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Undergraduate Reform in Science Courses:
Synthesizing Themes from the Research Literature

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Abstract

Undergraduate science teaching needs to be re-evaluated and reformed. In this paper, we present an analysis and synthesis of 23 studies of moderate rigor, published from 1999-2006, regarding undergraduate science course reform. Within the studies, we discovered two major strands related to undergraduate course reform: a faculty strand and a student achievement strand. Within those strands, themes can be identified. Our synthesis indicates that more rigorous design methods are needed with regard to undergraduate science course reform studies, reform efforts are needed in science courses serving pre-service elementary teachers, and undergraduate science faculty professional development needs improvement.

Reform in Undergraduate Science Courses: Synthesizing Themes from the Research Literature

Reports document deficiencies in teaching science at the K-12 and higher education levels. These concerns, expressed by coalitions of professional societies and governmental groups in documents beginning with *Nation at Risk* (1983), led to the creation of new standards such as *National Science Education Standards* (NSES) (1996); *Benchmarks for Science Literacy, Project 2061* (1993); *Shaping the Future* (1996), *Educating Teachers of Science, Mathematics and Technology* (2001); *College Pathways to the Science Education Standards* (2001); and *No Child Left Behind* (2001). The standards provide criteria that can be used to judge whether particular actions serve the vision of a scientifically literate society. They bring coordination, consistency, and coherence to the improvement of science teaching (National Research Council [NRC], 1996).

Standards-based reform in undergraduate science cannot be separated from effective K-12 science education reform (Lederman & Gess-Newsom, 1999). The literature documents common features of introductory science courses that discourage students from taking more science courses or from pursuing a science major. These features include lack of relevance, passive student roles, emphasis on competition, and focus on algorithmic problem solving (Tobias, 1990, 1992; Seymour, 1995). To address standards-based reform recommendations, suggestions for effective undergraduate science courses for pre-service teachers include course experiences that involve connections between scientific ideas; provide social, historical, and philosophical context; include meaningful laboratories; teach for inquiry; involve diverse learners; and address important unifying themes (Floden et al., 1995; Lederman & Gess-Newsome, 1999; Sunal et al., 2001). Higher education faculty members are under pressure to create increasingly effective science teaching to achieve congruency with recommendations found in major reports on undergraduate science and pre-service teacher education (Magner, 1992; Sunal & Bland, 2004).

In response to calls for reform and to the perception that reform is needed, reports indicate higher education faculty members have been attempting to improve the effectiveness of undergraduate science courses, especially those aimed at non-majors and within that group, pre-service elementary teachers (Fedock, Zambo, & Cobern, 1996; Barinaga, 1991). The central question the authors are addressing in this synthesis of literature is "What is the current extent and impact of efforts to offer reform science coursework at the undergraduate level, particularly to pre-service elementary teachers?"

The two major national science standards from the 1990's are *Benchmarks for Science Literacy, Project 2060* published by the American Association for the Advancement of Science in 1994, and the *National Science Education Standards* published by the National Research Council in 1996. To respond to the central question, therefore, the related literature from 1999-2006 was examined to identify patterns. The authors selected this time span because it was expected that higher education faculty would need about three years to become aware of the standards, reflect on them, and design or re-design undergraduate science coursework to implement the inquiry-oriented teaching described in the standards.

The literature reviewed from 1999-2006 includes 79 articles, books, reports, or position statements. None of the studies could be described by the authors as experimental. The most common group in the literature is program descriptions and general references aimed at researchers involved in the reform effort (47%, N = 37). Another group included surveys of professors and/or students about their experiences with reform programs and/or courses (10%, N = 8). A small group of studies focused on student achievement of science content knowledge (8%, N = 6). The remainder of the studies, (45%, N = 51) were a mix of case studies, observations, and other measurements of reform classes and the teaching and learning occurring within them.

Of the 79 publications examined, we selected 23 studies for further review based on whether the research exhibited moderate rigor in design using quasi-experimental, and/or case studies to examine a reform effort in undergraduate science. Each study then was reviewed by the authors to identify the type of study, subjects, measurement instruments utilized, outcome variable, course content (if applicable), and overall results and conclusions. The authors analyzed the selected literature to identify themes from the patterns (Miles & Huberman, 1994). This analysis yielded twenty themes.

Further analysis of the studies yielded two major strands with one relating to faculty reform involvement and the other to student achievement. We further subdivided the faculty strand into the major themes of collaboration among faculty and the use of inquiry-based teaching in science with undergraduate students. The second strand, student achievement, we initially divided into two strands, works dealing with undergraduate student content achievement and those dealing with science achievement and inquiry-oriented teaching in the classrooms of teachers who had been reform course participants. We further subdivided each of these strands into sub-themes. The synthesis we report below is organized by the two major strands and then by the themes and sub-themes each major strand incorporates (see Table 1).

Table 1

Strands, Themes, and Sub-Themes Synthesized from the Literature Sample

Strand: Faculty Reform Involvement

Theme: Collaboration

Sub-Themes:

- Collaborative Teams
- Administrative Support
- Instructional Grants
- Focused Reform
- Action Research

Theme: Use of Inquiry Teaching in Science with Undergraduates:

Sub-Themes

- Cooperative Learning
- Modeling
- Linking
- Assessment
- Action Research
- Incremental Change

Strand: Student Achievement

Theme: Undergraduate Students' Science Content Achievement

Theme: Science Achievement and Inquiry-Oriented Teaching the Classrooms of Reform Course Graduates

Strand 1: Faculty Reform Involvement

Theme 1: Collaboration

Collaboration and its role in efforts at undergraduate science reform is a central component of seven reports: Ballone-Duran, Czerniak, and Haney (2005); Wainwright, Flick, Morrell, and Schepige (2004); Sunal, MacKinnon, Raubenheimer, and Gardner, (2004), Blackwell (2002); Krockover, Shepardson, Adams, Eichinger, and Nakhleh (2002); Sunal, (2001); and Bland-Hodges (1999). We identified five sub-themes within the reports: collaborative teams, administrative support, instructional grants, focused reform, and collaborative action research.

A sub-theme we found in all of these studies except for Wainwright et al. is the use of *collaborative teams*. Course reform is described in these studies as most effective when the planning and implementation are shared, often between a small team of faculty. Sunal et al. (2001) and Bland-Hodges (1999) described teams of three including a faculty member from science, a faculty member from teacher education, and an administrator. Blackwell (2002) reported a meta-ethnography in which teams were more broadly conceived as partnerships and included a state education agency, a higher education research institution, one or more teacher education colleges, and one or more school systems. Krockover et al. (2002) focused on teams of science faculty as did Ballone-Duran et al. (2005). We found networks of teams and other faculty members to be effective as supports for an individual team (Sunal et al. 2001; Bland Hodges). Regardless of the size of the team or how it may be networked, interpersonal skills and a sense of trust were identified as necessary for effective team collaboration (Sunal et al. 2001; Bland-Hodges, 1999).

Some team configurations include administrators. Such a configuration recognizes the importance of *administrative support for collaboration and reform*, a second sub-theme we found in four of the studies. Institutional support is integrated into a team when one member is an administrator. Administrators were helpful in garnering collegial support for reform efforts from other faculty. They also supported a reform effort by working with faculty on appropriate scheduling of classes, on setting appropriate class sizes, on providing graduate student assistance when needed, and importantly, in taking the time and effort spent on reform into consideration when making decisions about merit pay increases and tenure and promotion (Sunal et al., 2004, 2001; Krockover et al., 2002; Bland-Hodges, 1999). Hence, these studies support the notion that pro-active administrative support is necessary for the planning and implementation of undergraduate science course reform.

Additional support in the form of *instructional grants to support collaborative reform efforts* is a third sub-theme discussed in two studies. Because of the time and planning required, instructional grants can take several forms including additional graduate assistance, the purchase of new or additional technology, or faculty release time. Outside instructional grants in the range of \$20,000 - \$35,000 are reported by Bland-Hodges (1999) and Sunal et al. (2001). These researchers indicated that internal grants also were a means of initial support for reform efforts strongly indicating administrative support for the innovation. They noted that the range of external and internal support should be consistent with the extent and type of reform effort.

Focused reform by faculty collaboratives is a fourth sub-theme we found in four studies. Krockover et al. (2002) reported that a focus on one topic of reform at a time such as the use of inquiry, technology, cooperative learning groups, or varied forms of assessment resulted in more progress than did a global approach. Work by Staples (2004) and Sunal et al. (2004) supported this conclusion. These studies noted that an entire course is complex, consisting of components including content, instructional strategies, and assessment. The course can aim at deeper understanding of content, greater use of critical thinking skills, and/or a sound understanding of the nature of science. Because of the complexity, collaborative teams may be overwhelmed by taking on too many components at a time. Particularly when reforming an existing course, effective collaborative teams began their work with one or a few course components. These instructors expected to become proficient at using and incorporating these components over several semesters rather than in one semester. As some confidence was gained with new components, additional ones were incorporated. In addition to focusing on incremental change when moving into reform of science coursework, Sunal et al. (2001, 2004) further noted that aligning reform efforts to the goals of the reform rather than attending to the barriers that must be overcome is an effective strategy.

The fifth and final sub-theme is *collaborative action research by faculty teams*. Sunal et al. (2001, 2004) reported that action research projects enabled faculty teams to address specific problems in implementing reform and to test out solutions. Carrying out action research projects strengthened collegiality and the focus of the reform. Faculty members discussed and modified reform elements based on targeted data they collected giving them greater confidence in the effectiveness of the solutions they tested. They saw course improvement as a result of their action research and then were more able and willing to take on another problem and try to solve it. Rather than falling back into traditional instruction because of a problem that arose with the reform, they were more willing to continue with the reform.

Theme 2: Use of Inquiry-Based Teaching in Science with Undergraduate Students

Reform efforts in undergraduate science teaching aim at the incorporation of inquiry-based teaching consistent with the strategies and focus identified in national science standards documents. Eight of the reports analyzed dealt with inquiry-based teaching: Ballone-Duran et al. (2005); Tinoca, Upadhyay, and Luft (2005); Weld and Funk (2005); Wainwright et al. (2004); Staples (2004, 2002); Sunal et al. (2004); Krockover et al. (2002); and Sunal et al. (2001). We identified six sub-themes within these reports: cooperative learning groups, modeling, linking concepts to real world examples, assessment, action research on course strategies, and incremental change.

Cooperative learning as a component of undergraduate science course reform is the first sub-theme and was stressed in two reports. Krockover et al. (2002) described the Collaborative Action-Based Research (CABR) program that focused on greater implementation of inquiry-based teaching to emphasize conceptual understanding in undergraduate science courses. Faculty in the CABR science program provided their students with opportunities to engage in cooperative learning experiences. Staples (2004) described the use of cooperative learning experiences among students in a reform undergraduate science class and compared these students with those in a traditional science class. Both studies reported that students in the reform class demonstrated greater scientific literacy (Krockover et al.; Staples). Later, as classroom teachers, these course graduates used more inquiry-oriented teaching in science with their students.

Modeling of inquiry strategies and techniques as another component of science course reform is the second sub-theme and was described in four studies: Krockover et al. (2002); Ballone-Duran, Czerniak, and Huey (2005); Staples (2002) and Hammrich (2001). In the CABR program, Krockover et al. found science faculty used modeling to facilitate inquiry. Scientists collaborating to reform coursework made pedagogical changes such as the use of modeling when collaborating with educators in a study by Ballone-Duran et al. Staples (2002) found the use of modeling by science faculty positively impacted the science teaching efficacy of pre-service elementary teachers. Hammrich worked with biology graduate teaching assistants to facilitate their development of science pedagogical content knowledge (PCK) to enable them to implement inquiry-oriented teaching. These graduate teaching assistants recognized that they needed to model inquiry thinking after experiencing training with Hammrich.

The effort to plan for and then *link concepts under study to real world examples* is a component of reform teaching and the third sub-theme identified. Efforts at such linkages were discussed by Krockover et al., Wainwright et al., Staples (2004), and Hammrich. The rationale for incorporating linkages is to make abstract ideas more concrete and relevant. Highlighting the processes and effects occurring in real-world contexts enables students to more meaningfully understand the key concept operating in such contexts according to these reports. An associated component was the effort to make connections for a concept with other disciplines (Wainwright et al.; Staples, 2004). Such connections enabled students to see the more global applications of the concept and to more deeply understand it as they considered its' use in various disciplinary contexts.

Three reports considered *assessment*, the fourth sub-theme: Krockover et al., Ballone-Duran, et al., and Staples (2004). Each focused on the use of diverse assessment strategies. Such strategies de-emphasize but do not exclude traditional multiple choice and

short-answer quizzes and exams or traditional laboratory reports. Other types of assessment used to supplement or replace traditional formats included student journals, projects, presentations, cooperative group tasks, application activities, and student-designed hypotheses and experiments. A variety of formats are thought to be more authentic assessment of inquiry learning. Efforts at authentic assessment typically have more focus on application and use of concepts in contexts that differ from that in which the concept initially was learned. Ellis, Taylor, and Drury (2006) describe a biology course integrating writing as a component and the use of students' writings as a form of assessment. Their study focused on helping students develop their scientific understanding as well as their written scientific expression. They found instructors need to help students recognize the potential of writing for learning science and to reduce emphasis on superficial aspects of the writing experience such as grammar. They concluded that instructors must assist students in identifying the scientific knowledge that underpins the writing experience. An associated component of a reform course, noted by the researchers in these reports, was allowing students to demonstrate their work in a variety of formats. In some instances differing formats for the demonstration of work were used in a single assessment. As a result, some students might give a presentation, some might demonstrate a process via a computer simulation, and others might set up a panel to discuss specific applications of a concept.

Action research as a means of identifying problems, addressing those problems, and assessing the results of the effort is the fifth sub-theme and was described in two reports, Sunal et al. (2004) and Sunal et al. (2002). Conducting action research was found to be an important element for course change. Action research can be carried out by the instructor or by a collaborative team responsible for a reform course. When doing such research, a small component of the course is investigated. The action research project can address a reform component added to the course, or it can recognize a need to enhance an element of the course that is problematic. The instructor or team identifies the problem and examines the literature to determine how it might be addressed. After implementing a strategy to address the problem, data are collected and analyzed to determine the effects of the implementation. If such effects are positive, the strategy is retained and another problem or element is identified as the focus of the next action research project. If the effects are not positive, then another strategy is considered and tested. This process uses a data-driven approach to reform.

The process of designing and implementing course change can be overwhelming if instructors and teams take on too many revisions at the same time. Three reports emphasize the need to focus on *incremental change*, working on one course aspect at a time, which is the sixth and final sub-theme: Krockover et al., Sunal et al. (2004), and Staples (2004). Each report noted that the successful use of a strategy whether it is cooperative learning groups or the use of student science journals as a form of assessment, will take time to implement and to develop skill in its use. Both the instructor and the students need to learn how to use the strategy and need some time in which to work with it. Hammrich (2001) noted that instructors must come to understand the rationale for reform in coursework and to focus on the need for planning for active student participation in activities that build on their prior knowledge. Before implementing incremental change, instructors must recognize the need to facilitate student construction of knowledge and use this recognition as they begin to work on course reform. Action research can support such incremental change as instructors examine the effects of a change and determine whether or not to continue it, or to revise it and then further examine its effects (Sunal et al., 2002, 2004).

Strand 2: Student Achievement

We also examined student achievement at the undergraduate level in relation to science course reform. A specific theme is *undergraduate student science content achievement*. A second theme is *science achievement and inquiry-oriented teaching in the classrooms of reform course graduates*.

Theme 1: Undergraduate Student Science Content Achievement

Undergraduate science content achievement correlated positively with participation in courses having greater focus on inquiry-oriented teaching in reports by Francis, Adams, and Noonan (1998), Hake (1998), Jewett (1998), Hubbard and Abell (2005), Luera and Otto (2005), Weld and Funk (2005), Staples (2004), and Sunal et al. (2004). Francis, Adams, and Noonan reported that students taking a reform physics course demonstrated a fundamental shift in their conceptual framework, retaining their “Newtonian ideas” of physics over several years. Hake examined another reform physics course and found significantly greater normalized average gains among reform course participants when compared to those among participants in a matched traditional physics course. Hubbard and Abell found more complete physics content understanding among elementary science methods course students who had participated in a reform physics course when compared to those students in their course who had participated in a traditional physics course. Jewett reported no statistically significant differences in the effects on student achievement of implementing web-enhanced features in microbiology when these students are compared to previous students who had taken a traditional microbiology course. While students in the reform microbiology course indicated the web-enhanced course components were useful in learning course material, their achievement was not tested with standardized instrumentation so that any conclusions made are limited. Sunal et al. (2004), Staples (2004), and Luera and Otto reported significant content achievement among participants in reform coursework in the biological, physical, and earth sciences. With the exception of Jewett, all of these studies reported greater science content achievement among undergraduate reform course participants.

Theme 2: Science Achievement and Inquiry-Oriented Teaching in the Classrooms of Reform Course Graduates

Science achievement among the students of teachers who participated in undergraduate reform science courses was described by Staples (2004). She noted successful facilitation of science pedagogical content knowledge in pre-service teacher education programs where reform undergraduate science coursework is occurring. Staples further found that teachers who participated in undergraduate reform science courses were modeling the reform strategies they experienced in their elementary classrooms. Such reform strategies enhanced their science pedagogical content knowledge. Others have noted similar effects (Luera & Otto, 2005; Weld & Funk, 2005; Staples, 2002; Lee & Krapfl, 2002, and McGinnis et al., 2002). The reports indicated that more inquiry teaching was found in the classrooms of graduates of reform courses and can be correlated with increased student science achievement in those classrooms.

Greater science pedagogical content knowledge may be attributed to a greater depth of understanding of the nature of science (Tinoca, Upadhyay, & Luft, 2004; McGinnis et al., 2002, Backhus & Thompson, 2000). A capstone nature of science course was discussed by

Backhus and Thompson. They reported that the course provided deeper insights into the nature of science augmenting science course content, and also science methods courses for pre-service teachers. Undergraduate non-science majors in a reform course were compared to those in a traditional course by Tinoca et al. in terms of the course's impact on students' understanding of the nature of science. Significant positive changes were noted for the reformed courses. McGinnis et al. similarly found that reform courses produced positive changes in undergraduates' understanding of the nature of science, and also that such understandings increased in the years following the course. At the same time, the understandings of the nature of science were not as deep and decreased over time among traditional course graduates.

Conclusions

One central goal in the position statements of leaders in science is increased student achievement in science and understanding of the nature of science. These position statements further document the lack of interest in science among many undergraduates after having completed traditional science coursework. Hence, the call has been strong for reform in undergraduate science coursework that builds upon national science standards. Yet, there is a paucity of substantive research using rigorous quantitative or qualitative designs. As a result of the limited number of studies of at least moderate rigor available, this report is a synthesis of quantitative and qualitative work that has attempted to look across a variety of different approaches. After synthesizing the research on undergraduate science reform since 1999, we identified a limited number of studies demonstrating moderate rigor in design. We identified two major strands, four themes, and several sub-themes within this literature. Each of these has some support in the literature and points to directions to be considered by higher education faculty when reforming undergraduate science courses.

Although none of the directions identified in this synthesis of the research is well supported, together they indicate that undergraduate course reform is a complex issue. As with all complex issues, an individual faculty member is unlikely to be able to initiate, carry out, and sustain significant science course reform alone and within a short time period. The attempts at reform documented in the literature report efforts where collaborative teams are involved, highlight the need for administrative support and describe the need to allow time for expertise with new approaches and strategies to develop.

Some of the studies reported here have followed reform course graduates over a period of time, sometimes for three or more years. It is difficult to compare studies because some of the studies are reporting reform in different disciplines such as physics and biology, some are looking at science content understanding and science literacy, some examine understandings of the nature of science, some studies assess science content achievement, and still other studies look at graduates science teaching abilities and efficacy.. This comparison difficulty led us to construct a synthesis.

Our synthesis finds, first, that research studies with higher levels of rigor in design are needed. The design of such studies may be quantitative, qualitative, or mixed methods in structure but need to adhere to rigorous standards. Since there are some studies that we judged to be of moderate rigor, it is evident that moderate rigor can be expected and that higher rigor is possible. It is important that faculty undertaking science course reform utilize the existing literature since this synthesis indicates that, despite its limitations, the moderately rigorous studies indicate directions to be considered by reformers.

Second, our synthesis finds that many undergraduate science faculty members are concerned with the need to develop science literacy among all students, not just science majors. While recognizing that the science major may benefit from many of the reforms being implemented is important, faculty members also must recognize that non-majors are not well-served by traditional courses and may be better served by reform strategies. Faculty members further acknowledge that science literacy is most likely to be accomplished when active and meaningful science education begins in the elementary school. The focus of many reform courses, therefore, is on better serving pre-service elementary teachers.

Third, our synthesis finds that undergraduate science faculty themselves have much to learn in regard to reform. Their own professional development is important, takes time, is incremental, and needs administrative support. No single strategy, such as the effective use of cooperative learning groups, is easily learned. Even more difficult are strategies such as the use of varied assessments, of smoothly integrating laboratory and lecture/discussion, and of facilitating students' generation of hypotheses and design of experiments rather than replication of "cookbook" experiments. The reform effort is thus conceptually demanding.

Finally, as noted previously, there are many indications in the literature of ideas and strategies faculty might consider in the context of undergraduate science reform. The limited research base synthesized here shows some trends of support that should validate a faculty member's decision to carry out a specific reform. We encourage such faculty also to design their reform effort in such a way that they will be able to report their results to others with at least a moderate degree of confidence.

Next Steps

To better understand those undergraduate science course reform elements that lead to greater science literacy and deeper conceptual understanding, especially among pre-service elementary teachers, it is necessary to study reform efforts at a number of institutions over more than one offering of a course. The most useful model will be one that uses a professional development impact model to compare a reform with a matched traditional course. Such a comparison also must consider courses at different types of institutions, for example Master's (M.A.) granting institutions and doctoral research institutions. Faculty designing and implementing reform courses at different institutions will have experienced professional development built around a set of the same components. The comparison will be even more useful if it follows graduates out into their classrooms and examines similarities and differences between graduates of matched reform and traditional courses from the same institution.

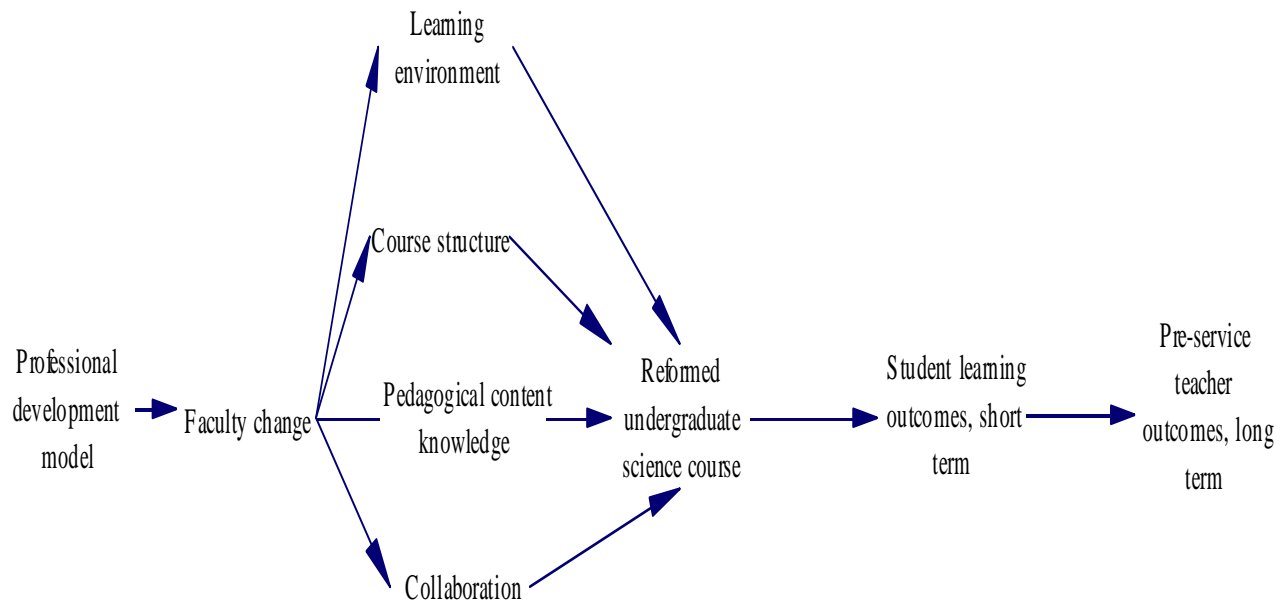


Figure 1. Professional development impact model

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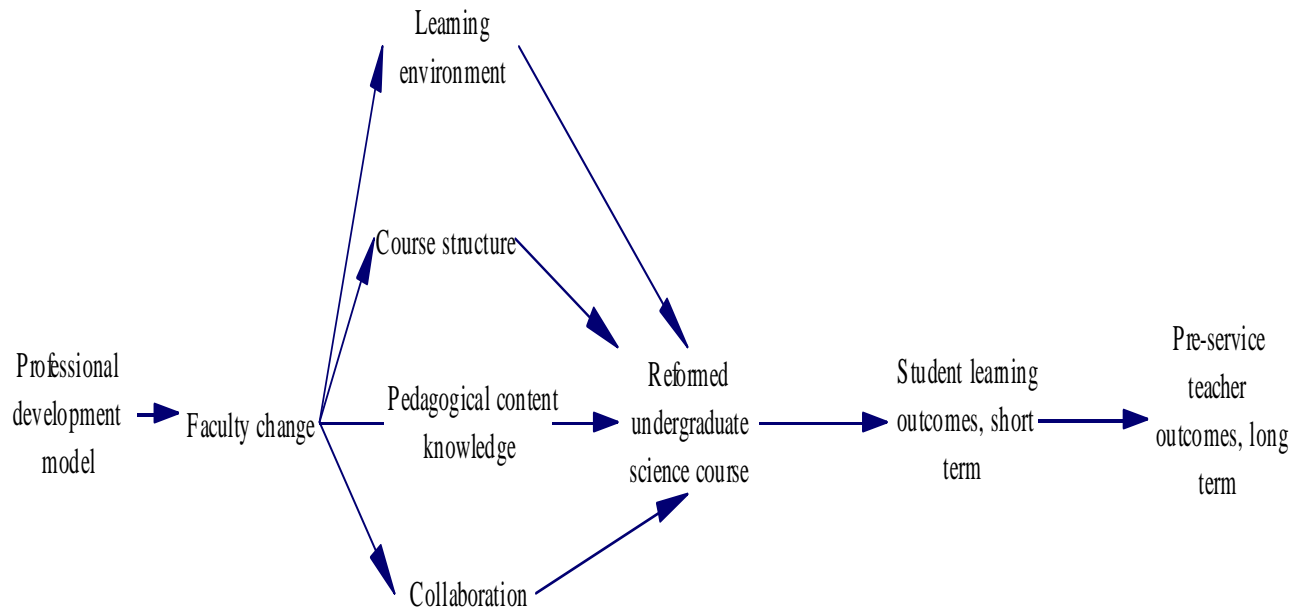


Figure 1. Professional development impact model