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A graduate program for high school physics and physical science teachers

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The Modeling Instruction Program at Arizona State University has demonstrated the feasibility and effectiveness of a university-based graduate program dedicated to professional development of in-service physics teachers. The program culminates in a Master of Natural Science degree, although not all students in the program are degree candidates. The findings draw from nine years of experience in developing, implementing, and evaluating the effects of the program (2001–2009).

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I. INTRODUCTION

For more than two decades, various reports have warned that K-12 science education is in dire disrepair.[1] These reports have led to proposals for K-12 science education reform as a priority in national science policy,[2] with emphasis on strengthening the education of scientists and engineers for sustaining economic growth, providing the foundation for an effective workforce, and producing science literate citizens and consumers.

Concomitantly, with broad input from the science and education communities, the National Research Council achieved a consensus on National Science Education Standards to guide K-12 science education reform.[3] Similarly, the National Council of Teachers of Mathematics created standards for mathematics education.[4] These documents have strongly influenced the content of individual state standards for science and mathematics. Reforms in physics education are recommended in three broad categories: pedagogy, curriculum that incorporates contemporary science, and technology infusion.

Although the influence of the National Science Education Standards is increasing,[5] their influence on classroom practice remains slight. Schools and school districts are ill-equipped to implement reform on their own, and they lack the necessary expertise in science and technology as well as resources to keep up-to-date with advances in science curriculum materials and pedagogy. These resources reside primarily in universities.

As of 2005, there were 23,000 physics teachers in the U.S., up from 17,900 in 1987 (see Fig. 1).[6] This 28% gain is less than the 77% increase in the number of students taking physics. Because class size has remained constant at 18 students, the only way this increase was accommodated is by increasing the average number of classes taught by each teacher. The report speculates that this disparity is due to the "long-standing shortage of qualified physics teachers." The annual graduation rate of 400 teachers with degrees in physics or physics education is only half the replacement rate for in-service teachers (see Fig. 1).[6,7] The loss of a physics teacher is often addressed by asking an unqualified teacher already on the staff to teach physics. For this reason the replacement rate for physics teachers in Fig. 1 is much larger than the production (graduation) rate for new teachers with physics education preparation.

Apart from the many problems of improving pre-service training, the data in Fig. 1 appear to support the likelihood that, absent widespread changes in induction and support, the impact of improved pre-service teacher preparation on physics teaching will remain small. If the current trend continues, 70% of physics teaching positions will be filled by post-baccalaureate teachers and crossover teachers (who do not have a degree in the subjects they are assigned to teach).

Graduate professional development programs at the nation's universities are needed to address the critical problem of upgrading qualifications of in-service and crossover physics teachers. As an exemplar, we describe one such program developed at Arizona State University (ASU). We hope our description will stimulate the creation of similar programs at other universities. A coordinated network of similar programs in physics departments across the nation would provide a powerful engine to drive continuous upgrading of K-12 science education.

II. A UNIVERSITY PROGRAM TO CULTIVATE TEACHER EXPERTISE

The key to reform is to cultivate teacher expertise. The need is especially critical for high school physics and chemistry teachers because they are in the best position to set the level and tenor of science in their schools and serve as local leaders of education reform.

Systematic efforts to introduce research-based physics education reform at ASU began with a decade of NSF funding for the Modeling Instruction Program under the leadership of David Hestenes.[8–10] It is not our aim to discuss modeling instruction in detail here but rather to account how it has

High School Physics Teacher Profile

Pipeline: (approximately 23,000 teachers in the U.S.)
Graduation (400/year), Attrition (1,000/year), Replacement (600-800/year)*

Background** (Degree):
Physics (32%), Math/Engineering (14%), Chemistry (11%),
Biology/other sciences (26%), Other (18%)

Teaching Assignment:
All physics (26%), Mostly (18%), Half (12%), Less (44%)

Prep for teaching (self-assessed):	Very good	Adequate	Not adequate
Basic physics:	66%	32%	2%
Recent physics:	13%	51%	36%

8% report some Physics Education Research influence

Attitude toward Physics First: For (24%) Neutral (21%) Against (55%)

Morale: strong élan and satisfaction:
- 78% would choose physics teaching career again (82% in 1997)
- 3% attrition rate after 4 years

*This population of replacement teachers represents crossover teachers from other science disciplines or new hires with provisional or post-baccalaureate certification
**Rounded to the nearest whole percent

Fig. 1. High school physics teacher profile (from Ref. 7).

become embedded in a comprehensive graduate program. For detailed accounts of the design, development, and theoretical framework of modeling instruction, see Refs. 8–12.

As the Modeling Instruction Program propagated across the nation during the last decade, we heard a rising chorus of teachers calling for more opportunities to collaborate and learn.[8] Our response was to create a full-fledged summer graduate program for high school physics teachers that extended and deepened the Modeling Instruction Program's Modeling Workshops (see Fig. 2 for program objectives).

Modeling Workshops had been institutionalized at ASU as methods of physics teaching courses for pre-service and in-service teachers. These courses were used as a basis for re-tooling an ill-defined graduate degree program for in-service teachers called the Master of Natural Science (MNS). The redesign resulted in a coherent program of courses designed to meet the needs and demands of physics teachers. The new MNS program requires significant participation from research physics faculty. Fortunately, it was unanimously ratified by the Department of Physics and Astronomy and subsequently passed through the necessary administrative channels to be incorporated into the official university catalog.

The MNS program in physics has been in place for nine years. The response of teachers has been so positive that it prompted the creation of comparable programs for in-service teachers by ASU mathematics and chemistry departments. In addition, in fall 2009 ASU received NSF Innovation through Institutional Integration funds to create a Middle School Modeling MNS program in science, technology, engineering, and mathematics.

Objectives of the MNS graduate programs for science and mathematics teachers:
1. To fulfill the obligation of higher education to provide science/mathematics teachers with opportunities for relevant, life-long professional development.
2. To enhance the professional status and qualifications of in-service teachers.
3. To link scientists to high school students through direct contact with their teachers, and thus create a channel for effective outreach activities.
4. To support continuous improvement of K-12 science/math curriculum and instruction.

Fig. 2. Master of Natural Science program objectives.

III. DESIGN OF THE MASTER OF NATURAL SCIENCE PROGRAM

Although the program is intended primarily for physics teachers, much of it is appropriate for teachers of chemistry, physical science, and mathematics. The main purpose of the program is professional development, so the option of obtaining an MNS degree is incidental. Most teachers who take MNS degree program courses do not apply to the MNS degree program.

The courses are designed to meet the needs of in-service teachers for up-to-date science content and pedagogy. Twenty courses have been developed. Most have been repeated at least three times and core courses are offered annually. Courses are either in physics pedagogy, interdisciplinary science, or contemporary physics (see Fig. 3). Syllabi for specific courses are available[11] but are intended as examples only because faculty members are free to design them as they see fit.

A. Physics pedagogy

Core courses on physics teaching (Physics 530/531) are required for everyone in the program. Physics 530 introduces modeling instruction with the study of Newtonian mechanics and physics 531 extends the modeling method to electricity and magnetism. These courses provide a thorough grounding in research-based physics pedagogy in accord with National Science Education Standards recommendations.[3] They institutionalize the Modeling Workshops,[8] which have introduced teachers for the past 20 years to modeling instruction, a guided inquiry approach to high school physics teaching that incorporates computer technology and insights from physics education research. Emphasis is placed on basic models, the practice of modeling—constructing, testing, and applying models, developing skills in scientific discourse and presentation, and assessment of student

Master of Natural Science in Physics for in-service teachers

- **Eligibility.** The degree program is open to in-service high school teachers who have completed college-level physics and a semester of introductory calculus. Under-prepared teachers can make up deficiencies in regularly scheduled courses.
- **Requirements.** A total of 30 graduate credits is required, selected from the *Courses in physics and physical science for teachers* listed below. A minimum of 15 credits must be taken in the "Teaching Methods" and "Interdisciplinary Science" categories listed there. This must include
  - six credits in "Methods of Teaching Physics," unless courses with an equivalent emphasis on physics pedagogy have been taken as an undergraduate.
  - an Action Research Project for two or three credits.

  A minimum of six credits must be taken in the "Contemporary Physics" category. Graduate courses in physics or other natural sciences can apply toward the remaining credits if approved by the student's supervisory committee.

Courses in physics and the physical sciences for teachers

Category I: Teaching Methods with Intensive Content
PHS 530: Methods of Teaching Physics I: mechanics (3) (see syllabus in Appendix 1)
PHS 531: Methods of Teaching Physics II: electricity and magnetism (3)
PHS 534: Methods of Physical Science Teaching I (3)
PHS 593: Applied Project: Action Research in Physical Science (1-3)
PHS 594: Modeling Workshops in Physics, Physical Science
PHS 598: Leadership Workshop (1)
SCN 598: Research in the Physical Sciences (3)

Category II: Interdisciplinary Science
PHS 505: Energy and the Environment (3)
PHS 540: Integrated Physics and Chemistry (3) (see syllabus in Appendix 2)
PHS 542: Integrated Mathematics and Physics (3)
PHS 550: Physics and Astronomy (3)
PHS 556: Astrophysics for Teachers (3)
CHM 594: Modeling Instruction in High School Chemistry I and II (3, 3)

Category III: Contemporary Physics
PHS 560: Matter and Light (3) (see syllabus in Appendix 3)
PHS 564: Light and Electron Optics (3)
PHS 570: Spacetime Physics (3)
PHS 581: Structure of Matter and its Properties (3)
PHS 593: Advanced Projects in Physical Science (1-12)

Fig. 3. ASU catalog description of Master of Natural Science Program.

learning. The models discussed include one-dimensional kinematics, inertia and interactions of free particles, force as cause of acceleration in one dimension, treatment of particle motion using conservation of energy, objects in circular motion due to a central force, and conservation of linear momentum. The effectiveness of this pedagogical approach has been well documented.[8–10,12,13]

Physics pedagogy courses, with a typical enrollment of 24 students per section, are typically taught by two-person teams of outstanding in-service physics teachers (with faculty oversight). This instructional design conforms to the peer teaching principles espoused by the National Science Education Standards,[3] which holds that professionals are best taught by peers who are well-versed in the objectives, methods, and problems of their profession. Most peer teachers hold Master's degrees; a few have a Ph.D. The Modeling Instruction Program has produced a large pool of expert teachers who routinely serve as workshop instructors at ASU and by invitation at other universities and school districts during the summer. We draw on this pool to assist in regular course review and improvement.

Participants in Physics 530 (see Ref. 11 for course syllabus and readings) are introduced to the modeling method as a systematic approach to the design of curriculum and instruction. The content of the first semester high school physics course (mechanics) is reorganized around five models to increase its structural coherence. Participants are supplied with a complete set of course materials and work through all the activities just as their students would, stepping back from time to time to analyze the experience from the teacher perspective. Teacher-participants improve their physics content knowledge and equip themselves with a robust teaching methodology for developing students' abilities to make sense of physical experience, understand scientific claims, articulate coherent opinions of their own, defend them with cogent arguments, and evaluate evidence in support of justified belief.

Because many teachers who participate in physics Modeling Workshops also teach chemistry, they advocated for the development of a modeling approach (with accompanying curriculum materials) for chemistry. To meet this demand, two chemistry Modeling Workshops (Chemistry 594 A and B) have been developed. The first semester course has been offered every summer since 2005, with a typical enrollment of 30. The second semester course is offered every other summer. A physical science Modeling Workshop (Physics 534) is offered each summer and recently has been offered in the spring semester as well. Physics, chemistry, and physical science Modeling Workshops are cross-listed as undergraduate science methods courses that pre-service teachers can take to fulfill initial certification requirements.

B. Interdisciplinary science

Courses in this category are intended to enhance teacher understanding of interdisciplinary connections to physics and the relation of science to society, help teachers determine how to use that understanding to enrich their own teaching, and foster collaboration between physics teachers and teachers in other disciplines. Because there are no precedents for most of these courses, they are under continual redevelopment by the professors who teach them, utilizing feedback from the teacher-participants.

The Integrated Physics and Chemistry course[11] (Physics 540) has been taught by research faculty in both subjects. The purpose of the course is to stimulate the integration of physics and chemistry concepts in high school with attention to the rationale for a "physics first"[6,14,15] sequence. This biannual course is popular with chemistry as well as physics teachers. The focus is physical foundations for chemistry, especially in thermodynamics, chemical bonding, and the periodic table. We have purchased numerous copies of the excellent out-of-print textbook by George Pimentel and Richard Spratley[16] for use in this course.

Some lecturing occurs in courses taught by regular faculty, but because most teacher-participants have previously taken at least one Modeling Workshop, they readily engage in small group interactions and whole class discussions centered on models and modeling, using 24" × 32" whiteboards. Whiteboards are utilized by small groups in all Modeling Instruction classrooms for collaboratively constructed representations of scientific models such as graphs, diagrams, and mathematical expressions.[17] For culminating projects in interdisciplinary science courses, participants develop and present experiments or other curriculum materials for use in their own high school classrooms.

C. Contemporary physics

These courses are taught by research faculty who work in areas addressed by the courses, and span the range of major research areas in contemporary physics and astronomy. They introduce teachers to the ideas, methods, and results of contemporary physics that are ordinarily taught only to physics majors in advanced undergraduate and graduate programs. These courses bring high school physics teachers into extended contact with research faculty to share the excitement of scientific research. In addition, they provide opportunities for researchers to explain their fields in lay terms to highly motivated, well-informed teachers and thereby influence their high school students.

As an example, Physics 560, Light and Matter,[11] was developed and taught by a physics professor and has been adapted to make it a more model-based course by an advanced graduate student in mathematical physics. It has been offered four times. The purpose of the course is to develop classical and quantum models of the interaction of matter and light and to explore how they can be used to understand a variety of phenomena. All classical and some quantum modeling are quantitative. Course content is at a higher level than high school physics. Most lecturing is replaced by group work, which includes experiments, computer simulations, interactive guided worksheets, and small group or whole group discussions. Students work together in small groups (typical group size is three) at whiteboards to visualize and represent the solutions to problems using graphs, diagrams and mathematical expressions. These small group whiteboards are then compared and discussed with the members of the entire class in a "board meeting," where students make sense of the problem and its underlying structure in conversation with their peers. The course is mathematically challenging for teachers, because it uses calculus concepts extensively, but teachers give it outstanding ratings and report increased confidence in their ability to teach advanced physics topics.

D. Master of Natural Science Program Culminating Experience: Leadership Workshop and action research

Leadership Workshop is a one-day-per-week seminar directed by a master teacher who is now a tenure-track faculty member in science education. It is taken primarily by candidates for the MNS degree and takes the place of a master's thesis. One purpose of this course is to build a cohesive peer learning community. Those enrolled in Leadership Workshop consider ways to improve their teaching, and to contribute to broader reform of the science curriculum. "Action research" is the process of teachers collaborating to study, reflect on and make systematic improvements to some aspect of their teaching practice. During Leadership Workshop teacher-participants form teams and design collaborative action research projects[18] and prepare a formal proposal detailing classroom research that they will carry out during the coming school year. After they conduct their research, they report their findings in a research colloquium the following summer.

E. Course scheduling

There is ample evidence that to effect a change in teaching practice, professional development activities must be of extended duration.[19–21] We have learned from many years of holding Modeling Workshops that immersive summer workshop courses of a minimum duration of three weeks are most effective in changing teaching practices and melding teachers into a cohesive learning community. Consequently, most courses in the program are given in the summer. This schedule also makes it possible to accommodate out-of-state and rural teachers. These three-credit courses meet daily for approximately 6 hours per day. ASU has two summer sessions, and MNS degree candidates typically take three courses each summer—one in the first summer session and two in the second summer session.

F. Faculty and teaching associates

ASU is a Research Extensive university, so most faculty members are committed to research and research conferences during the summer. It has therefore been a priority to organize their teaching of core content courses so that they do not impede their research activities. This flexibility is achieved through shared responsibility so that course assignments in the program are distributed across the faculty. Ideally there should be at least two faculty members who are responsible for each course and its development, with course content closely related to their research specialties.

A teaching associate (TA) is assigned to each interdisciplinary science course to assist faculty in course design, development, and conduct until it is well-established. Teaching associates are outstanding, experienced in-service teachers who are well versed in the methods and objectives of the Modeling Instruction program. Their responsibilities include advising faculty on course level and pacing and on specific course objectives, helping with course design and selection of instructional materials (including a survey of suitable instructional resources and websites), helping organize and manage teacher work in collaborative groups, and providing faculty with objective feedback on teacher needs.

G. Course objectives

The ultimate target of the MNS program is not the teachers themselves—it is their students. Each course addresses the subject at a level that prepares them to motivate and inform their students. Teachers engage in activities and projects they can readily take back to their classrooms. Because the standard high school curriculum does not include contemporary physics, teachers need the material to be in a modular form, which can be used for extracurricular projects and interest groups or in advanced enrichment courses for seniors. In the long run, this approach to course design serves to prepare teachers for sorely needed content reform of high school science.

Table I. MNS course design principles.

Topics	Selection of topics is influenced by preferences and needs of high school teachers
Homework	Teachers utilize course content to create instructional modules that they can use with their own students.
Level	Subjects are addressed at the level of a *Scientific American* article, using algebra, calculus, and vectors as needed and appropriate.
Modeling	Teachers are involved in explicit formulation and analysis of the conceptual models inherent in the subject matter.
Collaborative Learning	Teacher expertise in collaborative learning is exploited in the design and conduct of class activities, experiments, discussions and presentations.
Lecture	Lecturing is limited in favor of discussion and collaborative learning.
Laboratory activity	Laboratory experiences acquaint the teachers with operation and use of modern scientific instruments such as lasers, the electron microscope, particle-induced x-ray emission and computer interfaces for data acquisition.

H. Teaching guidelines

Faculty who teach the MNS courses agree to adhere to the teaching guidelines (Table I), in accord with the general philosophy of Modeling Instruction.

IV. RESULTS AND CONCLUSIONS FROM ONGOING EVALUATION

During the four years of NSF funding (2002–2005), the summer course enrollment grew to 150 participants each year and served teachers from 41 states. It has held steady at about this level even after funding expired, although increases in out-of-state tuition have contributed to a decline in the enrollment of non-residents from 60 to 20%.

Almost 800 different teachers participated in the program from 2001 through 2009. Of this number, 490 took one or more Methods of Teaching Physics courses (physics Modeling Workshops), 150 took chemistry Modeling Workshops, and more than 100 took physical science Modeling Workshops. Of the 490 teachers who completed a physics methods course, only 25% have a degree in physics or physics education. Of the 370 who did not, about 30 did not intend to teach physics. In its nine years of existence, the MNS program has contributed to the preparation of about 340 crossover physics teachers. About 20% of these teachers have a degree in biology, 20% in chemistry, 15% in engineering, and the rest in other sciences, mathematics, and non-science disciplines (see Fig. 4).

Of the teachers who attended during the NSF grant period, 85% were assigned to teach high school physics: half taught one or two courses and 30% taught physics only. Crossover teachers indicated they were "retooling" from other

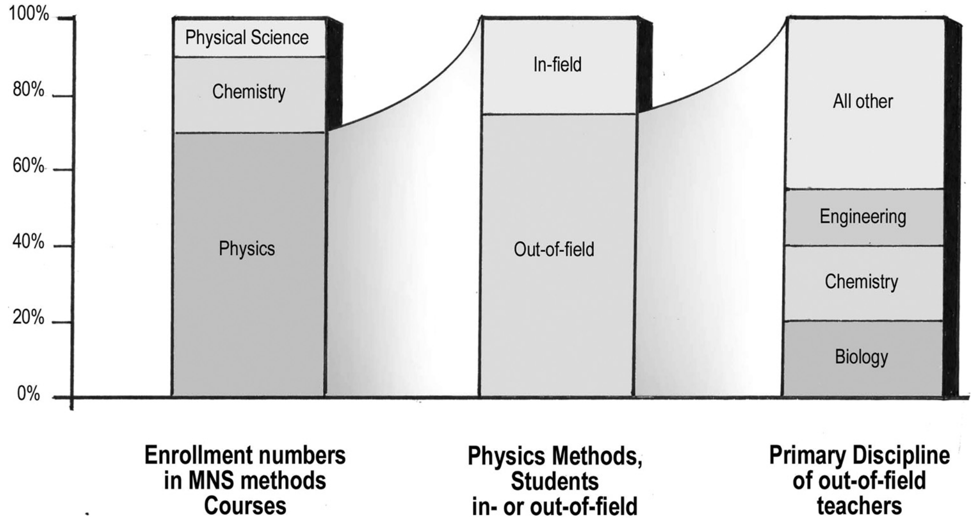

Fig. 4. Master of Natural Science program participation by out-of-field teachers.

disciplines, often to teach "physics first." Two-thirds of the teachers who took Physics 530 had taught physics for three years or less. One-third had never taught physics, including the 16 pre-service teachers who were enrolled during this period. One-third of the participants during this period were female.[22]

A. Master of natural science program participants

Of the 600 teachers who participated in the MNS courses from 2001 to 2007, 67 enrolled in the MNS degree program during that time. Forty-six (69%) of these teachers graduated, with more than half taking only two to three years to finish. Seven (10%) teachers are still active in the program and intend to complete the degree. Nearly half of the MNS teachers were Arizona residents (42% from the greater Phoenix metropolitan area and 6% from rural areas), and 52% of the teachers were out-of-state residents from within the U.S. (49%) or other countries (3%). A higher proportion of out-of-state residents (80%) than in-state residents (56%) graduated. Although a chi-square analysis of the relation between in-state/out-of-state status and program completion indicates that the difference is not significant (χ^2 [1, $N = 67$] = 4.38, Fisher's exact $p = 0.06$; probability of type 1 error for all analyses = 0.05), the low p-value suggests that there may be factors that influence out-of-state residents' likelihood of completing the program.

Only 21 (31%) of those enrolled in the MNS degree program had majored in physics or physics education. Eighteen (27%) were biology or chemistry majors, six (9%) were mathematics majors, and the other 22 (33%) majored in other sciences or social sciences. Eighteen (27%) had never taught physics before and 15 (22%) had taught physics less than two years. No significant relation was found between major and degree completion (χ^2[5, $N = 67$] = 5.12, $p = 0.40$).

Women comprised 39% of the degree candidates and were 1.6 times more likely than men to graduate (χ^2[1, $N = 67$] = 7.74, $p < 0.01$). Only 12% of those enrolled in the degree program held previous masters or doctoral degrees, with most being men. Although the sample is not large enough to reliably assess whether there is an interaction among gender, previously held degrees, and likelihood of completion, a lack of a higher degree may be a motivating factor in the MNS degree completion. The ethnicity of most teachers was white (85%), with 9% Hispanic and 6% Asian/Pacific Islander. No significant relation was found between ethnicity and program completion (χ^2[2, $N = 67$] = 1.12, $p = 0.58$).

B. Force concept inventory and mechanics baseline test performance of master of natural science degree program teachers

Force Concept Inventory (FCT) and Mechanics Baseline Test (MBT) are widely used measures of conceptual and problem solving knowledge in mechanics.[23,24] In the four years of NSF funding, we analyzed FCI data from 226 teachers, with higher scores reflecting higher competence with Newtonian concepts and a score of 85% a threshold for expert performance. About half of the 226 teachers scored over 85% on the pretest and two-thirds scored over 85% on the posttest. Lower FCI pretest scores often came from crossover teachers with little background in physics, yet their pre-post gains were substantial. The average posttest FCI score of 85.6% of 131 crossover teachers was 13.2 percentage points higher than the average pretest score compared to 4.6 percentage points higher (94.9%) for teachers with physics, physical science and engineering backgrounds. The overall normalized gain[25] was similar for the two groups (0.47 for physics and physical science majors and 0.48 for other majors). However, the physics/physical sciences group went from a very high percentage to an even higher percentage, and the other majors started with lower scores and experienced a larger increase.

Of the 67 MNS degree program teachers who enrolled from 2001 to 2007, 81% ($N = 54$) completed the FCI pretest and posttest and 57% ($N = 38$) completed the MBT at the end of Physics 530. Not all participants completed all measures, as the instruments were for evaluation, not course requirements, and may not have been re-administered if a teacher was late or absent on the day administered.

The mean pretest score on the FCI was 24.26 ($\approx$81%) (standard deviation $SD = 6.00$) out of a maximum of 30 points. The mean posttest FCI score was 27.11 ($\approx$90%) ($SD = 3.85$), significantly higher than the pretest, with a dependent samples t-test value of 5.64 (degrees of freedom $df = 53$; $p < 0.01$; 95% confidence interval of the mean difference extended from 1.84 to 3.87). Several teachers entered with very strong pre-existing knowledge in mechanics; 13 pretests gave perfect scores of 30, skewing the distributions of pretest and posttest scores (pretest *median* = 27 and posttest *median* = 29). Although the dependent samples *t*-test is very robust to violations of the normality assumption for samples over 30, the non-parametric sign test was also conducted due to the high skewness and repeated perfect scores. For the non-parametric test, posttest FCI scores were significantly higher than pretest scores, with a sign test value of 4.04 ($p < 0.01$). With the perfect scores removed, the remaining 41 teachers scored a mean of 22.44 (≈75%) ($SD = 5.80$) on the pretest and 26.37 (≈88%) ($SD = 4.13$) on the posttest. The difference between the pretest and posttest was also significant for this subset ($t = 6.92$; $df = 40$; $p < 0.01$; 95% confidence interval of the mean difference extended from 2.78 to 5.07). The overall normalized gain was 0.50 for the group of 54 and was 0.57 for the subset of 41 without perfect pretest scores.

The MBT was administered in most years. Thirty-eight MNS students completed an end of course response to the MBT, with a mean of score 18.45 (≈71%) ($SD = 4.60$) out of a maximum of 26 points. The correlation between MBT and FCI posttest scores ($N = 33$) was moderately strong ($r = 0.47$; $p < 0.01$). During the first two years of the program, the MBT was also administered as a pretest, and ten teachers completed a pretest MBT in addition to the posttest. The mean pretest MBT score for these teachers was 14.20 (≈55%), for a normalized gain of 0.37. These results are consistent with results of the larger group of 226 Physics 530 participants during the four NSF grant years.[22]

C. Student achievement of master of natural science program teachers

Research has shown that students taught with interactive engagement instructional methods have higher pretest–posttest gains on the FCI than students taught with traditional instruction. For example, Hake[25] found an average normalized gain of 0.25 for students receiving traditional instruction and an average gain of 0.48 for students receiving instruction using interactive engagement methods. Thirty-two MNS program teachers provided student FCI pretest and posttest data during their first academic year after taking the Modeling Workshop in mechanics. Of the 32 teachers, 40% had degrees in physics or physics education, and half had taught physics for two years or fewer. Sample sizes for these teachers ranged from eight to 124, with most between 20 and 40 students. The pretest and posttest mean FCI scores for 1117 students were 7.58 (≈25%; $SD = 1.15$) and 15.68 (≈52%; $SD = 3.46$) points, respectively. Normalized gains (calculated at the class level, with matched pretest and posttest student data) ranged from 0.15 to 0.76, with over 80% of pretest–posttest gains exceeding 0.25, the average gain found for courses taught traditionally, and over 30% of pretest–posttest gains exceeding 0.48, the average gain found for courses utilizing interactive engagement methods.[25] The average normalized gain was 0.36 (weighted by the number of students per class).

Figure 5 provides pretest and posttest scores for students of these 32 MNS program teachers, ordered by pretest percentage mean. The six teachers with the lowest student mean posttest scores are crossover teachers; and those who submitted student data in subsequent years showed improvement. Results are consistent with findings from a previous study[8] on student achievement and gains observed in students of the greater population of teachers attending MNS courses but not pursuing the degree.

D. Evaluation responses

Feedback is formally solicited through extensive questionnaires and informally through conversations and discussions, especially during the Leadership Workshop course. Participants complete course evaluations during the courses, at the end, and later during the school year.

Nine university faculty members have taught MNS courses; all reported that they were pleased by the eager and receptive attitudes of the teachers.[22] One professor, who had been

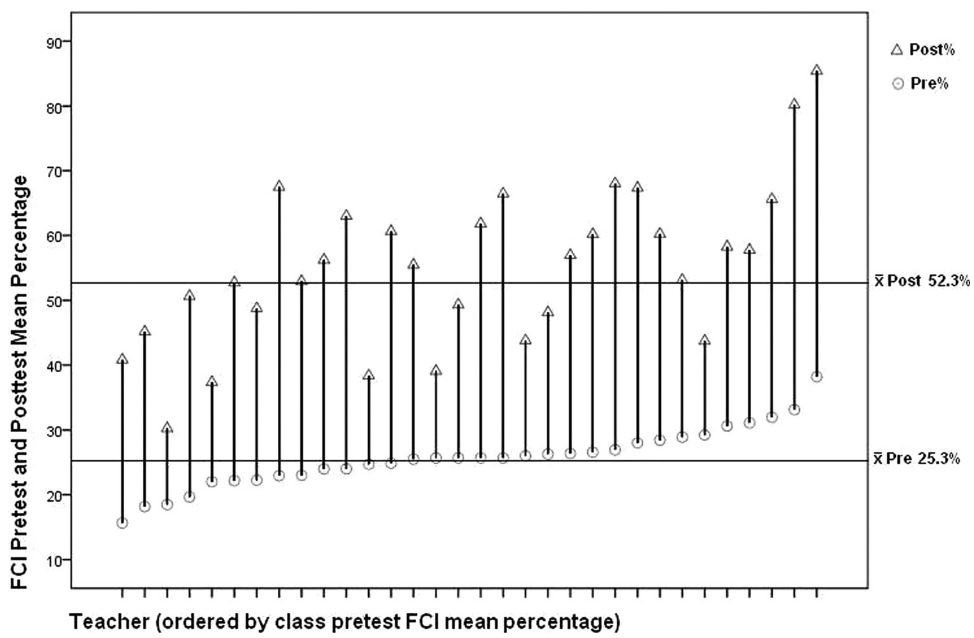

Fig. 5. Pretest and posttest student FCI percentages by Master of Natural Science degree program teachers.

dismissive of teaching reform, began his course with the announcement "I don't do pedagogy, I just teach." Nevertheless, he adhered to the MNS teaching guidelines while conducting a demanding course. The teachers responded enthusiastically. Afterward he wrote, "I never had a group of students so eager to hang around and talk physics."

On a ten-point scale, the 226 teacher-participants surveyed have given the MNS courses an average overall rating of 9.0 (with a range of 5.9–10). Written comments confirm high teacher satisfaction with every course. This average rating has held constant even after NSF funding expired and teachers from other states have assumed the burden of non-resident tuition and living expenses. Teacher feedback indicates that faculty members are open and collegial.

E. Academic level

The teachers in the program have a broad range of academic backgrounds, from minimal introductory physics to graduate physics or engineering and even doctorates. Reports from teachers with the weakest backgrounds show that they are not overwhelmed in any course. One reason for this outcome may be the collaborative and supportive instructional design of the program. Some teachers organize into study groups outside of class; and teachers can get support from an experienced TA when they need it.

F. Course content

A primary objective of the courses in contemporary physics is to develop teacher appreciation and understanding of physics on the atomic and molecular scale, to prepare teachers for reforms needed to update high school science. The following teacher comments illustrate typical teachers' responses to these course offerings: The course "renewed my interest in the small scale." "I need to incorporate more lessons on how technology is used in research and industry." "The class exceeded my expectations in every respect."

The teacher-participants do not subordinate their critical faculties with undiluted praise. They have provided many important observations and suggestions for improving these courses, particularly in instructional design (for example, the addition of whiteboarding and board meetings to MNS content courses) and the revision of course assignments to make them useful to teachers beyond the MNS degree program. Faculty members have been most appreciative and responsive to these suggestions. Unlike many academic programs, teacher-participants work collaboratively with faculty in shaping the courses that are offered.

G. Sustaining the program

Because MNS courses are part of a regular academic program, classroom facilities, course scheduling, and payment of instructors are covered by the university. The remaining costs for teacher recruitment, tuition, travel, housing and per diem come from other sources. Our experience is that few principals seem willing to commit funds to upgrade the qualifications of their physics teachers. Thus grant funding is needed. Since NSF funding ended in 2005, the program has been funded by No Child Left Behind state "Improving Teacher Quality" higher education grants and by 55 tuition waivers each summer contributed by the ASU College of Liberal Arts. These sources support 100 Arizona high school and middle school teachers of physics, chemistry, physical science, and mathematics each summer.

In a typical summer, about two-thirds of the Arizona teachers who take MNS courses are physics or chemistry teachers, and the rest teach multiple subjects. Half teach in high poverty schools, mostly urban rather than rural. Half teach out-of-field. Most commute to the university for classes and some drive up to two hours daily.

An additional 25–50 teachers come to ASU each summer from other states. These teachers pay nonresident tuition ($2418 per 3-semester hour in 2009, about one and a half times as much as resident tuition) and must find their own funding. Several teachers have come to ASU from other nations to take MNS courses. The Ministry of Education for Singapore,[26] values Modeling Instruction so highly that for the past three summers they have sent 15 physics and chemistry teachers to ASU for Modeling Workshops.

Overall, the MNS program is popular with teachers and effective in transforming their teaching practices,[27] in three cases rejuvenating them to the extent that they tell us it "saved their careers."[28] Teachers vote with their feet. Many return for more coursework even if they are not seeking a degree. (In the nine summers, 785 different teachers participated, and the total enrollment was 1200.)

Ninety percent of participating teachers wrote on surveys given over multiple summers that their chief reason for taking MNS courses was to become a better teacher, and half wrote that the joy of learning content was also a prime reason. Many teachers indicate that they believe most courses in education are of little value. On a survey of 89 Arizona high school physics teachers from 1997 to 2002, most of whom were beginning their first Modeling Workshop, they were asked, "Overall, how valuable were your education courses to you?" 49 teachers (55%) answered of "little" value, 29 teachers (33%) answered "somewhat" valuable, and 11 (12%) answered "very" valuable. Most were not qualified to take graduate courses in physics, and such courses are not offered in summer, nor would such courses be applicable in their teaching. The two online content courses offered by Bruce Sherwood of North Carolina State University are well regarded by teachers who have taken MNS courses, but these courses are insufficient to meet the need for a coherent degree program that is applicable to their classroom teaching. Few states have enough physics and chemistry teachers to support a statewide professional development program for them.

Some teachers who enroll in Modeling Workshops and other MNS courses are primarily chemistry teachers. They come to learn chemistry modeling instruction and to deepen their understanding of chemistry content and to explore the relation between physics and chemistry. A dearth of master's degree programs exists nationwide for chemistry teachers, so some of them have completed this MNS degree, even though they do not intend to teach physics.

H. Outreach and recruitment

Between 2001 and 2009, the Modeling Instruction program provided assistance to 32 universities and colleges across the U.S. and 12 school districts outside of Arizona in setting up Modeling Workshop courses at their institutions. In many cases, out-of-state teachers who traveled to ASU in the summer for the MNS program have stimulated their local universities' interest and willingness to sponsor Modeling Workshops. University or school district-sponsored Modeling

Workshops are scheduled for summer 2010 in 23 states,[29] and Modeling Workshops in physics are the foundation for master's degree programs in education at the University of Wisconsin at Oshkosh and at Buffalo State College in NY. Modeling methods are taught to pre-service physics teachers at Brigham Young University, the largest physics teacher preparation program in the nation, and at Illinois State University and the University of North Carolina at Chapel Hill.

A major objective of the MNS program is to foster professional ties between teachers and research faculty, thereby recognizing teachers as valued members of the scientific community. Through these teachers, scientists can establish a presence in high school classrooms to inspire students with the wonders of science and technology. Based on numerous teacher comments over the years we believe that the professional ties which arise as a result of teachers' participation in programs such as the one we have described are much more likely to be effective in recruiting students to science and engineering majors than career-path admonitions and advertising.

V. CONSOLIDATING THE MASTER OF NATURAL SCIENCE PROGRAM

The value of the MNS program is summarized in this quote from the May 2005 report of the North Central Accreditation Academic Program Review Committee:

"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."[30]

The history of the ASU Master of Natural Science program demonstrates that, with committed leadership and support from the physics department, it is neither costly nor difficult to establish an effective professional development program for physics teachers at a major urban state university. It is not costly because it has paid for itself without additional outlays from the university budget and not difficult if there are faculty members willing to organize it, and because a collection of courses has been developed, vetted, and are ready for export. However, even though these are regular university courses, teachers can hardly afford them without financial support—a problem that is not unique to this program but common to many university programs for in-service teachers. Therefore, external funding is needed for participant support.

The development of a degree program such as this is about all that can be done at the grass roots level. For the program to thrive and realize its potential to revitalize science education in the local schools, leadership at the highest levels of the university administration is essential to ensure commitment of adequate resources and establish partnerships with local school districts.

For the MNS program at ASU to reach its full potential, the following steps remain to be taken:

(1) Expansion of the MNS degree to meet professional development needs of all mathematics and science teachers.
(2) New faculty in mathematics and science education research to anchor the MNS degree program and drive sustained research to improve it.
(3) Provision of incentives for faculty to participate, such as counting summer MNS degree teaching as part of the regular teaching load.
(4) Formal recognition and adjunct faculty status for outstanding in-service teachers with leadership roles in the MNS program.

The growth and development of ASU's MNS degree program has shown that it is scalable, given institutional support. It has also demonstrated that there is continued teacher demand for a content-focused degree aimed specifically at high school science educators, which suggests that the program is also readily replicable at universities with the necessary supportive physics faculty. Syllabi and curricula exist and are available for dissemination (Ref. 11). At the three dozen universities that have already sponsored one or more Modeling Workshops, a potential source of master teachers is already in place. Experienced modelers live in 48 states—an ample supply of talent to assist university faculty in ensuring that courses are developed that are tailored to meet the needs of the local K-12 science teaching community.

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The MNS program is an outgrowth of the Modeling Workshop Project, which was continuously supported from 1989 to 2005 by various grants from the National Science Foundation. Since 1994, about 3000 high school physics teachers have participated in Modeling Workshop, and 2000 are still teaching physics and maintain contact by subscribing to the Modeling listserv. A program of this magnitude can be successfully developed only with support from a dedicated and talented staff. The late Malcolm Wells and now Professor Ibrahim Halloun played crucial roles in starting the program. Teachers Larry Dukerich and Gregg Swackhamer provided indispensable leadership in developing and conducting workshops. They have been assisted by a cast of exceptional teachers numbering between 40 and 400, depending on how their contributions are counted.

[1] See for example, National Commission on Excellence in Education, A Nation at Risk, The Imperative for Educational Reform (U.S. Department of Education, Washington, DC, 1983). Melvin D. George, "Shaping the future," National Science Foundation Report # 96-139 (1996). "Third international mathematics and science study (TIMSS)," U.S. Department of Education and the National Center for Educational Statistics, 1998). Glenn Commission, "Before it's too late; A report to the nation from the national commission on mathematics and science teaching for the 21st century," 2001, <www.ed.gov/inits/Math/glenn/index.html>. "Rising above the gathering storm: Energizing and employing America for a brighter economic future," <www.nap.edu/catalog/11463.html>.

[2] Committee on Science, U.S. House of Representatives, 105th Congress (1998), Unlocking Our Future: Toward a New National Science Policy; Vernon J. Ehlers, "Calling for improvement in math and science education in America," Congressional Record House: H11679 (November 8, 1999). See also recommendation #1 of the K-12 Focus Group in Appendix C-4 of "Rising above the gathering storm: energizing and employing America for a brighter economic future." See Ref. [1].

[3] National Research Council, National Science Education Standards (National Academy Press, Washington, DC, 1996).

[4] National Council of Teachers of Mathematics (NCTM) Standards, <standards.nctm.org>.

[5] For example, American Physical Society Council "Policy statement on K-12 science and mathematics education" (#00.5, Nov. 2000), and statement on "Physics education research" (#99.2, May 1999).

[6] M. Neuschatz, M. McFarling, and S. White, "Reaching the critical mass: Findings from the 2005 nationwide survey of high school physics teachers," American Institute of Physics (2008), <www.aip.org/statistics/trends/reports/hs05report.pdf>.

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