

# Applying ISLE ideas to Active Engagement in the Spins Paradigm

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**Abstract.** Oregon State University's (OSU) upper-division physics courses rearrange the traditional content to center around conceptual and mathematical ideas, with the aim of having students engage in authentic practices of physics in an interactive environment. The physics majors' introduction to Quantum Mechanics is the Quantum Measurements and Spin Paradigm (Spins). I taught this course using the existing activities in my first year at OSU. I am heavily influenced by the Investigative Science Learning Environment (ISLE) curriculum model that mirrors the goals of these upper-division courses. Having since spent two years implementing ISLE in the lower-division courses, when I taught the Spins course this year I modified some activities to align with ISLE methodology. I will discuss how the constructivist, scientific-abilities approach of ISLE helped me personalize the Spins course by providing connectivity between activities and a stronger emphasis on the goals surrounding preparing our students to think like physicists.

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## FOUNDATIONAL CURRICULUM MODELS

### The Paradigms

The junior year for physics majors at Oregon State University has been re-arranged into the paradigms year; students take three-week intensive courses grouped by conceptual and mathematical knowledge rather than traditional physics topics. (For more information, see the paradigms web page [1].) These courses are a result of roughly a dozen years of curricular development, and their success is described in publications [2,3] and backed by continuing NSF support. The year-long sequence roughly covers the first half of Griffith's-level Quantum Mechanics and Electricity and Magnetism, Classical Mechanics, Thermodynamics, Oscillations and Waves, and Reference Frames. However, instead of having the students, for example, take classical and quantum mechanics in parallel, they take a 3-week intensive course on central forces that addresses both planetary orbits and the hydrogen atom, enabling discussion of similarities and differences such as classical and quantum angular momentum. These short-courses have concrete aims of developing deep knowledge of canonical problems, and use activity-based learning to enable students to better develop authentic skills used by physicists, such as finding approximations, limiting cases, representational fluency, open-ended problem solving, and so forth.

The paradigms courses are held for one hour Monday, Wednesday, and Friday, and two hours

Tuesday and Thursday (for a total of seven hours per week) in a classroom specifically designed to transition between lecture, group work, and lab. With this structure, lab and shorter activities can be integrated seamlessly into the course on any day. In the particular course that this paper addresses, students turned in homework assignments two times per week and one lab write-up per week (the labs were done in groups). The paradigms courses make use of a number of pedagogical tools backed up by documented activities (detailed on the web page), including compare-and-contrast activities, small white board questions, kinesthetic activities, computer simulations, and small group activities.

### ISLE

The Investigative Science Learning Environment (ISLE) [4] is a curricular model aimed at helping students learn scientific abilities and practice skills needed to succeed in physics in an authentic way (for more information see the ISLE web page [5]). ISLE is a constructivist approach strongly emphasizing an experiment cycle which starts with observations followed up by hypothesized explanations of those observations, then experimental tests of those observations, and once an explanation is found to be robust, it is applied to new situations. There is strong emphasis on having students explain how they know what they know, having students use multiple

representations to describe observations and make predictions from explanations, and discussing the assumptions and limitations of the applied models. Detailed examples of applying the ISLE cycle are available on the web page.

An important idea the ISLE cycle addresses is falsification: we can show an explanation is not correct if it fails to correctly predict what will happen, but we can never show an idea is ‘correct.’ In addition, it allows for students to directly address confusing ideas, such as ‘we will observe a current if a magnet is inside a coil’ - because they can directly test this hypothesis and show for themselves that without relative motion there is no observed current.

### Overlapping Goals

Both the Paradigms sequence and the ISLE curriculum aim to have students engaging in authentic practices of physics and have explicitly sequenced the development of skills needed to do so. They are each examples of goal-based reform, where the goals that extend beyond the traditional physics content drive the development and sequencing of activities. The paradigms courses aim to teach physics as physicists think about it, grouping the short-courses by concepts that broadly underlie multiple subfields so student see the connections. The courses are structured to encourage mastery of key concepts with mathematics taught as needed in context of the physics.

The ISLE curriculum is built around helping students develop specific scientific abilities which include representing information, conducting experiments, thinking divergently, collecting and analyzing data, constructing, modifying and applying relationships and explanations, and being able to coordinate these abilities. The development of ISLE drew heavily from research on the needs of the 21<sup>st</sup> century workplace, scientific epistemology, brain research, and cognition; and draws on research from cognitive apprenticeship to help students acquire cognitive skills [4].

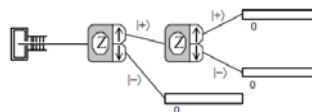
### THEORETICAL PERSPECTIVE

Teacher orientation toward teaching and learning has a strong impact on how a teacher implements reform [6]. As a teacher experiences inquiry-based teaching methods, their view of teacher and student role changes, and their ideas about appropriate activities and assessment shift. Having a curricular model which embodies its philosophy about teaching and learning (such as ISLE) helps to make these shifts explicit, enabling flexible implementation and adaption with new materials and other courses.

ISLE is as much a philosophy as it is a curriculum. In adopting ISLE for the introductory calculus-based physics course, I started by implementing specific activities found on the website, and with experience, was able to implement more each subsequent year. I am now to the point where I do not see ISLE as a collection of materials, but rather as a lens through which to ask myself the appropriate questions about how to implement activities into my classroom. As my pedagogical content knowledge has developed, my ability to implement reform has deepened (an effect well-documented in the literature [7]).

### THE SPINS COURSE

The Quantum Measurement and Spins Paradigm (Spins) is the students’ first introduction to Quantum Mechanics, and occurs about half way into their junior year. It is based on the Stern-Gerlach (SG) experiment, giving students a tangible and historical grounding from which to build understanding of difficult quantum ideas. The course starts with a description of the SG apparatus and how the classical prediction is inconsistent with the observed experimental outcome. Then a simulation (see Figure 1) is introduced to allow students to make observations with different configurations of SG devices. The mathematical model for probability and later state collapse is then brought in to explain the observations and address new situations. Using the simplicity of the 2-level spin system in the historical SG experiment, the course focuses predominately on spin-1/2 systems, but then generalizes to spin-1.



**FIGURE 1.** This is a snapshot from the simulation students use to make consecutive SG ‘measurements’ with various orientations.

The course has four specific problem-solving goals for the students, which are stated at the start of their text (available on the paradigms web page) and on the first day of class, for example to use time evolution to understand spin precession. In addition, the course has the aim of helping students understand the six main postulates of quantum mechanics (also detailed on the web page).

There are many aspects that make this course challenging, but students report that this course presents a strong introduction to quantum mechanics they then build on in later courses (excerpts from student exit interviews conducted at the end of the senior year are on the web page). Since this course

deals with spin-1/2 and spin-1 systems, it is entirely taught using matrix mechanics. There is no need to introduce differential equations, which eliminates some of the cognitive overload that many students would have in a traditional quantum course that requires differential equations. However, students are still new to linear algebra and the math must be explicitly taught along with the content.

The most difficult aspect for the students is learning to use the language and representations of quantum mechanics. The students are using many terms for the first time, the mathematical representations are new, and the mathematical spin space is not a one to one mapping onto real space, causing a lot of difficulty with interpreting spatial representations of spin. This can manifest in incorrect interpretations which cause confusion for the students. We also address difficult concepts such as state collapse, the probabilistic nature of matter, and quantization. The Spins course aids students by grounding each of the concepts through clear observations of the concrete SG system.

## ISLE AS A LENS FOR TEACHING THE SPINS PARADIGM

While a strong curriculum for the Spins course was in place long before I joined the faculty at Oregon State, new teachers are encouraged to make improvements to the paradigms courses. The first time I taught the course, I followed the notes of the previous professor and implemented few additions to the existing activities, mainly to make calculations clearer for students. However, after spending two years reforming the introductory calculus-based course using the ISLE philosophy, I had a new perspective on sequencing and modifying the existing Spins activities.

One impact ISLE had was to orient me toward the importance of grounding the students in physical observation, and the importance of falsification. I began the Spins course by reminding them of the classical result for a current loop in an inhomogeneous magnetic field, and having a lengthy discussion about the importance of the SG experiment as falsification of the Bohr model (including the longer history of how this falsification wasn't correctly interpreted for over five years [8]). I reminded the students daily of the experimental grounding by constantly mentioning tangibles such as the silver atoms.

I also paid closer attention to representations than I had the previous time I taught the course. The most notable place this became important was when discussing physical representations for spin. I found that students misinterpreted the figures even though we repeatedly discussed the fact that spin did not mean

'physically spinning.' I found it necessary to bring in new analogies and representations to aid the students. I also had them move between mathematical, physical, and verbal representations with mini-quizzes to emphasize sense-making for the difficult concepts. They also obtained considerable practice moving between vector and Dirac notation (already in place in the Spins curriculum).

### First activity sequence example

Students work through lab 1 during the second day of the course. This lab has them observe simple outcomes from two consecutive SG measurements (with various orientations of the two devices, for example Z then X) using the simulation shown in Figure 1. They make a table of their data and are asked to see if they can observe a pattern, and make a prediction about new observations based on that pattern. Students then do subsequent measurements to see if the observations match their prediction. They then build a mathematical model for probabilities.

The next day, their model is challenged when we consider three consecutive SG devices aligned by Z, X and then Z. Students are asked to use their mathematical model to calculate the final probability for measuring spin down in Z if initially we only collect atoms from spin up in Z out of the first device. Their calculations show that the probability is non zero, even though their intuition (typically) does not. We then observe this with the simulation, and then observe an analogous phenomenon with crossed polarizers to help ease any conflict between their intuition and the outcome of their model and observations. In the following lab, students must take any relevant data (by measuring probabilities) to work backward to find an initial unknown state. This is a challenging lab mathematically, requiring extensive use of Euler's formula and the ability to realize that two angles can both yield the same value, for example, when solving  $\cos(\theta)$  for  $\theta$ .

While these labs were pre-existing, they were written in a traditional prescription-based format. My experience with ISLE helped me reframe the activities as an ISLE-cycle of observation, testing, and application experiments. I changed the questions posed to the students which impacted the types of discussions we had in the classroom following the activities. I also took advantage of physical experiments to ground the students' conceptual understanding and tie it to the mathematical model.

### Second activity sequence example

In another activity, not previously used in the Spins course, I had students calculate all combinations of  $S_x$ ,  $S_y$ , and  $S_z$  operators acting on all possible eigenstates (written in the z-basis):  $|+\rangle$ ,  $|-\rangle$ ,  $|+\rangle_x$ ,  $|-\rangle_x$ ,  $|+\rangle_y$ ,  $|-\rangle_y$ . Students counted off in such a way that each student had a different student independently check the same calculation. They then went to the board and filled out a large table with all of the results. As a class, we looked for patterns in the table, observing that in specific cases the original eigenstate only changes in magnitude but not direction (the ones matching the eigenvalue equation) and in other cases the eigenstate changes directions. For these calculations, in this 2-state system, the operator changes the state from one eigenstate to the other; it ‘flips’ the state. This facilitates a discussion of ‘what does it mean to be in a particular basis, and what is special about eigenstates.’

Observing that the operators change magnitude and/or orientation of the state vectors solidifies students’ understanding that operators are transformations. This is the definition they learn in their introduction to matrix mechanics, but we have observed in our own courses (faculty at other institutions have told us they experience the same thing) that students conflate operators with measurements [8].

Students follow-up this activity by testing their model for operators through different calculations and applying it to understand state projection. This activity was built around the ISLE idea of an observation experiment, allowing students to observe patterns for themselves, and to make and test their own hypothesis. It was observed to help students with mathematical representations, understanding operators, bringing out discourse to further their understanding of basis vectors, and to minimize conflation of operators with measurements.

## STUDENT ACHIEVEMENT AND GENERAL REMARKS

While I did not take explicit data on student learning either time I took the course, I believe that my final exam this year was harder than the one I gave when previously teaching the course. I asked similar computational questions but extended this year’s exam to include vocabulary, sense-making, and explanations. The average on the final this year was 79.7% with no curve, while the previous time it was 70.0%. I also had students write more extensive lab reports (more along the ISLE format) and felt the reasoning shown and conclusions drawn were far more solid than before I implemented these changes.

Students were more forthcoming with difficulties and were actively engaged with thoughtful questions

this year. Discussions came up such as ‘how do we know how many eigenvalues a matrix has? What is state collapse? What do Hermitian operators represent? What is a basis, and when do we have to be in a particular one? Should some calculations be basis-independent?’ I also observed more correct use of the language of quantum mechanics. (For example, I did not observe any conflation of operators with measurement.)

Overall, I found that applying the ISLE philosophy helped me create a more fluid course, tie ideas and activities together, and build stronger activities to help students overcome common difficulties. It changed the way I asked questions of the students, and changed the classroom discourse. I felt the students obtained a more sophisticated understanding with increased confidence compared to the previous time I taught the course. I also had more confidence as an instructor, using a strong framework from which to develop changes to the course.

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