

Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of “Teams and Streams”

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Luckie, Douglas B., Joseph J. Maleszewski, Sarah D. Loznak, and Marija Krha. Infusion of collaborative inquiry throughout a biology curriculum increases student learning: a four-year study of “Teams and Streams”. *Adv Physiol Educ* 287: 199–209, 2004; doi:10.1152/advan.00025.2004.—Are traditional laboratories in the core introductory biology courses teaching physiology majors the art and trade of science, or simply leaving them with a memory of trivial experiments done for unknown reasons? Our students, a population dominated by premed and physiology majors, think the latter and have encouraged us to challenge this model, and it turns out scientists and education researchers agree with our students (4, 31, 32). In an effort to remedy this, we began a long-term redesign of the introductory biology sequence to become what is now a sequence of inquiry laboratories we term “Teams and Streams” (TS). In these TS inquiry labs, student research teams pose a scientific question/hypothesis, propose an experimental design, perform multi-week investigations and then present their findings in various forms (web, interviews, and papers). The response to this classroom laboratory design has been overwhelmingly positive. In a qualitative study of student opinion (where 260 student responses were studied), surveys conducted at the end of semesters where traditional scripted labs were used ($n = 70$ comments) had predominately negative opinions (80% negative responses), whereas the reverse was true for students ($n = 190$ comments) who participated in courses using the TS inquiry labs (78% positive responses). In a quantitative assessment of content knowledge, students who participated in new TS inquiry labs ($n = 245$) outscored their peers in traditional labs ($n = 86$) on Medical College Admission Test-style standardized exams ($59.3 \pm 0.8\%$ vs. $48.9 \pm 1.3\%$, respectively; $P < 0.0001$). We believe these quantitative data support the qualitative findings and suggest the TS inquiry lab approach increases student learning.

laboratory; cooperative; undergraduate; research

SCIENCE IS CLASSICALLY defined as the pursuit of new knowledge and scientists practice this process every day by employing techniques (both conventional and novel) in their laboratories (28). However, when science students (especially in introductory courses) work in the classroom laboratory, they rarely experience this process (24, 27, 32, 39, 44). It is not unusual for a college freshman to change their science major after their first semester (20, 24, 44), reasoning, “I don’t think I could do that stuff, like in my 101 lab, for my career.” It is difficult to explain to the student why the experience in that classroom lab has little in common with the fun in a real lab. The current standard of educating undergraduate students in the art of laboratory biology generally involves issuing a laboratory manual and charging the students with replicating a “science

experiment” that thousands of other students have done before them (4, 36, 50). The assessment of learning that follows is often based on whether they replicated the experiment well or not and if they wrote a good lab report. The fact that hundreds of similar papers for each lab written by students from past semesters are floating around campus, further complicates this assessment. The thought behind this traditional teaching method is to expose students to a variety of techniques in the hopes they will come to understand and appreciate them later, but many of the students don’t stick around for “later” (24, 44).

In introductory biology classes in the Lyman Briggs School of Science at Michigan State University, our students have encouraged us to challenge (and indeed change) this model.¹ When we asked students what they liked least about their laboratory experience we consistently received answers like: “labs are boring and time consuming.” Students told us that it wasn’t how they imagined science would be (39). Upon reflection, we agreed that “real science” was very different than the way we taught it (24, 32, 38). Why couldn’t we teach all of the important techniques and allow them to think and problem solve like a real scientist, even at this introductory level?

On the basis of this feedback, we changed our classroom laboratory curriculum. Our goal was to allow students to develop a biological question and then devise a series of experiments that would enable them to gather evidence to support or refute their hypothesis (2, 11, 12, 21, 25, 26, 35). We also made it a goal to increase the cognitive level targeted by our assessments, which had previously been directed at assessing primarily the “Knowledge” level as defined by Bloom (3). New assessments were created with an eye to go beyond this level and perhaps approach Application, Analysis, and Synthesis (Table 1). We also strived to create a formula that followed the mantra, “Less Teaching, More Learning.” We knew the new approach would have the best chance to be sustainable if we could decrease the workload of the teacher(s) while at the same time increasing the learning of the student (10, 43, 51). As we developed rigorous goals for the students’ experiments as well as their learning, we soon realized that the burden of this project would likely be too great for one student to bear alone (35, 49). With the help of cooperative learning experts like Karl Smith and others (19, 46), we decided that group work would give us more flexibility, be more like “real science,” and enable us to raise the bar and expect a higher

¹Lyman Briggs School of Science is a residential undergraduate science program established at Michigan State University in 1967. It is a residential college modeled after those at Oxford University that has a focus of educating undergraduates in a “liberal science” curriculum defined as a solid foundation in the sciences and a significant liberal education in the history, philosophy, and sociology of science.

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Table 1. *Bloom's taxonomy*

Level	Title	Definition	Example
1	Knowledge	Knowledge is the lowest level of cognition, and it involves remembering factual material	To assess knowledge have students recite facts. For example, ask students who discovered the structure of DNA.
2	Comprehension	At the Comprehension level, you are checking for understanding.	Asking students to paraphrase a theory not just recite its definition.
3	Application	At the Application level, students take what they know and use it in new way.	Use the "law" of Evolution, to solve problems, or explain why sickle cell anemia is maintained in the gene pool.
4	Analysis	Analysis is a skill that involves taking a process, or thing, and breaking it down into its basic parts.	A student might analyze a lysosome organelle by its parts and chemistry, or analyze the cause(s) of a storage disease due to loss of a critical enzyme.
5	Synthesis	Synthesis is the ability to put pieces of evidence together to form new ideas, theories, or explanations.	Student examines a research question, available assays, and constraints of their lab situation, and design a research plan to find the answer.
6	Evaluation	Evaluation, involves intelligent critiquing of a product, a process, or a theory.	To make a reasoned judgment, students need to have relevant knowledge, skills, and be able to analyze the situation to synthesize their ideas.

Distinctions can be made among cognitive levels, and one classification of cognitive skills is Bloom's taxonomy (3). Bloom established six ascending levels of thinking: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation.

level of learning and research from the students (5, 8, 25, 26, 40). After all, scientists rarely work in isolation. What we strived to create were structured learning teams that experienced active and cooperative inquiry during independent research projects (13, 17, 47).

Revisions in Curriculum

We started examining the traditional cookbook laboratory sequence first only in the Cell and Molecular Biology Course (Introductory Biology II), later these revisions were applied throughout the biology curriculum of Lyman Briggs, a residential college at Michigan State University (MSU).² The innovations tested in this study were in the laboratory while the lecture was unchanged. The classroom laboratory had previously been divided into numerous 3-hour scripted lab experiments that students performed individually. The schedule of the laboratories mirrored that of the lecture topics and was just as brief and diverse. Although we, as instructors, "saw" the relationship between all the labs, the students did not (42, 44, 45, 49, 50). To them it was just a buffet of a different topic every week. The first few traditional labs were cell biology-related and dealt with macromolecules and carbohydrate chemistry, hormones and plant tissue culture, enzymes kinetics, and light and dark reactions in photosynthesis (Table 2). The labs during the second half of the semester were more molecular biology-related and had been recently revised to involve the students in a slightly more proactive version of learning standard techniques in molecular biology (*Escherichia coli* transformation, Plasmid miniprep, and DNA restriction analysis) (53). For the purposes of simplicity and space in this report, we will only focus on the first half of the semester, what we now call Stream I. For more information and details on the innovations beyond what is discussed here, view this website (<http://surf.to/teamstreams/>).

²Introduction to Cell and Molecular Biology is a five-credit sophomore-level course. It is the second in a core two-semester sequence for science majors (and the last 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, one recitation (50 minutes each), and two laboratory sections (6 hours) each week.

Developing Long-Term Independent Research Experiences, or "Streams"

Semesters at MSU are 15 weeks in length, so we decided to divide the laboratory sequence into two 7-week streams. In our revision of the laboratory curriculum of Stream I, we wanted students to choose their own topics and design their own long-term research projects (12, 15, 25, 26, 30, 36, 41, 47, 52). We decided the first stream would need 1 week of orientation (15–16, 21, 28), followed by 6 weeks of laboratory time, in which the students would be exposed to new material, equipment, and techniques, and then implement them in their unique research projects. But how would we get students to learn proper techniques and still allow them independence?

For us, the answer was to divide the six weeks into three two-week blocks on each topic. The first week of each block is devoted to having the student group perform one of our best traditional cookbook labs on that topic, while the second week was reserved for independent research (Table 3). The traditional lab served to train the students in techniques and assays, and its results could be utilized as initial experiments (controls, in fact) for their independent investigations (13–16, 21, 28). The second week was "open" and allowed students to apply the methods learned in the previous week to test their own research questions (1, 6, 7, 23). For example, in the first traditional lab week, the student team would follow a lab guide and perform various chemical assays on carbohydrate solutions of glucose, fructose, xylose, etc. They would test known sugars for structural characteristics like aldehyde vs. ketone groups, polysaccharide vs. monosaccharide status etc, as well as then characterize an unknown sugar. After this traditional lab, during *week 2*, students would create their own protocols and plans and could utilize any of these techniques/assays (or find/create their own) to perform experiments to help answer their research question. The equipment and reagents used in cookbook labs are all that were made available, yet students were permitted to do more with the help of scientists on campus. Time was not limited except by the due date of each draft of their paper. Thus each student group would follow a structured schedule where they complete a traditional lab on carbohydrate macromolecules, followed by a week of independent research, next perform a traditional lab on photosynthesis and a week of

Table 2. *Before: Traditional curricular design and assessment strategy of Introductory Biology before redesign*

Week	Laboratory Topic	Assessments Used	Assessed "Skill"	Bloom Level
1	No laboratory	NA	NA	
2	Lab 1: Traditional "Structured" lab: Cell Structure via Microscopic Analysis	"Notebook check" at end of lab	<i>Indirectly</i> : using microscope and following directions.	1-Knowledge
3	Lab 2: Traditional "Structured" lab: Tissue Culture and Hormones (5 week long experiment)	See week 8 (TC lab report on the process and answering questions posed in lab manual).	Capacity to write a lab report well and understand topic	1-Knowledge 2-Comprehension
4	Lab 3: Traditional "Structured" lab: Carbohydrate Chemistry plus lipids etc	Quiz, Individual CHO lab report (on the process and answering questions posed in lab manual).	Sugar content knowledge, writing a report, draw sugars.	1-Knowledge 2-Comprehension 3-Application
5	Lab 4: Traditional "Structured" lab: Photosynthesis I (Light Reactions).			
6	Lab 5: Traditional "Structured" lab: Photosynthesis II ("Dark" Reactions).	Individual PHS lab report (on the process, questions, described in manual).	Photosynthesis content knowledge, writing a report.	1-Knowledge 2-Comprehension
7	Lab 6: Traditional "Structured" lab: Enzyme Kinetic Studies.	Midterm Exam (draw illustrations and in class multiple choice exam)	Macromolecular structures and biol. content knowledge	1-Knowledge 2-Comprehension
8	Lab 7: Traditional "Structured" lab: Enzyme Kinetic Studies II and finish the Tissue Culture (Lab 2 completed).	Individual lab report(s) on Enzymes and TC studies (on the processes described in manual).	Content knowledge on lab procedures and topics.	1-Knowledge 2-Comprehension

TC, tissue culture; CHO, carbohydrate; NA, not applicable. This is the first half of a semester-long Biology classroom laboratory, the second half of semester is not shown here.

independent inquiry, and again, one week of a structured lab on enzymes, followed by an open research week (Table 3). While this restructuring of the curriculum was laudable by itself, the most important requirement we implemented was that all the different experiments performed and the manuscript created by the research team, needed to focus on just one research question (and a first draft of the entire research plan for all six weeks be submitted at the end of the first week of class!). Some of the 130 titles of student research plans include: "Differences in Carbohydrates, Polyphenoloxidase, and Photosynthesis Between *Pinus strobus* and *Malus domestica*"; "The Chemical

Difference Between Pancrease and Lipram"; "A Description of How a Pluot is Similar to a Plum Through Carbohydrate, Pigment and Enzyme Activity Tests." (See more online <http://surf.to/teamstreams/>)

Creating Cooperative Groups With Individual Roles, Also Known As "Teams"

During the first day in the classroom laboratory, students meet their group and immediately choose roles for the rest of Stream I. Although each student in the group (typically 4

Table 3. *After: TS Inquiry curricular design and assessment strategy of Stream I after redesign described in this study*

Week	Laboratory Topic	Assessments Used	Assessed "Skill"	Bloom Level
1	Introduction to "Teams and Streams." (read labs, meet group, make plan)	Draft 1 of group manuscript (proposal) on student topic.	Experimental design, writing, content knowledge	1-Knowledge 2-Comprehension 4-Analysis
2	Lab 1: Traditional "Structured" lab: Carbohydrate Chemistry	Quiz, Formal Interview by Prof	Sugar content knowledge, Experimental design	3-Application 4-Analysis 5-Synthesis
3	Lab 1: <i>Inquiry</i> : Apply sugar tests to your question/investigation.	Draft 2 of group manuscript (only on group's topic, experiments and data, etc not traditional lab).	Writing, content knowledge, data analysis, experimental design	1, 2-Knowledge & Comprehension 3-Application 4-Analysis
4	Lab 2: Traditional "Structured" lab: Photosynthesis (Light Reactions).	Peer Review of Draft 2	Reflective critical analysis, data analysis, design	4-Analysis 6-Evaluation
5	Lab 2: <i>Inquiry</i> : Apply photosynthesis tests to your inquiry.	Concept Maps (online)	Connections in content knowledge	1-Knowledge 2-Comprehension 5-Synthesis
6	Lab 3: Traditional "Structured" lab: Enzyme and Protein Studies.	Midterm Exam (essay questions, and in class multiple choice exam, then in class pyramid exam)	Content knowledge (exam, exp design knowledge) essays.	1-Knowledge 2-Comprehension 3-Application
7	Lab 3: <i>Inquiry</i> : Apply enzyme tests to complete your group's inquiry.	Draft 3 final manuscript (only on group's topic, experiments and data, etc not about traditional labs).	Writing revisions, data analysis, math, interpretations.	1-Knowledge 2-Comprehension 4-Analysis
8	Debriefing and Prep for Stream II (complete group writing, clean up areas, prepare for next stream)	(interested in adding a form of performance based assessment here, aka a practical skills test)		

This is the first half *Stream I* of a semester long Biology classroom laboratory, second half of semester, *Stream II*, is not shown here.

people) is expected to help out in all tasks to complete the assignment, each student has a primary role. These roles were titled: Primary Investigator (PI), Protocol Expert (PE), Data Recorder (DR), and Laboratory Technician (LT). For example, the PI is responsible for primary organization of the team as well as oversight of the experiment as a whole. It is the job of the primary investigator to be responsible for implementing troubleshooting techniques throughout the investigations. The PE, on the other hand, is responsible for overseeing the creation of scientific protocols for each week's independent investigation (what experiments/steps you plan to do) as well as is responsible for construction of websites (when necessary), and other computer related activities and so on. These individual roles help to organize the team and give each person a job in the group (5, 19, 46).

In addition, to foster group identity and ownership, they name their teams and are given a permanent home in the lab (5, 19, 34, 46). We wanted their lab bench to mimic those in our own laboratories, in both appearance and functionality, which is also a recommendation of the NRC and others (4, 31, 32, 48, 54). They were provided with their own lab bench for the semester and appropriate modern molecular biology lab instruments (including a computer, digital camera, microfuge, pipetmen, vortex, spectrophotometer, etc.). These benches were essentially "time shares" where during any particular assigned lab time the same students returned to their bench, yet during other labs that bench was another groups' property.

Assessment of the student group's performance in their research project was designed, like in real science, to be highly dependent on their capacity to communicate their findings via a publication. In addition to attendance, the students were charged with presenting their research via interviews and authoring of several drafts culminating in the submission of a final manuscript formatted for publication in a scientific journal of their choosing. This process required the groups to come together and prepare for labs, record data diligently during labs, study the prose used in scientific journals (i.e., *American Journal of Physiology*, *Nature*, *Journal of Molecular Biology*, etc.) and then emulate it. The difficulty in grading a group project is, of course, dissecting out individual performance (5, 19, 46). How do we assign individual grades from a group assignment? Not unlike the division of the group into specialty roles that were responsible for particular lab tasks (above), different members in the group were also assigned the responsibility for authoring different sections of the paper for each draft. This "individual authorship" responsibility rotated, i.e., for Draft 1, the PI authored the Introduction and Methods, for Draft 2, PI authors/revises Results and Figures, etc. Hence each student is responsible for their sections as well as the paper as a whole. As a final method of getting the group involved in all the sections, we require that each student sign a "group responsibility contract" attesting to the fact that each of them has read through, and edited the entire paper to their satisfaction. They agree that it is complete, accurate, original, and cohesive and that they accept their grade will be a 50:50 mix of their individual section and the full manuscript scores.

Revisions In Assessment

As indicated above, changes in the way the students were taught in the entire course were accompanied by changes in the way student learning was assessed (Table 3). New assessments such as: interviews, concept mapping, and peer reviews were introduced in an attempt to evaluate student learning at higher cognitive levels than previously (1, 5, 31–33, 37, 48). In addition, the 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 understanding has always been dominated by writing in our courses, yet how we implemented writing assignments changed. We will specifically focus on those revisions that directly impact the laboratory portion of the course in this section (writing, interviews, and peer review).

Scientific Writing

In our old curriculum, that was replete with cookbook laboratories, student performance was primarily assessed through individual lab reports. Since all lab reports were written nearly weekly and individually about each topic, there were numerous reports to grade every week. In addition, because many lab reports from past semesters were available on campus, much effort had to be focused on looking for signs of plagiarism. As a result of both the magnitude of papers and concern for plagiarism, the scoring of each report was rather superficial and thus the formative feedback and evaluation of student writing and learning was minimal. Under these circumstances the students had to work hard to create numerous reports about the same topics their roommate and older sibling may have done before (39, 44, 50), student comment: "I'm just doing the exact same thing every student did before me." Simultaneously, much of the instructor's time and effort was wasted trying to detect plagiarism (which is now admittedly less of an issue with services like www.turnitin.com). Clearly this was not the optimal scenario in assessing learning, but we don't consider it unusual in the realm of introductory biology at large universities (4, 31, 32).

In our new curriculum, student groups write only one paper about Stream I and only about their research project. They are not expected to write anything about the cookbook labs they perform unless it is relevant to their own research (i.e., as control experiments). In addition, instead of writing multiple reports about different topics, the student group composes multiple drafts of their manuscript for one topic, their own. This approach allows them to choose what themes and subjects to discuss in their own writing, and to experience multiple drafts with revisions suggested by the instructors and their peers (through peer review). In addition, the possibility of plagiarism diminishes significantly. Given that every student group's research topic tends to be unique, all the resulting manuscripts are quite diverse. Students also create a final website to report their findings, and next semester's students read the research published by prior cohorts for inspiration, but because that work has already been done, new projects must be developed (just like in the real research world).

In the first week of the semester, the student groups write about their research projects and initially submit a "Draft 1." In this draft, the students spell out what they propose to do in their six-week research project and what results they predict they

will find from the experiments they plan to do on the topic. This Draft 1 serves as a proposal but is written in the format of a final manuscript being prepared for publication. In this draft, the RESULTS section includes the students' predictions, and the DISCUSSION contains their interpretations of the expected results. Of course, the above necessitates that students learn about scientific writing. This is done with a weekly dissection of primary literature in recitation section of the course. We feel the first week of the semester is the ideal time to place this large burden on the student group. It requires them to read all the labs, meet and discuss potential research projects, study up on the topic, take on roles in the group and write and edit a full manuscript. This initial workload occurs right when the rest of classes on campus are still just reading through their syllabus in lecture and present no competition for student time and effort. In fact, we have found that if the group workload at the start of the project isn't heavy, overachievers will not see the value of working in a group and will start asking for the opportunity to do the project solo (19, 25). Front loading the course in this manner also helps prepare student groups for the research project well in advance (15, 32). It requires students to page-through the manual and plan experiments thus organizing the content/concepts in their mind before beginning their lab experience (2, 10, 11, 28, 29, 37, 43).

We believe this approach has more creativity, collaboration, better writing experience and is more like real science (12, 17, 25, 26, 30, 31, 32). We consider it closer to the optimal scenario and believe it is somewhat unique in the realm of introductory biology at large universities (4, 31, 32). We, as instructors, also find it less burdensome to run this type of curriculum than the traditional one (45, 51). Scientists need no special training for this sort of teaching since it is just like the work they do in their own laboratory. Hence, it succeeds in supporting our mantra of "Less Teaching, More Learning."

Student Interviews

After student research teams have completed and submitted their Draft 1 manuscript, we require the group to pass a formal interview with the professor before being allowed to proceed in the laboratory. All four students in a group schedule a 60-minute meeting with the professor to sit down to discuss their idea and plans (28). This event by itself is amazing. The fact that this new curriculum allows an instructor to have small group meetings with every student in the course is quite novel (2, 12). Previously our class was composed of at least 100 individuals where there really was no way to set up 100 meetings. But now the class is composed of 25 teams and over about the first 10 days of the course, the professor gets to meet and discuss research with all of his or her students.

The interviews are often very predictable. In most cases, while the group is rather excited about the topic they have chosen to investigate, they need to think about what is practical in the time allotted, what controls and replicates are needed, and so on. Also any supplies they need are identified and the group is encouraged to find and buy simple things on their own (groceries, plants, etc.). Once a group has "passed" the interview, they are given an interview receipt with comments that will then alert TAs in the lab that this group is permitted to begin their independent research. These interviews go on during all of *week 2* (when lab is just a traditional cookbook

experiment) and into *week 3* as the deadline for their first independent research day approaches. This moment, early in the semester, is once again a time in the course that helps the student see that the activities of this class are going to be different than what they may have expected. Sitting down with the professor and discussing their scientific research project is an excellent model of what should happen in introductory biology (4, 48, 52). We believe this approach moves closer to the optimal experience for undergraduates and is quite exciting for the instructor (another experience that may be too rare). We also believe interviewing is perhaps one of the best assessment approaches and this gives the students an opportunity to go beyond the Knowledge level as defined by Bloom and approach Application, Analysis and perhaps Synthesis levels (Tables 1–3).

We have incorporated several diverse formal assessments that attempt to provide both the student and the instructor with periodic (formative) feedback, as well as final (summative) evaluation of learning. These assessments work to assay both the individual's and group's ability to implement the scientific method. Unfortunately, neither in the previous traditional laboratory sequence (all cookbook labs), nor in the new TS Inquiry sequence have we directly assessed skills or mastery of techniques. However, we are currently working on ways to add some simple performance-based assessments ("mini-practicals") to better evaluate individual accountability in learning how to operate equipment and solve basic questions in the laboratory. In addition to these formal assessments, the teaching assistants provide valuable informal assessments through their questions and mentoring in the lab that dynamically evaluate teams and provide continuous personalized feedback. In this paper, we will not attempt to consider the numerous valuable learning moments (and assessments) that occur in the day-to-day operation of the classroom laboratory but our teaching assistant to research group ratio in the lab often approaches 1:1. Hence our TAs tend to "adopt" and mentor a student research group, knowing their project, their successes/failures, and their aptitude which helps to further personalize the teaching and make it closer to Socratic (45).

Peer Review of Manuscripts

After student groups submit Draft 1 of their research paper, feedback comes from the instructor level (i.e., the Prof). Yet, in addition to feedback from the Instructor, Draft 2 is also peer reviewed by each individual in another research group. The reviewers are graded upon how well they follow the guidelines on a peer-review worksheet (that requires them to evaluate both the science and the writing), yet their evaluation of Draft 2 is not used in the grading of the manuscript. As they follow the format of the peer-review worksheet, they are asked to read a section of the paper and then briefly explain what the research question is, or how the method is being done, etc. When they review either a poorly constructed draft or an excellent one, they gain an opportunity to reflect on their own experiment and writing and how well it might hold up under the same scrutiny. Of course, they soon find out when receiving the reviews of their own paper. This peer review process is quite effective at both alerting a student to problems in their own manuscript, and allowing a student to view another group's writing/thinking (and thus become more reflective about their learning). If a

student experiences only reading and rereading his or her own paper, eventually it becomes difficult to see what needs revising. In addition, having students review each other's papers may once again succeed in supporting our mantra of "Less Teaching, More Learning." We believe the peer-review assignment also helps give the students an opportunity to go beyond the Knowledge level as defined by Bloom (3) and approach Analysis and perhaps Evaluation levels (Tables 1 and 3).

RESULTS

We have attempted to assess the impact of this new curriculum on student learning with both qualitative and quantitative approaches. In designing this study, some of the questions we heard from our colleagues in the field of education and human subjects were qualitative and general: e.g., "Have you asked these students what they think?" On the other hand, some of the questions we heard from our science colleagues were more quantitative and specific: e.g., "Will these students do better on the MCAT?"

Qualitative Survey Results

To assess the students' perspective on the course's laboratory, we studied MSU Student Instructional Rating System forms from semesters using the traditional laboratories compared to those implementing the new Teams & Streams (TS) approach. Here are some of the comments we routinely read in student feedback forms in semesters where the traditional laboratories were used.

- Question: What do you think of the course laboratories and what changes would you suggest?
- Student 1: "Some things that we did in lab were mainly that the TA did them for us. I didn't learn a thing. . ."
- Student 2: "Weak point was the dullness of some lab experiments."
- Student 3: "It's lab, there aren't really changes you can do."
- Student 4: "The labs were good, but I think they could have done higher level labs. I had done most of them in high school. (What changes would you suggest) Higher labs. Labs requiring more thought. More complex labs."
- Student 5: "I didn't like the potato lab with all the test tubes. Don't remember the name."

In semesters utilizing the TS inquiry laboratories, we still found some brief negative reviews, but overall student feedback has changed for the better in tone and frequency.

- Question: What do you think of the course laboratories and what changes would you suggest?
- Student 1: "Lab was a lot of work. The groups sucked."
- Student 2: "The lab was set up much better than previous classes. This was the best lab I've had here. I loved working in large lab groups. Overall this class has improved my understanding of many biology related systems."
- Student 3: "I really enjoyed the entire lab but mostly the group work. When you think about it real research is always done in teams."
- Student 4: "I liked the lab—I'm usually not in favor of group work, but this was different. I learned so much from them and understood what we were doing when we designed our own labs. The fun independent labs made the beginning

cookbook labs seem really dull. Because we had to write the big scientific papers I really feel confident in my skills and I think that aspect was very worthwhile."

- Student 5: "The lab was an excellent experience to gain real experience and to think rather than follow a 'cook-book' guide."
- Student 6: "Overall the class as a whole was big pain in the butt. However, it is definitely the most worthwhile class I have taken in my entire life. With having the class and lab together it allowed for greater understanding of many biological concepts. Future classes along with ours will complain about the workload, but what comes out of the learning is amazing."

In addition to comments from student feedback surveys, we studied the frequency of positive (+) vs. negative (-) feedback on the topics of the "lab" or "class" from student surveys over semesters using traditional structured laboratories versus those semesters using TS (Table 4). First, not surprisingly, we found semesters using the TS approach had a greater number of student comments concerning the topic of the laboratory: 74 comments from TS students vs. 5 from traditional students. In addition TS students made a greater number of positive comments about the laboratory portion of the class: 78% positive vs. 20% from students who performed traditional labs. Interestingly, while the students didn't like the traditional labs, in those same semesters the data indicates the students did like the topic of biology and their class. Some 80% of the comments about the "class" (lecture/class/teacher) were positive. These student responses concerning the "class" were similar to those from students who participated in the TS courses (90% positive).

Quantitative Results

In response to the data our scientific colleagues requested, we developed and administered a standardized exam (called the MAT) during the final week of five semesters from 2000–2003. Our MAT exam is built from Medical College Admis-

Table 4. Student feedback about laboratory and classroom

	(+)Lab	(-)Lab	(+)Class	(-)Class
Traditional labs (S'2000, n = 91)	1	1	46	1
TS Inquiry labs (S'2001, n = 90)	35	7	68	2
Traditional labs (F'2001, n = 63)	0	3	6	12
TS Inquiry labs (F'2002, n = 81)	1	0	11	4
TS Inquiry labs (S'2003, n = 99)	22	9	25	6
Totals: Traditional labs	1 (20%)	4 (80%)	52 (80%)	13 (20%)
Totals: TS Inquiry labs	58 (78%)	16 (22%)	104 (90%)	12 (10%)

Data from student feedback surveys (MSU SIRS forms) show frequency of positive (+) vs. negative (-) feedback on the topic of the "lab" or "class" over semesters using traditional structured laboratory versus those semesters using Teams & Streams inquiry labs (TS). Comments were evaluated directly from student feedback forms administered in lecture as well as those administered in recitation sections during the final week of listed semesters. Number of student comments do not equal number of students enrolled in each course (n). Classes are listed in chronological order. A semester prior (Spring 2000) and following (Fall 2001) the first use of the full TS approach used traditional cookbook labs.

sions Test (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, comprised with relevant and rich passage-style questions (9, 18, 22, 29). Review it online (<http://surf.to/teamstreams/>).

Students from semesters that used the TS inquiry approach in the classroom laboratory have significantly higher scores on the MAT exam (Figs. 1 and 2). As shown in Fig. 1A, the average TS student MAT exam score was 60% (S'01 = 56.9 ± 1.3 , $n = 80$; F'02 = 61.5 ± 1.5 , $n = 77$; S'03 = 59.5 ± 1.5 , $n =$

88), while that of traditional students was 50% (S'00 = 49.4 ± 1.6 , $n = 55$; F'01 = 48.3 ± 2.2 , $n = 31$).

In pooled comparisons, students who participated in new TS inquiry labs ($n = 245$) outscored their peers in traditional labs ($n = 86$) on MCAT-style standardized exams: $59.3 \pm 0.8\%$ vs. $48.9 \pm 1.3\%$, respectively ($P < 0.0001$). Hence, statistically the pooled TS data sets are significantly higher than the traditional data sets. ANOVA analysis of data from individual semesters in 5 separate sets (not pooled) also found a significant difference between TS student and traditional student scores $P < 0.0001$. Yet, the 95% confidence intervals show different semesters using TS are not statistically different from each other (the same for the two traditional semesters) (Fig. 1B). The performance of students from TS courses increased and moved the MAT scores distribution curve to the right from a prior distribution that skewed and gathered students at a lower performance level (Fig. 3).

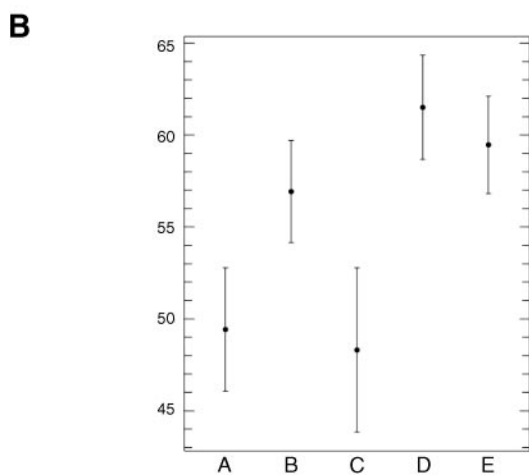
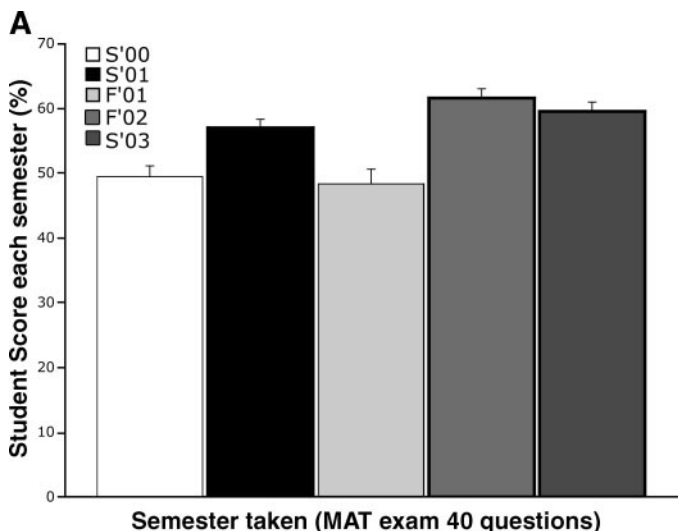


Fig. 1. Medical Assessment Test (MAT) student score results from five sampled semesters. *A*: in chronological order (left to right) is a comparison of the average class score on the MAT post-test for semesters Spring 2000 ($n = 55$), Spring 2001 ($n = 80$), Fall 2001 ($n = 31$), Fall 2002 ($n = 77$), and Spring 2003 ($n = 88$). Course instructors varied in 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) laboratories were first introduced in Spring 2001 and in Fall 2001 the instructor reverted to the traditional labs. TS laboratories were used again in Fall 2002 and Spring 2003. Light gray shading represents traditional labs and dark gray shading indicates TS labs. Error bars are means \pm SE. *B*: comparison of the means and 95% confidence intervals of the same data with an expanded y-axis. x- and y-axes are the same data as in Fig. 1A. Letters A–E are semesters Spring 2000 ($n = 55$), Spring 2001 ($n = 80$), Fall 2001 ($n = 31$), Fall 2002 ($n = 77$), and Spring 2003 ($n = 88$), respectively. A and C are significantly different than B, D, and E, ANOVA. $P < 0.0001$.

DISCUSSION

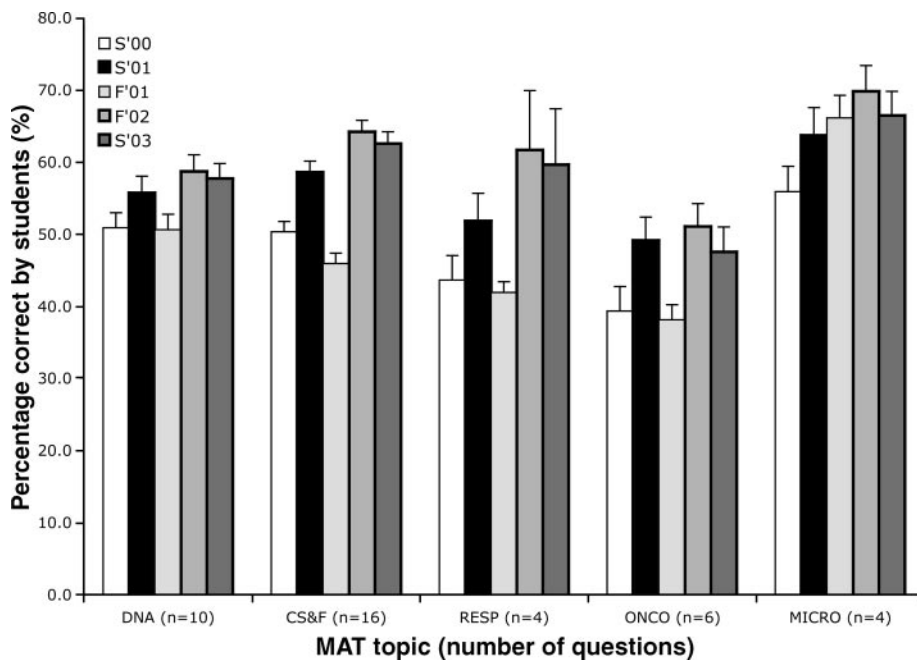
While the curricular revisions reported in this study are not unique among reports in the literature, our scientific colleagues have yet to be convinced. The majority of undergraduate laboratory experiences in the US are traditional scripted cookbook ones (4, 31–32). We hope as new publications report more assessments of their curricular interventions via both qualitative and quantitative tests, our peers in science may begin to examine these findings with more interest.

Qualitative Findings

Human subjects studies have several variables and are quite difficult to control, thus in our experimental design to remove the instructor-dependent variable we utilized three experienced professors who have won student and university teaching awards in varying sequence. We were not able to perform interviews (55), yet over the four years we tracked student opinion using an end-of-course evaluation process. In addition to the study of specific comments from student surveys, we recorded the frequency of positive and negative feedback on the topics of the lab or class.

As indicated earlier, students who participated in the TS inquiry laboratories had many more positive comments about the laboratory portion of the class: 78% positive compared with 20% positive from students who participated in traditional labs. Yet, the same students who did not enjoy their traditional cookbook labs, in fact enjoyed their instructor and the rest of their biology class. We believe this suggests these students were not unusually resistant to the topic of biology, and in fact recognized that they experienced an excellent course but for the cookbook laboratories. Their written comments sometimes verbalized this opinion. On the other hand, we noticed a trend where a significant percentage of students from the traditional classes did not include any written comments whatsoever on their surveys. They did fill out Likert scales in response to specific questions on the survey, but wrote no explanations in the large area soliciting extended responses. The fact that this phenomenon did not occur with students from TS inquiry courses may indicate the laboratory experience engaged the students more and made them more active participants with a feeling of ownership in the course.

Fig. 2. MAT results from different subtopics of the exam from five sampled semesters. In chronological order (left to right) is a comparison of the average class score on the MAT subcategories and the number of questions for each category is indicated as (*n*). The categories are as follows: "DNA" stands for DNA structure and function, *n* = 10 questions; "CS&F" is cell structure and function, *n* = 16 questions; "RESP" is respiration, *n* = 4 questions; "ONCO" is oncogenes and cancer, *n* = 6 questions; and "MICRO" stands for microbiology, *n* = 4 questions. Within each subtopic are the post-test scores for students who took exam during sampled semesters: Spring 2000 (*n* = 55 students), Spring 2001 (*n* = 80 students), Fall 2001 (*n* = 31 students), Fall 2002 (*n* = 77 students), and Spring 2003 (*n* = 88 students), respectively. The TS laboratories were first introduced in Spring 2001 and in Fall 2001 we reverted to the traditional labs. TS laboratories were used again in Fall 2002 and Spring 2003. Light gray shading represents traditional labs and dark gray shading indicates TS labs. Error bars are means ± SE.



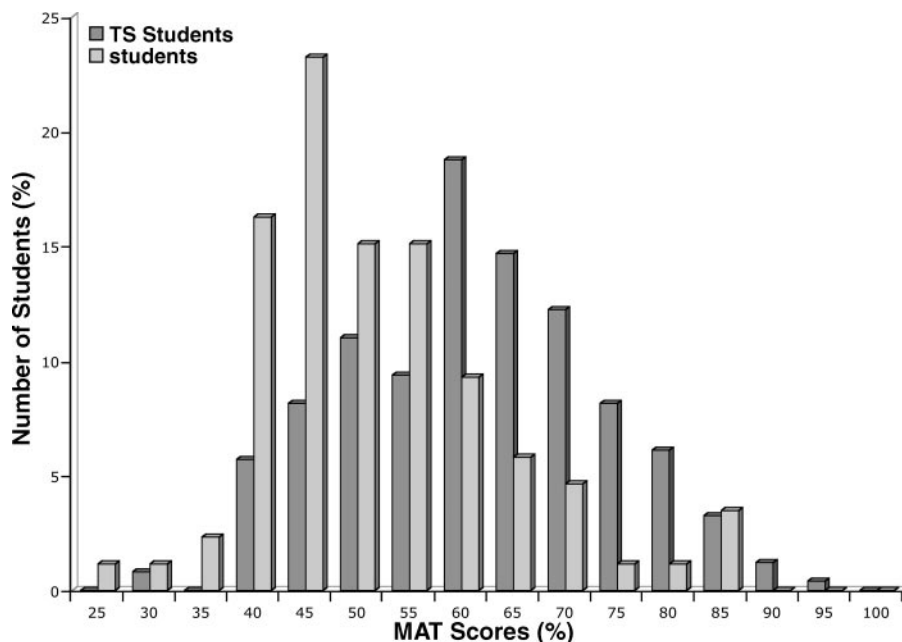
Quantitative Findings

In designing this study, we believed that to convince our colleagues in physiology to engage in significant change, longer studies over multiple semesters and with "content" exams would be necessary. While better content exams and better experimental designs will be necessary to convince scientists that "it works," we consider this study a first step in that direction. As mentioned earlier, our MAT exam is built from Medical College Admissions Test (MCAT) practice test questions. The questions were selected to match topics from lecture, but they do have a great deal of overlap with the topics relevant to lab. While these questions do test at the lower end of the Bloom taxonomy (3), we predicted better learning at the higher levels would also lead to more

meaningful learning at the basic levels. In addition, in our case the MAT also had an affective element. Our freshman are motivated to make a real attempt to do well on MCAT questions, given the majority are premed. We also designed this study to have more than just pre- and post- intervention data. After we fully implemented the first TS inquiry labs in Spring of 2001, we reverted to traditional labs when teaching the same course in Fall 2001. The TS inquiry approach was then fully implemented again and has continued as the default curriculum ever since. Hence, we believe the experimental design and the resulting data are more robust as a result.

We found that the students that participated in the TS inquiry laboratory have significantly higher scores on the MAT exam.

Fig. 3. MAT performance distribution comparing TS students (*n* = 245) vs. pooled traditional lab students (*n* = 86) from the semesters sampled. To compare the score distribution of the 86 students sampled from classes utilizing traditional cookbook labs to the 245 students who participated in classes utilizing the TS inquiry labs, the number of students was represented as the percentage of total and the MAT scores were sorted into bins of those who scored between 20.01–25% (label "25"), 25.01–30% ("30"), 30.01–35% ("35"), and so on. No students scored lower than a 20.01% on the MAT exam. Students in courses with traditional labs (labeled "students") are represented by light gray shading and those in courses with TS labs ("TS students") are indicated by dark gray shading.



While this may not seem surprising, the capacity to detect an increase in student performance on content exams is not common in the literature. Education researchers often must be satisfied to report that their innovations do not have a negative impact on the performance of students in the experimental section (i.e., no significant difference). In our findings, both with individual semester and pooled comparisons, students who participated in new TS inquiry labs outscored their peers in traditional labs on MAT exams (pooled results: $59.3 \pm 0.8\%$ vs. $48.9 \pm 1.3\%$, respectively; $P < 0.0001$). We believe these quantitative data support the qualitative findings and suggest this TS inquiry lab approach increases student learning. The fact that our TS students performed better on knowledge and application-level questions from the MCAT is good, yet we predict the greatest separation would occur at questions directed to higher cognitive levels (54). This has yet to be demonstrated and would require better instruments and ideally expert panel interviews like those described by Wright et al. (55). Although we have not yet developed an exam to assess experimental design and critical thinking skills (we are reviewing a quantitative reasoning exam developed at James Madison University) our direct assay of content knowledge still shows a respectable increase in student 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” (19) and represents a student-centered classroom, having instructors do all the work does not make sense. Laboratory instructors in particular can spend numerous hours before and after the 3-hour cookbook lab, preparing for and then completing the “research” of the students. The evidence suggests this scenario results in both more effort by the instructor and less learning by the students (19). In the lecture setting the paradigm is for the instructor to actively engage and perhaps entertain passive students. Engaged instructors continually ramp up their effort to increase learning in their classroom, with good results, yet we believe eventually this high level of effort cannot be maintained (45). Thus in our revisions we applied the cognitive and educational knowledge in the literature to seek a synergism between constructivism/active learning and the practicalities of instructor time and effort. The goal of our design is that the student does more of the work, and as a result, does more learning.

We believe this simple TS inquiry format is modular and adaptable to any other laboratory topics or science disciplines. Other instructors could just pick their own favorite labs and proceed. Of course, there is a good amount of organization to be done before the student research projects in the laboratory begin. Teams have to be generated, students have to be mandated to read the laboratory manual, teams need to be helped by instructors in coming up with ideas for their independent investigations and so on. Even so, once you become accustomed to the preparation necessary, we believe this approach fulfills the mantra of “Less Teaching, More Learning.” We found the day-to-day operation of the laboratory to be much easier and even less costly than the traditional “different laboratory each week” paradigm (53).

Controlled Chaos

The laboratory section of a science course must have originally been designed to be an innovative “active-learning” section for science students. The cookbook or scripted labs themselves likely began as adventurous inquiry experiences that evolved to be cookbook because that was the way to be sure the lab “worked” every time. We believe for meaningful learning to occur, the learners must be confronted with events that shake loose the naive ideas or concepts the students already embrace (1, 4, 5, 11). Chaos is critical. Instructors need to resist the temptation to fix the experiment for the student, or fix the lab so it works perfectly. Just as veteran instructors know it is best to answer a student’s question with another question, the laboratory should require increasingly greater thinking to succeed. The students will naturally desire ease in the lab and for experiments to succeed every time (so do scientists), but the real learning occurs when the experiment fails (2, 12, 24, 32). This TS inquiry approach is designed to create a safe environment for controlled chaos. We value when a student experiment fails and use it as our opportunity to help them troubleshoot and revise their plans. In our experience, the students that learn the most and really master the critical thinking and techniques are the ones that fail initially.

On a related topic, we believe that student potential has been far underestimated by university instructors (25, 38, 50). At first, we were apprehensive that it would be too challenging for a team of students who had never worked together to produce a rough draft of their final paper (which included “predicted” results and interpretations) during the first week of classes. But, much to our surprise, the students not only rose to the occasion, but came up with ideas for research projects that we could have only dreamed of (see list of some research project titles, or view a documentary film online <http://surf.to/teamstreams/>).

We claim the success of this curriculum is also evidenced by the increased complexity of our student’s experimental design, data analysis, and primary literature cited. This is showcased by the examples where colleagues in the Department of Physiology as well as across campus to use additional expertise, equipment and assays to answer their research questions. Year after year, with every form of assessment we use, our data and experience supports university students can do it all. Our teaching assistants see a significant change in the way students talk about their research and even the laboratory equipment in the room. We believe the students have made a personal connection to the science, in a way such that it isn’t just something to be memorized for a quiz, but rather is a tool that helps them answer their own questions (1, 5, 11, 33).

What We Have Learned

Challenging introductory biology courses represent our best chance to prepare students before they enter the upper-level courses of the physiology sequence. Students are ready to do amazing things when they come to “college”; if we don’t challenge them early and often, they quickly “learn” that classes in college are no different than high school, just more facts to memorize and forget (4, 39, 45, 50). We conclude that bringing “activity” back to the laboratory portion of a science course in the form of inquiry does increase learning in many domains (5, 11, 35, 36). The revised curriculum also changed the attitude of students and instructors alike. Another group

that benefits from the TS inquiry approach is, in fact, the teaching assistants (42). They learn quite a bit more about teaching and about the process of science in this new format than in the traditional one. Both groups find the laboratory portion of the courses more relevant and like “real science” because it is real science (2, 12, 13, 54). The large class size does not impede the use of this approach; in fact, this approach allows large classes to shrink fourfold through the use of groups. At large research universities like MSU, this approach in the classroom laboratory segues very nicely into the undergraduate research experiences available across campus in the many laboratories (24, 32, 44). This TS inquiry curriculum serves nicely to move students from a comfortable zone existing as anonymous passive “receivers of facts” to a less comfortable domain where they are active “investigators of ideas.”

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