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Understanding Bloom's Revised Taxonomy in Biology Education: Implications and Applications for Assessment

A Thesis submitted in partial satisfaction of the requirements

for the degree Master of Science

in

Biology

by

Bianca Hanako Endo

Committee in charge:
    Stanley M. Lo, Chair
    Ella Tour, Co-chair
    Laurie Smith

2019

The Thesis of Bianca Hanako Endo is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Co-chair

Chair

University of California San Diego

2019

DEDICATION

My journey in education would not be possible without the support from family and friends. To Mom and Dad, who have always been my inspiration to work hard. To Brittney and Nikita, who have always given me their confidence. To Nobu and Scooby, for being my piece of home after every day. To the friends that I gained along the way in these shared experiences in the classroom who continue to inspired me.

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I would also like to acknowledge the DBER journal club that continues to generate important conversations about education for both students and instructors.

Chapter 2, in full is currently being prepared for submission for publication of the material as it may appear in CBE Life Sciences, 2019. The thesis author was the primary investigator of this paper.

Chapter 2 is coauthored with Yee, Alexander and Larsen, Victoria. The thesis author was the primary author of this chapter.

Chapter 3, in full is currently being prepared for submission for publication of the material as it may appear in the American Biology Teacher, 2019. The thesis author was the primary investigator of this paper.

Chapter 3 is coauthored with Hinchey, Tiffany. The thesis author was the primary author of this chapter.

ABSTRACT OF THE THESIS

Understanding Bloom's Revised Taxonomy in Biology Education: Implications and Applications for Assessment

by

Bianca Hanako Endo

Master of Science in Biology

University of California San Diego, 2019

Stanley M. Lo, Chair
Ella Tour, Co-Chair

Bloom's original taxonomy (1956) has been instrumental in facilitating course alignment, identifying assessment objectives in undergraduate courses and standardized tests, and assisting faculty in writing exams that test a variety of cognitive skills. Despite the wide reception of this framework, subsequent studies could not find strong support for the taxonomy's cumulative hierarchical structure leading to its revision almost two decades ago. Since then, little research has been done to explore how the revised taxonomy can be used to inform biology instruction. The aim of this study was to explore how Bloom's revised taxonomy can be understood and applied to biology education, particularly in assessments. This investigation involved a series of studies. First, a biology-specific revised taxonomy was articulated using supporting theoretical frameworks. Subsequent classifications of biology test items from various sources (n=940) using this articulation found that most biology items tested students' ability to *Remember Factual knowledge* and *Understand Conceptual knowledge*. This is consistent with previous literature that suggests biology assessments place an emphasis on memorizing facts rather than deploying other skills associated with critical thinking, problem solving, or learning transfer. A second study examined the relationship between categories of each dimension by considering all types of knowledge and cognitive processes that are involved in solving each item (n=148). In the knowledge dimension, items that drew from *Procedural* and *Conceptual knowledge* also involved *Factual knowledge*. In the cognitive process dimension, items that prompted students to *Analyze, Evaluate,* and *Create* simultaneously deployed tasks such as *Remember, Understand, and Apply*.

CHAPTER 1: INTRODUCTION

In recent years, STEM education reform has pushed for skills such as problem solving, learning transfer, and critical thinking to assure the successful transition from education to employment (National Research Council [NRC], 2003; NRC, 2007; NRC, 2012; National Academies of Sciences, Engineering, and Medicine [NASEM], 2018; Alberts, 2009). In biology, multiple guidelines and core competencies, such as *Vision and Change* (AAAS, 2010) and *Next Generation Science Standards* (NRC, 2013), have put forth guidelines to help facilitate this new direction. Though these resources are available, aligning these goals with course curriculum, instruction, and assessment can be challenging to achieve (Crowe et al., 2008; Momsen et al., 2010; Jensen et al., 2014). How do we bridge this gap with the interest of preparing students for life outside the classroom?

Bloom's taxonomy is one such tool that can systematically evaluate alignment in biology education (Crowe et al., 2008; Momsen et al., 2010; Jensen et al., 2014; Allen and Tanner, 2002). Empirically developed by professors, psychologists, and educational researchers, Bloom's *Taxonomy of Education Objectives* (1956) has been recognized as one of the most influential writings impacting education in the twentieth century due to its wide application across subject and level (Kridel, 2000). According to the original taxonomy, learning can be categorized into hierarchical learning objectives, progressing from simple cognitive functions to more complex: *Knowledge*, *Comprehension*, *Application*, *Analysis*, *Synthesis,* and *Evaluation*. In biology education, Bloom's taxonomy has been instrumental identifying assessment objectives in introductory undergraduate courses (Momsen et al., 2013; Jensen et al., 2014) and standardized tests (Zheng et al., 2013), and mapping out strategies to write effective assessments of varying difficulty (Bissell and Lemons, 2006; Lemons and Lemons, 2013) in addition to assessing course alignment (Crowe et al., 2008; Momsen et al., 2010).

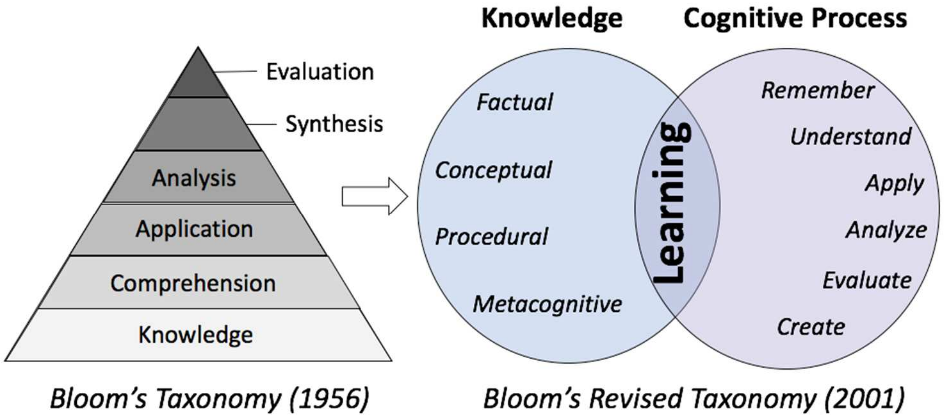


Figure 1. Bloom's original taxonomy of learning objectives (right) was revised into two dimensions. As the *Knowledge* objective from the original taxonomy was inconsistent with other objectives, it was designated its own dimension. The remaining objectives were converted to their verb equivalents, making up the cognitive process dimension. Learning can be demonstrated in a multitude of ways when any combination of knowledge is used to perform a cognitive process.

Despite the wide reception of this classical hierarchical structure, previous studies could not find strong support for the taxonomy's cumulative hierarchical structure (Kreitzer and Madaus, 1994; Hill and McGaw, 1981). Educational researchers and instructors recognized the distinction between knowledge and skill, often referring to learning as a dyad involving both (Bransford et al., 1999). Given these inconsistencies, the taxonomy was revised, suggesting learning is the interaction between two dimensions: knowledge and a cognitive process (Fig. 1). As its own dimension, knowledge consists of four categories: *Factual, Conceptual, Procedural*, and *Metacognitive knowledge.* The remaining learning objectives from the original taxonomy were converted into their verb equivalents and designated as the cognitive processes dimension, consisting of *Remember,* *Understand, Apply, Analyze, Evaluate*, and *Create*. Rather than emphasize rank, the revised taxonomy showcases the different combinations in which knowledge and cognitive process can be coupled to produce a variety of learning objectives (Anderson and Krathwohl, 2001).

Since its publication, the revised taxonomy has been applied to several educational efforts in various disciplines. In the field of cognitive science, researchers provided several examples for assessing each of the six cognitive actions in the cognitive processes domain, in hopes of consistent use by instructors (Thompson et al., 2008). A similar study was done in Family and Consumer Sciences (Picard, 2007). In addition, the revised taxonomy served as a basis to evaluate the effectiveness of E-learning in the undergraduate level (Halawi et al., 2009). While there are multiple publications that illustrate how the original taxonomy can be a powerful resource in biology education, very little has been done to consider what we can learn in from the revised taxonomy.

This study explores how the revised taxonomy can be applied to biology education to inform instruction and assessment. This investigation was carried out in two projects, currently being prepared for submission for publication, and are designated as individual chapters hereafter. The first project is a theoretical paper in understanding the taxonomy in biology by articulating a biology-specific articulation of the revised taxonomy. Using this coding scheme, biology test items (n=940) from various sources, such as lower and upper division biology course and standardized tests, were classified to get a general sense of what combinations of knowledge and cognitive processes are seen in biology assessments.

In addition, we were interested to see if prompt words had any association with specific cognitive processes.

The second project addresses how the revised taxonomy might be used in a meaningful way for both students and instructors. Previous studies in biology education used the original taxonomy to classify test items, assigning each test item with a *single* learning objective; however, there may be multiple types of knowledge and cognitive actions involved in solving a single item alone (Anderson and Krathwohl, 2001). The goal of this study is to understand how the categories within each dimension associate with each other in biology assessments by mapping out all possible types of knowledge and cognitive processes involved when solving a given test item. Using these data, we hope to illustrate how categories within each dimension associate with each other, and explore if specific cognitive skills can facilitate other cognitive processes simultaneously (Anderson and Krathwohl., 2001). By introducing this revised structure and its application in the biology education, we hope the revised taxonomy offers a new perspective on instruction and assessments in biology.

CHAPTER 2: Understanding Bloom's Revised Taxonomy in Biology

This study aims to understand how the revised taxonomy can be used in biology education. After developing a biology-specific revised taxonomy for student and instructor use, test items (n=940) from various sources were classified to get a general sense of what combinations of knowledge and cognitive processes are seen in biology assessments.

THEORETICAL FRAMEWORK

At a glance, the classifications of both dimensions from the revised taxonomy may seem comprehensive; in practice, however, such classifications can vary in interpretation (Anderson and Krathwohl, 2001). As both dimensions intentionally used language that was generalizable across all classrooms and encouraged more detailed expansion according to discipline (Anderson and Krathwohl, 2001), our first step was to operationalize the revised taxonomy for use in biology. This is our articulation of the taxonomy- a culmination of our discussions throughout the iterative coding process, teasing out ambiguities to offer an elaboration on the revised taxonomy through the lens of biology. As said with other biology-specific expansions of Bloom's (Crowe et al., 2008; Arneson & Offerdahl, 2018), this rubric is not "definitive" for all biology assessments; rather, it reflects the coders' articulation of the revised taxonomy that may be useful for students and educators studying biology. Though some terms can be easily confused and even may remain somewhat muddled, we hope our articulation, supporting frameworks, and examples give instructors and students more confidence to delineate these classifications.

Table 1. A summary of a biology-specific articulation of Bloom's revised taxonomy. Each category under the knowledge and cognitive process dimensions have their own definitions, characterized by specific defining features.

Cognitive Process	**Definition**	**Features**
Remember	Retrieve relevant information from memory	• Little to no abstraction • Information retrieved with little to no deviation from how it was initially presented
Understand	Make sense of information to construct a relationship or draw a connection	• Interpretation is involved; there may not be a single right or wrong answer • Only necessary to make a single connection, not multiple (*Analyze*) • Analogous to Biggs's Uni-structural learning outcome
Apply	Use previously established methods or patterns	• Common methods: lab techniques, calculations, reading graphs and figures
Analyze	Determine how multiple components of larger whole relate to one another other	• Relationships between components serve an overall structure or purpose • Interpretation is involved; there may not be a single right or wrong answer • Analogous to Biggs's Multi-structural learning outcome
Evaluate	Make a judgment based on multiple pieces of information/evidence	• Evidence-based criteria and standards, specified in question • Evidence may be contradictory
Create	Format multiple components to form a novel coherent and functional whole	• Reorganize elements into a novel pattern or structure
Knowledge	**Definition**	**Features**
Factual	Discrete, isolated information	• *Doesn't* require understanding of a large context • Facts can be isolated as separate, discrete elements in contrast to those that can be known only in a larger context • Facts can be complex
Conceptual	The interrelationships among information within a larger structure that enable them to function together	• Concepts are largely the result of agreement and convenience, whereas facts stem more directly from observation, experimentation, and discovery (49) • Concepts can build on each other to make larger, more complex concepts (i.e. principles, theories)
Procedural	Information on how and when to use skills, algorithms, techniques, and methods	• Pertaining to a systematic way of doing something • Reading a graph is a subject specific skill in Biology that happens to be shared by other fields • Transcribing and translating gene sequences • Lab techniques (e.g. PCR)
Metacognitive	Awareness of self and cognition in general	• Testing and studying strategies; self-regulation • Strengths and weaknesses, sources of motivation

The Knowledge Dimension

The most significant revision to the taxonomy was the addition of the knowledge dimension as a part of the two-dimensional approach to learning. Statistical analyses studying the structural integrity of the cumulative hierarchy found that the *Knowledge* learning objective was not consistent with the other objectives, as it was more of substance rather than action (Kreitzer and Madaus, 1994; Anderson and Krathwohl, 2001). For this reason, the revised taxonomy distinguished knowledge as its own dimension, emphasizing the idea that there is difference between knowing something (knowledge) and putting that knowledge to use (cognitive process). The authors of the revised taxonomy categorize knowledge into four types, ordered along a "continuum" from concrete to abstract: *Factual, Conceptual, Procedural* and *Metacognitive knowledge* (Anderson and Krathwohl, 2001). Each class of knowledge encompasses several more specific subcategories of knowledge that can be used as a reference for classification.

Factual Knowledge vs Conceptual Knowledge

A point of constant discussion between coders was the distinction between *Factual* and *Conceptual* knowledge. As past research used the original taxonomy that did not include the knowledge dimension, no studies necessitated the distinction between these two knowledge types. The revised taxonomy describes *Factual knowledge* being "bits of information," concerning *Knowledge of specific details* and *Knowledge of terminology*, while *Conceptual knowledge* is more general, interconnected knowledge, encompassing the *Knowledge of classifications and categories*, the *Knowledge of principles and generalizations*, and the *Knowledge of theories, models and structures* (Anderson and

Krathwohl, 2001). In the past, there have been multiple attempts to identify important concepts, foundational to biology and other science-related fields (Batzli et al., 2016; Brownell et al., 2014; NRC, 2013). Although science and education experts validate these ideas as "concepts" by consensus, our challenge was operationalizing a "concept" at its most basic form. The revised taxonomy necessitates this, as *Conceptual knowledge* encompasses simple, less complex "concepts" to more complex knowledge structures such as principles or theorems. To make matters more complex, Anderson and Krathwohl (2001) distinguished the two knowledge types as context-dependent that "lie along a continuum" of relative abstractness. Where does a fact end and a concept begin?

The revised taxonomy states that *Factual knowledge* is information that is not disputed in the community: "facts" can be verified, observed, and hold true for everyone. That is not to say that concepts are not "true." Concepts are bits of organized knowledge that may not necessarily be "fact," but knowledge that was generated by the discipline for more accessible use (Anderson and Krathwohl, 2001). For example, the functional groups of amino acids are an easy way for students to organize twenty amino acids based on structural similarity. A simple laundry list of several functional groups may seem "factual"; however, these classes were made for easy reference and organization. Students can use this conceptual knowledge of functional groups to carry out a variety of cognitive processes, like predict how a protein might behave in charged environments or suggest what codon to target for gene therapy, for example.

Factual and *Conceptual knowledge* can also be distinguished based on the context of the question (Anderson and Krathwohl, 2001). If asked to explain the process of transcription, for example, students might draw upon *Factual knowledge* to restate a detailed information of facts or terminology. On the other hand, if the question inquires after how or the why these elements work together, this item is more likely to involve more organized *Conceptual knowledge*.

A. Which of the following levels of protein structure is correctly defined?

a. Primary: interaction between subunits of a protein.
b. Secondary: hydrogen bond arrangement of polar R-groups.
c. Tertiary: three-dimensional arrangement of all atoms in a single peptide.
d. Quaternary: order of amino acid residues in the peptide chain.
e. None of the above are correct.

B. Which of the following statements is NOT characteristic of k_{cat}/K_m?

a. It corresponds to a second-order rate constant.
b. It provides an excellent parameter for comparison of the catalytic efficiency of enzymes.
c. It reflects the property of the enzyme when substrate concentration is at saturation.
d. The upper limit for the k_{cat}/K_m value is fixed by the diffusion-controlled limit for reactions, which is 10 $M^{-1}s^{-1}$.
e. It is also referred to as the turnover number.

Figure 2. Examples in biology assessing students' ability to *Remember Factual knowledge* (2A, right) vs *Remember Conceptual knowledge* (2B, left). Both involve recall of information; however, the type of information differs. Panel A relates to isolated, discrete facts (*Factual knowledge*), while Panel B draws from more abstract, interconnected knowledge (*Conceptual knowledge*).

Consider the examples in Figure 2 that ask students to *Remember* different types of knowledge. Panel 2A asks students to *Remember Factual knowledge*, as they must discern which, if any, definitions are correct. Here, students must simply recall the meaning of terminology to make the correct selection. On the other hand, Panel 2B requires students to go beyond terminology: they must also remember the characteristics of k_{cat}/K_M, how it can be used, and why it is significant, to inform their selection. Although subtle, it is important to be able to distinguish these knowledge types to inform instructors on how to think in both contexts.

Procedural Knowledge

Anderson and Krathwohl (2001) describe *Procedural knowledge* as information on how and when to use skills, algorithms, or methods, which all coders agreed with. *Procedural knowledge* can be drawn both in theory or practice (i.e. in a lab and on paper assessments) and can be broken down into three subcategories. Examples of *Knowledge of skills and algorithms* in biology include knowing how to read a graph, *Knowledge of techniques and methods*, the scientific method, or proper pipetting. Finally, *knowledge of criteria for determining when to use appropriate procedures* might involve knowing when a Western blot is a more appropriate technique to test a hypothesis instead of a Northern blot. Figure 3 draws upon this subcategory of *Procedural knowledge*, as it requires students to know how to use these pieces of information in the appropriate equation to inform their selection.

What is the pH of an acetic acid solution where the concentration of acetic acid is 2mM and the concentration of sodium acetate is 20mM. The pK_a of acetic acid 4.76:

a. 5.76
b. 10.6
c. 12.6
d. 8.8

Figure 3. A biology test item assessing students' ability to *Apply Procedural knowledge.* Using an equation or method presented in class, students follow a general procedure using the information in the question to solve for pK_a.

Metacognitive Knowledge

Although use of this type of knowledge was not found in our sample, *metacognitive knowledge* refers to information or awareness about yourself and "cognition in general," that includes *strategic knowledge, conditional knowledge*, and *self-knowledge* (Anderson and Krathwohl, 2001). Students draw upon metacognitive knowledge when thinking about effective testing strategies (e.g. mnemonics or process of elimination) or knowing one's strengths and weaknesses. Instructors expand on this type of knowledge when learning about teaching strategies, getting feedback, or attending workshops. Recent studies have placed an emphasis in metacognitive knowledge, as it perpetuates that there is power in knowing your strengths and weaknesses, as well as the various tools available for learning and assessment (Bransford et al., 1999; NRC, 2012; NASEM, 2018; Tanner, 2012; Stanton et al., 2015). The taxonomy itself builds on this type of knowledge by making readers aware of the different combinations of knowledge and cognitive processes as learning outcomes.

The Cognitive Process Dimension

As the *Knowledge* learning objective from the original taxonomy was expanded into its own dimension in the revised taxonomy, the remaining objectives were turned into their verb equivalents to make up the cognitive processes dimension. These cognitive processes include: *Remember*, *Understand, Analyze, Evaluate,* and *Create*. Like the knowledge dimension, each cognitive process consists of multiple subcategories of skills or functions that distinguish each process.

Remember

In the revised taxonomy, *Remember* occurs when relevant information is retrieved from memory, consistent with how it was initially presented. Two subcategories make up this cognitive process: *Recognize* and *Recall*. To *Recognize* is to identify previously seen information, typically encompassing question formats in which the solution must be selected from given options (i.e. true/false or multiple choice). On the other hand, *Recall* involves students remembering information with no options to select from. Both subcategories of *Remember* retrieve information from memory consistent with how it was initially presented, however, to *Recall* is more cognitively demanding than to *Recognize*. In this case, little to no abstraction is embedded in the question to allow for the retrieval of information in a similar fashion to how it was initially presented (Anderson and Krathwohl, 2001).

Understand vs Analyze

The original taxonomy recognized the similarities between the *Comprehension* and *Analysis* objectives, taking form as *Understand* and *Analyze* in the cognitive process dimension in the revised taxonomy (Anderson and Krathwohl., 2001; Bloom et al., 1956). Faculty of health sciences and non-health sciences struggled to make this distinction when raking items using the original taxonomy, correctly classifying 41.9% and 45.1% of items, respectively (Welch et al., 2017). In its revision, Anderson and Krathwohl elaborated their description of both cognitive processes with the addition of subcategories in hopes of articulating a more discrete characterization between the two processes. These descriptive subcategories, however, may seem synonymous between the two processes: *Classifying* as a subcategory of *Understand* parallels *Organizing* of *Analyze*, *Comparing* corresponds to *Differentiating, and Explaining* is mirrored with *Attributing.* Such close equivalencies remained a constant point of dispute between coders.

To maintain consistency in the classification of both cognitive processes, coders referenced a second theoretical framework: Biggs' Structure of the Observed Learning

Outcome (SOLO; Fig. 4). Like the original taxonomy, SOLO is a framework of learning outcomes: Pre-structural, Uni-structural, Multi-structural, Rational, and Extended Abstract. These outcomes can be applied to classify a student's level of understanding based on the quality her answers (Biggs and Collins, 1982).

According to SOLO, students demonstrate the Uni-structural learning outcome when they are able make a *single* generalization between two things (Biggs and Collins, 1982). This best corresponded to our articulation of *Understand,* a cognitive process that emphasizes the construction of a *single* relationship. These connections can take many forms, classified by seven subcategories: *Interpreting, Exemplifying, Classifying, Summarizing, Inferring, Comparing,* and *Explaining.*

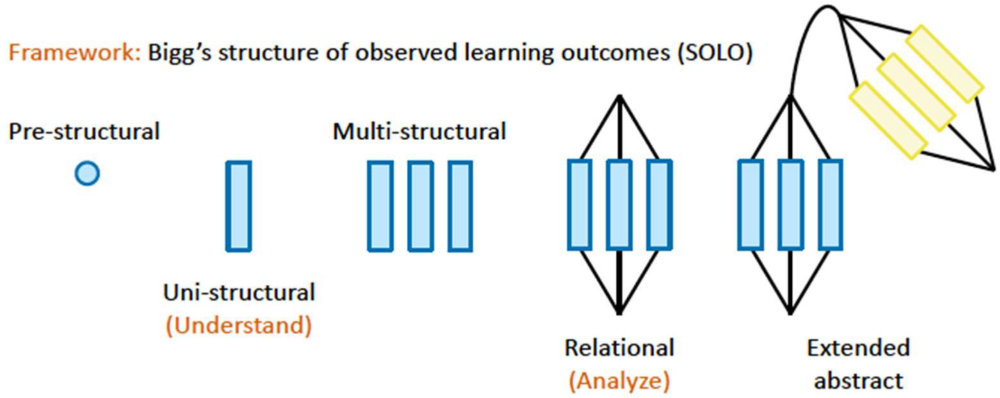
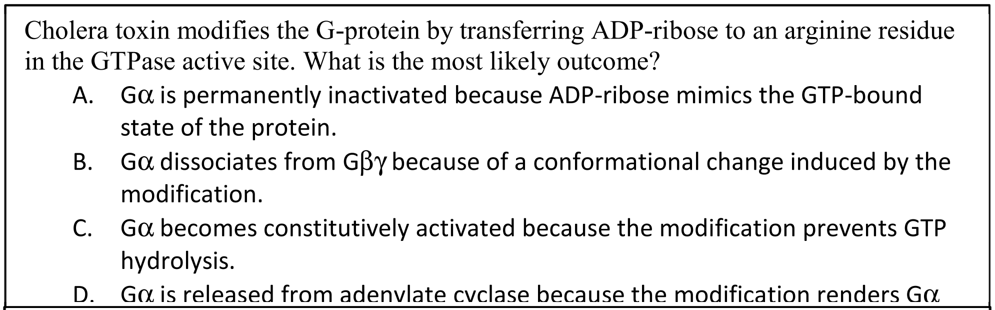


Figure 4. Cognitive processes *Understand* and *Analyze* mirror the Uni-structural and Rational learning outcomes form Biggs' SOLO. As there were many equivalencies between the subcategories of both cognitive processes, coders used SOLO as a supplementary reference framework to distinguish the two cognitive tasks: *Understand* involves making a *single* connection, while *Analyze* necessitates piecing together multiple connections that make up a larger whole.

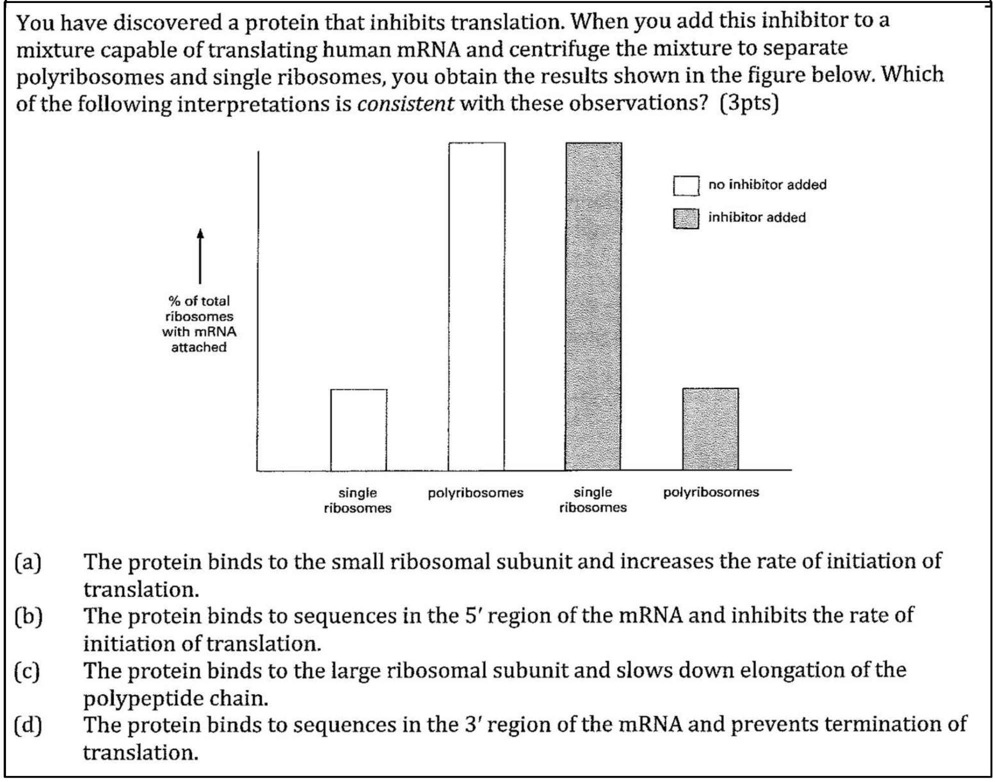
When students are tasked with drawing *multiple* connections and necessitate the piecing together of these relationships in the context of a larger whole, students are asked to *Analyze*. This process is mirrored by Biggs' Rational learning outcome, in which generalizations are made through the inner workings of multiple context-dependent aspects (Fig. 4). To *Analyze,* therefore, implies determining the significance of a structure or process, how its constituent parts work, and how it relates to other elements (Dewey, 1933; Zagzebski, 2001). *Analyze* is characterized by three subcategories: *Differentiating*, *Organizing*, and *Attributing*.

The difference between *Understand* and *Analyze* is exemplified in Figure 5. In the top panel (Fig. 5), the solution to this question prompts students to *Explain* how the structure of a G-protein affects its function. Students reflect their *Understanding* of a singular cause-and-effect relationship: once a single residue is changed, the protein structure morphs to take on a new function. In contrast, the lower panel (Fig. 5) utilizes requires drawing more than one connection to form a conclusion or *Analyze*. Here, multiple components from the question and graph must be interpreted and pieced together to hypothesize how the overall process is affected: What is the effect of an inhibitor on translation? How are single and polyribosomes related to the process of translation? What do they signify? What are the important differences observed when an inhibitor is present or absent? Students must establish numerous connections between these aspects to inform how the overall whole works in concert to produce such results. Although both *Explaining* and *Organizing* require drawing relationships, cognitive processes associated with *Understand* only require the establishment of a relationship while *Analyze* emphasizes how multiple connections work in concert to serve an overall purpose or structure.



Cholera toxin modifies the G-protein by transferring ADP-ribose to an arginine residue in the GTPase active site. What is the most likely outcome?

A. Gα is permanently inactivated because ADP-ribose mimics the GTP-bound state of the protein.
B. Gα dissociates from Gβγ because of a conformational change induced by the modification.
C. Gα becomes constitutively activated because the modification prevents GTP hydrolysis.
D. Gα is released from adenylate cyclase because the modification renders Gα



You have discovered a protein that inhibits translation. When you add this inhibitor to a mixture capable of translating human mRNA and centrifuge the mixture to separate polyribosomes and single ribosomes, you obtain the results shown in the figure below. Which of the following interpretations is *consistent* with these observations? (3pts)

(a) The protein binds to the small ribosomal subunit and increases the rate of initiation of translation.
(b) The protein binds to sequences in the 5′ region of the mRNA and inhibits the rate of initiation of translation.
(c) The protein binds to the large ribosomal subunit and slows down elongation of the polypeptide chain.
(d) The protein binds to sequences in the 3′ region of the mRNA and prevents termination of translation.

Figure 5. Biology items involving cognitive actions *Understand* (top) vs *Analyze* (bottom). Similar to Biggs' Uni-structural learning outcome in the SOLO framework, the top item prompts students to make a single connection between structure and function to inform their selection (*Understand*). In contrast, the bottom item asks students to make sense of the graph, as well as contextualize these conclusions in the larger process of translation to inform their selection (*Analyze*).

Apply

Apply involves using previously established methods or patterns in a given situation (Anderson and Krathwohl, 2001). Here, established methods or patterns are those presented in class, such as steps to read a Northern Blot or reviewing phases of PCR. When no such pattern exists, this task would call upon a different cognitive process (e.g. *Create*). The idea is that *Applying* entails students work within the same systematic framework to solve a problem. *Applying* methods or patterns is not limited to performing a technique in a laboratory; *Application* can also be done in theory, on paper (Anderson and Krathwohl, 2001). Some common patterns in biology may involve using an equation (e.g. Hardy Weinberg) to solve for an unknown, transcribing a piece of DNA to RNA, or applying a lab technique, such as a Western Blots, to investigate the aim of novel situation. This cognitive task can be illustrated by its subcategories: *Executing* and *Implementing*.

Anderson and Krathwohl (2001) point out that *Apply* is often associated with *Procedural knowledge*, as this type of knowledge encompasses methods and patterns. Both knowledge and cognitive process are used in unison to perform a specific learning objective or task. Accessing the knowledge of how or when to do something (i.e. *Procedural knowledge*) is different from carrying out a task that uses these established methods or patterns (i.e. *Apply*).

Evaluate

Evaluate involves making judgments based on pieces of information or evidence. These assessments are based on a set of metrics specified in the question, such as the efficiency of a given lab technique or how consistent a hypothesis is with supporting evidence. In their articulation of such judgments, students are asked to make an argument: there is no definitive right or wrong answer, only better or worse arguments. Students can make such evaluations in two ways: *Checking* and *Critiquing* (Anderson and Krathwohl, 2001). The nature of this cognitive process requires students to construct their own argument; therefore, *Evaluate* questions are generally formatted as free response, rather than multiple-choice.

Create

To *Create* is to organize multiple components to form a novel, coherent, and functional whole. This echoes some of the ideas from *Analyze* by taking different elements of a structure into consideration; however, what sets *Create* apart is the requirement that something novel must be generated. *Hypothesizing, Planning,* and *Producing* are all characteristic subcategories under this process (Anderson & Krathwohl, 2001).

Hypothesizing is alternative term for what Anderson and Krathwohl as *Generating* in the revised taxonomy (2001). Here, *Hypothesizing* speaks directly to the scientific method in biology, prompting multiple propositions to explain a given phenomenon, thereby *Creating* new possibilities of knowledge. *Planning* and *Producing* are the other pieces of the puzzle that carry out the scientific method. The two processes often go hand in hand as one must *Plan* a course of action to implement a given task or solution. Questions that involve these subcategories may ask students to design an experiment to investigate novel phenomenon. Like *Evaluate*, this cognitive action requires the communication of novel ideas, rather than a selection of an idea from a set of possible answers. For these reasons, *Create* questions are formatted as free response (Anderson and Krathwohl, 2001; Crowe et al., 2008; Jensen et al., 2014).

METHODS

Preliminary Coding

To familiarize ourselves with the revised taxonomy, coders read a variety of Bloom's related literature in biology education before classifying items (e.g. Bissel & Lemons, 2006; Zheng et al., 2008; Crowe et al., 2008; Momsen et al., 2010; Jensen et al., 2014). From these publications, a preliminary rubric based on the revised taxonomy was created to assist in the early coding phase of test items. Our sample included questions (n=829) from standardized tests, such as the biology sections from the Medical College Admissions Test (MCAT) and Advance Placement (AP) exams, as well as upper and lower division biology course assessments from a private, medium-size research university with very high research activities in the Midwestern United States (McCormick, 2005). Each test item was coded for a single type of knowledge and cognitive process that was primarily being assessed. Like the approach of Crowe and colleagues (2008), coders classified the first 50 questions independently, then discussed each classification until all coders reached an agreement. Subcategories of specific types of knowledge or cognitive processes were used as discussion points for classification rather than for data analysis. After several iterations, our biology-specific classifications were summarized in a rubric (Table 1), and used to code the remaining test items (n=940).

Four coders were involved in this project. Coders 1 and 2 were both undergraduate students who completed at least half of the introductory biology course sequences for their respective majors at the beginning of the project. Undergraduates are especially suited for this type of project because they are proximal in expertise to students who would encounter these problems on exams or standardized tests. Coder 3 was a graduate student in the biology division. Having completed both lower and upper division biology courses in her undergraduate, she provided another level of proximal expertise for the classification of test items. Coder 4 was a professor at a four-year research institution who engaged in the initial literature associated Bloom's taxonomy as well as subsequent discussions when comparing codes. This coder was consulted when there was disagreement in classification and provided supplemental theoretical frameworks for distinguishing between ambiguous categories in the taxonomy to justify a given code.

Data Analysis

While classifying these items provides a distribution of the types of knowledge and cognitive processes assessed in biology tests, we were also curious as to whether the two dimensions were independent from each other. To test this hypothesis, we used contingency analysis, a test that tabulates multivariate, categorical data from observed frequencies. This analysis displays the distribution of cognitive processes observed in each type of knowledge, illustrating potential relationships between the two dimensions. Subsequently, a chi-squared test asses the independence of both dimensions.

To further demonstrate prevalent ties between types of knowledge and cognitive processes, we ran a cluster analysis from the contingency table, formatting the data into a two-dimensional graphical representation. Otherwise known as correspondence analysis, this statistic uses pairwise distance between all points to graph hierarchical relationships.

Multi-dimensional principle axes are then calculated to capture as much variation in the data as possible. Both statistical tests used JMP Pro (versions 11.0-13.0).

Prompt Words

Can certain words in a question prompt a specific cognitive process? Along with coding each test item for knowledge and cognitive process, prompt words were recorded. Shannon diversity index (*H*) was calculated to measure the spread of each cognitive process for a single prompt word. Commonly used in ecology, *H* measures both diversity and spread in a population by considering the frequency and number of different species present (Beals et al., 2000). In our case, we are observing how the six cognitive processes (i.e. the species) are spread across each prompt word. As we are interested in the spread alone, and not diversity, we calculated equitability (*E*) for each prompt word using the following formula:

$$H = -\sum_{i=1}^{S} p_i \ln(p_i)$$

$$E = \frac{H}{\ln(S)}$$

Here, p_i denotes the proportion of a specific cognitive process used out of the total frequency of a given prompt word. Classically, *S* denotes the number of categories observed rather than those existing; however, for our purposes, *S* remained fixed at a value of 6. Although we did not observe prompt words utilizing every cognitive process in our sample, there is a possibility that they exist outside our sample. *E* ranges between 0-1, with higher values signifying a more even distribution of the use of the prompt across all six cognitive processes and lower values signifying a stronger association of a prompt word to a given cognitive process.

Some questions did not have discrete prompt words, consisting of words such as "be," "to," or "as" to infer a cognitive process. Other questions used formatting to imply the cognitive process that students were expected to deploy, such as fill in the blanks. For these reasons, 18% of test items (n=169) were omitted from the prompt word data, leaving a sample size of n=771 for prompt word analysis.

RESULTS

Interrater Reliability

To assure consistency in the coding process, Fleiss' Kappa was used to measure interrater reliability between the three primary coders (n=159). Interrater reliability for both the knowledge and cognitive processes dimension fell within the 0.60-0.80 range of "substantial agreement" (κ=0.70 and κ= 0.68, respectively). Given the high reliability and consistency among coders at the start of the coding process, we decided it was not necessary for all coders to code all items. Of the test items coded using Rubric 2 (n=940), 17% of items were coded by all three coders, 47% of items by two, and 36% of items by a single coder.

Statistical Analysis

Regarding the knowledge dimension, the contingency analysis revealed over 90% of questions called for *Factual* or *Conceptual knowledge* (45% and 46%, respectively), with the remaining questions requiring *Procedural knowledge*. With respect to the cognitive processes dimension, *Remember* and *Understand* were deployed much more frequently than other cognitive actions (45% and 40%, respectively).

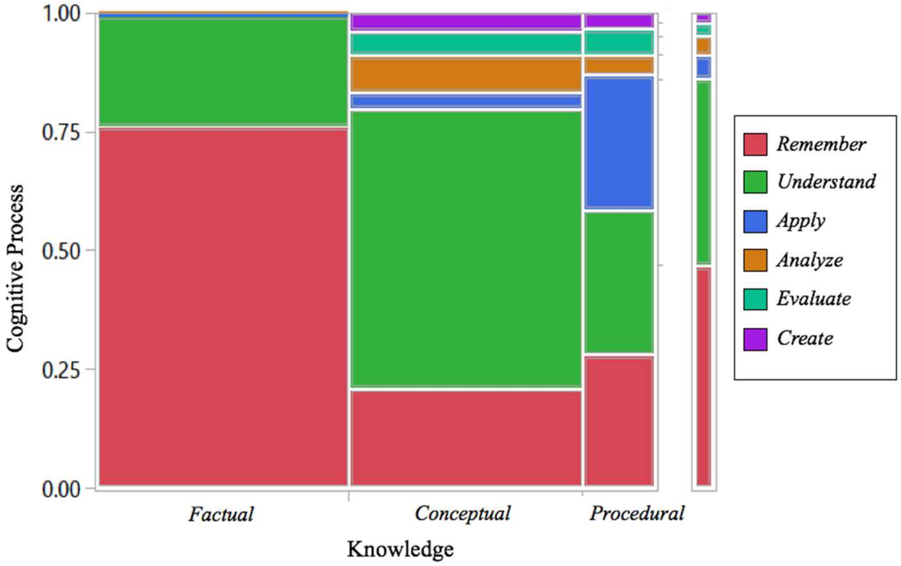


Figure 6. *Remember factual knowledge* and *Understand Conceptual knowledge* are the most common objectives assessed in biology tests. Individual biology test items (n=940) from standardized tests, upper and lower division undergraduate biology courses were classified using a biology-specific articulation of Bloom's revised taxonomy. This contingency analysis revealed distributions of each cognitive process within categories of knowledge. The area of each category of knowledge and cognitive process is proportionate to the number of questions coded. Subsequent Chi-squared tests revealed both dimensions are dependent on each other at a statistically significant level (p<0.0001).

When these factors are oriented two dimensionally in a contingency analysis (Fig. 6), *Remember Factual knowledge* (32% of all test items) and *Understand Conceptual knowledge* (25%) are among the most prevalent combinations of knowledge and cognitive process assessed. The data showed little variation in the cognitive processes associated with *Factual knowledge*: nearly three quarters of these questions asked students to *Remember*, and only some questions asking students to *Understand*. Conceptual knowledge was used in combination with a variety of cognitive processes, accounting for over 80% of all *Analyze*, *Evaluate*, and *Create* items. Most of the items using this type of knowledge, however, prompted students to *Understand* (54%). *Procedural knowledge* was often used to *Apply* (37% of *Procedural knowledge* questions), with similar proportions asking to *Understand* and *Remember*. Subsequent chi-squared tests between the knowledge and cognitive processes dimensions revealed a low p-value (p<0.0001) of statistical significance, suggesting that the two dimensions are indeed dependent on each other.

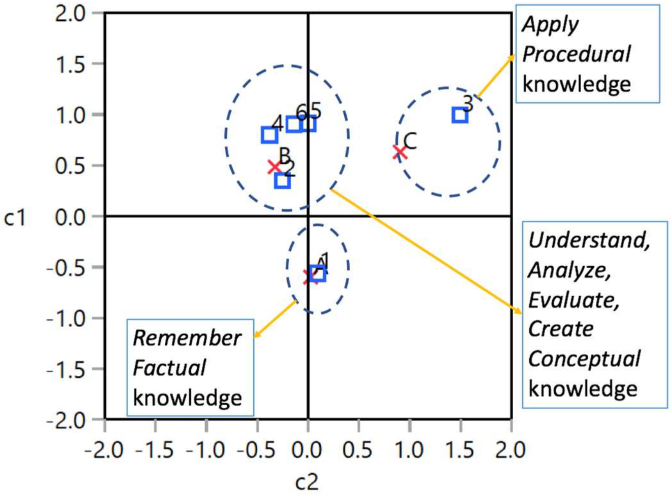


Figure 7. Correspondence analysis reveals three distinct groupings of knowledge and cognitive processes in biology assessments: *Remembering Factual knowledge*, *Applying Procedural knowledge*, and *Understanding, Analyzing, Evaluating,* and *Creating Conceptual knowledge*. Frequencies of knowledge and cognitive processes codes were used to measure the correspondence between the two dimensions. Coordinates of each knowledge (A-D) and cognitive processes (1-6) plot are determined by numerical values denoting relativity of one criteria. Closer distances between any two plots denote the relationship between categories. C1 and C2 principle axes accounted for 61% and 39% of variation, respectively.

These observed combinations of knowledge and cognitive process are best illustrated through a graphical representation (Fig. 7). The data revealed three distinct groupings of knowledge-cognitive process associations: 1) *Remembering Factual knowledge, 2) Applying Procedural knowledge*, and 3) using *Conceptual knowledge* to *Understand, Analyze, Evaluate*, and *Create*. The strongest association is seen in *Remembering Factual knowledge*, signified by the direct overlap of both plots (1, A). A subsequent cluster analysis confirmed these groupings observed in the correspondence analysis (Appendix A).

Table 2. Most frequently used prompts among the most spread words across the six cognitive processes. Prompt words were recorded for each test item, along with Bloom's coding for knowledge and cognitive process. Equitability (*E*) was used to calculate the diversity and evenness of the prompt words among the six cognitive processes. Indices closer to 1 indicate a more even distribution of questions across the cognitive dimensions. Bolded words and corresponding *E* values mark the five most spread prompts.

A. Most Common Prompts	Cognitive Process						Total	E
	Remember	*Understand*	*Apply*	*Analyze*	*Evaluate*	*Create*		
Which	85	91	2	8	11		197	**0.590**
What	55	62	25	14	7		163	**0.763**
Describe	30	20	1	4	1	3	59	**0.660**
How	9	30	5	2	1		47	**0.590**
Explain	6	27		1	3	1	38	0.517
Total	185	230	33	29	23	4	504	

B. Most Spread Prompts	Cognitive Process						Total	E
	Remember	*Understand*	*Apply*	*Analyze*	*Evaluate*	*Create*		
What	55	62	25	14	7		163	**0.763**
Describe	30	20	1	4	1	3	59	**0.660**
How	9	30	5	2	1		47	**0.590**
Which	85	91	2	8	11		197	**0.590**
Write	2	2		1			5	**0.589**
Total	181	205	33	29	20	3	471	

C. Most Common Question Prompts	Cognitive Process						Total	E
	Remember	*Understand*	*Apply*	*Analyze*	*Evaluate*	*Create*		
Which	85	91	2	8	11		197	**0.590**
What	55	62	25	14	7		163	**0.763**
How	9	30	5	2	1		47	**0.590**
Why	7	15			2	1	25	0.555
Where	2	3				1	6	0.565
Total	158	201	32	24	21	2	438	

D. Most Common Verb Prompts	Cognitive Process						Total	E
	Remember	*Understand*	*Apply*	*Analyze*	*Evaluate*	*Create*		
Describe	30	20	1	4	1	3	59	**0.660**
Explain	6	27		1	3	1	38	0.517
Name	13	14					27	0.386
Draw		14	2			2	18	0.382
Identify	3	5				1	9	0.523
Total	52	80	3	5	4	7	151	

Prompt Words

For each test item, prompt words were recorded to investigate a if such words were associated with a specific cognitive process. After calculating equitability (E) or spread for each prompt word across the six cognitive processes, the data revealed the five most frequently used prompt words were among the most spread (Table 2A). These five words, “Which,” “What,” “Describe,” “How,” and “Explain,” were used as a prompt for almost two thirds of the questions in our sample, yielding *E* values ranging from 0.52-0.73. These relatively high *E* values closer to 1 suggest a moderate spread of these words being used across all six cognitive processes, indicating no strong association to any cognitive process.

When broken down into categories of prompts, question words, like “what” or “why,” were also among the most frequently used (Table 2A and 2C), accounting for more than half of the questions (57%). Verb prompts, such as “describe” or “explain” (Table 2D), were not as common, with the five most frequently used verbs accounting for only 20% of all prompts. This group of prompts also had lower *E* values, ranging from 0.38-0.66, reflecting somewhat lower evenness of the use of these prompts across the six cognitive processes. This, however, could be due to the small sampling size of such prompt words.

DISCUSSION

The goal of this study was to update the biology education community on the improvements made to the taxonomy in its revision. We articulated how the revised taxonomy can be operationalized for use in biology education by developing a biology-specific rubric, then classified test items from various sources to get a general sense of what combinations of knowledge and cognitive processes are seen in biology.

Limitations

When ranking biology test items (n=940), interrater reliability between the three primary coders for both the knowledge and cognitive dimension remained high, falling within the range of "substantial agreement" (0.6-0.8) in a Fleiss' Kappa analysis (Landis and Koch, 1977). Though this level of consistency was deemed considerable, there are several reasons why both κ values from each dimension did not fall within the "perfect agreement" range of 0.80 or higher (Landis and Koch, 1977). For one, having less coders artificially lowers the κ value, as there is a higher probability of people agreeing by chance (Zapf et al., 2016). In addition, the sheer number of categories artificially κ lowers as well (Thompson and Walter, 1988; Zapf et al., 2016), which could explain why the κ value was higher for the cognitive processes classifications (κ=0.70; six categories) in comparison to the knowledge classifications (κ=0.68; four categories). Though imperfect, the "substantial agreement" between coders lends itself to the utility of this rubric to consistently operationalize the revised taxonomy for use in biology.

Although the rubric was developed to maintain consistency between coders, we could not account for the potential misalignment between in the coders' perception and the instructor's intent for each test item. Potentially all questions could be *Remember Factual knowledg*e if the instructor presented the same question in class. Even analogies in class would alter the knowledge type and cognitive process used if students were not given any guidance in tackling the problem. Like other Bloom's related publications, coders had to use their best judgement when classifying each question, assuming the novelty of each question (Thompson et al., 2008; Allen and Tanner, 2002; Crowe et al., 2008). Both the intent of the instructor and the reception by students of each question could be validated through a series of interviews with both the instructor who wrote the question and the students who took the exam (Anderson and Krathwohl, 2001). This exercise could be useful for instructors as well to see how their questions are being perceived and thought through by their students, feeding into future alignment.

This study limited each test item to reflect a single type of knowledge and cognitive process; however, it is possible that drawing from variety of knowledge or multiple processes is necessary to solve a single question. Understanding the skills and knowledge necessary for students to arrive at their answers may be informative to guide future instruction. Coding for each step could provide support for a possible hierarchy or secondary structure within the two dimensions of the revised taxonomy.

Remember Factual Knowledge and Understand Conceptual Knowledge Were the Most Common Objectives

Although not complete equivalents, we can draw some comparisons between the literature surrounding the six learning objectives from the original taxonomy and our findings from the cognitive processes dimension of the revised taxonomy. Nearly one third of the test items asked students to *Remember Factual knowledge* (32%), with almost a quarter of prompting students to *Understand Conceptual knowledge* (24%). These results mirror the overwhelming majority of questions categorized as *Knowledge* and *Comprehension* using original taxonomy in introductory biology courses (Momsen et al., 2010; Jensen et al., 2014) and biology portions of standardized tests (Zheng et al., 2008).

Despite the publication of multiple core competencies and many instructors' intent for introducing more diverse sets of cognitive skills and knowledge (Momsen et al. 2010; Bissel and Lemons, 2006), these types of questions tend to be most abundant as they are easy to write and grade in a multiple-choice format (Crowe et al., 2008; Jensen et al., 2014).

Evaluate and *Create* were the least tested cognitive processes in our sample (>6% of all test items), consistent with previous findings that revealed little to no items testing of the *Evaluation* or *Synthesis* objectives with the original taxonomy (Zheng et al., 2008; Momsen et al., 2010; Momsen et al., 2013). Time is one limitation when prompting students carry out either of these processes, as these questions are typically free response and may take more time for students to construct an answer (Crowe et al. 2008). Grading can also be challenging, as these more open-ended assessments allow for unique answers and creativity (Zheng et al. 2008). Though we see a lack of *Evaluate* and *Create* questions in exam settings, it is possible that these skills may be assessed outside of a high stakes environment, such as take-home essays or group projects (Momsen et al., 2010; Momsen et al., 2013;). When testing for either of these cognitive tasks, note that both commonly drew from *Conceptual knowledge* and none drew from *Factual knowledge*. This association is important to note, as this infers teachers should emphasize *Conceptual knowledge* in their instruction for students to successfully demonstrate these cognitive skills.

The frequency of *Apply* and *Analyze* items were comparable to *Evaluate* and *Create*, accounting for a mere 5% of questions each. Although these kinds of questions take more time and effort to write in comparison to *Remember* items (Lord and Baviskar, 2007; Jensen et al., 2014), these cognitive processes can be assessed using multiple choice. Regardless of the formatting of the question, the most infrequently used cognitive processes (i.e. *Apply, Analyze, Evaluate,* and *Create*) are the skills that must be introduced and assessed in hopes of generating stronger scientific literacy, deep conceptual understanding, and problem solving in the workforce that national standards are pushing for (Bransford et al., 1999; Laverty et al., 2016; Anderson and Krathwohl, 2001; Zheng et al., 2008; Jensen et al., 2014).

In the revised taxonomy, Anderson and Krathwohl note the "direct correspondence" between certain types of knowledge and processes, which include *Remember Factual knowledge, Understand Conceptual Knowledge,* and *Apply Procedural knowledge* (107). The remaining cognitive processes to use a more than one type of knowledge (Anderson and Krathwohl, 2001). The data from the correspondence analysis (Fig. 6), however, suggest otherwise in the field of biology. Three distinct groupings of knowledge and cognitive processes were revealed in our sample: *Remember Factual knowledge, Apply Procedural knowledge,* and use *Conceptual knowledge to Understand, Analyze, Evaluate*, and *Create*. Thus, these data suggest that *Analyze, Evaluate,* and *Create* are used in combination with *Conceptual knowledge*, more so than other knowledge types. These grouping could vary between disciplines. It is also important to note, this finding may be due to the methodology of this study, as each item was designated a single category of knowledge and cognitive process being assessed. As mentioned, classifying each step in one's thought process for these items may be insightful to illustrate how these categories interact in future studies.

Prompt Words Are Not Predictors of Cognitive Process

In the past, each level of Bloom's was typically accompanied by a list of verbs that were associated with a certain cognitive process (Stanny, 2016; Allen and Tanner, 2002; Crowe et al. 2008). Our finding suggest that we should use these prompts as a guide, rather than a definitive way to classify learning objectives. The five most frequently used prompt words were among the most spread, suggesting that prompt words are not associated with the cognitive process used. This may be due to the influence of context: a single word can be contextualized in a variety of ways to ask very different cognitive processes (Stanny, 2016). The prompt "what," for example, is typically posed to prompt *Remembering* information (e.g. "what does DNA stand for?" or "what is the central dogma?"). Given the right context, however, "what" can be used to test a variety of cognitive processes outside of simply *Remember*. "What conclusion can you draw from this graph?" asks students to *Understand* instructional information. "What criticisms might you give to this procedure?" prompts students to *Evaluate*. Even prompts such as "Describe," that may seem more specific, can be contextualized in a similar manner (Anderson and Krathwohl, 2001): "Describe the relationship between x and y given the data show above" (*Understand*), "Describe what you like and what you would do differently given the procedure and results" (*Evaluate*). These results emphasize the importance of context to suggest the cognitive action, rather than the presence of a single word.

Implications for Teaching

The revised taxonomy can aid in addressing the well documented misalignment between course objectives, instruction, and assessment in biology in the last decade. While instructors intend to deepen biological understanding, and build cognitive skills, assessments of such objectives tend to fall short by largely emphasizing the importance of rote memorization, or *Remember Factual knowledge* (Crowe et al., 2008; Zheng et al., 2008; Momsen et al., 2010; Jensen et al., 2014). While many educators recognize the importance of problem solving, few tailor their instruction and assessment towards developing these skills (Paul et al., 1997). Our hope is that this biology-specific rubric equips instructors with detailed guidance on how they can assess these objectives they intend. For students, this tool is a means for transparency with their teachers, allowing clarity of learning expectations and outcomes.

Multiple publications of national standards in STEM continue to emphasize the need for scientists with skills that go above and beyond capabilities of mere memorization, and harness skills of problem solving and critical thinking (Bransford et al., 1999; NRC, 2012; NRC, 2013; NASEM, 2018). As graduates advance from classroom to the workplace, they must transfer their skills and knowledge into real-world problem solving by demonstrating their capacity to *Apply, Analyze, Evaluate* and *Create*. How do we push students to go outside of their comfort zone to successfully demonstrate skills and knowledge that national standards urge? Alongside the revised taxonomy, instructors can experiment with manipulating context to vary their assessments. As the results revealed, context does not take the shape as a single prompt word or phrase, but the surrounding cues and details in the question that dictates the cognitive skill and knowledge deployed by students (Crowe et al., 2008; NASEM, 2018). Challenging students with questions that facilitate problem-solving allows them to make their own meaningful connections and build complexity of their own understanding of biology. With the proper instruction to push for meaningful learning, students can learn how to use this information to translate into deeper, meaningful, and long-lasting learning.

Training students how to successfully demonstrate both skill and knowledge requires feedback. Students enter classrooms with different levels of prior knowledge and experience with biology, and for this reason, the demonstration of certain skills or knowledge may be more challenging for some than others. Thus, for all students to integrate meaningful integration of these skills, instructors must be clear of their expectations in student response, whether this be individual comments, providing a rubric, showing examples in class, or teaching them how to use the revised taxonomy. With more practice and the right tools such as the revised taxonomy to guide these practices, students can leave the classroom prepared and confident in their careers.

Chapter 2, in full is currently being prepared for submission for publication of the material as it may appear in CBE Life Sciences, 2019. The thesis author was the primary investigator of this paper.

Chapter 2 is coauthored with Yee, Alexander and Larsen, Victoria. The thesis author was the primary author of this chapter.

CHAPTER 3: Implications of Biology Assessments Using Bloom's Revised Taxonomy

The goal of this study is to understand how the categories within each dimension associate with each other in biology assessments. There may be multiple types of knowledge and cognitive actions involved in solving a single item alone. We were interested in mapping out all types of knowledge and cognitive processes involved when solving a given test items. Using these data, we hope illustrate how categories within each dimension associate with each other to inform instructors and students.

METHODS

Coding Scheme

Coders classified each test item using a biology-specific articulation of Bloom's revised taxonomy (in preparation for submission to publish; Table 1). Each coder mapped a series of steps reflecting their thought process to solve each test item in a concept map or table format. Every step was then classified with a single type of knowledge and cognitive process. Coders made two additional specifications in their coding scheme: 1) items that prompt students to *Understand* inherently requires them to *Remember*, and 2) *Conceptual knowledge* is built from *Factual knowledge*. Rational for these stipulations can be found in the Discussion.

A subset of test items (n=128) was taken from a large dataset consisting of assessments from multiple sources including biology portions from standardized tests, such as the MCAT and AP, as well as upper and lower division biology course assessments from a private, medium-size research university with very high research activities in the

Midwestern United States (McCormick, 2005). Items in this sample reflect variation in formatting (e.g. multiple choice and free response), discipline, and difficulty.

Two primary coders were involved in the classification of test items. Coder 1 was an undergraduate student who completed at least half of the introductory biology course sequences for her major at the beginning of the project. Undergraduates are especially suited for this type of project because they are proximal in expertise to students who would encounter these problems on exams or standardized tests. Coder 2 was a graduate student in the biology division. Having completed both lower and upper division biology courses in her undergraduate, she provided proximal expertise for the classification of test items. Coder 3 was a professor at a four-year research institution who engaged in the initial literature associated Bloom's taxonomy as well as subsequent discussions when comparing codes. This coder was consulted when there was uncertainty in classification and provided supplemental theoretical frameworks for distinguishing between ambiguous categories in the taxonomy to justify a given code.

Interrater reliability was calculated by averaging an agreement rating out of 10. For any given test item, each category of knowledge and cognitive process received either a 1, reflecting agreement between coders, or 0, signifying a difference in code. These numbers were totaled, with 10 signifying perfect agreement between coders across all categories. These scores were averaged to give an overall score for interrater reliability.

Data Analysis

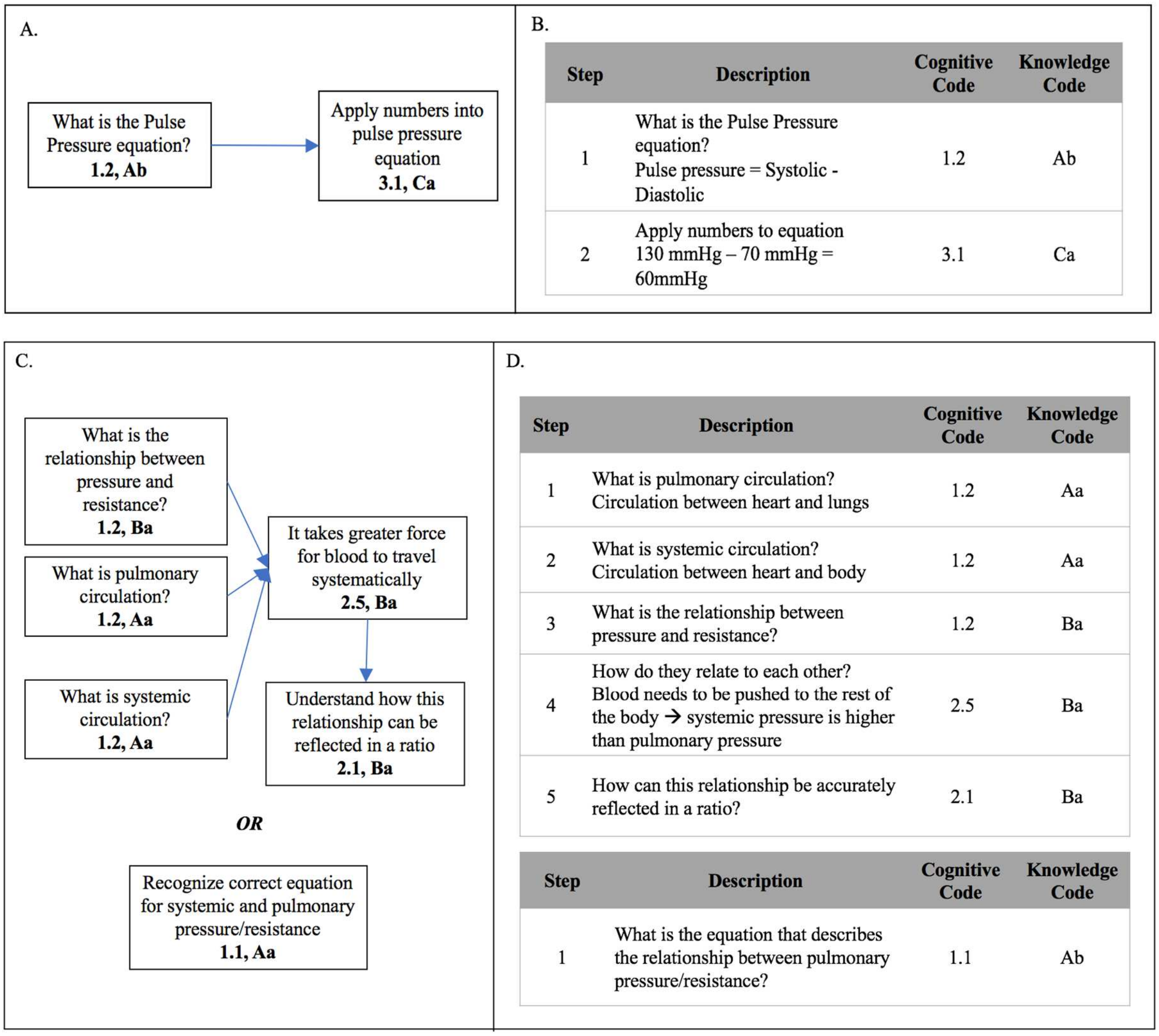
Coders marked the different categories of knowledge and cognitive processes that were used to solve each test item, similar to the Taxonomy Table proposed by the authors of the revised taxonomy (Anderson and Krathwohl, 2001). This means that a question that requires students to *Remember* multiple bits of *Factual knowledge*, for example, would be marked the same as a question that only necessitates recalling one fact. After marking the taxonomy table, we formatted the codes into a Venn diagram to illustrate the relational associations between categories of each dimension.

RESULTS

Thought processes took multiple forms in the coding process, varying from question to question. Mapping out thought processes in student answers can be illustrated in concept maps or a table format (Fig. 8). Consider Figure 8A, illustrating a linear concept map, where ideas follow a distinct path to explain a process. Other questions involved multiple ideas coming together to inform their answer (Fig. 8B).

Both coders attempted to consider multiple ways in solving a single question, in which multiple thought processes were recorded. In Figure 8C, there are two possibilities when solving this item, one more complex than the other. This duality highlights the potential difference in how an instructor intends a problem to assess certain objectives, and how a student might approach the same item.

Coding is an iterative process; we continued to refine the coding scheme to ultimately outline the biology-specific revised taxonomy (in preparation for submission). There were significant modifications made to the theoretical framework that took place after Coder 1's analysis, while Coder 2 began the coding process with a much more solidified coding scheme. Despite these differences in coding, interrater reliability scores remained high (8.7/10). As Coder 2 closely aligns with our articulation of the revised taxonomy in a biology context, our findings are more clearly reflected in Coder 2's classification (Fig. 9).



Step	Description	Cognitive Code	Knowledge Code
1	What is the Pulse Pressure equation? Pulse pressure = Systolic - Diastolic	1.2	Ab
2	Apply numbers to equation 130 mmHg – 70 mmHg = 60mmHg	3.1	Ca

Step	Description	Cognitive Code	Knowledge Code
1	What is pulmonary circulation? Circulation between heart and lungs	1.2	Aa
2	What is systemic circulation? Circulation between heart and body	1.2	Aa
3	What is the relationship between pressure and resistance?	1.2	Ba
4	How do they relate to each other? Blood needs to be pushed to the rest of the body → systemic pressure is higher than pulmonary pressure	2.5	Ba
5	How can this relationship be accurately reflected in a ratio?	2.1	Ba

Step	Description	Cognitive Code	Knowledge Code
1	What is the equation that describes the relationship between pulmonary pressure/resistance?	1.1	Ab

Figure 8. Examples of student thought processes in biology assessments. Some items involve a sequence of steps (A-B), while others involve an intricate network of individual ideas coming together (C-F). Some items can be approached in different ways (E, F). Thought processes can be diagrammed in concept maps (A, C, E, F) as well in tabular form (B, D).

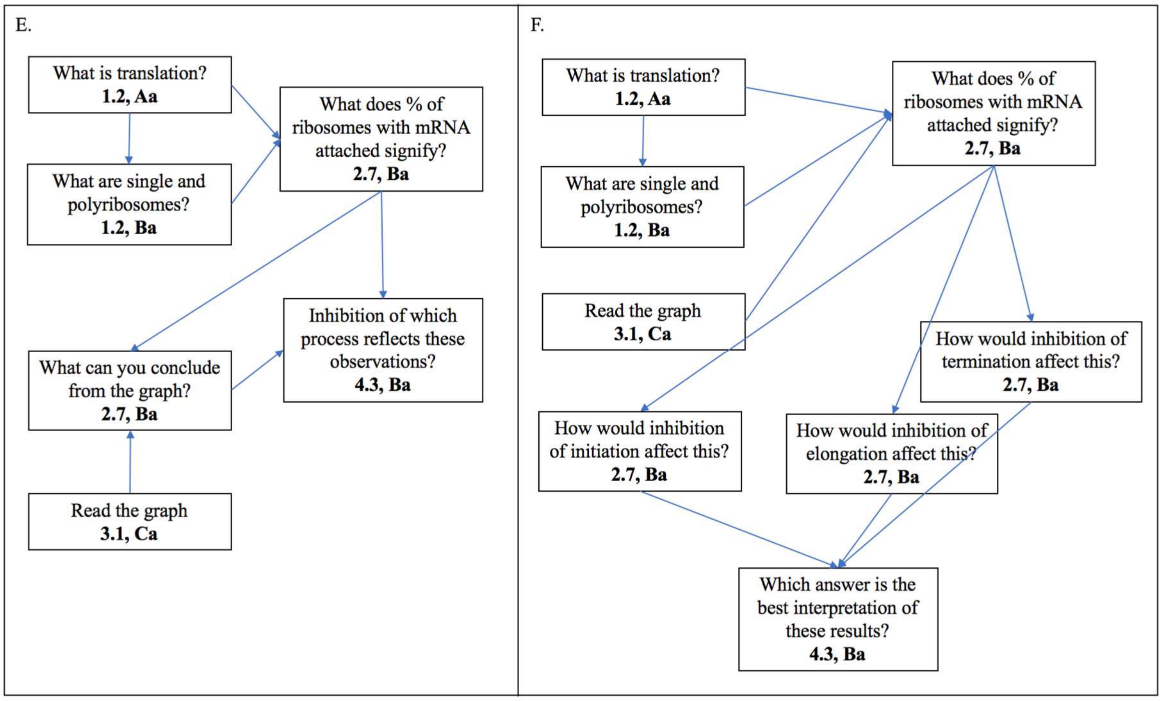


Figure 8. Examples of student thought processes in biology assessments, Continued. Some items involve a sequence of steps (A-B), while others involve an intricate network of individual ideas coming together (C-F). Some items can be approached in different ways (E, F). Thought processes can be diagrammed in concept maps (A, C, E, F) as well in tabular form (B, D).

Exhaustive coding of the sample (Fig. 9) revealed a strong association between the processes *Remember, Understand*, and *Analyze*. In other words, questions that prompt students to *Analyze* simultaneously involved *Understanding* and *Remembering* information in their solution. Similarly, in the knowledge dimension, *Factual knowledge* is concurrently consulted when students draw from *Conceptual knowledge*.

Both *Procedural knowledge* and the cognitive action *Apply* do not fall systematically within this association. About a third of the questions that asked students to *Apply*, only entail that they *Remember* information and not *Understand* it. A similar proportion of questions that drew from *Procedural knowledge* was associated with *Factual knowledge*, and not *Conceptual knowledge*.

There were very few questions that prompted students to *Create* knowledge (n=4) as well as *Analyze* information (n=6), and no questions in the sample prompted students to *Evaluate*. To confirm where these categories lie within the cognitive processes domain, coders went back to the large dataset to code at least 10 questions for each category (Fig. 9). Note that while the relative sizes of each circle vary between diagrams as an artifact of the sample, the structure and placement of the categories remains the same. The structure of the knowledge dimension remained unchanged.

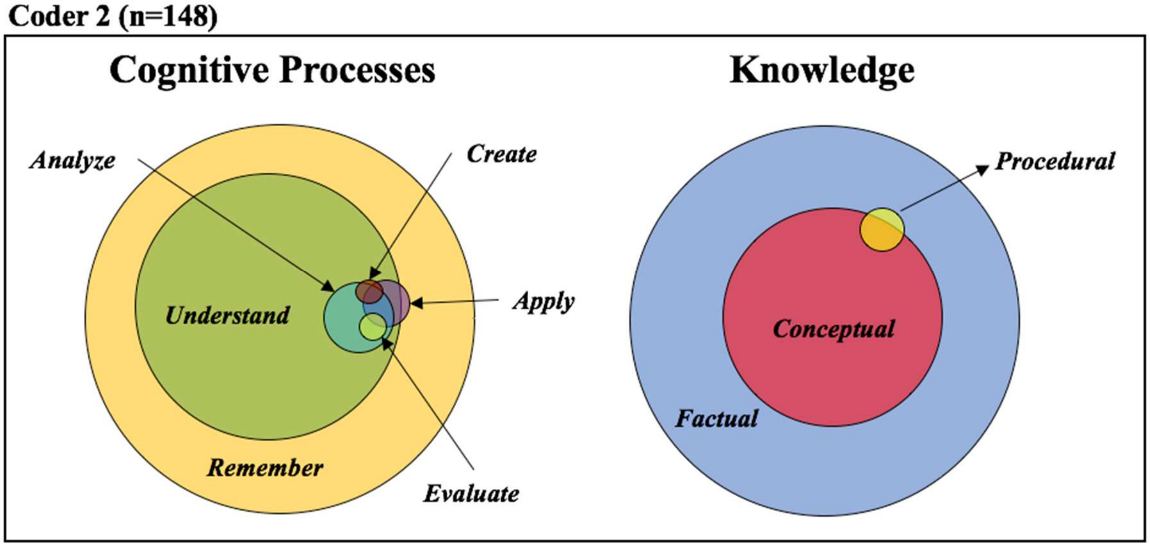


Figure 9. Biology test items that ask students to *Analyze, Evaluate*, and *Create* simultaneously involve two or more cognitive processes. Biology assessments (n=148) from standardized tests, upper and lower division undergraduate courses were coded using a biology-specific articulation of Bloom's revised taxonomy. Past literature designated one learning objective to each test item; however, this study coded for all types of knowledge and cognitive processes involved in solving a single question. Items that drew from *Procedural* and *Conceptual knowledge* also drew from *Factual knowledge*.

With *Evaluate* items, students concurrently *Remember, Understand*, and *Analyze*. Only a few of these items with some questions involving *Apply*. *Create* items asked students to simultaneously *Remember* and *Understand* at a minimum, while varying implications to *Apply* or *Analyze* in the solution. While *Analyze*, *Evaluate* and *Create* were among the least tested in this sample, these cognitive actions involved three or more processes, and at times, all three types of knowledge.

DISCUSSION

Refining the Coding Scheme: **Understand** *Simultaneously Implies* **Remember**

In following the biology-specific revised taxonomy, we came across two recurrent questions: 1) Is it possible to *Understand* without *Remembering* any information? And 2) Can one draw upon *Conceptual knowledge* in isolation, without *Factual knowledge*? There's a fine line between categories that is often hard to distinguish (Anderson and Krathwohl, 2001); however, supporting literature suggests certain refinements in our coding scheme that were kept constant.

Firstly, to *Understand* or extrapolate "instructional meaning" from a test item (Anderson and Krathwohl, 2001), students *Remember* the terms, concepts, or procedures that the question refers to. In this way, students inherently *Remember* to *Understand*. This was demonstrated in a 2014 study where students in an introductory biology course who were quizzed on higher level cognitive skills had better factual recall than those who were tested on recall alone (Jensen et al.). We concluded that it all questions require some recollection, whether it be the initial steps in a thought process or the final. In other words, questions that ask to *Understand* inherently prompts them to *Remember* information in their thought process.

Similarly, larger concepts are supported by facts (Bransford et al., 1999; NASEM, 2018; Anderson and Krathwohl, 2001). Take for example a question referring to the central dogma. Is it possible to think of the central dogma without acknowledging its constituent processes and components (e.g. transcription, translation, DNA, or RNA)? Though implicit, this factual reference demonstrates the necessity of *Factual knowledge* to support any construction of meaningful *Conceptual knowledge.* Seeing these trends in the coding process, this connection between both types of knowledge was then solidified. In this way, coders inferred that *Conceptual knowledge* is built on *Factual knowledge*.

Coders did, however, find exceptions to these specifications in the coding scheme. There were several items from the MCAT that demonstrated how students might draw from *Conceptual knowledge* alone, and *Understand* without the need to *Remember*. These items tend to provide substantial detail to contextualize novel situations by defining all relevant terminology. This, in turn, relieves the stress on students to *Remember Factual knowledge*, leaving them to think conceptually. Though these items tend to emphasize conceptual thinking and “higher order” cognitive skills (Zheng et al., 2008), reading through these questions can be time consuming. As these questions are not reflective of the typical assessments of the larger sample, these items were omitted from our results.

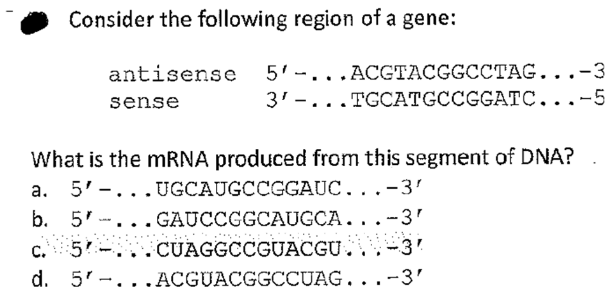
Limitations

Although two coders were involved in the classification of all items, only one coder adhered to the updated theoretical framework of the biology-specific revised taxonomy. This study could have had multiple coders to assure consistency and reliability; however, our goal was not to draw a universal representation to reflect all biology test questions. Rather, our aim was to exemplify possibilities of how students think and approach test items. Instructors can devise similar methods to discern their students’ thought processes. Students can answer questions in a step-by-step manner, whether it be outlining steps in table format or in concept maps. This methodology makes it easy to point out misconceptions and areas of improvement for cognitive skills.

Coders must make inferences about the intent of each test item during the classification process (Anderson and Krathwohl, 2001; Crowe et al., 2008; Bloom et al., 1956). Apart from standardized test items, potentially all questions solely assess students' ability to *Remember Factual knowledge* if the same question is presented in class (Allen and Tanner, 2002). Test items analogous to those reviewed in class might suggest the use of different types of knowledge or cognitive skills, as they are no longer novel to students. Coders approached each question as if it was novel to the student; however, this can be confirmed with subsequent classroom observations, and interviews with instructors and students in future studies (Anderson and Krathwohl, 2001).

***Analyze* Items Simultaneously Prompt *Understanding* and *Remembering* Information**

Empirical studies of the hierarchical structure of the original taxonomy suggested slight support for a cumulative hierarchy between *Comprehension* (*Understand*), *Application*, and *Analysis* (Kreitzer and Madaus, 1994; Anderson and Krathwohl, 2001). Our data, however, revealed that students' ability to *Analyze* information is not contingent on their ability to *Apply* it. Instead, items that asked students to *Analyze* simultaneously deployed both *Understand* and *Remember,* and rarely *Apply*.



Consider the following region of a gene:

antisense 5′-...ACGTACGGCCTAG...-3′
sense 3′-...TGCATGCCGGATC...-5′

What is the mRNA produced from this segment of DNA?

a. 5′-...UGCAUGCCGGAUC...-3′
b. 5′-...GAUCCGGCAUGCA...-3′
c. 5′-...CUAGGCCGUACGU...-3′
d. 5′-...ACGUACGGCCUAG...-3′

Figure 10. Some items that prompt students to *Apply Procedural knowledge* do not involve the cognitive task *Understand* or draw from *Conceptual knowledge*.

When students *Apply* knowledge, they concurrently *Remember* information and at times, *Understand* it. Similarly, when students draw from *Procedural knowledge*, *Factual knowledge* is always simultaneously consulted, while *Conceptual knowledge* is consulted most of the time. For questions that *Apply Procedural knowledge* without simultaneously *Understanding Conceptual knowledge*, consider a test item that asks to transcribe a fragment of DNA (Fig. 9). To start, students must make sense of the illustration itself by *Remembering* terms such sense, antisense, and mRNA. Students can then *Apply* their *Procedural knowledge* of how transcribe DNA to mRNA. As transcription is systematic, there is no need for students to make connections (*Understand*) or draw from deeper *Conceptual knowledge* to inform their selection from the possible solutions.

Why is it that *Applying Procedural knowledge* does not have a concrete, established network like *Analyze Conceptual knowledge*? The revised taxonomy suggests that the types of knowledge are ordered on a spectrum of concrete (*Factual*) to abstract (*Metacognitive*); however, it is possible that some *Procedural knowledge* is more concrete than the most abstract concepts (Anderson and Krathwohl, 2001). The example above is one such case in which students can follow a concrete, straight forward procedure without needing to reference deeper *Conceptual knowledge*. When considering the cognitive dimension, *Apply* is highly associated with *Procedural knowledge* (Anderson and Krathwohl, 2001) which can explain the similar number of questions that involve *Apply* or *Procedural knowledge*.

When looking at the remaining cognitive processes, our results parallel the hypotheses of Anderson and Krathwohl (2001) who suggested that *Analyze*, *Evaluate* and *Create* can help advance "lower-order" cognitive processes, such as *Remember*, *Understand*, and *Apply*. When students are prompted to *Evaluate*, for example, the cognitive actions *Remember, Understand,* and *Analyze* were often implied. Similar trends are seen with *Create*. As the categories in the cognitive processes dimension supposedly reflected a hierarchy "relative difficulty" (Anderson and Krathwohl, 2001), these data support this statement by suggesting *why* this might be the case. Cognitive processes, such as *Analyze, Evaluate*, and *Create*, are complex because they simultaneously involve multiple types of knowledge and cognitive actions, such as *Remember*, *Understand*, and *Apply*, in a variety of combinations.

Although these items involved several categories of knowledge and cognitive process, they were also the least tested in our sample, consistent with the existing literature in biology using the original taxonomy (Jensen et al., 2014; Momsen et al., 2010; Zheng et al., 2008). This may have to do with the issue of time. From the instructor's perspective, these questions can be difficult to write and take much more time to grade (Paul et al., 1997; Lord and Baviskr, 2007; Lemons and Lemons, 2013; Bissell and Lemons, 2006; Crooks, 1988), as these items were mostly free response. Instructors must also be cognizant of how much time students take to craft their answers during their assessment, as opposed to selecting from the answers provided in a multiple-choice format.

Implications for Instruction

Given the structure underlying both the knowledge and cognitive actions, do these findings support a cumulative learning progression? In other words, do these data perpetuate the need for students to *Remember* all *Factual knowledge* to demonstrate other objectives? We don't think so. Though all items, no matter the format or difficulty, simultaneously involve some form of *Remembering Factual knowledge*, this does not suggest that students must "master" the recall of all information, as proposed in the original taxonomy. Rather, these findings emphasize the importance of learning in context to demonstrate "higher-order" learning objectives. Students need not know *all* facts to perform cognitive tasks such as *Analyze* or *Evaluate*, just the *right* ones to make the *right* connections, and so forth.

Our data supports the assertion that assessing cognitive actions, such as *Analyze*, *Evaluate*, and *Create*, students inherently utilizes skills such as *Remember* or *Understand* to carry out these processes (Jensen et al., 2014; Anderson and Krathwohl, 2001; Bloom, 1994). Though scarcely tested, as evident in past literature (Momsen et al., 2010; Zheng et al., 2008; Jensen et al., 2014) and our dataset, these processes imply the simultaneous involvement of multiple types of knowledge and cognitive actions, which is a hallmark for successful learning (NASEM, 2018). Moreover, demonstrating these skills is important in developing more abstract skills of problem solving and critical thinking, which is a central theme in the Next Generation Science Standards, AP biology, and *Vision and Change* framework. The application and regular practice of utilizing critical thinking is an essential skill needed to succeed in one's educational and professional career in STEM (NRC, 2013). Such skills often involve a combination of these actions and types of knowledge (Anderson and Krathwohl, 2001).

Recognizing the different types of learning objectives, the taxonomy gives instructors a guide on how to engage students in critical thinking. In the taxonomy, this involves students using higher order cognitive processes such as *Analyze, Evaluate,* or *Create*. Yet, time is of the essence when teaching a course, and it is up to the instructor as to how to split her time between teaching content knowledge and manifesting diverse types of knowledge and cognitive skills (Pickard, 2007; Momen et al., 2010; Anderson and Krathwohl, 2001; Crowe et al., 2008). This study highlights the complexity of cognitive actions and knowledge embedded in "higher-order" objectives in biology, and we hope this encourages instructors to explore these implications in their instruction and assessments.

Chapter 3, in full is currently being prepared for submission for publication of the material as it may appear in the American Biology Teacher, 2019. The thesis author was the primary investigator of this paper.

Chapter 3 is coauthored with Hinchey, Tiffany. The thesis author was the primary author of this chapter.

CHAPTER 4: DISCUSSION

> "The taxonomy offered easily understandable guidelines for expanding both curriculum and evaluation beyond simple knowledge is perhaps its greatest legacy… [but] The taxonomy is not perfect. Hence, it should neither be reified nor used blindly. When used to stimulate thinking about curriculum and evaluation, however, it has few peers." (Postlewaite, 1994).

The aim of this study was to explore how Bloom's revised taxonomy can be understood and applied to biology education. The first chapter was a theoretical study of the revised taxonomy, articulated through the lens of biology education, operationalized for student and instructor use in their assessments (Table 1). Subsequent classifications using this articulation found that most biology items tested students' ability to *Remember Factual knowledge* and *Understand Conceptual knowledge*, thereby encouraging educators to emphasize the use of deeper knowledge structures to perform cognitive skills such as *Analyze, Evaluate,* and *Create*, in alignment with the recommendations of national standards and core competencies (NRC, 2013; NASEM, 2018; AAAS, 2011). Prompt words within test items were not indicative of the cognitive process deployed, supporting the notion that context plays a larger role to prompt a specific cognitive task (Stanny, 2016). Finally, the second chapter revealed the complexity of both the knowledge and cognitive process dimensions when students solve biology questions. When coding for all possible types of knowledge and cognitive tasks involved in each item, *Procedural* and *Conceptual knowledge* were simultaneously associated with *Factual knowledge*. Items that prompted cognitive tasks such as *Analyze, Evaluate*, and *Create* involved three or more concurrent cognitive actions. Such implications provide a framework for instructors to consider when writing in their assessments, and students to consider when preparing for such assessments.

Considering these findings, perhaps the most important take away from this project informs a type of knowledge that was not observed in our data set: *Metacognitive knowledge*. In recent years, educators and researchers have come to understand that regular self-reflection and monitoring leads to successful, meaningful learning (Bransford et al., 1999; NRC, 2012; NASEM, 2018; Crowe et al., 2008; Tanner, 2012; Stanton et al., 2015). Yet, this idea metacognition is abstract, and therefore has been described in slightly different ways over the past four decades (Tanner, 2012; Veenman et al., 2006). Moreover, metacognition, self-regulation, and self-reflection are all interrelated terms that are often used interchangeably (Sebesta and Speth, 2017). For our purposes, we adhere to Anderson and Krathwohl's idea of metacognitive knowledge as "knowledge about cognition in general as well as awareness of knowledge about one's own cognition" (2001).

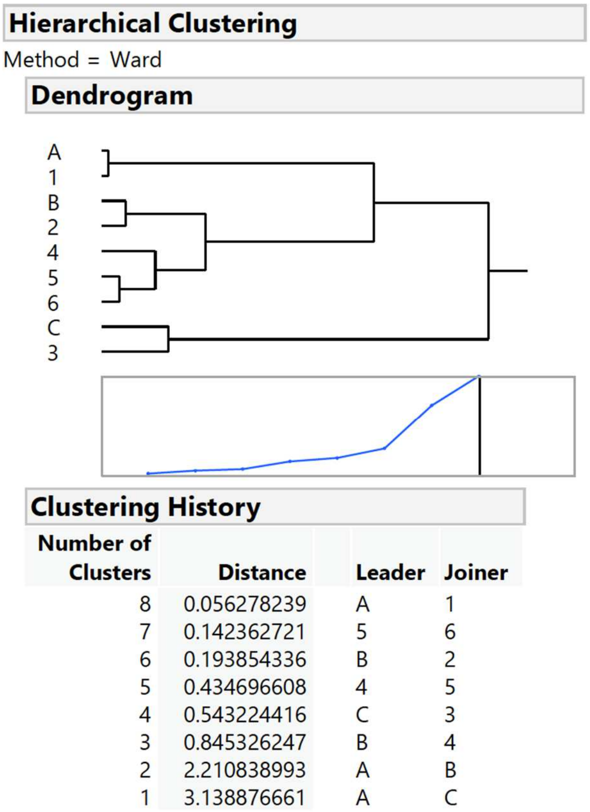
Students often do not develop metacognitive knowledge until college, as students are faced with responsibility to learn on their own for the first time (Dye and Stanton, 2017). The lack of experience with self-regulated learning may be perpetuated by the shared preconception that success in biology is heavily ingrained in one's ability to memorize information (Jensen et al., 2014), and reinforced by assessments that stress *Remembering Factual knowledge*, that continue to be prominent (NRC, 2007, 2012; Zheng et al., 2008; Momsen et al., 2010). Thus, when students are faced with novel situations that require them to apply their biological knowledge or think critically, a hallmark of thinking like a biologist (AAAS, 2011), students often struggle to succeed using existing study strategies and become discouraged (Dye and Stanton, 2017).

Bloom's revised taxonomy is a tool that allows students to take ownership and agency in their educational success by making them aware of the different combinations of knowledge and cognitive process, demonstrating distinct learning objectives. When students were asked to routinely classify assignment and test items in an undergraduate physiology course using the Blooming Biology Tool (BBT) based on the original taxonomy, students were made aware of the items they excelled at, as well as the ones that they needed to improve on (Crowe et al., 2008). This study went a step further by uncovering the underlying structure within both dimensions of the revised taxonomy. Thus, to successfully demonstrate one's ability to *Evaluate Conceptual knowledge*, for example, can involve any combination of *Remembering, Understanding,* or *Analyzing Factual* and *Procedural knowledge*. Being cognizant of these implications, in addition to the instructor's testing style and feedback from past assessments, students direct their learning to make the best use of their time preparing for a test (NASEM, 2018; Momsen et al., 2013).

The metacognitive benefits to understanding Bloom's revised taxonomy is not limited to students, instructors benefit as well. With every semester, every iteration, instructors can learn from their teaching experience. Anecdotally, they may find several activities, methods, assignments, and assessments that work well for them. On the other hand, there may be multiple instances where such strategies were unsuccessful. For instructors, Bloom's revised taxonomy is a resource that can guide instructors to teach with intention, reaching course objectives they find most important. With such intention in mind, instructors can systematically formulate learning objectives they aim to teach, be cognizant of class activities chosen to reinforce these objectives, and evaluate how their assessments demonstrate proficiencies in these objectives (Crowe et al., 2008). Given the need for students to develop and demonstrate problem solving and critical thinking skills, as evident through this study and past literature, biology instructors can use the revised taxonomy to evaluate their own practices through reflection: How can I engage with students to develop analytical skills? What activities can introduce the deep conceptual knowledge of a larger principle? Regular self-reflection allows the evolution of teaching practices (NASEM, 2018).

Monitoring skill development and self-regulation may be secondary to the material instructors want to teach. Nevertheless, to push the boundaries and past traditions of lecture-based teaching, instructors should be encouraged to introduce these ideas to students to facilitate pedagogical change. With the right tools, such as the revised taxonomy, we hope that both instructors and students are instilled with the confidence to take on this challenge.

APPENDIX



Hierarchical Clustering

Method = Ward

Dendrogram

Clustering History

Number of Clusters	Distance	Leader	Joiner
8	0.056278239	A	1
7	0.142362721	5	6
6	0.193854336	B	2
5	0.434696608	4	5
4	0.543224416	C	3
3	0.845326247	B	4
2	2.210838993	A	B
1	3.138876661	A	C

Appendix A. Cluster analysis of contingency table reveals close associations between knowledge and cognitive processes. *Remember* (1) and *Factual knowledge* (A) are the closest in association, suggesting that this cognitive action and knowledge type occur frequently together. This combination is followed by *Understand* (2) *Conceptual knowledge* (B).

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