ISEE Inquiry Demonstration Labs: Active Learning Units for Teaching Scientific Concepts, Practices, and Collaboration

1. Project Background

In fall of 2014, the University of California, Santa Cruz (UCSC), received a five-year, $1.5 million grant from the Howard Hughes Medical Institute (HHMI) to redevelop introductory courses in biology, chemistry, and physics, with the goal of increasing undergraduate students' persistence and broadening participation in science, technology, engineering, and mathematics (STEM) fields. Persistence, particularly of students from underrepresented[1] groups, is a known problem in STEM. A study by the Higher Education Research Institute shows that only ~40% of all students who enter college intending to major in STEM complete a STEM degree in five years, and the completion rate drops to ~20% for underrepresented minority students [1].

While the STEM degree completion rates at UCSC are higher than average in the U.S. (57% for all STEM students; 51% for underrepresented minority students [2]), there is still much room for improvement. The UCSC HHMI project focuses on introductory courses with the perspective that undergraduates' persistence in STEM tends to erode within the first two years of college. The project aims to engage students in "doing science" by incorporating active learning elements into these courses. Studies show that involving students in research and research-like activities, where they *practice* science, can positively influence persistence [3]. Furthermore, fostering positive interactions among students (e.g., during class activities) can bolster the students' sense of belonging to a STEM community, and in turn increase persistence [4,5].

The UCSC HHMI project benefits from the involvement of the Institute for Scientist & Engineer Educators (ISEE), which is headquartered on the UCSC campus. For well over a decade, ISEE's Professional Development Program (PDP) has trained graduate students and postdoctoral researchers in science and engineering fields to teach through *inquiry*, which is a particularly effective way of engaging students of all backgrounds in active learning. PDP participants attend a series of workshops in which they experience an inquiry activity from a learner's perspective, and then work in a team to design their own inquiry activity. They then complete a practical teaching experience, and reflect on that experience. In ISEE's definition [6], an inquiry activity teaches students core scientific concepts while simultaneously engaging students in scientific practices, such as generating hypotheses or designing experiments. Inquiry activities also provide opportunities for students to take ownership over their learning process, and receive recognition for their accomplishments, elements that are also known to support equity and inclusion [7]. Inquiry is called for in a number of national reports, including the 2012 report of the President's Council of Advisors on Science and Technology, which calls attention to the need for more STEM graduates [8].

The ISEE community of PDP participants is in a prime position to contribute to the UCSC HHMI project by demonstrating inquiry and by working with faculty and other instructors who will implement changes to introductory science courses at UCSC. In 2015, four PDP teaching teams[2]

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[1] Groups underrepresented in STEM as compared to the general U.S. population include Native Hawaiians and other Pacific Islanders, Blacks or African Americans, Hispanics, Native Americans, Alaska Natives, and women. *Underrepresented minorities* refer to the above groups, with the exception of women of races or ethnicities that are well represented in STEM (e.g., White women).

[2] PDP teaching teams are comprised of 3-4 PDP participants who work together to develop a new inquiry activity. The PDP produces ~20 teams (and therefore ~20 inquiry activities) per year from a range of scientific and engineering disciplines.

designed biology-oriented inquiry laboratory activities as a demonstration for the UCSC HHMI project. The teams taught their activities in informal venues, including Demonstration Labs for undergraduates, and the WEST program (Workshops for Engineering and Science Transfer students). **This report is a study of the two inquiry activities taught at the Demonstration Labs event, with a focus on what students gained from the activities, what the UCSC HHMI project can draw from these activities, and how the UCSC HHMI project can benefit from future Demonstration Labs events.** This is a semi-external report, as the author is affiliated with ISEE, but is not a member of the UCSC HHMI project personnel.

This year's Demonstration Labs were held as a one-day event in May 2015 for a group of 30 undergraduates who participated voluntarily. Two 6-hour inquiry activities were taught concurrently during the event – one on meiosis (20 students participated) and one on water transport (10 students participated). This report is based on the PDP teams' documentation of their activities in team-authored lesson plans, as well as observations of the activities during the Demonstration Labs event, analysis of surveys and focus group interviews conducted during the event, and follow-up discussions with the PDP teams.

2. Developing Students' Deep Conceptual Understandings

A goal of teaching via inquiry is to enable students to deeply learn *and to apply* core scientific concepts. As they begin to design inquiry activities, PDP teaching teams are required to identify a concept that their inquiry activity will focus on, and justify why that concept is considered a "core concept" within their discipline. PDP teams then develop a "content learning outcome" for their students in which they articulate how students will apply their understanding of the content (or concept) in the activity. They develop a rubric, identifying components of the content that students will learn, what evidence of understanding would look like, and what an incomplete understanding would look like. They also identify teaching strategies they could use to help their students reach a sufficient understanding of the content. The two PDP teams that designed inquiry activities for the Demonstration Labs chose to focus their activities on the concepts of meiosis and water transport, as these are important concepts that are taught in the Biology 20A and 20B courses at UCSC, respectively (see Table 1; also note that hereafter the PDP teaching teams are designated as the "Meiosis team" and the "Water Transport team").

> UCSC science faculty describe the need for undergraduates to develop deep understandings of core scientific concepts:
>
> - ***"They can write out a definition, but don't have an intuitive understanding."***
> - ***"They don't understand how new things work together."***
> - ***"The application of a concept is important – connecting all the pieces that they've learned."***

Table 1. Assessment-driven activity design to address common student difficulties with scientific content
Notes in white boxes below are gathered from PDP teams' lesson plans

	Meiosis Team	Water Transport Team
Content learning outcome identified by PDP team	Students will use their understanding of the maternal and paternal origin of chromosomes and how they segregate during meiosis to explain chromosome number abnormalities.	Learners will be able to use principles of osmosis and diffusion to develop reasonable explanations for biological phenomena that rely on osmotic principles (e.g. guard cell opening, marine iguana salt gland, kidney function)

Aspects of content targeted in activity	1. Modeling the correct stages of meiosis 2. Distinguishing between chromosomes from the same parent and different parents 3. Identifying the stage of meiosis at which the error in chromosomal segregation occurred	1. Modeling salt as being actively transported using energy 2. Showing that water is passively transported 3. Showing that water moves down its concentration gradient
Common misunderstanding or incomplete understanding that activity addresses	1. Student model does not show stages of meiosis in correct order, or some stages are missing 2. Chromosomes from parents are not properly indicated in student model, or are segregated incorrectly in meiosis I or meiosis II 3. Student indicates that an abnormality occurred but does not designate the stage at which it occurred, or student's diagram does not show proper chromosomal numbers for all 4 gametes.	1. None of the salt channels in student model use ATP 2. Student model shows water being actively transported, or students uses words "water pump" or "active" when describing water transport 3. Student model shows water moving in the "wrong" direction – water moving towards a higher concentration gradient or towards a lower solute environment
Evidence that a student has sufficient understanding	1. Student model shows correct meiotic stages in correct order 2. Student model shows chromosomes from different parents segregating away from each other in meiosis I into two daughter cells, and chromosomes from same parents in meiosis II resulting in four daughter cells total 3. Student indicates the missegregation event occurred in the right parent/parents and in the right stage/stages of meiosis; student diagram has proper chromosomal number for all 4 resulting gametes.	1. Student model indicates ATP/energy is used in a least some channels 2. Student model shows water moving passively; no ATP is associated with water; student indicates that water needs a channel to pass through 3. Student model shows water moving towards high solute side

After identifying their content learning outcomes, identifying learning goals related to scientific practices (see Section 3 below), and developing rubrics, the Meiosis and Water Transport teams planned out what they and their students would do during the inquiry activities. A brief summary of the activities follows.

Meiosis inquiry: Students were given a brief introduction to meiosis. Then, in "starters" meant to pique students' interest, the students rotated around the lab, where they reviewed eight abnormal karyotypes. They wrote down questions about the information they were presented with, and formed groups of 2-3 based on which question they were interested in investigating. During investigation time, students were prompted by instructors to construct a model of meiosis (drawn, or using materials such as pipe cleaners). They were then asked to use their model to determine in which stage their abnormality occurred. Toward the end of the activity, each of the student investigation groups each gave a poster presentation on what they had found. Instructors then gave a lecture to synthesize what students had learned.

Water Transport inquiry: After a general introduction to the activity, students rotated through three "starters" in which they watched short videos about plant guard cells, marine iguanas, and kangaroo rat kidneys. Students discussed the videos and chose which subject they would like to investigate, and then grouped in pairs based on the subject of their investigation. During the investigations, student pairs worked with data sheets that listed evidence statements drawn from the literature. They developed models to explain the evidence, with frequent check-ins and occasional input from instructors. At the end of the activity, students drew their models and presented them to students from other investigation groups in a "jigsaw" activity. Instructors then synthesized what students had learned in a short lecture.

Students who had participated in both the Meiosis lab and the Water Transport lab overwhelmingly noted that they learned concepts from the labs. In a survey conducted at the end of the Demonstration Labs event, students were asked whether they had a "deeper, more intuitive understanding of an important biological concept than you might get in a typical lecture or lab". The majority of students (25 out of 30, or 83%) answered that they had a "better understanding" or a "much better understanding" of a concept.

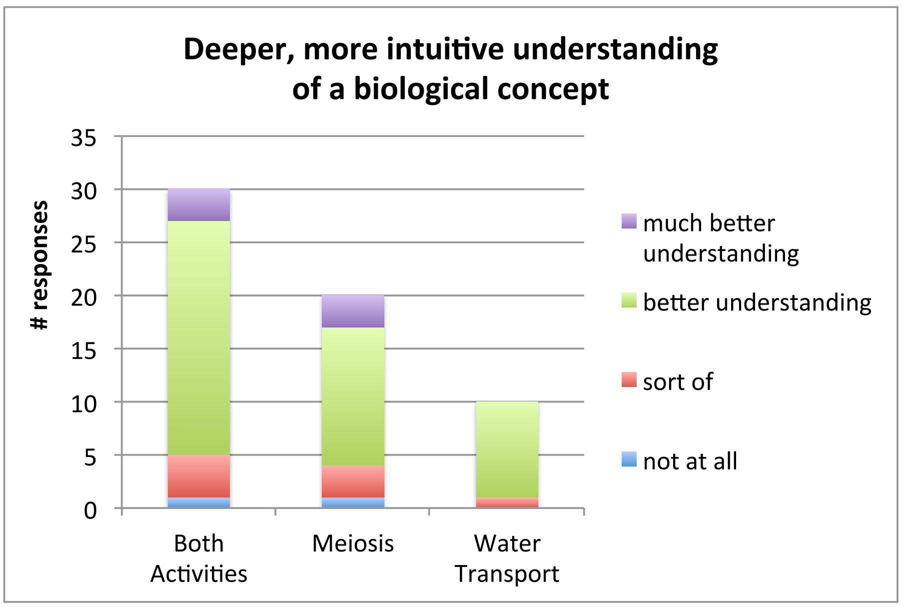

Figure 1. Student survey responses to the question of whether the inquiry activity they participated in gave them a deeper, more intuitive understanding of a biological concept than they might get in a typical lecture or lab.

Students' comments on the surveys and in the focus group discussion also indicated that they felt they came away from the activities with deeper understandings of the relevant concepts. Several students indicated that the activities helped the concepts "stick" in their minds. Students also appreciated being able to apply concepts. A sample of student comments follows:

- "learned something beyond what I already knew"
- "I have a better understanding of water transport because this activity taught me how to apply concepts I had learned earlier as well as how to think like a scientist. Rather than these concepts leaving my mind after class, this activity has cemented the ideas in my mind."

- "It was really interesting to be presented with *how* does this occur."
- "It was a much different way of learning, great. You have to trust your own knowledge and intuition, something I was never able to do before."

3. Developing Students as Practitioners of Science

A key aspect of inquiry activities, as defined by ISEE, is that they not only impart scientific concepts, but they also engage students in scientific practices. This is important, as many faculty perceive that undergraduates lack experience with these practices. Furthermore, teaching scientific practices has been shown to enhance under-represented students' success in introductory biology courses, and may support diversity in science more generally [9].

> UCSC science faculty describe the need to engage students in scientific practices:
>
> - ***"Students lack problem solving skills."***
> - ***"I'd like for them to understand how to do science (hypothesize, propose, and experiment)."***

As part of their PDP training, the Meiosis team and Water Transport team each specified a scientific practice they wanted their students to develop experience with during their inquiry activity (see Table 2 below). Defining a "practice learning goal" for their students was an early step in the design of their inquiry activities. The PDP teams each focused on a practice that has been identified in a scientific framework as being integral, and they identified important aspects of the practice that students could engage in. They then designed the inquiry activities so that students would gain experience with the identified aspects of the practice. As they prepared to teach their inquiry activities, the teams also articulated what it might look like when students were having difficulty with the practice goal, and what proficiency with the practice might look like. They noted what they might say or do to help students become proficient with the practice.

Table 2. Assessment-driven activity design to address common student difficulties with scientific practices

Notes in white boxes below are gathered from PDP teams' lesson plans and presentations

	Meiosis Team	Water Transport Team
Practice goal identified by PDP team	Explaining results	Building and using models, especially using evidence to support the model
Aspects of practice targeted in activity	1. Claim: making a statement or conclusion that explains a result 2. Evidence: referencing scientific data or other evidence that supports the claim 3. Reasoning: incorporating a justification that links the claim and evidence	1. Representing an idea as a complete picture 2. Modifying model to accommodate new evidence 3. Supporting model with evidence
Common student difficulties activity was designed to address	1. Student doesn't make a claim based on results, or makes a claim but it is incorrect or flawed 2. Student doesn't use evidence, or uses insufficient evidence to support the claim 3. Student does not connect evidence to claim, or justify why data are sufficient for claim	1. Student cannot state what each part of their model represents 2. New evidence that does not fit with model is ignored 3. Student may not be able to relate components of their model to specific pieces of evidence that were given

Evidence of a student's proficiency with that aspect of the practice	1. Student makes a claim that can be supported by the evidence 2. Student uses appropriate evidence to support claim 3. Student connects claim with evidence and justifies why data support claim	1. Student can state exactly what each component of model represents 2. Student will be able to change model to explain new evidence OR will be able to see how new evidence can be explained with the current model 3. Each component of the model is linked to a specific piece of evidence via a written or verbal explanation
Teams' recommendations for designing an activity that will teach students this practice	Activity should: • Engage students in constructing explanations from observations, in a way that incorporates content knowledge • Give students practice with the most challenging parts of generating explanations, such as working with and evaluating the relative merits of multiple explanations	Activity should: • Engage students in translating evidence statements into a drawing or other model • Encourage students to state evidence in plain language / their own words • Engage students in building up models, e.g., by making simple drawings from straightforward evidence statements, and then adding complexity to models as more evidence statements are considered

The students who participated in the Demonstration Labs recognized opportunities the inquiry activities gave them to engage in scientific practices. When surveyed about whether they got a "more authentic experience in 'doing science' than you might get in a typical lecture or lab", a majority of students noted that the experience was either "more like doing science" or "much more like doing science" (21 out of 30 students, or 70%, gave one of these ratings; see Figure 2).

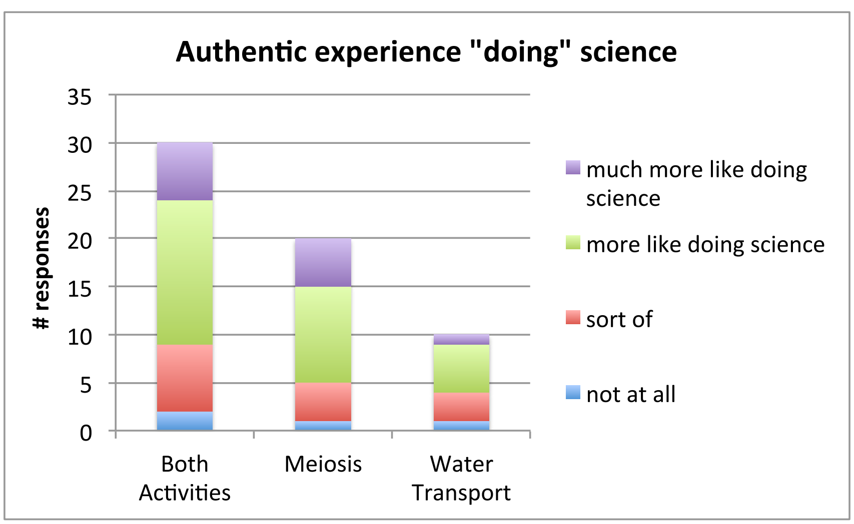

Figure 2. Student survey responses to the question of whether the inquiry activity they participated in gave them a more authentic experience "doing science" than they might get in a typical lecture or lab.

In some cases, students expressed that they didn't think they were fully conducting experiments because they were primarily working with models. Conveying authenticity is important – for example, stating explicitly that professional biologists work with models, too. However, many students' written survey comments and focus group responses implied an appreciation for the opportunity to engage in scientific practices:

- "Using info to create my own model was more science than lectures or premade labs"
- "Doing this gave me a much better idea what a 'real life' microbiologist would do."
- "Interactive activity and critically thinking of the solution, as opposed to sitting in a lecture hall being talked to"
- "We were doing and understanding at the same time."

> ***"For the first time, it felt like we were at a research university. We used our minds."***
> – focus group comment from Demonstration Labs student

4. Enabling Students' to Build and Explain New Understandings with Peers

An important element of inquiry activities, as designed through the PDP, is that they provide students with opportunities to conduct investigations in small, collaborative groups. For example, students worked in pairs in the Water Transport inquiry, and in groups of 2-3 in the Meiosis activity. In these activities, students must work together to figure things out – they explain their thinking to one another, and build on each other's understandings. Students must also explain their thinking to instructors, who regularly check in with investigation groups. Instructors make sure the student groups are on productive investigation paths, but only intervene if students show misunderstandings or are stalled. Toward the end of the activities, students present what they learned to each other in ways that mirror the ways that professional scientists present their work. In the Meiosis lab, students gave poster presentations reminiscent of conference presentations. In the Water Transport lab, each student presented their work to a group of four others who had worked on different but related investigations – similar to a lab group meeting. All of this means that students collaborate, build knowledge together, and learn from each other through inquiry.

The students in the Demonstration Labs noted that they were able to actively engage in learning together as they worked in investigation groups. When surveyed about whether they were able "to actively contribute to your team's knowledge and new understandings", all but one of the students answered "yes" or "very much", with the majority of students answering "very much" (16 out of 30, or 53%).

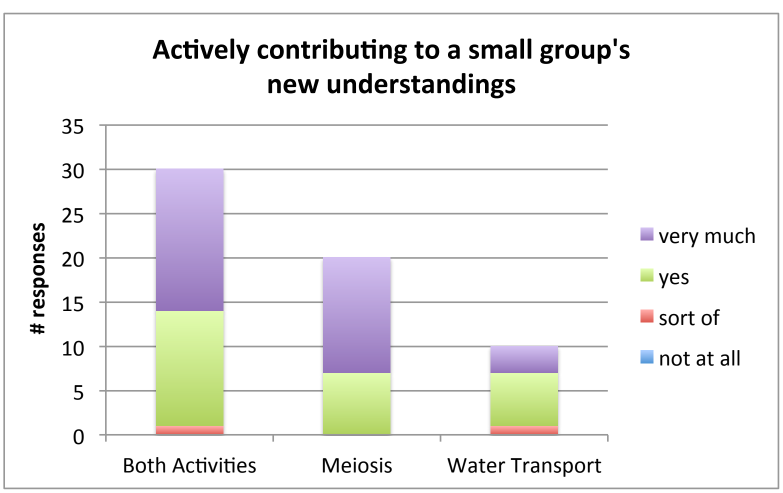

Figure 3. Student survey responses to the question of whether they had a chance to actively contribute to their team's knowledge and new understandings.

Students' survey and focus group comments conveyed an appreciation for the collaborative group work:

- "We all taught each other, this was done very well. Difficult ideas are a lot less daunting when discussed in a group."
- "We had to work together, we each had our own strengths, we found a way to bring out what we know."
- "we used our half-baked ideas to create a whole-baked idea"
- "I usually work solo, but I got a deeper understanding with a partner. It was a great experience."

5. Demonstration Labs to Support UCSC STEM Course Transformation

Below are themes and related recommendations that come forward on reviewing the aspects of the Meiosis and Water Transport inquiries presented above, as well as further reviewing the teaching teams' lesson plans, and observations and student surveys. **A major recommendation is to continue to hold Demonstration Labs, as a way of demonstrating possibilities for curricular change in the UCSC HHMI project, and more broadly at UCSC.**

5.1 Targeting student difficulties

An important aspect of the design of the Meiosis and Water Transport activities is that the PDP teams that designed them chose content learning goals first, before delineating what would happen in the activities. This process of choosing learning goals first, then designing an activity that will enable students to reach those goals, is a curricular approach that is called "backward design" [10]. In order to choose their learning goals, the Meiosis and Water Transport teams targeted concepts that students often struggle with. By identifying common student difficulties, their learning goals became more concrete, and the teams were better able to identify what student success might look like. Below are excerpts from the teams' lesson plans.

> *From the Meiosis lesson plan:*
> "…as a genetics TA, I have … experienced that students often have a hard time understanding the concept of meiosis and how it differs from mitosis. Furthermore, there is published data showing that students struggle with the concept of meiosis (Brown, 1990; Kindfield, 1991; Dikmenli, 2010)."

> *From the Water Transport lesson plan:*
> "Two core concepts that students classically struggle with are how the nephron functions to concentrate urine and how water moves through plants. Both of these concepts rely on basic principles of passive water movement in biological systems. Without a solid understanding of water movement it is difficult for students to achieve a more sophisticated understanding of these ideas such as how disease processes may influence urine formation (e.g. diabetes)."

Because activities can be more time-intensive than lecture, but can help to "cement" ideas in students' minds, a recommendation is to focus activities on core concepts that students find challenging, as was done in the Demonstration Labs. By continuing to hold Demonstration Labs events in the future, with new and/or revised activities, PDP teams will continue to develop learning goals and demonstrate inquiry activities that are based on important, but difficult concepts. The learning goals, and aspects of the activities themselves, can then be adopted by faculty who are invested in curricular change.

5.2 Early and ongoing assessment

Both the Meiosis and Water Transport inquiry activities engaged students in writing or speaking about their ideas and hypotheses early on, during "starters". In the Meiosis starter, students wrote down questions they had after being presented with abnormal karyotypes. As they rotated around the classroom viewing karyotypes, students could review questions written previously, and build off those ideas, or they could write new questions. During the Water Transport starter, students viewed short videos and were prompted by instructors to ask questions about the videos during discussions. These starters not only got students interested and actively thinking about the relevant concepts, but they also gave instructors an early opportunity to assess the students' understandings, and adjust the activities if needed.

Throughout the activity, instructors checked in with students to find out about their progress. They developed ongoing dialogs with student investigation teams, and provided students with multiple opportunities to explain their understandings. This gave instructors several opportunities to assess students' work and scaffold students' progress if needed. As they explained their work to their instructors, students had opportunities to self-assess. They also had opportunities to demonstrate improvement as they moved forward in their investigations.

The starter components of the inquiry activities taught at the Demonstration Labs event are short curricular elements that could be used, stand-alone, directly in a course. In fact, a Biology 20B instructor is planning to adopt the Water Transport starter in her course. Furthermore, by holding future Demonstration Labs events, PDP teams will develop more starters that could be adopted in courses at UCSC. Furthermore, faculty could observe the Demonstration Labs to learn about how instructors trained through the PDP facilitate their students' learning through ongoing assessment, and the Demonstration Labs instructors could document the strategies they use to do this.

5.3 Applying concepts by intertwining learning of scientific content and practices

Inquiry activities are notable because they actively engage students in scientific practices while they learn concepts. In both the Meiosis and Water Transport inquiries, this was achieved by encouraging students to ask questions early on, and by providing time for students to follow up their questions with experimentation. This gave students an opportunity to apply concepts, to put ideas together in new ways, and to actively learn the content.

As instructors worked with students, they often encouraged students to engage in scientific practices in order to gain a better understanding of the concepts they were working with. The following observation of a Water Transport instructor working with a pair of students illustrates this:

> Instructor: "Do you want to explain what you've got so far?"
>
> Student 1 gives slightly incorrect explanation.
>
> Instructor asks if other student agrees, Student 2 says yes.
>
> Instructor: "Okay, imagine one cell in this area, and one in this area [points to students' drawing]. Then what would happen?"

In this scenario, the instructor is asking students to engage in further modeling (a practice) in order to help them reach an understanding about the transport of water. A recommendation for future Demonstration Labs is to have the PDP-trained instructors document the specific ways in which they ask students to engage in practices, and how those practices help students reach deeper conceptual understandings.

5.4 Providing students with ownership and challenge

Both of the inquiry activities taught at the Demonstration Labs event provided students with opportunities to take ownership over their learning. At the beginning of both activities, instructors made it clear to students that the students would drive their own investigations, and instructors were there to ensure they made progress, but not to give answers. The instructors also put this in context by noting that this kind of open-endedness is authentic to real research. While in some cases students were frustrated with this teaching approach, which they were not used to, many students appreciated the challenge. A hybrid of both sentiments can be found in the following quote from a student survey:

> "The instructors didn't fully answer yes or not (right or wrong) to our thoughts and questions (which got frustrating!) but it really helped me see where I went wrong without making me necessarily feel like I was getting the question wrong. I got to build off my 'wrong' theories to result in the correct answer."

> ***"As soon as I got it, it was the best thing ever!"***
> – focus group comment from Demonstration Labs student

Overall, while students generally found the Demonstration Labs activities challenging, they also enjoyed the activities (see Figures 4 and 5 below). As curricular changes are implemented in courses at UCSC, providing students with opportunities for ownership is recommended. Future Demonstration Labs events are recommended, too, to give faculty opportunities to observe the strategies PDP-trained instructors use to facilitate students' learning and provide challenge while maintaining students' ownership over their learning process.

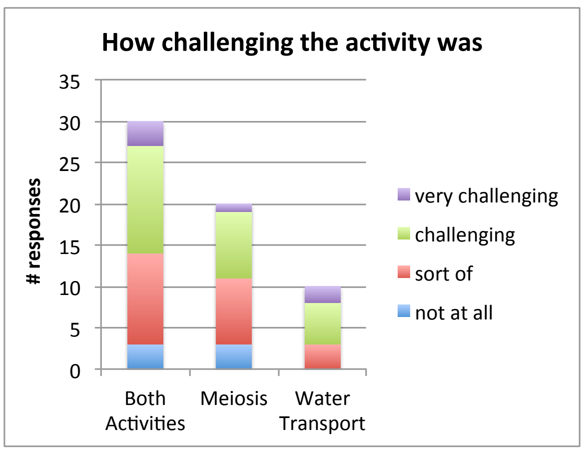

Figure 4. Students' survey ratings of how challenging the activity they participated in was. The majority (16 out of 30, or 53%) rated their activity as "challenging" or "very challenging".

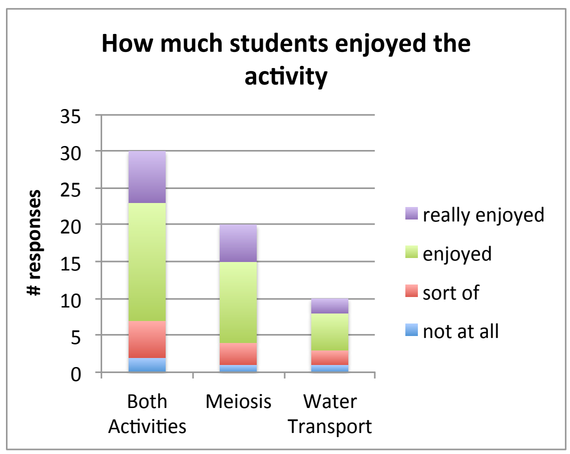

Figure 5. Students' survey ratings of how much they enjoyed the activity they participated in. The majority (23 out of 30, or 77%) noted that they "enjoyed" or "really enjoyed" the activity.

5.5 Designing and facilitating productive group work

Another important aspect of the Meiosis and Water Transport inquiry activities is that students worked productively together in small groups. This was due in part to the fact that the PDP teams instructed the students to keep their investigation teams small (students were grouped in pairs in the Water Transport lab, and groups of 2-3 in the Meiosis lab). Small groups meant that no student could step back from the investigation – input from everyone was needed within a group. Instructors also monitored group dynamics and used specific strategies to make sure no one dominated a group and no one disengaged (e.g., by saying, "I'd like to hear what Joe thinks about this", if Joe appeared quieter within a group). As noted above (in Section 4), the students appreciated being able to build knowledge together. By working in groups, they built small learning communities. They worked with each other's explanations and justified their ideas to one another.

The Demonstration Labs provide examples of structures where students work in groups and meaningfully contribute to the group's progress. Future Demonstration Labs events are once again recommended, as faculty could observe how instructors foster productive group work, instructors could document their successful strategies, and the activities could be recorded via video for future analysis of curricular elements and instructional strategies.

Summary Statement

Overall, ISEE's Demonstration Labs are a way of building infrastructure that will support curricular change at UCSC, not only by demonstrating curricular elements, but also by demonstrating successful instructional strategies. The inquiry activities demonstrated thus far show success at engaging students in applying concepts, *practicing* science, and in working productively and collaboratively together. The UCSC HHMI project would greatly benefit from future events like the one held in May 2015.

Acknowledgments

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