Chapter 2

Course Design: Making Choices About Constructing Your Course

Designing or redesigning a course can be a creative and rewarding effort, but it is always a challenge. Science is characterized by continuous change and an ever-growing (and already large!) body of knowledge, and our courses often seek to help students understand the core knowledge, experimental tools, and ways of thinking in a field. It's a big task. Further, a course may play a particular role in the curriculum, serving as a prerequisite, a capstone, or *the course* in which students learn a particular skill. How do you pick what to focus on, and how do you organize your course to help your students be able to transfer their knowledge to a new setting? How can you design the course to help your students build a conceptual framework that can expand and grow as their understanding grows? This chapter describes six principles to guide your course design and provides suggestions for more detailed resources (Box 2.1).

BOX 2.1 Course Design: An Overview

Consider the Big Picture

Identify the key learning goals for the course.

Identify one or two big questions that help students see the interest and ongoing importance of the course.

Emphasize the conceptual organization of the course.

Link the Big Picture to Practical Elements

Develop graded assignments that align with your learning goals.

Incorporate formative as well as summative assessments.

Let your learning goals drive your choice of teaching approaches.

WHAT ARE PRINCIPLES TO GUIDE COURSE DESIGN?

Consider the Big Picture

1. *Identify the key learning goals for the course.*

   We often begin thinking about our courses by considering the content we need to cover. It's how our departmental curricula, our textbooks, and

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even our journals are organized, and it seems natural to start from that perspective. It can be transformative, however, to ask instead what you want your students to be able to do at the end of the course. This question often leads us to think about the big ideas that underpin the course material and how students should be able to use them. For example:

- A genetics course might ask students to be able to describe the mechanisms by which an organism's genome is passed on to the next generation and to predict how the different mechanisms affect the frequency of different types of genetic disorders.
- A physics course might ask students to be able to translate a physical description of a problem to a mathematical equation that can help solve it, and to be able to articulate their expectations for the solution.
- An organic chemistry course might ask students to be able to depict the three-dimensional structure of organic compounds, be able to predict thermodynamically preferred conformations, and to describe how this might affect the rate of a reaction.
- Any science class might ask students to be able to interpret data to draw conclusions and to relate this process to how the field builds knowledge.

In all cases, the course content is essential, but the focus is shifted to consider what the students should be able to do with the content. That shift can help both the instructor and the students. It can help the instructor consider what is really important for students to carry away from the course and what activities can help them reach that goal. It can help students understand not only what they're going to learn, but also why it should matter and what they can do with it. A focus on learning goals, in other words, is a way to explain why what we're doing in the course matters.

Into what categories do learning goals fall? It can be helpful to recognize that learning goals may fall into different categories (Bloom et al., 1956). The most familiar is the cognitive domain, which encompasses the types of intellectual knowledge and skills targeted in the learning goal examples provided above. We may also, however, have goals related to our students' attitudes, motivations, and values. For example, we may want our students to feel empowered to extend their own learning or to value evidence-based claims. Goals like these fall within the affective domain that relates to feelings, values, appreciation, motivation, and attitudes. Finally, we may have goals that require physical movement, coordination, and motor skills, and therefore fall within the psychomotor domain. These skills can range from accurate pipetting, to use of an intricate lab instrument, to specific clinical techniques, and are often critical elements of particular professional progressions. Being explicit about our goals in the affective or psychomotor domain as well as the cognitive domain can help ensure that we build them into the course.

Melanie Cooper and colleagues provide a valuable starting point for identifying learning goals in undergraduate biology, chemistry, and physics courses (Laverty et al., 2016). Using the National Research Council's (2012) *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* as a starting point, they identify seven scientific practices (Table 2.1) and eight crosscutting concepts (Table 2.2) from the three disciplines as well as core ideas for each that translate to the undergraduate college classroom (Table 2.3). While the work has a solid basis in the NRC's report and was carried out to create a tool for the development of assessment tasks, their adaptations and refinements produce a resource that is particularly valuable for undergraduate instructors considering their learning goals in these disciplines.

How many learning goals should a course have? It is often useful to shape a course around a relatively small number of learning goals that focus on key ideas—perhaps as few as three, perhaps as many as ten. Within the course, however, it is valuable to generate "topic-level learning objectives" that spell out what students should be able to do within different parts of the course at a more granular level. Each of these topic-level learning objectives is associated with a course goal, and can help provide guidance to both the instructor and the student as they think about how

TABLE 2.1 Scientific Practices

Asking questions: Generating scientific questions about a real world event, observation, phenomenon, data, scenario, or model.
Developing and using models: Constructing and/or using a mathematical, graphical, computational, symbolic, or pictorial representation to explain or predict an event, observation, or phenomenon.
Planning investigations: Designing an experimental method or identifying a set of observations that can be used to answer a scientific question or test a claim or hypothesis.
Analyzing and interpreting data: Given a question, claim, or hypothesis and relevant data, analyzing the data and interpreting the meaning.
Using mathematics and computational thinking: Using mathematical reasoning or a calculation to interpret an event, observation, or phenomenon.
Constructing explanations and engaging in argument from evidence: Providing reasoning based on evidence to support a claim.
Evaluating information: Making sense of information or ideas.

Source: Adapted from Laverty, J.T., Underwood, S.M., Matz, R.L., Posey, L.A., Carmel, J.H., Caballero, M.D., et al., 2016. Characterizing college science assessments: the three-dimensional learning assessment protocol. PLoS ONE 11(9), e0162333.

TABLE 2.2 Crosscutting Concepts

Patterns
Identifying patterns or trends emerging from three or more events, observations, or data points.
Cause and Effect: Mechanism and Explanation
Identifying mechanistic links between cause and effect.
Scale
Comparing objects, processes, or properties across size, time, or energy scales to identify relevant interactions.
Proportion and Quantity
Predicting the response of one variable to changes in another or identifying the relationship between two or more variables from data.
Systems and System Models
Defining a system, its relevant assumptions and surrounding, and how the system and surroundings interact with each other.
Energy and Matter: Flows, Cycles, and Conservation
Describing the transfer or transformation of energy or matter within or across systems, or between a system and its surroundings, with explicit recognition that energy and/or matter are conserved.
Structure and Function
Predicting or explaining a function or property based on a structure, or describing what structure would lead to a given function or property.
Stability and Change
Determining (1) if a system is stable and providing the evidence for this; or (2) what forces, rates, or processes make a system stable (static, dynamic, or steady state); (3) under what conditions a system remains stable; (4) under what conditions a system is destabilized and the resulting state.

Source: Adapted from Laverty, J.T., Underwood, S.M., Matz, R.L., Posey, L.A., Carmel, J.H., Caballero, M.D., et al., 2016. Characterizing college science assessments: the three-dimensional learning assessment protocol. PLoS ONE 11(9), e0162333.

they will reach the course's broad learning goals during the semester. Examples are provided in Table 2.4, and the Spotlight on Bloom's taxonomy and learning objectives provides more detailed guidance.

Is there evidence that using learning goals helps students learn? Jeffrey Froyd identified the use of learning goals as one of eight promising practices in undergraduate STEM education in a white paper for the National Academies' Board of Science Education (Froyd, 2008). He noted that there is a dearth of studies comparing courses with and without

TABLE 2.3 Core Ideas for Biology, Chemistry, and Physics

Biology Core Ideas	Chemistry Core Ideas	Physics Core Ideas
Chemical and physical basis of life: Life processes are the result of regulated chemical and physical interactions and reactions governed by the laws of physics. *Matter and energy:* Free energy and matter are used in regulated processes that establish order, support growth and development, and control dynamic homeostasis. *Cellular basis of life:* Cells are the fundamental units of all living things. *Systems:* Ecosystems, organisms, tissues, and cells act as systems. *Structure and function:* The functions and properties of ecosystems, organisms, tissues, cells, and biological molecules are determined by their structures. *Information flow, exchange, and storage:* Hereditary information is stored, used, and replicated. *Evolution:* Evolution drives the diversity and unity of life.	*Electrostatic and bonding interactions:* Attractive and repulsive electrostatic forces govern noncovalent and bonding (covalent and ionic) interactions between atoms and molecules. The strength of these forces depends on the magnitude of the charges involved and the distances between them. *Atomic/molecular structure and properties:* The macroscopic physical and chemical properties of a substance are determined by the three-dimensional structure, the distribution of electron density, and the nature and extent of the noncovalent interactions between particles. *Energy:* Energy changes are either the cause or the consequence of change in chemical systems, which can be considered on different scales and can be accounted for by conservation of the total energy of the system of interest and the surroundings. *Change and stability in chemical systems:* Energy and entropy changes, the rates of competing processes, and the balance between opposing forces govern the fate of chemical systems.	*Interactions can cause changes in motion:* Changes in an object's motion are the result of interactions between it and one or more other objects. Multiple interactions between an object and its surroundings can result in a predictable change in motion. *Energy is conserved:* Energy comes in many forms and can be transformed from one form to another within a given system or transferred between systems. *Exchanges of energy increase total entropy:* Multiparticle systems tend toward states that are more statistically likely to occur. At a macroscopic scale, this can be described by concepts such as entropy, temperature, and pressure. *Interactions are mediated by fields:* Fields are generated by charges/masses. Fields affect charges/masses. In circuits, fields induce currents. *Energy, momentum, angular momentum, and information can be transported without a net transfer of matter:* Mechanical waves move through matter. Electromagnetic waves can move through vacuum or matter. Properties of waves can be used to parameterize the information or amount of energy, momentum, or angular momentum is transported.

Source: Adapted from Laverty, J.T., Underwood, S.M., Matz, R.L., Posey, L.A., Carmel, J.H., Caballero, M.D., et al., 2016. Characterizing college science assessments: the three-dimensional learning assessment protocol. PLoS ONE 11(9), e0162333.

TABLE 2.4 Example Course Goals and Learning Objectives

Genetics course goal Students can describe the mechanisms by which an organism's genome is passed on to the next generation and predict how the different mechanisms affect the frequency of different types of genetic disorders.	*Associated learning objectives* • Students should be able to diagram the process of meiosis. • Students should be able to explain the events that occur at each stage of meiosis. • Students should be able to compare the predicted frequency of a disorder that arises from a recessive mutant allele and a dominant mutant allele from a given cross.
Organic chemistry course goal Students can interpret data to draw conclusions and can relate this process to how the field builds knowledge.	*Associated learning objectives* • Students should be able to identify structural characteristics of small molecules from NMR data. • Students should be able to explain how NMR as a technique allows chemists to understand reaction mechanisms.

learning goals (termed learning outcomes in the paper), but that multiple application studies report their value. Further, the use of learning goals is the centerpiece of most course design frameworks (e.g., Wiggins and McTighe, 2005; Fink, 2003; Chasteen et al., 2011) and is recommended as a key practice for improving undergraduate science education by representatives of the Association of American Universities and the Research Corporation for Science Advancement Cottrell Scholars (Bradforth et al., 2015). Given the value that learning goals can provide for guiding both the students and the instructor, it's a good place to begin course design.

2. *Identify one or two big questions that help students see the interest and ongoing importance of the course.*

   Big questions can act as a sort of invitation to a course, an intellectual hook that can draw students into the ways of thinking and the engaging problems within a field. These questions can focus on the foundational ideas and ways of thinking that define science and can be framed around the core concepts in a field, such as those identified in the NRC's *Framework for K-12 Science Education*. For example, the following questions revolve around core concepts in genetics:

   - How can individuals of the same species and even siblings have different characteristics?
   - How do organisms change over time in response to changes in the environment?
   - What evidence shows that different species are related?

- How can there be so many similarities among organisms yet so many different plants, animals, and microorganisms?

These questions are characterized by Wiggins and McTighe (2005) as essential, and can be a valuable way to help students understand both the questions that science seeks to answer and the approaches that are used to answer those questions. Undergraduate science classes can also, however, take things a step further and ask questions that are more explicitly tied to the edge of our understanding, such as:

- Given our growing understanding at each end of the scale of life—from the microbiome to prions—how do we define an organism?
- How do galaxies form and evolve? How do new discoveries challenge our understanding of this process?
- Does our growing understanding of epigenetic events lead to new understanding of "nature vs nurture"?
- What constitutes consciousness?

These questions point to examples where our understanding has changed very recently—and is still changing—and may welcome students to join in the intellectual endeavor of science. They are also big picture questions that encourage students to see connections across courses and disciplines. This combination can be powerful: our students often learn about the process of science in course-associated labs, where they can develop the analytical and experimental design skills but where they may see only a tenuous link to larger questions that shape our understanding of the world. By using one or two provocative, big-picture questions to shape our course, we can capture students' attention, help them understand the potential import of smaller projects, and invite them to be intellectual participants in the scientific journey.

In his study leading to the book *What the Best College Teachers Do*, Bain (2004) found that many transformative college professors design their courses around big questions. They used these questions not only to welcome students to the intellectual work of the course, but also to motivate students to share the instructor's goals. Importantly, these big questions also served as another lens for instructors to consider their learning goals, thinking about the abilities and knowledge students would need to tackle those big-picture questions. Thus questions like these can serve not only as useful hooks to draw your students into the course, but also as a tool to help you define satisfying and meaningful learning goals.

3. *Emphasize the conceptual organization of the course.*

One of the most important factors to consider when designing a course is that your students are relative novices to your field. When faculty members look at a syllabus from their discipline, they do so from the perspective of experts: they have a deep and seemingly intuitive understanding of the key ideas and ways of thinking that underpin the discipline. Students certainly come to the class with knowledge and skills, but they are very unlikely to arrive with a deep-seated understanding of the key features that characterize *biology* or *chemistry* . . . much less *genetics* or *physical chemistry*. They therefore encounter the syllabus in a very different way; they see a list of topics but don't yet have a framework to understand how they fit together.

This difference is characteristic of the ways that experts and novices organize their knowledge (Ambrose et al., 2010). Experts have richly connected mental models that allow them to access their knowledge from a variety of points and that allow them to see connections across apparently disparate observations. Novices, on the other hand, tend to have less connected knowledge structures and often have discrete pockets of knowledge or pieces of information that they connect in a linear fashion. In addition, experts also tend to organize knowledge based on deep features rather than surface features, whereas novices often only see the surface features. For example, Kimberly Tanner and colleagues have used a card-sorting task to investigate expert and novice knowledge organization in biology (Bissonette et al., 2017). When given 16 problems, the novices sorted the problems based on the type of organism identified in the problem—a surface feature—while the experts sorted the problems based on key biology concepts, such as structure/function relationships and evolution/natural selection.

By articulating the conceptual organization of the course for yourself, you can emphasize that organization to your students, giving them a more coherent view of the course. This approach has two advantages: it can increase student motivation by helping students see the end goal, and it provides an expert template that students can use to start building their own knowledge structures (Hoskinson et al., 2017).

Link the Big Picture to Practical Elements

4. *Develop graded assignments that align with your learning goals.*

Sometimes, the assessments in our courses are a bit of an afterthought. Many of us hate grading our students—we love our subject, we want students to love our subject, and we see our assessments as unfortunate but necessary interventions that make students study and give us the information we need to assign them a grade. If we make designing important graded assignments an early and integral part of our course design, however, it can change the way we think about assessment, turning it into a tool that helps us refine our learning goals and select learning activities for our students.

In some cases, these assignments may be exams. If so, it can be useful to consider what types of questions will allow students to demonstrate understanding of big-picture concepts, perhaps through working with concrete examples. For example, questions could ask students to identify the underlying problem in a case study and to make recommendations from their analysis of the case; to identify the principle needed to solve a particular problem; to describe a commonly used model and evaluate whether it could be used to predict behavior for a particular example.

In other cases, assignments may take other forms that allow students to demonstrate understanding in less time-constrained settings. For example, students could write a research proposal that illustrates their understanding of a particular topic, identifies an unanswered question, and proposes experiments to answer it. They could design educational materials related to the class for communicating with their peers within the institution, children at local schools, or the general public.

Whatever form the graded assignment takes, the key feature is alignment (Biggs, 2003; Blumberg, 2009). Does it assess how well students are reaching topic-level learning objectives, and does it map back to one of the course's key learning goals? For exams, these questions can be asked on an item-by-item basis; for other types of assessments, alignment may be more holistic. Laverty and colleagues provide tools for evaluating assessments in relation to the scientific practices, crosscutting concepts, and core ideas shown in Tables 2.1–2.3 (Laverty et al., 2016). Aligning assessments with learning goals and objectives increases students' trust in the instructor, places the teaching and learning emphasis on the elements of the course the instructor cares most about, and has the potential to promote student metacognition by giving students a means to compare their self-assessed attainment of learning objectives to the instructor's assessment.

If you are redesigning a course rather than starting from scratch, it may be useful to examine your existing assessments to help you think about your learning goals. Although it's always a good idea for learning goals to drive course design, our existing assessments often have important but unarticulated learning goals embedded in them. Since we often emphasize to students what we consider most important through the points we use, considering existing assignments may help uncover or clarify key things we want our students to learn.

5. *Incorporate formative as well as summative assessments.*

At the beginning of this chapter, we said that we often begin thinking about our courses by considering the content we need to cover. Likewise, when we think about assessment—that is, determining whether students "got" what we want them to get—we often think about exams. Exams and other summative assessments can be important. We often need these relatively high-stakes tools to measure whether students achieved our learning goals and are prepared to move forward in their undergraduate or postgraduate trajectory. It's also important, however, to incorporate formative assessments into the course to allow you and your students to determine how well they are moving toward the learning goals before they need to perform on the summative assessment (NRC, 1999; Couch et al., 2015). Building opportunities for these low- or no-stakes assessments into your course design can help ensure that your students get feedback that can help them succeed in the course.

Formative assessment can take many forms. Some formative assessments can take place in class and be ungraded (or graded for completion). For example, questions that students discuss in small groups before reporting out and hearing the instructor's explanation allow students to evaluate their understanding. If these questions are also answered by all students with clicker-like devices, then they can also let the instructor get a measure of most students' understanding. Cases or problems on which students work in class serve the same function, allowing the students and instructor an opportunity to identify what skills and knowledge students have developed and which areas need more attention. An even simpler form of formative assessment is the "muddiest point" exercise, in which students take 1–3 minutes to write about the idea from the day's class that is most confusing. This serves as a metacognitive exercise for students by prompting them to consider what they do and do not understand and can provide information that can help the instructor determine what additional resources students may need.

Other formative assessments take place out of class. For example, preclass reading responses that ask students to identify key points and areas of confusion from the reading not only help motivate students to prepare for class but also serve as a metacognitive activity and a point of information for the instructor. Out-of-class problem sets or other homework assignments serve the same purposes, allowing students to practice skills and identify points of confusion and giving instructors a window into students' understanding. In addition, having students submit drafts of papers, posters, or other projects for review can allow identification of areas for improvement—and having some of the review be self- and peer review can both promote student metacognition and keep the instructor's burden manageable.

Angelo and Cross's classic (1993) *Classroom Assessment Techniques* describes many formative assessment approaches with specific instructions for implementation.

6. *Let your learning goals drive your choice of teaching approaches.*

The single most important thing you can do in designing a course—the reason it is listed as the first principle in this chapter and other resources on course design—is to identify your learning goals. Not only do your learning goals serve as a tool for your students to assess their own learning and a guide for you in developing your assessments, they also give you a tool for determining the teaching approaches and learning activities you use.

As noted above, it is useful to identify topic-level learning objectives that tie your course learning goals to specific sections of the course. Those topic-level learning objectives are often powerful ways to think about what your students should do before, during, and after class. Two examples are provided in Table 2.5.

TABLE 2.5 Example Learning Activities Aligned to Course Goals and Learning Objectives

Genetics course goal	*Associated learning objectives*	*Aligned learning activities*
Students can describe the mechanisms by which an organism's genome is passed on to the next generation and to predict how the different mechanisms affect the frequency of different types of genetic disorders.	Students should be able to diagram the process of meiosis. Students should be able to explain the events that occur at each stage of meiosis. Students should be able to compare the predicted frequency of a disorder that arises from a recessive mutant allele and a dominant mutant allele from a given cross.	Before class: Students read chapter on meiosis and complete short, autograded quiz on your institution's learning management system (e.g., Blackboard or Canvas). During class: • Instructor gives mini-lecture on points of confusion identified from quiz and from student questions. • Students diagram meiosis in pairs and write short explanations of events. • Instructor chooses one example diagram to project; class reviews, corrects the example diagram and their own diagram as necessary. • Instructor poses a problem: What would be the outcome of a mutation in a protein necessary for crossing over? Students discuss in pairs and vote for one of four responses. • Instructor poses a follow-up question: Would your prediction differ for a dominant mutation vs. a recessive mutation? Students discuss in pairs and vote. • Instructor requests student explanations of their responses and then uses those to provide correct response. After class: Students complete additional problems asking them to predict frequency of disorders from particular crosses and, conversely, asking them to interpret the crosses that could result in particular outcomes.

(*Continued*)

TABLE 2.5 (Continued)

Organic chemistry course goal	*Associated learning objectives*	*Aligned learning activities*
Students can interpret data to draw conclusions and can relate this process to how the field builds knowledge.	Students should be able to identify structural characteristics of small molecules from NMR data. Students should be able to explain how NMR as a technique allows chemists to understand reaction mechanisms.	Before class: Students watch videos describing how to interpret NMR (e.g., https://my.vanderbilt.edu/ochem2/homework-2/), completing a short worksheet to help them remember key elements. During class: • Instructor gives a mini-lecture summarizing key points and responding to student questions. • Students complete worksheet in small groups assessing their ability to apply the concepts from the videos. Example: https://my.vanderbilt.edu/ochem2/files/2015/01/Workshop1.pdf. The instructor circulates, answering individual questions as needed and stopping the whole class at major points of confusion. After class: Students do a homework problem in which a reaction and several possible products are shown. The NMR spectrum of the observed product is provided. Students interpret the NMR spectrum to identify the product and explain how the spectrum allows them to differentiate among the possible products.

In both examples, the learning activities are explicitly tied to the topic-level learning objectives. They use independent student work, small group work, and instructor explanation to help students develop the ability to meet the learning objectives. Further, there are opportunities for the students and the instructor to assess student understanding, because formative assessment and learning activities are often intrinsically linked. Finally, after completing these learning activities, students should be able to achieve the learning objectives—or should have a clear sense that they cannot and that they should seek additional help and practice prior to the summative assessment.

The examples provided in the table are not the only learning activities that could help students reach these learning objectives, of course. For example, instead of having students watch videos before class, the instructor could intersperse lecture with short opportunities for students to practice—essentially alternating between the information that is in the videos and in the example worksheets in the second example. What is important, however, is that the learning activities are clearly tied to the learning objectives: students know what they are supposed to be able to do and are given opportunities to practice those skills with peer interaction and instructor feedback.

CONCLUSION

An essential part of designing a course is determining for yourself and sharing with your students why the course matters. What are students going to learn to do? What big questions will they consider? What will they come to understand about the way your discipline organizes knowledge? Design that considers these big-picture questions results in inviting, exciting courses, giving students a sense that the course will be a compelling and rewarding experience. Of course, the second essential piece of course design is linking the big picture to practical elements. Developing assignments that align with (and help students fulfill) your learning goals, giving students chances to practice and get feedback in a low-stakes way, and choosing teaching approaches that are a good match for your learning goals are critical for fulfilling the big picture promise.

There are several well-established frameworks for course design that can provide more detailed guidance for developing a course. Two of the most widely used are Grant Wiggins' and Jay McTighe's "backwards design" process, described in *Understanding by Design*, and Dee Fink's integrated course design process described in *Creating Significant Learning Experiences: An Integrated Approach to Designing College Courses*.

Thus far, we have considered inclusive approaches to teaching and principles of effective course design, two foundational elements for science teaching. We now turn to approaches to developing assignments and exams, considering principles that ensure that these critical assessments are an integrated part of our courses.

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