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Learning is synthesizing seemingly divergent ideas and data.
- Terry Heick (Founder & Director of TeachThought)

Exam design: To assess the application of the course material in addition to knowledge and comprehension

(Reading time: 16 minutes)

Each student's ability to apply the key course learnings, beyond just understanding the material, was assessed using a 30 question short answer, case-based exam design in a number of undergraduate and graduate courses (Table 1). Such a design provides a foundation for not only assessing each student's knowledge and comprehension, but also their higher-level thinking surrounding the major concepts being taught. Developing such higher-level thinking abilities (application, analysis, synthesis and evaluation), which requires critical and creative thinking, is a transferable skill which should be a central focus of the educational process. Hence, student assessments of these abilities are valuable to the student, professor and educational institution.

Background:
Assessment tools including exams (and tests) can serve a variety of objectives with the primary one being the evaluation and grading of students to verify their learning. These grades, in turn, provide course statistics for comparative purposes, support accreditation of qualified students, and provide feedback on the professor's teaching. In addition, exams can benefit the students: motivating them to review the course material for better comprehension, aiding in the identify areas of weakness which can be improved upon, and serving as an additional form of learning when the material is presented from a different perspective.[1] These objectives can only be effectively and efficiently achieved through the development and employment of a comprehensive, well-structured, objective, equitable and demanding assessment tool, which is the goal of this exam design.

[1] Preparing Tests and Exams. Centre for Teaching Excellence, University of Waterloo

Table 1: Example applications of the 30 question, short answer exam design.

Course	Structure	Questions	Cases
2018 Bachelors Science Biotechnology: Science & Business	120 minutes fixed 30 questions + bonus ~50 words/case	A: 10 of 11 B: 10 of 12 C: 10 of 13	Mini-cases within 1/3 of the individual questions to provide some context.
2019 Masters Biotechnology Biomaterials & Protein Chemistry	120 minutes + Any 30 of 35 questions + bonus ~100 words/case + a figure	A: 7 B: 5 C: 8 Four more: 3	A: Pharmacodynamics B: Design of a biologic C: Cell encapsulation 4: Liposomes, peptides, drug delivery, stem cells
2019 Masters Biotechnology Agriculture & Industrial Biotech	180 minutes allowed 30 questions + bonus ~500 words/case (full page => 6') + a figure	A: 13 of 14 B: 9 of 10 C: 8 of 10	A: Genetically modified crop trait B: Bioethanol C: Green chemistry synthesis

Higher-level thinking skills, as described in Bloom's taxonomy,[2] fall on a continuum beyond knowledge (the recalling of facts) and comprehension (the understanding of the facts) incorporating application (problem-solving), analysis (finding evidence), synthesis (combining elements) and evaluation (making judgements).[3] Various versions of Bloom's taxonomy are supplemented with lists of key words, actions and questions associated with each of these six levels of cognitive activity (Table 2). These lists are used to guide the development of the exam questions.

Exam Structure:
The core of the exam structure involves 30 short answer questions. Each question is subsequently marked out of 3, resulting grade out of 90. With this format, two hours (120 minutes) or an average of 3-4 minutes per question depending on the time required to read the cases has been found to be adequate for the vast majority of students. However, it is recommended to schedule the exam for a three hour block, while informing students that two hours will likely be sufficient. This relieves some of the unnecessary time pressure on students, so they can focus on demonstrating their thinking abilities as opposed to quickness to respond.

Building on the core exam, the basic exam structure comprises three sections, each led off by a 1- to 2- page case which requires approximately 6 minutes to read, followed by 12

[2] Schinkel, S.L. (2019, March 14). How do I love Bloom's Taxonomy…let me count the ways… [Blog post]. Retrieved from /mygrowthmindset.home.blog/2019/03/14/how-do-i-love-blooms-taxonomy-let-me-count-the-ways/

[3] Bloom's Taxonomy Teacher Planning Kit

Table 2: Bloom's taxonomy[4]

Definition	Verbs	Question Formats
Evaluation - make and defend judgements	Choose, compare, contrast, explain, predict	What are three advantages of …? Why would …?
Synthesis - compile ideas, propose alternatives	Arrange, design, explain,	Explain how… What would happen if …?
Analysis - break down ideas, provide evidence to support generalizations	Analyse, compare, contrast, list, choose, select, prioritise	Why was …? How is this similar to …? What are the features of …?
Application - apply knowledge to actual situations	Calculate, select, illustrate, interpret, solve, show	Show how …
Comprehension - understand the facts	Classify, compare, describe, explain, outline, predict	Briefly outline the three steps … How does …?
Knowledge - remember	List, name, define, label	List three ways … Name …

short answer questions, for which the student must complete 10, and only 10, of the 12. An additional 2-point bonus question has always been included. The answers are recorded right on the exam paper. Following a title page, each case is allocated 2 pages, followed by the 12 associated questions, 4-to-a-page with space and lines below each question. Leaving space on the exam paper gives an implicit indication of the expected length of the answers. As a result, the basic exam is 9 pages, double-sided (Title + 6 case pages + 9 question pages + bonus question page + blank back page). This basic exam structure is the recommended approach as it is simple and symmetric. Variations in the basic design include: more or fewer sections to better match the course structure/modules (e.g. 2 or 4), more cases (e.g replacing a larger case with two shorter cases in one or more sections), more choice among the questions (e.g. 10 of 13-14 questions), and non-symmetry in the number of questions per section (e.g. 12 of 14 + 10 of 12 + 8 of 10 = 30 of 36), all while mantaining the core exam structure.

[4] Adding rigor and technology into your lesson plans. (2015). *Bloom's Taxonomy: Teacher Planning Kit*. Adding Rigor and Technology Into your lesson Plans. Retrieved from http://techinfusedlessons.weebly.com/blooms-taxonomy-teacher-planning-kit.html

Case Structure:
Seven principles should guide the selection and building of the cases: 1) The cases should provide a rich story that touches on multiple aspects of the lectures. 2) Ideally, the cases should bridge two or more distinct aspects of the lecture material as it is at these intersections that problem-solving, synthesis and evaluation are often the richest. 3) The cases must be real situations and only include correct and accurate information. One way to simplify the research process is to base the cases on existing or proposed commercial or industrial processes as these tend to provide more detail, especially in the patent literature. Similarly, new approaches to an existing problem or issue are a good starting point. 4) It is easiest to base the cases on a particular published scientific paper or report and then supplement with additional background information as required. 5) Consider the cases as teaching moments in themselves where new and detailed information, approaches or applications are being presented. 6) Since "a picture is worth a thousand words," the inclusion of an appropriate figure or diagram is recommended. Frequently these need to be modified or redrawn to ensure they convey (only) appropriate information. 7) Finally, providing additional, extraneous information is acceptable as it makes the cases richer, however efforts need to be made to avoid omitting or providing misleading information. You want the students to demonstrate their abilities not your ability to trick them. Table 3 provides three actual examples of mini-cases.

Question Structures:
The exam questions should, of course, relate to the lecture material, especially the core concepts while leveraging the case material to trigger the correct thinking and responses. This is accomplished primarily by referencing aspects of the case in the question. For example, "How do Vistive Gold® soybeans (MON 87705) serves as an example of both transgenesis and cisgenesis (intragenesis)?" (Analysis/Easy).

The 12 or so questions relating to each case should also be a mix of the six levels of cognitive activity as outlined in Bloom's taxonomy (Table 2), as well as a mix of easier and more challenging questions. Indeed, in most cases these are correlated (Table 3). Employing the question formats associated with Bloom's taxonomy is invaluable here (Table 2). It is also recommended that each question be classified to verify that there is a good balance.

Consistent with the 3 point marking scheme, where possible questions should be design to have three part answers, such as: List three examples…, List three features…, Describe three ways…, and Give three possible reasons … Even if the expected answer has more or less than three parts, it is better to specify that than to leave the question too open, For example, "Briefly explain the four major steps in the development of Vistive Gold®

Table 3: Shorter case and question examples

Case and Question	Answer
Lignin, a wood component, is considered a potential source of non-petroleum-based platform chemicals for the synthesis of polymers, pharmaceuticals and other value-added chemicals. As a fuel, lignin has an estimated value of US$0.18/kg and if converted to useful chemicals US$1.08/kg or six times the value. The sources of lignin are pulp and paper (45 x10^9 kg/year) and cellulosic ethanol production (currently only 0.125 x10^9 kg/year). What is the major class of chemicals that can be derived from lignin? (Knowledge/Easier)	• The major class of chemicals derived from lignin are aromatics. Chemically, lignins are cross-linked phenolic polymers (phenylpropanoids) that form key structural materials in the support tissues of vascular plants and some algae. They are initially synthesized from the amino acid phenylalanine. Efforts are underway to develop efficient ways to derive bio-BTX (a mixture of benzene, toluene and xylene) and cyclohexanol from lignin.
D-glucose isomerase (correctly called D-xylose ketol-isomerase 5.3.1.5) is the largest commercial enzyme product with 10 x10^9 kg produced annually. It is primarily used in the conversion of glucose to fructose to produce high fructose corn syrup (HFCS) which is three times sweeter. HFCS is the major sweetener in soft drinks. Why is this reaction carried out at 60-65^{o}C with immobilized enzyme in a fixed-bed bioreactor? (Application/Medium)	• Higher temperature = higher reaction rate improving efficiency, • Immobilized enzyme = improved stability and hence lifetime. • Fixed-bed bioreactor = enzyme is retained and can be reused numerous times reducing costs.
On November 13, 2017 Brian Madeux, who suffers from Hunter syndrome, underwent the first ever *in vivo* gene editing treatment. Hunter syndrome is an X-linked deficiency in the iduronate-2-sufatase enzyme (IDS 3.1.6.13) resulting in the accumulation of heparin sulphate and dermatan sulphate causing a lysosomal storage disease. Sangamo Therapeutics Inc. treated him intravenously with SB-913 comprising three adeno-associated viruses (rAAV2/6) coding a pair of ~40 kDa (~1,100 bp each) zinc finger nucleases (ZFN) designed to work as a heterodimer to cleave a specific intronic region just downstream of the native albumin promoter, and a 61 kDa donor IDS enzyme with 5' and 3' sequences homologous to the albumin intron sequence (~2,300 bp). Briefly outline the strategies behind any three aspects of SD-913. (Analysis/Challenging)	• Delivered *in vivo* so IDS can be supplied to liver cells. • Three viruses = limited in the size of each insert so needed three: 2 nucleases and the donor IDS gene. • Adeno-associated virus (AAV) = demonstrated to be safe in humans and works in non-dividing cells. • AAV6 = transduces primary human hematopoietic stem cells (HSCs) a good host to express the desired IDS. • Zinc-finger nucleases = cleave the human DNA at one specific site, one of the older, established technologies that does this. • Heterodimer = to target a non-palindromic DNA site. • Albumin promoter = strong and constitutive expression. • Albumin intron site = known site, within the highly expressed albumin gene. • Donor IDS enzyme with homologous regions = provides a system (HDR) to integrate the new gene at the cleavage site.

soybeans." (Comprehension/Medium) is a better construct than "Explain how Vistive Gold® soybeans were developed." In other cases, such as the transgenesis/cisgenesis question described earlier, the question implies the number of parts expected in the answer (in that case two).

Grading Process:
To mark these exams, a five step process is recommended: 1) An answer key is developed for each question. The key points (frequently three) are recorded as well as likely part answers and in some cases anticipated incorrect answers. 2) A scoring system comprised of a series of 0's, 1/2's or 1's is assigned to each component or partial component of each answer. In some cases the total score may exceed 3 where alternate answers are feasible or acceptable. 3) Approximately 20% of the exams (8 in a class of 40) are marked from start to finish using the key and scoring system. If any additional correct or partially correct answers are uncovered, they are added to the key. 4) The first page/4 questions of each exam is then marked with the previously marked 20% being included and potentially remarked as well. Again, if any additional correct or partially correct answers are uncovered, they are added to the key. This is both faster as the questions and correct answers can be committed to memory (it requires approximately 1 minute/page of 4 questions to mark), and it minimizes bias, as each page is marked somewhat blindly to the author and independently from previous or subsequent pages. 5) Finally, all the scores are entered into a spreadsheet and the totals by section and overall are calculated. In addition, the average and standard deviation of each question is calculated. In those cases where the average is below 2 out of 3 (difficulty) and/or the standard deviation is greater than 1 (discrimination), the question is examined to ensure that it was error-free, clear (i.e. not misleading) and fair (i.e. reasonable). In one or two cases, a question may be deemed unfair or difficult. In those cases, the scores of the students are maintained (i.e. the numerator) but the test total score (i.e. the denominator of 90) can be adjusted down as appropriate. For example, if the majority of students received 2 out of 3 on a specific question and it was determined that few if any identified the third point, the exam would be adjusted to be graded out of 89. Fortunately most grading software will perform this calculation automatically, so the raw scores for each student do not need to be altered.

Conclusion:
This 30 question short answer case-based exam design involves a significant effort to develop given the case research and question development required. Nevertheless, it has been found to be effective in not only assessing each student's knowledge and comprehension, but also their higher-level thinking surrounding the major concepts in a number of University science courses. Informal student feedback indicates that this type of exam is seen as a fair and appropriate assessment tool, with the focus being on applying facts and concepts as opposed to memorizing them (often in a vacuum). However this design would benefit from a more formal and thorough assessment.