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The Changing Nature of JPTEO

The *Journal of Physics Teacher Education Online* was started eight years ago – the summer of 2002 – in an effort to provide a medium of exchange for physics teacher educators. In many ways this publication has achieved that goal. In many other ways it has not.

The most significant impact on the future of this publication has been a lack of an adequate number of suitable submissions. Consequently, as of July 13, 2010, *JPTEO* suspended regular publication. *JPTEO* will continue as an irregular publication serving the Physics Teacher Education program at Illinois State University as well as those who are directly affiliated with its work. Effective with this issue, *JPTEO* will no longer solicit contributions. Neither will it be peer reviewed. It will include only articles authored by or in cooperation with members of the ISU Physics Teacher Education group.

I express my sincere thanks to all *JPTEO* authors over the past eight years. I also express thanks to those who have served as reviewers of the articles that have been published herein. I could not have done it without you.

With my recent retirement, I am now looking to spend more time working on articles, writing a high school physics teaching textbook, and enjoying the company of my family. This is not a farewell, but it is an "until we meet again."

Cordially,

Carl J. Wenning, Ed.D.
Editor in Chief, *JPTEO*

Arizona State University's preparation of out-of-field physics teachers: MNS summer program

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Arizona State University (ASU) has demonstrated the feasibility and effectiveness of a university-based graduate program dedicated to professional development of in-service physics teachers. This article is an expansion of my contributed talk at the AAPT Summer Meeting in 2010; included is an overview of the program, why it is needed, how it prepares out-of-field physics teachers, outcomes, and advice on how similar programs can improve high school physics nationwide.

I. Introduction:

Physics is crucial to civilization in this time of great challenges in technology, environment, and society. Our nation faces a severe shortage of scientific and engineering professionals and technical workers. The problem starts in K-12 education (BHEF, 2005). High school physics is crucial for hundreds of types of jobs, including automotive technicians, machinists, heating/air conditioning mechanics, physical therapists, and engineers.

More broadly, we need a populace who can think critically and creatively. That is a chief goal of Modeling Instruction. Joseph Vanderway, a young physics teacher near Los Angeles who graduated with a degree in physics from M.I.T., tells his physics classes on the first day, "I'm here to teach you to think, and physics is my vehicle."

A problem is that two-thirds of all physics teachers in the U.S.A. do not have a degree in physics or physics education (Neuschatz et al., 2008). They need professional development! In fact, even teachers who have Ph.D.s in physics need research-informed professional development such as Modeling Instruction workshops to improve their effectiveness (Hestenes et al., 1992, Wells et al., 1995).

Arizona State University (ASU) has demonstrated the feasibility and effectiveness of a university-based graduate program dedicated to professional development of in-service physics and physical science teachers. We refer to this program as the MNS program, as it can culminate in a Master of Natural Science degree.

A snapshot view of the program: in summer 2010, 120 teachers participated in the MNS program, choosing from five different Modeling Workshops, an astronomy course, and a Leadership Workshop. Most are Arizona teachers, supported financially by ASU physics professor Robert Culbertson's and my NCLB Title IIA "Improving Teacher Quality" state grant (ESEA, 2002) and by ASU's College of Liberal Arts and Sciences, which provides 55 tuition exemptions. (No Child Left Behind – NCLB -- is the nickname for the Elementary and Secondary Education Act, ESEA.) Among the 120 teachers were 16 who are enrolled in our summers-only MNS degree program in physics; one-fourth of these degree candidates are from other states, and only one majored in physics.

From inception in 2001 through 2010, about 840 different teachers participated in the MNS program, including twenty-one of Singapore's best physics and chemistry teachers. (Singapore's K-12 science scores are best in the world! For four years the Singapore Ministry of Education has had a yearly competition to send teachers to ASU; and each summer they fly two Modeling Workshop leaders to Singapore to lead introductory workshops for a week.)

Of these 840 teachers, 515 took one or more Modeling Workshops in physics, 175 took chemistry Modeling Workshops, and 140 took physical science Modeling Workshops. Of the 515 teachers who completed a physics Modeling Workshop (called a "methods of teaching physics" course), only 25% have a degree in physics or physics education. Thus 385 did not, and of this group, about 35 did not intend to teach high school physics. In ten years of existence, therefore, the MNS program has contributed to the professional development of about 350 out-of-field physics teachers. About 20% of these out-of-field teachers have a degree in biology, 20% chemistry, 15% engineering, and the rest in other sciences, mathematics, and non-science disciplines.

This article is an overview of our MNS program, why it is needed, how it prepares out-of-field physics teachers, outcomes, and advice on how programs like ours can greatly improve high school physics nationwide. The MNS program is described at http://modeling.asu.edu/MNS/MNS.html.

We take for granted the pedagogical effectiveness of Modeling Instruction, as that was thoroughly documented in the Findings of a National Science Foundation (NSF) Teacher Enhancement grant entitled *Modeling Instruction in High School Physics* (Hestenes, 2000). Modeling Instruction is an inquiry method for teaching science by actively engaging students in all aspects of scientific modeling. Modeling is about making and using scientific descriptions (models) of physical phenomena and processes (Wells et al., 1995, Jackson et al., 2008). Two Panels of Experts commissioned by the U.S. Department of Education evaluated modeling Instruction. In 2000, Modeling Instruction in High School Physics was designated as one of seven Exemplary or Promising K-12 educational technology projects out of 134 projects reviewed. After a nationwide study, in 2001 Modeling Instruction was one of two K-12 science projects designated as Exemplary out of 28 projects reviewed. Ratings were based on: (l) Quality of Program, (2) Educational Significance, (3) Evidence of Effectiveness, and (4) Usefulness to Others (Expert Panel Reviews 2001, 2000).

II. Essential components of the MNS program are:

1) A complete graduate curriculum of eighteen courses designed expressly for in-service teachers, offered in three- or 4.5-week sessions in summer, providing extended intensive peer interaction.
2) Core courses that model ideal high school courses (i.e. Modeling Workshops) in workshop format that integrates pedagogy and content (Wenning, 2007), taught by a team of experienced in-service teachers (not university professors!), providing teachers with instructional materials and course designs ready for immediate implementation (Schneider et al., 2002). The courses are cross-listed as undergraduate courses and offered for pre-service science education majors.
3) Engagement of university research faculty in teaching advanced physics and chemistry courses aimed at educating teachers about current developments in science, and thus linking research faculty to high school students through their teachers,
4) An integrated program of interdisciplinary courses, especially in chemistry and physical science, since many participants teach all these subjects.

III. Why the MNS program? The need.

Ultimately, all educational reform takes place in the classroom. Therefore, the key to science education reform is to cultivate teacher expertise. That is what the MNS program is designed to do. Lifelong professional development is as essential for teachers as it is for doctors and scientists.

The national physics teacher workforce crisis: Many observers of the science education scene are alarmed by the severe and growing shortage of qualified physics teachers (PTEC). The annual graduation rate of 400 teachers with degrees in physics or physics education is scarcely half the replacement rate for in-service teachers. The attrition rate is about 1,000/yr, so a replacement rate of 600-800/year is needed (Neuschatz et al., 2008). Obviously, the problem will be compounded if the widely advocated increase in high school physics courses is implemented. The bottom line is that to have a significant impact on physics education in the schools, we must deal directly with the in-service teachers as they are. Thus we conclude that the impact of pre-service physics education reform is small and slow! Only in-service professional development can be broad and fast!

The MNS program confirms this conclusion, as it has addressed the physics education needs of a hundred or more out-of-field (crossover) teachers who are <u>new</u> to physics (coming in about equal numbers from chemistry and biology, and even larger numbers from all other majors considered together). Moreover, we have good news to report: In the Modeling Instruction Program the vast majority of crossover teachers soon lose any lingering fears of physics and technology to demonstrate that they are eager and able to learn what is needed to be a proficient physics teacher.

As of 2009, 8% of the currently active 23,000 physics teachers in the U.S. had taken a Modeling Workshop, and most of them are strong advocates of the approach. This 8% figure is troubling, for an American Institute of Physics nationwide survey of high school physics teachers reveals that only 8% report that physics education research (PER) has an impact on their teaching (Neuschatz et al., 2008). We surmise that it is mostly the same 8 percent, for PER is a specific emphasis in Modeling Workshops. The success of Modeling Instruction is largely attributable to its thorough grounding in PER and its design for continued upgrades in methods and materials with strong PER input. We physics educators must greatly improve the influence of PER on high school physics.

Steps to extend the MNS program to all sciences are underway, though progress is heavily grant dependent. The need is great, for the problem of out-of-field teachers is even worse in physical science (Ingersoll, 2002) and almost as bad in chemistry. ASU is prepared to be a national leader in professional development for K-12 science teachers.

IV. Strengths, weaknesses, and prospects of the MNS program.

Strengths of the ASU MNS program are these:
1) It is high quality and effective in student learning, since it is founded on Modeling Instruction.
2) Therefore it attracts smart, committed teachers and peer leaders like Tim Burgess of Mobile, Alabama,

and Michael Crofton of Minneapolis, Minnesota, both of whom regularly have student mean posttest scores on the Force Concept Inventory of 80% or higher, with normalized FCI gains (Hake, 1998) of 0.75 to 0.80 -- better than in any other reform program that we are aware of.
3) ASU is located in a metropolitan area approaching four million, where a large number of physics, chemistry, and physical science teachers can commute. Of Arizona's 280 physics teachers, more than half live within commuting distance of ASU.
4) Affordable housing is available, essential for long-distance teachers.
5) It has support from the ASU Department of Physics and the Dean of Natural Sciences, who has authorized 55 tuition exemptions each summer.

Weaknesses of the MNS program are these:
1) Only one state funding source is available: the Elementary and Secondary Education Act (ESEA) Title IIA "Improving Teacher Quality" (ITQ) program (ESEA, 2002). This is an intervention program of the U.S. Department of Education; 2.5% of formula Title IIA funds that currently go to each state are set aside for the State Agency of Higher Education (SAHE) and are must be used for a yearly competition among institutions of higher education in the state for sustained, high quality K-12 in-service teacher and/or principal professional development in core academic subjects.

Unfortunately, the ITQ program is slated to die if/when the ESEA re-authorization occurs (probably in early 2011); it is not part of the published "Blueprint" of the U.S. Department of Education (ESEA, 2010, SHEEO, 2010). We have applied for NSF grants to partially replace the imminent loss of ITQ funding.

The state Math-Science Partnership program, another intervention program of the U.S. Department of Education (ESEA, 2002), is not an option, for the state designed it for each grant to be for one high-need school district; the paperwork and procedures are daunting for state-level high school science programs such as ours, which has participants each year from two dozen school districts, a dozen charter schools, and several parochial schools, with one or two participating teachers from each school.

NSF Math-Science Partnerships are not an option, for they are highly competitive and not cost-effective because they require research and $1000 per week stipends; too few teachers could be funded.
2) Instability: ITQ grants are short-term (one or two years), and they require yearly requests for budgets. Also, physics competes with all other K-12 academic core subjects and grade levels.
3) Tuition and fees at ASU are expensive. In summer 2011 the cost is almost $2000 for a three-semester-hour Modeling Workshop for Arizona teachers and $2900 for out-of-state teachers. Our dean's authorization of 55 tuition exemptions is dependent upon our having a grant to pay 17% of tuition back to ASU. Teacher salaries are typically around $35,000; three-fourths of Arizona physics teachers are men, many of whom are young, have children, and are the chief breadwinner of their family. The economic downturn exacerbates their financial problem.

Future prospects: The ASU Department of Chemistry has expressed interest in developing a few courses so that high school chemistry teachers can earn a MNS degree with concentration in chemistry. Currently some chemistry teachers earn the MNS degree, but their concentration must be in physics.

V. Supporting evidence:

In our Final Report submitted to the NSF for the grant entitled *A Graduate Program for Secondary Physics Teachers (2002 – 2005)* (Hestenes and Jackson, 2006), we documented four types of evidence for the importance and effectiveness of the MNS program. Here we discuss only teacher competence as measured by the Force Concept Inventory (FCI) (Hestenes et al., 1992).

We administered the FCI to all 226 teachers who took the three-week Modeling Workshop in mechanics during the four summers of the NSF grant (2002-2005), at the beginning and end of the Workshop. Actual test questions were not reviewed during the Workshop, though how to teach the force concept was a central theme of the course. Pretest and posttest results show a substantial gain. Low pretest scores come from out-of-field teachers (many from biology) with very little background in physics, and their gains are impressive. We know from previous studies that their scores will continue to rise during a year of teaching what they have learned in the Modeling Workshop (Hestenes, 2000). We conclude, therefore, that most participants are adequately prepared for teaching mechanics after the initial Workshop, and many have excellent preparation. Of course, this is the result of just the first in a sequence of four Workshops on high school physics.

Of participating teachers during the NSF grant period, 85% were assigned to teach physics: half taught one or two sections and 30% taught physics only. Crossover teachers indicated they were 'retooling' from other disciplines, often to teach "Physics First" (23 teachers in one summer!). Two-thirds of the teachers who took Methods of Teaching

Physics I (the Modeling Workshop in mechanics) had taught physics for four years or fewer. One-third had never taught physics, including 38 (17%) who were experienced teachers of other subjects who had been drafted into teaching physics, and 16 pre-service teachers. One-third of participants were female.
To analyze FCI data, we categorized these teachers as follows. In-field: One-fourth of the 226 teachers (62) majored in physics or physics education. Twenty-one teachers (9%) majored in engineering. Eight teachers had degrees in physical science, for a total of 91 in-field teachers (40%). Out-of-field: The second and third most popular degrees were biology and chemistry, with about 17% each (39 and 35 teachers, respectively). The remaining 30% of teachers had content majors in geology, general science, math, social sciences, humanities, elementary education, and home economics. A total of 131 teachers were out-of-field (60%).

FCI data were disaggregated according to content major, physics teaching experience, and gender. FCI results are in Figure 1.

The Modeling Workshop produced the largest FCI gains for out-of-field teachers and teachers with little physics teaching experience. Sixty-five new physics crossover teachers were prepared: 32 who had never taught physics but intended to, and 33 who had taught physics for one to three years. (One might consider adding the 21 teachers with engineering degrees, who are in some sense out-of-field but have had courses in what is essentially applied physics.) (Note that women had less physics teaching experience and lower FCI scores than men.)

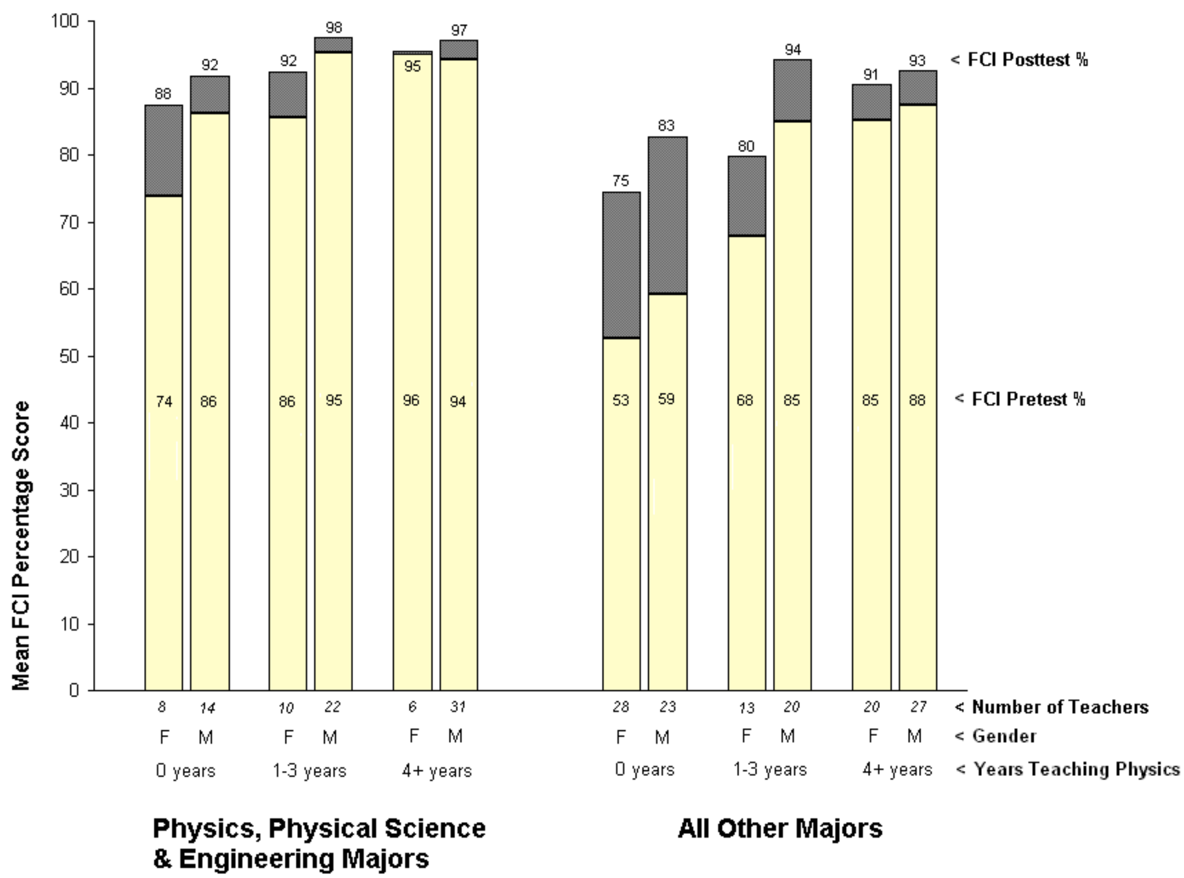

Figure 1: Force Concept Inventory mean percentage scores (pretest and posttest) for 222 women and men in Modeling Workshop in mechanics, correlated with physics teaching experience and content major in college.

Additional quantitative data and graphs on the Mechanics Baseline Test (MBT) are in the NSF final report; also qualitative data and feedback from these teachers (Hestenes and Jackson, 2006).

VI. Outcomes of the MNS program

Reactions to the MNS program from both teachers and professors have been overwhelmingly positive. A North Central Accreditation Academic Program Review Committee evaluating the ASU physics department reported in May 2005: "One of the important ways that ASU is currently elevating science education in Arizona is its unique Master of Natural Science (MNS) program for in-service teachers. There appears to be no comparable program at any other university in the United States, and it stands as an exemplary model of how physics departments can improve high school physics education" (Brodsky et al., 2005).

Most outcomes are similar for in-field and out-of-field teachers, but here we highlight outcomes of Modeling Instruction for out-of-field physics teachers in regard to their preparation and retention, and their students' choices of STEM majors in college.

1) **Certification and NCLB Highly Qualified status.** In fall 2008, Dr. Stamatis Vokos of the National Task Force on Teacher Education in Physics (see http://www.ptec.org/webdocs/TaskForce.cfm) asked us to report on effects of the ASU MNS program on physics certification and Highly Qualified (HQ) status (ESEA, 2002) of metropolitan Phoenix physics teachers. We conducted a survey and found that half (24 out of 52 respondees) of the 60 newer local public school physics teachers (i.e., those who taught physics six years or less) became certified or were progressing toward HQ due to ASU Modeling Workshops. Eighteen (~75%) did not have a degree in physics, physics education, or physical science. All 24 teachers cited Modeling Workshops as their most important preparation. (Thirty-eight of the 52 teachers, i.e. three-fourths, had taken a Modeling Workshop, but some of them took it after becoming HQ and/or physics-certified). Also, eight long-distance out-of-field Arizona public school physics teachers were progressing toward HQ via multiple ASU summer Modeling Workshops.

We did a preliminary survey of non-Arizona teacher participants (65 responses out of 220 teachers surveyed) and learned that six out-of-state teachers and four Arizona teachers had recently achieved National Board Certification. All ten of them cited Modeling Workshops as their most important preparation. Most of the ten are out-of-field.

On both surveys, prevalent comments are that Modeling Workshops improved or transformed their classroom teaching. Typical comments by Arizona teachers are, "By far the Mechanics modeling course was THE best preparational course." "… the modeling courses were a tremendous help. Waves, Light and Mechanics helped the most." "I am a big supporter of the modeling program ... the courses have been more useful to me in terms of helping me teach than any courses I took through the College of Education while I was getting my post-bac certification."

2) **Retention of physics teachers.** Out-of-field and in-field physics teachers have written that Modeling Workshops "saved their careers" and kept them in the profession. Quotes by teachers are at http://modeling.asu.edu/SuccessStories_MI.htm.

A response from the 2008 Arizona survey that may become more common and bears noting is this one: "As an alternative track teacher, I teach 4 different types of classes (math and physics) and take education courses to become fully certified, so it has been wonderful to have many of the physics lessons planned out before the school year started. … Without the Modeling course I could have easily become one of the many alternative track teachers that leave the teaching profession before they have a chance to become proficient."

Several crossover teachers have become Modeling Workshop leaders, notably Larry Dukerich, whose degree is in chemistry. After teaching chemistry and physical science for a decade, he became a physics teacher and seven years later took two five-week Modeling Workshops from Malcolm Wells in 1991 and 1992. He has distinguished himself from 1993 to the present day by leading many Modeling Workshops in physics, chemistry, and physical science and leading teams of experienced teachers and faculty researchers to develop educative curriculum materials (Schneider et al., 2002). In summer 2007, Kelli Gamez Warble, a long-time mechanics Modeling Workshop co-leader at ASU whose degree is in mathematics, surprised a group of us by stating that she would have left teaching years ago for a more lucrative career in finance if it weren't for Modeling Instruction.

3) **STEM majors in college.** Many teachers, in-field and out-of-field, report that a larger percentage of their students choose STEM majors in college than before they began using Modeling Instruction. We have not had funds nor time to conduct research on this, but anecdotal reports by teachers are at http://modeling.asu.edu/SuccessStories_MI.html. For example, Carmela Minaya, a chemistry teacher in Hawaii who earned an MNS degree, wrote: "I have several [former] students who are majoring in science

related fields largely due to the implementation of Modeling Instruction in my classroom. The percentage has gone up from 13% (pre-modeling) to 51% in more recent years."

VII. Recommendations: how the nation can improve high school physics.

Modeling Instruction is a grass-roots, bottom-up nationwide program of 2300 active physics teachers and 700 chemistry teachers, led by enthusiastic, dedicated, smart teachers, with guidance from physics and chemistry education research faculty. Our decade-long summer program at ASU and our experience helping to coordinate 300 intensive three-week Modeling Workshops nationwide has convinced us of several key insights to improve physics, chemistry, and physical science teaching and learning in the U.S.A. The problem of out-of-field physics teachers will persist, and our recommendations take this into account.

1. The need is overwhelming for in-depth, stable, research-informed professional development programs that unite physical sciences content and effective pedagogy. K-12 teaching is a 'revolving door', even in physics. The job turnover, the huge percentage of out-of-field teachers (Ingersoll, 2002), and the low 8% of physics teachers who are influenced by physics education research are evidences of the need.

2. School districts can't solve the problem; it needs regional and Federal solutions. Few school districts have enough physics, chemistry, and physical science teachers to support professional development for them; and school districts are not equipped to conduct the necessary professional development on their own because they lack expertise in science and technology as well as resources to keep up to date on science curriculum and pedagogy. These intellectual resources reside in universities, chiefly in physics and chemistry departments. Note that a recent report by the business community puts STEM professional development as the responsibility of universities (BHEF, 2007).

In the impending ESEA reauthorization, helpful legislative action would be an ITQ-like program that gives priority to high-need STEM subjects and that encourages long-term grants and interstate cooperation. The ITQ program is intervention, not research nor development, and thus cost-effective.

The best legislative action, we believe, would be to implement the top recommendation of the K-12 Focus Group of "Rising Above the Gathering Storm". That group was charged to come up with the "top three actions the federal government could take so that the United States can successfully compete, prosper, and be secure in the global community of the 21st century" (NRC, 2005). The top recommendation has not been implemented. It is:

> "The federal government should provide peer-reviewed long-term support for programs to develop and support a K-12 teacher core that is well-prepared to teach STEM subjects.
>
> a. Programs for in-service teacher development that provide in-depth content and pedagogical knowledge; some examples include summer programs, Master's programs, and mentor teachers.
>
> b. Provide scholarship funds to in-service teachers to participate in summer institutes and content-intensive degree programs.
>
> c. Provide seed grants to universities and colleges to provide summer institute and content-intensive degree programs for in-service teachers."

Apparently current NSF policy prevents a solution of NSF funding, for the NSF's mission is research and development, not intervention. The NSF Education and Human Resources (EHR) Division set policy under Judith Ramalay's leadership that they lack enough resources for interventions (Colby, 2010).

3. Modeling Workshops are fundamental courses. This is evident from their outstanding evaluations by teachers of all content backgrounds and degrees, from all states, and from ages 21 to 69. In the ten years at ASU, on a scale of 1 (poor) to 10 (excellent), teachers gave almost every Modeling Workshop an overall rating above 9, with little individual variation in their rating.

Modeling Workshop leaders are convinced that in-person, face-to-face Modeling Workshops are essential to teach the pedagogy, including model-centered discourse and use of classroom technology in modeling cycles. They believe that hybrid advanced Modeling Workshops can be developed but are inferior to in-person workshops. We will explore this if we can get funding.

4. Costs to teachers must be minimal. Eighty Phoenix-area physics teachers wrote in surveys in 2006 and 2007 that they can afford to pay a maximum of about $150 for a three-credit course. Out-of-state teachers tell us that costs are prohibitive. We find that in most cases only upper-middle class schools, mostly private, can give financial help; and the economic downturn is hampering even these. Almost all Arizona schools have not given any financial help to their teachers, even though we urge teachers to ask for school district Title IIA funds and we give them a sample proposal. Teachers want only to have tuition, room, board, and travel expenses met; they tell us that they don't expect an additional stipend (Hestenes and Jackson, 2006).

To amplify our recommendation #2: school districts and states can't or won't pay; so the funding initiative must come from the Federal government or private philanthropy. How else can education in the physical sciences serve the nation's needs for 21st century technological workforce preparation and economic development? Our nation neglects in-service STEM teacher development at our peril.

5. Chemistry Modeling Workshops are essential. Many physics teachers are primarily chemistry teachers. They need instruction in chemistry modeling, they need to deepen their understanding of chemistry content, and they must relate the two subjects. A dearth of professional development and masters degree programs exists nationwide for chemistry teachers. A result is that several teachers who have earned a MNS degree in physics are strictly chemistry teachers.

6. Cultivate physics teachers to lead reform. We see positive effects on teachers' leadership in their schools and regions. Many out-of-state teachers lead Modeling Workshops in their regions, thereby building local communities of practice. Teachers become more effective by this type of leadership. A promising prospect is to prepare instructional leaders in science to serve in schools and school districts, as called for in the Blueprint for the impending ESEA re-authorization, with its emphasis on data-driven instruction and effective teachers via job-embedded professional development (ESEA, 2010).

7. Lifelong learning must be the focus. ASU's MNS program is unique: it is the only content-centered, research-informed graduate program in the nation specifically designed for all physics teachers, no matter what their background, and focused on lifelong learning, with a degree as a subsidiary focus. Few other research-informed programs for physics teachers exist. Some remedial programs for out-of-field teachers are conventional lecture/problem solving and don't give teachers what they really need. (We believe that MNS-like programs are insufficient for lifelong learning; ideally, they should anchor local physics alliances.)

We must do better as a nation, and the success of the MNS program shows an effective way. Most teachers come to ASU for lifelong learning. In written surveys that we gave in summers 2006 and 2007 to 80 participating Arizona physics and chemistry teachers, almost all teachers responded that lifelong professional development is "extremely important" or "very important" to them. (See http://modeling.asu.edu/MNS/ProfDevNeeds-STEMtchrs.htm for a summary.)

Overwhelmingly these teachers indicated that three-week summer Modeling Workshops are their preferred type of professional development, rather than short content courses in summer, summer research in business or university, Saturday workshops in the academic year, online courses, and several other choices. Example responses are, "It is exactly what I need" and "the only useful professional development I have ever had".

Acknowledgement: My thanks to David Hestenes, founder of the MNS program. Many of the best ideas expressed here are his. A pertinent quote that he had from his father, and that he shares with us, is: "Ideas belong to whoever wants to work on them."

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Levels of inquiry: Using inquiry spectrum learning sequences to teach science (Shaded sections added January 2012)

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The inquiry spectrum is a hierarchical approach to teaching science in a fashion that is likely to increase student conceptual understanding as well as develop their understanding of scientific inquiry and the nature of science. Inquiry spectrum learning sequences – or more simply learning sequences – present an explicit hierarchical framework for inquiry-oriented teaching and learning. Such sequences help to ensure that students develop a wider range of intellectual process skills than are promoted in a typical introductory physics course that uses more limited modes of instruction. It is imperative for teachers and teacher educators to have a thorough understanding of the full spectrum of inquiry-oriented approaches to teaching so that they can more easily help students and teacher candidates achieve a higher degree of science literacy. To give a more practical understanding of the inquiry spectrum framework and associated learning sequences, contextualized examples are provided.

Many science teachers the world over use different inquiry-oriented teaching approaches without having a comprehensive understanding of their interrelationships. Consequently their teaching is not systematic and often fails to address important intellectual processes skills that must be integrated into teaching if students are to develop a more comprehensive understanding of the subject matter as well as a complete set of scientific reasoning skills. In addition, failure to treat scientific inquiry systematically can result in the failure to develop among students an understanding of the processes and nature of science. In other words, teachers need to include in their teaching logical, coherent, and systematic approaches to inquiry that help students become scientifically literate in a much more comprehensive fashion.

The literature of science literacy encourages teachers to employ inquiry as a regular part of teaching practice (e.g., *National Science Education Standards, Science For All Americans: Project 2061*). Unfortunately, this doesn't always happen. One of the chief reasons cited in the literature is that the teachers are often inadequately prepared to use it (Costenson & Lawson, 1986). In addition, science education literature does not provide a framework that helps teachers and teacher candidates clearly understand the scope and sequence of different inquiry approaches. Scientific inquiry is too often presented as an amalgam of skills to be taught in no particular order or fashion.

Some teachers seem to believe that students learn about the processes and nature of science through osmosis; that is, no direct instruction is needed. In practice, this approach leaves students with an incoherent and incomplete understanding of these topics. It also leaves many science teachers and teacher candidates confused as to differences between such approaches as demonstrations, lessons, and labs, and what role inquiry plays in each. For instance, couldn't a good lesson consist of an interactive demonstration? If so, how would the interactive demonstration differ from a lesson? A good lab activity would seem to be a good lesson. So, what is the difference between a lesson and a lab activity? The differences between demonstrations and labs seem readily apparent; the real problem resides in defining the transitional phase between a demonstration and a lab – the inquiry lesson (Wenning, 2005).

There is a clear need to present a broader framework for inquiry approaches that can differentiate between various inquiry approaches and their scope in scientific investigation – each with its associated activities and intellectual process skills. Indeed, a hierarchy must be provided for effective transmission of this knowledge. A model is needed for science teaching that integrates an understanding of the hierarchy of inquiry approaches and instructional practices. One such model has been proposed, and it is known as Levels of Inquiry (Wenning, 2005).

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<u>Scientific Inquiry in the Classroom</u>

Science education reform literature presents no clear and precise definition of what constitutes student inquiry. Student inquiry has been defined in the *National Science Education Standards* (NAS, 1995, p. 23) as "the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world." The *Standards* do define the abilities necessary for students to conduct scientific inquiry: "identify questions and concepts that guide scientific investigations, design and conduct scientific investigations, use technology and mathematics to improve investigations and communications, formulate and revise scientific explanations using logic and evidence, recognize and analyze alterative explanations and models, [and] communicate and defend a scientific argument" (pp. 175-176). Nonetheless, the *Standards* provide precious little guidance about how inquiry processes are to be utilized or taught.

To address these perceived deficiencies, the author introduced an "inquiry spectrum" (Wenning, 2005) to described what he saw as a variety of inquiry-based teaching/learning approaches that progressively move from less sophisticated to more sophisticated, and in which the locus of control shifts from the teacher to the student. In this teaching framework, outlined in Table 1, the levels of inquiry within the inquiry spectrum are shown: discovery learning, interactive demonstration, inquiry lesson, inquiry lab (3 types – guided, bounded, and free), real-world applications (2 types – textbook and authentic), and hypothetical inquiry (2 types – pure and applied).

The inquiry spectrum also can be characterized in a number of additional ways such as from simple to complex, from conceptual to analytical, from concrete to abstract, from general to specific, from inductive to deductive, from broad to narrow, from general principles to mathematical relationships, and in some sense from lower to higher grade level appropriateness. (Education of elementary children will focus on the left end of spectrum, and high school and college students the entire inquiry spectrum.) The inquiry spectrum reflects modern educational thinking about how education of students is best accomplished. The present article attempts to further explicate the inquiry spectrum by providing a variety of *learning sequences* suitable for teaching concepts, principles, and laws in science using subject matter encountered in a typical introductory physics course. Additional learning sequences will be provided in a follow-up article.

Discovery Learning	Interactive Demonstration	Inquiry Lesson	Inquiry Lab (3 types)	Real-world Applications (2 types)	Hypothetical Inquiry (2 types)
Lower		← Intellectual Sophistication →			Higher
Teacher		← Locus of Control →			Student

Table 1. *The scientific inquiry spectrum adapted from Wenning's Levels of Inquiry article (2005).*

Learning sequences present an explicit hierarchical framework for inquiry-oriented teaching and learning. Such sequences help to ensure that students develop a wider range of intellectual process skills than are promoted in a typical introductory physics course that uses more limited modes of instruction. Table 2 provides two examples of successive learning sequences associated with springs. The first cycle is focused on the development of Hooke's law, and the second on the relationship between the masses and period of oscillation for a horizontally mounted spring system. Neither learning sequence includes hypothetical inquiry.

	Discovery learning	**Interactive demonstration**	**Inquiry lesson**	**Inquiry lab**
Hooke's Law	Students are given a variety of springs to examine with the teacher focusing student action on and attention to the following concepts: spring constant, applied force, restoring force, equilibrium position, displacement from equilibrium, compression, and extension.	The teacher demonstrates effects of attaching masses to a vertically suspended spring. Focus is on students developing an understanding of the relationship between force on a spring and its extension from equilibrium position. Misconceptions are addressed as appropriate.	The students, conducting a whole class lab under the guidance of the teacher, work out Hooke's law for springs ($\boldsymbol{F} = -k\boldsymbol{x}$). The apparatus from the interactive demonstration is used, but now with data collection and graphing to find the relationship between $\boldsymbol{F}$ and $\boldsymbol{x}$.	Students extend their study of Hooke's law by determining the effect of adding two springs with different spring constants (k) in series, and the effect of adding two identical springs in parallel.

Oscillating Springs	Students are provided with a suspended spring and masses and encouraged to examine the system. The teacher asks, "Is there a relationship between mass on the spring, how far it is displaced from equilibrium, and between how frequently is goes up and down? Develop the concepts of frequency, period, and amplitude.	The teacher pulls down on a weight attached to a vertically suspended spring and asks, "What happens when the amount of suspended mass is increased?" and "What happens with the same amount of mass but with different spring constants?" The teacher, working with student participation, conducts activities addressing misconceptions as appropriate.	The teacher helps the students to develop a mathematical model to represent an oscillating horizontal system using dimensional analysis. That is, $f = c\sqrt{k/m}$. (For information about dimensional analysis, see the Illinois State Physics Department's online *Student Lab Handbook* at www.phy.ilstu.edu/slh/).	Students experimentally verify the model's relationship $f = c\sqrt{k/m}$ and find the constant of proportionality, $c = 1/2\pi$, through a controlled experiment where the mass is varied and the corresponding frequency measured. Students are given horizontal springs attached to a car on a track and a set of masses to conduct the experiment.

Table 2. *The above table provides two examples of successive learning sequences associated with springs. Neither includes real-world applications nor hypothetical inquiry.*

Table 3 depicts a somewhat more sophisticated learning sequence based on the inquiry spectrum. It deals with Ohm's law and electrical circuits. The subsequent sections of this article explain in detail the various levels of inquiry in the inquiry spectrum using this more complex learning sequence to show what a complete learning sequence (one that includes hypothetical inquiry) looks like in actual practice. Watch for a follow-up of this article (currently in development) for more examples of inquiry sequences addressing a wide array of topics taught in most introductory physics courses.

	Discovery learning:	**Interactive demonstration:**	**Inquiry lesson:**	**Inquiry laboratory:**
Ohm's Law and Electrical Circuits	Students are given batteries, wires, and light bulbs and asked to light one or more bulbs using one or more batteries. Socratic dialogues are used to develop the concepts of voltage, current, and resistance. Students are presented with simple series circuits with light bulbs of varying brightness and are asked to explain potential causes for the differences. Simple relationships relating voltage, current, and resistance are elicited.	Students are introduced to multimeters as a means of measuring voltage, current, and resistance. Principles first proposed in the discovery-learning phase are examined. Focus is now placed an explanation of observations made during discovery-learning phase. The teacher proposes the analogy of water flowing in a pipe as a model for electrical flow. Students analyze alterative explanations and models.	The teacher uses a "think aloud" protocol and Socratic dialogue to help students derive a mathematical relationship between current and voltage for a series circuit containing a power supply and a single resistor. This is done a second and third time with 2 and then 3 roughly identical resistors in series. In effect, students derive various parts of Ohm's Law. Socratic dialogue is use to generate the more general form of the relationship V=IR.	Students find relationships between resistors in series and then in parallel working in small groups. Before students begin working on parallel circuits, they are introduced to the concept of the inverse ohm or 'mho' (with the unit of 1/Ω or ℧) – a measure of electrical conductance or admittance – to make finding the parallel relationship simpler. The y-intercept is related to the system parameter – the value of the fixed resistor.
	Real-world applications: In the area textbook applications, students can use Ohm's laws to analyze circuit diagrams including current flow and voltage drops across various circuit components or the entire circuit. In the area of authentic applications, students can apply a provided definition of electrical power ($P=IV=I^2R$) to analyze energy utilization in a household over the course of an entire month.			
	Hypothetical inquiry: In the area of pure hypothetical inquiry, students use Ohm's law and resistance relationships to explain why resistance in series is additive (conservation of energy) and why resistance in parallel is inversely additive (conservation of charge). In the area of applied hypothetical inquiry, students can be presented with an array of circuit puzzles. They form hypotheses as to how current flows in a given circuit using their understanding of conservation of charge and energy. Based on their understanding, they predict the direction and amount of current flow in each branch of various circuits. They then use meters to check their prediction and revise hypotheses in light of the evidence.			

Table 3. *The above table constitutes a sample learning sequence based on the introduction of simple electrical circuits and the development Ohm's law.*

The following sections of this article are designed to more fully explicate the relationship between the inquiry spectrum and the associated learning sequences using Ohm's law, electrical circuits, and resistance relationships as practical examples.

Discovery Learning

Discovery learning is perhaps the most fundamental form of inquiry-oriented learning. It is based on the "Eureka! I have found it!" approach. A series of directed activities and follow-up questions are used. With Wenning's (2005) definition of discovery learning, the teacher is largely in control of both intellectual and manipulative processes (unlike some other definitions where students might "play" with materials without direction from a teacher in the hope that they will stumble upon concepts or principles). The sophistication of the intellectual processes needed and demonstrated by students are of a lower order. The focus of this form of discovery learning is not on finding explanations of phenomena or applications for knowledge; rather, emphasis is placed on constructing conceptual understanding based on first-hand experiences. New terms are introduced to match concepts only after they are developed. Simple conditional relationships or principles are discovered (e.g., if x occurs, then y results). While explanations are excluded from this level of inquiry, future explanations will be based on experiences at this and more advanced levels of inquiry. Note, too, how the locus of control resides primarily with the teacher in the discovery-learning phase of the inquiry sequence. The teacher does not seek direction from the students and maintains control over student activities.

A Detailed Example of Discovery Learning

Consider the discovery-learning example of Table 3. Students are given batteries, wires, and light bulbs and asked to light one or more bulbs using one or more batteries. Socratic dialogues are used to develop the concepts of voltage, current, and resistance. Students are presented with simple series circuits with light bulbs of varying brightness and are asked to explain potential causes for the differences. Simple relationships relating voltage, current, and resistance are elicited.

After the students get the bulb to light, discussing what happens, and clarifying concepts and introducing terms, the teacher directs the students to wire the electrical components in different configurations, and to think about associated observations. In so doing, and with the teacher's use of Socratic dialogues (Wenning et al., 2006; Wenning, 2005b), students develop not only the concepts of voltage, current, and resistance, but a simple understanding of several principles contained within Ohm's law as well. In this example, findings are based on batteries and bulbs wired in series only. In conducting this phase of the learning sequence, the teacher could perform the following steps:

1. Give students 1 battery, 1 light bulb, and 1 or 2 wires. Ask students to use the battery and wire(s) to get the bulb to light. Once they do this, ask what is happening, and why other wiring configurations do or don't make the bulb light. The students, through teacher questioning, should be able to understand that the battery is the source of something (say, electricity) and when this something is supplied to the bulb in a certain way, it lights. The students, again through appropriate teacher questioning, should be able to develop the concept of a closed circuit.
2. Give the students 2 batteries, 1 light bulb, and enough wires to develop a series circuit of all items. (You'll have to tell the students to wire the batteries + to – so that they are in a series configuration.) Have students wire one bulb and one battery in series, and then have them compare what happens with the light bulb when it is wired in series with two batteries. Through questioning, students can see that more batteries mean more "electricity". The students can be helped through questioning to develop the concept of current.
3. Next, have students wire one battery in series with two light bulbs. Have students compare the results. They will note that more bulbs reduce the amount of something flowing through the circuit (current). Students can be led to see that the more "resistance" there is in a circuit, the less current there is in the circuit.
4. To check the above idea, students should be asked to wire two batteries with two bulbs, all in series, and compare this with one battery and one bulb wired in series. The brightness of the bulbs will be the same on both circuits. Ask the students why this happens. With appropriate Socratic dialoguing, students should be able to see the relationship between the amount of electricity (current) and resistance.
5. Ask students to think of an analogy using water flowing in pipes. The teacher asks about a definition for current. The teacher explains about current use analogy between current that flows in the circuit and flow of water. The teacher guides the student to find that $I=Q/t$. The teacher asks a question about what determines to the amount of water flowing through a pipe (the pressure and the size or the pipe which is related to resistance). Coming back to the example with wires, they

should be able to develop through appropriate teacher questioning the relationship between current and voltage, current and resistance – relationships that are special cases of Ohm's law.

While going through discovery learning, students employ **rudimentary** intellectual process skills (see Wenning, 2005, page 11). Perhaps the most obvious in this example are observing, formulating concepts, estimating, drawing conclusions, communicating results, and classifying results. It is unlikely that any one example of discovery learning will address all these forms of intellectual process skills. Over the course of a school year and with different subject matter and inquiry sequences, all these intellectual skills can be introduced and developed with practice.

Interactive Demonstration

An interactive demonstration generally consists of a teacher manipulating (demonstrating) an apparatus and then asking probing questions about what will happen (prediction) or how or why something might have happened (explanation). The teacher is in charge of conducting the demonstration, developing and asking probing questions, eliciting responses in pursuit of identifying alternative conceptions, putting students in a case of cognitive dissonance so that they might confront alternative conceptions that are identified, soliciting further explanations to resolve any alternative conceptions, getting students to commit to a prediction and comparing the prediction with the outcome, and helping students reach appropriate conclusions on the basis of evidence. The teacher consciously elicits students' preconceptions, and then confronts and resolves any that are identified. The teacher begins to seek additional direction from the students beginning to shift the locus of control from teacher to students. The teacher models appropriate scientific procedures thereby *implicitly* teaching the inquiry process.

A Detailed Example of an Interactive Demonstration

Consider the interactive-demonstration component in Table 3. Students are introduced to multimeters as a means of measuring voltage, current, and resistance. Principles first proposed in the discovery-learning phase are examined. Focus is now placed an explanation of observations made during discovery-learning phase. The teacher proposes the analogy of water flowing in a pipe as a model for electrical flow. Students analyze alterative explanations and models.

The students are asked to pay attention to the simple electric circuit that is shown by a teacher in front of class. Students are asked to observe what happens to the brightness of a light bulb as more and more batteries are added (in series) to the circuit. The teacher introduces electrical meters and measures potential difference across and current through the bulb using a voltmeter and ammeter. The students are shown that by adding batteries in series, they can make the bulb brighter. From this they can conclude on the basis of evidence that higher potential differences produce higher current for a given light bulb (resistance). In conducting this phase of the learning sequence, the teacher could perform the following steps:

1. Call students' attention to the simple circuit at the front of the classroom. The circuit consists of a light bulb and a battery (cell) wired in series. The bulb is lit. Ask students to explain what is happening within the circuit that results in the light bulb being lit. Ask what happens when any wire is disconnected. Elicit preconception that electric current is "used up" by the light bulb.
2. Ask students to predict what will happen if another and another battery (cell) is subsequently added in series. Ask them to explain their reasoning. Add another battery (cell) and see if student predictions correspond with what is experienced. If not, seek further explanations.
3. Now, with a fixed number of batteries (cells), increase the number of light bulbs in series. Before the circuit is connected, have students predict and explain what will happen. Connect the circuit and see if student predictions correspond with what is experienced. If not, seek further explanations.
4. Introduce the analogy of water flowing in pipes as a model for electrical circuits. Have student re-explain what is happening in steps 1-3 using the water-in-pipes analogy. Students should relate the terms of pressure (voltage), flow (amperage), and resistance.
5. Introduce the voltmeter and ammeter, and explain their use. Repeat steps 1-3, this time observing current, voltage, and resistance at teach step. Have students make a table of data for each circuit configuration and then attempt to identify the relationships between voltage and current, current and resistance.

While going through interactive demonstrations, students employ **basic** intellectual process skills, as well as others that they demonstrated in the first phase of the learning sequence. These more sophisticated intellectual processes include such things as the following: predicting, explaining, estimating, acquiring and processing data, formulating and revising scientific explanations using logic and evidence, and recognizing and analyzing alterative explanations and models. Notice, too, that responsibility for critical thinking is slowly beginning to become the purview of students. Note, again, that the teacher models appropriate scientific procedures thereby *implicitly* teaching the inquiry process. At the same time, the teacher begins to *explicitly* teach general procedures and practices of science (see Wenning, 2006).

<u>Inquiry Lesson</u>

The pedagogy of an inquiry lesson is one in which the activity is based upon the teacher slowly relinquishing charge of the activity by providing guiding, indeed leading, questions. The teacher places increasing emphasis on helping students to formulating their own experimental approaches, how they would identify and control variables, and define the system. The students are asked to demonstrate how they might conduct a controlled experiment. The teacher now speaks about scientific process *explicitly* by providing an ongoing commentary about the nature of inquiry.

A Detailed Example of an Inquiry Lesson

Consider the inquiry lesson component in Table 3. The teacher uses a "think aloud" protocol and Socratic dialogue to help students derive a mathematical relationship between current and voltage for a series circuit containing a power supply and a single resistor. This is done a second and third time with 2 and then 3 roughly identical resistors in series. In effect, students derive various parts of Ohm's Law. Socratic dialogue is use to generate the more general relationship V=IR.

Students are confronted with the question, "What is the relationship between current, voltage, and resistance?" Now, a teacher could merely tell them the relationship known as Ohm's law, V=IR, but this defeats the purpose of science education that sees students as independent thinkers who can draw their own conclusions based on evidence. Determining the relationship for the first time can be much more instructive for students, as well as more interesting. Consider the following inquiry-based approach. T stands for teacher talk, and S stands for student talk.

T: So, who can summarize from our earlier experiences what the relationships are between, say, current and voltage, and current and resistance?

S. When voltage is increased, the current also increases.

T. And how do you actually know that?

S. When we put more batteries together in series, the brightness of the light bulbs increased.

T. Good, and who can tell me about the relationship between resistance and current?

S. When light bulbs are added in series their resistance increases and the light bulbs together are dimmer than one alone. So, the greater the resistance, the less current there is flowing through a circuit.

T. Good. Now, today we will spend some time learning the precise relationships between these variables – all three of them in fact. Examine the simple series circuit I have before me – a power supply, a set of differently valued resistors, and wires for making complete circuits. Here are two multimeters that will be used measure both the voltage across and the current through any resistors used in the circuit or circuits we build. Now, how can I conduct a controlled experiment to find the relationship between say voltage and current?

S. Using one resistor, vary the voltage while observing the current. The resistance will be held constant – a parameter of the system. While the voltage is varied, watch the value of the current. Then, make a graph of voltage versus current to see how they are related. Examine the slopes of any linear relationships that might be found, and relate them to the system parameters.

T. Excellent, let's do just that. (Teacher observes as student collect and record data, make and interpret a graph. The students then communicate the results of the experiment.)

S. We found that current is proportional to voltage for a given resistance. The form of the specific relationship we found was V=IR.

T. So, how can we generalize this relationship for all values of R?

S. We could conduct the experiment again and again using a different value of resistance each time.

T. That's acceptable; let's give it a try.

While going through inquiry lessons, students employ **intermediate** intellectual process skills, as well as others that they demonstrated in earlier phases of the learning sequence. These more sophisticated intellectual processes include the following: measuring, collecting and recording data, constructing a table of data, designing and conducting scientific investigations, using technology and math during investigations, and describing relationships.

<u>Inquiry Labs</u>

Inquiry labs generally will consist of students more or less independently developing and executing an experimental plan and collecting appropriate data. These data are then analyzed to find a law – a precise relationship among variables. Students involved in an inquiry lab are more independent in terms of formulating and conducting an experiment that in any level of inquiry that precedes it. The teacher is present to assist with difficulties, but the primary responsibility for designing an experiment, using technology to collect data, analyzing and interpreting the data, and communicating the results is borne by the students. This inquiry lab approach is not to be confused with the traditional "cookbook" laboratory activity. The distinction between traditional cookbook labs (sometimes called "structured inquiry") and true inquiry-oriented labs is profound (Wenning & Wenning, 2006).

A Detailed Example of an Inquiry Lab

Consider the inquiry lab component in Table 3. Students find relationships between resistors in series and then in parallel working in small groups. Before students begin working on parallel circuits, they are introduced to the concept of the inverse ohm or 'mho' (with the unit of $1/\Omega$ or $\mho$) – a measure of electrical conductance or admittance – to make finding the parallel relationship simpler. The y-intercept is related to the system parameter – the value of the fixed resistor.

In the first part of this two-part lab students use inductive reasoning to show that as resistors are added in series, the total value of the resistance is explained by the following relationship:

$$R_t = R_1 + R_2 + R_3 + \ldots.$$

During the second part of the lab students build a parallel circuit using a fixed resistor (the value of which is a system parameter) and a variable resistor. A multimeter is used to measure the equivalent resistance. Plotting the equivalent resistance in mhos and the independent resistance in mhos, the students find a linear relationship with a non-zero intercept. Replacing the mho variables with inverse resistance variables, the students discover the expected inverse relationship. The parameter of the system is identified with its inverse resistance. That is, students find the following relationship:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$$

While going through inquiry labs, students employ **integrated** intellectual process skills, as well as others that they demonstrated in earlier phases of the learning sequence. Typical of this aspect of the sequence, students will commonly utilize the following intellectual process skills: measuring metrically, establishing empirical laws on the basis of evidence and logic, designing and conducting scientific investigations, and using technology and math during investigations.

Textbook and Authentic Real-world Applications

Real-world applications in the inquiry spectrum consists of two types of problem solving – completing textbook-based end-of-chapter problems or conducting authentic investigations. Solving simple textbook problems does not generally lend itself to use with the learning cycle as this type of problem solving consists primarily of applying current knowledge to new situations in a mathematical sense. Still, this is an important element of learning to apply science to real-world situations. There are well-known frameworks for structured problem solving that can be recommended such as that developed by Heller & Anderson (1992).

While end-of-chapter problems can be "beefed up" with the use of increased context as in the case of context-rich problem solving (Physics Education Research and Development Group, 2012), they still not provide the authenticity of real-world situations.

In authentic real-world problem solving, students conduct either issues-based problem solving (e.g., dealing with the science-technology-society interface such as whether a low-level nuclear waste dump, a wind farm, or a nuclear power plant should be built in a community) or project-based problem solving (e.g. engineering solutions to specific problems). Only real-world applications such as these teach the great variety of necessary problem-solving skills in a real-world context.

Examples of Real-world Applications

Following the development of Ohm's law and the equivalent resistances for parallel and series circuits, it is fruitful to have students apply this information in textbook-based circuit analysis. Students can determine voltage drops across and currents through various resistors and equivalent resistances for various part of or an entire circuit.

The utility of physics can be driven home through the use of problem-based learning in which students conduct an efficiency analysis of their own homes or through the use of project-based learning in which students wire a scale model of a home. In doing the former students examine the power ratings of household appliances and light bulbs, and relate this to the month's electrical bill. In doing the latter, students wire parallel circuits, work on current requirements, figure out suitable gauges of wire to use for various appliances mimicked by light bulbs, figure out two-way switches, and can even put in working fuses. The possibilities are almost endless.

While working their way through real-world applications, students learn to employ **culminating** intellectual process skills: collecting, assessing, and interpreting data from a variety of sources; constructing logical arguments based on scientific evidence; making and defending evidence-based decisions and judgments; clarifying values in relation to natural and civil rights; and practicing interpersonal skills.

Pure and Applied Hypothetical Inquiry

Hypothetical inquiry can take on two forms as described in the inquiry spectrum – pure hypothetical inquiry and applied hypothetic inquiry. Both versions are geared toward developing explanations about why things are or work the way they do. Pure hypothetical inquiry is research made without any expectation of application to real-world problems; it is conducted solely with the goal of extending our understanding of the laws of nature. Applied hypothetical inquiry is geared toward finding applications of prior knowledge to new problems. The two types of hypothetical inquiry essentially employ the same intellectual processes; they tend to differ on the basis of their goals.

Detailed Examples of Hypothetical Inquiry

Consider the hypothetical inquiry component in Table 3. In the area of pure hypothetical inquiry, students use Ohm's law and resistance relationships to explain why resistance in series is additive (conservation of energy) and why resistance in parallel inversely additive (conservation of charge). In the area of applied hypothetical inquiry, students can be presented with an array of circuit puzzles. They form hypotheses as to how current flows in a given circuit using their understanding of conservation of charge and energy. Based on their understanding, they predict the direction and amount of current flow in each branch of various circuits. They then use meters to check their prediction and revise hypotheses in light of the evidence. Consider first the underlying cause for the series relationship for resistor:

$$R_t = R_1 + R_2 + R_3$$
$$R_n = \frac{V_n}{I_n} \quad (Ohm's\ \ Law)$$
$$\frac{V_t}{I_t} = \frac{V_1}{I_1} + \frac{V_2}{I_2} + \frac{V_3}{I_3}$$
$$I_t = I_1 = I_2 = I_3$$
$$\therefore V_t = V_1 + V_2 + V_3$$

That is, the series law for resistors holds because of conservation of energy. Similarly, the parallel law for resistors holds because of the conservation of charge.

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$\frac{1}{R_n} = \frac{I_n}{V_n} \quad (Ohm's\ Law)$$
$$\frac{I_t}{V_t} = \frac{I_1}{V_1} + \frac{I_2}{V_2}$$
$$V_t = V_1 = V_2$$
$$\therefore I_t = I_1 + I_2$$

In terms of applied hypothetical inquiry, students might be confronted with a rather confusing electrical circuit such as that shown in Figure 1. Using their knowledge of the conservation energy and charge in an electrical circuit (essentially Kirchhoff's loop and junction rules), as well as the resistor and battery values, students can hypothesize how current flows through a circuit and, on the basis of Ohm's law, predict the voltage drop over each resistor. By comparing predictions with experimental values, students can refine their knowledge of current flow and voltage drop in a complex circuit.

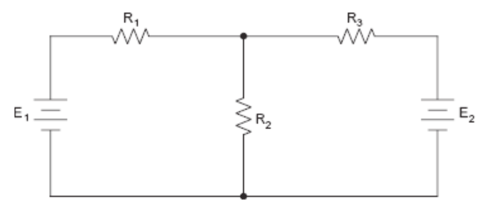

Figure 1. *A "complex" circuit for applied hypothetical analysis and testing.*

While going through hypothetical inquiry, students employ **advanced** intellectual process skills, as well as others that they demonstrated in earlier phases of the learning sequence. These more sophisticated intellectual processes include the following: synthesizing complex hypothetical explanations, analyzing and evaluating scientific arguments, generating predictions through the process of deduction, revising hypotheses and predictions in light of new evidence, and solving complex real-word problems. This process provides the added bonuses of helping students understand the joy and mystery of the scientific endeavor, as well as developing a broader understanding of the nature of science and respect for its processes.

Applications of Learning

Readers are cautioned that while inquiry is at the heart of the learning sequence, by no means is the application of knowledge to be divorced from the educational process. Helping students to learn content without application is akin to educational malfeasance – for what else is the purpose of education? Clearly students will have learned to work in groups, use technology, make observations, draw conclusions, communicate results, and so on through the use of inquiry practices. Still, inquiry would not be complete if applications of newfound knowledge are not made.

A teacher need not wait until the end of the learning sequence to have students utilize knowledge gleaned from the inquiry process to practical, real-world problems. Algebraic problem solving is quite a natural process that will result from students' findings. They can use formulas to predict and then verify the results of inductive work – the hallmark of scientific work. Deducting predictions base on laws and principles, which are themselves derived from induction, shows a more comprehensive view of the nature of science. Throughout the educational process, students should be required to utilize their knowledge discovered through the inquiry process. They might be given worksheets, problem sets, case studies, projects and so on dealing with the various principles and laws learned in the classroom.

An Inquiry Spectrum Redux

To more fully appreciate what the inquiry spectrum does for both teacher and students, it is imperative to examine the primary pedagogical purposes of each of the levels of scientific inquiry. They are outlined in Table 4.

Levels of Inquiry	Primary Pedagogical Purpose
Discovery learning	Develop concepts on the basis of first-hand experiences; introduce terms.
Interactive demonstration	Elicit, identify, confront, and resolve alternative conceptions.
Inquiry lesson	Identify scientific principles and/or relationships.
Inquiry labs	Establish empirical laws based on measurement of variables.
Real-world applications	Apply prior knowledge to authentic problems.
Hypothetical inquiry	Derive explanations for observed phenomena.

Table 4. *Primary focus of each of the six main levels of scientific inquiry. This table is suggestive, not definitive.*

The roles that various intellectual process skills play in each of the levels of scientific inquiry are detailed in Table 5 found on the following page. This table is a refinement of Table 5 in Wenning (2005). The revision is based on the explication of Levels of Inquiry in this article. Each of the skills is now partitioned differently and linked to an increasingly sophisticate hierarchy of inquiry processes. Note the introduction of a new class of intellectual process skills – intermediate skills – in the third column. This table in it entirety is intended to be suggestive, not definitive.

Levels of inquiry, lesson sequences, and classification of their associated skills will continue to be refined as more sequences are developed and research is conducted. Such is the development of an educational theory.

Discovery Learning	Interactive Demonstration	Inquiry Lesson	Inquiry Labs	Real-world Applications	Hypothetical Inquiry
Rudimentary skills: • observing • formulating concepts • estimating • drawing conclusions • communicating results • classifying results	*Basic skills:* • predicting • explaining • estimating • acquiring and processing data • formulating and revising scientific explanations using logic and evidence • recognizing and analyzing alterative explanations and models	*Intermediate skills:* • measuring • collecting and recording data • constructing a table of data • designing and conducting scientific investigations • using technology and math during investigations • describing relationships	*Integrated skills:* • measuring metrically • establishing empirical laws on the basis of evidence and logic • designing and conducting scientific investigations • using technology and math during investigations	*Culminating skills:* • collecting, assessing, and interpreting data from a variety of sources • constructing logical arguments based on scientific evidence • making and defending evidence-based decisions and judgments • clarifying values in relation to natural and civil rights • practicing interpersonal skills	*Advanced skills:* • synthesizing complex hypothetical explanations • analyzing and evaluating scientific arguments • generating predictions through the process of deduction • revising hypotheses and predictions in light of new evidence • solving complex real-word problems

Table 5. *A refined notion of which intellectual process skills are most closely associated with the six various levels of scientific inquiry. This table is a refinement of Table 5 appearing in Wenning (2005).*

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