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Developing critical thinking in STEM education through inquiry-based writing in the laboratory classroom

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Abstract

Laboratory pedagogy is moving away from step-by-step instructions and toward inquiry-based learning, but only now developing methods for integrating inquiry-based writing (IBW) practices into the laboratory course. Based on an earlier proposal (Science 2011;332:919), we designed and implemented an IBW sequence in a university bioinformatics course. We automatically generated unique, double-blinded, biologically plausible DNA sequences for each student. After guided instruction, students investigated sequences independently and responded through IBW writing assignments. IBW assignments were structured as condensed versions of a scientific research article, and because the sequences were double blinded, they were also assessed as authentic science and evaluated on clarity and persuasiveness. We piloted the approach in a seven-day workshop (35 students) at Perdana University in Malaysia. We observed dramatically improved student engagement and indirect evidence of improved learning outcomes over a similar workshop without IBW. Based on student feedback, initial discomfort with the writing component abated in favor of an overall positive response and increasing comfort with the high demands of student writing. Similarly, encouraging results were found in a semester length undergraduate module at the National University of Singapore (155 students).

KEYWORDS

active learning, assessment of educational activities, computational biology, genomics proteomics bioinformatics, inquiry based teaching, laboratory exercises, molecular biology, text mining, topic modeling

1 | INTRODUCTION

Science and Engineering courses at universities are often structured as classroom lectures paired with laboratory sections.[1,2] Lectures typically provide most subject matter content, while students in the laboratories develop their technical skills and convert theory to practice. While lectures and labs are often assessed separately, classroom assignments, laboratory exercises, and laboratory reports all expose students to simulated, simplified, and well-controlled scientific problem situations.

Lecture-based pedagogy is in the midst of a shift toward more active learning, in which students construct their own understanding of a subject through learning activities instead of receiving the learned perspective of the instructor. The benefits of active learning appear substantial: a recent large meta-analysis showed that active learning in undergraduate science classes increases

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student performance when compared with expository lecture-based learning.[3]

Compared with the lecture, learning activities in the laboratory have been slow to change despite evidence that reform to laboratory pedagogy can be effective.[4,5] There are obvious practical challenges—such as cost and safety issues—to laboratory classroom reform. Beyond practical matters, activities in the laboratory may also be slow to change because they already have the appearance of active learning. What could be more active than a group of students beavering away in the laboratory and writing reports on their work?

Despite this appearance, the traditional cookbook laboratory has been challenged by research-based, problem-based, and inquiry-based reforms.[6] Research-based pedagogy, encouraged by the AAAS report *Vision and Change in Undergraduate Biology Education*, increases student engagement and retains the uncertainty of authentic scientific inquiry.[7] Problem-based learning works by providing a more constrained problem context than research-based laboratories. Inquiry-based learning (IBL) takes the pedagogical position that authentic scientific activity arises out of an ongoing practice of inquiry, and that modeling inquiry is one way to model authentic science. While the traditional classroom laboratory presumes both the design and the desired outcome of an experiment, IBL classrooms provide scenarios that relax these presumptions to varying degrees.[8]

Students in classroom laboratories are commonly assessed through the writing they produce. In the traditional lab report, students describe objectives, methods, and results, and sometimes produce a discussion; this structure is meant to imitate the activities of scientists producing science. A common alternative uses the Science Writing Heuristic (SWH), where students are asked to answer specific and more focused questions that directly address the main learning objectives.[9]

Both lab reports and the SWH may be examples of writing to learn (WTL), where the activity of writing reinforces the course content for the student learner. Although WTL tends to favor low-stakes and reflective writing activities,[10] structured questions such as the SWH and lab reports can also be used to meet WTL objectives.[11] When students write about newly acquired knowledge, they may develop a deeper understanding of major concepts, especially when writing assignments require students to analyze and synthesize information. However, compared with activities not requiring writing, laboratory reports do not *necessarily* result in either more engaged student learning or more effective assessment.

The main hindrance to such engagement is the lack of authenticity: in the traditional laboratory classroom, both students and instructors know what the lab report should "correctly" say before having to write or read one. In a laboratory classroom built around inauthentic problems, both students and instructors will tend to focus on the correctness of the answers. In an authentic inquiry-based learning environment, by contrast, students have the opportunity to construct meaning for themselves, modify pre-existing concepts, and enrich their understanding by deciding the course of inquiry.[8]

The primary site of reform in IBL laboratory courses, including research-based and problem-based labs, has been the laboratory activity itself,[5] leaving the primary assessment tool—the lab report—relatively unchanged. One proposal[12] suggested developing inquiry-based writing (IBW) assignments that would address limitations to inquiry found in the traditional lab report. To implement IBW fully in the laboratory classroom, both the nature of the problem and the nature of the assessment need to be changed. Students should be given authentic problems in which no fixed answers are known to anyone, including the instructors, and no two individuals receive exactly the same problem. Assessment of IBW in this implementation would use rubrics based on the written argument and evidence, much like an actual scientific manuscript review. In IBW, writing is skillful or unskillful, convincing or unconvincing, rather than closer to or farther from a closely guarded correct response.

Here we report on the implementation of an inquiry-based writing laboratory classroom for university-level bioinformatics education at two sites. We generated double-blinded DNA sequence-based problems for student inquiry. Each student was provided a different sequence as a basis for inquiry and was assessed through a set of increasingly challenging individual (and later group) IBW assignments. We examined student performance on written tasks as well as student response to the class experience. Together, these results suggest that a laboratory IBW assessment in a laboratory classroom can enrich course content in a way that is both challenging and satisfying for students. We examine possibilities and difficulties for future IBW development along these lines.

2 | METHODS

2.1 | Educational setting

Two IBW laboratory implementations are discussed in this article. The first (the *pilot*) was a week-long continuing education workshop organized by Perdana University in Selangor, Malaysia. The second (the *course*) was a semester-long undergraduate course for second year Life Sciences students at the National University of Singapore (NUS) (Table 1).

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TABLE 1 Comparison of settings for the two implementations discussed in this work

	Pilot	Course
Setting	Perdana University	National University of Singapore
Cohort	Continuing education students	NUS undergraduate students
Duration	8 days	One semester (13 weeks)
Lecture hours	14	26
Laboratory hours	24	44
Class size	30	155
Format	Interleaved lectures and labs each day	Separate lecture and lab sessions each week

This analysis was initially conducted purely for an internal assessment of the effectiveness of IBW pedagogy. Because of this context, we did not seek IRB approval, but we did obtain informed consent for the anonymous surveys that supplemented the standard course evaluation forms. Standard end-of-semester course evaluation forms, as generated anonymously for all courses at NUS, were provided by the NUS computer center to GTK as the lead instructor for these courses. Course work itself is discussed only in aggregate terms and cannot be traced back to individual students.

2.2 | Week long workshop (pilot)

The pilot was conducted at an eight day introductory bioinformatics workshop in July 2013. Participants varied from a recent high school graduate to researchers in related industries. Each full workshop day included interspersed lectures and laboratories. We introduced the assessment structure and the inquiry-based writing assignments on Day 1, and assigned the first inquiry-based writing assignment on Day 3. Assignments were due in the morning, marked during the day, and handed back after the day's activities.

2.3 | One semester module (course)

After the pilot, we implemented IBW into LSM2241, Introductory Bioinformatics, at NUS during the 2013/2014 academic year. The class included 2 h of lectures and one 4 h laboratory session per week. In prior iterations of the course, students were assessed through an oral team-based presentation on a topic, a midterm test, and a final exam. With the introduction of IBW, students were assessed through two individual written reports, one group written report, a midterm, and a final exam. All lectures were given by the same instructor (GTK) in both iterations.

2.4 | Contents and pedagogical structure

Both implementations were built around a theme of sequence comparison viewed through the lens of molecular evolution. Topics included literature databases and reference management software, pairwise and multiple sequence alignment, BLAST and related database search, basic molecular phylogenetics, and protein structure comparisons. Each lecture was paired with a laboratory session, some of which were inquiry-based. In conventional and problem-based laboratory sessions, students practiced what they learned and explored problem sets to reinforce the content of the lectures.

2.5 | Inquiry-based writing assignments

Three IBW assignments were developed for the pilot and expanded for the course, as shown in Table 2. The IBW assignments were designed to be linked: the work of the later assignments was built on the results of the earlier assignments. This linkage was intended to allow the students to use their inquiry-based sequences throughout the semester.

For inquiry-based problems, individual students were provided unique but biologically plausible DNA sequences whose identities were unknown to both students and the teaching staff.

After each learning unit (Table 2), students submitted a written report of their inquiry. Later assignments could build on the results from previous assignments. The third (team-based) assignment required students to reflect as a team on their previous findings and write about their learning.

2.6 | Assessment of inquiry-based writing reports

Rubrics (Supporting Information) were designed specifically for each assignment, and provided to students as part of the assignment. All assignments included assessment criteria for rhetorical expectations, writing clarity, and proper use of literature references. The marking rubric for the group assignment included a teamwork component and a reflection component.

Teaching assistants were first trained for assignment marking by G. T. K. and A. J. J. A randomly selected subset of student submissions was reviewed by all teaching

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staff before marking the entire cohort for each assignment. For the pilot, IBW assignments were marked independently by the lead teaching assistant (A. J. J.) and the lead instructor (G. T. K.). For the course, each assignment was marked independently by two teaching assistants, and assessments were moderated by the lead instructor (G. T. K.). Student submissions were anonymous, identifiable only by student ID number.

2.7 | Generating individual and authentic sequences for inquiry

DNA sequences for inquiry were designed to provide unique sequences consistent with the learning objectives of the course, as outlined in Figure 1. Individualized sequences were automatically generated from actual sequences starting from a recently published transcriptome study of the vampire bat *Desmodus rotundus*.[13] DNA sequences were translated to protein and mutated using PAM matrix-directed mutation probabilities, which were converted back to DNA using vertebrate codon frequency tables as codon probabilities. To ensure plausibility, mutated protein sequences were discarded if mutations altered key residues required for domain recognition. To ensure challenge, sequences were mutated to the extent that the closest "blastp" hit shared less than 60% identity with the mutated protein sequence. Finally, DNA sequences were converted to a random coding frame.

The computer generation of sequences was performed by A. J. J. who then discarded the original sequences. As a result of this process, the teaching and marking staff were blinded from any specific knowledge of the assigned DNA sequences or the sequences from which they were derived. Students were randomly assigned individual DNA sequences, and told that sequences should be treated as possibly incomplete cDNA sequences.

TABLE 2 Learning units of LSM2241, introductory bioinformatics, and inquiry-based writing assignments for each unit

Learning unit	Learning concepts	Inquiry-based writing assignment
Sequence alignment	• Sequence dotplots • Dynamic programming • Pairwise alignment • Blast and other database search methods	Sequence annotation
Molecular evolution	• Position-specific scoring • Phylogenetic inference	Inferring phylogeny
Structural bioinformatics	• Sequence/structure relationships • Structural homology • Distant relationships	Homology modeling (team-based)

3 | ANALYSIS

3.1 | Student feedback data

Standard end-of-semester student feedback included choices on a five point Likert scale, as well as free text answer questions. We used limited information from these data, along with in-class surveys at the end of the workshop and course, to gauge student perceptions of different modes of learning. All data analysis was conducted in R.[14]

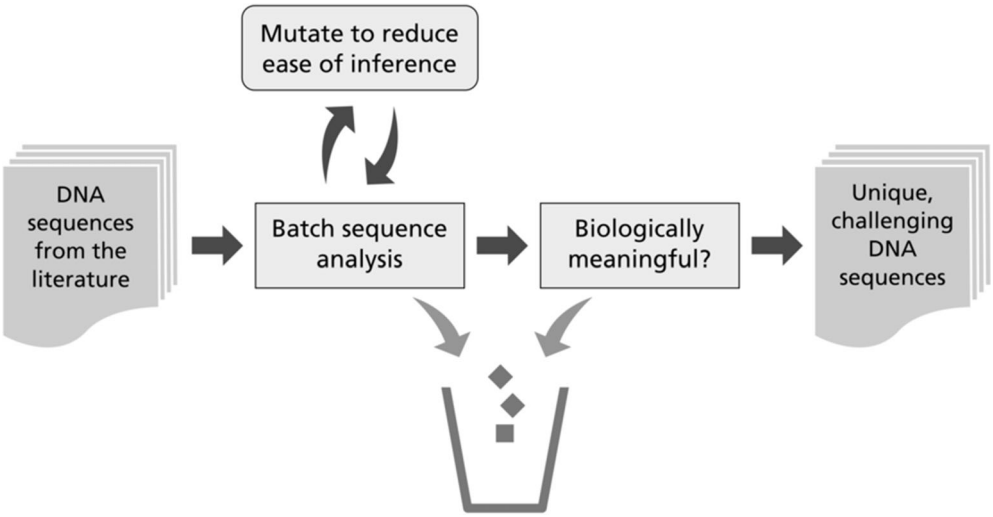

FIGURE 1 Process for random inquiry-based sequence generation

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3.2 | Text mining analysis of student perceptions of learning

We performed text mining of student SET comments using the stm package[15] in R. After stemming and limiting to course-related comments, we were left with 260 student comments for structural topic modeling. Topics were labeled by examining comments highly weighted to each topic.

4 | RESULTS

4.1 | Assignment 1: sequence characterization

The first IBW assignment required students to annotate their assigned sequence using methods covered in class (Table 2). The wording of the assignment suggested identifying repetitive sequences, inferring homology to known sequences or families, and functional annotation. Because the sequences were based largely on incomplete mRNA sequences, and because sequences were unique, students could not compare specific answers to see if they were correct, but could discuss their strategies of inquiry.

Students took a wide variety of approaches to the problem. We noticed in class that many students first attempted to apply every method they had learned, in the order they had learned it. For example, many students first calculated a dotplot of the sequence against itself. If some internal similarity was observable, some students then performed pairwise alignment of the similar regions using global or local alignment (or both, in that order). When it came to BLAST search, many students attempted all BLAST variations possible using a nucleotide query, in the order they had been introduced in the lectures: blastn, blastx, and tblastx.

The chronological order of inquiry was often reflected in the organization of the IBW report. Many students wrote about everything they attempted, whether or not it was a productive line of inquiry. Because figures and tables were not counted against the page limit of the assignment, students often attached screenshots of every attempted analyses, with pages far exceeding the main text.

To address these common mistakes, we conducted a review session with students after returning their first marked assignment. In this review, we discussed scientific writing using examples from the literature and patterns in student reports, with a focus on differences between a laboratory notebook and a written report of discovery.

4.2 | Assignment 2: phylogenetics

In the second assignment, students were required to collect a set of related sequences in order to construct a phylogenetic tree that included their assigned sequence. Student inquiry-based decisions in this assignment included what kind of tree to attempt (e.g., whether try to create a tree of a gene family or attempt to collect putative orthologs and create a species tree), what inference methods to use, how to assess tree reliability, and whether to attempt to root the tree.

When marking this assignment we did not see a repeat of the chronological ordering that was so prevalent in the first assignment, but we did uncover student misconceptions on important topics such as homology. One of the more interesting student findings arose from a flaw in our computational sequence generation process. Because of the way in which we generated sequences for students, the novel sequences were often assigned to an especially long branch in a tree of inferred orthologs. Some students correctly inferred from this unusual tree structure that their sequence was computationally generated.

4.3 | Assignment 3: homology modeling

The last portion of the module covered sequence-structure relationships and included homology modeling. We had determined beforehand that a substantial minority of the assigned sequences could be used for homology modeling by students running SWISS-MODEL or MODELLER[16,17] and that this could be a good basis for IBW. Unlike the first two assignments, however, we could not safely assume that every sequence presented the opportunity for a productive inquiry. Assignment 3 was therefore assigned to groups of up to five students, with the high likelihood that some of the sequences would yield interesting results.

The group setting of Assignment 3 also presented an opportunity for group reflection, so we included a requirement for critical reflection on their first two assignments in the third assignment. We devoted part of one laboratory section to facilitate discussion within each group about the different approaches students had taken for their individual first two assignments.

4.4 | Student feedback on experience

We used data from standard end-of-semester student evaluations of teaching (SETs) along with informal, anonymous, postcourse surveys to assess student

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experience. Quantitative responses included Likert-scale data of various factors, as well as whether students would recommend continuing the inquiry-based writing in future years. Qualitative responses included student perceptions of differences between the inquiry-based writing and conventional laboratory sessions.

The top two panels in Figure 2 show SET responses for the course before and after the introduction of IBW. We noticed (Figure 2(a)) that the introduction of inquiry-based writing was associated with increased overall ratings of the module as "excellent," even though students perceived the module to be at least as difficult with the IBW pedagogy as with a traditional pedagogy (Figure 2(b)).

We asked students whether they enjoyed the experience of IBW (Figure 2(c)) as well as about their level of stress (Figure 2(d)). Students who took the workshop reported both higher enjoyment and higher excessive stress than students who took the semester long course, though students in the course reported higher overall stress. We asked students in both the workshop and the course whether they would prefer assessment from inquiry-based writing assignments or examinations. Students responded in favor of IBW

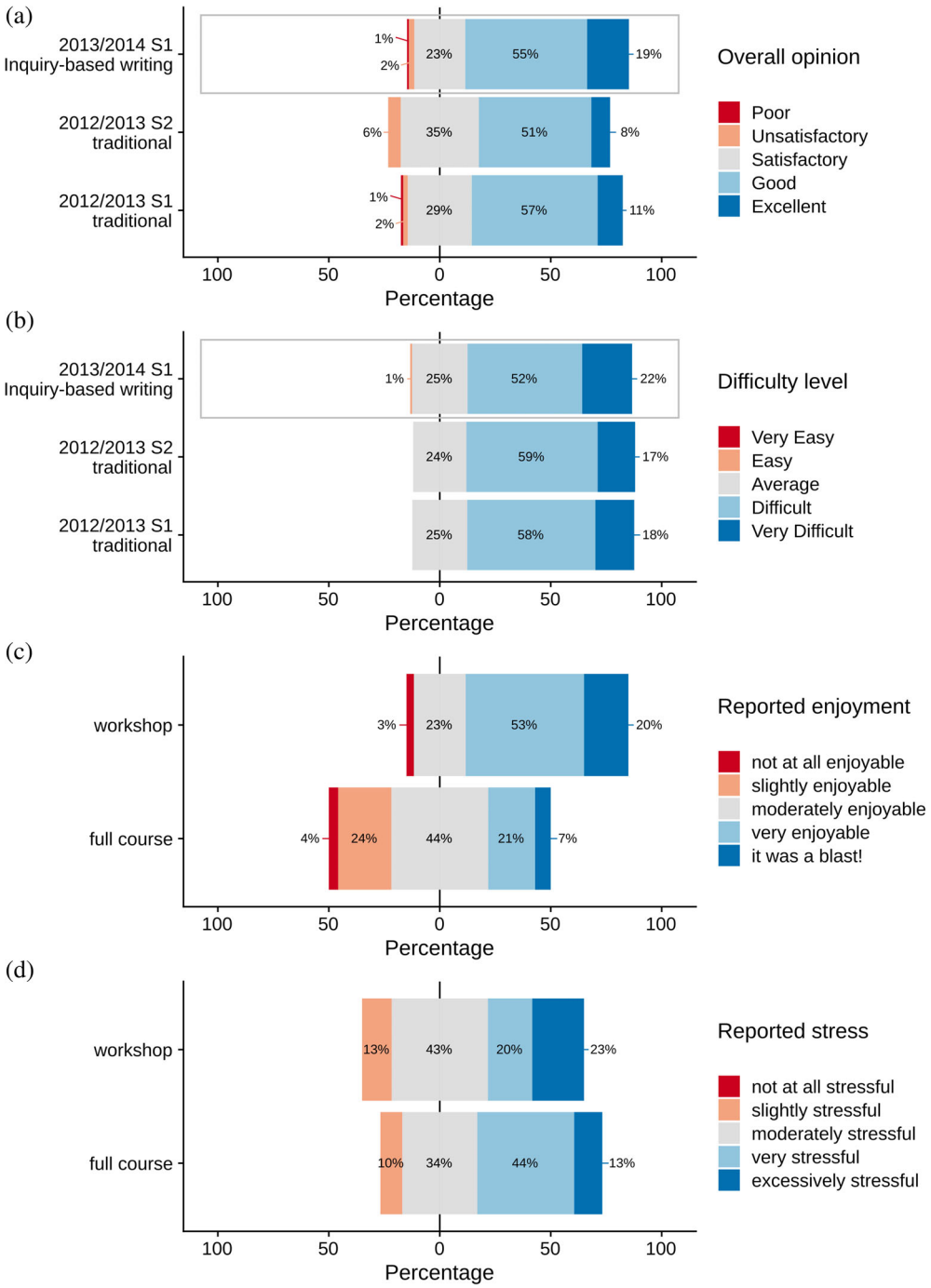

FIGURE 2 Responses of student experience. Responses are on a 5-level Likert scale; data are presented as stacked bar charts centered on the neutral response. (a) Overall opinion of the course, from student evaluations of teaching (SETs) (b) Perceived difficulty of the course, from SETs. (c) Reported enjoyment, from end of course feedback. (d) Reported stress, from end-of-course feedback [Color figure can be viewed at wileyonlinelibrary.com]

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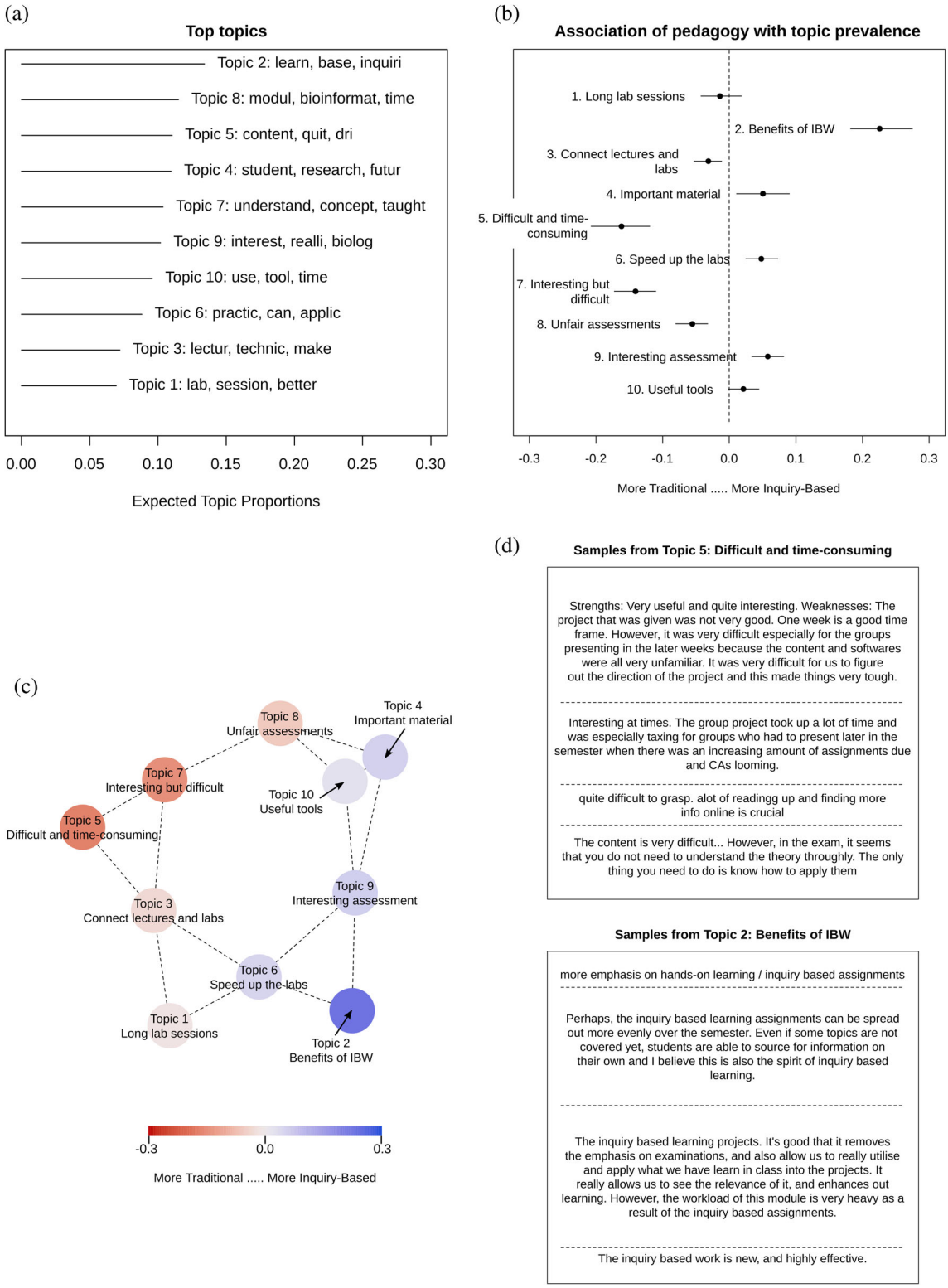

FIGURE 3 Structural topic modeling of student feedback. (a) Topical prevalence for all topics, with top stemmed words from each topic. (b) Relative prevalence of topics depending on pedagogy. Topics more strongly represented in the inquiry-based pedagogy are to the right, those more prevalent in the traditional pedagogy are to the left. (c) Graph-based representation of correlation among topics; topics are colored by association with pedagogy. Highly correlated topics are connected. (d) Sample comments from two topics most strongly associated with traditional (top) and inquiry-based (bottom) pedagogy [Color figure can be viewed at wileyonlinelibrary.com]

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in both the workshop (29 of 30 respondents) and the course (48 of 72 respondents). For the course, we also asked students if we should continue the inquiry-based writing, and the response was overwhelmingly positive (61/72 yes, 4/72 no, remainder "other"). Students were often candid about their reasoning, telling us things like "even though it was difficult, it really helped us to discover the various tools used in bioinformatics," and "It was a good learning experience which improved my writing skills." Students who recommended against continuing IBW generally found it too difficult, like having been "thrown in the deep end of the pool" (see Supporting Information).

4.5 | The change in pedagogy was recognizable from text mining of student feedback

Topic modeling[18,19] treats a collection of documents as arising from a mixture of abstract "topics" that can be discovered from a document collection. We were interested in identifying topics from student SET comments associated with the change in pedagogy, but conventional topic modeling using Latent Dirichlet Allocation (LDA) does not allow simultaneous discovery of topics and associations with metadata. We therefore used structural topic modeling (STM), a recent development in text mining[20,21] designed for exactly this purpose.

We treated each nontrivial feedback comment on the course as a document, labeling it according to the pedagogy used ("traditional" or "inquiry-based"). We developed a model of 10 topics from 260 comments, as summarized in Figure 3(a), and assigned names to the topics based on comments highly weighted to particular topics. When we examined relative topic prevalence, we noticed that some topics were more prevalent in the IBW pedagogy, while other topics were more prevalent in the traditional pedagogy (Figure 3(b)). The topics most associated with each pedagogy were also highly correlated with each other (Figure 3(c)).

Topics 2, 5, and 7 were most strongly associated with the change in pedagogy. Comments from Topic 5 ("Difficult and time-consuming"), the topic most associated with traditional pedagogy (Figure 3(d), top) show students struggling with the challenge of learning in the course, a theme that motivated the introduction of IBW in the first place. In contrast, comments from Topic 2 ("Benefits of IBW"), strongly associated with the IBW pedagogy (Figure 3(d), bottom), show students commenting on the inquiry-based learning itself. Many students commented positively, or noted that it was difficult but valuable for their learning. More broadly, the topics most associated with the IBW pedagogy were filled with reflections from students on their own learning, or on the connection between the course and their experience outside of it. Topics associated with traditional pedagogy also showed objections to the assessment (Topic 8, "Unfair assessments") or struggles connecting content with practical work.

5 | DISCUSSION

5.1 | Observations of student engagement

The appeal of IBW was motivated in part by observed disengagement among students in previous years; we therefore paid attention to any anecdotal signs of change. Informal observations of the lab classroom were encouraging, as it appeared that student activity was much more focused and more animated in the inquiry-based session. The most discouraging behaviors from previous years, such as students using social media during class, virtually disappeared.

We also noticed an elevated level of stress among students. During the pilot, some students found the written assignments so stressful that they began to complain to the workshop coordinator (MAK). In response to these complaints, we decided to make the second project optional, though we offered to provide feedback and "mark" the second project for any students who turned it in. We also allowed groups to choose a traditional exercise (based on the previous year's workshop) instead of carrying out the group-based inquiry-based assignment.

To our surprise, most students turned in and requested feedback on the optional individual inquiry, and *every* group chose to continue with the inquiry for their group project. This apparent combination of high stress and high student engagement was consistent with survey feedback in which students recorded high levels of stress despite overwhelming student preference for inquiry-based writing over conventional lab activities (Figure 2 and Supporting Information).

5.2 | Observations of learning and development

When we designed the first assignment, we asked students to state a hypothesis for their inquiry. We were hoping that students would use concepts (such as homology) from the lectures to frame their hypotheses. While we received some well-formulated hypotheses, we received many hypothesis statements that were wild guesses (e.g., the sequence is human). The most striking

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common mistake was to form a hypothesis around the results (e.g., the sequence is from a specific family of transporter protein genes). We referred to this as "the retrospective hypothesis."

The chronological ordering observed in the first assignment is both rhetorically and scientifically weak, but by the second assignment, most students had begun to internalize the need for essential rhetorical and scientific decisions. That learning was reflected in their writing: hypotheses were better formed, arguments were better made, and students made clear choices between analysis strategies instead of trying everything they had been taught. While students were engaged with inquiry-based work through the semester, their questions became more sophisticated and their group discussions more animated. In the second assignment, we noticed students making different choices based on what they had learned in the first assignment. Some students chose to focus on potential species of origin for their sequence, while other students developed phylogenetic trees of protein families.

In the third assignment, students worked in small groups to develop homology models of their sequences. Usually some sequences failed in this assignment to produce a good model. Different groups handled this failure differently, with some groups choosing to write only about the sequences that succeeded, while other groups organized their inquiry as a "compare and contrast" setting between the different sequences.

Our overall impression was that over time the students took increasing responsibility for the scientific decisions of their inquiry, and increasing ownership of the work product. We did not measure the effect of IBW pedagogy on student learning, so we cannot say whether the patterns we observed were a result of pedagogical change.

5.3 | Student feedback

We decided to use Student Evaluations of Teaching (SETs) in this project specifically because SETs do not prompt students regarding the inquiry-based work, so provide a consistent forum for students to raise it of their own accord. SETs are problematic instruments when used to evaluate teacher performance, because open-ended feedback is inherently confounded with student biases.[22,23] Here, however, the Structural Topic Modeling methodology allowed us to systematically identify topics from open ended survey questions that were associated with the pedagogical innovation of inquiry-based writing. The clarity of these results suggests that structural topic modeling may be a powerful tool to examine SET data in other contexts, including examination of student biases and topics associated with teacher performance ratings.

5.4 | Objections and weaknesses

The original proposal for IBW in the laboratory course[12] led to objections from scientific and writing educators. Michael Goggin (a physicist) argued that the double-blind assessment would undermine the teaching of science (see Reference 24 and response), and undervalues the writing involved in documentation. In our view this objection misunderstands the purpose for reforming laboratory writing to be more like authentic scientific inquiry, but does suggest a related concern: might the double-blind setting penalize students who performed correct work but wrote poorly, or reward students who wrote their way out of a poorly executed experiment? We did not examine that issue directly here, but are testing the correspondence between blinded and unblinded assessment in a separate study.

From the humanities, Catherine Prendergast has argued in support of Goggin that compositionists advocating for laboratory-centered WTL undervalue the importance of manual activities in the lab for constructive learning.[25] Prendergast observes that undergraduate students and mentors in a Research Experience for Undergraduates (REU) program learned a great deal by practicing manual laboratory activities, even though the REU required little writing. The REU program is similar to the Undergraduate Research Opportunities in Science (UROPS) program at NUS. As several of us are practicing research scientists, we appreciate the learning value of hands-on lab work, and the importance of the apprenticeship experience to develop "good hands." But as Prendergast observes, the REU program (like the UROPS program at NUS) includes a regular schedule of constructive activities: presenting at group meetings, providing research updates, chalk talks, and perhaps journal clubs. The REU site in Prendergast's study required a poster presentation instead of a written report; the NUS UROPS program requires a written report. The balance between different *forms* of composition expected in genuine research-based education will vary from program to program, and indeed from lab to lab.

Even given the exceptional value of research-based education such as REU and UROPS, students still benefit from laboratory classrooms. The laboratory classroom experience not only provides skills training that students can use when they take up research-based education, but also may help students decide whether to enter a research-based education program at all. A laboratory classroom that exposes students not just to the range of technical skills working scientists need to practice, but to reasoning about the open-ended possibilities of scientific inquiry, is a setting that we believe better prepares students for research-based education.

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For pedagogical purposes, the original proposal suggested that students write not full lab reports but component parts to be dealt with separately depending on the level of student expertise. This suggestion dovetails with positions in the debate over inquiry-based learning that emphasize appropriate scaffolding for the problem at hand.[26–28] For similar reasons, the difficulty of problems should be controlled so that appropriate problems are given to the students. While we did control the problem difficulty, we did not adopt the original proposal's recommendation to limit writing to component parts of an article; our decision not to do so increased stress for both students and teaching staff. In later implementations of IBW this and other settings, we implemented several changes to address this issue, including limiting writing to component parts and introducing student peer review of writing assignments.

5.5 | Potential for IBW laboratories in other disciplines

Controlled variation of experimental problems can be created via computer simulations or virtual laboratories,[29,30] which have had a powerful impact on medical education, distance learning, and massive open online courses (MOOCs). A computer-based laboratory thus offers a possible setting for inquiry-based writing where multiple variations on a scenario can be developed without raising the safety concerns that might be presented in the analogous experimental chemistry or physics laboratory. We do not advocate mimicking the scenarios of an experimental laboratory through computer simulations or virtual environments, because such an approach would likely lead to inauthentic student experiences. Rather, we suggest that in an inherently computational subject such as bioinformatics, authentic problems can be computer-generated and solved in a laboratory classroom.

More broadly, any laboratory course devoted to experimental data *analysis* rather than experimental data *generation* could utilize the strategy we outline here to generate double-blinded individualized problem sets for students, assessed by inquiry-based writing assignments. Problem sets in biology could be generated by simulation (such as evolutionary games, simulated DNA sequencing data from genomics experiments) or by providing real experimental data available in excess (such as microscopy images).

Our work here focuses on the laboratory classroom, as did,[12] but field-based courses can naturally provide individualized and blinded problem sets. Field-based courses may therefore provide opportunities for inquiry-based writing on experimentation without changing the experimental setting at all. While field-based learning may have inherent safety concerns, those concerns are not altered by the nature of assessment.

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