Stimulating Critical Thinking in Engineering Students

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Before Cal Poly, Dr. Oulton was a consulting engineer at Cannon in San Luis Obispo, where her projects included the Guadalupe Restoration Project, storm water management for Diablo Canyon Nuclear Power Plant, water management and wastewater treatment projects for local municipalities, and pollution control design for numerous development and remediation projects throughout California.

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Introduction

Fostering critical thinking is a goal that is found in almost all university programs at all levels, from outcomes and objectives in individual courses to University learning objectives and mission statements. However, helping students develop their critical thinking skills can be one of the greatest challenges instructors face, in any discipline.

In engineering instruction, this challenge presents itself clearly when students move beyond their fundamental classes in math and science to their engineering design classes, where – perhaps for the first time in their educational careers – there may be more than one valid approach to solve a problem and more than one "right" answer to that problem. With this challenge in mind, a "Signature Assignment" was developed to help students develop effective critical thinking skills. Here, a "Signature Assignment" as defined as a coordinated series of in-class activities and individual assignments, collectively consisting of approximately 20% of instructional time and a corresponding percentage of the overall grade.

Discussion of development of the Signature Assignment in this paper is intended to be useful for engineering educators in many different disciplines. The material presented was developed for a groundwater hydrology class for senior-level civil and environmental engineering students, and examples of classroom application as well as select student artifacts from this class are included for illustration. However, the instructional ideas presented are expected to be broadly applicable.

Justification

Critical thinking is defined by characteristics such as "interpretation, analysis, evaluation, inference, explanation, and self-regulation" (Facione, 1990, 2011; Romkey & Cheng, 2009). It is linked with responsible decision making and the level of intellectual curiosity and inquiry necessary to research societal challenges, solve complex problems, and discover new solutions (Facione, 1990; Schafersman, 1991). Effective critical thinking incorporates other higher-level skills such as planning, written and verbal communication, and leadership (Facione, 1990, 2011; Viswanathan & Radhakrishnan, 2015). I would assert that professional engineering is defined by these same characteristics and skills. As such, critical thinking skills are an essential aspect of an engineering curriculum that intends to prepare students to become effective professionals (Lafayette, 2014; Ralston & Bays, 2010; Romkey & Cheng, 2009; Viswanathan & Radhakrishnan, 2015).

While some may feel that critical thinking is inherently included in engineering curriculum (Ralston & Bays, 2010; Romkey & Cheng, 2009; Schafersman, 1991), most studies agree that deliberate instruction in, and reinforcement of, critical thinking skills is the most effective way to encourage development of those skills (Cooney, Alfrey, & Owens, 2008; Schafersman, 1991; van Gelder, 2005). If our goal as engineering educators is to teach students not just “what to think” but “how to think” for themselves (Lafayette, 2014; Schafersman, 1991), explicit and structured exercises to help develop and practice critical thinking serve as valuable tools to achieve that goal (Jessop, 2002; van Gelder, 2005; Viswanathan & Radhakrishnan, 2015). Achieving this goal requires significant effort on the part of the instructor to develop both in-class and individual assignments that engage and challenge students at an appropriate level (Romkey & Cheng, 2009; Viswanathan & Radhakrishnan, 2015) and help them develop and exercise critical thinking skills.

One characteristic of effective critical thinking is appreciation of multiple perspectives on a single issue (Facione, 1990; Jacquez, Gude, Hanson, Auzenne, & Williamson, 2007). In engineering, this characteristic manifests itself in the appreciation that there may be more than one approach or solution to a design challenge. For example, the individual needs of the client, the economic circumstances of the project, or the regulatory climate may all dictate different approaches to design. Accepting that engineering design may allow a varied number of approaches or may require a circuitous path from concept to completion can be a challenge for junior and senior level engineering students whose education to that point has been dominated by problem solving with a single correct approach and correct answer (Gnaneswar, 2015; Lafayette, 2014).

Deliberate development of critical thinking skills can help students navigate this challenging aspect of their engineering educations. This paper discusses development of a Signature Assignment to complement course curriculum and help meet this goal.

Curriculum Development

The over-arching goal of this Signature Assignment was to help students learn to identify, support and accept diverse points of view on a technical challenge. This goal was addressed through a series of sub-assignments developed by using stages of Bloom’s Taxonomy as a guideline for helping students increase their competency and comfort with critical thinking through the duration of the quarter-long (10-week) class.

Bloom's Taxonomy presents a hierarchy of levels of complex or critical thinking skills, as illustrated in Figure 1 (Pappas, Pierrakos, & Nagel, 2013; RMIT University, n.d.). The theory of the hierarchy is that skills presented go from more simple "foundation" skills to more complex "higher order" skills as one goes up the hierarchy (Anderson et al., 2000; Pappas et al., 2013; RMIT University, n.d.). It is suggested that mastery of the more basic-level skills is essential before mastery of the higher-levels skills is feasible (Anderson et al., 2000; Pappas et al., 2013). Each level of Bloom's Taxonomy may be described with key verbs describing actions by which students can demonstrate critical think skills (Pappas et al., 2013). Bloom's Taxonomy, then, offers a framework for guiding students through development of critical thinking skills, focusing first on foundation-level skills and moving upwards through the hierarchy over the course of instruction. This inherent framework in Bloom's Taxonomy provided guidance in development of the Signature Assignment. Activities focused on helping students develop and demonstrate foundation-level skills early in the quarter and progressed in challenge as the quarter progressed.

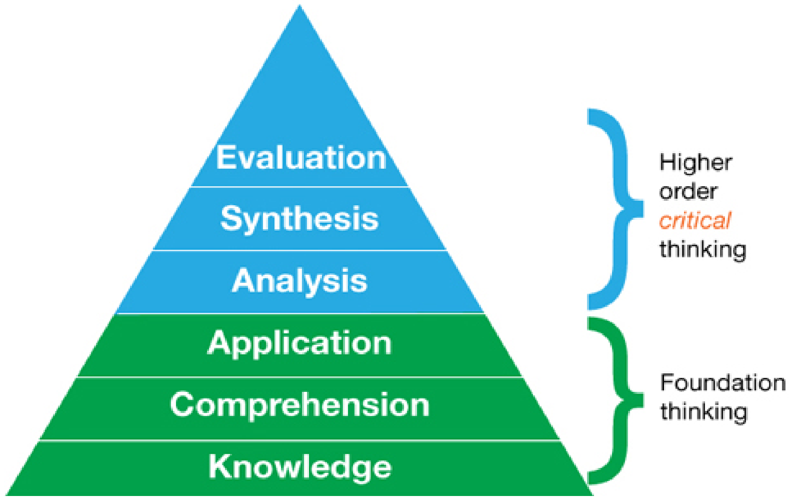

Figure 1. Bloom's Taxonomy for Critical Thinking (RMIT University, n.d.)

This specific Signature Assignment was developed for a senior-level civil engineering class in groundwater hydraulics and hydrology. My larger goal for the Signature Assignment was that students would be able to develop their critical thinking skills to embrace the idea that there may be multiple valid perspectives on and solutions to a technical challenge, rather than a single "correct" answer. As a scaffold for this larger goal, this Signature Assignment focused on the recently-passed California Sustainable Groundwater Management Act (SGMA) and how it could impact both local stakeholders and students' future careers as engineers. I was fortunate to be able to consult with the SGMA Coordinator for San Luis Obispo County in development of this material as well (Carolyn Berg, n.d.). She provided insight into SGMA implementation and helped me prioritize the SGMA material for presentation to the students.

By focusing on a current, relevant issue in the field, the Assignment engaged students' prior knowledge and provided real life context for the instruction of new technical material in the class (Lynch & Wolcott, 2001; Pappas et al., 2013; Romkey & Cheng, 2009). The Assignment also deliberately focused on critical-thinking skills by encouraging students to consider multiple perspectives and to reassess their assumptions (Lynch & Wolcott, 2001).

In developing this curriculum, I followed a backward design method (Ralston & Bays, 2010). I focused first on the larger educational objective of teaching students to accept that a complex technical challenge requires considering of multiple valid perspectives on the issue, and I developed the final activity that would allow students to demonstrate these higher-level skills. I then worked backward through the ten-week quarter and downward along Bloom's Taxonomy to develop in-class exercises and individual assignments that would help students develop their skills throughout the quarter toward this end goal.

Table 1 below presents the progression of in-class discussions and activities of this Signature Assignment: the stages of Bloom's Taxonomy, specific in-class exercises and activities associated with the critical thinking skills associated with the stage, and the timing for each activity over the duration of the quarter. Note that this material is presented in the order in which it was developed, from the end of the quarter moving backward toward the first week of class, the opposite of how it was presented in class. In actual implementation, students are challenged to progress from foundation-level skills through the hierarchy toward higher-order critical thinking skills, moving from "Knowledge" to "Evaluation" over the duration of the course (Pappas et al., 2013).

Table 1: In-Class Discussions and Activities

Bloom's Taxonomy	In-Class Discussion/Activity	Week in Quarter
Evaluation	Town Hall Meeting	8
Synthesis	Prep for Town Hall Meeting	7
Synthesis	Form "firms" to represent key stakeholders	6
Analysis	Discuss merits and challenges of technical options	5
Analysis	SGMA Guest Speaker– how is this challenge being addressed in reality?	4
Application	Regulations: Role Playing Exercise	3
Comprehension	Discussion "Sustainable Management"	2
Knowledge	Identify and classify stakeholders	1

Note that the in-class exercises and activities listed above were intended to be interactive, in-class experiences to engage the students in the material in a manner deliberately different in style from the typical lecture format of most of the class. The goal of these in-class activities was to engage the students in active, rather than passive learning (Romkey & Cheng, 2009; Viswanathan & Radhakrishnan, 2015). I generally served as facilitator, rather than a deliberate guide in these discussions, making sure students felt comfortable and had a chance to have their opinions heard, but not explicitly directing the discussion (Jacquez et al., 2007).

Along with the in-class SGMA materials, each weekly homework assignment included a SGMA-specific question, as did the midterm(s) and final exams. As shown in Table 2, these individual assignments also progressed through the Bloom's Taxonomy hierarchy. They were generally more open-ended than the typical homework problems (Jacquez et al., 2007) and incorporated uncertainties or required students to question and analyze assumptions inherent in the technical material (Lynch & Wolcott, 2001). Other questions required a reflective response that challenged students to express and support an opinion in a brief essay-style format (Ralston & Bays, 2010; Romkey & Cheng, 2009; Schafersman, 1991).

The SGMA questions on the midterm(s) and final exams were designed to not only prompt critical thinking, but also to review material previously covered and address the full range of Bloom's Taxonomy (Brown, Roediger, & McDaniel, 2014). They were designed to allow students still working on mastery of more fundamental levels of the hierarchy to be able to respond while also presenting a critical thinking challenge for more adept students.

Table 2: Individual Assignments

Bloom's Taxonomy	Individual Assignment	Week in Quarter
Knowledge	Calculate Sustainable Yield of an Aquifer Identify key features of SGMA	1 Final Exam
Comprehension	What does "sustainability" mean for a specific stakeholder?	2, Midterm
Application	Identify the assumptions and determine the range of answers for different assumptions Explain the difference between sustainable yield and sustainable management	3 Midterm
Analysis	Same as above, plus "support why a different assumption may be appropriate" Explain how key features of SGMA help achieve its goals	4 Final Exam
Synthesis	"Calculate the effect of this change" and *discuss its impact"*	5
Evaluation	How do the key features of SGMA present *potential failures* to achieve its goals?	Final Exam

The SGMA Signature Assignment was conducted throughout the duration of the ten-week quarter, including weekly in-class discussions or activities and at least one SGMA-specific question on each weekly homework assignment. This curriculum has been used twice, during

Fall quarter of 2015 and 2016, with an average class size each year of approximately 35 students. This senior-level class typically includes a mix of environmental engineering students and civil engineering students with an emphasis on water resources or geotechnical engineering.

Course Implementation

This section includes further details on development of specific activities for each level of Bloom's Taxonomy. This discussion of activities and assignments is intended to provide insight for new engineering educators in many disciplines, with examples of in-class activities, individual assignments, and select student artifacts from the SGMA Signature Assignment provided for illustration.

Foundation Levels 1 & 2: Knowledge & Comprehension

The first level of Bloom's Taxonomy (Knowledge) emphasizes data recall, as exemplified through skills such as memorization of facts or by-rote learning and recollection of material (Omar et al., 2012). Students are expected to simply recall or recognize material to which they have been previously exposed (Anderson et al., 2000). Key verbs such as "describe, identify, recognize, and record" may be used to direct and assess student Level 1 activities (Pappas et al., 2013).

The second level of Bloom's Taxonomy (Comprehension) emphasizes students' understanding of information, as exemplified through skills such as data interpretation and explanation of previously-learned concepts (Anderson et al., 2000; Omar et al., 2012). Key verbs such as "discuss, explain and summarize" may be used to direct and assess student Level 2 activities (Pappas et al., 2013)

In-Class Activity 1: Power/Investment Diagram

The first classroom activity, the Power/Investment (P/I) diagram, was selected specifically as an icebreaker activity that would help engineering students feel comfortable speaking out in class. Student comfort with this skill would be essential for later activities, and establishing an open atmosphere during the first week of class was important. The activity starts with a brainstorming session, identifying key SGMA stakeholders (Level 1 - Knowledge). Brainstorming as a class can provide a comfortable entry to speaking out in class for engineering students; the nature of brainstorming assumes that there are no wrong answers, and the group nature of the activity provides reticent students with some anonymity if desired (Jessop, 2002).

The second part of the activity requires students to classify the identified stakeholders on a graph, showing their relative power on the x-axis and investment or level of caring on the y-axis.

This activity requires comprehension of the nature of the identified stakeholders and their respective relationships to the issue at hand (Level 2 – Comprehension) (Anderson et al., 2000).

This exercise was originally taught to me by one of my students pursuing a Master's Degree in Public Policy, as a common tool used in that arena to organize constituent groups. Clearly, the axis labels can be changed according to the specific classroom need or application. Engineering students are generally quite comfortable with the graph as an organizational tool, so it allows them to stretch their thinking about new concepts within a familiar framework.

Successful creation of a P/I diagram opens an opportunity for the instructor to gently push students to the third level of Bloom's Taxonomy: Application (Anderson et al., 2000). The P/I Diagram is intended as a decision-making or classification tool. Once it is complete, the instructor can then ask the class to use their P/I Diagram to draw conclusions about the stakeholders in different quadrants of the graph. While students are generally comfortable with the knowledge-level and comprehension-level tasks to create the P/I Diagram, application may be beyond their comfort zone at this point.

SGMA Implementation Example

Students were assigned a brief document describing the goals and implementation timeline of SGMA as background reading. In class, students generated a complete list of stakeholders with very little prompting. For the second part of the exercise, students organized their list of stakeholders into a graph based on how much interest that stakeholder group had in SGMA outcomes and how much power or influence they would be able to exert to affect those outcomes. This exercise was conducted with me at the white board and students simply calling out "high" or "low" for the relative positions of each stakeholder. Generally the class came to easy consensus regarding placement of most stakeholders onto the graph. Figure 2 recreates the stakeholder list and P/I Diagram created by the class in F16.

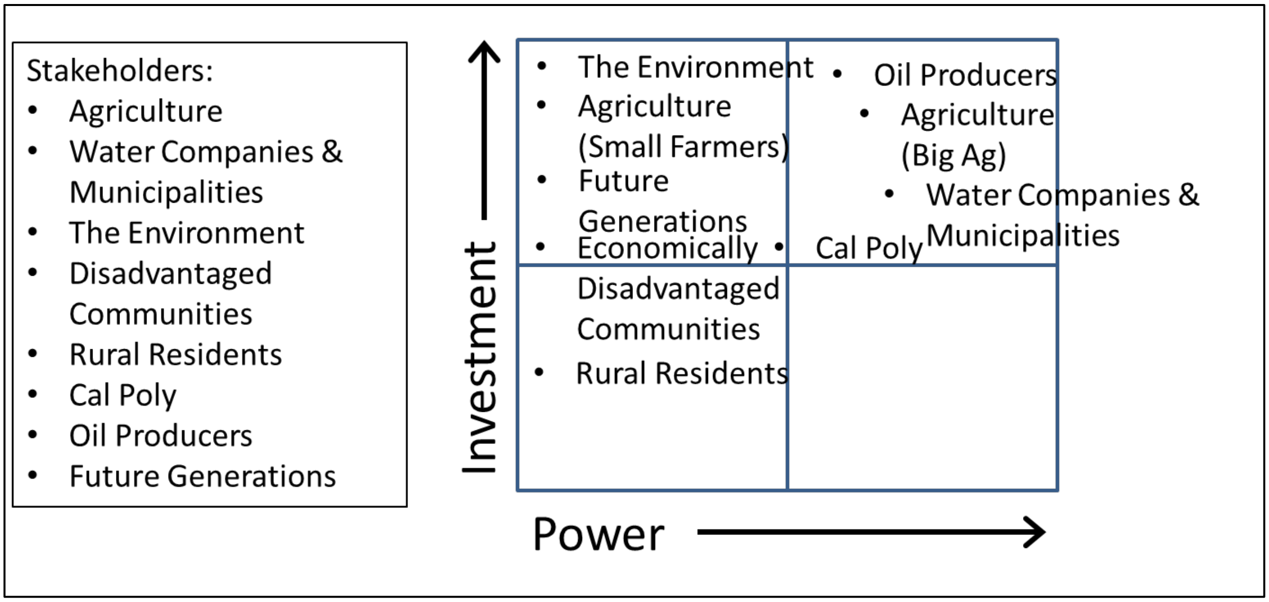

Figure 2: Power/Investment Diagram (F16)

After completion of the P/I Diagram, I asked the class where engineers fit into the graph. Both years this activity was conducted, this question stumped them. Students has not identified engineers as SGMA stakeholders, even though a review of the goals and implementation requirements of SGMA revealed that engineering would be involved in every aspect. We discussed that engineers could potentially serve as consultants for many different stakeholders, in addition to working directly for the agencies overseeing SGMA implementation.

Looking at the P/I Diagram, it was easy for students to identify that the stakeholders in the upper right quadrant (High Power and High Investment) would be most likely to hire engineers to represent their interests. Those in the lower quadrants (Low Investment) would likely not have sufficient interest to hire an engineer, while those in the upper left quadrant (High Investment but Low Power) would likely not have sufficient influence or money to be able to afford a consultant. Looking at this quadrant of stakeholders was a sobering moment for both classes, as they considered the social inequity revealed by this exercise. The F16 class had included "Future Generations" among their list of stakeholders, so this moment was especially significant when the students realized that they personally were among the "future generations" who would be affected by but not specifically represented in SGMA planning and implementation.

In-Class Activity 2: In-Class Discussion & Reflection

While all lectures in this course are conducted to invite student questions and responses, the SGMA discussions and activities were intended to have a decidedly different "feel" to them, to clarify to the students that my expectations for their level of participation was different from "normal" lectures covering the standard technical class material (Morse, 2001; Schafersman, 1991). Questions were typically open-ended and designed to elicit dialogue rather than simply a response (Romkey & Cheng, 2009; Viswanathan & Radhakrishnan, 2015). This expectation may push the comfort level of many engineering students (Jacquez et al., 2007). To help them be comfortable with this expectation, I assigned background reading material prior to each in-class activity so students would have an opportunity to prepare themselves to be actively engaged in the discussion or activity each week.

As instructor, my role in these in-class reflective discussions is primarily as facilitator. I have found that it has been effective to allow students to ask and answer their own questions, to develop and process material themselves rather than more actively guiding them through. As facilitator, I focus largely on confirming the relevant ideas they develop and transcribing these key points onto the board at front of the classroom (Jacquez et al., 2007).

SGMA Implementation Example

Originally, I had planned a fairly straightforward guided discussion to help students develop an understanding of the complex issue of "sustainability." Students were given a background reading assignment on sustainability metrics, and I posed to them the challenge of defining "groundwater sustainability" (GWS) from the point of view of one of the stakeholder groups identified the previous week. An email from a student in F15 (quoted below) in response to this assignment prompted me to change the nature of the discussion, and I started by posing his query back to the class:

> *When* [the assignment] *asks that we come up with a definition for GWS for a stake holder, each stake holder will try to define GWS in a way that allows them to continue their interest and allow it to grow. However I would argue that then it no longer is a definition rather a wish that they hope to achieve. For Ag an example may be that they can continue to have enough water to grow the same amount of crops and even expand indefinitely but that isn't GWS that is Ag sustainability. It would even be contrary to GWS because eventually levels will diminish and wells will run dry at this rate. Then they cannot achieve their 'interest'. Rather each perceived 'interest' definition ultimately boils down to the underlying idea of sustainable yield so that levels do not deplete over time and subsidence doesn't occur which will diminish this sustainable yield. Thus it seems that their* [sic] *is only one definition and many interests that are used as definitions to achieve goals for a period of time because they aren't sustainable indefinitely. Could you provide any additional clarification on this matter? As it stands I can not find an answer that properly addresses the question.*

I was excited to receive this email, since it demonstrated in-depth critical thinking about the challenge I had posed, in addition to inviting a more interesting discussion for class that afternoon. Discussion of the nuanced questions posed in this email would require comprehension of the technical concepts and application of those concepts in a social context, relating to the second and third levels of Bloom's taxonomy and prompting professional-level analysis (Anderson et al., 2000; Pappas et al., 2013).

In facilitating this discussion and transcribing key points students brought up in response to the questions posed in the email, I placed student comments strategically on the board in front of the class. In so doing, students were easily able to see the distinction between the relatively static value of sustainable yield and the dynamic activity of sustainable management. The fact that both the discussion prompt and the responses came directly from the students themselves made the outcome much more effective than if that same information had been prompted from me or delivered in a more typical lecture format.

Foundation Level 3: Application

The third level of Bloom's Taxonomy (Application) requires utilizing learned information in a specific scenario (Omar et al., 2012). Students are expected to complete a procedure, such as correctly using a formula to solve a problem (Anderson et al., 2000). Key verbs including "change, choose, apply, and assess" may be used to direct and assess student Level 3 activities (Pappas et al., 2013). Clearly, Application requires a higher order of thinking and processing than Knowledge or even Comprehension, but it is comfortably within the realm of skills that should be expected of a junior- or senior-level engineering student (Gnaneswar, 2015).

In-Class Activity 3: Role Playing Activity

Engineering in any discipline is conducted in a social context. Human needs, environmental and municipal regulations, and societal expectations all dictate the technical activities that engineers conduct. In developing an activity to make discussions of this social context relevant to the students, I thought a social activity would be well-suited to the task. I developed a role-playing activity, which could be risky to attempt with typically reserved engineering students. However, I was fortunate that my students were comfortable enough with open discussion by this point in the quarter that some of them were willing to stand in front of the class and play a role.

The goal of this exercise was to help the class understand the connection between concepts, goals, and actions. This exercise would require both analysis of the potential options and consideration of how those options might be applied to achieve the goal, giving students the opportunity to demonstrate both second- and third-tier skills from Bloom's Taxonomy (Anderson et al., 2000).

As with the reflective discussions, I served as facilitator, allowing the students to organically direct the activity (Jacquez et al., 2007). To ensure that the entire class had an opportunity to reflect on the exercise and to underscore the key take-home points, I also led a talk-back at the end of the role-playing activity, requesting responses primarily from the students who had served as observers during the role-playing itself.

SGMA Implementation Example

Understanding how to develop a Sustainable Groundwater Plan (SGP) to achieve SGMA goals within the indicated timeframe was an important aspect of understanding SGMA itself. I chose key stakeholders that students had identified during Activity 1, and several students played stakeholders who used groundwater from the “aquifer” (represented by a clear shoebox full of beads) according to specific rules I established for each stakeholder. Another group of students played the Sustainable Groundwater Agency (SGA), who were tasked with developing one new rule each “year” to achieve sustainable management within 20 years. I also allowed for adjudication should the SGA pass any rules not palatable to the stakeholders. This is not exactly how SGMA works, but it was an effective way to run an in-class exercise.

Each year, students truly embraced this exercise and got creative with it. One interesting outcome from each year is that the “SGA” group proposed a technical solution that led to significant debate among the “users” and/or the general public. At this point, the SGA rule making process was abandoned, and time restrictions required that I end the activity when progress got bogged down either in adjudication or internal negotiations. However, the controversial nature of the proposed technical solution made it a good basis for the Town Hall debate later in the quarter.

At the end of the activity, I led a brief talk back with the class to cement the lessons learned from the role playing. Both years, students acknowledged the challenge of developing rules that would both achieve the goal and work for the beneficial users of the aquifer. This was a fairly obvious but important take away from this exercise.

Students also noted a less obvious and perhaps more important point. Both years, the stakeholders had stood together on one side of the table holding the “aquifer” while the SGA group stood together on the other side. While the two groups both talked amongst themselves, at no point in either year did they talk to each other. (I did not arrange their positions; it occurred naturally both times.) During the talk back, the students acknowledged that if the SGA had crossed the table to speak directly with the stakeholders during their discussion about what rule to impose next, they might not have been brought to adjudication or left out of the discussion.

Students appreciated that involving those affected by the rules in the formation of those rules is an effective way to both achieve mutual goals and obtain user cooperation.

This was an important insight which demonstrated higher-level critical thinking. That the students arrived at this insight through their own experience again made it significantly more effective than if that information had been delivered through a lecture or open discussion.

Critical Thinking Level 4: Analysis

The foundation levels of Bloom's Taxonomy are generally comfortable skills for most junior-and senior-level engineering students (Gnaneswar, 2015; Jessop, 2002). Guiding their skill development in the higher-orders of critical thinking can be a challenge, but it is an essential part of students' development into engineering professionals (Gnaneswar, 2015; Jessop, 2002). Indeed, allowing opportunity for development and practice of these higher-order critical thinking skills may be one of the most important challenges we take on as engineering educators (Jessop, 2002).

The fourth level of Bloom's Taxonomy (Analysis) requires students to consider information and break it down into manageable pieces that allow them to understand it. It may include tasks such as data classification, identification of assumptions, and recognizing correlations (Omar et al., 2012). Key verbs such as "analyze, classify, research, and compare" may be used to direct and assess student Level 4 activities (Pappas et al., 2013).

In-Class Activity 4: Exposure to Classroom Material in a Real Life Context

Putting classroom exercises into a real life context is valuable for students of all disciplines. It allows students to put the abstract technical material of the class into a solid reality-grounded context, thereby developing a more thorough understanding of the technical material itself (Jacquez et al., 2007). Indeed, understanding real world applications of material, in both technical and social contexts, is an essential element of thinking critically about that material (Lafayette, 2014; Marshall, Maine, Marshall, & Joseph, 2006; Viswanathan & Radhakrishnan, 2015). It is an essential element in developing professional engineering judgment.

Students often wonder how the material they see in class will relate to their future careers, so a visit from the local professional to address that issue directly was an important aspect of this project. I invited a local professional to come to class as a guest speaker. The professional's visit tied together a number of the technical concepts and theories we had been discussing in class and demonstrated their application in a specific context. Her visit verified for the students that everything we had discussed in our classroom discussions and activities was relevant to real life. It provided students the opportunity to analyze the material from a real world perspective, from the fourth level of Bloom's Taxonomy (Anderson et al., 2000).

Another benefit to the students was validation that they were successfully developing their professional engineering judgment and forming appropriate solutions to complex challenges. Students saw that the issues and ideas they had developed throughout the quarter for this Signature Assignment were the same issues and ideas developed by professional engineers.

SGMA Implementation Example

For this project, I had contacted the SGMA coordinator for the County during the summer to get her advice on the project while it was in development (as discussed above), and to invite her to come to my class to share the County's perspective on and efforts regarding SGMA implementation. The SGMA Coordinator's classroom visit gave a simple overview, similar to the presentation she offered to key stakeholder groups throughout the County.

However, her visit served to verify to students that they were developing their professional engineering judgment and forming appropriate solutions to complex challenges. For instance, their brainstormed list of stakeholders from Activity 1 matched the key stakeholders working with the County. The challenges they had identified with defining appropriate metrics and data to sustainably manage aquifers were the same issues the County was navigating. In the role-playing exercise, student had identified the value in having agencies meet directly with stakeholders to come to mutual agreement on appropriate sustainability measures; the County SGMA Coordinator described the Town Hall meetings they were conducting with key stakeholders for exactly this purpose. Also in the role-playing exercise, students had identified specific technical solutions for achieving groundwater sustainability; these were technical measures the County was exploring as well.

Critical Thinking Levels 5 & 6: Synthesis & Evaluation

The highest levels of Bloom's Taxonomy are those most essential for the process of engineering design. They require putting together the skills from the previous levels and developing an original conclusion or outcome (Anderson et al., 2000).

The fifth level of Bloom's Taxonomy (Synthesis) requires students to relate separate pieces of data or aspects of information to form a new result (Omar et al., 2012). Students are expected to utilize criteria or standards to make judgments about the data or to help form their outcome (Anderson et al., 2000). Key verbs such as "create, design, integrate, and construct" may be used to direct and assess Level 5 activities (Pappas et al., 2013).

The sixth level of Bloom's Taxonomy (Evaluation) involves drawing new conclusions or creating new designs, based on critical judgment of available information and insightful understanding of appropriate assumptions (Anderson et al., 2000; Omar et al., 2012). Key verbs such as "assess, choose, evaluate, prioritize, predict, and justify" may be used to direct and assess Level 6 activities (Pappas et al., 2013).

In-Class Activity 5: Town Hall Meeting

The culmination of the Signature Assignment was a Town Hall-style meeting. This activity was planned for an entire two-hour class period, toward the end of the quarter. This exercise provided the students the opportunity to synthesize the material we had been reviewing and evaluate its relevance to their selected stakeholder. It would also give them the opportunity to challenge each other's evaluations of other stakeholders' points of view. These are higher level skills on Bloom's Taxonomy (Anderson et al., 2000), so several weeks in class were devoted to preparing for the Town Hall Meeting.

The premise of the Town Hall Meeting was that student groups would act as consulting firms, representing their key-stakeholder "clients" in a debate. The Town Hall Meeting itself was divided into presentations during the first hour of class and debate during the second hour. The presentation portion of the assignment gave each group a relatively comfortable opportunity to present prepared information, before going into the more spontaneous debate.

From a critical thinking skills perspective, the debate portion was certainly the more valuable of the two. While there were some planned questions that students were told to be prepared to address, they were first given the opportunity to question each other. It was in the back-and-forth between groups, the questions delivered and answered, that their critical thinking skills were allowed to shine. Especially instructive were the types of questions students directed at each other: did questions simply seek information or did they require depth of analysis?

As an instructor, there was one primary advantage of a debate-style format in term of assessing critical thinking skills. With a written assignment, there is no opportunity to push for depth. If students do not show the desired level of critical thinking skills, instructors have no opportunity to determine if that is because the student genuinely has not developed those skills or simply did not display them in the assignment. With a debate-style format, when students gave superficial answers or unintentionally contradicted themselves from a previous statement, there was an opportunity for other students or me as moderator to immediately pose a follow-up question or ask for clarification. This format provided an immensely valuable opportunity for me as instructor to gauge the level of critical thinking students had developed.

SGMA Implementation Example

Three weeks before the Town Hall meeting, we reviewed potential SGP measures in an interactive discussion. These measures were those proposed by the SGA students during the role playing activity that had prompted significant debate at the time. This discussion was the most traditional lecture-style format SGMA discussion of the quarter. The primary purpose was to ensure that all students, regardless of individual background, had a sufficient understanding of the technical, economic, and social complexities of the proposed solutions to be able to engage in fruitful debate (Pappas et al., 2013). This was important due to the mix of water resources, geotechnical, and environmental engineering students in the class.

The next week, I presented the actual assignment for the Town Hall meeting and the rubric I would use for evaluation (see Attachment 1). In brief, student groups acting as separate consulting firms were to prepare a presentation representing their client's definition of sustainable groundwater management and the unique challenges and opportunities that client may experience or offer regarding SGMA requirements. After the presentations, the firms would engage in a structured debate regarding the proposed sustainability measure discussed the previous week. Students then self-selected into "firms" to represent the key stakeholder of their choice.

Students were expected to conduct research outside of class during the week, and I met one-on-one with each "firm" the following week to discuss their questions and concerns in preparing for the Town Hall Meeting. During these meetings, I challenged the students to consider not just the position of their client, but also the position other stakeholders might take that could affect their client. I also challenged them not to fall into easy stereotypes but to be genuine in their representation of their stakeholders. In a role-playing situation such as this, stereotypes are easy and defeat the goal of critical thinking.

During the actual Town Hall meeting, my role as moderator allowed me to make notes that were later used for completing the rubric. Due to the fast-paced nature of the discussion, I did not want to try completing the rubric during the debate itself, but I kept a copy nearby to inform my note-taking. I completed individual rubrics promptly after class, while student participation was still fresh in my mind. I found the Town Hall Meeting to be a very effective opportunity for students to demonstrate their understanding of SGMA and their critical thinking skills. They also generally had fun with it, which is an important consideration as well.

Individual Assignments

One challenge with in-class activities and discussions being the dominate mode of curriculum delivery for this Signature Assignment is that the quieter or less interested students could remain relatively uninvolved. I made a strong effort to include all students in discussions, but some students are more naturally reticent or reluctant to engage, for a variety of reasons. Another challenge with a largely discussion-based curriculum is that an essential aspect of a technical curriculum includes solving technical problems. To ensure that all students had some level of engagement with the SGMA Curriculum and that it achieved an appropriate degree of technical rigor, I developed SGMA-specific questions for every weekly homework assignment, as well as the midterm and final exams. As discussed below, these assignments also allowed for individual assessment of their developing critical thinking skills.

In general, the homework questions complemented the rest of the technical material on the weekly assignment, while requiring student to reflect critically on that material (Cooney et al., 2008). For example, instead of simply giving students the data necessary to perform a straightforward calculation to determine water budget (a first step in determining sustainable yield for an aquifer), the SGMA question asked the students to review a published groundwater hydrology report for a local aquifer and extract the necessary information to calculate the water budget. Another SGMA question required students to identify the assumptions implicit in a previous problem, then to recalculate that problem with an alternate set of assumptions and determine which assumptions were more appropriate for a given set of circumstances.

Midterm and final exams included essay questions asking for both identification and evaluation of concepts discussed in class, "true or fix" questions where students had to not just identify but correct false statements, and open-ended problems that required students to synthesize material and make appropriate assumptions prior to being able to complete the problem.

Like the in-class discussions and activities, the individual assignments increased in required level of critical thinking throughout the quarter. They were designed not only to help students develop their critical thinking skills, but also to allow them to understand *in context* that complex technical issues may have more than one valid approach and more than one valid solution (Cooney et al., 2008; Marshall et al., 2006).

This effort also allowed review of the technical material and simultaneous improvement of critical thinking skills, responding to the challenge of working critical thinking instruction into an already full curriculum (Cooney et al., 2008; Morse, 2001). Often, critical thinking exercises are not added to existing curricula because it is felt that some of the technical material will have to be sacrificed to make room for the critical thinking instruction. Rather, studies suggest that not only are critical thinking skills for engineers are most effectively developed in context of technical material, but that alternate instructional approaches allow better understanding and retention of that technical material (Cooney et al., 2008; Marshall et al., 2006; Schafersman, 1991).

Methodology of Assessment

Multiple modes of assessment were used throughout the duration of the quarter. Studies suggest that multiple, low-stakes assessment provide for more effective, long-term comprehension and retention of the material (Brown et al., 2014). Further, multiple opportunities of deliberate practice of critical thinking are required to truly develop those skills (van Gelder, 2005).

For the majority of the in-class discussions and activities, no assessments were conducted. The primary goal of these discussions and activities was to generate student interest and engagement. Low pressure activities with no assessments are more likely to allow students to become freely involved (Brown et al., 2014). For example, the initial P/I graph exercise facilitated this open discussion format. Generating a list of stakeholders is a straightforward brainstorming exercise, with no “wrong” answers. Even students who had not done the reading before class were able to follow the discussion and contribute logical suggestions. Building from this open brainstorming exercise to place these stakeholders on the P/I Diagram required group discussion to reach consensus about proper location of each stakeholder. However, since the conversational ice had been broken in listing the stakeholders, students seemed comfortable with the natural evolution from brainstorming to the discussion and debate involved in creating the P/I Diagram. Since there was no assessment associated with this discussion, students felt no pressure beyond reaching agreement with their peers.

One benefit of assessments is to require students to take assignments seriously, to give them proper consideration (Brown et al., 2014). Adding a SGMA question to each weekly homework assignment served this purpose. As discussed above, the SGMA homework questions, like the overall SGMA in-class curriculum, were developed following Bloom’s taxonomy, guiding the students through increasing levels of critical thinking, generally via reflection questions (Cooney et al., 2008; Morse, 2001).

Assessment of their developing critical thinking skills on homework assignments varied. In some cases, students were asked to express and support their opinion on a SGMA-related issue. Assessment of these questions started with the premise that there were no right or wrong answers, but that some answers were better supported than others were. Points were assigned based on the quality of support students provided for their opinion.

Some questions required students to repeat a set of calculations with different assumptions (for example, dry year, rainy year, or average year). In this situation, there was a correct answer for each calculation. Additional points were then assigned for the quality of the student’s response to the critical thinking reflection question: When would you support using one assumption compared to another? Again, the portion of the question requiring more advanced critical thinking skills had no right or wrong answer, but points were assigned based on the depth of thought of the students' responses.

The single-most significant assessment opportunity for this Signature Assignment was the culminating event, the Town Hall Meeting. A rubric was provided to the students along with the assignment details (see Attachment 1), so they would understand the basis of assessment for this event. This rubric was based on Bloom Taxonomy and modified from a Critical Thinking Assessment rubric developed at the University level. At my University, formal Critical Thinking Assessment has primarily been conducted in English, Philosophy, and Communication Studies GE classes, rather than STEM classes (Academic Programs & Planning, 2015). The Town Hall Meeting rubric was modified from the University standard rubric to reflect the technical nature of the material, while still assessing students' critical thinking abilities on several levels of Bloom's Taxonomy.

Since the Town Hall Meeting occurred several weeks before the end of the quarter, it was appropriate to revisit SGMA concepts and provide an additional opportunity for individual assessment on the cumulative final exam. The final exam included an essay-style question with three parts: to *identify* key goals and features of SGMA legislation (Level One on Bloom's Taxonomy); to *explain* how those key features would be effective in achieving SGMA goals (Level Four on Bloom's Taxonomy); and, to *evaluate* how those features might limit efficacy of SGMA (Level Six on Bloom's Taxonomy). The first part of the question, simple identification, was intended to be straightforward for all students who paid attention to class discussions. The second part of the question required higher-level critical thinking but had been discussed extensively in class. The third part of the question is considered an even higher-level of critical thinking on Bloom's Taxonomy because we had NOT discussed this issue in class previously. It required students to make connections between known material and draw conclusions for an unknown situation (Anderson et al., 2000; Facione, 1990).

Results & Analysis

This Signature Assignment has yielded a number of important results. Over the course of the quarter, students showed improvement in technical knowledge, engineering judgment, professional abilities, and critical thinking skills.

Students were exposed to a current, course-relevant situation that is an ongoing challenge for professionals in the field. The guest speaker reinforced that the class material was in fact a real life challenge. Using a recently-passed regulation that presents an ongoing technical challenge added relevancy to the project; this was not a previously-solved problem that required students to learn what had been done in the past. Rather, this was an active challenge for professionals in the field, and the students posed similar questions and developed similar responses as the professionals. The relevancy of this project also allowed students to appreciate that their developing skills will allow them to hold their own among other engineering professionals after graduation. (As a side note, the County SGMA Coordinator was thrilled to learn that this project was going on, and that she had a potential employee pool of entry-level engineers already familiar with this regulation and its challenges.)

Students developed increased comfort and confidence in discussing technical issues. Professional engineers repeatedly stress the importance of both written and verbal communication skills for engineering students (Cooney et al., 2008), so this result is a key element of improved professional skills. For SGMA discussions specifically, students were able to successfully support their client's position and respectfully debate that position when it differed from the position of another group's client. Moreover, this confidence was increasingly evident throughout the quarter not just during the SGMA discussions but during all of the lectures. By fostering a spirit of open communication throughout the quarter, students showed increasing comfort levels in both responding to questions asked and in asking their own questions during all lectures. For example, at the beginning of the quarter, their questions focused on asking for straightforward clarification of material presented; by the end of the quarter, their questions focused on searching for a greater depth of understanding beyond the lecture material. These questions showed evidence of active, engaged learning, a key element of critical thinking (Jacquez et al., 2007; Schafersman, 1991).

Using a current regulation as the framework for this Signature Assignment also helped students appreciate the social context for their engineering activities. Outside of the classroom, engineering is driven by social and economic demands, and it always has a social ramification. Indeed, the increasing complexity and integration of science, technology, and modern society requires that effective engineering professionals be well-versed in not just the technical aspects but the social and regulatory aspects affecting their work (Lafayette, 2014; Romkey & Cheng, 2009). Allowing students to realize that technical solutions may vary based on the social context was one of the key goals of this project; a number of students commented that they appreciated the social context for the technical material of the class.

- *Being able to see from the perspective of the landowners and the engineer provided insight that I would not have considered before, and I found it interesting.*

Students demonstrated genuine organic learning, in that they realized many of the important take-home messages through their own experiences and reflections rather than through lecture-style delivery. Many aspects of subsequent in-class activities were taken from student-generated responses in previous activities. For example, the key stakeholders represented during the role playing activity and Town Hall meeting were identified by students during the first in-class activity. The proposed solutions to achieve the goals were generated by students during the role-playing activity. An appreciation for the distinction between nuanced points such as sustainable yield versus sustainable management was generated from student-initiated questions. Students' increased technical knowledge and professional skills came about from their own experiences and ideas, resulting in much more reflective and effective learning.

Perhaps most rewarding, students enjoyed the class. Based on representative comments on evaluations (shown), they appreciated the social context of the material, the application of the technical material to a real-life context, and the unique learning opportunities this Signature Assignment provided.

- *Very effective at communicating concepts and relating technical info to bigger picture*
- *Class/material was very organized and easy to understand. Very engaging. Made class very enjoyable*
- *Town Hall meeting was fun and informative*

By the end of each term when this Signature Assignment was conducted, students were able to represent and support the specific point of view of their client, and effectively and respectfully debate merits of a proposed solution with representatives of the other clients. They had not only accepted but embraced the idea that there may be more than one "right" way to approach an engineering challenge, and that finding effective and sustainable solutions requires both understanding and respecting multiple perspectives on the issue.

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Attachment 1: Town Hall Meeting Assignment & Rubric

Assignment:

The local Groundwater Sustainability Agency has convened a Town Hall Meeting for all interested stakeholders, to discuss a proposed component of the Groundwater Sustainability Plan (GSP): use of reclaimed water for agricultural irrigation to offset groundwater demand, and to supplement natural groundwater recharge. Two sources of reclaimed water are available within the community: treated municipal wastewater and treated process water from oil field operations. The GSA wants to get input from all stakeholders on their opinions and concerns about groundwater sustainability in general, and this proposal specifically.

Your firm represents one of seven key stakeholders (Big Oil, Big Ag, Small Farms, Water Purveyor, an Economically Disadvantaged Community, an Environmental Advocacy Organization, and "Future Generations") under GSA jurisdiction, and they have asked you to represent their interests at the Town Hall Meeting. Specifically, you have been hired to:

1. Develop a formal presentation to explain your stakeholder's position regarding Groundwater Sustainability:
    - What does the term "groundwater sustainability" mean to your stakeholder?
    - What are your stakeholder's beneficial uses of the aquifer and how much groundwater do they need annually to support those end uses?
    - What are your stakeholder's opportunities and challenges regarding groundwater sustainability? (Consider their ability to increase conservation, use or develop alternatives to groundwater, provide seasonal storage, etc.)
    - What are your stakeholder's priorities that might affect GSP development?
2. Following the presentations, the stakeholder representatives will engage in a moderated discussion regarding the proposed GSP component. Your firm should be prepared to discuss the following issues regarding the proposed uses of reclaimed water, *from your stakeholder's point of view.*
    - What is your opinion regarding use of either treated process water from oil field operations or treated municipal wastewater for
        - Agricultural irrigation to offset groundwater demand?
        - Supplemental groundwater recharge?
    - What are the physical limitations and opportunities of the proposed solution?
    - What are the environmental concerns and opportunities of the proposed solution?
    - What are the economic limitations and opportunities of the proposed solution?
    - Is the proposed water reclamation plan an effective long-term solution?

Be prepared to support why you feel your stakeholder has that point of view for any of these issues. You should also be prepared to challenge other firms as needed to advocate for your own client.

Rubric

Criteria	Professional Engineer (5)	Entry-Level Engineer (3)	Intern (1)
Preparation & Technical Accuracy *(x2)*	You clearly put exceptional effort into preparation; your calculations or data are complete and accurate.	You put sufficient effort into preparation; your calculations or data are generally complete and accurate.	You put some effort into preparation; your calculations or data may have some minor errors.
Content *(x2)*	Completely addressed all aspects of the assignment in sufficient detail.	Addressed all aspects of the assignment or most aspects in details.	Addressed most aspects of the assignment but some important details were omitted.
Organization	Your presentation and discussion were exceptionally clear, logical and superbly organized.	Your presentation and discussion were generally organized and clear.	Your presentation and discussion were generally organized, but lacked some clarity.
Presentation Skills *Includes nonverbal skills (such as eye contact and body language) and verbal skills*	Group members made effective use of both nonverbal and verbal skills and seemed very comfortable in front of an audience	Group members demonstrated use of both nonverbal and verbal skills and seemed mostly comfortable in front of the audience	Group members demonstrated presentation skills to varying degrees of success
Group Involvement	All group members are involved equitably and assist each other as needed.	All group members are involved but there is little connection between group members	Not everyone participated in both preparation and presentation of the material
Time Management	Your showed exceptional time management skills.	Finished within the allotted time.	You went over the time limit or your presentation was too short to adequately address the assignment.
Discussion Management *(x2)*	Addressed questions and handled discussion with other stakeholders with confidence; all group members able to address questions	Handled discussion and questions well overall with multiple group members participating	Handled discussion and questions fairly well, or only one member of the group was involved in discussion and questions