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Less teaching, more learning: 10-yr study supports increasing student learning through less coverage and more inquiry

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Luckie DB, Aubry JR, Marengo BJ, Rivkin AM, Foos LA, Maleszewski JJ. Less teaching, more learning: 10-yr study supports increasing student learning through less coverage and more inquiry. *Adv Physiol Educ* 36: 325–335, 2012; doi:10.1152/advan.00017.2012.—In this study, we compared gains in student content learning over a 10-yr period in which the introductory biology laboratory curriculum was changed in two ways: an increase of inquiry and a reduction of content. Three laboratory formats were tested: traditional 1-wk-long cookbook laboratories, two 7-wk-long inquiry laboratories, and one 14-wk-long inquiry laboratory. As the level of inquiry increased, student learning gains on content exams trended upward even while traditional content coverage taught decreased. In a quantitative assessment of content knowledge, students who participated in the 14-wk-long inquiry laboratory format outscored their peers in both 7- and 1-wk-long lab formats on Medical College Admissions Test exam questions (scores of 64.73%, 61.97%, and 53.48%, respectively, $P < 0.01$). In a qualitative study of student opinions, surveys conducted at the end of semesters where traditional 1-wk laboratories ($n = 167$ students) were used had low response rates and predominately negative opinions (only 20% of responses were positive), whereas those who participated in 7-wk ($n = 543$) or 14-wk ($n = 308$) inquiry laboratories had high response rates and 71% and 96% positive reviews, respectively. In an assessment of traditional content coverage in courses, three indexes were averaged to calculate traditional forms of coverage and showed a decrease by 44% over the study period. We believe that the quantitative and qualitative data support greater student-driven inquiry in the classroom laboratory, which leads to deeper learning in fewer topic areas (less teaching) and can reap gains in scientific thinking and fundamental understanding applicable to a broader range of topic areas (more learning) in introductory biology.

laboratory; inquiry; cooperative; undergraduate; research

EACH YEAR, the field of biology grows with new developments in knowledge and skills that require increased mastery of topics by our students. While we, the faculty, are concerned that the increased number of topics taught in lecture and laboratory courses might not lead to increased learning, we hope that if we speak clearly and energetically enough, perhaps it will. We often consider our best laboratories to be those with detailed protocols, which have been refined over the years to produce experiments that work in the hands of students, yet these are also "cookbook" in nature (10, 18). Unfortunately, this evolution to increased content coverage and more structured experiments for majors in the course lecture and laboratory does not produce learning gains to match our aspirations (11, 18, 21). Nor does this inspire creativity, flexibility, and inquisitiveness in our students or help them develop deeper critical and integrative thinking skills (7, 8, 22, 23, 27).

In the late 1990s, our department's approach to teaching introductory biology laboratory and lecture courses was predominantly that of a traditional format, with many weekly cookbook laboratories strung together, each focused on a different biological topic. Just as lecture topics jumped from one chapter to the next, so did topics in the laboratory. For example, the week that the topic of photosynthesis was covered in lecture, we would also have photosynthesis "experiments" in the laboratory. In the past, this approach was considered the most efficient for increasing student gains because it enabled teachers to reinforce material presented in lecture. However, student feedback and research data have suggested that these traditional laboratories provide little gain in student learning (18, 23).

In the late 1990s, our faculty members revisited the learning goals of our curriculum and came to an agreement that in the laboratory portion of a course we wanted our students to learn *1*) more about the topic studied, *2*) the techniques used, and *3*) the process of research. Past and current evidence have suggested that the majority of our students learned little of the above when performing cookbook laboratories (7, 11, 27). Upon review of our assessments as evaluated by Bloom's taxonomy, we also found that our laboratory assignments did not require higher-level or critical thought and thus needed revision (19). The literature suggests that our experience is not unique. When reviewing traditional undergraduate biology courses, Momsen et al. (21) found that of 9,713 assessments as evaluated by Bloom's taxonomy, 93% leveled 1 or 2 (knowledge and comprehension) and <1% were a 4 or above on Bloom.

Our review of the education literature and consultations with experts as well as negative student comments on course evaluations catalyzed a formal curricular reform and research effort. We redesigned introductory biology courses to increase inquiry as well as instituted standardized assessments to collect data regarding student opinions and academic performance (17, 19, 26, 28). While our previous publication in 2004 simply compared traditional structured/cookbook laboratories to "teams and streams" inquiry laboratories, in this report we extended those studies to compare gains in student performance in three different laboratory formats: traditional 1-wk-long confirmatory laboratories, two 7-wk-long inquiry laboratories, and one 14-wk-long inquiry laboratory. A full decade of data now supports that the learning gains found in 2004 were sustained and trend upward as emphasis in the laboratories

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shifted from traditional content coverage to inquiry-driven laboratory formats.

METHODS

In the last decade, the laboratory format we used to teach introductory biology to undergraduate physiology majors has changed dramatically. It evolved from 3-h-long structured cookbook laboratories where students were expected to work individually to multiweek-long inquiry laboratories where research is done by students in groups in a format we defined as "teams and streams" laboratories. In these teams and streams group inquiry laboratories, student teams pose a scientific question, propose an experimental design, and perform multiweek investigations and, along the way, present their research via posters, interviews, papers, and talks. What we refer to as the "two-stream" format uses two separate 7-wk-long inquiry experiments each focusing on a different biological topic (e.g., *stream I*: DNA fingerprinting with PCR and gels, and *stream II*: cellular responses to the environment with cell culture and drugs). In the "one-stream" laboratory, student research teams spend the full 14 wk on a single research topic (e.g., cell and molecular biology stream: develop a PCR-based diagnostic assay to detect a mutation known to cause a genetic disorder/disease).

Population and sample. Lyman Briggs College of Science is an undergraduate science program established at Michigan State University (MSU) in 1967. It is a residential college modeled after those at Oxford University that creates a learning community focused on educating undergraduates in a liberal science curriculum. Overall, its goal is to establish a solid foundation in the sciences as well as a significant liberal education in the history, philosophy, and sociology of science.

The Introduction to Cell and Molecular Biology course is a five-credit freshmen-level course. It is the second in a core two-semester introductory biology sequence for science majors (and the last taken before a two-semester physiology sequence). It is taught in sections of ~100 students with accompanying recitation and laboratory sections led by the professor or teaching assistants. Students attend two lectures and one recitation (50 min each) and two laboratory sections (3 h each) per week.

Chronology of curricular reform. While in the late 1990s we made changes to the lecture and recitation portions of the course, from the year 2000 forward we focused on the laboratory and started revising our traditional cookbook laboratory sequence. Early efforts just altered the sequence of cookbook laboratories. We rearranged three cookbook laboratories in a natural multiweek sequence (or stream), specifically *1*) DNA transformation of bacteria, *2*) miniprep purification of plasmid DNA, and *3*) restriction analysis and gel electrophoresis, where the same "unknown" plasmid DNA sample was tested by each pair of students over several weeks in an effort to determine the identity of the plasmid (28). This format, as described in detail in our report in 2002, was still dominated by traditional cookbook laboratories and low-level assessments but was the initial small change that sparked the larger reform to follow. It is the traditional format shown in Table 1 and in our data set is represented by two semesters, spring 2000 and fall 2001.

In 2001, we more dramatically renovated the laboratory curriculum by purposefully introducing two elements: authentic inquiry and formal group work. The details of all the changes done to instruction and assessments in this phase is described in our 2004 publication (19) and the corresponding website (http://surf.to/teamstreams/). The two-stream model used during spring 2001–spring 2007 contained two 7-wk-long laboratory sequences each semester. The first stream typically consisted of macromolecule, enzyme, and photosynthesis experiments, and the second stream dealt with techniques of molecular biology (Table 1). In this new format, the majority of time was focused on mentoring independent inquiry research by student teams of four students. Each of the three experimental topics (e.g., macromolecules, enzymes, and photosynthesis) was initiated with 1 wk for a cookbook laboratory designed to help students to learn techniques followed by 1 wk for independent investigations, where students then applied those techniques to the study of the their chosen research

Table 1. *Curricular organization and timeline: cookbook versus inquiry laboratories in the tradition, two-stream, and one-stream laboratory formats*

Week	Traditional Curriculum	Two-Stream Curriculum	One-Stream Curriculum
1	No laboratory	Introduction to Teams and Streams	Introduction to Teams and Streams and Project Goals
2	Lab 1: Cell Structure Microscope Analysis*	Lab 1: Carbohydrate Chemistry and Lipid Tests*	Introduction to Basic Lab Skills; Students Propose Projects
3	Lab 2: Plant Tissue Culture: Start Hormones Study*	Lab 1 Inquiry: Apply Lab 1 Tests to Your Question/Investigation	Lab 1: PCR of the *Escherichia coli* Genome*
4	Lab 3: Carbohydrate Chemistry and Lipid Tests*	Lab 2: Photosynthesis I: the Light Reactions*	Lab 1 (cont.): Repeat Attempts Until Successful
5	Lab 4: Photosynthesis I: the Light Reactions*	Lab 2 Inquiry: Apply Lab 2 Tests to Your Question/Investigation	Lab 2: Genome Preparation From Cells*
6	Lab 5: Photosynthesis II: the Dark Reactions*	Lab 3: Enzymes (and Proteins): Kinetics Study*	Lab 2 (cont.): Repeat Attempts Until Successful
7	Lab 6: Enzymes (and Substrates): Kinetics Study*	Lab 3 Inquiry: Apply Lab 3 Tests to Your Question/Investigation	Lab 3: Design an Ethical/Historical/Social Experiment
8	Enzymes (cont.) and Finish Study*	Debriefing Stream I and Introduction to Stream II	Independent Investigations
9	Lab 7: Bacterial Transformation*	Lab 1: Bacterial Transformation*	Independent Investigations
10	Bacterial Transformation (cont.)	Bacterial Transformation (cont.)	Independent Investigations
11	Lab 8: DNA Purification*	Lab 2: DNA Purification*	Independent Investigations
12	DNA Purification (cont.)	DNA Purification (cont.)	Independent Investigations
13	Lab 9: Restriction of DNA*	Lab 3: Restriction of DNA*	Investigations and In-Lab Final Practice Presentations
14	Restriction of DNA (cont.)	Restriction of DNA (cont.)	Final Paper and In-Lecture Final Formal Presentations
15	No laboratory	Wrap up final experiments	Briggs Symposium (present research to public)

*Cookbook laboratories.

question. Later, these revisions were applied throughout the biology curriculum in Lyman Briggs College of MSU. The methods used by two faculty members who converted cookbook laboratories to teams and streams inquiry laboratories for another course, Introduction to Organismal Biology, have been described in a recent publication (26).

During semesters from fall 2007 to spring 2011, we implemented a new one-stream inquiry format, allowing student groups to focus on one project for the full 14 wk of a semester. It was designed to naturally allow more time for student teams to repeat and revise experiments and gain experience at troubleshooting. In this one-stream format, only two of the laboratory weeks remained cookbook and were used to teach the students laboratory protocols and techniques such as PCR, gel electrophoresis, and genome purification. An example of this one-stream semester-long laboratory sequence is described in Table 1. After the two introductory cookbook laboratories used to teach techniques, students were given more freedom and were able to choose their experiment's direction with careful monitoring. This one-stream format also allowed students more time to read scientific publications related to their research topic and apply their findings to their own research. For example, students who pursued PCR projects had more time to read research papers on PCR and then design and redesign their experiments to include better controls, replications, and adjustments to variables (reagent concentrations, temperature, etc). Instructors also had more opportunities to challenge students to spend time troubleshooting and problem solving, e.g., careful analysis of their gel results with peers in their research group. Teaching assistants were trained to respond to student questions with answers in the form of guiding questions and always direct the individual student to return and confer with their group to seek answers, rather than literally telling students what to correct.

Revisions in assessment. Changes in the way that the students were taught in the reformed laboratory course (in both two-stream and one-stream formats) were accompanied by changes in the way that student learning was assessed. New assessments, such as interviews, concept mapping, and peer reviews, were introduced in an attempt to evaluate student learning at higher cognitive levels than those previously used. Quizzes and exams were modified to include more short-answer responses rather than just multiple-choice responses. Evaluation of a student's laboratory research results as well as their content understanding had always been dominated by writing, yet how we implemented writing assignments changed from requiring each student to author many short laboratory reports to expecting a group to generate many drafts of a single research manuscript. These changes were described in detail in our 2004 publication (19) and the corresponding website (http://surf.to/teamstreams).

Collection of data on student performance and opinion. Two sources were used as primary data sets for analysis of student opinion and performance during the experiment. Content exams with questions derived verbatim from Medical College Admissions Test (MCAT) practice tests were used as a standardized posttest each semester. This served as a comparative measure of student learning. Student feedback via extended written responses on end-of-semester course evaluation forms was used to evaluate student opinions and assess affective or qualitative elements in response to different laboratory formats.

Quantitative data. We developed and administered a small, standardized exam named the medical assessment test (MAT) as a posttest during the final week of all semesters. Our MAT exam was built from a subset of unaltered MCAT practice test questions developed, validated, and purchased from the Association of American Medical Colleges. This MCAT-style exam was a 40-question multiple-choice test composed of relevant and rich passage-style questions (31). The MAT exam instrument consisted of questions from five general categories: cell structure and function, oncogenes/cancer, respiration, microbiology, and DNA structure and function. Student performance on the MAT exam was tracked and compared with the laboratory format used each semester. The MAT instrument has been used since the year 2000 and can be found online (http://surf.to/teamstreams/).

To attempt to calibrate variation that would naturally occur semester to semester due to shifts in student cohort academic ability, student ACT science scores were used to normalize MAT data. The average ACT score for all students in each course was used to calibrate MAT comparisons between semesters. Normalized MAT scores were calculated for fall 2000 to fall 2011 semesters to generate the data shown in Fig. 1. Scores were normalized by setting the highest course average ACT score to 100% and converting the remaining course average ACT scores to appropriate relative percentages. These percentages were then used to determine the appropriate multipliers needed to adjust each semester's MAT score proportionally to normalize all results.

In addition, since every MAT exam question was carefully coded for topic, we were able to compare what percentage of questions on the exam were covered in any formal way during any part of the course each semester. While the MAT exam itself remained unchanged, the percentage of questions covered by traditional teaching methods from course to course decreased greatly during the 10-yr study.

Qualitative data. The course evaluation form used in this study was the Student Instruction Rating Survey (SIRS) form commonly used at MSU. Rather than interviewing all students in the study, we focused our attention on the comments section on each student's SIRS form. The back of each form is entirely for free response feedback. To interpret the student feedback on these forms, each individual's written opinions were examined and coded depending on the nature of the comments. Individual quotes that were noticeably frequent or typical among students in the class each semester are shown in Table 2. In addition, we studied the frequency of positive versus negative feedback on the topics of the course laboratory (laboratory) or course lecture (class) as well as for each of coded category (groups, laboratory skills, mental skills, and inquiry) from student surveys over the semesters studied (see Tables S3 and S4 in the Supplemental Material).[1]

Analysis of content coverage. To evaluate the changes in traditional coverage that occurred over the 10-yr period, past syllabi were analyzed regarding topics covered in the laboratories and lectures from spring 2000 to fall 2011. We quantitated content coverage and compared that with performance scores over the decade. We quantitated topics covered in laboratories by counting the number of weeks committed purely to cookbook laboratories (Table 1, laboratories marked by asterisks). To quantitate "pages covered," the pages that were required readings of the textbook for the course were counted for each semester. Finally, and perhaps most interestingly, while the MAT exam was originally created based on what was covered in the course back in the late 1990s, in 2011 we no longer have formal instruction on a number of the topics still tested on the MAT. We therefore determined the number of exam questions that were on topics covered in class lecture for each semester. As a result, we could document "MAT coverage," i.e., the percentage of the MAT exam that the instructor covered each semester, and compare that over time. We then could also calculate student performance on MAT questions that were or were not addressed in the course.

Data analysis. Significant differences between group means of measured variables were determined using general linear model ANOVAs and *t*-tests. Post hoc comparisons were done using Tukey's honestly significant difference test. For all statistical tests, differences were considered statistically significant at P values of ≤ 0.05. Data are presented as arithmetic means $\pm$ SE.

Institutional human subjects review. With the approval of the Institutional Review Board of MSU (nos. X00-475 and 10-543),

[1] Supplemental Material for this article is available at the *Advances in Physiology Education* website.

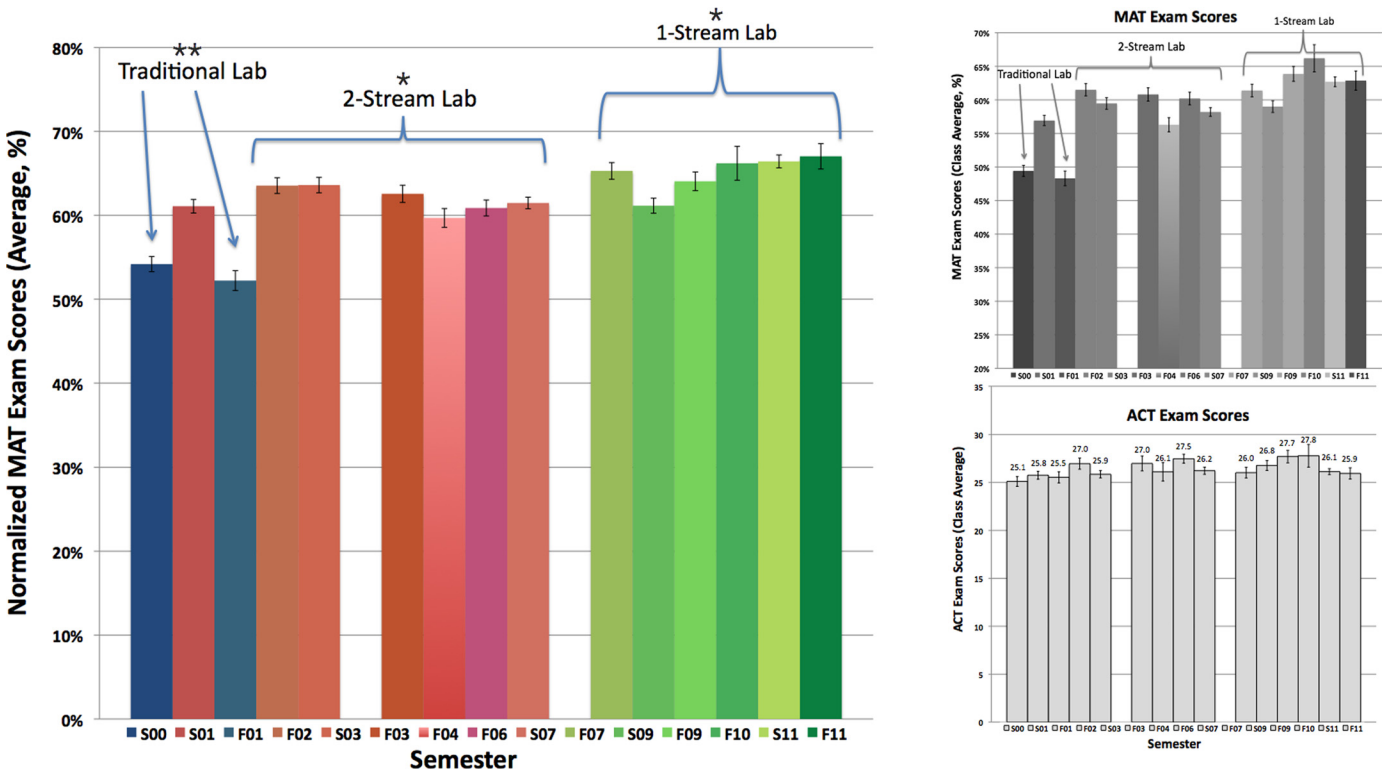

Fig. 1. Normalized medical assessment test (MAT) student score results from 15 semesters. Moving chronologically *left* to *right* is a comparison of the normalized class average score on MAT exams from semesters from 2000 to the present. Course instructors varied in the semesters shown, and these results are from semesters in which the MAT instrument was used as a summative evaluation in the last week of classes. The "teams and streams" (TS) inquiry laboratories were first introduced in spring (S)2001, and in fall (F)2001, the instructor then reverted back to traditional cookbook laboratories. TS laboratories were used again in fall 2002 and continued to be used until the present. Blue indicates a traditional cookbook laboratory, red indicates a two-stream version of the TS laboratories format used until fall 2007, and green indicates a one-stream version of the TS lab format used ever since. *Top inset*: for comparison, MAT scores in all semesters are shown before normalization. *Bottom inset*: class average scores on the ACT for the semesters studied are represented and were used to normalize MAT scores. Error bars are SEs. Student scores from both TS laboratories formats were found to be statistically significant from students who participated in the traditional cookbook laboratory format (**$P < 0.0001$ by ANOVA). Scores of students who participated in the two-stream format were also significantly different from those in the one-stream laboratory format (*$P < 0.01$ by ANOVA).

student data were collected from the 1,018 students who completed our Introduction to Cell and Molecular Biology course at MSU from 2000 to 2011. All students were enrolled at MSU; the research program was described to all participants, and participant consent was obtained.

RESULTS

In 2004, we reported results from 4 yr of data collection that simply compared two curriculums: traditional cookbook laboratories versus a form of inquiry laboratory we termed "teams and streams." We have now revisited the original data set and added all the years since that publication to create an even more robust longitudinal study.

Curricular change. Before 2000, we implemented only traditional cookbook approaches in our weekly course laboratories. A reform of both curriculum and assessments generated the nontraditional laboratory formats tested, two versions of teams and streams inquiry laboratories. The reformed inquiry formats implemented in the laboratory raised the time committed for inquiry over the semester from what was 20% in 2000 to >60% today (Table 1).

Quantitative results. We administered a standardized content exam, the MAT, during the final week of semesters from the years of 2000 to 2011. Our MAT exam was built from MCAT practice test questions developed, validated, and purchased from the Association of American Medical Colleges. The normalized MAT scores from each semester indicated that students who participated in the inquiry formats of the course laboratory made significant gains in learning. One-stream inquiry laboratory semester score averages (64.73%) were found to be significantly higher than two-stream inquiry laboratory scores (61.97%, $P < 0.01$), and students in both scored significantly higher than those in the traditional course laboratory (53.48%, $P < 0.0001$; Fig. 1). Raw MAT scores for all semesters were normalized for variations in each cohort's prior academic performance using ACT scores (Fig. 1, *insets*).

In addition, when the student performance data were pooled into three bins based on the laboratory format used, a stepwise movement of the distribution became apparent (Fig. 2). The mode for performance of students who participated in the full semester-long one-stream laboratory was 70%, whereas the two-stream laboratory format had a mode of 65% and the cookbook laboratory format mode was much lower, at 45%. Not surprisingly, higher levels of content mastery, for example, scores of 75% and 80%, were more frequent among students who participated in one-stream laboratories than the other two formats (Fig. 2).

We examined student performance on each subtopic area evaluated on the MAT instrument. The data showed a positive

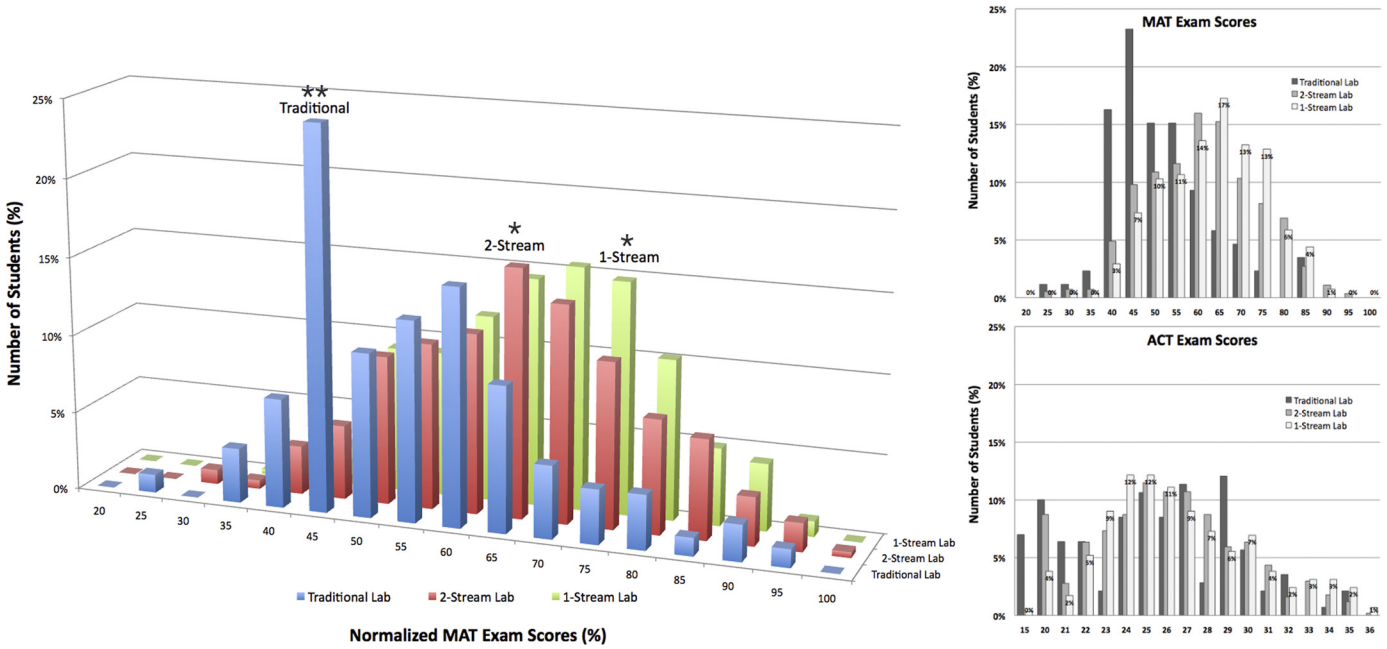

Fig. 2. Students who took courses that offered inquiry laboratories scored higher on the MAT exam than their peers with traditional cookbook laboratory experiences, and students who participated in the recent one-stream version of inquiry laboratories did best. Normalized MAT performance distribution compared students who participated in two semesters that offered traditional cookbook laboratories ($n = 86$) versus two-stream inquiry laboratories between 2001 and 2006 ($n = 551$) and one-stream inquiry laboratories ($n = 306$) between 2007 and 2011. Student scores are represented by sorting MAT scores into bins ranging from 20.01% to 25.0% (labeled 25), 25.01% to 30.0% (labeled 30), and so on. No students scored below 20.01% or above 95.0%. Students in courses with traditional laboratories are represented by blue. Students in courses with a two-stream version of the inquiry laboratory are represented by red. Students in courses with a one-stream inquiry laboratory are represented by green. *Top inset*: for comparison, the distribution of MAT scores in all semesters is shown before normalization. *Bottom inset*: ACT performance distribution comparing students in the three treatment groups. ACT scores for the semesters studied were used to normalize all students' MAT scores. Student scores from both TS laboratory formats were found to be statistically significant from students who participated in the traditional cookbook laboratory format (**$P < 0.0001$ by ANOVA). Scores of students who participated in the two-stream format were also significantly different from those in the one-stream format (*$P < 0.01$ by ANOVA).

trend for normalized scores in all five subtopic categories on the MAT (Fig. 3). Slopes for the associated linear trend lines for MAT subtopics of cell structure and function, cancer, respiration, microbiology, and DNA were +.014, +.0103, +.0037, +.0039, and +.0039, respectively, and were not significantly different from each other. The 95% confidence intervals shown in Fig. 3 demonstrate that students who participated in inquiry laboratories performed far better than their peers on topics of cell structure and function, cancer, and, in some semesters, respiration.

We also looked for trends in the data that might literally support what in 2004 we put forward as our philosophy of "less teaching, more learning." Student normalized performance on the MCAT-based content exam increased from a 54% average

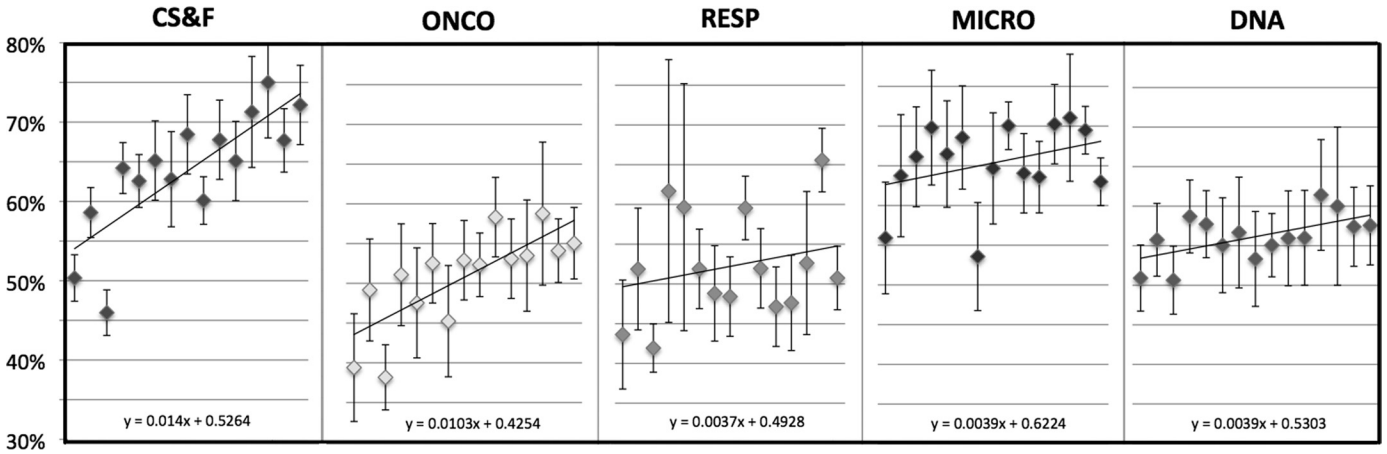

Fig. 3. Student performance on separate topics of the MAT exam. Semester averages and associated trend lines on MAT subtopics are from 15 semesters from 2000 to 2011. The *y*-axis of the average score for each category (in %) is the same scale for all graphs. The *x*-axis is time (in semesters; not shown). The 40 questions on the MAT exam were divided into 5 categories based on the topic tested: cell structure and function (CS&F; $n = 16$ questions), oncogenes and cancer (ONCO; $n = 6$ questions), respiration (RESP; $n = 4$ questions), microbiology (MICRO; $n = 4$ questions), and DNA structure and function (DNA; $n = 10$ questions). Error bars represent 95% confidence intervals for each point. A linear trendline was plotted for each set of points, and the resulting equation is shown.

in 2000 to 67% in 2011, yet at the same time several traditional indicators of content coverage have clearly decreased. We quantitated content coverage and compared that graphically with the performance scores over the decade (Fig. 4). Until 2000, the classroom laboratory was composed of 100% traditional cookbook laboratory experiments, but since that time the amount of traditional cookbook laboratory content has continually decreased to the present, relative, 33%. Additionally, the number of pages covered in the textbook for lecture also decreased over the semesters from what was set to be 100% coverage in 2000 (281 pages) to 73.63% coverage in 2011 (241 pages). Finally, and perhaps most interestingly, while the MAT exam was originally created in the late 1990s based on what was covered in the course, by 2011 we no longer had formal instruction on a number of the topics still tested on the MAT. In a careful examination of each test question, we found that the number of exam questions that were on topics covered in class decreased over the semesters, from 87.5% (35 questions covered) to 60% (24 questions covered). While this varies somewhat from instructor to instructor, we rarely cover the topics of viruses, oncogenes, or some organic chemistry and microbiology that we once did. Overall, it seems that there has been a great decrease (44% when averaged over three indexes) in traditional coverage (Fig. 4).

Since we gave the same test to every cohort, the data suggest that students are doing as well (or better) on an exam for which they receive less traditional preparation (Fig. 5). Surprisingly, student performance even rose on questions in topic areas not covered in any traditional way in the course (Fig. 5, *inset*). Therefore, while coverage decreased by as much as 44%, the normalized MAT scores increased by 13%, suggesting that less teaching, or perhaps more accurately less time dedicated to instructor talking, can lead to more learning.

Qualitative survey results. To assess student feedback about the classroom and laboratory, MSU SIRS forms were examined during all semesters studied from spring 2000 to spring 2011. Throughout these semesters, the classroom lecture and recitation have remained reasonably fixed in format, whereas laboratory experiences have changed significantly from traditional laboratories to those implementing inquiry approaches, and so have the responses on the SIRS reports.

Student feedback and comments were sorted/coded using a number of categories. Examples of frequent student comments in categories of laboratory skills (writing), laboratory skills (technical), mental skills, affective, and groups are shown in Table 2. Broadly, feedback from the one- or two-stream laboratories suggested that the students often felt that the workload was higher than that of traditional laboratories; however, students also commented on the great knowledge gains they believed they had made from the inquiry laboratory experience.

In addition to the comments describing the students' experience in the class, we also studied the frequency of positive comments and negative comments related to the general topic areas of "lecture" and "laboratory" and the coded categories described above (Fig. 6). This was done on a semester basis and sorted according to whether the students experienced a semester of traditional cookbook laboratories, a two-stream inquiry laboratory, or a one-stream inquiry laboratory (see Table S3 in the Supplemental Material). Very few comments were given for the traditional laboratory format (<1% response rate), and only 20% of students gave positive responses (n =

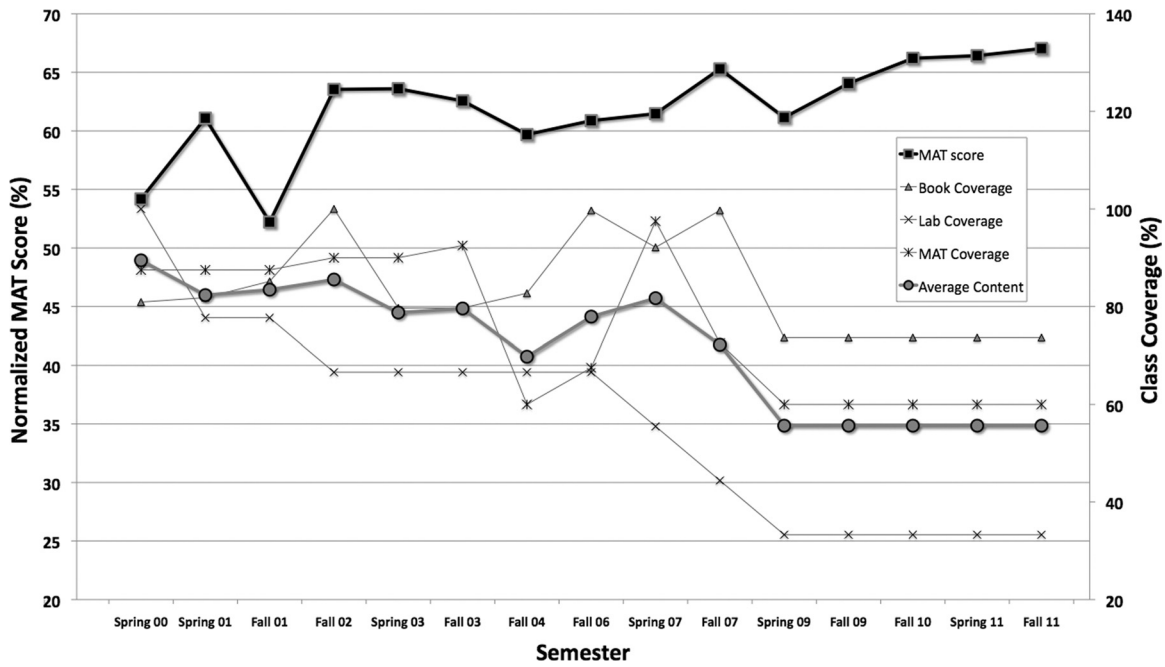

Fig. 4. Comparison of student performance on the MAT (exam scores) with the amount of material "covered" in course. The black line (with squares) shows the change in normalized MAT exam scores over the study period (2000–2011) with the *y*-axis on the *left*. The *y*-axis on the *right* is used for the percentage of coverage. The thin gray line (with triangles) depicts the change in the required reading of pages covered in the course textbook; the highest number was set to be 100%. The thin gray line (with gray ×) represents the change in laboratory coverage over time. The thin gray line (with gray *) corresponds to the percentage of MAT questions that were on topics covered in the course. The broad gray line (with circles) represents the content average of laboratory, textbook, and MAT coverage by semester. While the amount of material covered decreased, student performance did not follow; in fact, an upward trend in MAT scores occurred.

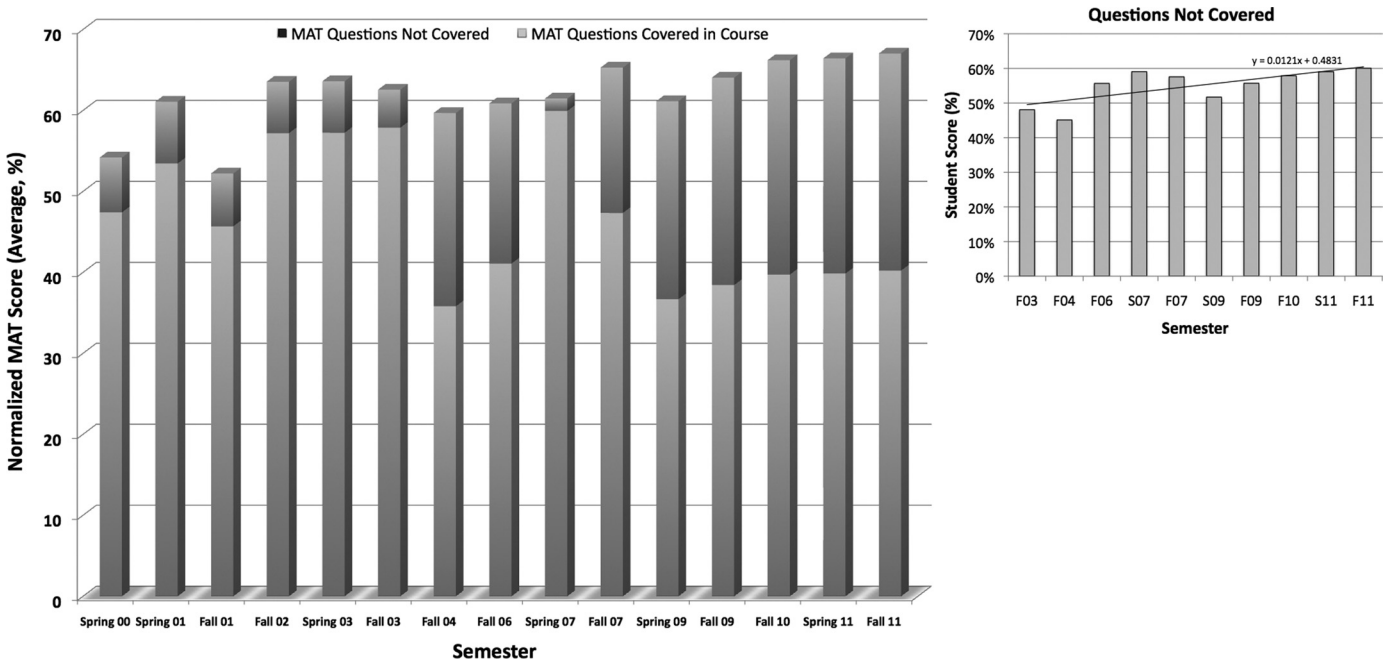

Fig. 5. MAT exam scores trended upward each semester, yet fewer questions on the exam were "covered" in class. Each semester's normalized MAT exam score is represented with the proportion of the exam questions that were covered (*bottom*, light gray) by explicit instruction in the course that semester. Over the years, the number of questions on the MAT exam not covered (*top*; dark gray) has grown. *Inset*: scores achieved by students on MAT questions not covered in recent semesters also trended upward.

70 comments; Fig. 6). In comparison, we found that feedback from all semesters using the two-stream inquiry approach was more plentiful (50% response rate) and averaged 71% positive responses (n = 473). Additionally, once the one-stream approach to laboratory was implemented, the response rate increased further, and the approval rating rose to 96% in the course evaluation reports (n = 304, 86% response rate). Student feedback regarding lecture or "class" remained generally

Table 2. *Examples of evidence collected from student response forms from fall 2003 to spring 2011*

Category	Learning Outcomes Reported	Semester
Laboratory skills (writing)	• "Also working in a group on the papers helped me to see areas in my writing that could use improvement."	Fall 2003
	• "The papers, as much of a pain as they were–helped me master the material because they forcer me to think a step further than basic lab protocols."	Fall 2003
	• "I feel that my scientific writing has improved due to the many manuscripts and drafts we had to write for lab. I walk out of here feeling accomplished and like I learned something."	Fall 2011
Laboratory skills (technical)	• "I actually learned so much about my disease, primer design, gel electrophoresis and troubleshooting. My confidence in performing these tasks has really gone up."	Spring 2011
	• "Since we were not doing cookbook labs every week it gave me more time to develop and really learn the skills that will be valuable in for any future lab position."	Fall 2009
	• "Because of the lab I now feel extremely confident conducting an experiment, using nearly all lab tools, and being able to analyze my results in a way that will allow me to continue with the experiment and build on it."	Fall 2010
Mental skills	• "I have learned more from this lab than any other lab because of the freedom of experimental design."	Spring 2007
	• "Feel confident I could leave this lab and lab work and do the things I did here somewhere else."	Fall 2010
	• "I know I made great gains in my precision and attention to detail as a scientist in the laboratory."	Spring 2011
	• "[Stream labs] Increased learning a lot–forced me to know details and use conceptual thinking/troubleshooting."	Fall 2006
Affective responses (positive)	• "I really enjoyed this class. My favorite class yet!"	Fall 2006
	• "Its (sic) cool to do your own research and come up with your own topics and experiments."	Fall 2007
	• "[Stream labs] Make it so much interesting to learn, and I learned so much!"	Spring 2009
	• "The lab not only increased my confidence in my knowledge of biology and lab techniques, it also made me feel like a scientist."	Fall 2010
	• "This lab was not your typical cookbook lab, which was a breath of fresh air."	Spring 2011
Groups	• "The groups are great! Since I was already part of a group in class, it was easy to find a study group or to find someone to ask questions."	Fall 2003
	• "I like having the group experience far more than just the lab, but also in the class and outside of the class."	Fall 2007
	• "Working in groups made a huge difference in my understanding of the material."	Fall 2010

Categories were arranged based on gains that reported by the students. Categories such as laboratory skills, mental skills, affective responses (positive or negative), and groups are addressed further in Tables S3 and S4 (available in the Supplemental Material).

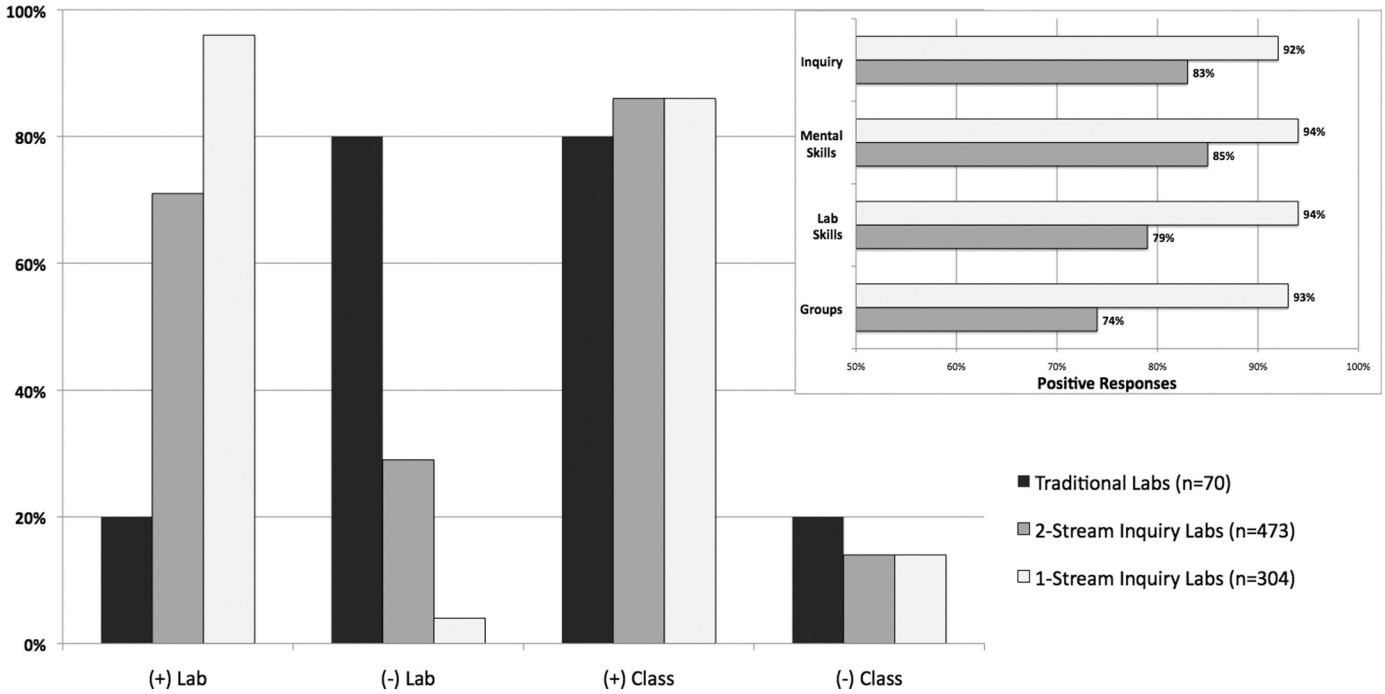

Fig. 6. Student feedback about their laboratory and class experiences from course evaluation forms. Data from student feedback surveys (Michigan State University Student Instruction Rating Survey and Student Assessment of their Learning Gains forms) show the frequency of positive (+) versus negative (−) feedback on the topic of the "lab" or "class" over the semesters studied using the traditional structured laboratory versus those semesters using two versions of the TS inquiry laboratories. Feedback on each topic area was coded and summed (traditional laboratories: $n = 70$ comments, two-stream inquiry laboratories: $n = 473$, and one-stream inquiry laboratories: $n = 304$). *Inset*: feedback on several subtopics associated with the laboratory over semesters using two different formats of the TS inquiry laboratories. Feedback was coded and summed for topics related to working in "groups" ($n = 97$), gain of "lab skills" (physical, $n = 194$), gain of "mental skills" ($n = 307$), and use of "inquiry" ($n = 195$). The numbers of student comments (n) do not equal the numbers of students enrolled in each course.

positive and unchanged throughout the time period studied (80%, 84%, and 86%, respectively; Fig. 6). We also compared student feedback for semesters that used two-stream laboratories versus those that used a one-stream format (see Table S4, in the Supplemental Materials). One-stream laboratories had 92% positive feedback for inquiry, 94% for mental skills, 94% for laboratory skills, and 93% for group work compared with 83%, 85%, 79%, and 74%, respectively, for the two-stream approach (Fig. 6, *inset*).

DISCUSSION

In previous years, we reported increased learning in student cohorts as we transitioned from traditional cookbook laboratory sequences to multiweek group inquiry investigations in our freshmen-level introductory biology classroom (19, 28). In recent years, we have implemented a full semester-long research experience in the hope that it would deepen the inquiry and raise the learning gains with more time spent on scientific writing, oral presentations, analysis of laboratory results, and troubleshooting during the same project. In this study, we compared student opinions and academic performance over a 10-yr period in which the science course laboratory curriculum changed dramatically. The three formats compared were as follows: traditional weeklong cookbook laboratories, two 7-wk-long inquiry laboratories, and one 14-wk-long inquiry laboratory. As expectations of the level of inquiry were raised in the classroom and far more time was dedicated to each project, a decade of data supports that learning gains on content exams trended upward even while the amount of traditional content coverage taught moved downward.

Students make significant learning gains when participating in inquiry laboratories. To gauge students' learning of content, through the decade study period we examined student performance on a 40-question MAT exam built with MCAT test questions. We found that students engaged in the one-stream inquiry laboratory scored the highest on the end-of-semester MAT exam. These students significantly outperformed those in the two-stream inquiry laboratories and those who participated in traditional cookbook-style laboratories (MAT raw scores: one-stream format, 62.6%; two-stream format, 59.3%; and traditional format, 48.9%). When we used students' prior performance on the ACT exam to normalize the MAT scores from each semester, the statistical significance of the increasing trend seen with raw performance scores was maintained (MAT normalized scores: 64.73%, 61.97%, and 53.48%, respectively). The data support our belief that students in the inquiry laboratories had the greatest gains in the understanding of biology compared with those in cookbook experiences and that the shift to longer full-semester inquiry may lead to the greatest learning.

Another aspect of this study involved documenting changes in the traditional content provided during the course. From 2000 to 2011, the amount of overall class coverage declined by ~44%, whereas the averages on MAT exams increased by 13% over the same period. Even when we evaluated test questions on topics not covered in any traditional way in the

course, student performance still increased. We believe that these data may help lessen a concern of our colleagues that they should at least "touch on" certain topics. Our data suggest that a more efficient use of time is mastering fewer topics deeply while fostering the development of critical thinking skills that enable the student to apply known information (with greater confidence) to new topics. We believe that these skills of critical thinking and transference are necessary for becoming a productive scientist as well as being useful in making informed life decisions.

Students appreciate the change to inquiry experiences. Student opinion was a motivator of change for our faculty. In the late 1990s, students' opinions about their laboratory experience were less than enthusiastic. Students asked biology faculty advisors whether they should leave the Physiology major because "I don't think I could do that stuff, like in intro bio lab, for my career." Comments on course evaluations were frequently just "labs are boring and time consuming." During interviews, students told us that it wasn't how they imagined science would be. Upon reflection, we agreed that "real science" was very different than the way we were teaching it. This led to the decade of changes that were evaluated and presented in this study. Looking backward in time, through the analysis of course evaluation forms, noticeable differences were observed between students who participated in each format of laboratory curricula. When examining the positive comments versus negative comments related to the laboratory, only 20% of students left positive comments regarding the early traditional cookbook laboratories. However, as the format of the laboratory changed, the number of positive responses increased to 71% of all responses for the two-stream format and 96% of all responses for the one-stream format of laboratories. The qualitative data showed positive changes in both the response rate on the topic of the laboratory as well as student opinions toward traditional versus active inquiry forms of pedagogy. The student responses strongly support that the students believed the changes in the laboratory curriculum were beneficial to their learning.

Challenges for instructors when changing to inquiry laboratories. Often faculty members find it hard to step out of their comfort zone to teach an inquiry laboratory and may find this especially difficult since they were not taught this way (25). However, this change in the curriculum has proven to be beneficial in a variety of classrooms and results in better test scores and increased learning in the long term (4, 5, 30). We found that changing the classroom laboratory from cookbook to inquiry was uncomfortable at first but ultimately liberating to faculty instructors. At each step in the process, our faculty members discovered the classroom laboratory became a more familiar environment, just like working with students in their own research laboratory. Once we became accustomed to running inquiry laboratories, we found the day-to-day operation of the laboratory to be much easier and in fact less expensive than the traditional "different laboratory each week" paradigm. The incredible effort associated just with preparing supplies and training teaching assistants each week for the next cookbook laboratory became a distant memory. Graduate students who serve as teaching assistants also spend a great amount of time working in their own, real laboratory, and although they too resist change, this is the type of change they can more quickly appreciate. Perhaps surprisingly, a recent study (9) has even documented that graduate students who teach in inquiry laboratories tend to master the critical thinking and practice of experimental design more quickly during their graduate studies.

How physiology majors respond to inquiry laboratories. Our students are a population dominated by Premed and Physiology majors, many with differing views of which teaching approach stimulates their learning most. A number of studies (3, 5, 14, 15, 18, 29, 30) have found that students find an inquiry-based research experience more beneficial than traditional cookbook laboratories. Furthermore, students tend to believe that their knowledge is not tested by cookbook laboratories (12). Student opinions certainly played a role in stimulating our faculty to switch to a creative, active, inquiry-based classroom laboratory, and we hoped this premed motivation might also help students engage with and value their performance on our standardized MAT posttest exam, even though it had no impact on their course grade. Given that exams like the MCAT include a number of higher-level thinking problems (31), superficial content coverage may not help students prepare well. If students have more time to focus on one topic in a laboratory and on the process of doing science, greater scientific literacy can be gained. Some studies (13, 15) have found that students experiencing inquiry laboratories become better able to integrate their knowledge and move seamlessly between published research and topics discussed in class, resulting in higher learning.

Less teaching, more learning. We define our use of the term "less teaching" as moving the burden of active effort from the teacher to the student. Given that active and collaborative construction of knowledge "works" (20) and represents a student-centered classroom, having instructors do all the work does not make sense. A number of studies (16, 24) have suggested that depth instead of breadth of coverage in introductory science classes correlates well with later success.

The research literature suggests our findings apply not only to introductory biology courses but also to upper-level classes. In many physiology classes, there is likely too much coverage to allow deep learning, and, as a result, many students reject meaningful learning and resort to using rote memorization to succeed. However, evidence presented in the literature suggests if less content was covered and students experienced an active learning environment, they could achieve greater gains in knowledge (6, 7, 30).

Conclusions. One of the goals of attempting the 14-wk-long one-stream inquiry laboratory was to give students more freedom to develop their own ideas and opportunities to troubleshoot and experience the process of improving their experimental design. The time that students devote to designing (and redesigning) their experiments can be extraordinarily beneficial and has been linked to a greater understanding and improved test scores (2). This greater freedom, combined with the challenges of an ill-structured problem, brings both "pain and gain" that rarely occurs in traditional cookbook laboratories. This challenging environment can ultimately help students make greater gains in learning and in the mastery of scientific laboratory skills (1, 23). Overall, our findings align well with the literature that suggests that by participating in a laboratory curriculum that is enriched for problem solving and authentic inquiry, students have a greater chance to gain more interest in biological research, increase learning, im-

prove critical thinking and analysis, and become better suited for future endeavors (27).

Over the years, faculty instructors in our department who made the change from teaching cookbook laboratories reported that using multiweek inquiry laboratories, especially the one-stream format, "felt more natural, like work done in my own lab." In our own basic science research, we take great care and time exploring our research topic deeply; we spend months/years performing experiments, reading literature, and thinking about our research. When students experience a similar opportunity in the classroom, the education research literature supports our own intuition, specifically that more time on task to achieve deeper understanding in fact "works." Students gain deeper more meaningful understanding of topics, techniques, and the process of doing science and can respond to probing questions like "OK, now design for me an experiment to test that idea." Pursuing longer inquiry experiences with more time yields more formal and informal opportunities for students to talk and write about science, which, not surprisingly, allows students to also makes gains in communication skills like scientific writing and public speaking (10).

While the curricular revisions reported in this study are similar to other reports in the literature, many scientific educators have yet to be convinced to change their teaching to be a more active, student-driven laboratory. The majority of undergraduate laboratory experiences in the United States remain predominately the traditional cookbook style. We hope with this publication and the support of others completing similar research with both qualitative and quantitative studies, more of our peers in science will begin to examine these findings with interest and make progress moving deliberately to challenge students with active, engaging teaching methods and, in particular, using more inquiry in the classroom laboratory.

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AUTHOR CONTRIBUTIONS

Author contributions: D.B.L. and J.J.M. conception and design of research; D.B.L. and J.J.M. performed experiments; D.B.L., J.R.A., B.J.M., A.M.R., L.A.F., and J.J.M. analyzed data; D.B.L., J.R.A., B.J.M., A.M.R., L.A.F., and J.J.M. interpreted results of experiments; D.B.L., J.R.A., B.J.M., A.M.R., and L.A.F. prepared figures; D.B.L., J.R.A., B.J.M., A.M.R., and L.A.F. drafted manuscript; D.B.L., J.R.A., B.J.M., A.M.R., L.A.F., and J.J.M. edited and revised manuscript; D.B.L., J.R.A., B.J.M., A.M.R., L.A.F., and J.J.M. approved final version of manuscript.

REFERENCES

1. **Anjur SS.** Student-centered physiology in high schools. *Adv Physiol Educ* 35: 161–167, 2011.
2. **Aronson BD, Silveira LA.** From genes to proteins to behavior: a laboratory project that enhances student understanding in cell and molecular biology. *CBE Life Sci Educ* 8: 291–308, 2009.
3. **Casem ML.** Student perspectives on curricular change: lessons from an undergraduate lower-division biology core. *CBE Life Sci Educ* 5: 65–75, 2006.
4. **Casotti G, Rieser-Danner L, Knabb MT.** Successful implementation of inquiry-based physiology laboratories in undergraduate major and nonmajor courses. *Adv Physiol Educ* 32: 286–296, 2008.
5. **Derting TL, Ebert-May D.** Learner-centered inquiry in undergraduate biology: positive relationships with long-term student achievement. *CBE Life Sci Educ* 9: 462–472, 2010.
6. **DiCarlo SE.** Cell biology should be taught as science is practised. *Nat Rev Mol Cell Biol* 7: 290–296, 2006.
7. **DiCarlo SE.** Too much content, not enough thinking, and too little fun! *Adv Physiol Educ* 33: 257–64, 2009.
8. **Donovan MS, Bransford JD, Pellegrino JW.** *How People Learn: Bridging Research and Practice*. Washington, DC: National Academy, 1999.
9. **Feldon DF, Peugh J, Timmerman BE, Maher MA, Hurst M, Strickland D, Gilmore JA, Stiegelmeyer C.** Graduate students' teaching experiences improve their methodological research skills. *Science* 333: 1037–1039, 2011.
10. **FitzPatrick KA, Campisi J.** A multiyear approach to student-driven investigations in exercise physiology. *Adv Physiol Educ* 33: 349–355, 2009.
11. **Handelsman J, Ebert-May D, Beichner R, Bruns P, Chang A, DeHaan R, Gentile J, Lauffer S, Stewart J, Tilghman SM, Wood WB.** Education. Scientific teaching. *Science* 304: 521–522, 2004.
12. **Henige K.** Undergraduate student attitudes and perceptions toward low- and high-level inquiry exercise physiology teaching laboratory experiences. *Adv Physiol Educ* 35: 197–205, 2011.
13. **Hoskins SG, Stevens LM.** Learning our LIMITS: less is more in teaching science. *Adv Physiol Educ* 33: 17–20, 2009.
14. **Howard DR, Miskowski JA.** Using a module-based laboratory to incorporate inquiry into a large cell biology course. *Cell Biol Educ* 4: 249–260, 2005.
15. **Jensen JL, Lawson A.** Effects of collaborative group composition and inquiry instruction on reasoning gains and achievement in undergraduate biology. *CBE Life Sci Educ* 10: 64–73, 2011.
16. **Knight JK, Wood WB.** Teaching more by lecturing less. *Cell Biol Educ* 4: 298–310, 2005.
17. **Krontiris-Litowitz J.** Articulating scientific reasoning improves student learning in an undergraduate anatomy and physiology course. *CBE Life Sci Educ* 8: 309–315, 2009.
18. **Lord T, Orkwiszewski T.** Moving from didactic to inquiry-based instruction in a science laboratory. *Am Biol Teacher* 68: 342–345, 2006.
19. **Luckie DB, Maleszewski JJ, Loznak SD, Krha M.** Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of "Teams and Streams". *Adv Physiol Educ* 28: 199–209, 2004.
20. **Luckie D, Harrison SH, Ebert-May D.** Model-based reasoning: using visual tools to reveal student learning. *Adv Physiol Educ* 35: 59–67, 2011.
21. **Momsen JL, Long TM, Wyse SA, Ebert-May D.** Just the facts? Introductory undergraduate biology courses focus on low-level cognitive skills. *CBE Life Sci Educ* 9: 435–440, 2010.
22. **Morgan E.** *BIO2010: Transforming Undergraduate Education for Future Research Biologists* (online). http://www.nap.edu/openbook.php?isbn=0309085357 [21 Oct. 2011].
23. **Myers MJ, Burgess AB.** Inquiry-based laboratory course improves students' ability to design experiments and interpret data. *Adv Physiol Educ* 27: 26–33, 2003.
24. **Schwartz MS, Sadler PM, Sonnert G, Tai RH.** Depth versus breadth: how content coverage in high school science courses relates to later success in college science coursework. *Sci Educ* 93: 798–826, 2009.

25. **Silverthorn DU, Thorn PM, Svinicki MD.** It's difficult to change the way we teach: lessons from the Integrative Themes in Physiology curriculum module project. *Adv Physiol Educ* 30: 204–214, 2006.
26. **Smith J, Cheruvelil K.** Using inquiry and tree-thinking to "March through the animal phyla": teaching introductory comparative biology in an evolutionary context. *Evol Educ Outreach* 2: 429–444, 2009.
27. **Treacy DJ, Sankaran SM, Gordon-Messer S, Saly D, Miller R, Isaac SR, Kosinski-Collins MS.** Implementation of a project-based molecular biology laboratory emphasizing protein structure-function relationships in a large introductory biology laboratory course. *CBE Life Sci Educ* 10: 18–24, 2011.
28. **Wilterding JH, Luckie DB.** "Stream"-lined education: increasing student-initiated learning with an investigative DNA "stream". *J Coll Sci Teach* 31: 303–307, 2002.
29. **Wood WB.** Inquiry-based undergraduate teaching in the life sciences at large research universities: a perspective on the Boyer Commission Report. *Cell Biol Educ* 2: 112–116, 2003.
30. **Wright RL, Klymkowsky MW.** Points of view: content versus process: is this a fair choice?: undergraduate biology courses for nonscientists: toward a lived curriculum. *Cell Biol Educ* 4: 189–196, 2005.
31. **Zheng AY, Lawhorn JK, Lumley T, Freeman Assessment S.** Application of Bloom's taxonomy debunks the "MCAT myth". *Science* 319: 414–415, 2008.