ACS Editors' Choice

Journal of Chemical Education

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The Safety "Use Case": Co-Developing Chemical Information Management and Laboratory Safety Skills

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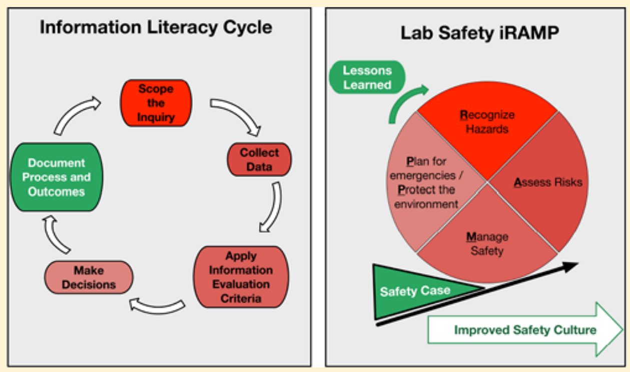
S Supporting Information

ABSTRACT: The 2015 edition of the American Chemical Society's *Guidelines and Evaluation Procedures for Bachelor's Degree Programs* identifies six skill sets that undergraduate chemistry programs should instill in their students. In our roles as support staff for chemistry departments at two different institutions (one a Primarily Undergraduate Institution, the other a research intensive university), we have been collaboratively studying these requirements and have found significant synergies between two in particular: "Chemical Literature and Information Management Skills" and "Laboratory Safety Skills". We believe that by integrating emerging tools in the laboratory safety field into information literacy frameworks, a strong foundation can be established for the development of all the skills called out by the ACS. This article describes this strategy and provides examples of how these concepts can be implemented in both the chemistry teaching and research laboratory settings.



KEYWORDS: *Upper-Division Undergraduate, Chemoinformatics, Safety/Hazards, Analogies/Transfer, Communication/Writing, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, Applications of Chemistry, Laboratory Management, Learning Theories, Nomenclature/Units/Symbols*

INTRODUCTION

In 2015, the American Chemical Society's Committee on Professional Training (CPT) released the latest edition of the *ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*.[1] These guidelines include a description of six skill sets that undergraduate chemistry majors should develop. These sets are:

1. Problem Solving Skills
2. Chemical Literature and Information Management Skills
3. Laboratory Safety Skills
4. Communication Skills
5. Team Skills
6. Ethics

In our support roles for academic chemists as a chemical hygiene officer and a chemistry librarian, respectively, we have been reviewing these expectations in order to develop materials and resources to help meet these standards. In this process, we have recognized that safety skills are a specific "use case" of information literacy skills. In this context, we are using "use case" in the computer science sense of "interactions between a role... and a system, to achieve a goal".[2]

The laboratory chemical safety use case presents an interesting challenge in that a holistic safety planning process involves a mix of laboratory specific considerations and organizational support services. For example, ventilation and personal protective equipment requirements are generally managed on a lab-by-lab basis, while waste disposal and emergency planning and response services are generally provided at the organizational level. Thus, a diverse set of roles are involved in a complete laboratory safety program, including laboratory chemists and their supervisors, chemical educators and their students, environmental health and safety professionals, and chemical information professionals. These stakeholders collaborate to develop risk assessments and management strategies for chemical hazards associated with laboratory procedures. However, they approach this task from different perspectives and with different vocabularies. Their professional literatures reflect these differences; thus the laboratory safety research and planning process can present significant information literacy challenges.

In this article, we organize emerging chemical risk assessment and management tools into a cyclical model that reflects the strengths and limitations of the information available at each step. This model is based on the knowledge practices outlined in the Framework for Information Literacy for Higher

Special Issue: Chemical Information

Published: November 17, 2015

DOI: 10.1021/acs.jchemed.5b00511
J. Chem. Educ. 2016, 93, 516−526

Education described by the Association of College and Research Libraries (ACRL).[3] This melding of information literacy and laboratory safety skills and tools at the undergraduate level is in keeping with the CPT's goal of engaging undergraduates in chemical research as "the most rewarding and educationally valuable aspect of an undergraduate chemistry degree."[4]

We believe that the CPT's vision can be integrated into a coherent whole by using the laboratory safety use case as an example of an information literate application of chemical data and information to support problem solving, communication, team building and ethical skills.

■ INFORMATION LITERACY AND LABORATORY SAFETY

In January, 2009, a laboratory technician in the Chemistry Department at UCLA died 3 weeks after being badly burned in a lab accident involving the use of pyrophoric chemicals. According to the C&EN report on this event,[5] she was an employee who had been on the job for three months, having received a bachelor's degree in chemistry from Pomona College in May 2008. The University's response to legal charges arising from the incident included the idea that she was an "experienced chemist" who could be expected to understand appropriate laboratory safety practices. California OSHA found that this assertion did not satisfy the regulatory requirements for safety training for employees working with hazardous chemicals and criminal charges were subsequently brought against the institution and her supervisor. This chain of events raises many questions, but particularly, "*What laboratory safety awareness and skills should be expected to be imparted during an undergraduate chemical education?*"

Chemists reviewing the UCLA incident noted that information about working safely with pyrophoric chemicals was available,[6] but it was scattered across a variety of sources. Collecting and organizing this safety information into an operational procedure was not part of the work practices of this laboratory, and many commenters in the chemistry community remarked that this is common in many academic research settings.[7] The UCLA fire highlights the need to strengthen the safety culture of academic chemistry, both in terms of laboratory safety skills and information literacy. For this reason, we have been exploring the connections between these skill areas and found significant opportunities to implement them together.

As articulated by the ACRL:

> *Information literacy is the set of integrated abilities encompassing the reflective discovery of information, the understanding of how information is produced and valued, and the use of information in creating new knowledge and participating ethically in communities of learning.*[3]

In practice, information literacy is the ability to collect and critically analyze information, and then use that information to systematically develop and document a concrete judgment. Thus, information literacy involves work at the upper levels of Bloom's taxonomy,[8] notably the synthesis and evaluation skills. Laboratory safety planning requires systematic research and thoughtful analysis to develop prudent operational plans for conducting the laboratory work at hand. Emerging chemical information and management resources and risk assessment tools support laboratory chemical risk assessment practice as a teaching opportunity that directly ties into the information literacy skill set. The ACRL framework emphasizes the strategic exploratory nature of research and describes key concepts involved in formulating, researching, organizing, evaluating, and synthesizing investigations.[3] We use these practices to describe a decision-making process for chemical safety planning.

Information Literacy and MSDSs

An illustrative example of the connection between information literacy and laboratory safety is the laboratory use of Material Safety Data Sheets (MSDS). The MSDS, which is the legal standard of practice for managing chemical safety information, arose in the mid-1980s with the OSHA Hazard Communication Standard.[9] At the time, these paper-based documents were crucial tools for people who needed to collect information such as flashpoints, chemical compatibility information and toxicity data. Previously, this information had been scattered across many different resources and challenging to organize and distribute effectively. The development of institutional,[10] manufacturer[11] and commercial[12] libraries of MSDSs accessible online made it much easier to acquire this information on an as-needed basis.

However, access to MSDSs alone is not enough to make them a useful tool in planning how to handle chemicals safely in the lab.[13] This is for several reasons:

- The OSHA requirements for MSDSs are general enough that the information provided on them varies among chemical suppliers
- The quality of this information is often limited by commercial considerations such as liability, legal jurisdiction, and trade secret considerations
- There is no regulatory requirement that the quality of the information be assured by the supplier of the chemical
- The preparation of these documents relies on published data and many laboratory chemicals are novel, with a paucity of safety data available.

These considerations all present significant challenges for planning safe laboratory operations. Thus, integrated use of MSDS and other sources of chemical safety information is important in the laboratory setting and engages both the ACRL information literacy practices and the chemical information management skill set described in the CPT guidelines.

■ EMERGING LAB SAFETY TOOLS

The context of laboratory safety in chemical education and research has evolved rapidly over the last two decades. New scientific frontiers,[14] changing laboratory technologies,[15] specific laboratory safety incidents,[16] and increasing emphasis on undergraduate laboratory research[4] have created new demands for broader laboratory safety education for chemists, at both the graduate and undergraduate levels.[17] These demands are reflected in the expansion of the CPT guidance on laboratory safety in 2015. Fortunately, newly emerging safety tools can support these needs. Those that are particularly important for this article are described in this section.

Tool 1: Safety Culture and Prudent Practices

The first tool for understanding the context of laboratory safety is the connection two core concepts: *laboratory safety culture* and *prudent practices*. These concepts have been evolving over the last 20 years, as various laboratory incidents have brought national attention to the issue of safe use of chemicals in academic laboratories.[18]

The term "safety culture" has been increasing in circulation since the mid-1980s and used in a variety of ways.[19] Since 2010,

DOI: 10.1021/acs.jchemed.5b00511
J. Chem. Educ. 2016, 93, 516−526

scientific societies[20] and professional organizations[21] have written about the importance of improving the safety culture of academic laboratories. The CPT guidance summarizes laboratory safety culture as a "...responsibility (that) goes beyond simply complying with federal, state and local regulations—it is about caring for the safety of fellow students, faculty, and staff."[22]

However, a "beyond compliance" approach to laboratory safety culture can be challenging to interpret in specific laboratory situations. Simply put, this approach means that regulations should act as the *floor* rather than the *ceiling* for safety practices and that laboratory operations should reflect "prudent practices" found in the professional literature as well as government regulation.

The National Research Council publication *Prudent Practices in the Laboratory: Handling and Management of Chemical Hazards* provides an overview of what constitutes prudent practices.[23] However, this document does not provide recommendations for laboratory-specific practices; in practice, laboratory work varies too widely and changes too rapidly for this to be an effective strategy for a single document. More specific expectations about prudent practices at a particular location can be found in institutional guidance, such as a local Chemical Hygiene Plan, emergency response plans, or institutional regulatory compliance plans when these are available. This institutional guidance incorporates the expectations of local authorities that have jurisdiction over specific safety issues such as fire code requirements, waste disposal restrictions, and safety services provided at the institutional level. While these guidance documents are valuable, they are not definitive for three reasons:

1. "Prudence" in this context does not mean that safety practices are expected to address every possible eventuality; an unforeseeable event would be considered beyond the scope of prudent planning. Therefore, the standard for prudence can vary between laboratories based on local circumstances. For example, planning for earthquakes is considered part of prudent work with hazardous chemicals in California, while it might be considered beyond prudence in locations without a significant seismic history. With this in mind, review of government regulations and professional publications as well as the chemistry primary literature is necessary to define what constitutes prudent practices in specific laboratories.
2. In this context, "laboratory scale" is based on the OSHA Lab Standard definition of laboratories.[24] This definition places important boundaries on the work to be considered within the purview of prudent practice.[25] There are many chemical research settings that fall outside this definition and the question of whether a particular process falls within this definition must be carefully considered as part of the research planning process.
3. As laboratory teams become increasingly interdisciplinary, it is important to recognize that there are significant hazards in the laboratory beyond chemicals. These include biohazards, equipment hazards, physical hazards, and radiation concerns. For regulatory and cultural reasons, there are different expectations for what is considered prudent in managing these hazards compared to chemical issues. Understanding that laboratory safety practices need to respond to varying circumstances in the multidisciplinary research setting relates to both the team and ethics skills described by CPT.

Together, these factors demand careful documentation of the development of safety practices being employed; a simple review of the chemical aspects of a procedure will not answer many of the questions that arise in defining how prudence is implemented during chemical work in the laboratory. Working effectively with these varied information sources is a classic information literacy enterprise.

Tool 2: The Global Harmonization System: Its Strengths and Limitations

Recognizing the limitations of MSDSs described above, the United Nations led an effort to develop an international standard for the classification and communication of chemical hazards. First published in 2003, the system is called the Globally Harmonized System of Classification and Labeling of Chemicals (GHS).[26] This system combines technical and communication considerations in addressing the need for consistent, understandable identification of chemical hazards. It accomplishes this by providing specific technical definitions for key terms that describe chemical hazards and organizes them into groups that support a user-friendly hazard communication system (see Figure 1).

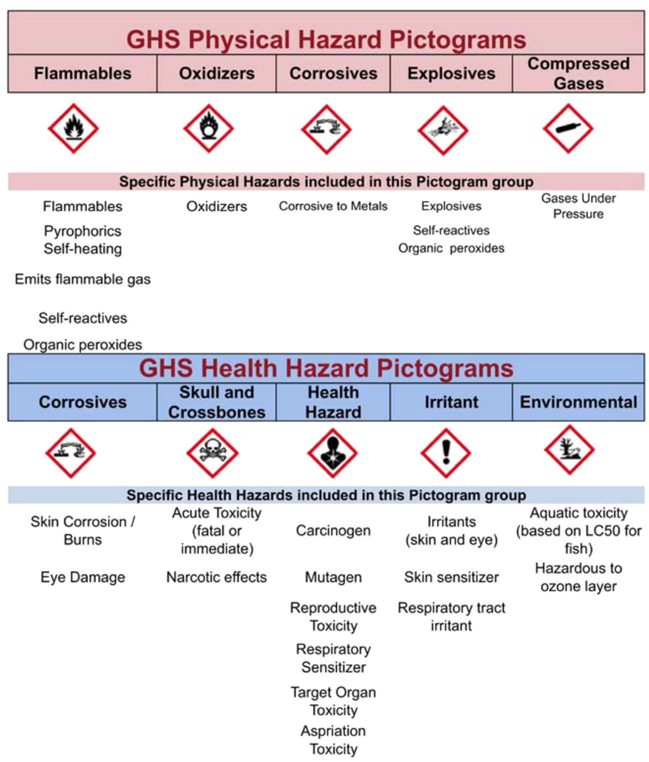


Figure 1. Hazard classes of the GHS system provide a framework to organize chemical safety information into a more effective hazard communication system.

In the United States, manufacturers are required to provide GHS information to people who purchase chemicals after 2015 through Safety Data Sheets (SDS), which represent the next generation of the traditional Material Safety Data Sheets. While the GHS approach is a significant step forward in chemical hazard communication, the new format still presents important

DOI: 10.1021/acs.jchemed.5b00511
J. Chem. Educ. 2016, 93, 516−526

information literacy challenges in the laboratory setting, including the following:

- SDSs are organized around single, specific chemicals and information beyond raw hazard data is quite broad (such as "use personal protective equipment as required") and requires further interpretation in use
- Hazardous interactions between chemicals during the course of a specific process are not included on most SDSs
- Changes in the quantities, concentrations and chemical products that arise over the course of a laboratory process are not addressed by the GHS recommendations
- Nonchemical hazards such as operating temperatures and pressures are not incorporated into the system
- The source of information is the chemical manufacturer and supplier, whose interpretation of the GHS standards can vary depending on what information sources they consult

For these reasons, the GHS information in itself does not provide adequate guidance for the day-to-day practice of laboratory research. A systematic approach to working with this and additional information is necessary to prudently plan chemical work in the laboratory.

Tool 3: The Laboratory Safety RAMP

Using GHS information to support decision-making in laboratory practice requires additional chemical safety information and analysis. The CPT safety guidelines describe a RAMP model to organize safety information in a consistent way that is transferable, scalable and sustainable as laboratory work evolves. The model, first introduced in Hill and Finster, provides a schematic path for safe management of laboratory scale chemical operations.[27]

The safety skills involved in the model spell out the RAMP mnemonic:

- **R**ecognize chemical hazards
- **A**ssess the risks of the hazards present
- **M**inimize the risks of those hazards
- **P**repare for emergencies

We have modified this model to include additional regulatory and ethical aspects of the laboratory safety use case. Specifically, we have changed "Minimize the risks" to "Manage safety" to recognize the ongoing nature of prudent practices as the process proceeds. We have also added "Protect the Environment" to the 'P' step in the model, to include compliance with laboratory waste disposal and emergency planning requirements, as well as "beyond compliance" considerations such as laboratory energy conservation and Green Chemistry opportunities.

We have also included two documentation components in the system, "Lessons Learned" and "Safety Case". These functions recognize the ethical responsibility of the researcher to share safety aspects of their work. Documenting the decision making process over the whole cycle in a Safety Case can help prevent "backsliding" as familiarity with the procedures develops and/or the people conducting the work change. Safety lessons complement the scientific knowledge gained in experimental research by supporting safe replication of the work. For this reason, ideally these lessons would be regularly included in the primary chemistry literature. By incorporating Lessons Learned and Safety Case documentation into the RAMP model, laboratory safety becomes a cyclical process that informs the next iteration of the lab procedure and provides an opportunity for reflective learning.

Our resulting model, illustrated in Figure 2, organizes the safety skills involved in the RAMP model into a cyclical process

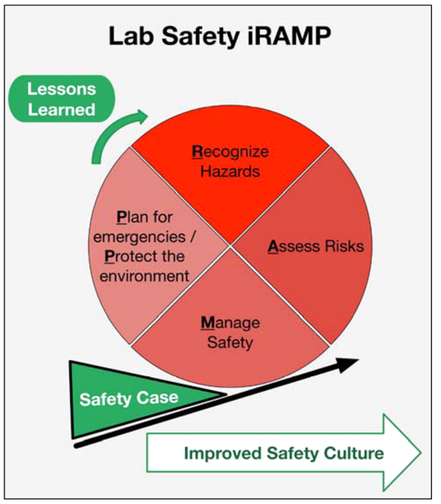


Figure 2. The iRAMP paradigm for managing chemical safety in the laboratory.

of continuous improvement in laboratory safety culture. We have dubbed this version the iRAMP model, to emphasize the iterative nature of the process. All of the skills involved in this model are based on effective understanding and use of the chemistry literature, as discussed in more detail later in this article. Our ongoing work to develop this process is described on the iRAMPp blog platform.[28]

Tool 4: Risk Assessment in the Laboratory

The **R**ecognition step of the iRAMP process is well served by the emergence of the GHS system. However, the operative elements in determining safe use of hazardous chemicals are the **risks** associated with the chemical process. Beyond the *hazards* of the chemicals being used, the *risks* are determined by the *exposures* of people to those hazards and the *potential damage* resulting from those hazards. The **A**ssessment step considers these factors to determine what constitutes prudent practice in proceeding with the lab work.

Fortunately, the GHS provides some support for assessing the degree of risk associated with the hazard of a single chemical by incorporating Signal Words into its hazard definitions (see Figure 3).

It is important to emphasize that, due to the general nature of the GHS classifications, additional analysis is necessary to fully assess chemical risks in the laboratory setting. There are a variety of chemical hazard evaluation methods that consider additional factors associated with lab processes and conditions. Describing these analyses in detail is beyond the scope of this article, but readers are referred to *Identifying and Evaluating Hazards in Research Laboratories* published by the ACS Committee on Chemical Safety in 2015.[29] This document provides several risk assessment methods appropriate to laboratory work and guidance about their effective use.

Tool 5: Safety Management Measures

Within the iRAMP model, **M**anaging safety involves the development of a hazard control system. The expectations for such a system are delineated for teaching and instructional

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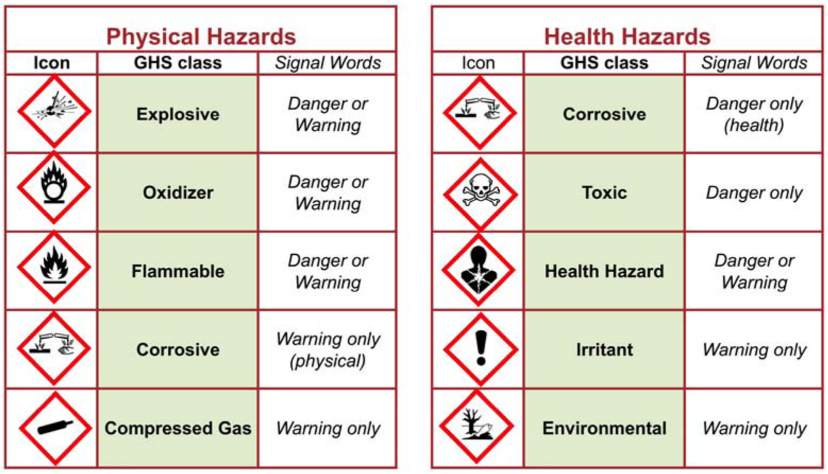

Figure 3. Risk variation within GHS classes.

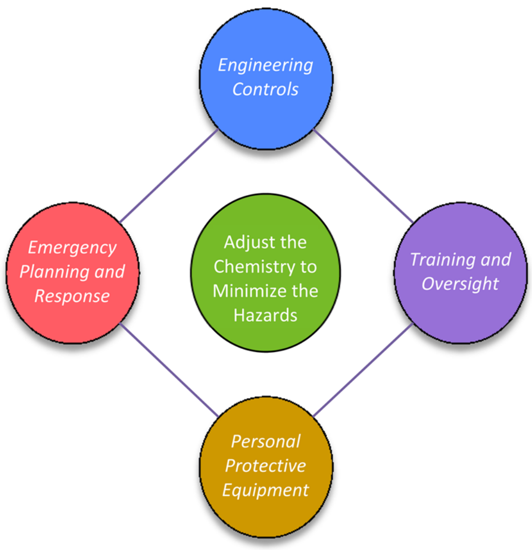

Figure 4. Elements of a laboratory safety management system.

laboratories by the National Fire Protection Association's 2015 amendments to the Standard on Fire Protection for Laboratories Using Chemicals.[30] *Prudent Practices in the Laboratory* provides both administrative and technical guidance for safety management in the research laboratory. In general, the components of a systematic approach to safety management fall into five categories (see Figure 4).

These elements include:

1. Adjusting the chemistry involved to ***minimize the hazards*** it presents. This can be accomplished by reducing the quantity or concentrations of the chemicals used; substituting reagents, solvents, or other chemicals involved; or implementing applicable principles of Green Chemistry.[31]
2. Identifying ***engineering controls*** that can be applied in laboratory spaces and procedures to minimize exposures. Common examples of such controls include general ventilation of the lab space, proper storage of volatile chemicals, and provision of local exhausts such as fume hoods.
3. ***Training, supervision and oversight*** of people working in the lab. This includes identification and ongoing oversight of specific precautions applicable to the planned work, as well as critical points in the system that may require adjusting the hazard control strategy (e.g., allowable temperature conditions during an exothermic reaction).
4. Assignment of ***Personal Protective Equipment*** (PPE) appropriate to the specific hazards involved to minimize direct exposure. This measure involves determining which types of PPE apply to each step in a laboratory process. It also covers standard dress practices such as long pants and closed-toed shoes. Specialized equipment that protects only the individual conducting the work, such as a blast shield, can also be included in this category.
5. ***Emergency planning and response*** involves development of laboratory protocols that address foreseeable events

Table 1. Planning for Multiple Hazard Controls for Specific Lab Activities

Lab Activity	Minimize Hazards	Engineering Controls	Oversight	PPE	Emergency Planning
General work-up and analysis	Maintain reagent quantities below 500 mL	General ventilation and fume hood as needed at various points in process	Daily close-out inspection	Eye protection, nitrile gloves, body and leg protection throughout process; careful attention to glove cleanliness	Spill preparedness, tabletop training, chemical storage
Spill cleanup	Minimize quantities	Work in ventilated spaces	Ask for assistance	Eye protection, rubber gloves, lab coat	Alert others; consider if emergency help is required based on hazard presented, be alert to symptoms
Dishwashing	Assure that all hazardous materials are collected for proper disposal	Work in ventilated spaces	Avoid working alone	Rubber gloves to protect from cuts; eye protection	Be prepared for cuts

DOI: 10.1021/acs.jchemed.5b00511
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not included in standard institutional emergency response plans, as well as effective, ongoing training of laboratory staff in how to implement these plans.

It is important to remember that these components operate together as a safety system; relying on a fume hood, personal protective equipment, or worker training alone to address hazards would not be considered prudent in most chemistry laboratory settings.[32] Examples of applying these systems to various lab activities are given in Table 1. This interconnected, systematic nature of the safety management practices means that there is no single formula that can be used to determine when, for example, particular PPE is required. It is necessary to apply the iRAMP approach to laboratory processes on a case-by-case basis to develop specific requirements for the safety management components.

■ USING INFORMATION LITERACY CONCEPTS TO ORGANIZE LAB SAFETY TOOLS

All of the tools described above have emerged in the 21st Century, most since 2010. While they usefully address specific aspects of the iRAMP cycle, they do not as yet form a coherent approach to laboratory safety planning. For such an approach to develop, it is necessary to have an overall guide to the process, to connect each step up the ramp, and especially to include systematic safety communication to aid in future planning. For educational purposes, it is also important to provide students with an overarching structure for implementing the principles and practices. In this section, we describe how to connect the ACRL and iRAMP models to support chemical information and laboratory safety skill development in the academic laboratory context.

When considering how to use these tools, two key questions arise: "*What chemical information is available to be used in risk assessment and management?*" and "*What is the most effective process for identifying, compiling, analyzing, and applying this information?*" The research practices described by the ACRL literacy framework reflect a process of iterative critical inquiry[3] that can be used to address these questions (see Figure 5). When used in a successive cycle, information processed in

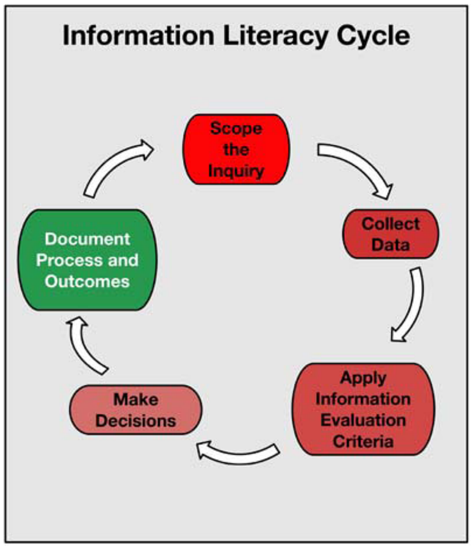

Figure 5. Skills associated with the ACRL information literacy practices.

previous study is available to inform further research. Knowledge is built up in this way as researchers increasingly gain competency in the process of inquiry in a topic, such as laboratory safety.

The CPT expectations for safety skills include developing an understanding of a culture of laboratory safety and how it is implemented through the four key skills described in the RAMP model. Each of these skills has analogs in the information skill set described by the ACRL. By connecting these skill sets, articulating and addressing laboratory safety questions becomes a tractable task that develops critical thinking habits without becoming formulaic. Table 2 illustrates the parallels between these frameworks.

Scoping the Inquiry: Safety Culture

> *Learners... formulate questions for research based on information gaps or on reexamination of existing, possibly conflicting, information.*[3]

Before a researcher can begin the iRAMP process of risk assessment, it is necessary to broadly scope the safety issues that are likely to be connected to a specific procedure under consideration. The initial question is often: "*How do we work safely in the lab with this collection of chemicals?*" In this form, the question is too general; "safely" can be interpreted to be a matter of opinion.

Addressing this interpretation requires an overall safety awareness that is supported by a proactive safety culture in the laboratory work group. As discussed in the National Research Council's publication "Safe Science",[33] "safety culture" involves a proactive approach to managing laboratory hazards that extends across an organization. In its supplementary resources for this report, the NRC provides specific recommendations for various roles in the organization in supporting a safety culture. These roles include Laboratory Researchers, Principal Investigators and Department Chairs, and University Senior Leaders.

A safety culture supports a safety planning process that extends beyond identifying what chemicals will be involved in the procedure, to consideration of other types of hazards that may arise, the scale and relative importance of each of these hazards, and the physical and management infrastructure available to support this work. In addition, interdisciplinary issues need to be considered. Emerging fields of study and technologies such as engineered nanoparticles and synthetic biology do not fit easily into the current chemical or biological safety paradigms. This is partly due to the lack of necessary hazard information associated with these materials and partly because these fields are too new for appropriate regulations that establish social expectations for how they will be handled and used. In such a vacuum, an awareness of prudent practices that apply to the work at hand is especially necessary.

A historical example of a safety culture in a rapidly changing laboratory setting is provided by Dr. Glenn Seaborg's oversight of the health hazards associated with the work of the plutonium lab in the Manhattan Project.[34] An example of how Lessons Learned can be applied to support an improving safety culture is provided in the SafetyZone blog entry: "*A safe lab culture 'should enhance what you do'*".[35] In this interview, Dr. Timothy Gallagher discusses how management and technical issues connect to establish a safety culture in a research laboratory. Thus, safety culture encompasses both the context for, and the goal of, the lab safety research process.

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Table 2. Parallels between ACRL Information Literacy Skills, Chemical Risk Management Skills, and Associated Chemical Safety tools

ACRL Skill	Safety Process Element	Safety Tools	Specific References
Scope the Inquiry and Develop the Question	Lab Safety Culture	Awareness of health and safety best practices and regulatory expectations	*Prudent Practices in the Laboratory*
Collect Safety Information	Recognize Hazards	Hazard information associated with specific chemical and processes	PubChem Laboratory Chemical Safety Summaries
Develop and Evaluate Criteria to Filter Information	Assess Risks	Data providing information about frequency and magnitude of specific risks; methods for organizing this data	*Identifying and Evaluating Hazards in Research Laboratories*
Apply the Data to the Question at Hand	Manage Safety	Hazard Management System development and documentation	Information from manufacturers of laboratory equipment and personal protective equipment
Document and Communicate the Process	Plan for Emergencies/Protect the Environment	Community resources available to support these aspects of laboratory work	Institutional plans and procedures

Table 3. Useful Places To Start for Finding Chemical Safety Information

Chemical Safety Information	Link	Source	Information Coverage
Chemical Safety Searches	https://en.wikibooks.org/wiki/Chemical_Information_Sources/Chemical_Safety_Searches	American Chemical Society Division of Chemical Information (CINF)	Review of chemical safety information sources with tips for searching, includes both open and subscription based sources
ChemSpider	http://www.chemspider.com	Royal Society of Chemistry (RSC)	Aggregates chemical data from several sources, including safety data from chemical catalogs
Enviro-Health Links: Laboratory Safety	http://sis.nlm.nih.gov/enviro/labsafety.html	NLM Specialized Information Services (SIS)	Guide to information sources relevant for laboratory scale work, including nonchemical hazards
Internet Resources for MSDS	http://www.ilpi.com/msds/#Internet	Interactive Learning Paradigms, Inc.	Overview of dozens of chemical information sites relevant to safety, including MSDS, manufacturers, and various government and nonprofit resources
Lab Safety Information Guide	https://library.stanford.edu/guides/lab-safety	Stanford University Libraries	Reviews an extensive diversity of information sources, ranging from substance information to protocols and reaction conditions; may not all be openly accessible or uses only Stanford's links
PubChem Laboratory Chemical Safety Summary (LCSS)	https://pubchem.ncbi.nlm.nih.gov/lcss/	NLM National Center for Biotechnology Information (NCBI)	Chemical safety view based on LCSS in Prudent Practices; aggregates chemical safety data from several sources, including incidents from Bretherick's Handbook of Reactive Chemical Hazards
TOXNET	http://toxnet.nlm.nih.gov/	National Library of Medicine (NLM)	Searches across several government databases related to toxicology and health, including the Hazardous Substances Data Bank (HSDB) and ChemIDPlus (further links to several chemical property sources)

Collecting Information: Recognizing Hazards

> *Learners... use various research methods, based on need, circumstance, and type of inquiry [and] understand how information systems (i.e., collections of recorded information) are organized to access relevant information.*[3]

Recognizing the potential hazards in an experiment or laboratory operation involves review of the specific procedure to be undertaken and collecting relevant data to support an assessment of risks associated with it. Types of data that may be useful range from basic hazard classifications, to chemical and physical properties that may be relevant to the experimental procedure, to handling and disposal protocols for hazardous materials. Information concerning chemical and laboratory hazards exists in a variety of forms and can be found in many disparate sources. However, not all of the information is appropriate for academic research and teaching laboratory situations. Researchers need to be aware of the range of information available to them, from stock bottle labels and SDSs to advanced chemical information databases. The extent of information required and searching necessary depends on the complexity of the situation.

The first type of information to collect is GHS classification and accompanying description for the roster of chemicals involved in the laboratory procedure. It is important to include in this list solvents and other chemicals that may be considered "incidental" to the chemistry under study but are used in significant quantities and concentrations (e.g., etching solutions). It is also important to consider the potential hazards of all products and intermediate chemicals generated during the course of the experiment. The Supporting Information for this article provides an example of how GHS information might be organized to document the hazard recognition and assessment process for a general lab procedure.

Useful chemical and physical properties for many commonly used chemicals have been collected and reported in various safety formats, such as those issued by NIOSH or ILO, and other authoritative handbooks and Web sites. Relevant properties for many more chemicals (hundreds of thousands) are reported by manufacturers in SDSs or compiled from the scientific literature in chemical databases. Fortunately, there are an increasing number of databases that aggregate searching across a broad range of these chemical data sources, including TOXNET and PubChem, available from NLM, and ChemSpider, available from the Royal Society of Chemistry. Many of these feature advanced searching options such as chemical structure and substructure in addition to keyword. The NLM and many campus libraries and EHS offices offer assistance for this search process in the form of guides and lists of preferred sources; some good places to start these searches are listed in Table 3.

A key information literacy skill is the ability to develop criteria that help select among many available commercial, government and professional sources of chemical safety information that are discoverable via a general Internet search by chemical name. For example, consider the coverage of basic hazard statement information found in Wikipedia, managed

DOI: 10.1021/acs.jchemed.5b00511
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through the ChemBox feature found in many specific chemical compound entries. In this way, Wikipedia serves as a third party source for safety related information, reporting GHS hazard information from a chemical manufacturer without systematic review of its sources or coverage. However, the availability of such information is highly variable. For example, the Wikipedia ChemBox for hexane includes the GHS hazard classes for the chemical as well as links that lead to SDSs from several manufacturers for further information.[36] However, the ChemBox for methanol does not include direct access to GHS information,[37] and a ChemBox does not even appear in the entry for butanol.[38] As with any database, coverage varies from chemical to chemical. It is very important for the user of any information source to recognize in this situation that missing hazard information does not mean lack of a hazard, and that all safety information collected should be verified against other credible sources.

The information literate chemist will also recognize the need for more extensive searching beyond the GHS hazard statements and basic properties to compile relevant information for chemical mixtures and lab processes. Most chemical information available is organized around known single compounds. While convenient for many purposes, this approach is not sufficient in itself for recognizing all hazards in the real world application of the laboratory. Additional physical, biological and equipment hazards associated with the process also need to be considered. Some specialized resources describe handling protocols for hazards substances, for example the Sigma-Aldrich Technical Bulletins.[39] However, relatively little other scientific literature focuses on chemical hazards in the context of specific processes.

Searching the aggregated databases mentioned above can surface additional information otherwise scattered in the literature, including chemical incompatibilities, and appropriate waste management practices and storage conditions. When using this information, it is especially important to also review local institutional policies, procedures and training materials to ensure the relevance to the local situation. For example, there is regulatory inconsistency between states in the US with regard to treatment of hazardous wastes and many protocols found in the chemical literature are forbidden by state law and/or state interpretation of federal regulations.[40]

Evaluating and Filtering: Assessing Risks

> *Learners... use research tools and indicators of authority to determine the credibility of sources, understanding the elements that might temper this credibility [and] organize information in meaningful ways.*[3]

Assessing the risks in a laboratory procedure is a process of prioritizing the collected hazard information to highlight those risks that will drive the approach to managing the hazards. This involves establishing ranking criteria based on the collected data and the specific conditions in the experimental procedure and laboratory environment, including new chemicals that are expected to arise during the process, as well as physical factors that may impact the progress and hazards of the procedure, such as temperature or pressure extremes.

Prior to data analysis, it is critical to have an appreciation of the limitations and biases of both the sources of information as well as the databases that deliver them. As discussed above, both MSDS and SDS information have limited applicability in the academic lab setting. Much of the data in aggregated source databases are quite variable in intended audience and context, addressing hazmat scenarios as well as providing information useful in OSHA-defined laboratory settings. For example, the data in the PubChem Laboratory Chemical Safety Summary (LCSS) view highlighted in Table 3 is provided "as-is" from the original source with clickable links. Thus, variability in the reported data reported in these original sources will show up in the LCSS view. This may by may be confusing at first, but provides the literate user the resources needed to make their own assessment of and document which data they decide to use for safety planning purposes. Thus, the PubChem LCSS provides conveniently consolidated view of an open Internet search on chemical hazard information, with nonauthoritative sources filtered out and available documentation on the context of each data point. The Institute of Museum and Library Services provides a suite of rubrics for assessing information literacy skills that can provide guidance on evaluating information sources used in research and teaching.[41]

To make an informed evaluation, researchers will need to devise an approach to organizing collected data, identifying patterns and determining information gaps or areas of particular concern. An example of this logic is found in the Supporting Information. GHS hazards are identified for the chemicals involved in the process to be assessed and the GHS Signal Words are entered into a table. The hazards are then ranked in terms of their importance with the aid of the GHS Signal Words and interpreted in the context of the work being done. It is important to note that the hazard assessment of mixtures is often based on professional judgment, as data specific to mixtures are not often reported in the literature.

Assessing risk considers both the types of hazards involved and the potential for exposure to those hazards. Characteristics of chemicals that most commonly influence exposure include, among others, quantity, concentration, physical form, route of exposure, and warning properties such as noxious odor. It can also be helpful to think about the likely probability, frequency and consequence of an exposure in the specific lab scenario at hand when prioritizing the potential for risk. Methods for assessing risks in these terms are described in "Identifying and Evaluating Hazards in Research Laboratories."[42]

Applying the Data: Managing Safety

> *Learners... synthesize ideas gathered from multiple sources [and] draw reasonable conclusions based on the analysis and interpretation of information.*[3]

Managing the hazards associated with a laboratory process involves mapping the identified risks with an appropriate profile of control measures from among those discussed above and illustrated in Figure 4. For example, flammability of the solvents was highlighted as the primary risk in the exercise included in the Supporting Information. The critical question then becomes "*How does one select and implement controls to address this particular risk in the context of a normal lab activities such as chemical procedures, storage and waste disposal?*"

In the laboratory, this involves working through the collected and organized data about hazards in light of previous experience with this and similar processes. On the basis of this information, a professional judgment of the risks involved must be made to arrive at prudent operational decisions and the management methods that will be used to control those risks. These professional judgments should be based on both best practices found in the literature and local experiences and support services. Thus, the laboratory supervisor and the host institution share legal responsibility for the safety management

DOI: 10.1021/acs.jchemed.5b00511
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Table 4. Developing Risk Management Decisions from Chemical Safety Information

Articulating the questions at hand	Collecting relevant data	Interpreting hazard and risk implications	Identifying relevant local guidelines	Implementing an operational judgment
Where will the acetone I use be stored?	Flashpoint (collected from a database search with agreement among three sources)	Specific interpretation: because of its flashpoint and boiling point, acetone presents a fire hazard from GHS label)	Local fire codes require cumulative totals of flammable liquids more than 10 gallons be protected from fire (from the local fire codes or Chemical Hygiene Plan)	Gallon containers of acetone will be stored in the flammables cabinet, but 50 mL appropriately labeled containers of samples dissolved in acetone can remain on the lab bench in secondary containment overnight
What Personal Protective Equipment should I use when pouring sulfuric acid?	Acid concentration (information specific to the reagent used, collected from lab notebook)	Because of its pH, sulfuric acid presents a corrosive health hazard (from GHS SDS)	Nitrile gloves provide excellent protection against sulfuric acid less concentrated than battery acid (45%) (from the Ansell glove chart)	Wear nitrile gloves and a face shield when pouring 37% sulfuric acid
How many chemical waste containers do I need for this lab?	Reactions between nitric acid and acetic acid generate gases (available from the chemical reactivity references)	Nitric acid and acetic acid form reactive mixtures that have exploded (available from the chemical reactivity references)	Waste containers must contain compatible chemicals (from institutional waste management plan)	Establish separate waste collection containers for acetic acid and nitric acid waste solutions
Is it acceptable to store daily use quantities of solvents in a fume hood in the lab where the work is being performed?	Four 500 mL containers of flammable solvents are needed during daily work. There are 2 excess fume hoods in the lab. The nearest available flammable cabinet is down the hall and involves opening two doors and travel in a public corridor.	Significant quantities of flammable liquids require storage that protects them from fire in their environment (from review of GHS information the chemicals involved)	*Manufacturer's precautions for these fume hoods say "Do not use the fume hood for storage of corrosive or volatile chemicals."* (from label attached to fume hood)	The risk associated with moving chemicals to and from the flammable cabinet each day outweighs the fire risk for the quantity of chemical involved, as long as users understand that the hoods with stored chemicals are not to be used for chemical processes.

choices made and consultation with local safety professionals is often an important step in establishing that these judgments are considered prudent when the chemistry being conducted presents risks beyond those described in the available literature.

Table 4 illustrates several examples of using the RAMP process for evaluating and managing laboratory hazards, from formulating relevant safety questions to collecting information, assessing risks and implementing decisions based on professional judgements. Because of the unique nature of these decisions, it is important that they are presented clearly and the Supporting Information sources are documented to refer to when questions arise.

Documenting and Communicating: Planning and Protecting

> *Learners... follow ethical and legal guidelines in gathering and using information [and] transfer knowledge of capabilities and constraints to new types of information products.*[3]

Planning for emergencies and protecting the environment involves coordinating with the larger institutional and local communities of researchers, safety professionals and the public. These interactions are usually governed in great part by economic, legal and social structures. It is critical that researchers are aware of legal requirements, institutional expectations and cultural norms for supporting successful research programs. This awareness of the obligations associated with using hazardous chemicals is manifested through documentation of the research process and outcome in sufficient detail to communicate the rationale for the conclusions made.

This comes into play most prominently at the most heavily regulated stages of the chemical process—emergency response and waste disposal. A strong safety culture supports the opportunity to do research and work with chemicals, and comes with the associated responsibility to handle materials in a legal, ethical and prudent manner. Some of the tasks associated with ethical and safety-aware conduct of laboratory work include the following:

- Review of institutional and legal requirements to determine if there is a difference between the actions planned and the relevant guidelines
- Documentation of the reasons that the procedures being planned are more prudent than following general guidelines, including the process of analysis and citation of sources supporting the approach
- Sharing of best practices that are more effective than those described in the general literature, by explicitly documenting this hazard assessment as part of the scientific reporting on the work
- Contributing to the larger Laboratory Safety Culture by sharing Lessons Learned that occur as the work proceeds. Useful process information can be included in the Methods or Results sections of journal articles, or as accompanying Supplemental Information. Emerging online avenues for sharing such information include Not Voodoo X.[43]

■ CONCLUSION

Since 2009, a series of fires and explosions in academic research laboratories have led to increasing national concern about the safety performance and safety culture of laboratory scientists in the higher education sector. In 2014, four educational demonstrations in high schools and museums involving methanol flames got beyond the control of the presenters and resulted in injuries to people in the audiences.[44] These incidents and rising concerns have prompted reports from research institutions,[45] government agencies, scientific societies, and academic professional organizations. These reports identified the need for improved education in laboratory chemical risk assessment in undergraduate laboratory sciences. This need is reflected in the 2015 version of the CPT guidelines that references the RAMP model for targeting safety skills in teaching.

Risk assessment is a process of inquiry, research and analysis that mirrors the process of experimental design and invokes the information literacy skills that underpin the scientific process. Bruehl et al. described the development of information literacy

DOI: 10.1021/acs.jchemed.5b00511
J. Chem. Educ. 2016, 93, 516−526

by incorporating use of primary scientific literature into experiment design curriculum.[46] We have extended this parallel to teach information literate processes for risk assessment as a core foundation for safety culture with chemistry researchers at the undergraduate level. The ACRL suggests that:

> *Gaining skills in information literacy multiplies the opportunities for students' self-directed learning, as they become...conscious of the explicit actions required for gathering, analyzing, and using information.*[47]

Awareness of the critical actions and informed decision making throughout an entire research process are core components of a lab safety culture.

Looking forward, it is likely that laboratory safety practice will continue to evolve rapidly, as laboratory science increasingly converges between traditional disciplines[48] and new hazards are recognized. These developments will create ongoing challenges in understanding and meeting social expectations for laboratory safety practice.

Continuous improvement of lab safety practice is an important element of meeting this concern. Key among the challenges will be understanding the most effective way to collect and share Lessons Learned from laboratory incidents. The connections we have outlined above between laboratory safety and information literacy skills will help future chemists and other laboratory scientists to meet those challenges in a proactive and productive way.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00511.

Excel file that demonstrates documentation of the iRAMP process for a general laboratory process (XLSX)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We would like to acknowledge the ongoing discussions with a wide variety of colleagues, primarily, but not exclusively associated with the Divisions of Chemical Information and Chemical Health and Safety of the American Chemical Society in developing these ideas. Parts of this work were supported by an Innovative Projects Grant from the American Chemical Society to these two divisions.

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DOI: 10.1021/acs.jchemed.5b00511
J. Chem. Educ. 2016, 93, 516−526