JOURNAL OF CHEMICAL EDUCATION

Article

Cite This: J. Chem. Educ. 2018, 95, 2134−2140

pubs.acs.org/jchemeduc

A Nonlinear, "Sticky" Web of Study for Chemistry: A Graphical Curricular Tool for Teaching and Learning Chemistry Built upon the Interconnection of Core Chemical Principles

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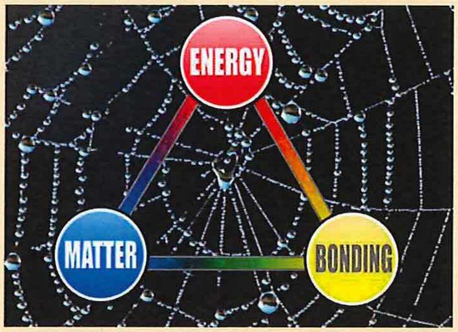
Supporting Information



ABSTRACT: The National Research Council's Framework for K−12 Science Education articulates the need to shift science curricula from being a collection of discrete facts to curricula that integrate core ideas and practices. To help teachers better integrate content and to respond to expressed frustration regarding extensive lists of standards often presented as collections of isolated topics in prescribed courses of study, we developed a web of study approach to general chemistry curricula. Instead of a traditional linear course of study for which lists of standards tend to shift teaching and learning toward coverage, the web of study approach emphasizes integration of concepts by which learners build a coherent and self-consistent body of knowledge. Using both spatial and color-coded relationships, a general chemistry course is mapped onto the triad of primary concepts, Matter−Energy−Bonding, each represented as a primary color. Subtopics, traditionally identified in bulleted lists of standards, are graphically placed and color coded with secondary colors to provide a visual representation of an entire general chemistry course. The nonlinear web of study approach offers a greater "sticking capacity", with deep learning achieved by teacher and learner as they reflect on how any given topic, concept, or practice relates to the entire web. While providing important contexts to understand the relevance and relationships of new material being learned, this visual representation of content facilitates seeing and thinking about interrelationships, provides a framework with which to formulate logical explanations of observed phenomena, and stimulates the most fundamental process of science: asking new questions.

KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Curriculum, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, Learning Theories, Standards National/State*

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■ INTRODUCTION

A persistent challenge in science education is finding an appropriate balance between the amount of content to be covered vs the depth to which that content should be understood. Addressing this challenge in his 1916 essay, "The Aims of Education", Whitehead enunciated "two educational commandments: Do not teach too many subjects, and again, What you teach, teach thoroughly".[1] A century later, the National Research Council's Framework for K−12 Science Education (NRC Framework) again suggests that the emphasis on discrete facts, with a focus on breadth over depth, does not provide students with engaging opportunities to experience how science is actually done.[2] In our professional development workshops with high school chemistry teachers in North Carolina, teacher responses continue to indicate the "breadth vs depth dichotomy" is a major barrier to quality instruction. A perceived pressure to cover the 13 pages of bulleted standards in the state's required standard course of study[3] is tremendous.[4] When lists of standards/topics become too extensive, the course focus shifts toward coverage rather than understanding.[4−6]

While lists of essential standards can be overwhelming, one also can make compelling arguments for the relevance of almost every topic. To address the "breadth vs depth dichotomy", the Next Generation Science Standards (NGSS),[7] developed out of the NRC Framework,[2] redirected more traditional broad lists of standards toward an integration of three dimensions of learning (core ideas, cross cutting, and practices). When teaching from the perspective of discovery, the practice of using data, measurement, and information can readily integrate multiple core ideas, while building deeper understanding by their application to relevant contexts.[1,8,9] Nevertheless, when unpacking the NGSS with teachers, we continue to observe a strong bias toward a mindset of coverage of the lists of performance expectations[10] and evidence

Received: November 15, 2017
Revised: September 5, 2018
Published: October 18, 2018

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DOI: 10.1021/acs.jchemed.7b00878
J. Chem. Educ. 2018, 95, 2134−2140

statements,[11] with much greater uncertainty about how to implement integration of ideas.

The expectation to cover lists of standards also frequently shifts activities, evaluations, and assessments to be narrowly focused on performance linked to standards as opposed to meaningful learning.[5,12] Herein it is useful to consider the distinction between performance vs learning goals articulated by Dweck as a growth-mindset approach to pedagogy.[13,14] The purpose of *performance goals* is to validate one's ability, whereas *learning goals* focus on the acquisition of new knowledge or skills to increase one's ability. Notably, through multiple studies, Dweck and co-workers demonstrated that a learning-goal approach to education (ref 14, p 552):

> *exerts a positive influence on both intrinsic motivation and performance when individuals encounter prolonged challenge or setbacks. In addition, although performance goals that are focused on validating ability can have beneficial effects on performance when individuals are meeting with success, these same goals can predict impaired motivation and performance after setbacks.*

The distinction between performance and learning finds an analogy in the framework of constructivism for which (ref 12, p 136)

> *During "strong" acts of construction learners connect new information with existing ideas to form meaningful knowledge that has a measure of internal coherence, can be integrated across topics, and can itself act as a tool for further constructions. "Weak" acts of construction are more arbitrary, only loosely connecting new information with existing ideas; those constructions are fragile, transient, and applicable only within a narrow range of contexts, and they often sustain themselves only through brute force of memorization.*

In our teaching at the high school level (K.A.N.) and collegiate level (J.D.M.), we regularly observe such student fragility associated with a performance mindset, manifest as a perceived inability to approach a problem for which practice examples have not been provided. We further recognize that the persistence and intrinsic motivation associated with a learning-goal approach to education is one of the foundational goals of the NRC Framework.[2] Whether teaching from a contextual,[15,16] model-based,[17] application-based,[9,18] or more fundamental science perspective,[2,5,7,19] literature and our classroom experience demonstrate that it is necessary to develop more explicit strategies to integrate conceptual content to achieve learning as opposed to mere performance.[4,12−14] Integration of fragmented content into coherent knowledge structures is, after all, the primary distinguishing feature between the novice and expert.[20] Practical strategies to teach with concept integration leading to deeper, more reflective learning, however, remain a constant challenge.

■ SYSTEMS THINKING: BEYOND A LINEAR COURSE OF STUDY

As part of ongoing professional development work with high school chemistry teachers in North Carolina, we began to consider ways to approach the state required standard course of study[3] in a manner that focused on integrated and deeper learning. In contrast to the linear modality implied by a course of study, we explored the conception of a web of study.

We drew inspiration from spider webs, for which radial themes connect to a central core element and are interconnected with tangential strands. A web construction, built with the same fine strands of silk, has a much greater chance of having things stick than if the silk remained a single linear strand. There is literature precedent for the concept of a web, or interwoven connection of ideas as an effective means of instruction.[15,19] Furthermore, framing instruction by integrating fragments of knowledge around sets of core principles is consistent with established learning theory, which demonstrates the creation of short-term memory, movement of information from short- to long-term memory, and retrieval of information from long-term back to working memory are all facilitated by organizing information into "chunks".[21−23] Specific to the field of chemistry, however, there is a range of perspectives as to the number and focus of effective curricular "chunks", alternatively framed as core ideas,[2,5] anchoring concepts,[24] AP big ideas,[25] central ideas,[26] etc.

Our initial attempt at creating a web of study focused around a core theme of bonding. A group of 6−10 teachers worked together parsing the North Carolina Standard Course of Study[3] to identify how each of the essential standards related to bonding. Atomic structure, energy, the periodic table, equilibria, acids/bases, solubility, phase transitions, chemical reactions... just about everything in chemistry relates to bonding. Some topics are needed to explain bonding, while for others, trends in bonding are needed to understand the topic. Sticky notes with each essential standard were arranged and rearranged as our first web was attempted. This process is analogous to concept mapping strategies described in the NGSS[27] and other references.[5,16,24,28]

The process of evaluating the entire set of essential standards from the perspective of a core concept or common theme can be a powerful exercise for a professional learning team.[5,16,24,27,28] Intentionally developing a holistic view of a course greatly facilitates teaching interrelationships of concepts, and reduces the probability of teaching isolated topics for performance coverage. Nevertheless, our resulting product, like many concept maps, remained heavily textual with numerical identifiers, being tied to the list of standards. Connector lines were drawn stemming from rich discussions of, for example, how the strength of bonding/intermolecular forces informs the basis of solubility rules. Those web-lines connecting core ideas to numerous standards in a concept map are informative to the person or group who determines the connection but often add complexity for someone not involved in the process, and can overwhelm new learners, i.e., students. We concluded after this attempt, like the authors of the American Chemical Society concept map, that "a static visual depiction that captures this level of detail becomes hopelessly complex".[24] Herein our challenge was to develop a better way to make relationships between standards visible.

Described below as the Web of Chemistry, we introduce a color-coding scheme to visualize the relationships between topics, a strategy pioneered by the transformative work of Joseph Priestley, who, in the mid 1700s, dramatically transformed pedagogical methods through concept charts.[29] Priestley, a scientist, historian, and theologian, was also an innovative educator and strong advocate for public education. Approaching the pedagogy of history from the perspective of a scientist, he translated tabulations of historical data into a visual medium. Priestley uniquely organized information to graphically represent time and concept or region, and then introduced color so that noncontiguous but related regions could be readily identified. These charts, most notably the

DOI: 10.1021/acs.jchemed.7b00878
J. Chem. Educ. 2018, 95, 2134−2140

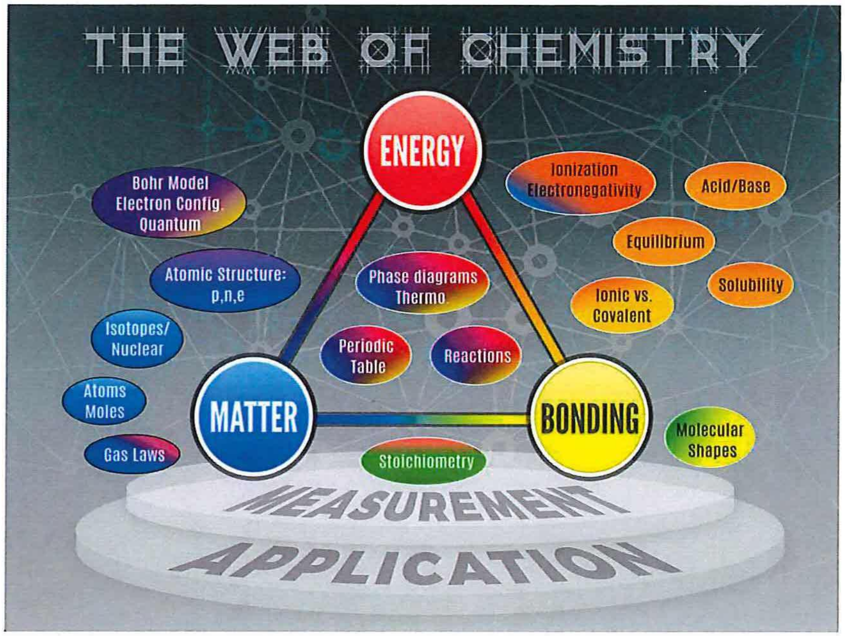

Figure 1. Web of Chemistry. A curricular map graphically and colorimetrically representing the conceptual integration of a general chemistry course.

Chart of Biography (1765) and the *New Chart of History* (1769), were recognized to be invaluable for a child learning history as well as to the scholar who, with the visual representation of information, is forced to understand history from a systemic perspective as opposed to a collection of isolated facts. As such, these charts became transformational to pedagogy in the late 18th and early 19th centuries.[29] Priestley's vision to create visual pedagogical tools to facilitate systemic, integrated, deep learning, as opposed to tabulations of isolated facts and concepts, was the same stimulus that inspired our pursuit of the Web of Chemistry. Furthermore, both Priestley's and our use of color to relate concepts that are noncontiguous by placement on the physical chart differentiate his charts and our conception of a web of study, from more traditional concept maps.

■ THE WEB OF CHEMISTRY

The Web of Chemistry presented in Figure 1 represents the current version from our iterative web development process. (A black-and-white version that can be reproduced for classroom use in which students can add color as they begin to understand concept interrelationships and a developmental narrative including earlier web versions are provided as Supporting Information.) For this version, instead of creating a web centered around a single core principle, our continuing work to find organizing themes in the content of the North Carolina Standard Course of Study[3] converged around the core principles of matter, energy, and bonding. These three core principles are aligned with portions of the NRC Framework (PS1, Matter and Interactions; PS3, Energy; and PS2, Motion and Stability: Forces and Interactions).[2,5,7] Essentially no topic in chemistry can be understood without considering its relationship to these three concepts. We chose not to expand the chart's complexity to the 6 AP Chemistry big ideas,[25] or the 10 anchoring concepts from the ACS concept map,[24] because, for example, we consider reactions and chemical/physical properties to be a result of the respective interactions of matter, bonding, and energy, rather than independent fundamental concepts. We recognize that, for a more advanced course, there would be value in adding time as a fourth fundamental concept, which, when integrated with matter, energy, and bonding, informs the concepts of mobility and reaction kinetics.

This chart was specifically designed for North Carolina's high school chemistry curriculum. However, as they observed the evolution of this project, undergraduate and graduate students working in J.D.M.'s research lab suggested this tool would be invaluable at the college level as well. Thus, J.D.M. also incorporated the use of this Web of Chemistry tool into his second semester undergraduate general chemistry course for majors.

For this Web of Chemistry we graphically organize the essential standards around the matter–energy–bonding triad. Each foundational concept is represented as one of the primary colors. Each of the subtopics reasonably covered in a high school chemistry course are spatially distributed and color coded with secondary colors representing conceptual interrelationships (i.e., blue matter + red energy = purple, blue matter + yellow bonding = green, and yellow bonding + red energy = orange).

As designed for a high school chemistry course, we chose atomic structure as a place to begin a journey through the Web of Chemistry. The concept of the atom, the concept of the mole, as well as a high school level understanding of nuclear chemistry are relatively independent of bonding and energy and thus are represented in their single primary color (blue). To more deeply grasp atomic structure, however, it is important to discover/understand the interrelationships of matter and energy. Hence, the purple color designates the combination of the blue matter and red energy. Additionally, atomic and electronic structure is what makes chemical bonding possible and provides foundational concepts to

DOI: 10.1021/acs.jchemed.7b00878
J. Chem. Educ. 2018, 95, 2134–2140

understand different types of bonding. Hence, yellow shading is added to designate this relationship.

The periodic table occupies a unique place in the center of the matter—energy—bonding triad. Its earliest origins came from observation of periodic trends in the properties of matter, specifically, molar volumes of elements and properties of gases. These concepts were refined by insight from chemical reactions. Amazingly, Mendeleev's periodic table was published in 1871, 25 years before the electron was discovered in 1896. However, because of the energy—matter relationship, those historically observed periodic trends become experimental measurements of quantum mechanics. The quantum concepts of atomic orbitals, energy levels, and electron configurations provide the modern description of the periodic table, which is fundamental for descriptions of bonding.

The concepts of ionization (formation of ions) and electronegativity describe the relative energy difference between different atoms and, thus, determine the various ways atoms become attached through bonding to create molecules or lattices. In the Web of Chemistry, ionization and electronegativity, along with ionic vs covalent bonding, are colored orange, because of their energy (red) and bonding (yellow) relationships. Equilibria, too, effectively described through discovery of strong and weak acid/base properties or solubility, are best understood by considering how the energy (red) applied to a system impacts the bonding (yellow) and intermolecular forces that hold matter together, and thus also are represented as orange.

Phase changes and chemical reactions occupy central positions in the matter—energy—bonding triad. By adding or removing energy from a system, bonds are broken, made, or rearranged, resulting in changes in the state of matter. Similarly, chemical reactions either require or give off energy as bonds are broken and made during the rearrangement of atoms and molecules from their reactant state to product state.[19]

Stoichiometry is the method to keep track of all the components of a chemical reaction to ensure the chemistry "checkbook" is balanced. Throughout a chemical reaction, it is not possible to create or destroy matter (blue), but its bonding (yellow) is frequently rearranged from one type of molecule or material to another. Thus, stoichiometry is represented as green. While stoichiometry is significantly used to keep track of atomic distributions between reactants and products, it is important to remember that energy (red), required or given off, is also part of a chemical reaction, and thus requires its own bookkeeping. We believe it is extremely important not to teach stoichiometry as an independent unit. Instead, stoichiometry should be taught by its use, integrated throughout all topics.

Underlying this entire Web of Chemistry must be a foundation of measurement. Consistent with the "Learning Cycle" theory of instruction based on exploration, invention, and discovery,[8] every topic taught throughout a course in chemistry should include students making measurement(s) from which scientific principles are derived. Critical to using measurement as a foundation for teaching/learning is an understanding that no number can stand alone; it must always be associated with units. It is the units of measurement that inform science. In math, for example, 2 + 2 = 4. But this is not necessarily so in chemistry where two atoms of hydrogen and two atoms of oxygen equal one molecule of hydrogen peroxide, H_2O_2. So, while there are four atoms, they still are of two different types that form one molecule. Thus, without specifying units a chemist does not know if $2_{atoms} + 2_{atoms} = 4_{atoms}$, or, if $2H_{atoms} + 2O_{atoms} = 1H_2O_{2molecule}$.

When making measurements, it is important for students to refine skills in accuracy and precision, learning to use the right scale and units to communicate meaningful information. This translation of measurements into meaningful information serves as a useful basis for teaching significant figures. Significant figures are simply the correct choice of unit and scale for the measurement and the scientific question being asked, not a list of rules. For example, it would make no sense to measure or report the distance between Los Angeles and Washington, DC, in kilometers to a precision of six decimal places. That would be a measurement in millimeters. At the same time, it makes little sense to measure or report the size of an atom in meters because that would require nine zeros after the decimal point before you have meaningful digits. Thus, picometers (pm) or angstroms (Å) are preferred units to appropriately reflect significant figures of atomic scale measurements.

The Web of Chemistry also can be overlaid on a foundation of chemical contexts or applications. Numerous authors suggest that real-world context and/or specific applications provide a preferred format with which to teach students to connect ideas and to think/problem-solve like a chemist.[9,16,18,26] While numerous chemical concepts must be integrated to understand real-world applications and the context of chemistry, we believe concept integration is equally critical to understanding the fundamental concepts. Thus, we suggest a "both/and" as opposed to an "or" approach, with respect to fundamentals vs application/context.

■ USE AND EVALUATION OF THE WEB OF CHEMISTRY

In the classroom, the Web of Chemistry graphic, Figure 1, is effectively used as a large format poster hung in the classroom or as a PowerPoint slide. The graphic tool should be referenced often as you learn and teach chemistry. The Web of Chemistry is a tool intended to help make visible the rigorous teaching and learning process of knowledge acquisition, integration, and application. As with most effective pedagogical tools, use of the Web of Chemistry elicits a strategy of teaching[4] in which teacher and student engage in strong constructivist practice[12] whereby new information is connected with existing ideas, integrated across topics, and further stimulates the generation of novel constructions. Specifically, in our classes, we reference the visual of the web when new topics are introduced, when transitioning between topics, throughout discussions of specific content, and frequently direct students back to the web to help them build evidence-based explanations of phenomena. Normally, the teacher will initiate the discussion, but effective use of the tool is collaborative with students investing ideas and alternatives to push the thinking of both teacher and learner. Recognize that the first time you or a student sees the Web of Chemistry, you will not fully grasp all concepts or their significant relationships. Nevertheless, we find that challenging students (and teachers) to discover where and how the topic(s) of a given class period fit into the overall Web of Chemistry is more effective for learning than the common strategy of posting statements of standards or learning objectives in the front of the classroom each day. Expert scientists are still learning and exploring these relationships. However, as Priestley recognized, the power of graphical

DOI: 10.1021/acs.jchemed.7b00878
J. Chem. Educ. 2018, 95, 2134–2140

presentation of data and concepts is that it informs and challenges both the beginning learner and the scholar.[29] A web of study is a tool to help see the big picture as details are learned, and to ensure details are not isolated from the big picture.

It is important to emphasize that there is no one right path to discover and explore this Web of Chemistry. If you do not meander around and through the web, you are unlikely to really understand chemistry. Aspects of each topic deserve their own unique focus but must always be integrated with other components of the web. In her high school chemistry courses (both honors and AP), K.A.N. started with discovery of the atom and its atomic structure, gradually building through periodic trends to an understanding of bonding and reactivity. In the professional development workshops we offer for high school teachers, we use a similar path through the web. In his second semester undergraduate general chemistry course, J.D.M. started by reviewing how topics from the first semester syllabus mapped onto the Web of Chemistry, largely the left portion of Figure 1, and then led the course as a discovery process of how bonding and energy determine reactivity, the right portion of Figure 1. Regardless of whatever path you choose as a teacher, to use the web as we suggest, it is important to regularly step back to reflect on the whole web and how ideas are integrated to more fully grasp the diverse richness of chemistry.

Teacher Professional Development

To date, we have introduced the Web of Chemistry in five professional development workshops with groups of 5, 14, 26, 12, and 8 teachers, respectively. In open response questions, participants overwhelmingly suggested that the Web of Chemistry approach provides an excellent format for integrating chemistry concepts and enhancing student understanding. The greatest challenge expressed by teachers is summed up in the following evaluatory comment:

> *I hope we get to a point where the standards change, the state exam is wiped away or replaced, and we can get more freedom to teach this [web] concept. Unfortunately, I'm unsure of how practical it will be to teach the more in-depth material if teachers are going to continue to be graded based off student performance on the current standards and state testing.*

This highlights the challenge of performance vs learning discussed in the Introduction and is consistent with Windschitl's description of the political challenges to reform-oriented teaching.[12] However, our data presented below suggests the web approach to instruction has a substantial positive impact on standardized performance assessments.

Classrooms

K.A.N. has utilized the Web of Chemistry tool and style of teaching for three classes of honors chemistry (73 students), and two AP chemistry classes (37 students). These classes are taught on a 4 × 4 block schedule with the honors course completed in the fall semester, and the AP course conducted in the spring semester. With the web approach, K.A.N. observed students grasping more higher order thinking concepts and readily discovering connections across the entire course, rather than looking at a single unit at a time. For example, on their own, while constructing Lewis dot structures based on the atoms location on the periodic table, students independently recognized/discovered connections between molecular shapes, ionic properties, electronegativity, dipoles, trends on the periodic table, and how those aspects of molecular shape and bonding impact solubility. Later, when solution chemistry was the course focus, students reinforced their earlier observations, reviewed intermolecular forces, and built a greater depth of understanding of solubility, clearly much richer learning than memorizing a set of rules.

In response to an open-ended question in a survey of K.A.N.'s honors students who went on to take her AP course ($N = 37$), asking about what connections were made across the curriculum, 32% describe how bonding impacts properties, 27% describe how stoichiometry is "connected to everything", and 16% highlighted how equilibrium makes sense when connected to bonding and energy. Importantly, the linguistic structure in student responses is replete with "I" language describing self-ownership of learning, as opposed to teacher directed delivery.[30] When asked what was confusing about the Web of Chemistry tool, the most common response was that the web was "confusing before I knew what the terms on the tool meant. ... [But] when I realized how I could apply concepts to other concepts or other units we learned, it was awesome to know that everything connected". When asked how using the Web of Chemistry compared to past science course experiences, not only did students report "everything in this class connects while previous science classes seem disconnected", but 16% of the responses also suggested that using the Web of Chemistry tool allowed them to connect the content of this class to previous science and math classes and to real life. 89% of the respondents indicated that a tool like the Web of Chemistry would be useful for other classes.

Beyond instructor observation and the student response survey, a perspective on the effectiveness of the teaching strategy facilitated by the Web of Chemistry can be gleaned from an evaluation of K.A.N.'s honors chemistry students' scores on the standardized North Carolina Final Exam in Chemistry (NCFEC). While no single factor is a conclusive determinant of the effectiveness of a pedagogical intervention, implementation of the Web of Chemistry tool in the method we suggest, which requires a shift in teaching style that incorporates extensive reflection about the interrelationships of both content and pedagogy, was the primary variant between her prior classes and those of the 2017–18 academic year. A plot of the NCFEC performance of her classes compared with all chemistry students in the Wake County Public School System (WCPSS) and with those in the state of North Carolina is given in Supporting Information as Figure S.1. In years prior to K.A.N.'s implementation of the integrated teaching strategy facilitated by the Web of Chemistry, her students' average performance was 2–8% below that of the honors chemistry students in WCPSS, but 5–10% above statewide student performance. With implementation of the Web of Chemistry approach, 100% of her students passed the NCFEC, with the class average performance now 6% above WCPSS honors students and 17% above the state average.

At K.A.N.'s school, multiple sections of AP Chemistry were taught by the same two teachers during the Spring 2017 and 2018 school years. The primary variants between different years of AP classes were an increased number of sophomore students, and K.A.N.'s use of the Web of Chemistry approach in the Spring of 2018. In-class assessments were jointly prepared by both teachers and administered to all classes. Notably, while student performance of both teachers' classes was essentially equivalent in 2017, in 2018, K.A.N.'s students' in-class grades increased from a class average of 81% in 2017 to

DOI: 10.1021/acs.jchemed.7b00878
J. Chem. Educ. 2018, 95, 2134–2140

90% in 2018 while those of the other teacher were essentially unchanged. Similarly, in 2018 9/39 of KAN's students scored a 3 or higher on the Chemistry AP exam compared to 1/16 in 2017, whereas 3/18 in 2018 and 3/19 in 2017 of the other teacher's students scored 3 or higher on the AP exam. Both teachers noted a substantial difference in student engagement between their sections, with the web approach eliciting much greater student engagement.

These data notably contrast the concern about performance outcomes expressed in the teacher comment above, suggesting the web approach should not be adopted until state standards and assessments are changed. Instead, our data is consistent with the conclusions of Dweck, that instruction focused on learning "exerts a positive influence on both intrinsic motivation and performance".[14]

J.D.M. has increasingly developed and utilized a web-type integrated approach to teaching undergraduate general chemistry for the last eight years. The Spring of 2018 section with 48 chemistry majors was the first year the specific Web of Chemistry tool was available to complement his integrative teaching strategy. The physical Web of Chemistry tool provides a visual reinforcement of the instructor's descriptions of content integration. Notably, in a survey administered 1 week after final grades were published (N = 19), 84% of the respondents agreed with the statement "I will be better prepared for advanced chemistry courses and the 'real world' by understanding how diverse topics in chemistry are interrelated." At the same time, 74% acknowledged that this web of study approach is more difficult than a traditional approach focused on covering a listed set of learning objectives. 68% agreed; 26% were neutral and 5% disagreed with the statement "A curricular diagram like the "Web of Chemistry" would be useful for other courses." Two exemplar comments demonstrate that students fully comprehended and valued the web of study approach to teaching and learning:

> *During the topic of thermodynamics, connecting all the different aspects of enthaphy [and] entropy to free energy and the favorability of a reaction allowed me to connect all that we have done throughout the semester and see how even the molecular structure and properties are connected to the mechanics of the reaction.*
>
> *This method of teaching was very helpful in the success I had in the class. Instead of treating chemistry as separate sub-topics in one huge topic, allowing them to connect is useful when learning new pieces of chemistry—it brings familiarity into what is supposed to be a new, and unfamiliar topic. This is especially important when discovering real-world problems, since people are dealing with unfamiliarity constantly. Having integrated learning helps connect the unfamiliar to the different aspects of chemistry and makes it seem like one topic interconnected.*

One group of students even created their own web of study in response to the problem session assignment to develop a final exam study guide, further evidencing student-perceived utility of the web of study approach. These students focused their course web around the big idea of intermolecular forces (IMFs), for which determine structure and phases of matter, as well as properties and reactivity. This is a clear example of a face-to-face tool, described by Windschitl, which the instructor created, or "priming" tool (our Web of Chemistry), "creates the conditions for entirely new types of tools to be developed".[4] As noted by Windschitl, such combination of the instructor prepared priming tool and student created face-to-face tools directly engage students in scientific reasoning and discourse, which results in higher level learning than is accomplished when only using an instructor pre-prepared tool.

CONCLUSION

It is important for students of chemistry to develop both an understanding of the body of conceptual knowledge about chemistry, and the ability to ask and test questions. Science is about curiosity, creativity, and discovery; thus, these attributes should be central to the teaching of science. To this end, the conception of a web of study, specifically the Web of Chemistry, is a tool that facilitates a novel teaching strategy to combat the breadth vs depth dichotomy. Class discussion, with regular reference to the visual tool of the Web of Chemistry, reinforces the inter-relationships between the many diverse concepts and principles of chemistry. The nonlinear web of study approach offers a learning structure by which students develop deeper understanding as they learn the subject matter, rather than focusing on development of the ability to validate some level of proficiency with respect to performance expectations and evidence statements.

Rediscovering the work of Priestley's concept charts,[29] we recognized that both the graphical organization of curricular content, along with the use of color to highlight interconnected content that may not be physically adjacent, is a powerful strategy to provide both the newcomer and the expert with a more systemic conception of the material being studied. As supported by student response, there would be value in developing similar webs of study for other disciplines. The web conception of learning and teaching provides a contextual framework with which to understand the relevance and relationships for all new material being learned. However, equally important, seeing and thinking about interrelationships stimulates the most fundamental process of science: asking new questions. Science cannot just be learned, it must be practiced, such that the student of science becomes a scientist. As such, we offer the Web of Chemistry as a tool and teaching strategy to help students, teachers, and experts discover, learn, question, and explore.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00878.

Black and white version of the Web of Chemistry (PDF)
Developmental versions of the Web of Chemistry (PDF)
Figure with K.A.N.'s student performance on the North Carolina Final Exam in Chemistry (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the numerous discussions and interactions with more than 125 high school teachers from across North Carolina that we have worked with since 2014. Joshua W. Martin's graphic art expertise is acknowledged for enhancing the design of the Web of Chemistry. This work was supported in part by the National Science Foundation via Contract DMR-1709370.

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DOI: 10.1021/acs.jchemed.7b00878
J. Chem. Educ. 2018, 95, 2134–2140