Research Article

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Classification of Features across Five CURE Networks Reveals Opportunities to Improve Course Design, Instruction, and Equity

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Course-based undergraduate research experiences (CUREs) are tools used to introduce students to authentic participation in science. Several specific CUREs have been shown to benefit students' interest and retention in the biological sciences. Nevertheless, CUREs vary greatly in terms of their context, methodology, and degree of research authenticity, so different types of CUREs may differently influence student outcomes. This programmatic diversity poses a challenge to educators who want to better understand which course components and features are reliably present in a CURE curriculum. To address these issues, we identified, catalogued, and classified 112 potential features of CUREs across the biosciences. To develop the list, we interviewed instructors experienced with teaching individual and large networked CUREs across a diversity of the biological disciplines, including: Squirrel-Net (field-based animal behavior), SEA-PHAGES (wet lab microbiology and computational microbiology), Tiny Earth (environmental and wet lab microbiology), PARE (environmental microbiology), and the Genomics Education Partnership (eukaryotic computational biology). Twenty-five interviewees contributed expert content in terms of CURE features and classification of those items into an organized list. The resulting list's categories encompasses student experiences with the following: (i) the scientific process; (ii) technical aspects of science; (iii) the professional development associated with research; and (iv) building scientific identity. The most striking insight was that CUREs vary widely in terms of which features they contain, since different CUREs will by necessity have different approaches to science and student involvement. We also identified several features commonly thought to be crucial to CUREs yet have ambiguous definitions. This ambiguity can potentially confound efforts to make CUREs research-authentic and aligned with the central goals of science. We disambiguate these terms and represent their varied meanings throughout the classification. We also provide instructor-friendly supplementary worksheets along with considerations for instructors interested in expanding their CURE course design, instruction, and equity.

KEYWORDS undergraduate, science, research, CUREs, equity

INTRODUCTION

Early research experiences that are authentic are shown to benefit college students' science, technology, engineering, and mathematics (STEM) knowledge, motivation, and academic plans compared to traditional learning contexts (1–3). However, access to faculty's individual laboratories at most research universities is limited to only a small number of students. While more students have access to conventional undergraduate laboratory classes, these experiences typically do not engage students in discovery with broad relevance and iterative research.

A solution that can provide access to early authentic research experiences for many students is the course-based undergraduate research experience (CURE). CUREs often combine some of the authentic characteristics of a research lab with the larger capacity of a course environment (4, 5). Their scalability and authenticity have led to CURE program expansion across universities and the establishment of several national and global CURE networks (6–10). This growth has been driven, in part, by research on CUREs, which shows that early and authentic research experiences can positively impact college STEM student outcomes and, in particular, those for historically excluded groups (11–14).

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CUREs can vary widely in terms of which research-related features they include (15), as well as institution type, research topic (e.g., microbiology, field ecology, eukaryotic molecular biology, animal behavior, etc.), and scientific approach (e.g., hypothesis-based, open discovery, data-driven, or observation-based). While this programmatic diversity allows for a great variety of student involvement in research and pedagogical creativity across the sciences, it can pose a challenge to educators and education researchers who want to understand which CURE components are most important to student outcomes (4, 5).

Past work sought to understand the diversity of CURE features by coming up with general criteria for CUREs. For example, many faculty in the CURE research community have referenced the efforts of a 2014 CURE working group to differentiate CUREs from traditional laboratory course experiences (4). Since then, other calls for further research to characterize (5) and assess (3) CUREs have helped to further articulate broad CURE content areas. While this work has been helpful in guiding CURE development, the currently available lists of CURE features have not been collected systematically from CURE instructors, for example, through instructor interviews. Previous work also lacked a level of specificity that could distinguish among many CURE nuances. For instance, this existing literature has different key definitions of some CURE features, perhaps in part due to a lack of specificity, resulting in the need to disambiguate commonly used CURE terms. Finally, further compounding this issue is that much of the CURE research has been disproportionally published on a small number of CUREs in a narrow range of biology, mainly large CUREs in the wet lab-based microbial sciences, including work by our own group and others (2, 8, 16).

To address the issue of CURE programmatic diversity and the features that are consistent or unique among a representative sample of CURES, the purpose of this study was to systematically identify and preliminarily classify features of CUREs representing the breadth of biological research approaches and study systems. To develop the list, we interviewed 25 participants experienced with CUREs that represent the diversity of the biological disciplines, including the following:

- Squirrel-Net (field-based animal behavior) (6)
- SEA-PHAGES (wet lab microbiology and computational microbiology) (7)
- Tiny Earth (environmental and wet lab microbiology) (8)
- Prevalence of Antibiotic Resistance in the Environment (environmental microbiology) (9)
- Genomics Education Partnership (eukaryotic computational biology) (10)

From these interviews, we constructed a classification of features relevant to bioscience CUREs and the intended student experiences in this type of learning and research environment. We also constructed the list to serve as a comprehensive, useful set of features that a CURE might include (as opposed to a list of requirements that a CURE must meet). Overall, this feature list can be a helpful reference for instructors reflecting on their own CURE course design in terms of learning objectives, scientific teaching, and inclusivity. We provide in the supplemental material worksheets some simple instructions for practical application of the list.

PROCEDURE

Overall approach

We used a qualitative concept development (QCD) approach (17). QCD is useful when building usable content in complex environments, such as the field of nursing practice, which has many incipient concepts with unclear boundaries between them. In particular, our overall approach relies on the QCD methods of synthesis (generating new ideas) and multiple concept development (including clarification and differentiation of multiple concepts) (17). An overarching goal was to capture the unique combination of activities students might encounter in CUREs, including students' scientific and technical experiences with research as well as students' social and cognitive experiences with research. With this in mind, we characterized the steps using a "process model" approach to identify key features (18, 19). Specifically, to define the CURE features in this study, the following steps were taken: (i) define the project scope; (ii) draft a preliminary scaffold of CURE features for use in our interviews; and (iii) generate a full feature list through in-depth interviews with diverse instructors from across bioscience CUREs.

Project scope

In order to be as specific as possible and to offer items of immediate practical use to instructors, we limited the study to CUREs in the biological disciplines. This list is intended to be a comprehensive list of the features that a science-based biology CURE might include, so we did not limit inclusion to features that instructors felt all CUREs must include. Instead, the list includes all items that instructors indicated could be included in either CUREs in general or items that might be only included in specialized CUREs. CUREs heavily vary based on format (methodology, student population, length, etc.), and so they are expected to have different features from one CURE to another (15). Throughout development of this feature list, we also followed the principle that science teaching should mirror the way science is done (19, 20).

Generating a preliminary list to use as a scaffold

The goal for a preliminary list of features was that it would serve as a conversational starting point during the instructor interviews. Going into the interviews with this

TABLE 1
Interviews were conducted with instructors representing a diverse range of introductory biology CURE contexts[a]

Research context	Course content	Squirrel-Net	GEP	SEA-PHAGES	PARE	Tiny Earth
Methodology	Wet lab			✓	✓	✓
	Field ecology	✓				
	Computational		✓	✓		
Biological domain or area	Bacteria			✓	✓	✓
	Eukaryotes	✓	✓			
	Viruses			✓		
Approach	Hypothesis-based	✓	✓		✓	
	Discovery-based		✓	✓		✓
	Observational	✓			✓	
	Data-driven		✓	✓		
CURE length	≥1 semester			✓		✓
	<1 semester	✓	✓		✓	✓

[a]CURE instructor-participants were recruited from five networked CUREs (Squirrel-Net, SEA-PHAGES, Tiny Earth, PARE, and GEP) that varied in terms of their typical methodology, biological domain topic, and length. At least four instructors associated with each network were interviewed, and at least one instructor from each network was interviewed for each of the four categories. Of the 25 participants, over half also taught a nonnetwork CURE on another topic (see Table 2).

content allowed us to (i) efficiently facilitate discussions that built upon a list of the most commonly encountered features and (ii) make the most use of the interview time by allowing participants to quickly identify missing features, in particular those not within our experience and those not yet captured in the existing literature. To make the preliminary list, we generated and catalogued the activities commonly encountered by professional research scientists, science trainees, and CURE students. To begin this process, we generated "lists of lists" of common CURE features described in the literature (see Text S1 [Supplemental Methods] and Fig. S1, stage 1, in the supplemental material) and attempted to group these features thematically (Text S1 and Fig. S1, stage 2). We then grouped these features into a set of hierarchical categories and subcategories (Fig. S1, stage 3); at this stage, we iteratively removed redundancies and then clarified definitions through informal conversations among ourselves and colleagues who work in academic research. We also referenced additional literature on CUREs to ensure representation of literature-identified features, focusing on four widely referenced peer-reviewed CURE reports and studies (3–5, 15). Each of the literature-based features was checked (by A.R.B.) to see if the feature was represented in the scaffold, resulting in a few missing literature items being added (Table S1).

Overview of interviews

The major phase of the CURE feature list construction occurred through iterative rounds of in-depth, semistructured interviews ($N = 25$) (Fig. S1, stage 4). We primarily interviewed instructors from five nationally networked CUREs: Tiny Earth (8), Squirrel-Net (6), SEA-PHAGES (7), Prevalence of Antibiotic Resistance in the Environment (PARES) (9), and the Genomics Education Partnership (GEP) (10) (Table 1). These networked CUREs were selected on their programmatic diversity (Table 1), as well as the ability to interview multiple instructors from each CURE network (Table 2). These networked CUREs have the additional benefits of being represented in the CURE literature and having success as sustainable CUREs that have reached many students. These five networked CUREs represent diverse research contexts, including methodology (wet lab, computational, and field work), biological domain (eukaryotes, bacteria, and viruses), research approach (hypothesis-driven, discovery-driven, data-driven, and/or observational), and CURE length (full semester to within-semester modules) (Table 1).

In addition to networked CUREs, our participants also reported teaching a wide variety of nonnetworked CUREs on a broader range of topics. Of the 25 participants interviewed, 23 taught networked CUREs, and 13 of those 23 instructors also discussed other nonnetwork CUREs they taught (Table 2) on topics ranging from microbiomes to marine zoology to tree morphology.

The Yale University Institutional Review Board granted approval for the research (study number 2000026056).

Participants

Most of the participants (23/25) were college-level CURE instructors affiliated with the formal networked CUREs ($N = 25$ total participants, some of which were associated with more than one network CURE) (Table 2). Two participants were not associated with networked CUREs; one of them was a research scientist and microbiology CURE developer not directly involved in instruction, and the other taught a nonnetwork field ecology CURE. All participants were from

TABLE 2
Instructor-interviewees' institution types and CURE network

Instructor affiliation	*N*	%
Institution type		
Public	17	68%
Private	8	32%
Highest degree granted		
Associate's	8	32%
Bachelor's or Master's	9	36%
Ph.D.	8	32%
CURE network		
Tiny Earth	6	24%
Squirrel-Net	5	20%
SEA-PHAGES	5	20%
PARE	4	16%
GEP	6	24%
Additional, nonnetwork CURE[a]	13	≥52%
Total	25	

[a]Many network CURE instructors also had experience teaching other, nonnetwork CUREs. The additional nonnetwork CUREs varied in discipline and topic, including molecular biology, environmental microbiology, marine zoology, microbiomes, genomics, mammalian behavior, tree morphology, and genetic cloning.

different universities or colleges representing a diversity of institution types, including community colleges, 4-year primarily undergraduate colleges, and research universities (Table 2). Instructors typically self-estimated having 10 semesters of CURE teaching experience (range, 4 to >20 semesters).

Interview procedure

We interviewed each instructor-participant for 1 h. Each instructor commented in detail on at least one major category of the CURE feature list, assessing each feature within it and discussing whether they used the feature in their CURE, whether they thought the feature was a potential addition to other CUREs, how features should be revised or moved, and whether any new features should be added. For a visual overview of the major categories, see conceptual Fig. 1. In order to make sure each category was evenly covered, the category for each interview was assigned by the researchers. To ensure a diversity of CURE types and institution types were represented across the feature list, we continued recruiting and interviewing participants until we reached the following three criteria for each major category of the list:

(1) At least one instructor from each of the five networked CUREs were interviewed on each of the four categories;
(2) At least one instructor from each institution type (Associate's, Bachelor's/Master's, and Doctoral) was interviewed for each of the four categories; and
(3) Each category reached saturation, indicated by infrequent or only minor adjustments to individual features within the category.

While care was given to recruit instructor-participants based on CURE network and institution type, recruitment was otherwise done via convenience sampling, primarily from (i) networked CURE websites' faculty directories; (ii) a variety of geographical locations, representing various regions of the United States, i.e., South ($N=8$), West ($N=5$), Northeast ($N=4$), and East ($N=5$); and (iii) those listed on previous publications from the CURE network as a proxy for ongoing CURE involvement and investment in CUREs.

The feature list was revised after each interview, so that each instructor iteratively commented on the full set of revised features present after the previous interview. Examples of changes based on instructor feedback included the following: adding features to reflect professional development at community colleges; adding features important to field-based ecology projects; revising feature wording to be inclusive of computational and data-driven approaches; removing features that were not phrased from a student perspective; and recategorizing features for improved clarity. Finally, four additional instructor interviews were conducted by having the participant comment on the reference list as a whole for cohesion, appropriateness of categorization, and completeness. If participants disagreed on whether something was essential to include, we generally leaned toward including more features rather than removing them, unless they were determined to be redundant. The list was then again internally

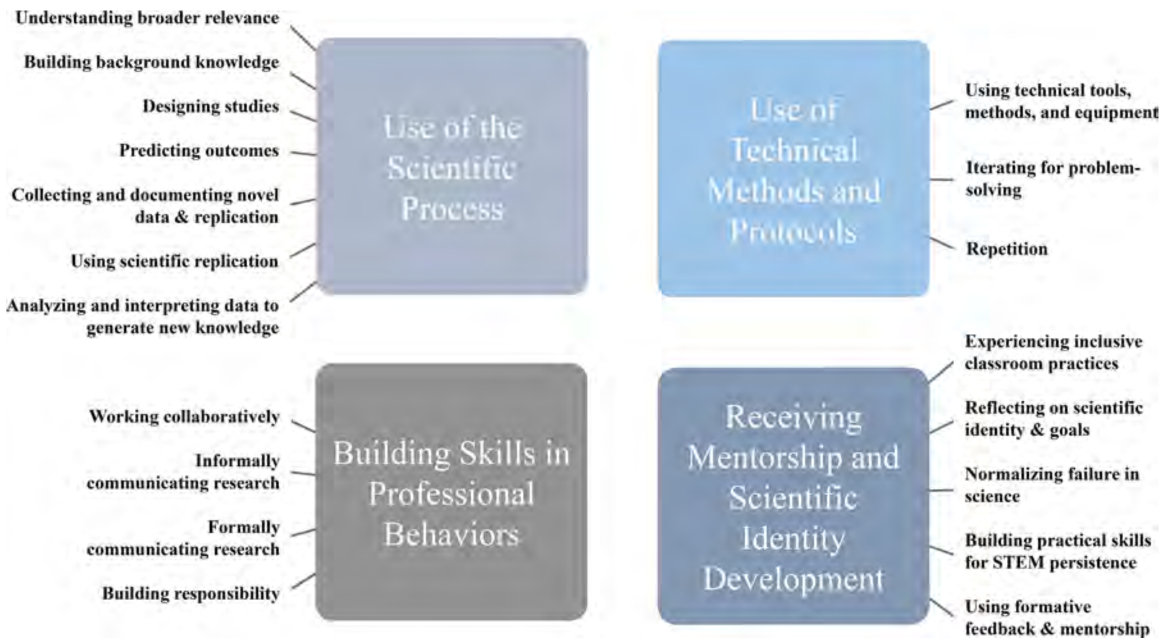

FIG 1. Visual summary of the resulting major categories (squares) and subcategories (radiating labels) of CURE features. The full and detailed list of all categories and items is given in Table 3.

reviewed for overall cohesion, appropriate placement of features within categories, redundancy among features, and clarity. The entire list was edited for readability (e.g., minor edits to the text to ensure parallel construction and consistent formatting of subcategories).

As a final check, we repeated the literature comparison again after instructor interviews to ensure representation of literature-identified features (Table S1, Fig. S1).

RESULTS

To help instructors inventory the content of their current and future CUREs, we developed a structured reference list that described features found in CUREs across the biological disciplines. To ensure a broad representation of CURE types across the biological disciplines, we built the list using interviews with CURE instructors from a wide variety of course contexts across the biosciences (Tables 1 and 2). The resulting list contained four categories of 112 unique features (summarized visually in Fig. 1 and presented in detail in Table 3) and represented the many different approaches to the scientific process used in CUREs, such as participating in any of the discovery-based, hypothesis-based, data-driven, or observational studies. All of the features were written in a student-centered manner that provides specific activities various scientists encounter (for example, "*Students collect data*" [Feature 18], and "*Students hear/evaluate stories of other people's failure(s)* [Feature 90]).

Disambiguation of common CURE terms

One especially useful aspect of the categorization is that it disambiguates CURE-related terms that are often ill-defined, which can lead to confusion around what students are experiencing. The most striking example of this type of disambiguation is with major categories *Use of the Scientific Process* versus *Use of Technical Methods and Protocols*. *Use of the Scientific Process* includes features that describe how students in various CUREs participate in or interact with various aspects of the scientific process, such as how they develop their own background understanding, participate in study design, collect novel data, use scientific replication, and analyze and interpret data (Table 3, Features 1 to 35). *Use of Technical Methods and Protocols* is related to the *Use of the Scientific Process* category, but the two categories are distinct in two key ways. First, in many cases, the scientific process can be accomplished independent of technical tools, methods, and equipment (Table 3, Features 36 to 46). For example, observing animal behavior and characterizing macro species' characteristics might not involve any particular technology. Second, technical methods and protocols are often used independently of the scientific process. For example, they are used widely in food production, quality assurance, medical diagnostics, and many traditional "cookbook" lab exercises, although these settings do not involve the scientific process. Despite these key conceptual and practical differences, ambiguous language is commonly used to refer to a combination of the scientific process (Table 1, Category 1) and technical methods (Category 2), for example with the combining term "scientific practices." In some contexts, the term scientific practices is also used to include practices related to professional development and identity building, such as scientific communication (15).

At the subcategory level, the CURE feature list provides another disambiguation involving the commonly used but ambiguous term "iteration." The term iteration is

TABLE 3
CURE course features in the biosciences[a]

Category and subcategory	Features (students will …)	Example implementation(s)
Category 1: Use of the scientific process		
Understanding broader relevance	1. Recognize how the project matters outside of the classroom	Understanding role in larger SEA-PHAGES community; discussing antibiotic resistance and tie-in to healthcare; talking about how the work links to environmental health
	2. Articulate the overall big picture scientific question or goal in of the project	Giving elevator pitches; relating a squirrel behavior project to other study systems (like elk-wolf relationships)
	3. Explain how the project will result in new findings, discovery, or knowledge	Learning about how past semesters of the course discovered new antibiotics
	4. Explain the course project's research hypothesis (for courses where there is a preexisting hypothesis that is provided to the students)	Writing an introduction to their study; giving class presentations
	5. Apply background knowledge to generate their own, new hypotheses or questions	Using their own BLAST-based protein comparison to hypothesize about gene percent identity across species phylogeny
	6. Understand where their data will go or belong	Discussing the Tiny Earth network-wide database and chemistry hub; discussing how SEA-PHAGES materials get shipped to the network hub and where annotations go on GenBank
	7. Work on projects uniquely related to their local community, environment, or issue	Investigating how local industrial pollution impacts metal resistance in bacteria
Building background knowledge	8. Learn required content knowledge	Using YouTube videos and referencing the lab manual; learning about restriction enzymes in general before applying to phage genome analysis
	9. Use the language of their discipline and project	Applying new language in a lab notebook, for example, what a plaque is
	10. Read the scientific literature	Reviewing articles to learn terminology and problems in the field
	11. Understand content and data on which they will or can build	Annotating a genome that was sequenced and assembled outside of class[b]
Designing studies	12. Choose parameters or conditions for an existing, set protocol	Using a set protocol for monitoring animal behavior while also deciding where to place feeding trays; choosing one's own medium type for isolating antibiotic-producing bacteria
	13. Design a study (choose technical methods, replication, and controls)	Using extra time in SEA-PHAGES to investigate phage particle stability under different conditions
	14. Explain or justify the design of a study (technical methods, replication, and controls)	Explaining how many replicates and controls are used
	15. Write an original protocol or procedure for an experimental, observational, and/or data-driven study	Writing a protocol and requesting materials for a new hypothesis developed in collaboration with the instructor or Principal Investigator (PI)[b]

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TABLE 3 (Continued)

Category and subcategory	Features (students will …)	Example implementation(s)
Predicting outcomes	16. Identify the possible outcomes of their study	Making predictions about protein function based on a specific putative domain
	17. Apply knowledge to predict specific outcomes of their study	Predicting phage genome novelty based on restriction digestion patterns[b]
Collecting and documenting novel data	18. Collect data	Collecting data on colony counts, DNA sequencing results, and PCR results; measuring phage plaque size
	19. Keep records of methods and data	Writing electronic lab notebooks; documenting BLAST results with screenshots; filling out data collection sheets on animal behavior
	20. Understand how they have practiced the ethical conduct of research for data generation, handling, or both	Discussing work with a guest bioethicist from the philosophy department; knowing that poorly conducted science not incentivized through grades and that it's okay to fail over and over as long as lab notebooks are detailed; learning about the class's IACUC protocol; following rules for soil sampling within state lines and on private property
	21. Share data by uploading to a collaborative or public repository	Entering data in the field into a datasheet which is shared with all network instructors via the cloud
	22. Have unique ownership over a component of the project that no one else does	Working with their own bacteria, phage, gene, or genome section; naming their own newly discovered phage
	23. Have the opportunity to come in on their own time to work on their research project	Managing time and coming in during CURE "open lab" hours[b]
	24. Collect additional data to address new questions that arose during the investigation	Predicting transmembrane protein topology for a gene product when standard bioinformatics practices yielded ambiguous results[b]
Using scientific replication	25. Use scientific replication to confirm results	Conducting GEP projects in parallel at two different institutions; counting one another's colonies to check count results; repeating phage plaquing to confirm titers
	26. Use scientific replication (i.e., sufficient sampling) to account for variation	Collecting behavioral data on multiple squirrels, e.g., $N = 2–10$
Analyzing and interpreting data to generate new knowledge	27. Analyze their own (individual or course) data (e.g., visualizing, summarizing, comparing, exploring)	Making charts and graphs for a final project report; checking for bioinformatics errors with a gene model checker
	28. Analyze preexisting data	Analyzing a genome that preexists and then comparing to genomes in the database
	29. Assess or discuss data strengths and limitations	Looking at data across the entire class to explain a question or try to understand a bigger trend
	30. Support interpretation of their results	Using splice junction data on an RNA-sequencing data set to identify location of an intron; searching primary literature that helps explain a finding from class
	31. Integrate multiple lines of evidence to make an argument or judgment	Combining evidence about phage plaque morphology and transmission electron microscopy; using multiple sources of evidence to make gene calls
	32. Articulate future directions, questions, or hypotheses; use data to make new predictions or hypotheses	Using the full class data set to address new questions, such as how weather, humans, dogs, etc. impact animal behavior

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TABLE 3 (Continued)

Category and subcategory	Features (students will …)	Example implementation(s)
	33. Use data to design new experimental, observational, discovery-based, and/or data-driven studies	Writing a future directions section based on their course project results
	34. Explain the extent to which results may be rediscoveries or new findings	Understanding a Tiny Earth project might result in new antibiotics or known antibiotics; discussing phage relatedness and cutoffs for species concepts; using 16S sequencing to determine if a bacterium has already been characterized and if it produces already-known antibiotics; making a "pitch" for their phage to be sent to the SEA-PHAGES network for sequencing
	35. Explain how the results matter outside of the classroom	Presenting at the regional SEA-PHAGES symposium, undergrad research day, and/or regional society meeting; explaining why documenting integrase genes is important for phage therapy
Category 2: Use of technical methods and protocols		
Using discipline-relevant technical, tools, methods, and equipment	36. Follow specialized protocols	Conducting BLAST searches; following data collection protocols for animal behavior
	37. Use technical tools and equipment	Using a genome browser; determining mass of a seed tray; using microscopy and culture techniques; extracting DNA; using bioinformatics databases; conducting antibiotic resistance assays
	38. Use quantitative approaches	Performing serial dilution math for microbiology projects; calculating percent resistance
	39. Use qualitative or descriptive approaches	Characterizing phenotypic traits like colony morphology; characterizing particle morphology based on transmission electron microscopy; collecting data on soil type or quality; assessing bacterial lawn morphology to check for contamination
	40. Use technical safety procedures	Learning that on the command line, there is no "undo" for some commands; when going into the field, using a buddy system and wearing safety vests; using biosafety equipment when working with unknown soil sample types
	41. Understand how technical tools and equipment work	Explaining PCR steps (annealing, extension, etc.); explaining DNA kit steps (lysis, RNAse, precipitation, etc.); explaining bioinformatic database sources (RNA expression data, splice site reliability, etc.)
Iterative problem-solving	42. Repeat procedures for troubleshooting to figure out why something isn't working	Working out why a gene model checker rejected a gene call and then making corrections; repeating serial dilutions to get a correct no. of colonies or plaques
	43. Repeat something because they forgot a step or made a mistake	Repeating PCR and gel electrophoresis; repeating an observational study because a feeding tray was left out overnight
	44. Repeat something because of extrinsic disruption	Repeating an observational study because it rained on a seed tray; repeating an observation because an animal just leaves the site; repeating a microbiological experiment because building power went out
	45. Repeat procedures to determine parameters for optimizing a method or to develop a new method	Optimizing DNA extraction

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TABLE 3 (Continued)

Category and subcategory	Features (students will …)	Example implementation(s)
Using repetition	46. Use the same method repeatedly for different iterations or parts of a project	Identifying multiple exons in a gene; applying plaque purification for multiple-round phage isolation
Category 3: Building skills in professional behaviors		
Working collaboratively	47. Help other students collect or analyze data	Working in pairs to collect data (e.g., one person observing animal behavior and the other person tallying, then switching roles); writing an accountability contract for group work
	48. Share and compare data with other students	Having a class-wide lab meeting where students ask for, receive, and give feedback
	49. Collaborate with their instructor(s) on a research project	Working with instructor or teaching assistant to come up with a hypothesis; asking questions with instructor acting as a Principal Investigator to provide guidance; seeking help from the lab technician for the course
	50. Collaborate as part of a networked research project	Reading a paper whose authors are SEA-PHAGES faculty and students
	51. Serve as mentors or as representatives of science	Emailing with high school students to discuss the project, antibiotic resistance, and college; working directly with high school students to demonstrate skills and sample soil
	52. Seek out expertise and advice from people outside of the course	Using background literature; getting advice from other faculty; answering questions from other microbiology instructors that visit class
	53. Work on a project that is investigated in the instructor's research program	Testing soil in conjunction with a physics research lab
	54. Have opportunities to continue the project or related work after the course	Doing independent projects after the course; coming back as undergraduate helpers for future semesters
	55. Acknowledge others' contributions to their research	Performing literature searches; including an acknowledgment section on a poster; understanding the data from the CURE collective
Informally communicating research	56. Discuss their research process through informal conversation	Giving other students updates on project status and struggles; while out in the field, writing down research ideas, results, questions, and troubleshooting; discussing when they don't get the correct number of colonies
	57. Discuss their research process through informal written communication	Communicating research-related content on social media; communicating questions and interpretations by email, Slack, and social media; answering guided questions in between lab write-ups; texting their work group to coordinate a time-course type experiment; keeping a biology journal on how things are going
	58. Learn and practice not to apologize for asking questions and seeking advice	Being honest with where they are at and having trouble; being prompted to ask again without the apology; being rewarded for questions as part of participation; conveying thanks instead of apology when asking a question; using WhatsApp feed to communicate content, to "nerd out," and organize lab supplies; learning that the instructor may not even know the answer
	59. Take ownership of their mistakes	Emphasizing moving forward; admitting to mistakes (like leaving Taq out of PCR); repeating an experimental trial; writing about mistakes in a Discussion section; addressing the frustration of science rather than being scared into inaction because of grades

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TABLE 3 (Continued)

Category and subcategory	Features (students will …)	Example implementation(s)
	60. Respectfully address research workplace issues	Communicating to lab mates if they will need to miss a lab; being respectful when someone leaves the freezer door open
	61. Professional communication outside the course to facilitate work or give updates	Coordinating with landowners to collect samples; coordinating with local schools to collect soil samples; presenting results at the high school; providing status update to CURE network administrators that DNA has been extracted and is being shipped
	62. Provide constructive criticism to classmates and challenge each other's interpretations	Asking questions and challenging ideas during other students' poster presentations; including peer feedback time in breakout rooms
	63. Provide positive feedback to classmates	Following class expectation that everyone gives an anonymous positive written comment on others' poster presentations; including peer feedback time in breakout rooms
	64. Communicate informally outside of your institution	Communicating across the CURE network; contacting professionals in upper-division courses; discussing with high school students
	65. Informally share their research with others outside of class	Presenting at an undergraduate research symposium; talking about projects with their families
Formally communicating research	66. Write a research proposal	Writing a grant proposal
	67. Write a lab report	Writing a 2–4–page scientific paper with introduction, methods, results, and conclusion
	68. Write components of a scientific article	Pulling in peer-reviewed literature to writing project; writing a rough draft, section by section
	69. Write an applied report	Writing a wildlife management plan
	70. Write poster or slide content	Practicing poster presentations in small groups for feedback
	71. Practice discipline-specific technical writing forms (tone, formatting, type of voice, etc.)	Using data to write results and discussion sections; analyzing published papers to pick up on writing patterns
	72. Prepare a summary of their research for a general audience	Presenting at "Phamily Phage Night" when family members visit the lab and poster session
	73. Make conceptual diagrams of their research	Using BioRender to make a methods overview[b]
	74. Revise drafts of written research findings or presentations based on feedback	Getting peer feedback; writing, getting feedback, and revising paper drafts for a new grade
	75. Present a poster or slide-based presentation of their research	Presenting at undergraduate research day; presenting at in-class lab meetings
	76. Present to an audience outside of class	Presenting at the HHMI symposium; presenting at a special session for community members, board of trustees, and other students
Building responsibility	77. Take responsibility for their own research progress	Working as part of a collective that incentivizes quality work; participating in research progress meetings; bringing in soil
	78. Are respectful of materials, cost, time, and funding sources	Acknowledging funding on a poster[b]; carefully planning experiments and replication[b]
	79. Are respectful of places and communities in which they do their science	If working with human DNA, discussing ethical, legal, and social issues; staying on trails when collecting data outside

(Continued on next page)

TABLE 3 (Continued)

Category and subcategory	Features (students will ...)	Example implementation(s)
	80. Respect external research rules	Discussing which animal research projects would require IACUC approval
Category 4: Receiving mentorship and scientific identity development		
Using inclusive classroom practices	81. Learn the work of diverse scientists	Discussing history of the discipline including racism in genetics; learning about traditional ecological knowledge by partnering with indigenous groups; reading literature by diverse authors
	82. Use one another's preferred names and pronouns	Using a first-day survey of preferred names and using appropriate collective nouns; encouraging pronoun use in email signatures and Zoom
	83. Equitably participate in class discussions	Discussing on an assigned side of a debate related to the Selfish Gene
	84. Equitably participate in active learning exercises	Participating for points via Canvas discussion boards, minute papers, case studies, and "jigsaw" activities; making and performing skits on metal resistance mechanisms
	85. Equitably participate in all aspects of their project (e.g., note-taking, cleaning up, data analysis, etc.)	Writing a contract for participation within a small work group; when working in pairs, divide work and report who did what; doing individual project towards bigger class goal
Reflecting on scientific identity and goals	86. Reflect on their own identity as a "science person" or researcher	Reinforcing verbally what steps are being taken; being part of a community, whose motto is "We're all part of the nerd circus. Let's go!"; hosting a high school student who is shadowing courses for a day; adding work to a science portfolio
	87. Reflect on how their course research benefits their own lives and goals	Reflecting on going on to a 4-year program after community college; learning about how skills will be useful in future contexts
	88. Understanding potential careers and qualifications	Looking up job ads and analyzing qualifications; looking up majors and courses at a 4-year school
	89. Reflect on whether they want to stay (or switch into) a research track or STEM field	Reflecting on conversational prompts like "Where did you think you were going? Where do you see yourself going?"
Normalizing failure in science	90. Hear and evaluate stories of other people's failure(s)	Discussing how good research is mostly failure, including an instructor story about how the first 14 months of their PhD, they couldn't get a virus to kill cells; discussing examples from previous semesters (especially useful when students feel frustrated); listening to an instructor story about how it took 9 months to make a transgenic animal strain
	91. Are not penalized for mistakes or getting an unexpected or negative result	Using low-stakes assessments; focusing on proper analysis rather than a particular outcome; not being penalized for not completing a project; hearing reinforcement that all data tell you something ("There isn't really a 'negative result,' it's just the data you get")
	92. Discuss their research successes, failures, and mistakes with peers	Asking things like "Are your bacteria doing the same thing as mine?"; sharing about their work and excitement with roommates and siblings; putting images of agar plates on the big screen and troubleshooting as a larger group; presenting what went right or wrong in final presentation

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TABLE 3 (Continued)

Category and subcategory	Features (students will …)	Example implementation(s)
	93. Identify what has been learned from a failed experiment or unexpected result	Honing technique for streak-plating based on results; using first-year results to modify plan for next 4 years of wildlife management plan
	94. Reflect on challenges and rewards of their course-based research	Having weekly discussions of major successes and challenges, with other groups helping to workshop solutions; answering a reflection question on the final
Building practical skills for STEM persistence	95. Identify specific research opportunities available to them after the CURE	Reading attention to Tiny Earth newsletters and social media posts about opportunities with companies the network collaborates with; learning about other places to go for more information, like out-of-class seminars; having one-on-one discussions with instructor; reviewing listservs and job boards
	96. Compare and contrast different undergraduate research opportunities	Learning about potential research careers and research opportunities and where to look if interested
	97. Conduct an informational interview of a researcher to learn what research jobs are like	Identifying and emailing a graduate student or postdoc to interview and reporting back on the interview[b]
	98. Compose an email to a potential supervisor with interest in joining their team (doesn't need to be sent)	Getting instructor feedback; learning about non-PI potential supervisors (such as waterfowl specialist at the DNR) for potential summer tech or permanent jobs
	99. Create a personal statement or cover letter for a specific research opportunity	Connecting CURE experiences to potential new opportunity in a draft cover letter[b]
	100. Compose a request for a recommendation letter	Learning about timing for letter requests
	101. Learn how to professionally follow-up	Follow a template and examples for concise and timely follow-up emails[b]
	102. Practice interview skills	Answering behavioral-based interview questions using examples from the CURE[b]
	103. Learn how to self-advocate in a professional setting	Addressing microaggressions and implicit biases on an as-needed basis
	104. Evaluate the culture of a research group and learning how to resolve conflict	Watching video-based professional development training on lab workplace and research ethics
	105. Evaluate different mentoring scenarios	Reviewing mentoring approaches and identifying advantages and disadvantages[b]
Using formative feedback and mentorship	106. Discuss and receive mentorship about science, careers, professional development, and related topics during designated class time	Using down time (like when gels are running) in class as a comfortable place where it is natural to talk and have a flow of advice; hearing guest speaker on careers related to the semester's learning goals
	107. Discuss and receive mentorship about science, careers, professional development, and related topics outside of class (e.g., after class, during office hours, one-on-one meetings, other class get-togethers)	Getting together with other students outside of class; stopping by the instructor's office informally; attending seminars about research opportunities and how to get in touch with professors; getting help writing cover letters outside of class
	108. Build relationships with a broad range of researchers from outside of the class	Connecting with potential future mentors at conferences; watching YouTube videos on how to participate in a poster presentation

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TABLE 3 (Continued)

Category and subcategory	Features (students will …)	Example implementation(s)
	109. Use formative feedback on scientific skills to make improvements and changes	Conducting weekly research checks; writing about skills they are mastering in class
	110. Use formative feedback on technical skills to make improvements and changes	Receiving feedback "on the fly" in lab; doing informal pipetting quizzes; getting feedback on streak plates; getting frequent feedback in the field from teaching assistants on where to set traps
	111. Use formative feedback on professional behaviors to make improvements and changes	Writing multiple drafts of final laboratory report sections and visual elements; doing peer and self-assessment on how things are going
	112. Use formative feedback on practical skills for STEM persistence to make improvements and changes	Getting feedback on and revising a draft email to a potential PI[b]

[a]Worksheets 1 to 4 in the supplemental material provide easy-to-print-and-use versions of this list (one category per page) along with self-guided workshop instructions for instructors. See also Fig. 1 for a concise visual summary of the feature categories.
[b]An example originating from outside of the participant interviews used in the study.

commonly used to describe any number of different repetitive processes in science. While constructing this list and interviewing participants, three different processes related to "iteration" emerged, and we refer to them as (i) iterative problem solving, (ii) scientific replication, and (iii) repetition. Iterative problem solving is the incidental repeating that becomes necessary when things go wrong (Features 42 to 45), and it includes items such as needing to repeat a failed PCR or a field experiment that was disrupted due to poor weather. Iterative problem solving was reported widely within our instructor interviews, especially in multiweek and semester-long CUREs. This type of iteration is well-represented in the CURE literature (Table S1) and often considered essential to the CURE experience (5). However, iterative problem solving (Features 42 to 45) is fundamentally different than scientific replication, which is planned into an experimental design and needed to verify results, collect multiple measures, and assess natural variation (Features 25 and 26). Scientific replication includes approaches used to understand scientific repeatability and variation, and it is essential to the concept of scientific process. The third type of "repeating" identified by our instructor-participants includes a category we term repetition, the use of a same method for different uses (Feature 46), such as for different parts of project. Instructors cited the examples of running agarose gels for different PCR samples and identifying the start codons for different genes. Additional examples of iterative problem solving, scientific replication, and repetition are provided in Table 4.

Clarifying definitions for CUREs, as we have done here, will be important to instructors for more precisely identifying what their students are actually experiencing and in identifying what they want their future CUREs to incorporate. In addition, it makes it easier for CURE researchers and program assessors to identify features of interest in evaluating programmatic and student outcomes.

Professional behaviors and scientific identity

This cross-disciplinary list also reveals the potential of CUREs to build scientific identity and to develop professional skills, two aspects of research commonly thought to be important for cultivating students as scientists (21): building skills in professional behaviors and receiving mentorship and scientific identity development.

Building skills in professional behaviors is important to being a professional scientist in academia, industry, and other settings. In traditional undergraduate research experiences (UREs, such as internships, summer research, and research-for-credit), students work and interact in a professional environment where they observe and learn how to behave as part of working group. These behaviors can take many different forms and are categorized into the subcategories of working collaboratively, informally communicating, formally communicating, and building personal responsibility (Table 3, items 47 to 80). As an extension of the principle that science learning should mirror the way science is done, these behaviors represent the importance of preparing students not only for the scientific and technical aspects of research but also the professional context in which it is conducted. Brownell and Kloser recognized this as important by specifying that scientific practice (4) includes "communicating like a scientist" (15) (Table S1). Example the features include "Students share and compare data with other students" (Feature 48), "Students write an applied report" (Feature 69), and "Students present to an audience outside of class" (Feature 76). This category highlights the importance of both formal and informal communication needs for scientists.

TABLE 4
Disambiguation of replication, iteration, and repetition in bioscience CUREs[a]

Disambiguated term	Examples	Hypothesized impact(s) on students
Scientific replication (Category 1, Features 25–26)	• Accounting for variation • Performing five replicates of a bacterial growth assay; collecting 20 observations of an animal's behavior • Confirming results • Repeating a host range assay for a phage	Reinforces the nature of science; often amenable to learning about statistics, probability, and natural variation
Iterative problem solving (Category 2, Features 42–45)	• Repeating procedures for troubleshooting to figure out why something isn't working • Rerunning a PCR did not produce a product • Repeating something because the student forgot a step or made a mistake • Regrowing a bacterial culture that was contaminated • Repeating something because of extrinsic disruption • Rerunning a field experiment that was rained on • Repeating procedures to determine parameters for optimizing a method or developing a new method • Performing an antibiotic concentration gradient	Failed experiments can lead to frustration, and having opportunities to overcome frustration can lead to growth (Lopatto et al., 2020 [26])
Repetition (Category 2, Feature 46)	• Using the same method repeatedly for different iterations or parts of a project • Identifying the start codons of five different genes; running agarose gels for different PCR products	Reinforces learning of methods and concepts

[a]The different constructs are often used interchangeably, sometimes under the common but ambiguous name of "iteration."

While traditional laboratory instruction has often focused on formal communication skills (for example, writing lab reports and giving presentations [Features 66 to 76]), informal communication appears in the everyday scientific process (Features 56 to 65), such as talking through the troubleshooting process, giving feedback to peers, and addressing workplace issues (21), and it is the first form of scientific communication students learn when in traditional UREs. Intentionally including learning objectives on these forms of science communication into CUREs will help to better prepare students and make CUREs more like traditional UREs.

Receiving mentorship and scientific identity development is also a key component of early research experiences in traditional settings; however, these components are infrequently included as formal components of research experiences and assessment (Table S1). While it is commonly thought that participating in the research process itself will cultivate scientific identity, this section of the CURE feature list includes course components that can be purposefully—and therefore equitably—included in CUREs (see Text S1 [Supplemental Results]).

DISCUSSION

The most striking result from classifying the items was that not all CUREs will contain the same features, and indeed, different CUREs will by necessity have different approaches to science and student involvement. For example, within *Use of the Scientific Process*, no single CURE will have all of the features, because courses vary based on the scientific goals, methodology, student population needs, amount of time available, and other factors. Different CUREs will have different levels of inquiry, including structured, guided, and open inquiry (15), which vary by the extent to which students are responsible for developing their own research questions, methods, and study background knowledge. For instance, students in most CUREs may work with an existing research question (Feature 3) or hypothesis (Feature 4), rather than generating their own question or hypothesis (Feature 5). In another example, students in some courses may analyze their own data (Feature 27), while in others they may work with preexisting data (Feature 28).

Likewise, features relating to building professional skills also vary widely across CUREs. For example, some CUREs will focus more on poster presentations, while others may culminate in writing an applied report, such as a wildlife management plan. The scale of collaboration (Features 47 to 55) also varies across CURE formats: some CUREs focus on student-student collaboration (Features 47 and 48) without significant instructor input, while others have a stronger student-instructor collaboration (Feature 49) or even a student-network collaboration (Feature 50).

Because of these differences, we want to emphasize that the list is not intended to be a set of criteria of requirements that a CURE must meet, as CUREs vary based on their format, and so they should be expected to have different features. Rather, this list will be useful as a guide for course design and assessment, such as evaluating how CUREs compare to UREs in professional academic and industrial labs, for instructors to articulate the components of their courses they already have, and to reflect on which opportunities exist to improve their courses.

While a goal of one branch of CURE education research is to ultimately generate a checklist of criteria for CUREs, here we have instead researched the different, but complementary, need to provide a comprehensive and instructor-generated reference of course features across a diversity of biology-based CUREs. While future work may reveal a list of strictly required CURE components that can be validated, our work here suggests that such a list may not be appropriate, or if such lists are developed, may need to be quite specific to methodology, biological subdiscipline, or both.

Using a feature list to improve student learning, and equity in the classroom

While CUREs often focus on student learning of the scientific process and technical methods (22), the new feature list (Table 3) also includes an expanded focus on the development of professional behavioral skills and scientific identity. Gaining knowledge in these areas is important for students to develop familiarity with academic culture and the cultural capital needed for continuing in science (23, 24). Students require cultural capital to identify and obtain noncourse research experiences (24), and CURE curricula can be used to help students develop knowledge that will assist them in continuing in research after the course (23). Examples of how to do this include the subcategories of normalizing failure in science (Table 3, Features 90 to 94) and building practical skills for STEM persistence (Table 3, Features 95 to 105).

Although the CURE feature list itself is not a curriculum, it can be used by instructors to aid course design, revision, and lesson planning, in particular as part of a backward design process (25) to improve student equity. We suggest that interested instructors work through the provided worksheets (see Text S [Supplemental Materials and Supplemental Discussion]) to identify features that would be useful for their particular course and student population and then craft appropriate learning objectives, assessments, and learning activities for the feature.

This list will also be useful for CURE education researchers and program evaluators in the biosciences (see Text S1 [Supplemental Discussion] for limitations). The list of features is a useful starting point for generating predictor variables for student outcomes, including the effect of many course features that remain understudied in the CURE literature. For instance, which course features relate to important affective experiences, such as frustration (26) and persistence (1, 3)? How are the quantity and quality of CURE features influenced by course format, such as course length (9, 27), scientific methodology (28), and level of inquiry (15)? Which course features offer meaningful levels of broader relevance to students (29, 30)? Leveraging this list will assist in guiding research to address these and other questions related to CURE features and student outcomes.

Conclusion

By reaching a greater number of students earlier in their undergraduate careers, CUREs can increase research access and equity. By developing professional behaviors and identity alongside experience with the process of science and technical methods and tools, students will be better prepared to engage in authentic research. Within a CURE, that research authenticity can allow students to contribute new knowledge to the world, sometimes through products that have broad relevance, such as research publications, new medical therapies, submissions to public databases, and data sets useful for future work. To further encourage our students in their contributions to discovery, we as educators and CURE researchers can be more systematic about articulating CURE features. With such a list in hand, we can reflect on how these features are made available to our students. Towards this end, we have provided in the supplemental material easy-to-use guides and worksheets to get instructors started on this process.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, XLSX file, 0.02 MB.
SUPPLEMENTAL FILE 2, DOCX file, 0.5 MB.

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