

Inquiry-based Chemistry Curriculum for Pre-service Education Students

Pat Meyer, Hang Hwa Hong, and Herb Fynewever*

The Mallinson Institute for Science Education, Western Michigan University
Kalamazoo, MI 49008-5410; **herb.fynewever@wmich.edu*

ABSTRACT

Pre-service teachers' reception of a course taught using inquiry pedagogy is measured using third party observations and student surveys. To facilitate a comparison, students are exposed to a probe lesson using contrasting direct instruction pedagogy and are asked to reflect on the perceived pros and cons of each method relative to each other. The necessity of using inquiry when teaching pre-service teachers is discussed in light of the National Science Education Standards.

KEYWORDS:

Research in Chemical Education

Area: First-Year Undergraduate / General, Pre-service Teachers

Subtopic: Thermodynamics

Focus: Heat Capacity, Phases / Phase Transitions / Diagrams

Pedagogy: Inquiry-Based / Discovery Learning

Specific: Measuring enthalpy of phase change

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All universities that train future K-12 teachers of chemistry and science should concern themselves with not only instruction in content but also with modeling effective pedagogy. We should pay special attention to national K-12 educational mandates. The mandate to include inquiry-based learning methods is spelled out by the *National Science Education Standards (1)*:

Students at all grade levels and in every domain of science should have the opportunity to use scientific inquiry and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments.

In the chemistry curriculum the word inquiry can mean many things (2). We use the definition given in *Inquiry in the National Science Education Standards (3)* which is summarized in Table 1. For the sake of brevity we will refer to *all* instruction methods that lie mostly to the *left side* of Table 1 as *inquiry* and those that lie mostly to the *right side* as *direct instruction*.

Table 1: Essential Features of Classroom Inquiry and Their Variations

Essential Feature	Variations			
1. Learner engages in scientifically oriented questions	Learner poses a question	Learner selects among questions, poses new questions	Learner sharpens or clarifies question provided by teacher materials, or other sources	Learner engages in question provided by teacher, materials, or other source
2. Learner gives priority to evidence in responding to questions	Learner determines what constitutes evidence and collects it	Learner directed to collect certain data	Learner given data and asked to analyze it	Learner given data and told how to analyze
3. Learner formulates explanations from evidence	Learner formulates explanation after summarizing evidence	Learner guided in process of formulating explanations from evidence	Learner given possible ways to use evidence to formulate explanation	Learner provided with evidence
4. Learner connects explanations to scientific knowledge	Learner independently examines other resources and forms the links to explanations	Learner directed toward areas and sources of scientific knowledge	Learner given possible connections	
5. Learner communicates and justifies explanations	Learner forms reasonable and logical argument to communicate explanations	Learner coached in development of communication	Learner provided broad guidelines to sharpen communication	Learner given steps and procedures for communication
	More -----Amount of Learner Self-Direction-----Less			
	Less-----Amount of Direction from Teacher or Material-----More			

NOTE: Degree of inquiry is defined in terms of five essential elements. A typical lesson in our course lies mostly along the inquiry side (lightly grayed) and the contrasting probe direct instruction lesson lies mostly along the opposite side (darkly grayed).

This paper describes how we use inquiry-based pedagogy and examines the reception of it as a pedagogical technique by future K-8 teachers. We ask the future teachers to evaluate the inquiry (learner self-directed) method normally used in our

course and to compare it to a probe lesson that uses a teacher/material directed lesson. We anticipate that student opinions of the inquiry curriculum will be informative for instructors of future science teachers as well as future scientists.

The case for inquiry – argument from principles

A persuasive case can be made that chemistry is best learned when it is taught using inquiry. The crux of this argument is that the most *authentic* and therefore *effective* way to learn science is to engage learners in activities similar to those of scientists conducting investigations. When scientists are “doing science” they are often *not* following detailed cookbook instructions. Therefore we are providing a false example of what science is like if we give students cookbook-like instructions in the chemistry laboratory. Instead, we should provide them with an environment in which they can develop and practice the skills that they will need as scientists. This does not mean simply following directions, but also making observations, forming hypotheses, planning and conducting experiments, and finally constructing explanations from evidence.

The case for inquiry – argument from empirical data

Instructors want to know whether inquiry pedagogy or direct instruction is best at achieving student learning outcomes. The literature contains several studies that conduct controlled experiments comparing learning chemistry by inquiry with learning chemistry by direct instruction. Of the eleven experiments found, three found no statistical advantage of inquiry over direct instruction *or vice versa* (4-6), five found that inquiry was significantly better than direct instruction for some outcomes or in some cases, but not statistically different for other outcomes/cases (7-11), and three studies found inquiry

to be significantly better than direct instruction for all outcomes tested (12-14). In no case was direct instruction found to be significantly better than inquiry. Since, in some cases, inquiry was found to be superior to direct instruction, the overall weight of the evidence must fall in favor of inquiry methods.

This paper is not an attempt to prove that inquiry is the best teaching method. This is a moot debate since our students are expected to comply with the National Science Education Standards and should, therefore, become familiar with using inquiry to teach science. In particular, because we should be reinforcing in teachers the importance of using inquiry, we are interested in whether the students leave our classes with a positive opinion of inquiry and its usefulness. Our data indicates ways in which students are receptive to inquiry and ways in which they are not.

Inquiry is not predominant

Although there is evidence that most of the science education community is in favor of curriculum predominated by inquiry (1-3), many practitioners have not yet made the switch. In General Chemistry, the latest survey data show that 91% of all universities “often” or “almost always” use a direct instruction format for laboratory instruction (15). Similarly, almost half of surveyed high school chemistry teachers indicate that they do not use any inquiry laboratory exercises in their classroom (16). It is hard to know all the reasons why curricula are not changing, but there is some evidence that in some cases instructors are in principle opposed to replacing direct instruction. For example, Ault argues that it is not practical to expect that students can develop experiments in organic chemistry without a measure of cookbook-like instructions (17). In this study we provide

an illustration of a course that is taught almost exclusively with inquiry and we find out the ways in which students both embrace and resist the pedagogy.

Context

Course structure.

The course under study is a semester long course which meets twice weekly for 2.5 hours per meeting. It follows a studio format with laboratory work, discussion, and problem solving work integrated as the instructor deems most effective. The course is capped at 24 students. The students work in groups of four or five at lab tables.

Roles of instructor, course materials, and students.

In a typical class period the instructor acts primarily as a facilitator of discussion and a resource during experimentation. The course is largely structured around a printed set of activities developed under a grant from the Department of Education, Fund for Improvement of Post Secondary Education (FIPSE Award #P116B51275). Examples of these activities are available in the supporting materials section of this article. These are inquiry activities and are generally structured around a question. In this paper the two activities focused on were entitled “How much energy is needed to melt one gram of ice?” and “How much energy is needed to vaporize one gram of water?” The activities are brief prompts for the students, meant to give them some scaffolding to make sense of the question. In no case are the students given a complete set of explicit instructions on how to conduct an experiment to answer the question. Frequently the class will spend time in brainstorming together before experimentation or discussing results after

experimentation. This communication happens in their table groups or with the class as a whole. The instructor generally facilitates the conversations by rephrasing student comments or asking clarifying questions. The instructor typically spends very little time lecturing – this technique is reserved for rare cases when students cannot work together to understand abstract ideas or non-logical conventions (e.g. definition of technical terms).

Content context

The course is entitled *SCI 2800: Physical Science for Elementary Education II*, and the majority of the content is chemistry with a minority of content from physics.

Topics include:

- Measurement
- Matter (particle nature of matter)
- Gases
- Density and buoyancy
- Temperature
- Heat
- Colligative properties
- Electricity
- Periodicity
- Atomic and molecular models (including Lewis Dot structures)
- Acid/Base
- Electrochemistry (batteries)

The two activities focused on in this study came towards the end of the content surrounding temperature and heat. The students had already conducted experiments in

and discussed the topics of thermal equilibrium, heat conductivity, the difference between heat and temperature, heat capacity and specific heat capacity, the definition of a calorie, combustion, and the heating curve for water. The learning outcomes for heat were nearly complete by this point in the course, and the scaffolding should have been in place for the students to conduct the inquiry activities studied in our assessment with virtually no guidance from the instructor or the materials.

Methodology

To gauge how students respond to the inquiry pedagogy used in this course, two of us (HHH and HF) observed the students' behavior for the course of one semester and conducted a written survey asking the students to evaluate their experience in the course. Additionally, to prompt students to reflect on how the way the course is with inquiry methodology to a more "traditional" pedagogy we inserted a probe lesson that was a direct instruction analog of inquiry lessons. This method was used in two sections each with the same instructor. In this paper we focus on two consecutive lessons, both having to do with the enthalpy of a phase change. For the two sections studied, the inquiry and the direct instruction lessons were "flipped-flopped" as described in Table 2. Using this research design we were able to have the students compare the two methodologies while limiting the advantage that one methodology might have over the other due to the difficulty of one lesson's content relative to the other. Additionally, we were able to gather some information regarding whether students are more able to transfer content from one lesson to a related lesson more easily with one pedagogy versus the other.

Table 2: Content and method for two class sections.

<i>Content</i>	<i>Section A method</i>	<i>Section B method</i>
Fusion lesson	Inquiry	Direct instruction
Vaporization lesson	Direct instruction	Inquiry

In the direct instruction versions of the lessons, the instructions for the experiment procedure were explicit and detailed; blanks were provided for data collection; equations were given for data analysis. Additionally, in the direct instruction version, the instructor spent time in “pre-lab” lecturing on what materials to use, how to conduct the experiment, how to collect the data, and how to analyze the data. In contrast, for the inquiry version of the experiment the instructor gave no explicit instruction whatsoever and did not directly answer any student questions during the experiment. For the inquiry lesson for the fusion experiment, the students’ materials simply read:

How Much Energy is Required to Melt One Gram of Water (at 0°C?)

In this problem-solving activity you will need to devise a way to determine the amount of energy (number of calories) required to melt one gram of ice at 0° C.

Results

Student reception of inquiry/direct instruction

Student surveys were conducted on the day of the probe (direct instruction) lesson. The survey had a closed response and an open response section. Student survey closed responses are summarized in Table 3 below. The numbers in each cell represent a percentage.

Table 3: Student attitude towards inquiry learning relative to direct instruction (n=41)

Statement	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
I prefer the way class was taught today – by direct instruction.	7.3	37	17	34	4.9
It was a relief to finally have [instructor name] just tell us what we were supposed to learn today.	29	46	20	4.9	0.0
Today's class, using direct instruction, was more boring than class usually is.	17	32	24	17	9.8
I learn more with inquiry (the way SCI 2800 is usually taught).	9.8	39	24	22	4.9
Inquiry is more frustrating than direct instruction.	24	49	17	12	0.0
Direct instruction is more challenging than inquiry.	0.0	22	37	41	12
Future instruction in this class should be more like today's class (direct instruction).	4.9	29	37	32	9.8

The open-ended questions were analyzed by one of us (HF) to look for common themes. Those comments that were common to three or more students are listed below along with the number of students making the comment in parenthesis.

“The things I like best about how SCI 2800 is usually taught (previous to today’s class) are:”

- Inquiry learning lets us think on our own. (14)
- With inquiry learning I understand better. (10)
- Inquiry doesn’t use formulas, labels, symbols I don’t understand. (8)
- I like working in groups. (4)
- I like that class is “hands-on.” (3)
- Inquiry is less boring. (3)
- Inquiry gives more time to learn. (3)
- I like it when the class has a “wrap-up” discussion. (3)

“Things I’d like to change about how SCI 2800 is usually taught (previous to today’s class) are:”

- We need more straight answers/certainty from the instructor before leaving class. (33)
- It would be good to have more guidance on experiments so that we knew what to look for. (12)
- Mixed methods (direct instruction and inquiry) would be better. (9)
- We dwell too long on concepts sometimes. (4)
- We should spend less time on labs. (3)

A final survey question asked the students to finish this sentence: “I believe that science should be taught using approximately....” Their choices to finish the sentence ranged from 100% inquiry methods to 100% direct instruction methods. The results are summarized in Figure 1.

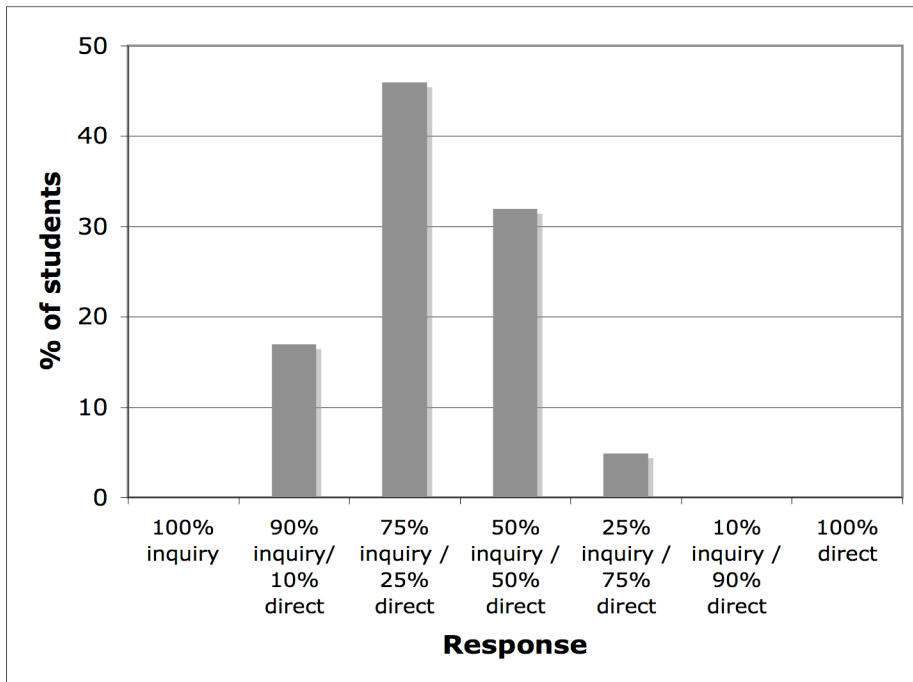


Figure 1: Student opinion of ideal ratio of inquiry to direct instruction

Discussion

Advantages of Direct Instruction over Inquiry

Direct instruction satisfies student desire for certainty. Perhaps the most positive feature of direct instruction from the students’ point of view is the feeling of certainty that comes with the instructor telling them what the “right answer” is. Indeed, in the open-ended exit survey a majority of the students (33/41) suggested that the course would benefit from “more straight answers” or more “certainty from the instructor,” etc. Similarly, on the day of direct instruction, 75% of students surveyed either agreed or strongly agreed with the statement “It was a relief to finally have [instructor name] just tell us what we were supposed to learn today.” By contrast, on the day of the fusion experiment, even though all of the groups designed and conducted substantially correct

procedures and calculations with very little guidance from the instructor, many students were frustrated with a feeling of uncertainty. Even after checking their work between groups and noting corroborative evidence of the correctness of their results they felt uneasy. One student expressed their feelings as “It’s like the blind leading the blind.” On the same day, in the direct instruction section a student expressed appreciation for the explicit detailed guidance on what data to collect: “I like how they list all the blanks.” A direct instruction section student also expressed enthusiasm that they could get straight answers whenever confused: “So we can ask you questions and you have to directly answer it? Cool!”

Significantly, it does not appear that students’ feeling of certainty translates to an understanding that can be transferred to understand analogous physical phenomena. In direct instruction the students’ newly acquired skill is so tightly bound to the context in which it was learned that it is virtually useless in other contexts. This is strikingly apparent in the inability for the students in the direct instruction/fusion session to apply their knowledge during the next class period during the inquiry/vaporization session. To be clear, these experiments are *very* related in content. In both cases a successful procedure involves adding a phase of extreme temperature (cold ice or hot steam) to the phase of moderate temperature (liquid water). In both cases, by measuring the temperature changes and the mass added the enthalpy of the phase change could be calculated with *the same* formula – only with changing the subscripts. It was not until the instructor intervened to hint at the analogy that students began to recognize the connection. Even then, with the previous lesson’s handout in front of them, they felt

uncertain about how to generalize the analysis: “We don’t know what we’re figuring out – you know, that formula.”

Instructor’s direct guidance may lead to more accurate student work. In a direct instruction classroom the instructor retains considerable control over student behavior and can guide students to correct procedures. 12 of 41 students specifically mentioned that they prefer the guidance that comes with direct instruction. In our experiment, the positive effect of this guidance was dramatically apparent in final results produced by the students. In the direct instruction/vaporization session 5 of 6 groups had error of less than 10% in their final result and as compared to only 1 of 6 in the inquiry session.

Although the direct instruction environment is more controlled by the instructor, this control is not absolute. Even with explicit and detailed instructions one group in the direct instruction/fusion session used too much ice and therefore was not able to calculate a final result without starting over.

Timing is more uniform with direct instruction. In a direct instruction classroom things happen more predictably and uniformly including the total time that it takes for different students to complete the activities. During the vaporization experiment, four groups in the direct instruction class finished virtually simultaneously and the remaining two groups were finished only five minutes later. By contrast, in the inquiry classes the first group finished the fusion experiment within 28 minutes, but the last group wasn’t finished until 60 minutes had elapsed. Similarly, although one group in the inquiry section had the correct procedure after 11 minutes, none of the remaining students had developed a correct procedure until after 40 minutes.

In a classroom efficiency is important but sometimes *uniformity* of efficiency is very important as well. If some students finish an activity very quickly and are forced to “wait around” until others figure it out, these students might perceive that their time is being wasted. Indeed, 4 of 41 students specifically mentioned that in the inquiry instruction some concepts are dwelled on for too long.

Advantages of inquiry over direct instruction

With inquiry students must be guided by their own understanding – not by following directions. Several students (14 of 41) mentioned that they like how inquiry lets them think on their own. Related to this, 10 of 41 students mentioned that they understand better with inquiry. Indeed, because each step of the experiment is designed by the students, it is automatically much more likely that they will understand the rationale behind each step in the experiment. This is in contrast to the direct instruction sections where the students *may* simply follow each step-by-step direction without understanding the purpose of each step. This contrast is evident in the types of questions that students ask each other during the experiment. For example, during the inquiry/fusion experiment one student asked, “Why do we have to melt the ice?” and another student responded, “Because that’s what we’re trying to figure out.” Although this response doesn’t articulate the specifics of the purpose of the experiment, it’s still evidence of grappling with the “big picture.” In the direct instruction sections, the questions show evidence that the students are getting lost in the details. For example: “Do we weigh both cups?” “Do we zero the balance?” “Do we need the lid on it to measure the mass?” “So what next?” The students could answer all of these questions

easily if they just realized the significance of each step. We don't mean to argue that students in inquiry sessions fully comprehend the connection of each step in their designed procedure to the overall goal of the investigation. Indeed, as we will see below, inquiry does lead to development of "dead ends" and other non-productive steps. But *if* and *when* inquiry students come to a *workable* procedure, it is almost certain that they have understood the key ideas. This type of understanding is *not necessary* in direct instruction because students are *given* a workable procedure.

With inquiry, students experience development and rejection of non-productive procedures. Students in an inquiry session will most likely spend some time pursuing data collection that is not relevant or use procedures that will turn out to be unworkable. For example, in the inquiry/fusion lesson some students used a stopwatch to keep track of temperature as a function of time. Another group used too much ice to allow for completion of the phase change. Several groups in the inquiry/vaporization section attempted to analyze the steam without combining it with the liquid phase. One could argue that this tendency in inquiry is evidence that students learning with the method will end up "wasting time" and therefore direct instruction should be used. On the other hand, it is precisely this feature that makes inquiry uniquely valuable over direct instruction. In using inquiry students get practice *recognizing* and *rejecting* unproductive procedures. This type of analysis is a higher-order thinking skill that cannot be taught when students simply follow directions in a direct instruction environment and the students know ahead of time that the procedure *should* work.

Inquiry is less boring. In the open-ended surveys a few students specifically mentioned that inquiry is less boring than direct instruction and 73% of students did not disagree with the statement “Today’s class, using direct instruction, was more boring than class usually is.” For many students, following explicit directions is less interesting than developing their own procedure. This is an important realization for future K-8 teachers to come to as they design lesson plans to meet national standards and engage their own students. This is also a useful insight to keep in mind for college chemistry instructors who find students sleeping in class or slumped over a lab bench.

Efficiency – Time Required for Instruction and Experimentation

Although some might take it for granted that direct instruction takes less class time than inquiry, we find that this is only partly true. For the fusion experiment, in the direct instruction section the first group to complete the investigation required only *12 minutes* to complete the exercise and perform the calculations. But, before the experiment was begun the students listened to 25 minutes worth of pre-lab direct instruction. For the inquiry section, there was essentially no pre-lab instruction for the fusion session and the first group to complete the experiment and calculation required 28 minutes. So in terms of *total* class time required, the inquiry section was actually more efficient (28 minutes vs. 37 minutes).

In the vaporization experiment the direct instruction section was more time efficient overall, but the results were not clear-cut. The direct instruction session began with 14 minutes of instruction, and after an additional 26 minutes four of the six groups

had completed the experiment and finished the calculations. In the inquiry section the first group to use the correct procedure required only 11 total minutes to devise and perform it, but they were not confident that they were on the right track and did not continue on to perform the calculation. Even after 40 minutes total *none* of the six groups had completed the experiment and performed the calculation.

Conclusion

As the National Science Education Standards push more primary and secondary teachers to use inquiry, more of our incoming students will have experience learning via inquiry. As chemistry instructors we can be reassured that inquiry methods can achieve the same learning outcomes as we are used to attaining with direct instruction. In fact, the total weight of evidence suggests that inquiry methods can be more effective than direct instruction. Students have mixed feelings on the issue, but most clearly prefer a predominance of inquiry (see Figure 1). And because students and educational researchers both prefer inquiry methods, we believe that inquiry may dominate the chemistry classroom and laboratory in the future.

Supplemental Material

The lesson materials and surveys are available in the supporting materials section.

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