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Setting Empirically Informed Policy Benchmarks for Physical Science Teaching

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Setting empirically informed content knowledge policy benchmarks for physical science teaching

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Abstract
In the United States, research on beginning science teachers provides little guidance regarding empirical minimum levels of discipline-specific science coursework for sufficient subject matter knowledge to teach science. Accordingly, in this study we analyzed secondary physical science teachers' science coursework for subject matter knowledge (SMK) and resulting misconceptions of chemistry and physics concepts. Findings were compared with state-level science teacher certification policies. Participants had either: (a) completed a master's level teacher preparation program

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with an undergraduate degree in science, (b) completed an undergraduate teacher preparation program with a minor degree or more in science, or (c) were undergraduate students enrolled in science courses required for chemistry and physics teacher certification. We analyzed participants' transcripts for discipline-specific science coursework credit hours and GPAs and identified possible predictors of SMK predictors of the likelihood of passing chemistry and physics misconceptions tests. We categorized teachers' level of SMK and used multiple variable and logistic regressions (n = 212 participants; n = 109 chemistry and n = 103 physics). To identify teacher candidates' possible misconceptions, we analyzed chemistry (n = 97) and physics (n = 91) participants' item responses with the corresponding science credit hours and GPAs. With increasing numbers of credit hours teachers held fewer misconceptions. However, even with medium to high SMK levels, teachers still held misconceptions about chemical bonding, electromagnetism, and Newton's laws until they reached critical credit hour and GPA thresholds. Lastly, we provide recommendations for physical science teachers' programs of study and state-level teaching certification policies, using empirical minimum quantity and quality of chemistry, physics, and mathematics coursework.

Keywords: beginning science teachers, chemistry, misconceptions, physical science, physics, specialized knowledge, subject matter knowledge, teacher certification policy

1 Introduction

In the United States, teacher qualifications have become a politicized and contentious issue, especially in light of specific policies (e.g., *No Child Left Behind*, *Every Student Succeeds Act*) regarding student performance and large-scale, high-stakes assessment practices (Penuel & Shepard, 2016). But critically, teacher quality has also been identified as an essential mediating factor in student performance, especially in diverse schools (Carter & Darling-Hammond, 2016), and educational researchers and scholars (National Academies of Sciences, Engineering, and Medicine, 2015) have focused their efforts on determining what knowledge and pedagogical skills result in effective teaching for all students.

Effective science instruction relies upon teachers understanding the science content they must teach at its most foundational level. That is, ensuring high-quality secondary science teachers requires robust subject matter knowledge (SMK) (Kind, 2014). Without robust disciplinary understanding, teachers risk misrepresenting science and undercutting students' opportunities to become scientifically literate as outlined in the *Next Generation Science Standards* (NGSS) (NRC, 2013). However, identifying the minimum amount of SMK that science teachers need to master, and at what level that mastery should reach (i.e., GPA), for example, to avoid misconceptions, has been challenging (van Driel et al., 2014). This information has been sorely needed for decades to reliably design science teacher education programs and sensibly set state-level teaching licensure standards and policy (National Research Council, NRC, 2010a; Lewis et al., 2020). To address this urgent and overdue need, we studied the number of credit hours and GPA in university-level physical science (i.e., chemistry and physics) and related courses (e.g., mathematics) of teacher candidates. We also measured retained chemistry and physics misconceptions using validated instruments. The results of this study: (a) identified variables that predict disciplinary-specific thresholds of strong physical science SMK, (b) describe the misconceptions that teachers held, on average, at multiple levels of formal discipline-specific coursework, and (c) connect teachers' different levels of SMK with a range of physical science and related content-area coursework.

1.1 Study rationale

Science education reform driven by the NGSS and its three dimensions of science learning (i.e., science and engineering practices, crosscutting concepts, and disciplinary core ideas) requires well-developed teacher SMK. As states implement the NGSS and related reforms in science instruction, the science education community must prioritize setting research-based professional qualifications for effective science teachers, among other aspects of teacher education (e.g., adolescent development, special needs, multilingual learners). Without empirically based recommendations, there will continue to be a patchwork of highly variable certification standards as teacher educators, and state policymakers are forced to default to speculation. Unfortunately, rigorous empirical studies about science teachers' SMK are few (Sadler et al., 2013), and are more often found in European studies of science teacher education (Wickman, 2014).

Requirements for teacher preparation program (TPP) admission, completion, and teacher certification in the United States have not converged on what TPPs should require, in either pedagogy or content area (Wilson et al., 2001). As a result, state-level secondary science teacher endorsement policies vary greatly (NRC, 2010a). Recently, some U.S. states (e.g., New York, Oklahoma, Utah, and Wisconsin) have begun to lower teacher certification requirements due to teacher shortages (Felton, 2016) and consider alternative or emergency pathways to certification from waiving certification exams and teacher preparation education coursework. At the time of this article's writing, preliminary data suggest that the COVID-19 pandemic has further exacerbated pre-existing teacher shortages in science, mathematics, and special education (Stewart, 2021).

While discipline-based SMK is not the only key factor in effective teaching, it is a vitally important foundation of teachers' curricular decision-making and instructional practices aligned with NGSS three-dimensional learning. Moreover, when teachers lack sufficient SMK, they may perpetuate and unintentionally support preexisting alternative conceptions (historically known as misconceptions) through their instruction. Determining how much discipline-specific SMK science teachers need to teach specific science subjects accurately (Lewis et al., 2020) empowers the science education community in its efforts to advance students' scientific literacy (Roberts & Bybee, 2014) and better informs teacher certification policy and teacher preparation program requirements. The paucity of rigorous studies of physical science teachers' SMK is, in part, attributable to the difficulty of measuring and predicting SMK, the multidisciplinary nature of science, and its relationships with teacher cognition. Furthermore, there is a lack of evidence about the scope of coursework and mastery level teachers should reach to facilitate science instruction (Sadler & Sonnert, 2016) and then to be able to apply the NGSS three-dimensional learning model effectively.

2 Conceptual framework of the study

Historically, Shulman (1986) and later other authors (Cochran-Smith & Lytle, 1999; Cochran- Smith, 2005; Crawford & Capps, 2018; Grossman, 1990) identified various kinds of knowledge in teaching, including, among others, SMK. Shulman (1986) described SMK as: (a) declarative and procedural knowledge of the field; (b) conceptual and explanatory frameworks; and (c) argumentation and epistemological

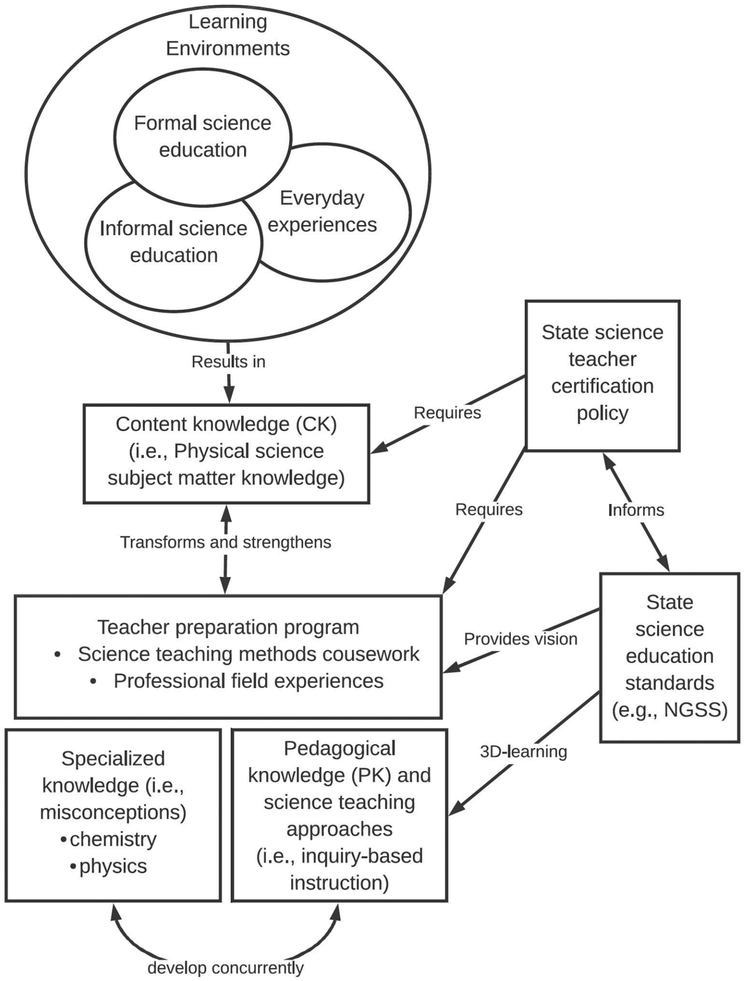

Figure 1 Conceptual framework for the development of physical science content knowledge (CK) for teaching enacted by science teacher preparation programs attending to state-level teacher certification policy

rules (Feiman-Nemser, 2001). These three aspects of teacher SMK are apparent in the three-dimensional approach to learning science in the NGSS. In our conceptual framework (**Figure 1**), we identify key factors that contribute to teachers' disciplinary-based science SMK for teaching. In this section, we outline and describe the relationships among these factors related to the underlying premise that state-level teacher certification policy can either support or undermine teacher preparation in professional degree programs. We used standardized science tests that measure specialized content knowledge (Ball et al., 2008) and college transcript analysis. This approach makes our study easy to replicate and would allow for a collective investigation of TPPs by the science education community across TPPs. Accordingly, we limited our focus to developing preservice teachers' physical science SMK in formal educational settings and not through in-service teacher professional development.

2.1 Transforming subject matter knowledge for teaching science

The juncture of SMK and the beginning of a TPP marks a professional preparation phase with the decision to become a science teacher. At this juncture, preservice teachers' SMK is transformed and strengthened through the process of engaging in educational coursework, most of which are required by their state's certification policy. "Early teacher learning may be dominated by the acquisition of fact-like knowledge about teaching and learning that is subsequently transformed to usable teaching knowledge through processes such as pedagogical reasoning and proceduralization" (Russ et al., 2016, p. 402). Therefore, the most direct coursework and experiences that further preservice science teachers' knowledge for teaching are science teaching methods courses and professional field experiences (i.e., student teaching). In these professional learning environments, teachers learn to reorganize and advance their science SMK and pedagogical knowledge (PK). Knowledge of commonly held misconceptions helps teachers select appropriate curriculum and instruction situated as a part of PK. Therefore, PK and specialized content knowledge are developed concurrently and this emergent professional knowledge should support PSTs' identification of, and address their own, misconceptions.

Misconceptions are "scientifically incorrect ideas that are persistent and commonly held" (Leonard et al., 2014, p. 180). Ball et al. (2008) described teachers' understanding of discipline-specific SMK as "specialized content knowledge." In terms of teacher preparation, it is the work of programs and teacher educators to model and provide opportunities for preservice science teachers to transform their formal science knowledge gained through college-level science coursework into knowledge for teaching. In this study, it is this critical time frame and interface of teacher certification (i.e., post-student teaching and becoming a first-year teacher) that we focus on to determine what level of SMK best prepares teachers to attend to their secondary students' physical science misconceptions. Therefore, we used validated tests of misconceptions as proxies for teachers' specialized content knowledge as has been done in studies of biology discipline-based SMK (Nehm & Reilly, 2007). Although the term *misconception* has been argued to be outdated (Maskiewicz & Lineback, 2013), there remain researchers (Leonard et al., 2014) who persist in its use. Many educational researchers and practitioners recognize that misconceptions are more than just learning obstacles and can be a productive starting point for refinement as part of the conceptual change process for learning (Maskiewicz & Lineback, 2013). Additionally, there has been much attention to learning progressions (Alonzo, 2018; Shepard, 2018) and the connection to formative assessments as a part of teachers' knowledge of how students learn.

As we show in the conceptual framework, preservice teachers' SMK changes over time, as the teacher gains experiences in different learning environments (Arzi & White, 2008; Charalambous, 2016). For this study, we focused on SMK from formal science education settings. Specifically, we aligned NGSS DCIs with physical science topics with common misconceptions. We collected teachers' relevant coursework and GPAs in formal undergraduate education as variables to predict strong SMK. Also, as part of strong SMK, we analyzed its component of specialized knowledge for teaching physical science, which includes an analysis of PSTs' misconceptions.

3 Literature review

To describe the potential impact of science teacher SMK on implementing U.S. national science education standards, we conducted a literature review concerning policymaking for TPPs about science SMK and teachers' specialized content knowledge of student misconceptions. Specifically, we focus on: (a) how state-level policy shapes TPP coursework and science teacher credentialing; and (b) research trends concerning teachers' SMK, specifically topics in chemistry and physics with common misconceptions for teaching science.

3.1 State policies and science education standards shape teacher education programs

How states choose to set and enact science teacher certification policy in part relies upon their goals for K-12 education, realized through setting science education standards and large-scale assessments that ultimately influence school and classroom educational settings. State minimum requirements form the basis for accredited TPPs. Such minimums include how much discipline-based science coursework must be completed and at what mastery level. Completed requirements are then certified by institutions of higher education *en route* to state-level endorsement and licensure. Darling-Hammond and Bransford's (2005) work on 21st-century teacher preparation emphasized that to be successful, new teachers must possess a beginning competency level in areas of essential skills, knowledge, and dispositions. Early studies showed that students who consecutively had competent teachers had significantly greater achievement gains than those with less effective teachers, with lasting effects (Sanders & Rivers, 1996). More work of this nature is needed in science education on how SMK affects the development of specialized knowledge and its relationship to effective and innovative teaching (Davis et al., 2006). In most studies, however, researchers have only used completed credit hours as a proxy for mastery of science concepts (NRC, 2010a) or only described teachers' typical coursework to teach science (Banilower et al., 2018 NSSME Report). Further research on the role of science teachers' SMK is necessary and understudied.

3.1.1 Science teacher certification enacted by state-level policies

Teacher credentialing policies are enacted inconsistently nationally due to deference to local state-level control based upon: (a) passing subject area tests in content and/or pedagogy; (b) completing arbitrary minimum science coursework requirements for teacher certification; and (c) completing education-based coursework (e.g., teaching methods, human development, curricular development, multicultural education, and teaching students with special needs, among others).

First, while many states require teachers to take a subject-matter test for certification, confusingly state policymakers have set different minimum cut-off scores for the same test (ETS, 2018). For example, cut-off scores for the Educational Testing Systems' (ETS) biology test range from a low of 142 in Arkansas to a high of 157 in Delaware. Does this mean that life science education is of better quality in Delaware? It might, but this is unknown without empirical studies. Also, not all states use the same tests. For example, 35 states use the ETS biology and chemistry tests for licensure, 34 use the ETS physics test, but only 25 use the Earth and space science test, and 30 states require the general science test (ETS, 2018). Some states (e.g., Massachusetts) have written their own tests and do not accept other standardized tests or National Board Certification (NBC) to grant initial science teaching licenses.

Second, regarding TPPs, as reported in *Preparing Teachers* (NRC, 2010a), Boyd and colleagues found that only 25 states required secondary teachers to major in the subject for which they plan to pass a subject test. However, in many cases, this major requirement can also be satisfied through a secondary science education major composed of some science courses and some education coursework (essentially only what the state has determined necessary for teacher certification) and not a full baccalaureate degree in a scientific field. Thus, beginning science teachers certified in undergraduate programs that do not require a double major in science and education may be operating with a deficit in their own scientific literacy (Bybee, 1997).

Finally, there is no agreement on minimum levels and what specific education coursework is necessary. For example, some states require courses such as educational technology, teaching multilingual learners, and reading in the content area, while others do not, even though partnering states have agreements for reciprocal licensure. Recent efforts to lower certification requirements (Felton, 2016) are a short-sighted response to the challenges of supplying and educating significantly more highly qualified science teachers.

While professional associations such as the National Science Teaching Association (NSTA) have established preservice science teacher standards (NSTA, 2020), there are no clear guidelines or evidence that ensures that all teacher preparation institutions have aligned their programs to meet them. Inconsistent standards from state-to-state in testing SMK and determining minimum scores required content-area course work and minimum GPAs and a wide range of education coursework has significant implications for credentialing and teachers being assigned to in- and out-of-field teaching in the classroom.

3.1.2 Science teachers' SMK, credentialing, and in- and out-of-field teaching assignments

Because there is no empirically derived teacher preparation model available to policymakers, science teacher credentialing varies significantly among states (NRC, 2010a; Allen, 2017). While a minor degree in science has been used as an indicator of some basic SMK competency, there is no clear evidence that this threshold indicates sufficient SMK for competent teaching. In other words, there has been insufficient empirical work to determine if a minor degree is the right benchmark for in-field SMK and is, in part, an argument for this study. It is also essential to consider how different content areas are articulated into individual courses and how they interact to produce an adequate mix of SMK for teaching. For example, it is unclear if 18 credit hours of chemistry content competence is equivalent to 18 credit hours of biology coursework for the same purpose. While the logical bimodal endpoints of the SMK spectrum (i.e., no science credit hours and a science major) are easy to accept as "too little" versus "sufficient" formally acquired SMK, it is unclear and arguably overly simplistic to draw a firm line between in- and out-of-field teaching. Educational researchers (Nixon et al., 2017) usually default to a minor or major science degree as "in-field" and anything less as "out-of-field." In this study, rather than use oversimplified terms that fail to acknowledge teachers' SMK as a wide spectrum, we employed multiple levels of SMK to investigate its relationship to levels of TPP-related SMK measures correlated with sufficient specialized disciplinary-specific content knowledge for teaching.

3.1.3 Teacher SMK certification policy as informed by science education standards

Table 1 lists specific grades 9–12 physical science and chemistry topics that science teachers need to know to enact curriculum and instruction aligned with the NGSS DCIs. Also, critical to supporting effective instruction is to identify specific college-level science coursework for mastery (i.e., GPA) so that teachers can meet these teaching competencies. There are too few studies about SMK minimums needed to teach physical science courses (i.e., chemistry and physics), despite

Table 1 Physics and chemistry concepts aligned with NGSS disciplinary core ideas

NGSS disciplinary core ideas	Physics concepts and topics (Grades 9–12)
(PS1A) Structure and properties of matter	Atomic structure, electric force, quantization of energy.
(PS2A) Forces and motion	Newton's laws of motion, momentum, conservation of momentum.
(PS2B) Types of interactions	Gravitational and electric force, force fields, electromagnetism, electrical conductivity.
(PS3A) Definitions of energy	Laws of thermodynamics; energy in motion, sound, light, and thermal energy; kinetic and potential energy.
(PS3B) Conservation of energy and energy transfer	Conservation of energy; quantization of energy.
(PS3C) Relationship between energy and forces	Gravitational and electric forces, force fields, kinetic and potential energy; energy stored in fields.
(PS4A) Wave properties	Wave properties, principle of superposition.
(PS4B) Electromagnetic radiation	Electromagnetic waves, electromagnetism, quantization of energy, electric and magnetic fields, wave and particle models of light.
(PS4C) Information technologies and instrumentation	Digitized information transfer.
NGSS disciplinary core ideas	**Chemistry concepts and topics (Grades 9–12)**
(PS1A) Structure and properties of matter	Atomic structure and particles; periodic table and periodicity; molecular structures; chemical and physical properties.
(PS1B) Chemical reactions	Chemical bonding; chemical equations and balancing; endothermic, exothermic reactions; reaction rates and kinetics; law of conservation of mass and energy.
(PS1C) Nuclear processes	Fusion, fission, and radioactive decay.
(PS3D) Energy in chemical processes	Macroscopic level chemical reactions (e.g., photosynthesis, fermentation, sun nuclear reactions).
(PS4B) Electromagnetic radiation	Electromagnetic spectrum.

SMK being a prerequisite to developing strong pedagogical knowledge within a content area (De Jong et al., 2002). While the processes of doing science are also key to being a scientifically literate individual and are summarized in the science practices in the NGSS, these are more difficult to measure with any single test, thus we limited our data collection to the study of teachers' mastery of science concepts and the DCIs.

3.1.4 Summary of controversies and research gaps

Research on U.S. science teachers provides little empirical evidence of what knowledge and skills are needed to be an effective teacher capable of planning and implementing the vision of the NGSS (Schwarz et al., 2017). Existing research on PSTs is limited in the areas of: (a) SMK mastery; (b) evolving teaching self-efficacy; (c) curricular practices; and (d) clinical experiences (NRC, 2010a). When states enact policies that set minimum requirements for professional expertise and licensure, the following questions inevitably arise repeatedly: (a) how much science content knowledge is enough to teach well? (b) what level of mastery should be required? and (c) which college-level science courses are positively correlated with specific teaching competencies and standards? We briefly describe how teachers' SMK develops.

3.2 Development of science teachers' SMK through learning environments

As already established and shown in our conceptual framework (Figure 1), content knowledge is complex and derives from various learning opportunities related to different ways of acquiring knowledge and learning environments. Learning environments are clustered into three types (i.e., everyday experiences, informal education, and formal education) (Russ et al., 2016); each is discussed below.

3.2.1 Everyday experiences and informal science education

Everyday experiences of students and future teachers alike drive preconceptions and misconceptions that become a part of prior knowledge (NRC, 2005) and are central to conceptual change (Driver et al., 2014; Russ et al., 2016). Examples of such everyday experiences involve learning from family members, daily interactions with one's community, and interests. Children may develop preconceptions of heat and temperature through learning to cook with their family members. However, the resulting enduring thermodynamic ideas are often incorrect such as thinking that objects made of different materials on a table in a room are of different temperatures because a metal spoon feels colder to the touch than a wooden spoon (Wiser & Amin, 2001). Teachers also must overcome their own accumulation of childhood misconceptions. With structured educational experiences teachers are better able to anticipate conceptual challenges that their students may encounter in a formal science course.

Informal education is another learning environment that intersects with everyday learning experiences. Informal educational experiences range from watching a science documentary at home to visiting a national park or science museum. In 2009, the National Research Council commissioned a report synthesizing informal science education standards, settings, and research (NRC, 2009). This pivotal report and its companion practitioner book, *Surrounded by Science* (NRC, 2010b), has fostered greater attention on informal educational spaces and resulting learning.

3.2.2 Teachers' K-12 and higher education formal learning environments

Before they become PSTs, students complete elementary and secondary science education programs in their K-12 academic career. When PSTs attend college, they continue formal science education by pursuing an undergraduate degree in science or majoring in science education, including teacher certification coursework. In higher education formal learning environments, it is problematic that constructivist learning approaches are still not the norm (Stains et al., 2018); large lecture settings do not adequately help PSTs deeply understand science concepts and practices for teaching (Özmen, 2010) nor the nature of science (Lederman & Lederman, 2014). This has critical implications for potential misconceptions that teachers hold and can inadvertently pass onto their students.

3.3 Research on physical science teachers' SMK and misconceptions

The lack of empirical studies to support which science course work is needed or which variables have an effect to predict less or more teachers' misconceptions comes from the complex nature of SMK and its epistemological foundations. SMK is derived from various learning environments related to different ways of acquiring knowledge that changes over time. For example, in analyzing recent (i.e., January 2014 to September 2019) published research articles from key science education journals (i.e., *Journal of Research in Science Teaching*, *Journal of Science Teacher Education*, and *Science Education*) we found that SMK has been studied from the perspective of in-service teachers' professional development (Ogodo, 2019; Wiener et al., 2018), and elementary teachers' SMK has been studied more than that of secondary teachers (Donna & Hick, 2017; Nixon et al., 2019). Also, SMK is differentiated from content knowledge (CK) when referring to content knowledge in general outside the United States (Kulgemeyer & Riese, 2018; Großschedl, Harms, Kleickmann & Glowinski, 2015). Overall, SMK research has not focused on connections between CK or specialized knowledge for science teaching and teachers' misconceptions.

More importantly, science teachers' misconceptions related to SMK have been neglected. In our review of these recent studies, we found few about teachers' misconceptions. Also, we found that researchers refer to students' or teachers' misconceptions frequently from a conceptual change perspective (Lucero et al., 2017; Potvin & Cyr, 2017). Although the latter approach is common, we found very few research articles about misconceptions connected to SMK or specialized knowledge for teaching (Huttner & Markman, 2016; Maerten-Rivera et al., 2015). Finally, we found only one article (Olson et al., 2015) that analyzed TPPs and SMK policies, confirming a lack of recent research in this area.

3.4 Transforming and strengthening SMK for teaching

As individuals start their teacher preparation, their cumulative scientific knowledge is not yet organized for teaching science (Kagan, 1992). The development of teaching content takes time and practice in a model of apprenticeship that is easily recognizable as situated learning (Lave & Wenger, 1991). Science teaching methods course content is generally undergirded by sociocultural theories of learning (Vygotsky, 1986), which lead to the development of constructivist teaching (e.g., 5E instructional model) and inquiry-based teaching practices that have long been the gold standard for science teaching (Bybee et al., 2006). Consequently, beginning science teachers need a deep understanding of both their science content and students' backgrounds, and use rigorous formative assessment and metacognitive practices to facilitate students' conceptual understanding to use with specialized content knowledge (e.g., by identifying and addressing students' alternative conceptions) (Bergqvist et al., 2016; Leonard et al., 2014). This is especially important with diverse and at-risk students (Nasir et al., 2015) for teachers to provide supportive and individual modifications to their instruction.

3.5 Teachers' specialized content knowledge: Misconceptions and physical sciences

Given that effective science teachers have transformed their understanding of physical science concepts into specialized content knowledge, understanding which misconceptions may persist is critical (Herman et al., 2017; Forbes et al., 2015; Osborne, 2014). Teachers can allow their own misconceptions to continue in student thinking (Erman, 2017) or fail to appropriately communicate science ideas to students (Brandriet & Bretz, 2014; Dhindsa & Treagust, 2014; Johnstone, 2010). For example, Kind (2014), in a study of 260 PSTs with different backgrounds (i.e., teaching chemistry in-field and out-of-field), found that they had chemistry misconceptions, and many of them matched those of their 15-year-old students. Sadler and Sonnert (2016) assessed physical science teachers' SMK, their knowledge of students' misconceptions, and the relationship of teachers' knowledge with students' learning. Overall, they found that students of teachers who could identify students' misconceptions embedded in test item distractors performed slightly better than those of teachers who could not. Kikas (2004) also identified insufficient teacher preparation as a source of misconceptions and the prevalence of using overgeneralizations or analogies and scientific terminologies that are ontologically different from everyday concepts in the presentation of scientific concepts. Other studies (Hashweh, 2002; Murphy, 2005) have shown that teachers' SMK influences their planning for instruction and use of explanatory representations, and with weak SMK, teachers hold similar misconceptions as their students. Consequently, misconceptions persist in teachers and students, and more studies are still needed to address and understand those common misconceptions.

3.5.1 Common sources and implications of chemistry misconceptions

Chemistry content knowledge enables students to understand matter and its organization. Chemistry misconceptions have been studied frequently and can be caused by four factors: (a) students, (b) textbooks, (c) nature of the material, and (c) teachers (Erman, 2017). Traditionally, chemistry concepts include multiple domains: (a) macroscopic, (b) submicroscopic, (c) symbolic, and (d) social (De Jong & Taber, 2014; Meijer et al., 2012). Teachers must understand all the concepts and connections between domains and find ways to communicate them to them as part of their specialized knowledge of teaching chemistry.

The interplay of these domains is a common source of chemistry misconceptions (Özmen, 2010) and could make chemistry disciplinary ideas difficult for some learners. For example, the particulate nature of matter (microscopic domain) is a source of common misconceptions (Mayer, 2011). Also, students can develop misconceptions about particles' bonding when teachers use, for instance, a dichotomous approach for classifying molecules and compounds as either covalent or ionic (submicroscopic domain) or when teachers use anthropomorphic descriptions (e.g., "fight for," "unfair sharing") to explain submicroscopic forces such as polarity, electronegativity, or electrostatics (Bergqvist et al., 2016; Luxford & Bretz, 2014; Erman, 2017). Another source of misconceptions is using oversimplified models (submicroscopic and symbolic domains) of the Bohr model (Zoller, 1990) to explain the atomic particles or the octet rule solely to frame ionic and covalent bonding (Bergqvist et al., 2016). Furthermore, Hamza and Wickman (2008) concluded that students developed misconceptions about electrochemistry when no context (social domain) was provided during their laboratory investigations.

Although studies about students' chemistry misconceptions (e.g., chemical bonding, acids, and bases, and the concept of a mole) are common in the literature (see Luxford & Bretz, 2014; Mayer, 2011; Wendt & Rockinson-Szapkiw, 2014), direct instruction and large lecture halls are unfortunately common in both high school and undergraduate chemistry courses (De Jong et al., 2002; Özmen et al., 2009), and can reinforce chemistry misconceptions. Traditional methods often superficially address multiple domains of chemistry concepts and do not allow students to build deep conceptual understanding. Studies about teachers' role or teaching in students' misconceptions are common in the literature (see Luxford & Bretz, 2014; Mayer, 2011; Wendt & Rockinson-Szapkiw, 2014), but other studies are needed regarding instructional practices centered on students' learning framed by the NGSS.

3.5.2 Common sources and implications of physics misconceptions

Secondary physics and physical science courses involve complex natural phenomena that students already possess everyday experiential knowledge. Much early physics education research has been devoted to studying misconceptions or naïve physics knowledge (Chinn & Brewer, 1993; diSessa, 1988; Halloun & Hestenes, 1985). Correspondingly, conceptual change literature has long described many difficulties in studying natural everyday phenomena such as force and motion due to students' experiential knowledge (e.g., Hestenes et al., 1992; Kikas, 2003; McCloskey & Kohl, 1983). One of the most common misconceptions concerning mechanics is the naïve impetus theory (see Kikas, 2004; Stinner, 1994, for details). Misconceptions about motion are based upon common sense perceptions and personal kinesthetic memory, while scientific understanding is based on internalist notions such as thought experiments (Halloun & Hestenes, 1985; Stinner, 1994).

In the same way, abstract physics concepts such as light, heat, and electricity are often difficult for students to grasp due to firmly held conceptions derived from everyday experiences with material substances and objects (diSessa, 1988). Reiner et al. (2000) proposed *substance schema* to refer to knowledge about material substance and objects and theorized that physics misconceptions are often associated with *substance schema*. For instance, we observe that objects may interact by pushing and pulling and fall when dropped; these experiences are sources of classic, persistent misconceptions (Halloun & Hestenes, 1985). Since properties of objects are learned at an early age, high school students' and teachers' misconceptions may have been part of their explanatory theories about natural, everyday phenomena for many years and are difficult to overcome.

3.6 Summary

Teachers require strong SMK and knowledge of common misconceptions, among other pedagogical elements, for selecting and using appropriate and effective teaching strategies (De Jong et al., 2002). Consequently, sufficient specialized knowledge to support deep understanding of NGSS DCIs and how to enact instructional strategies to develop students' physical science conceptual understanding is needed to address students' misconceptions. Teachers whose knowledge reaches expert levels can more effectively teach students as they encounter challenges, dispelling misconceptions in search of coherent scientific explanations. Unfortunately, a specific amount of teacher SMK needed has yet been identified empirically. The purpose of this study is to address this gap to improve educational systems and inform teacher certification policy by addressing teachers' competence and professional qualifications.

4 Methodology and methods

4.1 Research questions

In our descriptive correlational study of beginning science teachers' SMK for teaching physical science, the following questions guided our investigation:

1. What teacher preparation program-related SMK variables are associated with sufficient discipline-based specialized content knowledge?
2. About which physical science DCIs do teachers have misconceptions at different levels of formal discipline-based coursework?
3. During the teacher preparation phase, what specific discipline-based coursework was commonly completed at multiple levels of SMK?

To address Research Question 1, we used the number of discipline-based science course credit hours and GPA to determine if these variables could reliably predict teachers' SMK as measured by misconception tests. For Research Question 2, we classified participants by their level of SMK based upon the amount of science course credit hours taken for their teaching certification. We also identified the NGSS DCIs in which participants presented more or fewer misconceptions using a standardized test. Finally, to address Research Question 3, we used a range of SMK levels to analyze participants' transcripts by listing and tallying physical science courses (including mathematics courses for physics teachers) to identify which courses were most commonly completed. More details follow in the next section.

4.2 Methodology

We used data from participants' transcripts and results of validated, multiple-choice tests of misconceptions in physics and chemistry to address our research questions. Specifically, we analyzed transcripts for the number of science credit hours and GPA in chemistry, physics, and mathematics courses, and the date of completion of these courses. We recruited participants from three groups: (a) undergraduate TPP students, (b) masters-level TPP students, and (c) potential TPP undergraduate students enrolled in courses required for endorsement in physics and chemistry (see *Study Participants*, below). In total, we analyzed coursework, GPA, completion date, and misconception test data from 212 participants (n = 109 chemistry, n = 103 physics). As discussed in the analytic methods section, we identified significant predictive variables of strong SMK and performance on tests of misconceptions (RQ1), identified specific topics in which participants retained misconceptions (RQ2), and which misconceptions were retained and overcome as levels of formal, discipline-based coursework in content areas increased (RQ3).

4.2.1 Methods

In previous analyses, multiple factors (e.g., SMK, education coursework, teaching self-efficacy) predicted inquiry-based instruction in the classroom (Lewis et al., 2020); we found that a significant difference between the two groups of preservice teachers was based upon discipline- specific coursework. Notably, there was little variance in the education coursework (**Table 2** as aligned with the NSTA (2020) Pre-service Science Teacher Standards) taken by undergraduate and MAT preservice teachers in their programs. In other words, the education coursework (i.e., adolescent development, special education, science teaching methods, curriculum development and assessment) provided, at best, highly bimodal levels of education coursework and demonstrably little variance. Our previous studies carefully considered possible covariates, and in no case did covariates: (a) significantly improve power (Hernández et al., 2004), (b) indicate predictions that were not theoretically spurious (Anderson et al., 2001; Rosenbaum & Rubin, 1983), (c) improve model interpretability (Ewert & Sibthorp, 2000), or relatedly (d) create unnecessary model complexity (Avalos et al., 2007; Zhang, 2016).

In this study, we focused exclusively on teachers' science SMK independent of education coursework as has been done effectively in higher education studies of biology instruction (Nehm & Reilly, 2007), chemistry (Banerjee, 1991), and broader knowledge of physical phenomena (Kikas, 2004). To examine quantitative values associated with content knowledge such as GPA and coursework, we used two analytic methods. We used a single regression when examining continuous outcome scores on tests of teachers' misconceptions. Logistic regression was used when the outcome measure was transformed into a simple pass/fail value (LeBlanc & Fitzgerald, 2000). In this way, while assumptions about the predictors in the regressions (linear or logistic) remained the same as the transcript data were continuous, the assumptions about the outcomes changed based on the type of regression we used; we used different regressions because the conceptualizations of the outcome also similarly changed. That we found generally similar results across types of regressions, with differing assumptions, only confirming our results as robust with respect to the assumptions of regression.

Specifically, we first collected participants' academic transcripts to analyze teachers' SMK developed in formal, discipline-based coursework in physical science content areas (i.e., chemistry and physics). Second, we administered two Misconceptions-Oriented Standards-Based Assessment Resources for Teachers (MOSART) tests in chemistry and physics designed for grades 9–12 students to reveal specific misconceptions (Sadler et al., 2011). MOSART tests are composed of

Table 2 NSTA standards and teacher education program components

	NSTA pre-service science standard																	
	Content knowledge			***Content pedagogy***			***Learning environments***				***Safety***			***Impact on student learning***			***Professional knowledge and skills***	
Teacher Education Program Components	***a***	***b***	***c***	***a***	***b***	***d***	***a***	***b***	***c***	***d***	***a***	***b***	***c***	***a***	***b***	***c***	***a***	***b***
Subject-specific content courses	×	×																
Science teaching methods course		×	×	×	×	×	×	×		×	×			×	×			
Curriculum principles and assessment course		×	×	×	×	×	×	×	×			×	×	×	×	×		
Internship I (with science teaching methods course)						×				×	×	×	×					
Internship II (with curriculum principles course)		×		×	×	×	×	×	×	×	×	×	×	×	×	×		
Student teaching		×		×	×	×	×	×	×	×	×	×	×	×	×	×		×
Student teaching seminar																	×	
Recruiting science professionals (MAT only)																	×	×
Teacher Action Research (MAT only)																	×	×

Further articulation of the NSTA standards (2020) can be found at: https://www.nsta.org/nsta-standards-science-teacher-preparation . The engineering education-specific preparation standard under Content Pedagogy (2c) is new for the 2020 version NSTA standards and was not yet addressed in the program under which these participants were prepared.

multiple-choice items developed using the misconceptions research base (Sadler et al., 2011). Test items were aligned with the *National Science Education Standards* (NRC, 1996), the precursor of the disciplinary core ideas articulated in the NGSS. MOSART tests have been mainly used in other studies to assess K-12 students' misconceptions, but some researchers (Sadler et al., 2013) have used the tests to assess teachers' misconceptions. Sadler and Sonnert (2016) explained that "multiple-choice tests function well in diagnosing popular misconceptions that can impede the learning of science concepts" (p. 27). Additionally, Ball et al. (2008) recommended analyzing teachers' understanding of the content they teach by using "the tests their students must be prepared to pass" (p. 394).

4.2.2 Context

Study participants

There were three participant groups in this study: (a) preservice teachers (PST) who had at least an undergraduate degree in physical science and completed their teacher preparation program as master's degree students (MAT PST) (chemistry, n = 52; physics, n = 45); (b) preservice secondary science education teachers who became certified through an undergraduate program (UG PST) without a science undergraduate major, but met the state's minimum SMK endorsement requirements at about the minor degree level (chemistry, n = 35; physics, n = 35); and (c) undergraduate students (UG science) in the process of taking chemistry or physics courses to be recruited as preservice teachers (chemistry, n = 22; physics, n = 23).

Initially, we only collected MOSART and transcript data from PSTs from the first two groups. However, when we reviewed the histograms of earned science credit hours, we noticed a strong bimodal distribution of individuals who had either a great deal or very little chemistry or physics coursework. This was because participants were PSTs seeking those endorsements or had only a few courses in each discipline because they sought a different endorsement (i.e., biology that only required ancillary physical science coursework). More participants with moderate levels of coursework were needed to fill the gap. Thus, we approached the physics and chemistry departments and recruited individuals taking "feeder" courses that PSTs would typically take to become a science teacher. Our rationale for selecting these new participants was that these undergraduate science majors are potential future science teachers. In this way, we adjusted the sample to better meet the regression techniques we would ultimately use. Data from 212 participants (n = 109 for chemistry and n = 103 for physics) were used in this study (see **Tables 3 and 4** for participant-related descriptive statistics).

State certification requirements

At the beginning of data collection for the study, the state's endorsement of preservice secondary science teachers required the following:

1. *Single-subject endorsement*: A total of 36 credit hours minimum of science courses with 24 hours in the major area (e.g., chemistry) and 12 additional hours among three ancillary science areas (e.g., one 4-credit course each in biology, physics, and Earth science).
2. *Broad field (general) science endorsement*: A total of 48 credit hours minimum of science courses with 24 hours in one area of science (e.g., biology) and 8 additional hours in each of the other three areas (e.g., chemistry, physics, and Earth science).

However, the state's requirements for its broad field (general) science endorsement changed in 2013. The new endorsement retained the 48-credit hour total but removed the requirement to develop one discipline-based area in greater depth resulting in 12 credit hours in each area. Despite this change, the university retained the single-subject requirement of 24 credit hours in one area and 12 hours in each of the other three areas. Thus, if undergraduate PSTs sought the general science endorsement, they were required to complete 60 credit hours in the sciences to hold both a single-subject and general science endorsements, which exceeded the state's broad field certification minimum. Undergraduates could also choose to complete a single-subject endorsement with only 36 total credit hours.

Teacher education program contexts

To produce highly qualified science teachers, we designed a MAT program that was more rigorous than our undergraduate TPP. The MAT program was a 14-month, 42-credit hour program that provides a pathway for recent science graduates and practicing scientists to

Table 3 Descriptive statistics, predictors, and results of regressions for MOSART chemistry (9–12) test

Predictor	*Mean (or mode where indicated)*	*σ*	*Sample Size*
MOSART Chemistry (9–12) test score	75.89	15.04	109
Pass/Fail (1/0) MOSART score	0 (mode)		109
Pass			51
Fail			58
Sex of participant	1 (mode)		109
Male			41
Female			68
Delay between last coursework and test (years)	3.17	5.77	87[a]
Total number of chemistry credit hours	16.45	11.32	109
Chemistry coursework GPA	3.23	0.56	108
Total number of physics credit hours	10.63	11.78	109
Physics coursework GPA	3.11	0.55	89[b]
Total number of mathematics credit hours	7.57	7.15	109
Mathematics coursework GPA 3.26 0.64 79			

Predictor	*Outcome*	*F*	*p-value*
Sex of participant	MOSART Chemistry (9–12) test score	1.95	0.17
Delay between last coursework and test (years)		0.04	0.84
Total number of chemistry credit hours		9.06	<0.01
Chemistry coursework GPA		42.21	<0.01
Total number of physics credit hours		1.91	0.17
Physics coursework GPA		16.43	<0.01
Total number of mathematics credit hours		0.60	0.44
Mathematics coursework GPA		2.90	0.09

Predictor	*Outcome*	X^2	*p-value*
Sex of participant	Pass/Fail MOSART Chemistry (9–12) test	2.29	0.13
Delay between last coursework and test (years)		0.23	0.63
Total number of chemistry credit hours		4.34	0.04
Chemistry coursework GPA		26.96	<0.01
Total number of physics credit hours of physics		1.06	0.30
Physics coursework GPA		7.24	0.01
Total number of mathematics credit hours		<0.01	0.96
Mathematics coursework GPA		1.69	0.19

a. Some participants were undergraduate science majors at the time of taking the test therefore there had been no delay between last science course taken and the test.

b. A number of undergraduate chemistry students had not taken any physics coursework, which was correctly coded as 0 total credit hours, but then resulted in no GPA, thus in the category of GPA it appears as if there is missing data, but in these cases GPA does not exist.

Table 4 Descriptive statistics, predictors, and results of regressions for MOSART physics (9–12) test

Predictor	*Mean (or mode where indicated)*	*σ*	*Sample Size*
MOSART Physics (9–12) test score	73.68	15.60	103
Pass/Fail (1/0) MOSART score	0 (mode)	N/A	103
Pass			48
Fail			55
Sex of participant	0 (mode)	N/A	103
Male (=0)			53
Female (=1)			50
Delay between last coursework and test (years)	3.06	5.84	81
Total number of chemistry credit hours	13.13	11.41	103
Chemistry coursework GPA	3.15	0.64	92
Total number of physics credit hours	15.36	13.97	103
Physics coursework GPA	3.14	0.56	99
Total number of mathematics credit hours	11.00	8.64	103
Mathematics coursework GPA	3.22	0.69	95
Predictor	*Outcome*	*F*	*p-value*
Sex of participant	MOSART Physics (9–12) test score	**7.09**	**0.01**
Delay between last coursework and test (years)		0.29	0.59
Total number of chemistry credit hours		**5.51**	**0.02**
Chemistry coursework GPA		**11.55**	**<0.01**
Total number of physics credit hours		**41.03**	**<0.01**
Physics coursework GPA		**22.18**	**<0.01**
Total number of mathematics credit hours		**18.08**	**<0.01**
Mathematics coursework GPA		**4.01**	**0.05**
Predictor	*Outcome*	X^2	*p-value*
Sex of participant	Pass/Fail MOSART Physics (9–12) test	**9.57**	**<0.01**
Delay between last coursework and test (years)		0.11	0.74
Total number of chemistry credit hours		**16.35**	**<0.01**
Chemistry coursework GPA		**4.68**	**0.03**
Total number of physics credit hours		**41.42**	**<0.01**
Physics coursework GPA		**6.73**	**0.01**
Total number of mathematics credit hours		**17.22**	**<0.01**
Mathematics coursework GPA		**5.18**	**0.02**

Predictors highlighted in bold were significant. Some undergraduate physics students had not taken any chemistry courses, which was correctly coded as 0 total credit hours, but resulted in no GPA, thus in the GPA category it appears as if there is missing data, but in these cases GPA does not exist.

obtain secondary science teacher certification. We followed Darling-Hammond and Bransford's (2005) framework and guidelines recommended by the National Science Foundation's (NSF) Robert Noyce Teacher Scholarship program that required its recipients, future science teachers, have an undergraduate science degree to ensure strong science SMK. We used the NSTA science teacher preparation standards (Veal & Allen, 2014) to evaluate the alignment of the TPPs from which the study participants graduated (Table 2).

The undergraduate program differed from the MAT program in several fundamental ways, discussed in our previous work (Lewis et al., 2020). Undergraduate PSTs completed less science and education coursework during their program; thus, while their SMK was more recent and perhaps more accessible than their MAT colleagues, it was completed at a lower level, with few upper-level science courses. Comparatively, MATs had completed their science requirements as science majors and could focus on learning pedagogy, cognition, and developing effective teaching practices (Darling-Hammond & Bransford, 2005). The MAT program incorporated three significant threads: (a) required science and education coursework for teacher certification, (b) graduate-level courses including a teacher action research project, and (c) extensive (650+ hours) clinical experiences over three semesters of internships. Our third pool of study participants, UG students completing a major in chemistry or physics, had a wide range of higher education science and general education credit hours but no education coursework.

4.2.3 Data sources

We collected transcripts from our study participants and administered the MOSART physics (9–12) and chemistry (9–12) tests. This resulted in a dataset with a range of coursework in terms of chemistry and physics credit hours. We used the MOSART test results and transcript analysis (e.g., chemistry and physics courses and associated GPAs) for participants who completed MOSART tests. After our initial analyses of chemistry and physics coursework, we added participants' mathematics courses to our database to ensure that we had addressed a potential "hidden" source of formal SMK. Some MOSART test items can be solved using both qualitative and quantitative approaches.

Analytic methods

To answer our research questions, we analyzed data using two different methods. For Research Question 1, we identified significant variables in predicting teachers' strong SMK and correlated possible predictors of SMK (e.g., coursework, GPA, gender) and their MOSART test performance. To examine the relationship between various predictors and the MOSART test scores, we used multiple variable regression. To examine the relationship between the MOSART pass/ fail scores and each possible predictor, we used logistic regressions; both used Bonferroni adjustments for conducting follow-up tests. We used different, possible predictors; these are provided in tables in the results section. As previously noted, the dependent variable was either the MOSART test scores or the MOSART pass/fail, binary value. Second, for Research Questions 2 and 3, to determine how misconceptions held by physical science teachers (i.e., chemistry and physics) changed with increasing levels of SMK from formal learning environments (i.e., science content coursework), we compared the MOSART test results (i.e., tallying correct and incorrect answers for each MOSART item to identify the most often correct and more difficult science concepts) with transcript information. We applied a Miles et al. (2014) qualitative approach, including data condensation (i.e., developing categories), data display (i.e., organizing data in displays), and drawing and verifying conclusions (i.e., interpreting and verifying the analysis). For each subject area analyses (i.e., chemistry and physics), we divided the participants into four SMK categories based upon the amount of credit hours taken in each subject: (a) Group 1 (Introductory) = 0–8; (b) Group 2 (Low) = 9–16; (c) Group 3 (Medium) = 17–24; and (d) Group 4 (High) = 25+. Minor and major degrees correspond to 18–24 and 32–40+ credit hours, respectively.

We chose equal increments of eight credit hours for the four SMK groups, understanding that no one course could be exactly equivalent to another, but that eight credit hours is roughly equivalent to two college-level laboratory-based science courses. In establishing these categories, we considered criteria such as credit hours needed for a minor (e.g., 18–24 credit hours) in a science area for undergraduates and our state-established minimum coursework requirements for one subject area (i.e., 24 credit hours) certification. We also presented our findings to several university chemistry and physics faculty as expert member checks.

5 Results

For Research Question 1, the results of our investigation into physical science teachers' SMK for teaching can be summarized as follows: (a) newly-certified teachers need to exceed a minor in chemistry to pass the MOSART chemistry (9–12) test reliably, which we empirically determined as about 30 credit hours at a 3.2 GPA; (b) commensurately, newly-certified teachers should have a minimum of 30 physics and mathematics credit hours with a 3.0 mathematics GPA to pass the MOSART physics (9–12) test reliably; and (c) our fine-grained analysis of levels of physical science SMK revealed an intricate pattern of persistent misconceptions among participants (see **Tables A1 and A2**).

5.1 Initial between-subjects analyses

We collected additional MOSART data on two groups of undergraduate physics and chemistry students (n = 23 physics, n = 22 chemistry) (M = 22.95, SD = 16.44 for physics; M = 13.05, SD = 2.84 for chemistry credit hours) to improve the distribution of SMK data in our analysis of MOSART test scores. For example, the group of undergraduate physics students had an average MOSART score of 86.36% (SD = 9.85), with 20 who had a passing score of 80% or above; the two undergraduate physics students who did not pass the MOSART test only had zero and five credit hours of physics. A comparable group of students (n = 35) from our undergraduate teacher education program with an average of 11.71 (SD = 4.26) credit hours scored an average of 70.17% (SD = 14.14) on the same MOSART physics test. This suggested that to teach physics without holding common misconceptions, science teachers should have at least 18 credit hours of physics coursework. We sought to refine this hypothesis with further analysis and identification of significant predictors of reliably strong SMK.

5.2 Predictors of participants' physical science subject matter knowledge

When examining participants' SMK in physical science content areas, we used two primary outcome measures for each content area:

(a) MOSART test scores and (b) the same MOSART test score transformed into a pass/fail or binary outcome. The recommended cut-off score by the test developers for a passing MOSART test score is 80%. Thus, we dummy-coded a "0" for less than 80% and a "1" for passing scores greater than 80%.

5.2.1 MOSART chemistry (9–12) test results

Participants' MOSART chemistry (9–12) test scores were used as the outcome or dependent measures in multiple variable regressions using eight predictors (Table 3) and logistic regressions with the pass/fail scores using the same possible predictors. Table 3 also provides the descriptive statistics associated with each predictor and outcome variable. We provide the results of each regression for the MOSART chemistry test in Table 3. The best predictors were consistently the chemistry coursework GPA and number of chemistry credit hours in the multiple variable regression. There was very little apparent collinearity between chemistry coursework GPA and number of chemistry credit hours (VIF = 1.0003). The interaction was statistically nonsignificant, and as a result, was omitted from the final model, which only included the total number of chemistry credit hours and chemistry coursework GPA. In the variability associated with MOSART chemistry test scores, the chemistry coursework GPA uniquely accounted for 52.2% of that variance ($\beta = 0.52$, $t = 6.54$, $p < 0.01$), and chemistry credit hours uniquely accounted for 21.7% of that variance ($\beta = 0.22$, $t = 2.72$, $p < 0.01$). In both cases, the relationship was positive, indicating that as teachers' chemistry coursework GPA and total hours of chemistry coursework increased, so did their MOSART chemistry test scores.

The statistically significant predictors were the chemistry coursework GPA, number of chemistry credit hours, and physics coursework GPA in the logistic regressions. However, only chemistry coursework GPA predicted chemistry test scores or pass/fail status when loaded into the same model. With a one-point increase in GPA, teachers were 8.18 times more likely to pass the MOSART chemistry test ($e^{\beta} = 8.18$), and for each 0.10 change in GPA, they were 1.23 times more likely to pass the MOSART chemistry test ($e^{\beta} = 1.23$). Using the following equation, one can calculate the probability of passing the MOSART test:

Probability of passing chemistry MOSART test =

$$\frac{e^{(-7.02\ +\ 2.12*\text{chemistry GPA})}}{1 + e^{(-7.02\ +\ 2.12*\text{chemistry GPA})}}$$

This indicated a strong relationship between prior performance in chemistry coursework and the likelihood of passing or failing the MOSART chemistry test. For practical purposes, using the average 3.2 GPA of all the test takers, we found that the regression line predicted passing the MOSART test when individuals had completed 30 chemistry credit hours. Thus, new teachers need to exceed a minor in chemistry with a "B/B+" or better average with 30 credit hours of chemistry coursework to pass the MOSART chemistry test reliably.

5.2.2 MOSART physics (9–12) test results

Participants' MOSART physics (9–12) test scores were used as the outcome or dependent measures in a multiple variable regression using the eight predictors listed in Table 4, and logistic regression with the pass/fail scores using the same possible predictors. The number of valid cases for analysis changed based upon the missing data missing completely at random, unable to be imputed sensibly. In other words, we could not account for the missingness of the data (Tsiatis et al., 2014).

The results of each regression for the MOSART physics test are provided in Table 4. In the multiple variable regression, the statistically significant predictors were chemistry coursework GPA, number of chemistry credit hours, physics coursework GPA, number of physics credit hours, math coursework GPA, total math credit hours, and sex. When all statistically significant predictors were included in the same regression, only physics coursework GPA and total physics credit hours were statistically significant. These results corresponded with our hypotheses, and they were selected for use in the final model. There was very little apparent collinearity between physics coursework GPA and number of physics credit hours (*VIF* = 1.06). The interaction term rendered only the physics coursework GPA as statistically significant, indicating a complex interaction between or collinearity between physics credit hours and how well they performed in those classes (i.e., the physics GPA associated with those credit hours).

This analysis indicated that: (a) to ensure interpretability, the final model would include physics coursework GPA and number of physics credit hours when predicting the MOSART physics test scores, and (b) that future investigations need to disentangle the complicated relationship between physics coursework and performance during that coursework. Specifically, in the variability associated with MOSART physics test scores, physics coursework GPA uniquely accounted for 31.6% of that variance ($\beta = 0.33$, $t = 3.91$, $p < 0.01$), and the number of physics credit hours uniquely accounted for 43.3% of that variance ($\beta = 0.45$, $t = 5.36$, $p < 0.01$). The overall model indicated a strong, positive relationship between MOSART physics test scores and the total number of physics credit hours and physics coursework GPA. That is, as physics coursework GPA and total credit hours of physics coursework increased, so did the test scores.

In the logistic regressions, the statistically significant predictors were numerous, specifically the number of chemistry credit hours, chemistry coursework GPA, physics coursework GPA, number of physics credit hours, mathematics credit hours, mathematics coursework GPA, and sex. However, when loaded into the same model, only the total number of physics credit hours and mathematics coursework GPA were statistically significantly related to the likelihood of passing or failing the MOSART physics (9–12) test. The interaction term was nonsignificant and rendered any other statistical relationship nonsignificant.

As a result, only the total number of physics credit hours and mathematics GPA were included in the final model as predictors. Each additional physics credit hour increased the relative likelihood of an individual passing the MOSART physics tests by 22% ($e\beta = 1.22$). Also, for each increase of one point in mathematics GPA, the likelihood of passing the MOSART physics test was increased by 136% ($e\beta = 2.36$). Essentially, this means that for each 0.10 change in GPA, test takers were 1.09 times more likely to pass the MOSART physics test ($e\beta = 1.09$). This indicated that the relationship between mathematics GPA and physics coursework credit hours was a function of the following form:

Probability of passing physics MOSART test =

$$\frac{e^{(-5.33 + 0.86 \text{ math GPA} + 0.20 \text{ physics credit hours})}}{1 + e^{(-5.33 + 0.86 \text{ math GPA} + 0.20 \text{ physics credit hours})}}$$

This was transformed into a simple odds ratio of passing/failing the MOSART test to yield the three-dimensional graph in the Supporting Information section. In a practical sense, in terms of teacher preparation programs, teacher educators should require a minimum of 30 physics-related credit hours at a 3.0 GPA (a “B” or better); a lower mathematics GPA could require more physics-related coursework overall, but this is addressed in the discussion section.

5.3 Common physical science misconceptions held by participants with a range of SMK

For Research Questions 2 and 3, we present analyses of individual, NGSS-aligned MOSART test item responses by participants with a range of chemistry and physics credit hours. This resulted in identifying the most and least frequent common misconceptions by topic held by future science teachers in Table A1. The topics and concepts that were most difficult for test-takers, interpreted as the most persistent misconceptions, had lower average percentages of correct answers (less than 50% of the group answered correctly), and those topics or concepts that were easier that on average the group held fewer misconceptions (greater than 90% of the group answered the item correctly).

5.3.1 Common chemistry misconceptions held by participants

More than 90% of all participants correctly answered questions on the MOSART chemistry test related to periodic law (items 7 and 16) and subatomic particles (items 6 and 22) with the highest percentages of correct answers. Most participants had taken General Chemistry I and II courses (93% and 88% respectively), which suggested that the chemistry content covered (see Supporting Information for detailed individual course content descriptions) developed sufficient knowledge about atomic particles and periodic table content and arrangement. Chemical bonding was the topic with the most frequent misconceptions for these participants. Specifically, only 40% of teachers gave correct answers about metallic bonding (item 12), the lowest score among all chemistry MOSART test items. The test developers also reported that only 21% of high school students answered this item correctly. The low score relative to other items on the test indicated a steady persistence of misconceptions in chemical bonding and other low-scoring items among secondary students and future science teachers.

The MOSART chemistry test allowed us to identify core topics with misconceptions among preservice teachers as they completed student teaching, showing that, on average, as chemistry coursework increased, the number of misconceptions decreased. In other words, more chemistry coursework helped these preservice teachers to hold fewer misconceptions of high school chemistry content. When we inspected the two endpoints of introductory and high levels of chemistry SMK, the average percentage of correct answers for Group 1 was 65% (*SD* = 15%) compared with Group 4 with a score of 88% (*SD* = 10%). On average Group 2 teachers, averaging 9–16 credit hours of chemistry coursework, scored higher (*M* = 74%, *SD* = 15%) and held fewer misconceptions as compared to Group 1 teachers with at most only two general chemistry courses, but still did not reliably meet the 80% passing cut-off score.

5.3.2 Common physics misconceptions held by participants

Analyses of all participants' responses to the MOSART physics test item revealed similarities and differences in their knowledge of specific physics topics. As with the chemistry results, we saw that the increase in the number of physics credit hours corresponded with better performance on the MOSART physics test (Table A2). For instance, 23 out of the 25 items (92%) in the MOSART test appeared to be easy for Group 4 test takers with at least 25 credit hours of physics as compared to those in Group 1 with only 0–8 credit hours who only performed well on 6 of 25 items (24%). Similarly, test takers with 17 or more physics credit hours exhibited few or no misconceptions (i.e., at least 90% of all in the group answered correctly) on topics with which their counterparts with less than 17 credit hours struggled. Table A2 identifies the highest and lowest scoring MOSART physics items. Table A2 shows that participants with less than 17 credit hours (i.e., Groups 1 and 2) on average did not meet the 80% passing score. In our analyses of participants' courses, we also observed that most test-takers (56%) with less than nine credit hours, if they took a physics course, only took either an algebra-based or a descriptive introductory physics course. These algebra-based introductory physics courses are less mathematically rigorous than calculus-based courses taken by most Group 3 participants who had at least 17 credit hours.

The study participants' coursework provided insight into their physics misconceptions, as revealed by the MOSART physics test. Group 1 participants usually had only taken one general physics course with a lecture and laboratory component. In our list of courses, General Physics, I only included topics in mechanics, heat, waves, and sound. Concepts in electricity, magnetism, optics, relativity, atomic and nuclear physics are covered in General Physics II (see Supporting Information for more detailed information of individual physics course content). Table A2 shows that Group 1 participants had persistent misconceptions about electromagnetic waves, electromagnetism, and quantization of energy, which are topics usually addressed in General Physics II. The test also revealed that Group 1 participants held persistent misconceptions about Newton's laws of motion and wave properties, even though these topics are commonly taught in undergraduate General Physics I and secondary level physical science course. As with Group 1, Group 2 participants also appeared to struggle with concepts in electromagnetism and modern physics. Surprisingly, misconceptions with Newton's laws of motion and wave properties persisted among Group 2 participants despite having a greater range of introductory physics courses than Group 1. This suggested that taking less than 17 physics credit hours was insufficient to develop the content knowledge needed to teach an upper level, high school physics course (i.e., the depth and breadth of topics covered in typical introductory physics courses is insufficient for future science teachers to understand core physics concepts).

5.3.3 Attending to mathematical knowledge for teaching physics

Our first analysis of minimum physics SMK did not include mathematics coursework and its GPA. When we initially reviewed the test results and the levels of SMK in physics, we found it surprising that the number of physics credit hours was much lower (about 40% less, or 12–13 fewer credit hours) than the minimum amount of chemistry credit hours (i.e., 30 credit hours) to pass the MOSART physics test reliably. We then hypothesized that there was "hidden" coursework that physics minors and majors take in mathematics that could also affect their test performance. This new analysis confirmed our suspicions that the individual's mathematics mastery level was a crucial factor in conjunction with physics coursework in determining the probability of passing the MOSART physics test.

Additionally, a review of MOSART physics test items also showed that most items could be solved using qualitative and quantitative approaches. Thus, we also identified the most common mathematics coursework and included it in our table of varying levels of physics SMK. We used the average number of mathematics courses and average GPA for each physics category of Group 1 to Group 4 participants. Less than one-half of Group 1 participants took introductory mathematics courses such as College Algebra (33%) and Calculus I (42%). More participants in Group 2 took Calculus I (71%), but very few took more advanced courses. Conversely, most Group 3 participants took Calculus I (88%), II (88%), and III (75%). This trend continued with Group 4 participants who took Calculus I (75%), II (88%), III (94%), and other more advanced mathematics courses such as Differential Equations (88%) and Matrix Theory (81%). Thus, teacher educators and state-level policymakers should explicitly require both physics and mathematics coursework for the robust preparation of physics teachers.

6 Discussion

The science education community has been faced simultaneously with the complexities of determining sufficient teacher SMK and absence of adequate evidence to inform teacher preparation program design and state-level certification policy. Nevertheless, it is clear that secondary teachers should have strong SMK, specifically discipline-based specialized content knowledge, in the science content they teach, not just have a general science background. Problematically, this is not always the case because individual U.S. states have not used common, empirically derived benchmarks to set certification policy that drives teacher preparation program design. As a consequence, for example, in schools where physics is offered fewer than 50% of all physics teachers have a degree in physics or physics education (White & Tyler, 2015).

Our study found that science teachers lacking strong physical science SMK still hold fundamental misconceptions that are likely to interfere with their potential for delivering high-quality chemistry and physics instruction. Developing SMK allows teachers to address their existing misconceptions and reduces the likelihood in the future of creating or perpetuating misconceptions in their students' thinking. Identifying relationships between teachers' physical science SMK and their misconceptions meets the urgent need to understand factors that predict teachers' robust SMK (Tatto et al., 2016) and informs the work of science teacher educators (NRC, 2010a; NRC, 2010b) to support NGSS-aligned science instruction (Achieve, 2014).

In this discussion, we respond to each of the research questions with recommended undergraduate credit hours and GPA for science teachers to avoid misconceptions for each of the NGSS physical science disciplines (i.e., chemistry and physics). We also identify chemistry and physics topics with typical misconceptions at different formal education levels. Finally, we propose two sets of discipline-specific undergraduate courses to help PSTs overcome everyday chemistry and physics misconceptions.

6.1 Chemistry teachers' subject matter knowledge and common misconceptions

The MOSART chemistry (9–12) test was initially designed as a diagnostic tool for teachers to use with high school chemistry students. However, our participants required many college-level chemistry courses to overcome common chemistry misconceptions. On average, study participants (n = 109) did not achieve the 80% passing score on the MOSART chemistry test (M = 75.89%, SD = 15.04). However, these participants had only taken an average of 16.5 chemistry credit hours (SD = 11.31), about four 4-credit hour lecture and laboratory-based chemistry courses. Using our participants' average GPA (M = 3.23, SD 0.56), we predicted the number of credit hours necessary for a passing score on the MOSART chemistry test. The likelihood of passing or failing the chemistry test was based on a linear combination of chemistry coursework GPA and total chemistry credit hours. A one-point increase in chemistry GPA increased the likelihood of passing the MOSART chemistry test by a factor of 8.18, and each increase of 0.1 in chemistry GPA increased the likelihood of a passing score by a factor of 1.23. When we considered the number of credit hours, our analysis indicated participants with at least a 3.2 GPA needed 30 h of chemistry to pass the MOSART chemistry test reliably. Thus, both high numbers of chemistry credit hours and robust chemistry GPA are needed to ensure chemistry content mastery and should be considered together when evaluating teacher candidates' chemistry SMK.

Similar to our findings, Kind (2014) found that secondary teachers with a chemistry major (i.e., teaching in-field) had fewer misconceptions than those teachers with other degrees who were teaching out-of-field. Also, Zoller (1990) found that first-year graduate students continue to develop misconceptions in various general chemistry (e.g., the mole, quantum model of the atom, electronic orbitals, acids and bases, entropy, and chemical equilibrium) and organic chemistry topics. It is plausible that university-level chemistry content is not often organized for teaching chemistry concepts (De Jong et al., 2002). Introductory chemistry undergraduate courses are commonly delivered in large lecture halls with 100–200 students using teacher-centered, traditional instruction (Stains et al., 2018). This format may not be ideal for future teachers to construct their own conceptual framework of chemistry to identify and address individual students' misconceptions easily.

For example, among our participants, the most common misconceptions were chemical bonding, one of the most central concepts in chemistry. This was likely because this topic requires multiple learning opportunities and the use of models and representations (Luxford & Bretz, 2014). Additionally, bonding has been traditionally taught using a dichotomy for classifying molecules and compounds as either covalent or ionic. Luxford and Bretz (2014) argued that oversimplified dichotomous conceptions of bonding could impede a deeper understanding of these concepts, and therefore exacerbate misconceptions.

6.2 Coursework for competency in chemistry subject matter knowledge for teaching

Overall, we recommend a minimum of 30 credit hours of specific chemistry coursework for teachers' robust chemistry SMK. Teacher preparation programs should require the following courses for their chemistry teacher candidates: (a) introductory chemistry courses with labs (e.g., General Chemistry I & II), including topics such as energy and matter, their properties and interactions; atoms, periodic table and elements; modern atomic theory, electron configuration; chemical bonding; chemical and nuclear reactions; and the electromagnetic spectrum; (b) organic chemistry courses with labs, including: carbon-based molecules, isomers, molecular geometry, functional groups, organic reactions, and biomolecules; (c) physical chemistry or biochemistry, to understand the interactions among scientific disciplines; (d) advanced inorganic chemistry with a lab, to deepen concepts from general chemistry courses, especially those connected to chemical bonding and nuclear reactions; and (e) an additional six credit hours of upper level chemistry coursework, in which students can develop projects using science and engineering practices. Ideally, students should pass these courses with an average GPA of 3.2 or higher. We strongly recommend that future chemistry teachers take as much upper level chemistry coursework to better understand scientific practices and the nature of science in chemistry.

However, developing strong SMK for teaching chemistry requires more than exposure to, and practice with, the discipline's essential concepts. To align with the vision of the NGSS, PSTs are expected to develop specialized knowledge to understand and address first their own, and later, their students' misconceptions. Our study demonstrated that a robust amount of chemistry credit hours is needed to avoid misconceptions. A focus on student misconceptions, constructivist learning, and formative assessment practices during TPP methods courses should also support PSTs' shift from teacher-centered instructional strategies that they might have experienced during their own SMK development. Such teacher learning activities and self-reflection for "ambitious teaching" (Windschitl et al., 2018) can support PSTs overcoming a superficial understanding of the content and reproduction of misconceptions, despite the lack of reform-based educational models they may have not experienced as learners in their formal science education (Windschitl & Stroupe, 2017).

Moreover, we highlight the importance of inquiry-based instruction and student-centered strategies, especially in undergraduate science courses. Large-group lecture-based instruction, among other problematic scientific literacy considerations (Stains et al., 2018), may not support an adequate development science knowledge needed to teach aligned with the NGSS. Consequently, science teachers with only a basic level knowledge derived from introductory chemistry courses could inadvertently perpetuate teacher-centered direct-instruction as a primary strategy with their high school students (De Jong et al., 2002; Özmen et al., 2009) despite efforts invested during their TPPs to use more constructivist approaches and formative assessment practices to identify and address students' misconceptions.

Nonetheless, in teachers' and students' science learning, misconceptions are persistent and resistant to change (Mayer, 2011). Therefore TPPs should focus their attention on developing PSTs' specialized content knowledge to conduct curricular interventions, design specialized instruction (Slotta & Chi, 2006; Hake, 1998), and organize remedial instruction (Yip, 1998) to mitigate them. Teachers need to apply such strategies with intention, create cognitive problems, and support students' assimilation and accommodation of new ideas. In sum, to teach chemistry concepts accurately, chemistry PSTs must have strong chemistry SMK and develop specialized knowledge for identifying and addressing student misconceptions.

6.3 Physics teachers' subject matter knowledge and common misconceptions

On average, study participants (n = 103) did not pass the MOSART physics test (M = 73.68%, SD = 15.60). Test takers had only taken an average of 15.36 credit hours in physics (SD = 13.97), with an average physics GPA of 3.14 (SD = 0.56). The average mathematics GPA was 3.22, with an average of 11.00 credit hours (SD = 8.64). The likelihood of passing or failing the physics test was based on a linear combination of math coursework GPA and the total number of physics credit hours; the likelihood of pass/fail MOSART physics test scores = −5.33 + 0.86 × math GPA + 0.20 × physics credit hours. Specifically, each additional credit hour of physics coursework increased the relative likelihood of an individual passing the MOSART physics tests by 22% (e^{β} = 1.22). A one-point rise in math GPA increased the likelihood of an individual passing the physics test by 136%. From a practical perspective, this translates to, for every 0.10 change in GPA, that participants were 1.1 times more likely to pass the physics test. Thus, both math performance and physics credit hours together indicated a more substantial mastery of the content and should be a regular part of evaluating a physics teacher candidate's probability of not holding common physics misconceptions.

6.4 Coursework for competency in physics subject matter knowledge for teaching

Specific program coursework to support robust physics SMK for teaching high school physics content should include the following courses: (a) General Physics I, II, and III with labs; (b) astronomy; (c) electrical and electronic circuits; (d) mechanics; (e) thermal physics; (f) experimental physics; (g) electromagnetic theory; (h) quantum mechanics; and (i) optics and electromagnetic waves. Because the mathematics GPA was an essential factor for predicting a passing score on the MO-SART physics test, it is also crucial to consider mathematics courses. While some first-year college students start with introductory level calculus courses, others do not. Physics teacher preparation should include (a) College Algebra and Trigonometry, (b) Calculus I, II, and III, (c) differential equations, (d) linear Algebra and matrix theory, and (e) modern algebra. It could be argued that two minors, one each in physics and mathematics, would be necessary for high school teaching, but further research is necessary to compare those who have a physics major with a mathematics minor with others who only have two minor degrees.

In an ancillary study (Lucas & Lewis, 2018), we found that more credit hours that included advanced, upper-level college physics courses not only improved teachers' SMK and promoted a deeper conceptual understanding also improved the likelihood of teachers using a constructivist approach to teaching physics. This corresponds with state-of-the-art modeling physics approaches to teaching physics that meets the NGSS and its three-dimensional learning design (NRC, 2013). While physics is often only seen as an upper-level high school elective course, K- 12 physical science DCIs are a critical part of students' overall scientific literacy and provide a rich context for integrating engineering standards and practices.

6.5 Summary

We argue that persistent chemistry and physics misconceptions are related to using traditional teaching methods (e.g., direct instruction) and superficially addressing a wide range of topics without focusing on deep conceptual understanding of the application of scientific practices (e.g., asking questions, scientific argumentation, modeling, planning and carrying out investigations) (Slotta and Chi, 2006; Hake, 1998). This is problematic because, although teachers' SMK alone is not enough (Charalambous, 2016), strong SMK can support the development of PSTs' knowledge needed to prepare them to apply responsive teaching strategies as new teachers (Burmeister et al., 2013; Nixon et al., 2019), including the development of relevant pedagogies, such as inquiry-based learning.

Finally, although this study did not address in-service teachers' SMK, we recognize teacher SMK is not a static construct and can grow over time (Arzi & White, 2008; De Jong et al., 2002) through informal personal interests and formal learning environments with additional coursework. The suggested courses and topics and common misconceptions we identified can also guide in-service physical science teachers' continuing professional development efforts.

6.6 Study limitations

It is important to note that to reduce the natural variation that occurs through multiple teacher education programs at different institutions across different U.S. states, we elected to conduct our study at one institution in one state. This allowed us to control the required TPP education coursework that the teacher candidates took and nearly exclusively focus on variable science content knowledge. Our results function as a detailed case study for other similar four-year colleges and universities that prepare secondary science teachers.

While other researchers and we have used MOSART tests as a fruitful research tool, the Praxis II science subject matter tests are more comprehensive discrete science content exams that are often required for teacher certification. Accessing such test scores would be a useful comparison with the MOSART test results in our study. We could not use Praxis II tests for all of our participants as they were initially not required for state certification; thus, only more recently prepared PSTs had available scores. While this study was motivated in part by the goals of scientific literacy as described in the NGSS framework, we also did not compare teacher certification policies nationally. This is another important line of educational policy research.

Other research that attends to participants' lack of education coursework and/or programs via emergency certification routes would be better situated to investigate those variables' effects. Such a future study would allow the investigation of important companion research questions about teachers with greater variability in both science content and education coursework. Lastly, while within-state comparisons are useful and provide valuable information for local stakeholders and policymakers, between-state comparisons are needed to take this conversation to the national level and generate other insights about science teacher certification. Such an undertaking would require systematic, standardized, comprehensive data collection and analyses, and is a clear mandate for future research in the area of teacher SMK, specialized knowledge, and teacher expertise, to directly respond to national calls for rigorous science education and scientific literacy (NRC, 2013).

7 Conclusion

This study of two levels of teacher preparation has findings that are transferable to other similar teacher education programs, including the hundreds of nationally funded NSF Noyce Teacher Scholarship-supported science TPPs and their required science courses for SMK mastery. We offer science teacher educators and professional development providers clear goals and guidelines for meeting teacher preparation priorities and beginning teachers' needs, especially those who may be teaching out-of-field. In other studies of teachers' SMK, GPA has been largely ignored, often because it is not readily available, and is likely to involve variation in grading practices among higher education institutions. In both physical science subject areas, only completing college introductory-level courses (i.e., general chemistry and physics courses) did not address common science misconceptions that high school level students are known to have. Thus, science teachers who have not met this study's empirical minimums of chemistry and physics content knowledge are prime candidates for teacher professional development to continue to build and refine their disciplinary content knowledge. With clearer and more precise guidelines, teacher educators, institutes of higher education, and teacher licensing policymakers can ensure that future policies support generating highly qualified science teachers. Our findings add to other researchers' investigations into the nuances of teachers' necessary minimum discipline-based SMK levels.

Considering this study's findings, recent efforts to lower requirements for certification (Felton, 2016) are a short-sighted response to the challenges of supplying, and goal to educate, more highly qualified science teachers (e.g., 100Kin10 (Handelsman & Smith, 2016)). The same case applies to charter schools that have unfortunately influenced loosening teacher certification requirements (Baker & Miron, 2015). The negative implications for student learning from the unintended consequences of U.S. state-level policy and increasing numbers of out-of-field science teachers will simply persist until higher certification standards are more routinely upheld.

We strongly encourage TPP developers and policy stakeholders who set teaching certification and evaluation criteria to consider this study's empirical results and implications for preparing high-quality teachers to deliver rigorous science education to its diverse students. U.S. states that only allow for minimal (i.e., "general") science endorsements are likely failing to meet criteria for highly qualified science teachers with sufficient SMK mastery to be able to meet national priorities for students' scientific literacy. Until greater consistency is achieved across state-level science teacher certification policies, little progress will be made in realizing the NGSS vision, national STEM education goals, and STEM career priorities for all students.

References

Allen, E. (2017). National Requirements for Secondary Science Preparation. *Model Science Teacher Preparation Programs: An International Comparison of What Works*. (185–203). Charlotte, NC: Information Age Publishing.

Alonzo, A. C. (2018). An argument for formative assessment with science learning progressions. *Applied Measurement in Education*, *31*(2), 104–112.

Anderson, D., Burnham, K., Gould, W., & Cherry, S. (2001). Concerns about finding effects that are actually spurious. *Wildlife Society Bulletin*, *29*(1), 311–316. http://www.jstor.org/stable/3784014

Arzi, H. J., & White, R. T. (2008). Change in teachers' knowledge of subject matter: A 17-year longitudinal study. *Science Education*, *92*(2), 221–251.

Avalos, M., Grandvalet, Y., & Ambroise, C. (2007). Parsimonious additive models. *Computational Statistics & Data Analysis*, *51*(6), 2851–2870.

Baker, B., & Miron, G. (2015). *The business of charter schooling: Understanding the policies that charter operators use for financial benefit*. National Education Policy Center. http://nepc.colorado.edu/publication/charterrevenue

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content knowledge for teaching: What makes it special? *Journal of Teacher Education*, *59*(5), 389–407.

Banilower, E. R., Smith, P. S., Malzahn, K. A., Plumley, C. L., Gordon, E. M., & Hayes, M. L. (2018). *Report of the 2018 NSSME+*. Horizon Research, Inc.

Bergqvist, A., Drechsler, M., & Chang Rundgren, S.-N. (2016). Upper secondary teachers' knowledge for teaching chemical bonding models. *International Journal of Science Education*, *38*(2), 298–318.

Brandriet, A. R., & Bretz, S. L. (2014). Measuring meta-ignorance through the lens of confidence: Examining students' redox misconceptions about oxidation number, charge, and electron transfer. *Chemistry Education Research and Practice*, *15*, 729–746.

Burmeister, M., Schmidt-Jacob, S., & Eilks, I. (2013). German chemistry teachers' understanding of sustainability and education for sustainable development—An interview case study. *Chemistry Education Research and Practice*, *14*(2), 169–176.

Bybee, R. (1997). *Achieving scientific literacy: From purposes to practices*, Westport, CT: Heinemann.

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Powell, J. C., Westbrook, A., & Landes, N. (2006). The BSCS 5E instructional model: Origins and effectiveness. BSCS, *5*, 88–98.

Carter, P. & Darling-Hammond, L. (2016). Teaching diverse learners. In D. H. Gitomer, & Bell, C.A. (Eds.), *Handbook of research on teaching* (pp. 593–638). The American Educational Research Association.

Charalambous, C. Y. (2016). Investigating the knowledge needed for teaching mathematics: An exploratory validation study focusing on teaching practices. *Journal of Teacher Education*, *67*(3), 11–13.

Chinn, C., & Brewer, W. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research*, *63*(1), 1–49.

Cochran-Smith, M. (2005). Studying teacher education: What we know and need to know. *Journal of Teacher Education*, *56*(4), 301–306.

Cochran-Smith, M., & Lytle, S. L. (1999). Relationships of knowledge and practice. Teacher learning communities. *Review of Research in Education*, *24*, 249–305.

Crawford, B. A., & Capps, D. K. (2018). Teacher cognition of engaging children in scientific practices. In Y. J.

Dori, Z. R. Mevarech, & D. R. Baker (Eds.), *Cognition, metacognition, and culture in STEM education* (pp. 9–32). Springer.

Darling-Hammond, L., & Bransford, J. (Eds.). (2005). *Preparing teachers for a changing world: What teachers should learn and be able to do*. Jossey-Bass.

Davis, E. A., Petish, D., & Smithey, J. (2006). Challenges new science teachers face. *Review of Educational Research*, *76*(4), 607–651.

De Jong, O., & Taber, K. S. (2014). The many faces of high school chemistry. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research in science education* (Vol. II, pp. 457–480). Routledge.

De Jong, O., Veal, W. R., & van Driel, J. H. (2002). Exploring chemistry teachers' knowledge base. In J. K. Gilbert, O. De Jong, R. Justi, D. F. Treagust, & J. H. van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 369–390). Springer.

Dhindsa, H. S., & Treagust, D. F. (2014). Prospective pedagogy for teaching chemical bonding for smarted sustainable learning. *Chemistry Education Research and Practice*, *15*, 435–446.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. B. Pufall (Eds.), *The Jean Piaget symposium series: Constructivism in the computer age* (pp. 49–70). Lawrence Erlbaum Associates, Inc.

Donna, J. D., & Hick, S. R. (2017). Developing elementary preservice teacher subject matter knowledge through the use of educative science curriculum materials. *Journal of Science Teacher Education*, *28*(1), 92–110.

Driver, R., Squires, A., Rushworth, P., & Wood-Robinson, V. (2014). *Making sense of secondary science: Research into children's ideas*. Routledge.

Educational Testing Service (2018). *The Praxis® passing scores by test and state*. Educational Testing Service. https://www.ets.org/s/praxis/pdf/passing_scores.pdf

Erman, E. (2017). Factors contributing to students' misconceptions in learning covalent bonds. *Journal of Research in Science Teaching*, *54*(4), 520–537. https://doi.org/10.1002/tea.21375

Ewert, A., & Sibthorp, J. (2000). Multivariate analysis in experiential education: Exploring the possibilities. *The Journal of Experimental Education*, *23*(2), 108–117.

Feiman-Nemser, S. (2001). From preparation to practice: Designing a continuum to strengthen and sustain teaching. *Teachers College Record*, *103*(6), 1013–1055.

Felton, E. (2016, August 30). *States loosen teacher-licensure rules amid shortage fears*. Education Week. http://blogs.edweek.org/edweek/teacherbeat/2016/08/states_loosen_teacher_licensure_shortages.html

Forbes, C., Sabel, J., & Zangori, L. (2015). Integrating Life Science Content & Instructional Methods in Elementary Teacher Education. *The American Biology Teacher*, *77*(9), 651–657. https://doi.org/10.1525/abt.2015.77.9.2

Grossman, P. L. (1990). *A tale of two hamlets. In the making of a teacher: Teacher knowledge and teacher education*. Teachers College Press.

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, *66*(1), 64–74. https://doi.org/10.1119/1.18809

Halloun, I. A., & Hestenes, D. (1985). Common sense concepts about motion. *American Journal of Physics*, *53* (11), 1056–1065.

Hamza, K. M., & Wickman P. (2008). Describing and analyzing learning in action: An empirical study of the importance of misconceptions in learning science. *Science Education*, *92*(1), 141–164. https://doi.org/10.1002/sce.20233

Handelsman, J., & Smith, M. (2016, February 11). *White House Blog, "STEM for All"*. Washington, D.C.: The White House. https://obamawhitehouse.archives.gov/blog/2016/02/11/stem-all

Hashweh, M. Z. (2002). Effects of subject-matter knowledge in the teaching of biology and physics. *Teaching and Teacher Education*, *3*(2), 109–120.

Herman, B. C., Feldman, A., & Vernaza-Hernandez, V. (2017). Florida and Puerto Rico Secondary Science Teachers' Knowledge and Teaching of Climate Change Science. *International Journal of Science and Mathematics Education*, *15*(3), 451–471. https://doi.org/10.1007/s10763-015-9706-6

Hernández, A. V., Steyerberg, E. W., & Habbema, J. D. F. (2004). Covariate adjustment in randomized controlled trials with dichotomous outcomes increases statistical power and reduces sample size requirements. *Journal of Clinical Epidemiology*, *57*(5), 454–460.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, *30*(3), 141–158.

Huttner, T., & Markman, A. (2016). Department-level representations: A new approach to the study of science teacher cognition. *Science Education*, *100*(1), 30–56.

Johnstone, A. H. (2010). You can't get there from here. *Journal of Chemical Education*, *87*, 22–29.

Kagan, D. M. (1992). Professional growth among preservice and beginning teachers. *Review of Educational Research*, *62*, 129–169.

Kikas, E. (2003). University students' conceptions of different physical phenomena. *Journal of Adult Development*, *10*, 139–150.

Kikas, E. (2004). Teachers' conceptions and misconceptions concerning three natural phenomena. *Journal of Research in Science Teaching*, *41*(5), 432–448.

Kind, V. (2014). A degree is not enough: A quantitative study of aspects of pre-service science teachers' chemistry content knowledge. *International Journal of Science Education*, *36*(8), 1313–1345.

Kulgemeyer, C., & Riese, J. (2018). From professional knowledge to professional performance: The impact of CK and PCK on teaching quality in explaining situations. *Journal of Research in Science Teaching*, *55*(10), 1393–1418.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge, UK: Cambridge University Press.

LeBlanc, M., & Fitzgerald, S. (2000). Logistic regression for school psychologists. *School Psychology Quarterly*, *15*(3), 344–358. https://doi.org/10.1037/h0088791

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. II, pp. 600–620). Routledge.

Leonard, M. J., Kalinowski, S. T., & Andrews, T. C. (2014). Misconceptions yesterday, today, and tomorrow. *CBE Life Sciences Education*, *13*(2), 179–186.

Lewis, E. B., Rivero, A., Musson, A., Lucas, L., Tankersley, A., & Helding, B. A. (2020). Chapter 4: Educating effective science teachers: Preparing and following teachers into the field. In J. Carinci, S. Meyer, & C. Jackson (Eds.), *Linking teacher preparation program design and implementation to outcomes for teachers and students* (pp. 87–129). Charlotte, NC: Information Age Publishing.

Lucas, L., & Lewis, E. B. (2018). Modeling inquiry-oriented instruction of beginning secondary science teachers. In O. Finlayson, E. McLoughlin, S. Erduran, & P. Childs (Eds.), *Electronic Proceedings of the ESERA 2017 Conference. Research, Practice and Collaboration in Science Education, Part 13 Pre-service Science Teacher Education (co-edited by Maria Evagorou & Marisa Michelini)* (pp. 1742–1752). Dublin City University.

Lucero, M. M., Petrosino, A. J., & Delgado, C. (2017). Exploring the relationship between secondary science teachers' subject matter knowledge and knowledge of student conceptions while teaching evolution by natural selection. *Journal of Research in Science Teaching*, *54*(2), 219–246.

Luxford, C. J., & Bretz, S. L. (2014). Development of the bonding representations inventory to identify student misconceptions about covalent and ionic bonding representations. *Journal of Chemical Education*, *91*(3), 312–320.

Maerten-Rivera, J. L., Huggins-Manley, A. C., Adamson, K., Lee, O., & Llosa, L. (2015). Development and validation of a measure of elementary teachers' science content knowledge in two multiyear teacher professional development intervention projects. *Journal of Research in Science Teaching*, *52*(3), 371–396.

Maskiewicz, A. C., & Lineback, J. E. (2013). Misconceptions are "so yesterday!". *CBE Life Science Education*, *12* (3), 352–356.

Mayer, K. (2011). Addressing students' misconceptions about gases, mass, and composition. *Journal of Chemical Education*, *88*(1), 111–115.

McCloskey, M., & Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interactions with moving objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*(1), 146–156.

Meijer, M. R., Bulte, A. M., & Pilot, A. (2012). Macro-micro thinking with structure-property relations: Integrating meso-levels in secondary education. In G. Tsaparlis & H. Sevian (Eds.), *Concepts of matter in science education* (pp. 419–435). Dordrecht: G.: G.: Springer.

Miles, M. B., Huberman, A. M., & Saldana, J. (2014). *Qualitative data analysis: A methods sourcebook* (3rd ed.). SAGE.

Murphy, C. (2005). The role of subject knowledge in primary trainee teachers' approaches to teaching in the topic of area. In D. Hewitt and A. Noyes (Eds.), *Proceedings of the Sixth British Congress of Mathematics Education* (pp. 113–119). Warwick: University of Warwick.

Nasir, N. S., Scott, J., Trujillo, T., & Hernandez, L. (2015). The sociopolitical context of teaching. In D. H. Gitomer & C. A. Bell (Eds.), *Handbook of research on teaching* (pp. 349–390). American Educational Research Association.

National Research Council, Donovan, S., & Bransford, J. (2005). *How students learn*, Washington, DC: National Academies Press. https://www.nap.edu/catalog/10126/how-students-learn-history-mathematics-and-science-in-the-classroom

National Academies of Sciences, Engineering, and Medicine. (2015). *Science teachers learning: Enhancing opportunities, creating supportive contexts*. The National Academies Press.

National Research Council. (1996). *National science education standards*. National Academy Press.

National Research Council. (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: The National Academies Press.

National Research Council. (2010a). *Preparing teachers: Building evidence for sound policy*. Washington, DC: The National Academies Press.

National Research Council. (2010b). *Surrounded by science: Learning science in informal environments*. The National Academies Press.

National Science Teaching Association (2020). *NSTA standards for science teacher preparation*. National Science Teaching Association. https://www.nsta.org/nsta-standards-science-teacher-preparation

Nehm, R. H., & Reilly, L. (2007). Biology majors' knowledge and misconceptions of natural selection. *Bioscience*, *57*(3), 263–272.

National Research Council. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Nixon, R. S., Smith, L. K., & Sudweeks, R. R. (2019). Elementary teachers' science subject matter knowledge across the teacher career cycle. *Journal of Research in Science Teaching*, *56*(7), 707–731.

Nixon, R. S., Luft, J. A., & Ross, R. J. (2017). Prevalence and predictors of out-of-field teaching in the first five years. *Journal of Research in Science Teaching*, *54*(9), 1197–1218.

Ogodo, J. A. (2019). Comparing advanced placement physics teachers experiencing physics-focused professional development. *Journal of Science Teacher Education*, *30*(6), 639–665.

Olson, J. K., Tippett, C. D., Milford, T. M., Ohana, C., & Clough, M. P. (2015). Science teacher preparation in a North American context. *Journal of Science Teacher Education*, *26*(1), 7–28.

Osborne, J. (2014). Scientific practices and inquiry in the science classroom. N. Lederman & S. Abell *Handbook of research on science education (Volume II)*. (593–613). New York: Routledge.

Özmen, H. (2010). Determination of science student teachers' conceptions about ionization energy. *Procedia— Social and Behavioral Sciences*, *9*, 1025–1029.

Özmen, H., Demircioğlu, H., & Demircioğlu, G. (2009). The effects of conceptual change texts accompanied with animations on overcoming 11th grade students' alternative conceptions of chemical bonding. *Computers and Education*, *52*(3), 681–695.

Penuel, W. R., & Shepard, L. A. (2016). Assessment and teaching. In D. H. Gitomer & C. A. Bell (Eds.), *Handbook of research on teaching* (pp. 787–850). American Educational Research Association.

Potvin, P., & Cyr, G. (2017). Toward a durable prevalence of scientific conceptions: Tracking the effects of two interfering misconceptions about buoyancy from preschoolers to science teachers. *Journal of Research in Science Teaching*, *54*(9), 1121–1142.

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction*, *18*(1), 1–34.

Roberts, D. A., & Bybee, R. W. (2014). Scientific literacy, science literacy, and science education. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of Research on Science Education, Volume II* (pp. 559–572). Routledge.

Rosenbaum, P. R., & Rubin, D. B. (1983). Assessing sensitivity to an unobserved binary covariate in an observational study with binary outcome. *Journal of the Royal Statistical Society: Series B (Methodological)*, *45*(2), 212–218.

Russ, R., Sherin, B., & Sherin, M. G. (2016). What constitutes teacher learning? In D. Gitomer & C. Bell (Eds.), *Handbook of research on teaching* (pp. 391–438). AERA.

Sadler, P., & Sonnert, G. (2016). Understanding misconceptions: Teaching and learning in middle school physical science. *American Educator*, *40*(1), 26–32.

Sadler, P. M., Sonnert, G., Coyle, H. P., Cook-Smith, N., & Miller, J. L. (2013). The influence of teachers' knowledge on student learning in middle school physical science classrooms. *American Educational Research Journal*, *50*(5), 1020–1049.

Sadler, P.M., Coyle, H.P., Cook-Smith, N., Miller, J.L., Murray, J., & Trenga Rumpf, A. (2011). *Misconceptions-oriented standards-based assessment resources for teachers*. Harvard University. https://www.cfa.harvard.edu/smgphp/mosart/credits_2.html

Sanders, W.L., & Rivers, J.C. (1996). *Cumulative and residual effects of teachers on future student academic achievement*. Knoxville, TN: University of Tennessee Value-Added Research and Assessment Center. https://www.beteronderwijsnederland.nl/files/cumulative%20and%20residual%20effects%20of%20teachers.pdf

Schwarz, C. V., Passmore, C., & Reiser, B. J. (2017). *Helping students make sense of the world using next generation science and engineering practices*. NSTA Press.

Shepard, L. A. (2018). Learning progressions as tools for assessment and learning. *Applied Measurement in Education*, *31*(2), 165–174.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, *15*(2), 4–14. Slotta, J. D., & Chi, M. T. H. (2006). Helping students understand challenging topics in science through ontology training. *Cognition and Instruction*, *24*(2), 261–289. https://doi.org/10.1207/s1532690xci2402_3

Stains, M., Harshman, J., Barker, M. K., Chasteen, S. V., Cole, R., DeChenne-Peters, S. E., Eagan, M. K., Esson, J. M., Knight, J. K., Laski, F. A., & Levis-Fitzgerald, M. (2018). Anatomy of STEM teaching in North American universities. *Science*, *359*(6383), 1468–1470.

Stinner, A. (1994). Providing a contextual base and a theoretical structure to guide the teaching of high school physics. *Physics Education*, *29*(6), 375–381.

Stewart, I. (2021, February 19). *COVID-19 didn't cause teacher shortage: But it sure didn't help*. Virginia Public Radio, NPR. https://vpm.org/news/articles/20515/covid-19-didnt-cause-teacher-shortage-but-it-sure-didnt-help

Tatto, M. T., Richmond, G., & Carter-Andrews, D. J. (2016). The research we need in teacher education. *Journal of Teacher Education*, *67*(4), 247–250.

Tsiatis, A. A., Kenward, M. G., Fitzmaurice, G., Verbeke, G., & Molenberghs, G. (2014). *Handbook of missing data methodology*. CRC Press.

van Driel, J. H., Berry, A., & Meirink, J. (2014). Research on science teacher knowledge. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education (Volume II)* (pp. 848–870). Routledge.

Veal, W. R., & Allen, E. (2014). Understanding the 2012 NSTA science standards for teacher preparation. *Journal of Science Teacher Education*, *25*(5), 567–580.

Vygotsky, L. S. (1986). *Thought and language (Revised edition)*. Massachusetts Institute of Technology.

Wendt, J. L., & Rockinson-Szapkiw, A. (2014). The effect of online collaboration on middle school student science misconceptions as an aspect of science literacy. *Journal of Research in Science Teaching*, *51*(9), 1103–1118.

White, S., & Tyler, J. (2015). *Underrepresented minorities in high school physics: Results from the 2012-13 nationwide survey of high school physics teachers*. Focus On. https://www.aip.org/sites/default/files/statistics/highschool/hs-underrepmin-13.pdf

Wickman, P. O. (2014). Teaching learning progressions: An international perspective. N Lederman & S. Abell *Handbook of research on science education (Volume II)*, (159–178). New York: Routledge.

Wiener, G. J., Schmeling, S. M., & Hopf, M. (2018). The technique of probing acceptance as a tool for teachers' professional development: A PCK study. *Journal of Research in Science Teaching*, *55*(6), 849–875.

Wilson, S. M., Floden, R. E., & Ferrini-Mundy, J. (2001). *Teacher preparation research: Current knowledge, gaps, and recommendations: A research report prepared for the US department of education and the office for educational research and improvement*. Center for the Study of Teaching and Policy.

A., & Stroupe, D. (2017). The three-story challenge. *Journal of Teacher Education*, *68*(3), 251–261.

Windschitl, M., Thompson, J., & Braaten, M. (2018). *Ambitious science*. Harvard Education Press.

Wiser, M., & Amin, T. (2001). "Is heat hot?" inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction*, *11*(4–5), 331–355.

Yip, D. (1998). Identification of misconceptions in novice biology teachers and remedial strategies for improving biology learning. *International Journal of Science Education*, *20*(4), 461–477. https://doi.org/10.1080/0950069980200406

Zhang, Z. (2016). Model building strategy for logistic regression: Purposeful selection. *Annals of Translational Medicine*, *4*(6), 111.

Zoller, U. (1990). Students' misunderstandings and misconceptions in college freshman chemistry (general and organic). *Journal of Research in Science Teaching*, *27*(10), 1053–1065.

Table A1 Relationship among amount of chemistry credit hours, average MOSART chemistry score, easier concepts, persistent misconceptions, and common chemistry coursework

SMK level (n = test takers) # of chemistry credit hours & GPA (SD)	Average MOSART test score % M (SD)	Easier concepts (MOSART test item number[a] with more than 90% of correct responses)	Persistent misconceptions (MOSART test item number[a] with less correct responses)	Most commonly taken chemistry courses (% of teachers with course on transcript)
Introductory level				
Group 1 (*n* = 10) CH = 0–8 Ave. GPA = 2.8 (0.6)	65 (15)	Atomic particles (20, 22) Chemical reactions and energy (1) Periodic table and periodicity (16) Structure of molecules (2)	Polarity of molecules (8) Chemical bonding (12) Macroscopic level chemical reactions (3) Atomic theory (9) Physical properties of matter and the atomic structure (13) Organic isomers (14)	General Chemistry I[b] (90) General Chemistry I[c] (50)
Low level				
Group 2 (*n* = 65) CH = 9–16 Ave. GPA = 3.3 (0.6)	74 (15)	Atomic particles (22) Periodic table and periodicity (7, 16)	Nuclear processes (15) Chemical bonding (12)	General Chemistry I[b] (97) General Chemistry II[c] (95) Organic Chemistry I (94) Organic Chemistry I lab (89)
Medium level				
Group 3 (*n* = 11) CH = 17–24 Ave. GPA = 3.3 (0.4)	77 (11)	Atomic particles (20, 22) Chemical bonding *(5)* Chemical reactions and energy (1) Organic isomers (14) Periodic table and periodicity (7, 16) Structure of molecules (2)	Chemical bonding (12) Atomic theory (9) Nuclear processes (15)	General Chemistry I[b] (91) General Chemistry II[c] (82) Organic Chemistry I (100) Organic Chemistry II (82) Organic Chemistry I Lab (100) Organic Chemistry II Lab (73)

SMK level (n = test takers) # of chemistry credit hours & GPA (SD)	**Average MOSART test score % M (SD)**	**Easier concepts (MOSART test item number[a] with more than 90% of correct responses)**	**Persistent misconceptions (MOSART test item number[a] with less correct responses)**	**Most commonly taken chemistry courses (% of teachers with course on transcript)**
High level				
Group 4 (*n* = 11) CH = 25+ Ave. GPA = 3.2 (0.4)	88 (10)	Atomic particles (6, 19, 22) Chemical bonding (5) Chemical reactions and energy (1, 17) Chemical reactions kinetics (18) Nuclear processes (11) Organic isomers (14) Periodic table and periodicity (7, 16) Structure of molecules (2)	Chemical bonding (12)	General Chemistry I[b] (100) General Chemistry II[c] (91) Organic Chemistry I (100) Organic Chemistry II (91) Organic Chem I lab (91) Organic Chem II lab (73) Physical Chemistry (64) Inorganic Chemistry (46) Inorganic Chemistry lab (46)
Overall				
All (*n* = 97) CH = 16.41 (11.06) Ave. GPA = 3.2 (0.6)	75 (15)	Periodic table and periodicity (7, 16) Atomic particles (22) Chemical reactions and energy (1) Structure of molecules (2)	Chemical bonding (12) Nuclear processes (15)	General Chemistry I[b] (93) General Chemistry II[c] (88)

a. MOSART test version #731.

b. We considered the course *Fundamentals of Chemistry* in this tally. When the teacher had both courses, we tallied them once.

c. We considered the course *Fundamentals of Chemistry II* in this tally. When the teacher had both courses, we tallied them once.

Table A2 Relationship among average MOSART physics score, easier physics concepts, persistent misconceptions, and common physics and mathematics coursework

SMK level (n = test takers) # of physics credit hours GPA (SD)	Average MOSART test score (%) M (SD) E	asier concepts (MOSART test item number with at least 90% of correct responses)	Persistent misconceptions (lowest scoring MOSART test item number)	Most commonly taken physics courses (% with course in their transcripts)	Most commonly taken math courses (% with course in their transcripts)
Introductory level					
Group 1 (*n* = 24) Physics CH = 0–8 Mean Physics GPA = 2.69 (0.68) Mean Math CH = 7.35 (5.87) Mean Math GPA = 3.12 (0.71)	66 (16.64)	Electromagnetic waves (1, 11) Electrical conductivity (2) Gravitational force (8) Newton's laws of motion (9) Electromagnetism (19) Conservation of energy (10)	Electric force (4) Newton's laws of motion (6, 13) Wave properties (14) Electromagnetic waves (15) Electromagnetism (16) Quantization of energy (17, 18)	Elementary General Physics I (46) Elementary General Physics II (17) Modern Topics: Physics and Astronomy (25) General Physics I (21) General Physics I Lab (21) General Physics II (13)	College Algebra (33) Trigonometry (13) Calculus for Management and Social Science (21) Calculus I (42) Calculus II (33) Calculus III (25)
Low level					
Group 2 (*n* = 48) Physics CH = 9–16 Mean Physics GPA = 3.23 (0.50) Mean Math CH = 8.23 (6.18) (0.73)	70 (12.62)	Electromagnetic waves (1, 11) Electrical conductivity (2, 24) Gravitational force (8) Newton's laws of motion (9) Electromagnetism (19) Laws of thermodynamics (25)	Electric force (4, 12) Wave properties (5, 14) Newton's laws of motion (6, 13) Quantization of energy (17)	Elementary General Physics I (85) Elementary General Physics II (85) Descriptive Physics (10) General Physics I (10) General Physics I Lab (10) General Physics II (13) General Physics II Lab (13)	College Algebra (17) Trigonometry (17) College Algebra and Trigonometry (13) Calculus I (71) Calculus II (31) Calculus III (19)

SMK level (n = test takers) # of physics credit hours GPA (SD)	**Average MOSART test score (%) M (SD) E**	**asier concepts (MOSART test item number with at least 90% of correct responses)**	**Persistent misconceptions (lowest scoring MOSART test item number)**	**Most commonly taken physics courses (% with course in their transcripts)**	**Most commonly taken math courses (% with course in their transcripts)**
Medium level					
Group 3 (*n* = 8) CH = 17–24 Mean Physics GPA = 3.20 (0.48) Mean Math CH = 22.25 (11.08) Mean Math GPA = 3.14 (0.57)	84 (9.80)	Electrical conductivity (2, 24) Gravitational force (8) Newton's laws of motion (9) Electromagnetic waves (11) Quantization of energy (18) Laws of thermodynamics (20) Electric force (23)	Newton's laws of motion (6)	Modern Topics: Physics and Astronomy (50) General Physics I (100) General Physics I Lab (88) General Physics II (88) General Physics II Lab (88) General Physics III (88) General Physics III Lab (75) Mechanics (25) Concepts of Modern Physics (25)	College Algebra (25) Trigonometry (38) Calculus I (88) Calculus II (88) Calculus III (75)

SMK level (n = test takers) # of physics credit hours GPA (SD)	Average MOSART test score (%) M (SD) E	asier concepts (MOSART test item number with at least 90% of correct responses)	Persistent misconceptions (lowest scoring MOSART test item number)	Most commonly taken physics courses (% with course in their transcripts)	Most commonly taken math courses (% with course in their transcripts)
High level					
Group 4 (*n* = 16) CH = 25+ Mean Physics GPA = 3.36 (0.32) Mean Math CH = 21.25 (6.15) Mean Math GPA = 3.30 (0.41)	92 (6.00)	Electromagnetic waves (1, 11, 15) Electrical conductivity (2, 24) Gravitational force (8) Electric force (4, 23) Wave properties (5) Conservation of energy (7, 10, 21) Newton's laws of motion (9, 13) Electromagnetism (16) Quantization of energy (18) Laws of thermodynamics (20, 22, 25)	Newton's laws of motion (6) Quantization of energy (17)	Modern Topics: Physics and Astronomy (81) General Physics I (88) General Physics I Lab (81) General Physics II (94) General Physics II Lab (81) General Physics III (88) General Physics III Lab (88) Electrical and Electronic Circuits (81) Mechanics (94) Lasers and Optics (31) Concepts of Modern Physics (50) Thermal Physics (94) Experimental Physics I (81) Experimental Physics II (44) Electromagnetic Theory (81) Optics and Electromagnetic Waves (63) Quantum Mechanics (75) Atoms, Nuclei, and Particles (44)	Calculus I (75) Calculus II (88) Calculus III (94) Differential Equations (88) Modern Algebra (63) Linear Algebra/ Matrix Theory (81)

SMK level (n = test takers) # of physics credit hours GPA (SD)	**Average MOSART test score (%) M (SD) E**	**asier concepts (MOSART test item number with at least 90% of correct responses)**	**Persistent misconceptions (lowest scoring MOSART test item number)**	**Most commonly taken physics courses (% with course in their transcripts)**	**Most commonly taken math courses (% with course in their transcripts)**
Overall					
All (*n* = 96) Mean Physics CH = 16.06 (14.15) Mean Physics GPA = 3.12 (0.57) Mean Math CH = 11.35(8.82) Mean Math GPA = 3.23 (0.66)	74 (15.59)	Electromagnetic waves (1, 11) Electrical conductivity (2, 24) Gravitational force (8) Newton's laws of motion (9) Electromagnetism (19) Laws of thermodynamics (25)	Newton's laws of motion (6, 13) Wave properties (14) Quantization of energy (17)	Elementary General Physics I (58) Elementary General Physics II (48) General Physics I (35) General Physics I Lab (31) General Physics II (33) General Physics II Lab (28) General Physics III (25) General Physics III Lab (24)	College Algebra (19) Trigonometry (15) Calculus I (66) Calculus II (40) Calculus III (38) Differential Equations (27)

Supplemental Material

Table SM-1

Comparison of Undergraduate and MAT Teacher Preparation Programs

Program	**Undergraduate**	**MAT**
Science Coursework	***Prior and concurrent to acceptance:*** Sufficient science coursework for a Nebraska secondary science teaching endorsement (24 credit hours in one area and another 12 hours among the other three areas).	***Prior to Acceptance:*** Undergraduate major in one area of science; some MA students have graduate-level science coursework or an advanced degree.
Education Coursework	***Pre-professional Education Coursework (including the common coursework with *):*** Foundations of Education; Adolescent Development & Practicum (13 credit hours)	***MAT Coursework:*** History and Nature of Science or Reading in the Content Areas; Teaching ELLs in the Content Area; Intro to Educational Research; Curriculum Theory; Teacher Action Research Project
Common Coursework	Accommodating Exceptional Learners, Adolescent Development* Science Teaching Methods (two classes, each with a practicum experience) Multicultural Education* or Pluralistic Society	
Resulting Degree	BA Secondary Science Education	MA with emphasis in science teaching

Table SM-2

Percentage of Correct Responses on the MOSART Chemistry (9-12) Test

Item	Question	Percentage of correct response					
		Students (Reported sample by test developers)	Participants in this study				
			0-8 credit hours (*n*=10)	9-16 credit hours (*n*=64)	17-24 credit hours (*n*=10)	25+ credit hours (*n*=11)	Total (*n*=97)
1	The chemical reaction of photosynthesis naturally occurs in the presence of sunlight because the light: D. Provides the energy to start the reaction.	D: 79% (n=3700)	100	88	100	100	92
2	What general shape will CCl_4 most likely have? C. Tetrahedral	C: 54% (n=1000)	90	89	91	100	91
3	Of the following, which are linked to chemical reactions in humans? A. Digestion B. Taste C. Vision E. a, b, and c	E: 20% (n=1219)	40	46	73	73	52
4	What is in between the electrons and nucleus of an atom? A. Nothing	A: 40% (n=269)	60	68	82	73	69
5	Chemists say that when these two atoms react the Na outer electron is: (Na and Cl Lewis dot diagrams) B. Transferred	B: 26% (n= 577)	60	60	91	100	68
6	The charge in a nucleus of an atom is: C. Positive	C: 30% (n=1447)	80	80	64	91	79
7	The rightmost column of the Periodic Table includes the noble gases, all of which E. Have filled electron shells.	E: 71% (n=485)	70	92	100	100	92
8	Which of the compounds below is	D: 21%	20	69	73	91	67

	most likely to have a dipole moment (be polar)? 1. H – F 2. O = C = O 3. O / \\ H H E. 1, 2, and 3	(n=576)					
9	If you were to hammer some gold into a thin sheet, the atoms: D. Are unchanged	D: 38% (n=891)	40	82	45	82	73
10	A portion of the Periodic Table is shown below. N O P S Which element(s) has exactly one more outermost electron than element N? C. O and S	C: 30% (n=552)	80	78	55	73	75
11	Which of the equations below best represents atoms in a fusion reaction? A. See figures on the test	A: 30% (n=890)	70	68	73	91	71
12	A sample of which of the following substances contains some kind of bond? D. Both (Cu and Co).	D: 21% (n=528)	30	46	9	45	40
13	When water goes from solid to liquid, the distances between the three atoms within a molecule: C. Don't change.	C: 20% (n=703)	40	74	82	82	72
14	The isomers of pentane always have the same: C. Formula	C: 39% (n=890)	40	86	100	100	85
15	Following a nuclear reaction that releases energy, the total particle mass is: C. Is slightly less than the original.	C: 46% (n=1454)	60	38	45	73	45
16	The Periodic Table is arranged according to the: A. Number of protons in each	A: 89% (n=674)	100	98	100	100	99

	element's atoms.						
17	The diagram below shows the reaction between hydrogen and iodine. The reaction between hydrogen and iodine B. Releases heat energy.	B: 52% (n=925)	70	78	82	100	80
18	Enzymes in your body will: A. Increase the chance that two different molecules will touch and react with each other.	A: 40% (n=296)	50	69	82	100	72
19	One isotope of oxygen differs from another isotope of oxygen in: C. The mass.	C:27% (n=267)	60	65	73	91	68
20	If the nucleus of an atom was left undistributed for several years, which of the following would mostly happen? E. Nothing.	E: 64% (n=576)	100	85	91	82	87
21	Which of the following best describes a sample of a radioactive element? B. It changes into a different element as time goes by.	B: 20% (n=890)	80	69	82	82	73
22	Atoms can interact with one another by sharing: C. Electrons	C: 80% (n=579)	90	98	100	100	98

Table SM-3

Percentage of Correct Responses on the MOSART Physics (9-12) Test

Item	Question	Percentage of correct response					
		Students (Reported sample by test developers)	Participants in this study				
			0-8 credit hours (*n*=25)	9-16 credit hours (*n*=45)	17-24 credit hours (*n*=7)	25+ credit hours (*n*=9)	Total (*n*=91)
1	After a light wave has reflected from a smooth glass mirror hanging on a wall: A: it may be traveling in a different direction.	A: 67% (*n*=327)	92	96	86	100	95
2	Copper is a good electrical conductor because: D: electrons flow readily through it.	D: 86% (*n*=600)	96	96	100	100	97
3	An astronaut weighs 150 pounds on the surface of the Earth. How much would he weigh standing on a planet exactly like Earth except it is one-half as far from the Sun? B: 150 pounds.	B: 34% (n=233)	72	73	86	91	76
4	Two positively charged objects are located 1 cm apart. If the distance between the objects is doubled to 2 cm, the electric force between the objects: D: is one-fourth as strong.	D: 30% (n=357)	52	48	71	100	57
5	If the amplitude of a wave were increased: D: the energy transferred would increase.	D: 32% (n=357)	60	50	86	91	60
6	If the cart is being pulled simultaneously toward points 2, 3 and 4, toward which point will the cart most likely move? (See diagram in item on test.) E: The cart won’t move.	E: 31% (n=357)	36	21	71	9	27

7	A car with a full tank of gasoline is driven non-stop until the tank is empty. What happened to the gasoline's energy? D: Some moved the car, some powered the car’s equipment, some heated the engine, and some went into noise and friction.	D: 47% (n=788)	72	81	86	91	80
8	A roller coaster cart goes through a loop as shown below. At which point is there no gravity? (See diagram in item on test.) E: Gravity is the same everywhere.	E: 72% (n=603)	96	98	100	100	98
9	If you are at rest and are watching a moving object and it suddenly changes direction, you can be sure that the object: A: was acted on by a net force.	A: 74% (n=368)	96	92	100	100	95
10	A battery works by: C: converting chemical energy into electrical energy.	C: 57% (n=608)	88	85	86	100	88
11	People wear light-colored clothes in the summer because the clothes: A: reflect more radiation.	A: 88% (n=2130)	100	98	100	100	99
12	In a hydrogen atom, an electron orbits a proton. What is true about the forces between the electron and proton? C: The electric force is stronger than gravity.	C: 13% (n=513)	64	46	86	91	59
13	A baseball is hit into the air. At the top of its trajectory: B: the baseball is subject to a net force.	B: 27% (n=421)	40	25	71	82	40
14	Light waves: D: oscillate at right angles to the direction they are moving.	D: 23% (n=420)	32	35	71	82	43
15	How do radio waves and x-rays differ? C: They have different wavelengths.	C: 41% (n=420)	40	54	71	100	57
16	An electric charge moving at right	A: 46%	36	50	57	91	52

	angles to magnetic field lines experiences: A: a force at right angles to its direction of motion.	(n=417)					
17	If you looked at a continuous spectrum in a darkened room through a red filter, the spectrum would appear: B: black except the red portion would remain red.	B: 8% (n=517)	20	40	86	27	36
18	Why does each kind of atom have a unique emission spectrum? A: The lines represent the differences between quantized energy levels for that atom.	A: 29% (n=413)	48	58	100	100	64
19	The primary purpose of an electric motor is to convert: C: electric energy to mechanical energy.	C: 56% (n=655)	100	90	86	82	91
20	Ice is placed in a container which is heated steadily and continuously. The ice is initially below its freezing point, and during the heating process it turns to water and finally the water boils. The graph below shows how the temperature varies with time during the heating process. Four distinct portions of the graph are labeled 1, 2, 3 and 4. Which portions represent phase changes? (See diagram in item on test.) B: Portions 2 and 4 only.	B: 46% (n=399)	72	85	100	100	85
21	An inventor wants to develop a light that uses 100% of the electricity it receives to emit visible light. What would a scientist say about this idea? E: Such a light is impossible to build.	E: 37% (n=515)	76	77	100	91	80
22	Metal block 1 is at a temperature of 100 F; identical metal block 2 is at 20 F. If the blocks are in contact, as shown below, what will happen?	A: 49% (n=420)	68	83	86	100	81

	(See diagram in item on test.) A: Only heat will flow from block 1 to block 2.						
23	If there is an electric force: B: there must be two charged objects, but they do not have to touch.	B: 44% (n=515)	60	79	100	100	78
24	Materials that make good electrical conductors must: C: allow electrons to flow easily.	C: 71% (n=368)	80	98	100	91	92
25	Four containers of water with different temperatures as shown below are placed on a table in a room where the temperature is 25 C. After four hours, which beaker of water will have lost the most heat energy to the room? (See diagram in item on test.) A: A	A: 81% (n= 843)	88	92	71	100	90

Table SM-4

*Undergraduate Chemistry Coursework and Topics**

Courses	Topics
General Chemistry I (CHEM 110/CHEM 113)	Lecture and laboratory serving as an introduction to chemical reactions, the mole concept, properties of the states of matter, atomic structure, periodic properties, chemical bonding, acid-base reactions, and molecular structure.
General Chemistry II (CHEM 113/CHEM 114)	Lecture and laboratory serving as an introduction to intermolecular forces, kinetics, oxidation-reduction reactions, chemical equilibrium, thermodynamics, and electrochemistry.
Organic Chemistry I (CHEM 251)	Chemistry of carbon compounds. Applications to the biological sciences, agriculture and pre-professional programs including premedical and pre-dental. Emphasizes basic principles.
Organic Chemistry Lab (CHEM 253)	Basic techniques of organic chemistry. Structure, identification, physical properties of compounds, molecular modeling, and introduction to the spectroscopic characteristics of organic compounds.
Organic Chemistry II (CHEM 252)	Chemistry of carbonyl compounds. Aspects of aromatic chemistry, heterocycles, carbohydrates and nitrogen compounds, with some emphasis on the organic compounds found in nature.
Organic chemistry Lab II (CHEM 254)	Synthesis of representative organic compounds. Qualitative analysis of organic compounds. Naturally occurring compounds.
Quantitative Analysis (CHEM 221)	Introduction to principles of quantitative analytical chemistry, including ionic equilibria and solution stoichiometry. Lab instruction includes titrimetry, gravimetry, separations, and use of pH meter and spectrophotometer.
Physical Chemistry (CHEM 471)	Conceptual and mathematical foundations of classical and statistical thermodynamics. Applications of thermodynamics to phase and chemical equilibria. Thermodynamics of solutions of small molecules and of polymers. Biological applications of thermodynamics. Introduction to chemical and biochemical spectroscopy.
Biochemistry and Lab (CHEM 435 & 433)	Fundamentals of chemical biology with an emphasis on the underlying principles of biomolecular structures, macromolecular-small molecule interactions, including mechanistic aspects of enzymes and cofactors, use of modified enzymes to alter biochemical pathways, and the use of chemical tools for understanding biological processes. Introduction to techniques used in biochemical and biotechnology research, including measurement of pH, spectroscopy, analysis of enzymes, chromatography, fractionation of macromolecules, electrophoresis, and centrifugation.
Analytical Chemistry and Lab (CHEM 421 & 423)	Chemical and physical properties applied to quantitative chemical analysis. Solution equilibria, stoichiometry, and instrumental theory and techniques. Applications of analytical chemical principles to laboratory problems. Introduction to typical inorganic chemistry laboratory techniques through the preparation and characterization of inorganic compounds.

Inorganic Chemistry and Lab (CHEM 441 & 443)	Structure, bonding, properties, and reactions of inorganic compounds with emphasis on the relationships and trends that are embodied in the periodic table of the elements.

* From 2018-19 Undergraduate Bulletin.

Table SM-5

*Undergraduate Physics Coursework and Topics**

Courses	Topics
Descriptive Physics (PHYS 115)	Qualitative approach to physics for the non-science major that emphasizes concepts and how they are used to understand the everyday physical world. Newton's description of motion and forces, the atomic view of matter, kinds and transformations of energy, the nature of electricity and magnetism, sound and light waves, and subatomic particles. Some topics selected according to student interest. Recommended for all students wanting a nonmathematical look at basic discoveries of physics.
Elementary General Physics I (PHYS 141/141H)	Algebra-based course. Mechanics, heat, waves and sound.
Elementary General Physics II (PHYS 142/142H)	Continuation of PHYS 141. Electricity, magnetism, optics, relativity, atomic and nuclear physics.
General Physics I (PHYS 211/211H)	Calculus-based course intended for students in engineering and the physical sciences. Mechanics, fluids, wave motion, and heat.
General Physics I Lab (PHYS 221)	Experiments in mechanics, heat and wave motion.
General Physics II (PHYS 212/212H)	Continuation of PHYS 211. Electricity, magnetism, and optics.
General Physics II Lab (PHYS 222)	Laboratory experiments in electromagnetism and optics.
General Physics III (PHYS 213/213H)	Continuation of PHYS 212. Relativity, quantum mechanics, atoms, and nuclei.
General Physics III Lab (PHYS 223)	Experiments in atomic and nuclear physics.
Modern Topics in Physics and Astronomy (PHYS 201)	Seminar/workshop that introduces students to topics in modern physics research in basic and applied areas. Students given an understanding of how their studies relate to current progress in physics and astronomy and to prepare for careers in physics-related disciplines.
Electrical and Electronic Circuits (PHYS 231)	Diode, transistor, and operational amplifier circuits and analog applications; gates, flip-flops, and elementary digital electronics.
Mechanics (PHYS 311)	Review of vector operations and of the kinematics and dynamics of a particle. Dynamics of a system of particles, motion of rigid bodies, central force problems, collisions, Lagrangian techniques, oscillations, and coupled oscillators.
Physics of Lasers and Modern Optics (PHYS	Physical principles and techniques of lasers and modern optics. Emphasis on practical experience with state-of-the-art techniques and applications.

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Concepts of Modern Physics (PHYS 361)	Some of the concepts and ideas underlying modern areas of physics through readings from non-technical works by noted physicists and science writers. Includes quantum mechanics, relativity, cosmology, chaos, and examples of modern technology.
Thermal Physics (PHYS 431)	Thermal phenomena from the point of view of thermodynamics, kinetic theory, and statistical mechanics.
Experimental Physics I (PHYS 441)	Methods and techniques of modern experimental physics.
Experimental Physics II (PHYS 442)	Continuation of PHYS 441.
Electromagnetic Theory (PHYS 451)	Theory of electric and magnetic fields and their interaction with charges and currents, Maxwell's equations, electric and magnetic properties of matter.
Optics and Electromagnetic Waves (PHYS 452)	Production of electromagnetic waves, wave guides and cavities, properties of waves, plane waves, reflection and refraction, interference and coherence phenomena, polarization. Optical properties of matter.
Quantum Mechanics (PHYS 461)	Basic concepts and formalism of quantum mechanics with applications to simple systems.
Atoms, Nuclei, and Particles (PHYS 462)	Basic concepts and experimental foundation for an understanding of the physics of atoms, nuclei, and elementary particles.

* From 2018-19 Undergraduate Bulletin.

Table SM-6

*Undergraduate Mathematics Coursework and Topics**

Courses	Topics
College Algebra (MATH 101)	Real numbers, exponents, factoring, linear and quadratic equations, absolute value, inequalities, functions, graphing, polynomial and rational functions, exponential and logarithmic functions, system of equations.
Trigonometry (MATH 102)	Trigonometric functions, identities, trigonometric equations, solution of triangles, inverse trigonometric functions and graphs.
College Algebra and Trigonometry (MATH 103)	First and second degree equations and inequalities, absolute value, functions, polynomial and rational functions, exponential and logarithmic functions, trigonometric functions and identities, laws of sines and cosines, applications, polar coordinates, systems of equations, graphing, conic sections.
Calculus for Management and Social Sciences (MATH 104)	Rudiments of differential and integral calculus with applications to problems from business, economics, and social sciences.
Calculus I (MATH 106)	Functions of one variable, limits, differentiation, exponential, trigonometric and inverse trigonometric functions, maximum-minimum, and basic integration theory (Riemann sums) with some applications.
Calculus II (MATH 107/107H/107R)	Integration theory; techniques of integration; applications of definite integrals; series, Taylor series, vectors, cross and dot products, lines and planes, space curves.
Calculus II (MATH 208/208H)	Vectors and surfaces, parametric equations and motion, functions of several variables, partial differentiation, maximum-minimum, Lagrange multipliers, multiple integration, vector fields, path integrals, Green's Theorem, and applications.
Differential Equations (MATH 221/221H)	First- and second-order methods for ordinary differential equations including: separable, linear, Laplace transforms, linear systems, and some applications.
Introduction to Modern Algebra (MATH 310/310H)	Elementary number theory, including induction, the Fundamental Theorem of Arithmetic, and modular arithmetic. Introduction to rings and fields as natural extension of the integers. Particular emphasis on the study of polynomials with coefficients in the rational, real, or complex numbers.
Linear Algebra/Applied Linear Algebra (Matrix Theory) (MATH 314/314H)	Fundamental concepts of linear algebra, including properties of matrix arithmetic, systems of linear equations, vector spaces, inner products, determinants, eigenvalues and eigenvectors, and diagonalization.

* From 2018-19 Undergraduate Bulletin.

Figure SM-1

Function of Physics Credit Hours and Mathematics GPA to the Likelihood of Passing or Failing the MOSART Physics (9-12) Test