Your Students as Scientists: Guidelines for Teaching Science through Disciplinary Inquiry

Kanesa Duncan Seraphin
University of Hawaii

Erin Baumgartner
Western Oregon University

Setting

The National Science Education Standards (NSES) stress that science is an active process (students doing science) as apposed to a passive process (science is done to students, National Research Council (NRC), 1996). In order to promote students' ability to investigate effectively, evaluate and articulate scientific issues both within and beyond the classroom community, we advocate learning-by-doing in the context of disciplinary inquiry. Disciplinary inquiry involves learning about a discipline by engaging in the complete practice of that discipline. In this way, students become involved in the complete scientific process. They learn that scientific investigation has many dimensions, that it does not always proceed in a strict linear fashion, and that it involves both the articulation of the investigation process as well as the outcome. One essential element emphasized in disciplinary inquiry is the communication of discoveries to peers and the broader community. This practice, in particular, prepares students to engage in civil discourse about issues, to clearly communicate and defend their conclusions, and to consider and incorporate alternative points of view and additional information in their interpretations.

Teaching Science as Inquiry (TSI)

Teaching science as inquiry means using disciplinary inquiry to teach science as it is practiced. In this form of learning, content is both an end goal as well as a framework for knowledge construction. By testing principles and connections through the generation and interpretation of their own data, students can begin to understand the fundamental underpinnings of science. For example, testing and retesting of ideas helps students to understand fundamental, but complex, ideas such as the underpinnings of what constitutes a "scientific theory". Through disciplinary experience, students can discover why "scientific theories" are not converted directly into facts but instead into more robust explanations and eventually subsequent theories, with greater predictive and connective power (Young, 1997).

Teaching disciplinary inquiry through the authentic practice of science involves students learning science as a community process. Students and teachers work together to discover and understand the natural world. By adopting the demeanors of scientists, students also learn to use a variety of knowledge-acquisition tools and communication skills. These scientific demeanors parallel the scientific "habits of mind", such as integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, imagination, and communication essential to scientifically literate individuals (American Association for the Advancement of Science (AAAS), 1990).

The incorporation of scientific demeanors into disciplinary inquiry teaching practices can be difficult, however, as it requires significant effort, practice and attention (see Hammer, 1999). Successful use of disciplinary inquiry requires that teachers themselves have a good understanding of the particular scientific discipline (Wee, Shephardson, Fast, & Harbor, 2007). Even those teachers who have a strong understanding of science content do not always demonstrate the scientific demeanors considered necessary by science experts (see for example the study of pre-service teachers by Zembel-Saul, Munford, Crawford, Friedrichsen, & Land, 2002).

This chapter describes a framework of teaching and learning developed to help overcome the difficulty in teaching the disciplinary inquiry of science. The framework comes from the *Teaching Science as Inquiry* (*TSI*) program developed at the University of Hawaii's Curriculum Research & Development group (CRDG). *TSI* helps engage teachers and students as a community in the process of doing science through a supportive, skills and content-based model that builds inquiry into existing teaching practice with gradual and sustained implementation of skills within the classroom (Pottenger & Berg, 2006). The *TSI* model promotes deep understanding of science content and processes, which allows teachers to conduct authentic science successfully within their classrooms, helping students to build their own scientific habits of mind (Pottenger, Baumgartner, & Brennan, 2007; Handler & Duncan, 2006), and to participate in true scientific disciplinary inquiry practices (Pottenger & Berg, 2006; Pottenger et al., 2007).

Description of Intervention

Non-linear phases of scientific investigation

The *TSI* learning model utilizes the non-linear progression of actual scientific endeavors; new questions may be initiated at any time during an investigation. Further, interpretation of data often leads to the invention of new hypotheses or study designs. *TSI* provides a framework of instruction through five integrated and overlapping instructional phases (see Table 1). *TSI* also allows students to engage in scientific thinking through multiple modes of inquiry (see Table 2), thereby permitting opportunities for investigation and exploration that are both personally relevant and locally important.

This *TSI* model of instruction is aligned with the NSES recommendations for more emphasis in science teaching (NRC, 1996). In the *TSI* learning model, students are the primary actors, asking and answering their own questions in longer-term investigations. *TSI* emphasizes the use of a few essential concepts coupled with skill development and instruction of students by one another. Because of this, students' communication of what they have learned both within and beyond their classroom scientific community is an integral feature of the learning model.

The five-phase structure of *TSI* shares elements of other accepted learning models (e.g., Bybee, 1993). The unique features of *TSI* include (a) its interwoven instructional phase and (b) the strong emphasis on the use of multiple modes of inquiry. In *TSI,* instruction is ongoing, multi-directional, and embedded throughout the learning process. This allows teachers the flexibility to lead students through a cycle of learning that is pedagogically and scientifically sound, yet flexible enough to accommodate student-driven interests. More importantly, *TSI* inherently results in a student-centered program. Students act as peer instructors. They also encourage communication and community-building throughout the entire process. Learning is accomplished through a variety of modes, enabling opportunities for individual talents of students to shine and for their weaker areas to improve.

Phases of Disciplinary Inquiry

The general philosophy of the *TSI* instructional approach involves cyclical processes integrated with instruction. This cycle addresses many of the NSES recommendations for "more emphasis" in the Science Teaching Standards as well as Content and Inquiry Standards (NRC, 1996; see alignments indicated in Table 1). As in scientific investigations, the *TSI* instructional model begins with **initiation** when a student identifies a problem to be solved or asks a question about their surrounding environment. Initiation can be fully student driven or guided by teacher questions, demonstrations, presentations of experiences, or anomalies that help students formulate initial questions about target content.

Following initiation, students engage in the **invention** of a means to solve their problem or answer their questions. In the *TSI* learning model, invention can be the development of a hypothesis that will guide an investigation through testing, or it can be the design of an experiment, field study, or even an apparatus that will answer the questions or solve the problems. Thus students can invent both mental models and processes or physical artifacts. By engaging in this kind of thinking about a problem, students develop their inquiry skills and gain deeper understanding of scientific concepts.

Investigation is the part of the *TSI* learning model that involves the actual gathering of new knowledge. During investigations the models and processes created during the invention phase are used to guide the making of observations, testing of hypotheses, and collection and analysis of data. In true scientific fashion, investigation frequently leads to initiation of new questions and invention of new processes or artifacts that can be incorporated into the current investigative framework or later used to stimulate new investigations. Thus learning does not proceed in stepwise fashion; students are encouraged to move back and forth in a fluid manner between phases. Emphasis is on cyclical, logical processes rather than rigid, linear procedures.

The information gathered during the investigation requires **interpretation**. Interpretation is both a reflective, internal process and an objective external process. During internal interpretation, student researchers must take the time to evaluate the information they have gathered, make conclusions, perhaps pose alternative explanations, and document potential scientific errors that may have occurred within their study. This information is then presented for external interpretation by the classroom community and ideally even to the scientific community as well as the general public for evaluation and review.

Instruction is integrated into each part of the inquiry sequence. Instruction in the *TSI* model includes teacher-to-student as well as student-to-student and student-to-teacher instruction. As students generate their own knowledge through investigation, instruction from teacher-to-student becomes more limited, and the process of students sharing their knowledge with their community (both within and beyond the classroom) constitutes the majority of instruction. The *TSI* cycle, as outlined above is well adapted to the formal classroom setting (see Baumgartner et al., 2009 for a description of how the *TSI* phases of disciplinary inquiry are specifically used in a high school classroom).

Table 1. *The Five Phases of The* TSI *Instructional Model as Grounded in the Nature of Scientific Inquiry (modified from Baumgartner, Zabin, Philippoff, Cox, & Knope, 2009) to illustrate connections to NSES recommendations for "more emphasis" in the science teaching standards as well as content and inquiry standards, NRC, 1996).*

<table>
<tr><th>Phase</th><th>Description</th><th>Alignment to NSES</th><th></th></tr>
<tr><td>1. Initiation</td><td>• Originate Interest that results in a problematic focus

• Develop a Focus for inquiry: a question, problem or need</td><td>Teaching Standards: Understanding and responding to individual student's interests, strengths, experiences, and needs</td><td rowspan="4">5. Instruction
(embedded in all phases)

• Communicate new concepts, methods, and connection within student community

• Communicate new concepts, methods, and connections through pedagogic and other broadcast means to the larger public

Alignment to NSES
NSES Content & Inquiry Standards: Communicating science explanations and Public communication of student ideas and work to classmates

Content & Inquiry Standards: Using evidence and strategies for developing or revising an explanation and Implementing inquiry as strategies, abilities, and ideas to be learned</td></tr>
<tr><td>2. Invention</td><td>• Create a Testable Resolution (hypothesis) of the question, problem or need

• Create a Test Design (experiment) or way to determine the workability or the degree of success of the resolution</td><td>Content & Inquiry Standards: Understanding scientific concepts and developing abilities of inquiry</td></tr>
<tr><td>3. Investigation</td><td>• Carry Out a Test according to design in the invention phase

• Carry Out an Analysis according to the design in the invention phase</td><td>Content & Inquiry Standards: Activities that investigate and analyze science questions

Content & Inquiry Standards: Using evidence and strategies for developing or revising an explanation and Implementing inquiry as strategies, abilities, and ideas to be learned</td></tr>
<tr><td>4. Interpretation</td><td>• Evaluate Results: researchers draw conclusions about the workability or success of testing

• Evaluate Conclusions: community evaluates the conclusions of the research; discussion of alternative explanations and additional information</td><td>Content & Inquiry Standards: Applying the results of experiments to scientific arguments and explanations</td></tr>
</table>

Multiple Modes of Knowledge Acquisition

In addition to the phases of inquiry, *TSI* emphasizes the flexibility of science by exploring a variety of different modes of inquiry (Pottenger & Son, 2005; Pottenger et al., 2007). This use of multiple modes of knowledge generation and acquisition is an important aspect of disciplinary inquiry because science is practiced in many ways (Windschitl, Dvornich, Ryken, Tudor, & Koehler, 2007), and investigating the nature of science in its various aspects supports student learning through conceptual change (Tytler, 2002).

The *TSI* modes of inquiry are detailed in Table 2. These modes of inquiry help to illustrate the variety of ways in which new knowledge can be acquired and employed as well as the ways in which teachers and students (indeed, all people) can legitimately do scientific inquiry. Use of multiple inquiry modes also reflects research on the process of knowledge development. Students build knowledge when they construct ideas or arguments using evidence from a variety of sources, and they achieve conceptual change when they re-construct their ideas in light of new knowledge or after taking part in discourse with others (Zembel-Saul et al., 2002).

The use of multiple modes is an important component of *TSI*, which emphasizes the incorporation of inquiry and investigation in a variety of ways – not just the traditional "hands-on" approach. Provision for multiple pathways to knowledge can give cautious teachers a toehold on teaching through disciplinary inquiry because it eliminates the perceived need for inquiry to always necessitate a full-scale experiment. For example, authoritative inquiry, the evaluation of information provided by an established source, is an excellent example of true scientific inquiry that is not hands-on. The use of multiple modes of inquiry also enables more student direction because there are multiple paths to knowledge generation. Moreover, the emphasis on inquiry modes like product evaluation illustrates how scientific thinking skills apply to the broader society, which can help connect students' science experiences to their life experiences. This emphasis also enables students to develop the critical thinking skills necessary for evaluation of information they receive from the world around them; it promotes engagement in the transitive mode of inquiry, which involves taking knowledge from one field, or one learning setting, and applying it to another. Such activities prepare all students to use scientific thinking to approach common daily problems relevant to their lives, whether they go on to become professional scientists or not.

By incorporating a variety of inquiry modes into an existing lesson, teachers are also able to involve students in more styles of learning, also an emphasis of NSES recommendations and good teaching practices. We suggest that teachers be explicit with students about the various ways that scientists acquire knowledge. For example, a unit might begin with authoritative inquiry, where students research current knowledge about the topic of interest. This can lead to inquiry through curiosity, where questions regarding the subject matter are developed. Finally, some of these questions may be addressed through experimental inquiry.

Table 2. *The Modes of Inquiry Addressed in TSI*

Inquiry Modes	Description
Curiosity	Search for new knowledge in informal or spontaneous probes into the unknown or predictable in external environments
Replicative	Search for new knowledge by validating inquiry through duplication; testing the repeatability of something seen or described
Technology	Search for new knowledge in satisfaction of a need through construction, production and testing of artifacts, systems, and techniques
Authoritative	Search for knowledge new to the seeker through discovery and evaluation of established knowledge via artifacts or expert testimony
Inductive	Search for new knowledge in data patterns and generalizable relationships in data association – a hypothesis finding process
Product Evaluation	Search for new knowledge about the capacity of products of technology to meet valuing criteria
Descriptive	Search for new knowledge through creation of accurate and adequate representation of things or events
Deductive	Search for new knowledge in logical synthesis of ideas and evidence – a hypothesis making process
Experimental	Search for new knowledge through testing predictions derived from hypotheses
Transitive	Search for new knowledge in one field by applying knowledge from another field in a novel way

Science is Really Thinking Class

Rather than presenting science as a strict, linear process (i.e., the so-called scientific method often presented by traditional textbooks) consisting of cookbook-style exercises that may seem irrelevant to students' lives, *TSI* promotes the use of local concepts to engage students. As NSES recommends (see alignment in Table 3), teachers and students begin where they are – both geographically and experientially – to take advantage of individual interests, experiences, and needs. Students are encouraged to accept ownership of their learning and discovery. Local resources, such as research scientists and conservation groups, are used to help motivate students and provide physical and academic resources. This molding of the curriculum to fit the expertise of other teachers and experts enhances science learning and provides real models for students.

Teaching through disciplinary inquiry allows, and even encourages, teachers the freedom to say, "I don't know the answer to that question" while still maintaining a leadership role in the classroom. As *TSI* emphasizes the process of discovery, investigations for which the result is unknown to both students and teacher are encouraged for better sharing of responsibilities between students and teacher. Rather than chronicling facts, teachers are encouraged to engage students in the process of inquiry by helping them to ask scientifically oriented questions to promote learning by analysis. Students are encouraged to connect their explanations to their personal body of scientific knowledge. They develop and evaluate explanations based on evidence. As part of the process, student researchers are also given time to interpret their own results. All of this, of course, much better exemplifies the authentic processes of science.

Furthermore, as scientists, students justify and communicate proposed explanations with their colleagues. This information is then presented within the classroom community, and even to the scientific community as well as the general public, for evaluation and review. In this way, students learn the difference between a statement that simply sounds scientific and a statement that they can support with scientific evidence.

Table 3. *Connections between disciplinary inquiry strategies emphasized in* TSI *and NSES recommendations for "more emphasis" in science teaching, content and inquiry, and assessment (NRC, 1996).*

Disciplinary Inquiry Strategy	**NSES More Emphasis**
Using multiple modes of knowledge generation and acquisition	*Content and Inquiry Standards:* • Learning subject matter disciplines in the context of inquiry, technology, science in personal • Social perspectives, and history and nature of science
Using local concepts to engage students by beginning where they are, both geographically and experientially	*Teaching Standards:* • Understanding and responding to individual student's interests, strengths, experiences, and needs
Using local resources (e.g. research scientists and conservation groups) to help motivate students and provide physical and academic resources	*Teaching Standards:* • Selecting and adapting curriculum • Working with other teachers to enhance the science program
Using investigations for which the result is unknown to both students and teacher	*Teaching Standards* • *Sharing responsibility for learning with students*
Helping students to ask scientifically oriented questions	*Content and Inquiry Standards* • *Activities that investigate and analyze science questions*
Treating students like researchers and giving them time to interpret their own results	*Teaching Standards* • *Focusing on student understanding and use of scientific knowledge, ideas, and inquiry processes*
Giving students the opportunity to justify and communicate proposed explanations within the classroom community and perhaps the scientific community / general public for evaluation and review	*Teaching Standards* • *Providing opportunities for scientific discussion and debate among students*
Assessing students' ability to observe, ask questions, and report on their ideas and process of thinking that has lead to investigations and new information	*Teaching Standards* • Continuously assessing student understanding (and involving students in the process) *Assessment Standards* • Students engaged in ongoing assessments of their work and that of others
Emphasizing flexibility at all levels (e.g. of content, process, and difficulty) and adaptation of assessment to fit teacher's needs	*Assessment Standards* • Teachers involved in the development of external assessments
Using project-based units as summative performance-based assessments that require logical thinking and organizing of ideas	*Assessment Standards* • Assessing scientific understanding and reasoning
Using performance-based assessments as opportunities for students to collect and share their data with scientists and the public, which requires rethinking and repackaging of knowledge	*Content and Inquiry Standards* • Groups of students often analyzing and synthesizing data after defending conclusions

Enacting the *TSI* Model in the Classroom

The *TSI* framework is flexible so that all elements can be effectively embedded into a teachers' ongoing practice. The amount of time devoted to project-based *TSI* units is variable. A teacher experienced with project-based learning might weave long-term projects throughout a year's curriculum, whereas a novice might implement only one or two projects during the course of a year. Even informal educators, whose contact time limits the nature of long-term projects, can effectively use the strategies from *TSI*.

An Exemplary TSI Unit - The Case of the Sick Coral

"The Case of the Sick Coral: translating authentic research into a classroom inquiry investigation of ocean literacy principles" is a *TSI* based lesson series that guides high school students in developing and testing hypotheses about the differential susceptibility of corals to bleaching (see Tice & Duncan, 2009 and supporting materials at www2.hawaii.edu/~katice/GK12/index_coral.html). This series of lessons was developed through a partnership between high school teachers, University of Hawaii educators, and Hawaii Institute of Marine Biology researchers (Figure 1). We offer it as a model of how *TSI* can be applied to classroom content.

Insert Figure 1 Here

Figure 1. Scientist and teacher work together to develop, through product evaluation, methods for sampling and mapping a coral reef (top). Scientist and teacher work together to experimentally sample and map a coral reef (middle). Students replicate the study using a mock coral reef in the classroom, performing the same investigative steps as the scientists and teachers (bottom).

"The Case of the Sick Coral" is place-based, allowing students to make connections between science and their own lives. In the lesson series, which was designed for Hawaii classrooms, **initiation** begins when students read a newspaper article about a recent coral bleaching event in the Northwestern Hawaiian Islands. Students are then charged with designing and implementing a study to investigate the causes of the bleaching event for the National Marine Fisheries Service. (This locally relevant "hook" can be adapted for classrooms in other parts of the world by providing students with a case study closer to their own home. For example, a group of students in the Pacific Northwest might read about salmon die-offs.)

Students are introduced to the concept of coral bleaching, and through a discussion on coral biology and physiology are led to the **invention** stage of scientific inquiry. At this stage, students develop hypotheses to explain why some corals on a given reef might bleach, while neighboring corals remain healthy. Several factors might contribute to these differences in bleaching susceptibility – different corals may have different types of zooxanthellae, some of which are more resistant to bleaching, corals may experience different microenvironmental conditions, or there may be genetic differences between corals that make them differently susceptible to bleaching. Again, this hypothesis formation activity could be adapted to local situations in other areas depending on the problem of interest.

Continuing the **invention** stage, students are charged with designing an experiment to determine which of their proposed explanations of coral bleaching is most likely to be accurate. To make the activity manageable, the zooxanthellae hypothesis is excluded, citing monetary restraints (which is reflective of an actual dilemma faced and decision made by researchers). At this stage, students are presented with the coral reef they have been charged with studying. The reef is simulated in the classroom, using broccoli florets to represent healthy coral colonies and cauliflower florets to represent bleached coral (see Figure 1). Students are shown the reef, and they are asked to develop a sampling protocol to determine whether genetics or environmental factors best explain the observed bleaching patterns.

In the **investigation** stage, students divide into research teams to map the location and collect a tissue sample for genetic analysis from every colony on the reef according to their sampling protocol. In addition, mock data loggers placed on the reef provide depth and temperature information. Each coral has an identifying number, and associated with each number is a specific genotype. When the class convenes to compile their data, the teacher presents the students with the genotype information specific to each coral colony's identification number.

With environmental data, genetic data, and locations of all the coral colonies in hand, students can then address their hypotheses regarding the cause of the patchy nature of coral bleaching. In their **interpretation**, students examine the genotype frequencies of the healthy and bleached corals to test for genetic differences between the two groups, and they create a map of the reef using Microsoft Excel to search for any correlations between microenvironmental conditions and bleaching prevalence on the reef.

As students begin compiling and examining their data, they are active participants in the **instruction** phase of inquiry. Students must reconcile the mass of data they have collected and weigh the evidence in support of the competing hypotheses. To do so, they must describe their activities and explain their reasoning to one another. The instruction phase culminates with formal research reports, in which students submit their findings in the form of a scientific report or a science article in the popular press. (Having the students choose a specific audience, such as a local newspaper, a community meeting, an airline magazine, a TV news station, or a scientific journal, for their report realistically replicates the activities of research scientists and provides a range of report formats.)

Additional TSI-Based Lesson Ideas

Effective *TSI*-based lessons or lesson units involve students in investigations of problems that promote findings from specific topics as well as the desire to learn about and debate general scientific topics. These investigations contribute to learning units that are authentic, aligned to instructional goals, appropriate to the learning level of students, and multidisciplinary. Because they tend to be more student driven, flexibility and clear communication are also necessary features.

Local issues like watershed or bird monitoring that have outcomes or products of real scientific use, can inspire authentic *TSI* based lessons. Community partnerships are another authentic way to provide opportunities for students to discuss their scientific thinking with the broader community (see Baumgartner et al. 2006 for suggestions on forming student-scientist-partnerships). For example, one *TSI* based project in Hawaii was built around a hammerhead shark tagging and growth project in Hawaii that ultimately involved multiple teachers and hundreds of student researchers in collecting data, which was later published in scientific journals (see Figure 2, Handler & Duncan 2006).

Insert Figure 2 Here

Figure 2. Student researcher prepares to weigh, measure and tag a juvenile hammerhead shark (*Sphyrna lewini*, top). The shark's electroreceptive organs, the ampullae of Lorenzini, are clearly visible (middle). The student releases the shark to swim away with a tag in its dorsal fin (bottom, photo courtesy of Chris Lowe).

Partnerships with professional researchers are not a precondition for authentic scientific experiences. Students can use techniques, tools, and strategies employed by professional scientists to look at their local environment. For example, on their school campus (or even at home), students can map the vegetation, conduct observations or experiments to monitor populations of migratory or nesting birds, monitor for invasive or pest species, or participate in testing and monitoring the water quality in local watersheds (lesson plans and ideas for these and other activities are collected at www.hawaii.edu/gk-12/evolution). Teachers can also construct scenarios or "mysteries" for students to investigate (e.g., forensics-style mysteries to teach basic biological, physical or chemical concepts, see Duncan & Daly-Engel, 2006).

TSI based units are also communicative, meaning that research ideas and results are shared among all participants and the general public in such a way that the human element of science is explored. This emphasis of science as a community of practitioners is an important aspect of teaching science as a discipline and can have real impact, not only on student learning but also on the scientific community. For example, the AntWatch project (www.hawaii.edu/ant), has been used to map the location of the invasive little fire ant, *Wasmannia auropunctata* in Hawaii. During the project, over 500 students participated, discovering multiple new incipient populations of *Wasmannia* as well as the first new record of another invasive species and a third species entirely new to science (Gruner, Heu, & Chun, 2003). Another project, Our Project in Hawaii's Intertidal (OPIHI) has involved over 15 teachers and nearly 1000 students in the monitoring of intertidal organisms in Hawaii (Baumgartner et al., 2009, www.hawaii.edu/gk-12/opihi). These projects are specific to local issues, but the principles are transferable across environments and across disciplines. In fact, the OPIHI project is similar to the California-based intertidal monitoring project, LiMPETS (see Pearse, Osborn, & ROE, 2003).

Teachers can involve students in sharing their results locally by hosting a class or school-wide symposium. The internet can be used to reach a larger audience and connect with other schools, parents and the community. A middle school might, for example, involve all students and teachers of one grade level in a watershed monitoring program. The participation of the entire grade level team would enable teachers and students to visit multiple sites in the same watershed on the same day to collect and test water samples. The data collected could then be compiled by the students in a school-wide research symposium and shared with the larger community on the school website. The involvement of all grade level instructors means that no-one has to be inconvenienced by missing a class for the field trip, and that the teachers have an opportunity to work together to build a multidisciplinary unit with mathematics, art, reading and writing around the common watershed theme.

Assessment

While the project-based approach fostered by *TSI* naturally lends itself to a capstone activity and summative assessment, there are also multiple opportunities for ongoing, formative assessment that is embedded in the lesson sequence. Assessment of *TSI* units can occur in a variety of ongoing and flexible ways; students observe, they ask questions, and they report on their ideas and their processes of thinking that has lead to investigations and new information. In "The Case of the Sick Coral", for example, student groups first work to construct a poster list of possible causes for coral bleaching and then a method for studying the mock reef. As a group, the class discusses and agrees on a sampling method. Assessment can also occur in the field, as with OPIHI where student knowledge is naturally assessed by their abilities to employ sampling techniques correctly and to identify organisms they encounter. Students participating in watershed monitoring projects, like the 7th grade teams described above, have a natural assessment opportunity when the various teams return to school to pool the data from the different sites. If each team has not employed the proper data collection techniques, it quickly becomes obvious as they present their results.

TSI emphasizes flexibility at all levels, and teachers are encouraged to adapt assessment strategies to fit their needs. The *TSI* structure is accessible to teachers across a broad spectrum of learning levels and content areas. And, because content is flexible, assessment can address the content targeted by the individual teacher in traditional ways (e.g., written tests, quizzes, oral questions and worksheets) as well as non-traditional ways (e.g., posters, essays, poems, oral stories, and ability to participate effectively in projects).

TSI lends itself particularly well to summative performance-based assessments, which require logical thinking and organizing of ideas. Typical end-of-project assessments seen in *TSI* lessons include formal presentations with PowerPoint, scientific reports, forensics "legal reports", pamphlets, town-hall meetings (i.e. classroom debates), science posters, and open-houses. Such performance-based assessments provide natural opportunities for students to collect and share their data with their school community, with scientists, and with the general public. In one *TSI* based project, for example, students who had been investigating the success of shearwater chicks on offshore islets in Kailua Bay, Hawaii developed signage for visitors to a local beach park to share information about the nesting birds and tips to avoid harming the birds.

Students in *TSI* based projects also communicate the knowledge they have learned beyond their classroom in informal ways. In the Hammerhead Shark Tagging & Growth Study, for example, one student wrote, "At first I thought sharks were mean and vicious, but now my perspective has changed a whole lot.... I will successfully take this knowledge and pass it on to my fellow friends and family." Another student wrote, "To tell you the truth, I was able to also teach my brother that sharks are not really all scary" (Duncan, 2010). These examples showcase the ability of *TSI* based projects to empower students to communicate and share their scientific discoveries.

Teachers can assess these often hidden gains in students' knowledge, as well as positive shifts in attitude, by asking students opinions about the learning unit and by asking how the students' perceive their own knowledge and attitude to have changed. This self-reflection on the part of students also helps provide explicit awareness of the inquiry phases and modes, enabling students to consciously learn the process of doing science. For example, at the conclusion of "The Case of the Sick Coral" lesson series, teachers asked students to rate their ability to apply knowledge from the coral genetics and mapping work to a problem of plants around their school. Students are first asked to score their confidence in doing this type of work, and then they are asked to detail some of the processes they might use and some of the factors that might need to be considered. In another example, students in the Hammerhead Shark Tagging & Growth Study conducted a mock tagging experiment as a form of assessment. Each group was given a picture of a different organism for which they had to design a tagging research program based on a research question they were interested in and using supplies available in the classroom "tagging kit", consisting of some real tagging equipment and some photographs of equipment. As a teacher participant observed watching her students conduct this mock tagging experiment, "I really like this. They (the students) are actually THINKING (emphasis teacher's). It is really hard to get them to think for themselves" (Duncan, 2010). This type of assessment addresses students' attitudes, feelings of competency, and ability to transfer knowledge and skills to a novel situation (the transitive mode of inquiry). Such transfer of skills is the essence of a persons' ability to conduct scientific observations and experiments. It is the hallmark of the *TSI* framework.

Directions for Future Work – Professional Development in *TSI*

Professional development in disciplinary inquiry can help teachers become successful facilitators of scientific inquiry, enabling them to create classrooms that function as a community of scientists – where students learn science by engaging in the practice of science. The professional development programs that we are establishing teach educators to facilitate students' scientific literacy by helping students understand not only basic scientific concepts, but also the process that has been used to gain and refine those concepts over time (Figure 3). Through the *TSI* program, teachers learn to develop authentic science activities that rely on and emphasize the use of tools and techniques that are also used by professional scientists. Teachers learn to help students evaluate and decide which tools and techniques to use, and teachers are encouraged to provide students the opportunity for social interactions within the context of science inside the classroom and beyond. When teachers teach disciplinary inquiry, they are effectively guiding students thinking and reasoning through the judicious use of discussion, insight, and assistance – thereby teaching science *as* and *through* inquiry rather than *by* inquiry (see van Zee, Hammer, Bell, Roy, & Peter 2005).

Insert Figure 3 Here

Figure 3. Teachers participating in a *TSI* physical aquatic science professional development course begin the process of understanding wave dynamics by inquiring into the effect of

shoreline incline on wave shape (top). Teachers then empirically derive formulas for calculating various wave properties such as wave height, length and period (middle). Finally, teachers apply this knowledge to the study of a real beach (bottom).

The *TSI* professional development institutes that we have facilitated were centered on specific content foci in order to provide teachers the most authentic experience possible. For example, theme topics for *TSI* institutes have included Astronomy (elementary), Aquatic Science (high school), Sustainable Energy (middle school), Physics & Physiology (middle to high school), and Why Things Sink and Float (middle school). (See Table 3 for an example instructional sequence for an aquatic science *TSI.*) In addition to creating new content foci for *TSI*, our future work will include the development of modularized *TSI* trainings that guide teachers through a series of institutes related to a central theme.

Our current *TSI* professional development structure consists of a two-day (17-hour) workshop combined with a three-hour follow-up experience. The purpose of the initial workshop is to ground teachers in the *TSI* instructional model through a range of topic-specific content. Participants are immersed in the phases and modes of *TSI* in a series of activities through an iterative process during which each aspect of instructional practice is introduced in an activity. Participants form a strong foundation in disciplinary inquiry while at the same time becoming part of a network of teachers and facilitators to interact with in support of their science inquiry teaching practice.

Three to four months after the initial workshop, teachers participate in a follow-up experience (three hours in length) to help them maintain the professional community developed during the institute and to provide further support for teachers. The follow-up also builds accountability by providing a venue for teachers to share the results of their implementation with their colleagues. In addition, this aspect provides opportunities for continued development as participants share with one another which inquiry strategies and which science lessons have (and have not) worked for them. During the follow-up efforts, teachers share their reflections on their attempts to incorporate inquiry, participate in a structured peer-feedback session, participate in Q&A with facilitators, and prepare a lesson plan to share with colleagues for critique.

In the past two years, we have developed and conducted *TSI* professional development institutes ($N = 18$) on the islands of Kaua‘i, Hawai‘i, Maui and O‘ahu, as well as in Guam and China. An external evaluation conducted by the Pacific Resources for Education and Learning (PREL) in 2008 indicated positive participant feedback. Ratings on the General Workshop Evaluation Survey, which PREL used to address participants’ opinions of the effectiveness of the PD, were high. The respectfulness of the learning climate (i.e., the community and collaborative nature of *TSI*) rated highest overall. On a self-report, follow-up instrument about the teachers’ implementation of inquiry-based practices in the classroom, topics related to the breadth of inquiry-based instruction scored the highest (Giuli, in preparation).

Teachers’ written comments for their PD accreditation portfolios also suggested positive influence of the PD on the implementation of *TSI* strategies into existing classroom practice. For example, a high school teacher on the island of Hawaii, stated, “The workshop has helped me immensely in my curriculum planning this year. . . . Everyday I see examples of how this type of learning is effective and engages the students in what they're learning." Another teacher, of 7th grade students on the island of Kauai, stated similar sentiments about the *TSI* workshop in her PD accreditation portfolio: "One of the most important things I gained from this workshop was a new perspective on teaching Scientific Inquiry. . . . There have been many previous occasions where I had a really great idea for an activity or project, but then scrapped the idea because it didn't really fit the traditional "scientific method" model. . . . I now understand that scientific inquiry does not always have to be a long, drawn out process of specific steps. . . . After attending the TSI workshop, I have tried to incorporate this newfound idea into my own lessons on a regular basis!"

Table 3. Instructional Sequence for TSI: Aquatic Science**.**

Instructional Component	**Content/Skills**
Introduction: Observations of an unknown marine object	**What is a scientist?** – Open-ended discussion on the professional and personal qualities of scientists.
Activity: Thought swap - Ocean Literacy Essential Principles (OLEP)	**Science concepts in teaching aquatic science** – Discussion of OLEP & relation to content standards (local & national)
Professional practice reflection: Scientific habits of mind & OLEP	**What is scientific literacy**? – How does ocean literacy promote & relate to scientific literacy & how can we support its development in students? – Discussion of human element of scientific research & interpretation of scientific habits of mind.
Activity: Practicing scientific habits of mind	**Fish printing & fish anatomy** –Teachers use scientific habits (e.g. curiosity & observation) to learn about fish.
Professional practice reflection: The phases of inquiry	**Inquiry instructional sequence –** Teachers are guided through CRDG's phases of inquiry: Initiation, Invention, Investigation, Interpretation & Instruction.
Activity: Practicing scientific habits of mind	**Observation & critical thinking** – Teachers are guided through a material safety exercise about the hazards of the "dangerous chemical" dihydrogen monoxide (H_2O).
Professional practice reflection: Scientific habits of mind	**Modes of inquiry** – Teachers explore the various ways that the demeanors of science are important in everyday life & how these demeanors can play out in daily instruction.
Activity: Working through the phases of inquiry using sand as a medium for exploration	**Sand investigation** – Teachers investigate properties of sand & learn about sand formation then apply their knowledge to match local "unknown" samples with the appropriate beach. Finally, they compare their samples with samples from around the world.
Professional practice reflection: The modes of inquiry	**Modes of Inquiry** – Teachers explore the various ways scientists go about their work through different modes of inquiry & apply the modes to their investigation of sand.
Activity: Combining phases & modes of inquiry into a complete lesson	**Beach Pollution** – Teachers work together to initiate, design & conduct a study of pollution at a nearby beach (located at an ocean, lake, stream or river).
Professional practice reflection: Application of inquiry	**Reflection & development of inquiry activity** – Using their existing curriculum, teachers redesign an existing lesson to be more inquiry-based with support from facilitator & their peers.
Implementation of strategies in classroom: With support from	**Extended practice** – Teachers try inquiry strategies with their students, examine impact on self & students, identify needs,

online resources & online learning community	challenges, & successes. Teachers are supported by peers & facilitators who "coach" online.
Follow-up trainig: Three-hour, face-to-face group training with *TSI* teacher cohort, including a series of three activities investigating density in aquatic science.	**Density stations, *TSI* review, support & accountability** – Teachers investigate density in 3 different activities (showing the flexibility of the *TSI* pedagogical structure to teach a concept through multiple modes) followed by discussion & debriefing with fellow participants about their own lessons as well as their implementation of inquiry strategies in their classrooms.

Summary

TSI provides a foundation for engaging both teachers and students in disciplinary inquiry. The use of a flexible and fluid learning cycle where student instruction and communication are interwoven with multiple modes of knowledge generation is the hallmark of the *TSI* approach. This learning model provides a way for learners to gain scientific literacy by engaging in the full and total practice of science, thus building the demeanors and habits of mind associated with practicing scientists. Because the model is so flexible, it can be easily incorporated at any level and with a variety of content. It is aligned with the NSES recommendations for more emphasis in recommendations for science teaching and has been used successfully in a variety of venues. The flexibility and applicability of *TSI* has enabled its use with programs sponsored through the National Science Foundation STEM Graduate students in K-12 Teaching (GK-12) program, Sea Grant, the Centers for Ocean Science Education Excellence (COSEE) network, the Berniece P. Bishop Museum, the Kohala Center, and the Maui Economic Development Board. Recent use of the *TSI* program as a framework for pre-service teachers in a biology methods course at Western Oregon University also shows promise for *TSI* as a mechanism for pre-service teacher professional development.

References

American Association for the Advancement of Science. (1990). *Science for all Americans*. Oxford University Press, New York, NY.

Baumgartner, E., Duncan, K.D., & Handler, A.T. (2006). Student-scientist partnerships at work in Hawai‘i. *Journal of Natural Resources and Life Sciences Education, 35*, 72-78.

Baumgartner, E., Zabin, C.J., Philippoff, J.K., Cox, E., & Knope, M.L. (2009). Ecological monitoring provides a thematic foundation for student inquiry. In Yager, R. (Ed). Inquiry: The Key to Exemplary Science. Arlington, VA: National Science Teachers Association.

Bybee, R. (1993). *Reforming science education: Social perspectives and personal reflections.* New York: Teachers College.

Duncan, K.M., & Daly-Engel, T.S. (2006). Using forensic science problems as teaching tools: Helping students think like scientists about authentic problems. *The Science Teacher*. Vol. 73(11): 38-43.

Duncan Seraphin, K. M. (2010). A partnership approach to improving student attitudes about sharks and scientists. In press by *School Science and Mathematics* for April 2010.

Gruner D.S., Heu, R.A., & Chun, M. (2003). Two ant species (Hymenoptera: Formicidae) new to the Hawaiian Islands. *Bishop Museum Occasional Papers*. Vol. 74: 35-40.

Hammer, D. (1999). *Teacher Inquiry.* Center for the Development of Teaching Paper Series. Report: ED433997. 25pp.

Handler, A.T. & Duncan, K.M. (2006) Hammerhead shark research immersion program: Experiential learning leads to lasting educational benefits. *Journal of Science Education and Technology*. Vol. 15(1): 9-16.

National Research Council (1996). *National science education standards*. Washington D.C.: National Academy Press.

Pearse, J., Osborn, D., & Roe, C. (2003) Long-term Monitoring Program and Experiential Training for Students (LiMPETS): Monitoring the Sanctuary's rocky intertidal with high school students and other volunteers. *Ecosystem Observations*, (Ed.) J. Caress, Monterey Bay National Marine Sanctuary, Monterey, CA, pp. 6-9.

Pottenger, F.M., & Berg, K. (2006, June). *Inservice training in science inquiry*. Paper presented at the Pacific Circle Consortium Conference. Mexico City, Mexico.

Pottenger, F.M., & Son, Y. (2005, June). *Inquiry, Socratic questioning, and student reflective assessment in the science classroom*. Paper presented at the Pacific Circle Consortium Conference. Sydney, Australia.

Pottenger, F.M., Baumgartner, E., & Brennan, C.A. (2007, September) *Teaching Science as Inquiry (TSI): Teacher professional development*. Paper presented at Hawaii Charter School Administrative Office Breaking Barriers to Learning Professional Development Conference. Honolulu, HI.

Tice, K.A. & Duncan, K.M. (2009). The case of the sick coral: Translating authentic research into a classroom inquiry investigation of ocean literacy principles. Accepted by *Current* January 2009.

Tytler, R. (2002). Teaching for understanding in science: constructivist/concepetual change teaching approaches. *Australian Science Teachers' Journal*, *48(4),* 30-35

van Zee, E. H., Hammer, D., Bell, M., Roy, P., & Peter, J. (2005). Learning and teaching science as inquiry: A case study of elementary school teachers' investigations of light. *Science Education*, 89(6), 1007-1042.

Wee, B., Shephardson, D., Fast, J., & Harbor, J. (2007). Teaching and learning about inquiry:

Insights and challenges in professional development. *Journal of Science Teacher Education*, *18(1),* 63-89.

Windschitl, M., Dvornich, K., Ryken, A.E., Tudor, M., & Koehler, G. (2007). A comparative model of field investigations: Aligning school science inquiry with the practices of contemporary science. *School Science and Mathematics*, *107(1),* 382-390.

Young, D. B. (1997). Science as inquiry. In *envisioning process is content: towards a renaissance curriculum*, editors A. Costa and A. Liebmann, pp. 120-139. Corwin Press. Inc., Thousand Oaks, CA.

Zembel-Saul, C., Munford, D., Crawford, B., Friedrichsen, P., & Land, S. (2002). Scaffolding preservice science teachers' evidence-based arguments during an investigation of natural selection. *Research in Science Education, 32,* 437-463.