type of assessment and given that the raters did not reconcile their results, the average range and covariance are reasonable and expected. Thus, moderate inter-rater agreement is satisfactory and reliable.

Conclusions

The objective of the FHWA project is to measure the effect of anchored classroom interventions on students’ ability to transfer fundamental engineering knowledge to bridge engineering applications. Since we measure this ultimate outcome during students’ senior year, we developed the FEK assessment described in this paper to better track their progress in their sophomore and junior years. In addition, we wanted an assessment which would reliably attain the same results regardless of the grader.

To date, we have completed two iterations of instrument development and have achieved a Fleiss’ Kappa inter-rater reliability, $\kappa = 0.445$ (95% CI, 0.415 to 0.475), $p < 0.001$, without reconciliation between the raters. In addition, each element of the rubric (graded on a 0 to 5 scale), for all five participants, had an average range of 1.2 and average covariance of 18%. Given the relative subjectivity of this type of assessment, these values are expected, moderate inter-rater agreement is acceptably reliable.

The instrument that is described in this paper will be used to help assess whether the use of an anchored approach is beneficial in helping engineering students transfer fundamental engineering principles to practice. In addition, the development of this assessment is thoroughly described in this paper to provide engineering educators with the information needed towards adapting or refining similar instruments.

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Appendix A

Fundamental Engineering Knowledge Assignment

This assessment is designed to evaluate your knowledge of fundamental engineering principles related to bridge engineering. Each question has multiple parts. Please read the instructions to each problem thoroughly and include annotations in your work.

Some of the following engineering principles will be used to solving the problems in this exam. For each question, you will be asked to identify the **most applicable** principle used to solve.

Table 1

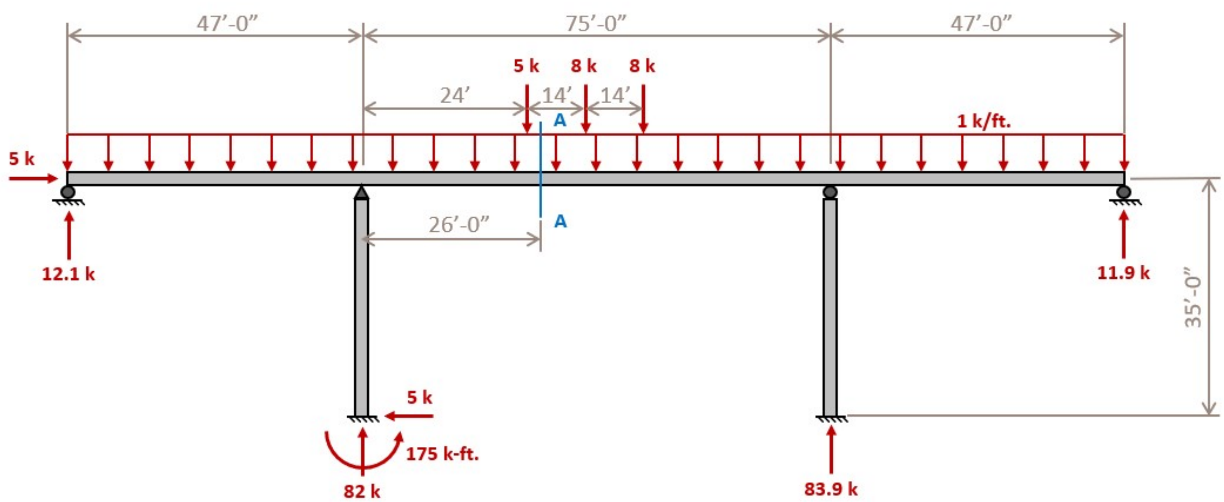
Fundamental Engineering Principles		
a) Section Properties	The ability of an object to resist stress is proportional to its area (A), first moment of area (Q), and second moment of area or moment of inertia (I).	$A = \int dA$ $Q = \int y \cdot dA$ $I_{xx} = \int y^2 \cdot dA$
b) Static Equilibrium	Sum of all forces on object, part, or particle at rest is zero. Forces between two connecting parts are equal and opposite.	$\Sigma F = 0$ $\Sigma M = 0$
c) Relationship between load (w), shear (V), and moment (M)	The change in internal shear in a beam is the integral of the externally applied transverse load and the change in internal moment is the integral of the shear.	$V = \int w \cdot dx$ $M = \int V \cdot dx$
d) Relationship between moment (M), slope (θ), and deflection (Δ)	Based on the Bernoulli Beam assumption of plane sections remain plane, the slope of the 1st order deflection of a bending member is the integral of the internal curvature, and the bending deflection the integral of the slope.	$\theta = \int \frac{M}{EI} dx$ $\Delta = \int \frac{\theta}{EI} dx$
e) Deformations by Energy Methods	Based on conservation of energy, the external work of loads applied to an object is stored as internal strain energy.	$U_e = U_i$
f) Constitutive Relationships	The normal and shear stress at any location within a member is related to the normal and shear strain according to the characteristic behavior of the material constituent.	$\sigma = f(\varepsilon)$ $\tau = f(\gamma)$
g) Stress	Stress is a force normalized by the area it acts upon. The state of stress at a point can be represented by the combination of normal and shear stresses on the orthogonal surfaces.	$\sigma = \frac{dF}{dA}$
h) Stability	If equilibrium of a body in its deformed shape is maintained, the structure is stable; if it is not maintained, the structure is unstable.	
i) Analytical Model	The limits of a structure can be represented as idealized rollers, pins, hinges, fixed supports, and/or springs. The loading on a structure can be represented as idealized concentrated loads, point moments, and/or distributed loading.	
j) Superposition	The net response caused by two or more forces and/or displacements at the same location is the sum of the response that would have been caused by each action individually at that location.	$F(x_1+x_2) = F(x_1) + F(x_2)$
k) Limit State	A state of failure beyond which a structure ceases to perform its intended function. A factor of safety, FS, expresses how much stronger a system is than it needs to be for an intended limit state.	$FS = \frac{\text{Actual}}{\text{Allowable}}$

1) The McConnell Drive bridge is a three-span continuous steel girder bridge. A photograph, looking west at the east elevation, is shown.

a) Determine all internal member forces [i.e., axial (N), shear (V), and moment (M)] at **Section A-A** and include the following steps:

- Draw a free-body diagram (you choose what side of cut)
- Write equations of equilibrium
- Solve for unknowns

Show all your work, including sides notes that explain your thought process at each step.



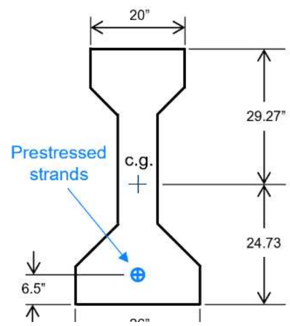
b) Select the **single most applicable** Fundamental Engineering Principle from Table 1 above, for solving this problem.

c) In 2-3 sentences and in your own words (i.e., **do not** re-iterate the definition), explain why you chose this principle.

2) A photograph, elevation view, FBD, and cross-section are shown for a prestressed Type IV AASHTO girder. Section properties of the girder are given.

a) <u>Compute</u> the **normal stress** at Section A-A **at the bottom fiber** of the cross-section.

<u>Show</u> all your work, including sides notes that explain your thought process at each step.

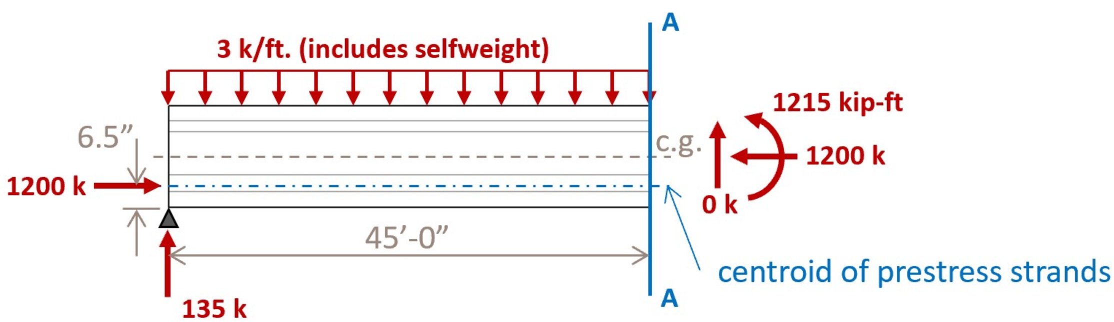


Section A-A

Cross-Section Properties:

Area	789 in^2
Weight	0.822 kip/ft
I_{xx}	260,741 in^4

Reactions at section A-A are given as shown:



b) <u>Select</u> the **single most applicable** engineering principle from Table 1 above, for solving part of this problem.

c) In 2-3 sentences and in your own words (i.e., **do not** re-iterate the definition), <u>explain</u> why you chose this principle.

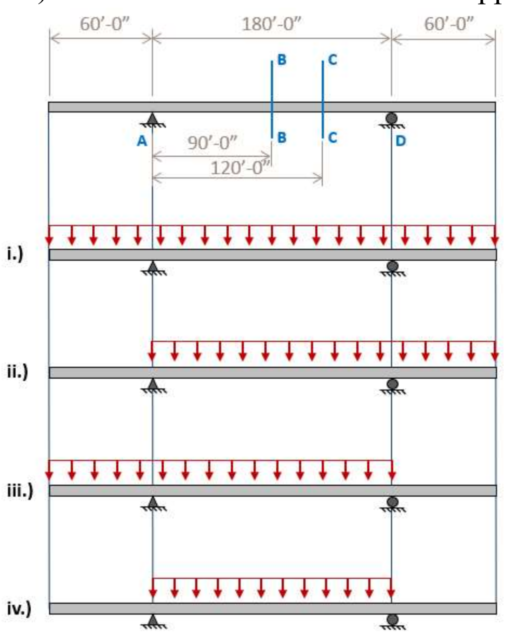
3) A photograph and analytical models a) through c) are shown for a segmental balanced cantilever bridge during construction.

<u>Select</u> which loading diagram results in a **maximum effect.**

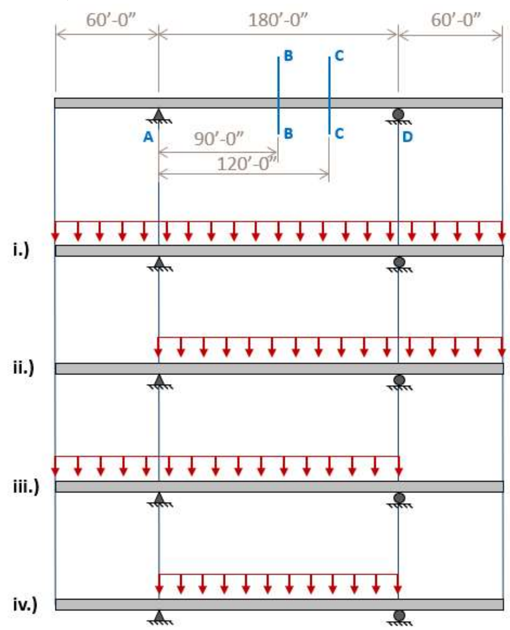
For each one of your selections, **<u>explain</u> your reasoning:**

- Why you chose the option you chose; and
- Why you did not choose the other options.

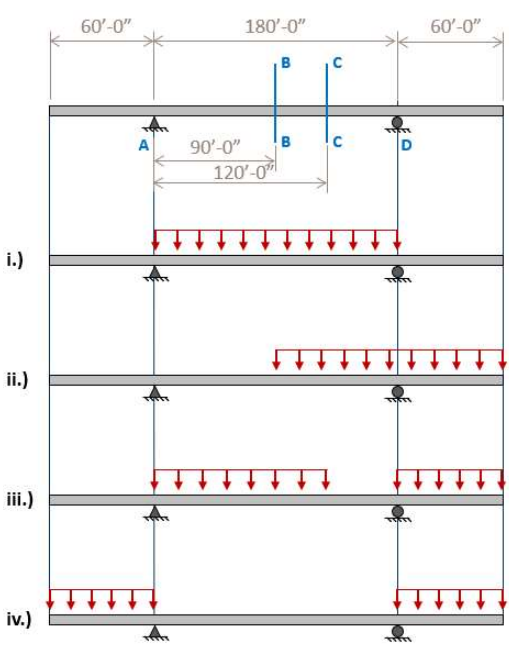
a) **Maximum reaction force** at support D.



b) **Maximum moment** at section B-



c) **Maximum shear** at section C-C



d) <u>Select</u> the **single most applicable** engineering principle from Table 1 above, for solving this problem.

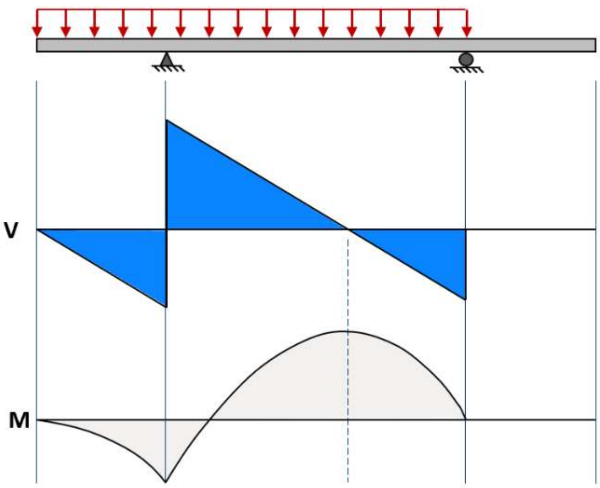
e) In 2-3 sentences and in your own words (i.e., **do not** re-iterate the definition), <u>explain</u> why you chose this principle.

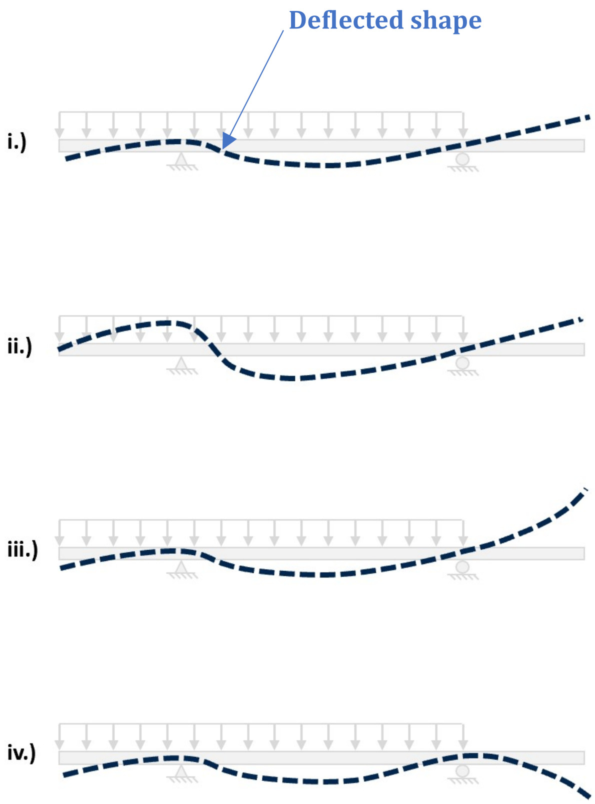
4) A photograph, analytical model and internal force diagrams are shown for a segmental balanced cantilever bridge during construction.

a) Select the deflected shape **which corresponds** to the shear and moment diagrams.

For your selection, **explain your reasoning:**

- Why you chose the option you chose; and
- Why you did not choose the other options.





b) Select the **single most applicable** engineering principle from Table 1 above, for solving this problem.

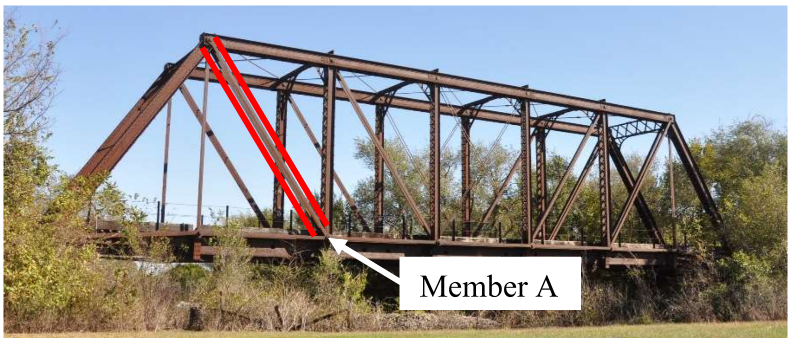
c) In 2-3 sentences and in your own words (i.e., **do not** re-iterate the definition), explain why you chose this principle.

5) For the bridge shown, Member A is made from **ASTM A36 steel**, and has the properties shown in the figure below.

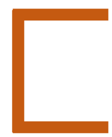
Member A has an internal axial tensile force of **5,600 kN**.

a) Draw an "X" on the stress-strain diagram below, approximate the state of stress in Member A and determine the **elongation** of member A (in mm) caused by the internal tensile force.

Show all your work, including sides notes that explain your thought process at each step.



Member A

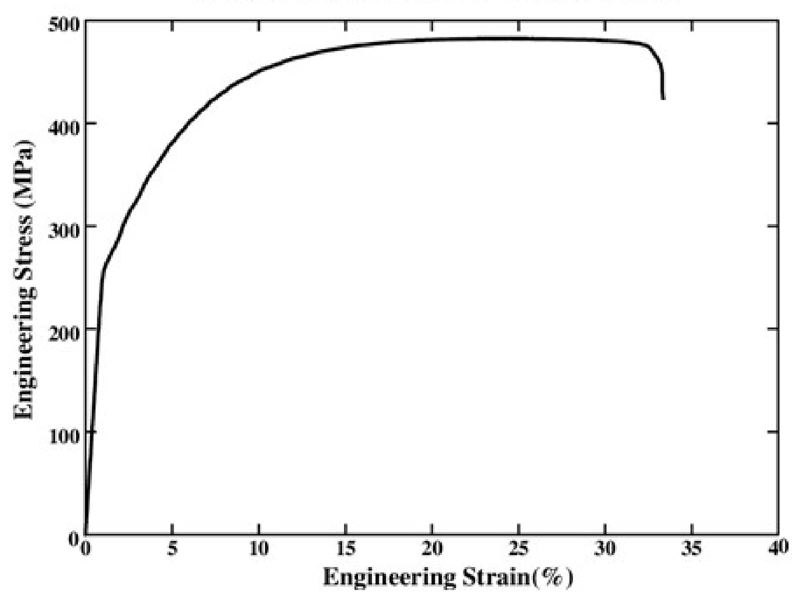


Cross Section
A = 16,000 mm^2

Original Length
L = 5 m

Material Properties of A36 Steel	
Yield Strength	250 MPa

Stress-Strain Behavior for A36 Steel



b) Select the **single most applicable** engineering principle from Table 1 above, for solving this problem.

c) In 2-3 sentences and in your own words (i.e., **do not** re-iterate the definition), explain why you chose this principle.

Appendix B

Grading Rubric

Question 1a				
Criteria	**Proficient** ***5 points***	**Competent** ***3 points***	**Novice** ***1 point***	**Grade/Score**
Thoroughness	All steps are shown with headers and logical flow. Clear and easy to follow. Includes annotations explaining their thoughts	Work is mostly complete and can be followed but thought process is not clear	Includes no indication of how that arrived at answer	
Appropriate process and model	Correct model, process, and equations were selected to set up and solve the problem	Mostly correct process with minimal errors/omissions setting up or showing equilibrium	Did not set up problem correctly including errors/omissions associated with <u>showing</u> equilibrium, showing resultant force	
Quality of answer	Got the correct answer	Setup was correct but there was an error with computing equilibrium, math error, and/or unit error	Multiple errors/omissions with math, units, or <u>computing</u> equilibrium.	

Question 1b		
Multiple Choice		**Grade/Score**
b - 5 pt. **c - 3 pt.** **i - 3 pt.**		

Question 1c				
Criteria	**Proficient** ***5 points***	**Competent** ***3 points***	**Novice** ***1 point***	**Grade/Score**
Explanation	In-depth explanation that accurately describes principle and relates it to their work, process, and model	Demonstrates a rationale for their answer but missing some key points	Appears to be a guess, reiterates the definition verbatim, and/or just plain wrong	

Question 2a				
Criteria	**Proficient** ***5 points***	**Competent** ***3 points***	**Novice** ***1 point***	**Grade/Score**
Thoroughness	All steps are shown with headers and logical flow. Clear and easy to follow. Includes annotations explaining their thoughts	Work is mostly complete and can be followed but thought process is not clear	Includes no indication of how that arrived at answer	
Appropriate process and model	Correct model, process, and equations were selected to set up and solve the problem	Mostly correct process with minimal errors/omissions setting up or showing equilibrium	Did not set up problem correctly including errors/omissions associated with <u>showing</u> equilibrium, using incorrect formula or incorrect variables	
Quality of answer	Got the correct answer	Setup was correct but there was an error with computing equilibrium, math error, and/or unit error	Multiple errors/omissions with math, units, or <u>computing</u> equilibrium.	

Question 2c		
Multiple Choice		**Grade/Score**
a - 3 pt. **f - 3 pt.** **g - 5 pt.**		

Question 2d				
Criteria	**Proficient** ***5 points***	**Competent** ***3 points***	**Novice** ***1 point***	**Grade/Score**
Explanation	In-depth explanation that accurately describes principle and relates it to their work, process, and model	Demonstrates a rationale for their answer but missing some key points	Appears to be a guess, reiterates the definition verbatim, and/or just plain wrong	

Question 3a, 3b, and 3c				
Criteria	Proficient *5 points*	Competent *3 points*	Novice *1 point*	Grade/Score
Part a) Quality of answer	Got the correct answer including calculations and/or notes explaining their selection	Got the correct answer and marginal notes/calculations or, incorrect answer and detailed notes/calculations	Got answer incorrect and no indication of how they got answer(appears to be guess)	
Part b) Quality of answer	Got the correct answer including calculations and/or notes explaining their selection	Got the correct answer and marginal notes/calculations or, incorrect answer and detailed notes/calculations	Got answer incorrect and no indication of how they got answer(appears to be guess)	
Part c) Quality of answer	Got the correct answer including calculations and/or notes explaining their selection	Got the correct answer and marginal notes/calculations or, incorrect answer and detailed notes/calculations	Got answer incorrect and no indication of how they got answer(appears to be guess)	
Question 3d				
Multiple Choice				**Grade/Score**
b - 5 pt. **c - 3 pt.**				
Question 3e				
Criteria	**Proficient** *5 points*	**Competent** *3 points*	**Novice** *1 point*	**Grade/Score**
Explanation	In-depth explanation that accurately describes principle and relates it to their work, process, and model	Demonstrates a rationale for their answer but missing some key points	Appears to be a guess, reiterates the definition verbatim, and/or just plain wrong	

Question 4a				
Criteria	Proficient *5 points*	Competent *3 points*	Novice *1 point*	Grade/Score
Quality of answer	Got the correct answer including calculations and/or notes explaining their selection	Got the correct answer and marginal notes/calculations or, incorrect answer and detailed notes/calculations	Got answer incorrect and no indication of how they got answer(appears to be guess)	
Question 4b				
Multiple Choice				**Grade/Score**
d - 5 pt. **e - 3 pt.**				
Question 4c				
Criteria	**Proficient** *5 points*	**Competent** *3 points*	**Novice** *1 point*	**Grade/Score**
Explanation	In-depth explanation that accurately describes principle and relates it to their work, process, and model	Demonstrates a rationale for their answer but missing some key points	Appears to be a guess, reiterates the definition verbatim, and/or just plain wrong	

Question 5a

Criteria	Proficient *5 points*	Competent *3 points*	Novice *1 point*	Grade/Score
Thoroughness	All steps are shown with headers and logical flow. Clear and easy to follow. Includes annotations explaining their thoughts	Work is mostly complete and can be followed but thought process is not clear	Includes no indication of how that arrived at answer	
Appropriate process and model	Correct model, process, and equations were selected to set up and solve the problem	Mostly correct process with minimal errors/omissions setting up or showing equilibrium	Did not set up problem correctly including errors/omissions with <u>showing</u> work on diagram, using incorrect formula or incorrect variables	
Quality of answer	Got the correct answer	Setup was correct but there was an error with computing equilibrium, math error, and/or unit error	Multiple errors/omissions with math, units, or <u>computations</u>	

Question 5b

Multiple Choice		Grade/Score
a - 3 pt. **f - 5 pt.** **g - 3 pt.**		

Question 5c

Criteria	Proficient *5 points*	Competent *3 points*	Novice *1 point*	Grade/Score
Explanation	In-depth explanation that accurately describes principle and relates it to their work, process, and model	Demonstrates a rationale for their answer but missing some key points	Appears to be a guess, reiterates the definition verbatim, and/or just plain wrong	