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Chemistry in the Field and Chemistry in the Classroom: A Cognitive Disconnect?

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Recent reform efforts *(1–4)* have identified the preparation of scientifically literate citizens as a goal of science instruction. The stability and prosperity of a modern democratic society in which public policy decision making often involves scientific issues, such as nuclear waste disposal, genetic engineering, and pharmaceutical development, requires a citizenry that understands the nature of the scientific enterprise. Yet most adults' formal education in science is completed in high school. Scientists keep abreast of current developments in their specialty through professional research publications (e.g., *Biochemistry*, *Cell*, *Materials Science*) and outside their specialty through general science magazines (e.g., *Science News*, *Discover*, *Scientific American*). The general public receives updated science news through the popular press (e.g., newspapers, magazines, television, World Wide Web). These journalistically reported versions of scientific developments inform the public of groundbreaking research results *(5),* but for pragmatic reasons simplify or summarize the technical details critical for determination of the validity of the research *(6).*

Research on text comprehension points to the need for a specific knowledge base for reader engagement in and thoughtful interpretation of a news article *(7, 8).* Development of this specific knowledge base has been an enduring goal of science education since the early 20th century *(1–4, 9).* A science knowledge base includes the nature of the scientific enterprise and the role of science in society as well as specific content *(10).* Textbooks, which focus on established scientific content and process, have been used in formal science education to develop this knowledge base. The exciting, interesting, and engaging "frontier science" presented in the popular press is not well-established scientific knowledge but rather dynamic new information *(11).* The difficulty with this arrangement is that just as specific new ideas enter and leave the scientific domain, so, too, does the domain change in structure; textbooks and school-based visions of the scientific enterprise do not always keep up. For a society to comprehend a specific domain of science requires that the public be able to use school science knowledge to interpret and use the news reports of cutting edge research to remain interested or when making personal choices or determining public policy.

Chemistry is a central science since "its methods, concepts, and practitioners are penetrating virtually every nook and cranny of science and technology" *(12).* There is, therefore, the need for a chemistry curriculum that produces a literate public in addition to a well-trained work force. Chemistry's evolution from a discrete scientific field in the 19th century to an ubiquitous presence within multiple realms of science in the 21st century suggests that not only the means of teaching need to be reformed *(4)* but also that the fundamental organization of the textbook-based vision might not be up to date; it further suggests the need for a current map of chemistry concepts that can serve to align the chemistry curriculum for the promotion of chemical literacy.

Conceptual Framework for Chemistry

The problem addressed in this article is to understand how closely chemistry texts and therefore their attendant curricula reflect, in a structural sense, the central, valued activities of the field. As new information arises, can it be located within the current knowledge system embraced by chemistry textbooks? Given that most students formally study chemistry for a limited time and only in high school, are chemistry textbooks (and educators) focusing and ordering instruction on the appropriate content? Before addressing these questions, a careful consideration of the structure of the field by examination of the activities in which chemists engage is needed.

Academic chemistry has been organized pedagogically around the subfields of analytical, biochemical, inorganic, organic, physical, and theoretical chemistry even though creativity and progress in academic and industrial research and development usually have occurred across such boundaries. A reexamination of the domain's structure in light of chemistry's assimilation into and collaboration with nearly all scientific and technological endeavors has suggested a more current description of what chemists do: they *explain* phenomena, they *analyze* matter to determine its chemical makeup, and they *synthesize* new substances. These three activities of chemistry reflect the view of recognized leaders in the field *(13).* To capture these activities of chemistry we present a diagrammatic representation of the organization of the domain (Figure 1). The top three boxes represent the major activities while the lower layers of the framework show the activities that make up the endeavors in each level. When *explaining* a phenomenon, a chemist constructs a hypothesis by sifting through a variety of theoretical frameworks and tests this hypothesis by designing an appropriate experiment. When *analyzing* matter, a chemist couples the goal of an analysis with a method for performing it. When *synthesizing*

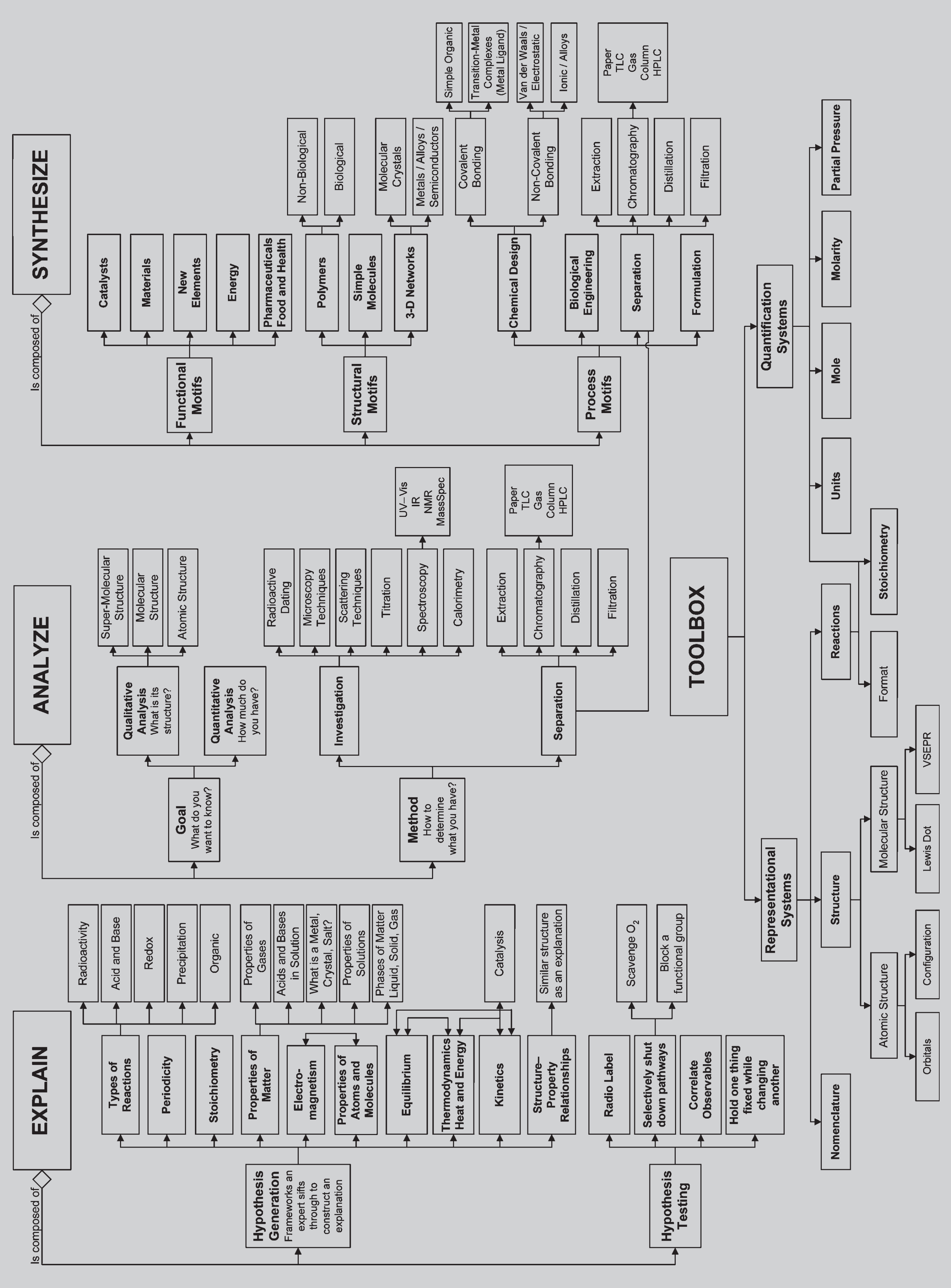

Figure 1. The conceptual framework for chemistry.

a new substance, a chemist simultaneously considers the functional motif that the new molecule is to possess, the structural motif that will lead to this function, and the process motif by which the structure may be assembled. Supporting these three activities of chemistry is the *toolbox*, a collection of procedures and models that are used as needed when directing syntheses, conducting analyses, and developing explanations. *Toolbox* items are cross-cutting and establish the technical vocabulary for participating in the domain. For instance, the basic notation of chemical structures and reactions and the units for quantifying amounts of substance are placed in the *toolbox* since they are needed for almost any activity in qualitative or quantitative chemistry, respectively. The hypothesis generation activity of the *explain* level is composed of important ideas of chemistry but unlike the contents of the *toolbox* it is possible to discuss many aspects of chemistry without utilizing all of them. For example, equilibrium and kinetics are placed in *explain* (hypothesis generation) since, although fundamental, it is possible to discuss many issues in chemistry without invoking them.

Development of the chemistry conceptual framework was initiated by a rigorous and ongoing discussion by the authors; they include a chemist, a chemistry teacher, an educational researcher, and an instructional designer. Refinement of the structure was an iterative process that made use of the *National Science Education Standards (1)* as elaborated by the chemistry section of the *Science Content Standards for California Public Schools, Kindergarten Through Grade Twelve (14),* current chemistry news reports, and consideration of valued activities in chemistry *(13).*

Methodology

One way to test whether the framework reflected the domain was to systematically locate important chemistry activities within the framework and ask: Are some activities missing? Are some things overly confounded? Are some things present in the framework but not present in chemistry as a domain? We chose fifty years of Nobel Prizes (1952–2002) to represent "important chemistry activities". Each award citation was coded jointly by the chemistry research professor, instructional designer, and high school teacher as either a new *explanation*, a new *analysis*, a new *synthesis*, or a new contribution to the *toolbox*.

In a similar manner, all chemistry-related articles from the 2002 *New York Times* Science Times and 2002 *Scientific American* News Scan columns were coded as either a new *explanation*, a new *analysis*, a new *synthesis*, or a new contribution to the *toolbox*. Newspapers and magazines are among the diverse media that disseminate recent scientific developments reported in the professional literature to the general public. The *New York Times* is one of the world's "prestige papers" *(15),* a standard of journalistic authority whose articles serve to raise public awareness and increase public understanding of current scientific issues. *Scientific American*, the oldest continuously published magazine in America, reports the latest groundbreaking events in science and technology through articles that have been written by more than 120 Nobel Laureates as well as esteemed world leaders, government officials, economists, and industrialists. Therefore, these genres *(16)* can be used to reveal the societal expectations for literacy in chemistry. The main theme of each article was determined by what made the reported scientific work new and noteworthy. In total, 86 articles were coded. Of these, one article from the *New York Times* and one from *Scientific American* each reported new work from two different areas and were coded accordingly.

Additional coding of each news article to the lowest level of the map that was consistent with the text was performed independently by the research chemistry professor, instructional designer, and high school teacher. For example, if the technique for an investigative method was not mentioned, the coding stopped at "*analyze*: method: investigation", even if an expert could infer the technique used from contextual clues (see "A Case of the Vapors," p 27, *Scientific American,* Jul, 2002). Coding to the level of a specific technique only occurred if the article explicitly mentioned the procedure or included text that made an attempt to explain it (see "What Lies Beneath," p 29, *Scientific American,* Aug, 2002). In addition to this explicit coding of the main theme of the article, the full text was examined for any discussion of auxiliary chemical topics that then were coded in a corresponding fashion. Disagreements among the coders were resolved through discussion.

In order to determine whether the curriculum in use in the vast majority of high schools reflects the active domain of chemistry, chemistry texts were coded against the framework. *Merrill Chemistry (17), Modern Chemistry (18),* and *Chemistry in the Community (19)* were chosen because theses three textbooks are aligned with the *National Science Education Standards* that "…describe a vision of the scientifically literate person and present criteria for science education that will allow that vision to become a reality" *(1).* Since most high school courses do not complete an entire textbook in one year, a number of teachers who routinely use these texts were interviewed to determine those chapters most commonly included in their courses.[1] The chapter objectives were coded jointly by the chemistry research professor and high school teacher as either *explanations*, *analyses*, *syntheses*, or belonging to the *toolbox*. Since textbooks are the dominant force for formal education in chemistry, their objectives reflect the focus of classroom chemistry. As with the news articles, additional coding of the objectives was performed to the deepest level of the framework consistent with text.

Results

The main themes from 50 years (1952–2002) of Nobel Prizes in chemistry, all news reports with chemistry content from the 2002 *New York Times* Science Times (54 reports) and from the 2002 *Scientific American* News Scan columns (32 reports), 103 (out of 195) objectives from *Merrill Chemistry (17),* 190 (out of 291) objectives from *Modern Chemistry (18),* and 120 (out of 120) objectives from *Chemistry in the Community (19)* are compiled in Figure 2. (Raw data are provided in the Supplemental Material.ʬ)

Contributions to the field of chemistry recognized by the Nobel Prizes are distributed evenly among the three activities of chemists: *explain*, *analyze*, and *synthesize*. News reports portray a somewhat similar pattern of noteworthy research. However, textbook objectives reveal a noticeably different emphasis. *Merrill Chemistry* and *Modern Chemistry* objectives are divided equally between *explain* and the *toolbox* with little or no representation of *analyze* or *synthesize* activities. In a similar fashion, half of *Chemistry in the Community's* (*ChemCom's*) objectives reflect the *explain* activity. The remaining objectives are distributed somewhat unevenly among *synthesize* and *analyze* activities, the *toolbox*, and topics *outside*[2] the domain of chemistry (Figure 2). We explore these findings further below.

News reports coded as a new *synthesis* or a new *analysis* usually were accompanied by support from the *explain* activities. Articles coded as new *explanations* were supplemented by *analyze* activities about a third of the time and by *synthesize* activities even less (Table 1).

When articles were coded further through the specific endeavors of *explain*, *analyze*, and *synthesize* activities the irregular distribution of data is worthy of note (Table 2). Articles specifically identified as new *explanations* always discussed the hypothesis generation activity and half explicitly discussed the method used for the testing of the hypothesis (see Supplemental Materials[W]). Within the hypothesis generation activity, types of reactions, properties of matter, electromagnetism, properties of atoms and molecules, and structure–property relationships occurred with the greatest frequency (34, 27, 25, 17, 14 codings respectively out of 132 total). Within the hypothesis testing activity, correlation of observables occurred with the greatest frequency (26 codings out of 34 total). Most *analysis* articles explicitly discussed both a goal and a method for undertaking an analysis but the fre-

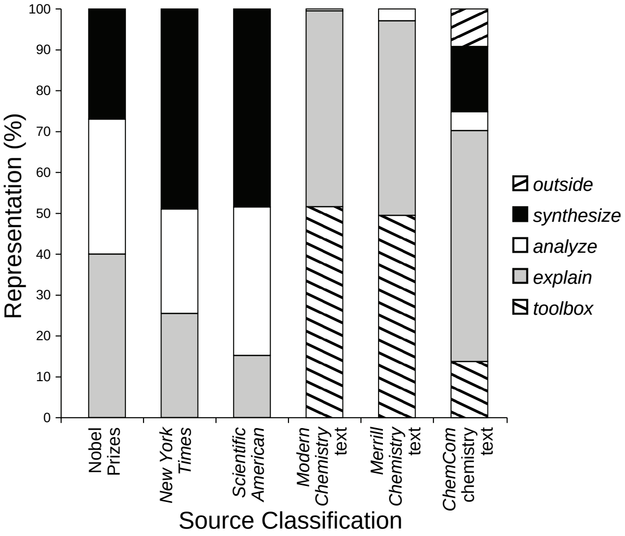

Figure 2. How the domain of chemistry is represented by the Nobel Prizes, in the press, and in textbooks. "*Outside*" refers to those textbook objectives identified as social, political, economic, or ethical issues related to but not included in the domain of chemistry.

Table 1. Relationship of Main Themes and Supplementary Topics in Chemistry News Reports[a]

Main Theme	Supplementary Topic	N[b]
Explain	None	10
Explain	Synthesize	3
Explain	Analyze	7
Analyze	None	4
Analyze	Explain	18
Analyze	Synthesize	3
Synthesize	None	6
Synthesize	Explain	34
Synthesize	Analyze	4

[a] *New York Times* and *Scientific American* combined. [b] Number of articles coded.

Table 2. Distribution of Coding in Chemistry News Reports

Activity		Number of Codings
Explain:	*Hypothesis Generation*	*132 (total)*
	Type of reaction	34
	Periodicity	1
	Stoichiometry	2
	Properties of matter	27
	Electromagnetism	25
	Properties of atoms and molecules	17
	Equilibrium	2
	Thermodynamics	4
	Kinetics	6
	Structure-property relationships	14
Explain:	*Hypothesis testing*	*34 (total)*
	Radio-labeling	0
	Selective pathway shutdown	1
	Correlate observables	26
	Control of variables	7
Analyze:	*Goal*	*34 (total)*
	Qualitative analysis	14
	Quantitative analysis	20
Analyze:	*Method*	*30 (total)*
	Investigation	27
	Separation	3
Synthesize:	*Functional motifs*	*54 (total)*
	Catalysts	2
	Materials	33
	New elements	1
	Energy	7
	Pharmaceuticals, food, and health	10
	Unspecified	1
Synthesize:	*Structural motifs*	*40 (total)*
	Polymers	13
	Simple molecules	6
	3-D networks	21
Synthesize:	*Process motifs*	*36 (total)*
	Chemical design	27
	Biological engineering	4
	Separation	2
	Formulation	3

NOTE: *New York Times* and *Scientific American* combined.

quency of specific activities within the endeavors of goal identification and methodology were unevenly distributed.

Nearly all the methodologies reported were investigatory in nature (27 codings out of 30 total) and more often than not involved spectroscopic data. Goal identification data were more evenly distributed between qualitative and quantitative analyses (14 and 20 codings respectively out of 34 total). In a similar fashion most *synthesize* articles explicitly considered functional, structural, and process motifs when reporting on the creation of new substances. Within each of these motifs one particular activity is more prevalent than the others: materials for functional motifs (33 codings out of 54 total), 3-D networks for structural motifs (21 codings out of 40 total), and chemical design (27 codings out of 36 total) for process motifs (Table 2).

In spite of the fact that *Merrill Chemistry* and *Modern Chemistry* are aligned with all of the *National Science Education Standards* for chemistry, an introductory high school chemistry course based on these textbooks addresses just over half of the stated objectives and text pages (Table 3). The content of the objectives addressed by users of both textbooks was similar. Approximately half of the objects were of a *toolbox* nature and the other half characteristic of the *explain* activity. An introductory high school chemistry course based on the *ChemCom* text addresses all of the stated objectives and text pages. Although more than half (57%) of the objectives were characteristic of the *explain* activity, only 14% were of a *toolbox* nature. The remaining objectives were divided somewhat unevenly among *analysis* (5%) and *synthesis* (16%) activities, and ideas *outside* (8%), albeit related to, the domain of chemistry (Figure 2).

Table 3. Textbook Coverage in a First-Year High School Chemistry Course

Measure	*Merrill Chemistry*[a]	*Modern Chemistry*[b]	*ChemCom*[c]
Total pages[d]	648	599	484
Covered pages[e]	373	393	484
Percent of total pages	58%	66%	100%
Total objectives[f]	195	291	120
Objectives covered[g]	103	190	120
Percent of total objectives	53%	65%	100%

[a]Ref *17*. [b]Ref *18*. [c]Ref *19*. [d]Sum of text pages only for each chapter. [e]Actual pages covered within the school year. [f]Sum of all the chapter objectives. [g]Actual objectives addressed within the school year.

Table 4. A Comparison of Hypothesis-Generation Themes in News Reports[a] and Textbook Objectives[b]

Theme	News Reports[c] (%)	*Merrill Chemistry*[d] (%)	*Modern Chemistry*[e] (%)	*ChemCom*[f] (%)
Types of reactions	25	4	14	24
Electromagnetism; Properties of atoms and molecules[g]	31	10	12	13
Stoichiometry	2	10	7	5
Properties of matter	23	51	44	24
Periodicity	1	18	15	2.5
Equilibrium; Thermodynamics; kinetics[g]	8	8	4	17
Structure–property relationships	11	0	1	14.5

[a]*New York Times* and *Scientific American* combined. [b]Coded as explain activity. [c]Percentages of explain: hypothesis generation codes. [d]Percentages of explain objectives (out of 49). [e]Percentages of explain objectives (out of 91). [f]Percentages of explain objectives (out of 74). [g]Related themes considered together.

Explain is the chemistry activity common to both the field, as represented by the Nobel Prizes and news reports, and the high school curriculum, as represented by half of the objectives from each of the textbooks (Figure 2). News reports reference hypothesis generation as well as hypothesis-testing endeavors but textbook objectives address only the hypothesis-generation component of *explaining* phenomena. Table 4 compares the frequency of hypothesis-generation themes in news reports and textbook objectives. (Figure 1 shows ten themes for hypothesis generation. Several were related and therefore considered simultaneously: electromagnetism with properties of atoms and molecules, and equilibrium with thermodynamics and kinetics.) Although the proportions of objective themes in *Merrill Chemistry* and *Modern Chemistry* are similar, they differ dramatically from the proportion of themes in news reports. For example, the percentages of objectives from these textbooks that address properties of matter (*Merrill*, 51%; *Modern*, 44%) and periodicity (*Merrill*, 18%; *Modern*, 15%) far exceed the percentages of news report codes for these topics (properties of matter, 23%; periodicity, 1%). Furthermore, the percentages of objectives from these textbooks that focus on types of reactions (*Merrill*, 4%; *Modern*, 14%), electromagnetism and properties of atoms and molecules (*Merrill*, 10%; *Modern*, 12%), and structure–property relationships (*Merrill*, 0%; *Modern*, 1%) are substantially less than the percentages of news report codes for these topics (types of reactions, 25%; electromagnetism and properties of atoms and molecules, 31%; structure–property relationships, 11%). When the distribution of themes within the *explain* objectives of *ChemCom* is compared to that of news reports, however, a different picture emerges. Except for differences in the simultaneously considered themes (electromagnetism and properties of atoms and molecules; equilibrium, thermodynamics, and kinetics) the thematic emphasis of *explain* objectives closely parallels that of news reports identified as *explanations* (Table 4).

Discussion

As the National Research Council wrote, “the …field of chemistry…has an exciting story to tell, with intellectual excitement and practical applications that are critical to modern civilization” *(13)*. Nobel Prizes from the past 50 years and recent news reports depict chemists as scientists who design and manufacture new useful substances, characterize and measure natural as well as manmade materials, and unravel the structure and behavior of molecules. Yet beginning high school and college chemistry students usually are not exposed to this excitement in the course of their studies. Instead, the acquisition of a vast collection of facts and principles has been the traditional prerequisite for later learning about the wonders of discovery and creativity at the very heart of chemistry. Such a disconnect between what is taught in school and what the field encompasses interferes with the development of a scientifically literate population.

Because of this disconnect between what chemists do, as reflected by the conceptual framework, and the focus of high school chemistry, as reflected by textbook objectives, students may leave an introductory chemistry course without a functional perspective on the field of chemistry. This lack of perspective may even be present in the *explain* activity of the framework, despite the number of textbook objectives that were mapped to this activity. These objectives were mapped under *explain* because a chemist used the content of these objectives to generate hypotheses regarding chemical systems. However, traditional instruction does not present this content in the context of authentic science, as evidenced by the lack of textbook objectives addressing the testing of hypotheses. Rather, traditional instruction presents this content as skills to be mastered by the student. Thus the coding of many textbook objectives under the *explain* portion of the framework does not imply that students are being given a good perspective on how chemists develop and test explanations. In traditional instruction, the content standards tend to overwhelm the inquiry standards.

The observed misalignment is the consequence of a bottom-up instructional approach in which instructors try to build a solid base of factoidal knowledge, often over several courses, by presenting students with a vision of chemistry consisting of abstract concepts and *tools* such as chemical and mathematical symbols, formulas, and equations *(20).* According to the information processing model of learning in chemistry *(21),* however, the separation of learning from its intellectual and practical use results in inert bits of unconnected knowledge that are rarely usable let alone memorable for students. Others have noted the disadvantages of a bottom-up approach. For instance, it assumes that high school students will go on to university education *(22),* but most of the population will not engage the discipline formally after high school: at best, only ten percent of a those who do take a first-year college course in chemistry will go on to become professional chemists or chemical engineers *(23).* Yet the pervasiveness of chemistry in all facets of modern society demands a public that is familiar with the domain. Shirley Tilghmann, a molecular geneticist and Princeton University's president suggests a different approach to instruction, one that reflects a particular stance toward literacy, "I think…we should begin with the most exciting ideas in chemistry…and how you go about studying it. What are the things you need to know? We should only teach what students need to know in order to understand what those are…I'd like to see us teaching more than a canon, a collection of facts, but why this is exciting…" *(24).* When chemists work through the problems associated with new and exciting ideas, they link the demands of a particular endeavor to the appropriate *tools* needed for execution of the solution. Use of a specific *tool* is embedded within the context of the problem. In a similar manner, this top-down approach to instruction can help students construct meaningful links within their chemistry knowledge base.

ChemCom is an impressive initiative for shaping future instruction in chemistry since it emulates the domain's valued activities presented in the conceptual framework (Figure 1). By introducing *tools* on a need-to-know basis, the number of objectives devoted to the *toolbox* has been greatly reduced from those found in more traditional texts. Furthermore, *synthesis* is addressed by many of *ChemCom's* objectives. Because of the spiral design of the text, even those students who complete less than the entire program are exposed to a similar distribution of objectives. However, the allocation of *ChemCom's* objectives only approaches the proportions of authentic chemistry activities represented by the Nobel Prizes and news reports. Conspicuously underrepresented among *ChemCom's* objectives (as well as those from the other textbooks) are *analysis* activities (Figure 2), even though many occupations such as forensics, medical diagnoses, and materials testing are based upon the goals and methods of chemical *analysis*. Furthermore, providing experience with hypothesis testing in addition to hypothesis-generation endeavors would more accurately represent the nature of *explain* activities to students. A note of caution, however, is in order. Whereas control of variables (hold one thing constant, vary another) historically has been the fundamental principle of the scientific method described in textbooks, correlation of observables is the dominant hypothesis testing technique described in news reports.

When teachers provide authentic *(25)* chemistry activities such as scaffolded problem-solving scenarios within the activities of the domain *(explain, analyze, synthesize)* for which the necessary *tools* are developed as needed, they can help students construct meaningful links within their knowledge base. Designing problems situated within the context of the frontier storylines reported in the media, for example, will not only help students form connections within their chemistry knowledge base but also will help them develop a perspective of the nature of the discipline. The argument we are making is that at the first level of literacy, the one that the greatest number of citizens is likely to experience, the enterprise of chemistry, its practices and activities, should be the focus, not the so easily forgotten disembodied and often useless tools.

wSupplemental Material

The coding system is shown in Supplemental Material, section A. Nobel Prize citations and their codes are shown in Supplemental Material, section B. News reports and their codes are shown in Supplemental Material, section C. Textbook objectives and their codes are found in Supplemental Material, section D. These four sections are available in this issue of *JCE Online*.

Notes

1. The maximum number of objectives addressed by any of the interviewed teachers was coded. Whereas teachers who used *Merrill Chemistry* or *Modern Chemistry* were interviewed locally, a broad national sample of teachers who used *Chemistry in the Community* was interviewed since the program was not in use locally.

2. An example of an objective coded as *outside* would be, "Describe the three major parts of earth," (Unit 2, Section B). See

Supplemental Materials,ʷ Part D, for a complete list of coded textbook objectives.

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