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Innovations and Renovations: Designing the Teaching Laboratory

In Innovations and Renovations: Designing the Teaching Laboratory; O'Connell, L.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2013.

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Innovations and Renovations: Designing the Teaching Laboratory

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Foreword

The ACS Symposium Series was first published in 1974 to provide a mechanism for publishing symposia quickly in book form. The purpose of the series is to publish timely, comprehensive books developed from the ACS sponsored symposia based on current scientific research. Occasionally, books are developed from symposia sponsored by other organizations when the topic is of keen interest to the chemistry audience.

Before agreeing to publish a book, the proposed table of contents is reviewed for appropriate and comprehensive coverage and for interest to the audience. Some papers may be excluded to better focus the book; others may be added to provide comprehensiveness. When appropriate, overview or introductory chapters are added. Drafts of chapters are peer-reviewed prior to final acceptance or rejection, and manuscripts are prepared in camera-ready format.

As a rule, only original research papers and original review papers are included in the volumes. Verbatim reproductions of previous published papers are not accepted.

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Preface

As any homeowner knows, the prospect of embarking on a renovation project is both exciting and scary. Will the finished space function as it was envisioned? Will the environment be both comfortable and aesthetically pleasing? Will the project be completed on time and within budget? Similar questions and emotions come into play when an academic institution undertakes a laboratory renovation or construction project. This highly collaborative process can be both complex and intimidating. Exploring a variety of designs that have succeeded in enhancing student learning in the laboratory and fostering positive attitudes toward science is an important first step on this journey. An impending teaching laboratory renovation project in my own department was the inspiration for the symposium that I coordinated for the Biennial Conference on Chemical Education at Pennsylvania State University on July 29, 2012.

The chapters in this volume describe projects at institutions that vary in size and type and are written from the perspective of faculty and staff, and even members of architectural firms who have worked on multiple academic laboratory projects. Large and small schools, public and private institutions, as well as both comprehensive universities and primarily undergraduate colleges, are all represented.

The impact of evidence-based teaching practices on chemistry education, such as the use of guided inquiry and cooperative learning, is reflected in these laboratory designs. Many schools are promoting interdisciplinary collaborations among the sciences by constructing spaces that are shared by multiple departments. In addition, a desire to make the field of chemistry more accessible to non-scientists, by including open communal areas and increased visibility into laboratories, is echoed in more than one chapter.

While common themes do emerge throughout the book, each chapter also offers its own unique perspective. You will learn about the history of teaching lab design via descriptions and photos of the original laboratory spaces, and then see how they were transformed into modern facilities. Laboratory construction projects that have resulted in award-winning “green” buildings are described. You will read about a school that connects the instructor to the students using monitors that are distributed throughout the lab. You will discover the flexibility of “super labs” and the convenience of an environmental chemistry mud room.

Cooperation and coordination are key components of any successful project, and the authors stress the importance of including all stakeholders in the design process. It is hoped that this book will give the constituents at your institution a chance to examine the innovations that have been incorporated into other educational labs and enable everyone involved to make informed decisions as your renovation or construction project moves forward.

I am grateful to the authors of these chapters for their willingness to share their experiences with others. I wish to acknowledge the staff at the ACS Books Editorial Office, especially Tim Marney and Kat Squibb, for their support and assistance throughout the process of compiling this book. In addition, I would like to thank the many reviewers for their constructive comments, as well as R. Lynn Rardin for his advice during manuscript proofreading.

Lastly, the result of my own department's renovation project is depicted in the cover photo, which shows the shared introductory and analytical chemistry teaching laboratory in the Merkert Center at Boston College, completed in August of 2013.

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Editor's Biography

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Lynne A. O'Connell

As the Director of Introductory Laboratories in the Chemistry Department at Boston College, Lynne O'Connell has been coordinating and developing curricula for the General and Organic laboratory courses since 1991. She has published papers about problem-based inquiry experiments and TA training and has given numerous presentations at chemical education conferences on a variety of topics. She is currently Chair of the Undergraduate Studies Committee in her department. She received a B.Sc. degree from McGill University and a Ph.D. from the Massachusetts Institute of Technology.

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Chapter 1

Strategies for Chemistry Instructional Laboratory and Curriculum Design

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Chemistry includes both theory and practice, and therefore instructional labs must be designed to support the investigation and synthesis of both ideas and materials. The needs of the physical facility and the curriculum together define the structural design of a particular laboratory, and the design process must account for both. This chapter presents a case study of the design process of a major renovation and expansion project of the Chemistry instructional laboratory facilities at the University of Iowa. The many complexities that can be expected during such a project and strategies for managing them are discussed.

Introduction

Chemists who engage in both chemistry research and chemical education commonly believe that a substantive laboratory experience is a vital part of a rigorous chemistry curriculum (*1*, *2*). Chemistry includes both theory and practice, and therefore instructional labs must be designed so that their layouts support and optimize the investigation and synthesis of both ideas and materials (*3*, *4*). It is the idealized belief that, in the laboratory, conscientious students are able to connect the concrete to the conceptual. Students are able to observe, measure, and engage in scientific thinking in a way that leads to new knowledge and understanding of the symbolic, particulate, and macroscopic natures of matter.

Many have noted, however, that the actual yield of learning in instructional laboratories is less than ideal (*5–8*). The creation of a laboratory teaching environment, both intellectual and physical, that moves the real towards the ideal is a worthy and ongoing goal of quality chemical education (*9*). This chapter will

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outline strategies that were developed and applied as part of a major renovation and expansion project of the Chemistry Building at the University of Iowa. The University of Iowa is a public research university, with an undergraduate enrollment of 22,000 and postgraduate enrollment of 9500. The focus here will primarily be on the instructional laboratories that serve large-enrollment general chemistry courses, with some comparisons to advanced undergraduate laboratory courses that illustrate the varying needs at different levels within the chemistry curriculum.

Historic Background

There is an unmistakable relationship between form and function in instructional laboratory designs (*10*). Thus, as design decisions are made that fix the layouts and infrastructures, implied decisions regarding near- and long-term functions are made with both dollar costs and opportunity costs. Consideration of these costs makes the process complex and painstaking. Competing needs and constraints must be identified, analyzed, prioritized, and acted upon as the design process progresses. The process is often slow, but each individual design choice must be guided by a vision of the larger goals.

For renovation and expansion projects, new instructional laboratories need to complement the existing institutional structure, and therefore, as the design project begins, the analysis of existing laboratories and their functions informs the process that defines the traits of the next generation of laboratories. In a historical context, this defines the manner by which evolution of the instructional laboratories occurs. Since the outcome can only be understood within the broader context of the institutional heritage, we will give a brief history of former instructional laboratories.

The central portion of the Chemistry Building was approximately 80 years old at the time of our recent renovation and expansion. However, its structure revealed that renovation and expansion are a natural part of healthy institutional growth and development. As shown in Figure 1, the central portion of the Chemistry Building was constructed in 1923, with five floors of space containing classrooms, a large auditorium (400 seats), a medium auditorium (60 seats), a chemistry library, offices, and instructional and research laboratories.

In 1927, a northeast wing was added to house the Botany Department. In 1960, a significant expansion of laboratory space was provided by the addition of a northwest wing, and in 1963, a second large auditorium was added to the building (Figure 1).

It is interesting to compare and contrast the instructional laboratories of the past with those of the present. Figure 2 shows students in instructional labs during the 1930's. Although the use of lab benches and chemicals is a feature that is shared with modern workspaces, the standards that relate to safety equipment and practices are obvious areas of change. It is also interesting to note the lack of chalkboards or other instructional tools within the laboratory space, and from the regular array-like distribution of students, it also appears that independent lab work was the paradigm.

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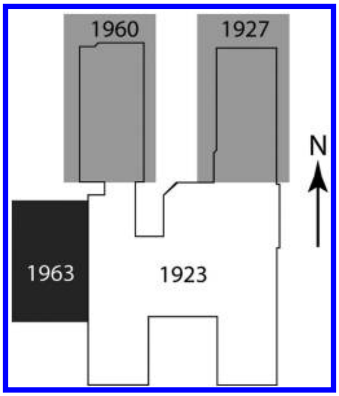

Figure 1. The Chemistry Building at the University of Iowa was built in 1923, with additions in 1927, 1960, and 1963.

Although there were renovations to the original laboratories in 1960 and 1985, the laboratories still relied primarily on infrastructure that traced back to the 1923 construction. Meeting the maintenance, energy costs, and modern safety standards were among the ever-increasing challenges of supporting instructional laboratory operations. Further, since labs were brought online through a stepwise process of expansion and renovation, the laboratories were often unique in structure and widely distributed throughout the building. Overall, this led to operational inefficiencies. Since research and instructional laboratories were in adjacent spaces, the traffic of students from the lecture and lab courses through research areas led to security and safety concerns.

For example, instructional labs were distributed between the northwest, southeast, and southwest wings of the building on three different floors. Three general chemistry labs were located on the second floor southwest wing (2nd-SW) along with the central chemical storage and reagent preparation areas. Two more general chemistry labs were located on 2nd-NW and one on 3rd-NW. Two organic labs were located on 4th–NW and one on 3rd-NW, which had reverted to research use because of temporary declines in enrollment. The organic/inorganic laboratory for Chemistry majors was located adjacent to the instructional NMR and GC/MS instrument room on 2nd-SE. A wet lab with adjoining instrumental laboratory was located on 2nd-SE and was used by physical and analytical chemistry courses. Overall, all ten labs and one prep-lab were in active use, with one additional lab used for fluctuations in course enrollments.

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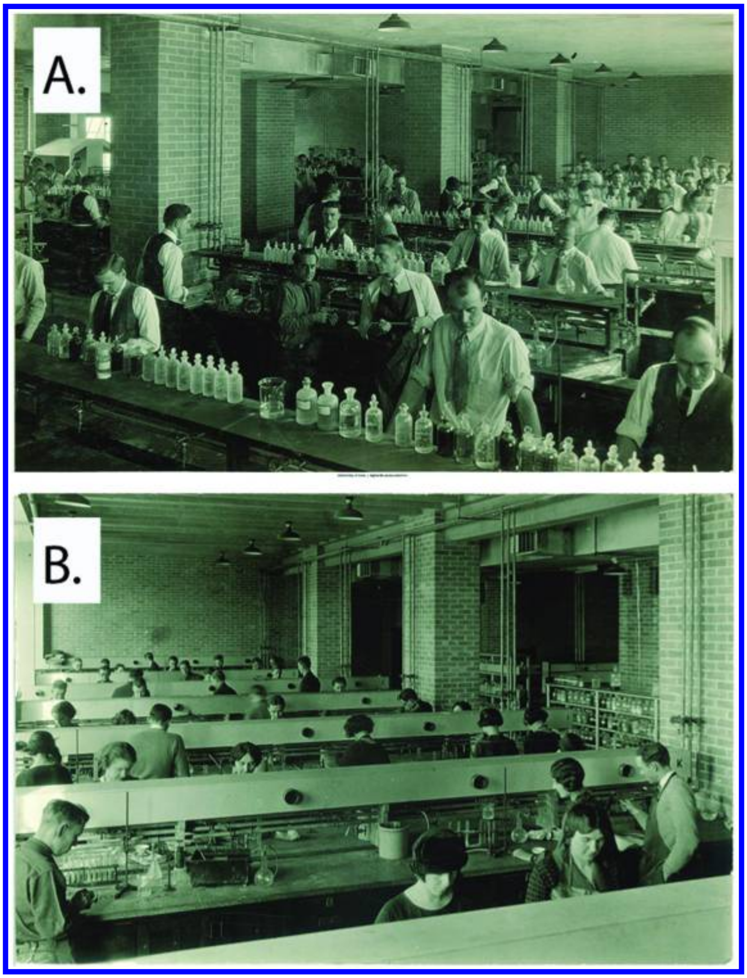

Figure 2. A. Students in an inorganic lab during the 1930's. B. Students in synthesis lab during the 1930's. [Reproduced by permission: Frederick W. Kent Photograph Collection, The University of Iowa Libraries, Iowa City, Iowa (11, 12)].

Renovation Project Overview

In 2003, The University of Iowa proposed a major renovation of the Chemistry Building and, in 2004, obtained funding authorization from the Governor and State Legislature. Significant planning moved forward quickly, and a lead group of University administrators, space and facilities management representatives, Departmental representatives, architects, and engineers was formed. In the end, the project would create 48,750 ft^2 of new space and 102,000 ft^2 of renovated space, with a project budget of over $35 million (*13*). The work was completed in phases to enable normal occupancy of the building in areas not directly impacted by each phase, and the project lasted through 2010.

The primary focus here will be on Phase 1b that demolished core components of the building and then reconstructed an expanded core. The concept of a central core expansion emerged early in the design process. The choice was made to allocate this space towards instructional tasks, after it was learned that the widths of laboratory spaces in the existing wings of the building did not meet the code requirements for egress.

Phase 1b led to removal of large and medium auditoria from 1923 that had undergone only minor changes; these structures are indicated by the dark-shaded regions in Figure 3A. Because of the University's need for a large auditorium, the demolition of the central core structures was made possible by the construction of a large auditorium in the adjacent Pomerantz Center that opened in 2005. Thus, all designs must be evaluated in the context of both immediate and long-term campus-wide needs.

A new central core was designed that would function as the central distribution point for utilities for the entire building, and thus would facilitate future renovation of other building areas. The core significantly expanded the building, as illustrated by the dark-shaded region of Figure 3B. Infrastructure modernization included new electrical systems, emergency power, addressable fire alarms, and telecommunications and data lines. Updated mechanical work included HVAC (heating, ventilation and air conditioning) with exhaust heat recovery, low-flow fume hoods (which reduced engineering, construction, and equipment costs associated with ductwork-mounted active controls and dampers for varying fume hood air exhaust), fire suppression, and piping of deionized water, air, natural gas, vacuum, dinitrogen, and hot and cold water (*14*).

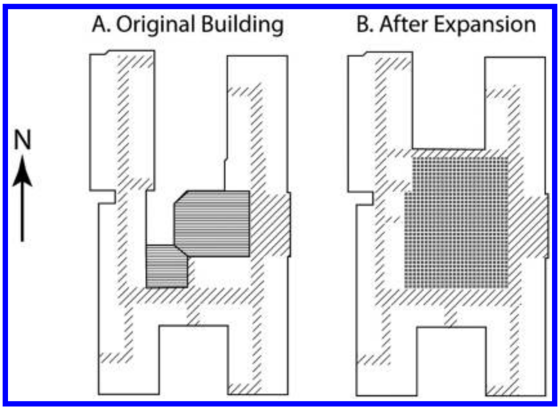

Figure 3. A. The outline of the Chemistry Building prior to expansion in 2005. Hallways and stairwells are shown by the hash marked paths. A medium and large auditorium are indicated by the darker shaded area. B. During the expansion, the central auditoria and attached structures were removed, and a new central core was constructed, indicated by the darker shaded area.

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The majority of the new space in the central core was allocated to support the teaching mission, with a large fraction allocated to instructional laboratories. Outdated laboratory space, 13,526 ft^2, was replaced by 19,923 ft^2 of new and efficient laboratory space. Phase 1b was initiated in 2005 and completed in December 2007. On-time completion was critical so that operations could be shifted to the new laboratories over winter break, and the next phase could begin on schedule. At multiple times during constructions, careful coordination was needed to ensure that student, Department and University needs were simultaneously met.

Introduction of the Case Study Instructional Concept

Although it is easy to get lost in the myriad details related to physical structures and costs, the true value of the new instructional laboratory space is its use to enhance the education of 1500-1800 students each semester. It is for this reason that we now focus on the pedagogical restructuring of our general chemistry courses that preceded the physical laboratory restructuring. For optimal function, the curriculum and the instructional spaces that support that curriculum should target common goals. Further, specific goals should adhere to a larger conceptual framework formed by knowledge of best practices and guided by theories of how to promote learning and development of problem solving skills.

In 1996, there was a significant effort by the Chemistry Department to move the laboratory experience beyond a traditional approach of explicit step-by-step instructions that directed students to verify chemical principles and practice basic laboratory techniques. The traditional methods were largely acknowledged to be less-than-optimal for student learning (*15*). By 1998, new experiments were implemented in which the laboratory activities were cast in a larger problem-based context that blended components of lab skills development, guided inquiry, and open-ended problem solving as appropriate for each topic (*16*). In addition, workstations that included computers, computer interfaces with probes, and USB-interfaced spectrometers were introduced to facilitate measurement and provide students with hands-on experiences with modern measurement and analysis methods. Further, it was recognized that projected video display from teaching assistant computers was important in communicating and sharing student results in the lab area during the new laboratory activities. Although this initiative increased student interest, engaged students in higher- order thinking, and used more modern measurement methods, the Department concluded that the extent of success was limited by the structure of the curriculum, which isolated the laboratory into its own separate course.

At that time, General Chemistry was a one-year course, three semester hours (s.h.) each semester, with three 50-minute lectures per week and one 50-minute discussion section. A related one-semester laboratory course (2 s.h.) was delivered as one 50-minute lecture and 170 minutes of laboratory work each week. The laboratory course was taken by students enrolled in the second-semester lecture course, but for various reasons, many students did not take the courses simultaneously. One of the assumed advantages of this course design was that students had already completed one semester of chemistry and were thought to

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be better prepared for the challenges of the laboratory. However, there were also significant disadvantages. The laboratory course was independent, and therefore no consistent connection was made between learning in the two courses (*17*). Further, of the 1200 to 1400 students who completed the first semester course each year, only 50-60% elected to enroll in the second-semester lab course. To the extent that the laboratory can provide a unique and powerful learning opportunity for students, this attrition of students between courses represented a significant lost opportunity.

To provide a better integration of laboratory and lecture components, the Chemistry Department restructured the general chemistry courses in 2002. A one semester hour laboratory component was integrated with the lecture courses (4 s.h. for each integrated course). A new course component, the case study, was introduced. The case study and laboratory activities function together within the integrated courses. These components use a problem-based approach to provide a context that challenges students to recognize and apply chemistry to real-world issues. Students are involved in activities that use a variety of tools, ranging from the traditional tools of chemistry to sophisticated instrumentation, computer models, and other learning materials.

The case study and laboratory sessions meet on alternating weeks. Students attend case study period (80 minutes, week 1) followed by a laboratory period (170 minutes, week 2). Students are divided into A-groups and B-groups, so that the laboratory facilities are used equally both weeks; each week one group uses the lab while the other participates in the case study activity. Each focus topic is initiated in the case study session with 24-96 students, and the topic is extended in the laboratory with sections of 24 students. In the case study, students are led by a faculty instructor through an activity meant to provide the background context of the case study topic and to highlight key ideas using demonstrations, class discussions, and written guided inquiry (*18*, *19*).

Since the focus is on the application of chemistry, rather than the chemistry itself, it is important to know the content knowledge that the students have encountered in the lecture side of the course prior to coming to case study (*20*). In the case study component, the activity typically takes the form of a guided inquiry; the student does not know the end result, but the intended outcome is known in advance by the instructor. In this way, the instructor works to scaffold the complex problem so as to maintain the cognitive load within a range that is not overwhelming to students (*21*). The instructor asks the students to recall relevant chemical information in a just-in-time delivery scheme that connects the larger issue to ideas that the students are encountering in a more focused chemical context in lecture and homework.

Case study presentations usually begin with a brief introduction (10-15 minutes) focused on defining the societal and scientific context of the topic. In the remaining time, students are led by a faculty member through an investigation of the problem, including aspects of experimental design that the student will use in the laboratory (*22*, *23*). As part of the course, students purchase a case study/laboratory manual that outlines the topics, provides reference information, gives laboratory information, and outlines the questions and problems that are to be addressed by the student during the case study and laboratory sessions.

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The students are responsible for recording data in their laboratory notebooks for the experimental-types of activities in case study, as well as the experiments in laboratory. A more detailed example of a case study and laboratory activity that is used to present the topic of nanotechnology is given in references (*22*, *23*).

Although the students know the general topic area, the exact nature of the demonstrations are not revealed in the students' manual, and therefore the instructor, by scaffolding questions and providing feedback, works to provide students with an opportunity to gather data and construct their own understanding of the problem. In the laboratory, activities often start by developing specific laboratory skills but usually have a second part in which students make more open-ended decisions regarding experimental design or analysis (*22–25*). Students often need to work in groups of two, four, or eight, depending on the scope of the problem and the diversity of parameters to be investigated.

This course structure had the immediate logistical impact of annually engaging 2300 students (for 1 lab s.h.) compared to the previous system of 700 students (for 2 lab s.h.). However, because of the alternating week schedule, students could be accommodated within the five laboratory rooms that had been allocated for the general chemistry sequence. It is also important to note that, although it had been traditional to check out individual equipment drawers to students, the increased number of students led to a shared equipment model. This shared equipment model greatly enhanced the ability of instructors to implement new experiments by reducing the investment necessary to purchase and time needed to distribute new equipment as experiments are modified.

This course restructuring immediately preceded the building expansion and renovation. Even though the case study-laboratory model had been in use for only a year when the expansion design process started, the case study-lab model was used to define and design the environment in the new general chemistry laboratories.

Matching Needs to Space

One of the first tasks of the formal design process was to complete a space survey of the current building so allocation plans could be provided for the project. An external consultant, using data gathered from the Chemistry Department, conducted the survey. In consultation with the architectural firm, it was concluded that ten instructional laboratories could be located within a newly-constructed central core and would meet the requirements of current laboratory course enrollments.

A major advantage of this central location was that it would enable laboratories to be clustered by similar usage patterns to gain maximal operational efficiency. Five labs on the third floor, as illustrated in Figure 4A, serve the general chemistry courses. Each lab has two doors into the central hallway of the building for safe and easy student access. The general chemistry labs each accommodate up to 24 students. The five teaching labs surround a central prep facility, and internal access from the prep-lab to each teaching laboratory is provided as shown in Figure 4B, which eliminates the need to transport chemicals and materials through busy hallways.

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To meet the needs of the case study sessions, auditoria with sink, natural gas, and dual projection displays were included in the core on the second and first floors. Since case study sessions involve multiples of 24 students, the largest of these auditoria has a capacity of 120 students, but is typically used for sections of 48-96 students. The second auditorium has a capacity of 60 students and is used for sessions involving one or two lab sections at a time.

The relative arrangement of the five advanced course labs, located on the fourth floor, is similar to the third floor with the following correspondence: labs 1 and 2 are organic labs, lab 3 is a general use wet lab similar in design to the general chemistry labs, lab 4 is an instrumentation lab for analytical and physical chemistries in alternate semesters, and lab 5 is an advanced organic/inorganic synthesis lab. The advanced labs accommodate between 20 and 24 students each and have different numbers of low-flow fume hoods, depending on the instructional and safety needs. The prep-lab area on the fourth floor is subdivided into an NMR room, laser room, small shared instrumentation lab, and satellite prep-facility.

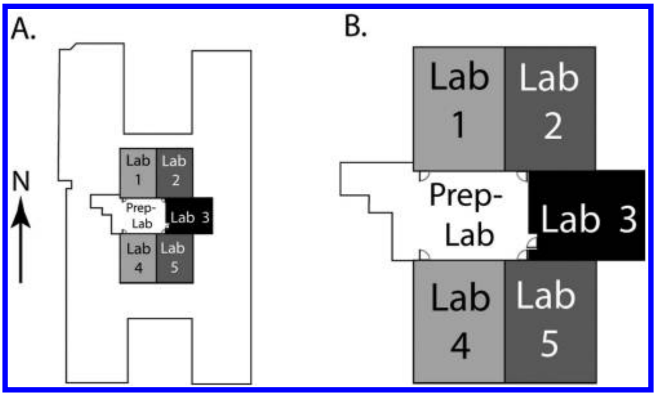

Figure 4. A. The 3rd-floor general chemistry laboratory area within the center core of the building. B. An expanded view of the 3rd-floor labs.

Overall, the concentration of the instructional activities into the central core on the first through fourth floors has drastically decreased student foot traffic in the research areas of the building, thus improving general safety and security. The one disadvantage of the core design, which was recognized at the time of planning, was that the laboratory capacity is inflexible. For example, if lab course enrollments were to expand beyond those at the time of the construction, then it would be necessary to move beyond the core. However, at the time, the risk was thought to be acceptable, and no specific accommodation was made to build in expansion capacity for instructional labs in the wing areas of the building. Although it could not have been predicted at the design time, enrollments in general chemistry and organic labs increased substantially. Initially, the increased number of students was accommodated by expanding into evening lab hours, but starting in spring 2012, it became necessary to expand into a laboratory that was originally designed for research. Although the immediate enrollment demand

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was met using this arrangement, the use of non-optimal learning spaces presented logistical challenges for both support staff and instructors.

This example illustrates that there are many decisions that are made in real time, based on the best available information. However, it is important to note that judgments with the benefit of hindsight should not be critical but rather should be acknowledged to guide future planning. The Department is currently in the process of adding a new capstone laboratory course in the B.A. curriculum, and in designing the new course, decisions that were made during the renovation process provided both benefits and constraints.

Description of Laboratories and Supporting Facilities

When students enter the general chemistry laboratory, they use cubicles to stow backpacks and other personal items before taking their positions at the laboratory benches. Eight students share a long bench (20’ x 5’) with four students on each side (Figure 5A). Most activities are completed at the laboratory bench. A side bench, with three sinks, drying racks, and above-bench adjustable shelving is available for shared use. Four 6-foot fume hoods are provided for workspace if volatile chemicals are used. When feasible, a complete set of shared equipment for each experiment is stored in the drawers at each workstation, and when it is safe to do so, chemicals are distributed from the center of the bench. This reduces the hazards of carrying chemicals around the lab and minimizes bottle necking and congestion. Further, there is plenty of cabinet space in the labs to store equipment, and if needed, labeled student samples between weeks. Storage of the equipment in the laboratory enables the prep-lab area to be used primarily for chemical storage and preparation. Labs are equipped with fume hoods, safety showers, eye washes, drench hoses, fire extinguishers, spill kits, emergency lighting, and video security and alarm systems.

Computers with interface, probes for measurement, and other laboratory equipment are set-up near the corners of the benches and have close proximity to the natural gas, vacuum, electrical outlets, and cup sinks near each station. In this way, students can turn out towards the corners and are well separated while working in pairs on experiments and measurements. Then, when comparing results or working in teams on analysis, the students gather in the central portion of the bench. Thus, teams of 2, 4, 8, or 24 are easily formed and managed within one laboratory, depending on the nature of the experiment.

Each room is equipped with a separate workspace and computer for the teaching assistant, and the computer output can be projected for viewing by the class. This is useful for the brief safety and highlight information at the start of the session and for collecting and displaying data from the students in the section as a whole. During the design phase, line of sight was a priority, and each laboratory station has an unobstructed view of the screen. Furthermore, visibility of every student by the teaching assistant is possible. This is very important to enable instructors and teaching assistants to easily monitor groups for safety, feedback, and group discussion during the laboratory activity.

To illustrate how courses with different instructional objectives lead to different laboratory structures, it is interesting to contrast the general chemistry laboratories to the advanced laboratories. We will not attempt to give all the details of these other laboratories, but rather will point out a few key characteristics and specialty features.

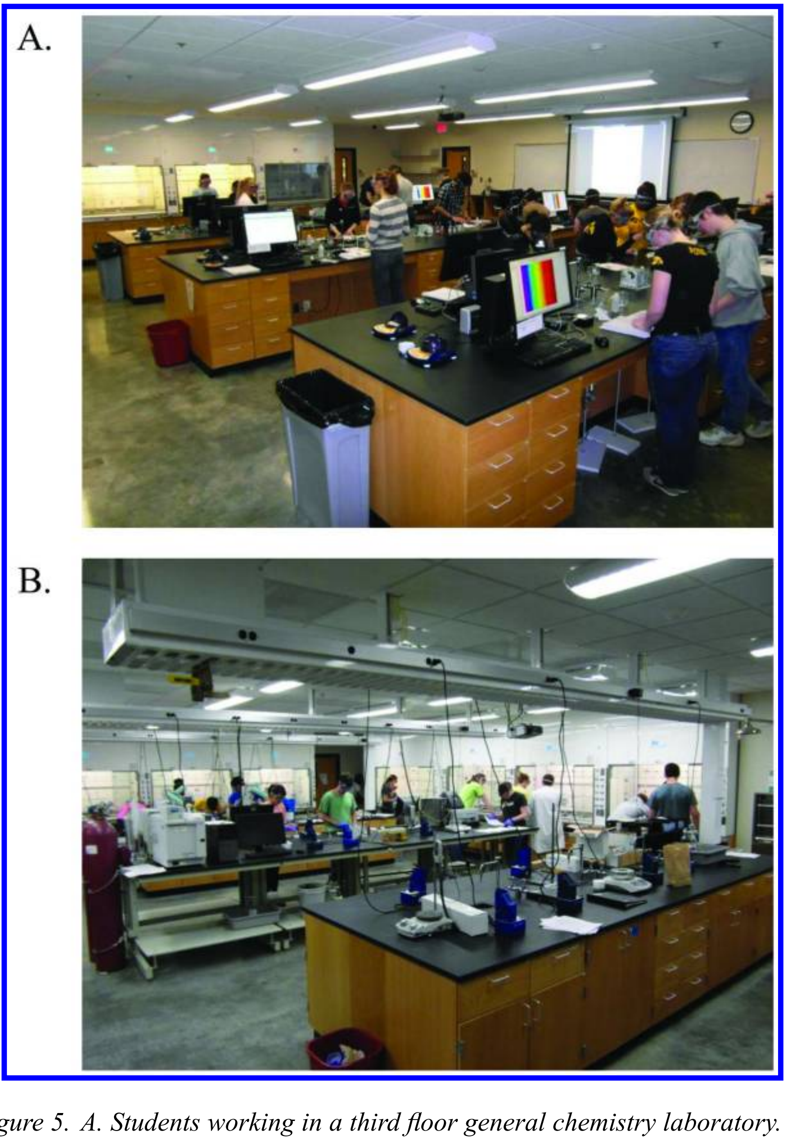

Figure 5. A. Students working in a third floor general chemistry laboratory. B. Students working in a fourth floor organic synthesis laboratory.

In the organic laboratory courses, training in the methods of organic synthesis is a major course objective (*26*). For this reason, additional fume hood space is necessary so that each student can safely develop competence in synthetic methods. Computer access at each station becomes unnecessary. The organic laboratories are equipped with ten 6-foot low-flow fume hoods and one 8-foot low-flow fume hood. These hoods are distributed around the periphery of the

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room to maintain good visibility (Figure 5B). The 8-foot fume hood is used for chemical distribution and collection of chemical waste. Shared equipment (IR, GC, and melting point stations) is available in the center of the laboratory, while larger shared instrumentation (400 MHz NMR, GC/MS, UV-VIS-NIR, and polarimeters) is available in the adjacent shared instrument laboratory. In the laboratory that is also used for inorganic synthesis, a four-station glove box is located in the center of the room.

In laboratory courses for analytical or physical chemistry, the need for multiple instruments becomes the dominant design consideration. For example, the instrument lab contains four main bench areas equipped with IR spectrometer, UV-Vis spectrometer, fluorimeter, HPLC, ICP, GC, STM, gas analysis mass spectrometer, electrochemical analyzer, IR spectrometer, capillary electrophoresis, BET, and other smaller or portable equipment. Within this laboratory space, movable benches are used with overhead service carriers and overhead ventilation to provide maximal flexibility. A separate laser room is located in the central prep-lab area of the fourth floor. A laboratory that facilitates the simultaneous use of multiple instruments is essential for these courses, since the students typically complete the experiments using rotations, with one student group per experiment and several experiments being performed simultaneously within the laboratory.

Conclusions

The instructional chemistry laboratory represents a complex learning environment. To provide a meaningful experience for students within this environment, the laboratory room must be carefully designed in the context of the associated course. A key to defining the overall design strategies is that the physical facilities must support and complement the pedagogical goals. We hope that this relationship is evident in the strategies that were applied to the renovation and expansion project that is reported here.

Projects at different institutions are inevitably going to be unique in their character based on their institutional heritage and size. To the extent that goals are shared, a certain commonality of features will also emerge. In this process of evolution of laboratory design, driven both by the changes in the chemical sciences and in associated changes in pedagogy, the sharing of experiences between institutions informs future strategies and improves outcomes. We hope that our experiences contribute towards the sustained improvement in the design and use of instructional chemistry laboratories.

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Chapter 2

Designing New Science Laboratories at Mount Saint Mary College: Reflections of a Faculty Shepherd

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The Project Kaleidoscope (PKAL) model for laboratory design calls for the assignation of a Faculty Shepherd to marshall the process. This model also calls for active participation of all college constituencies in designing spaces that promote active student learning, integrate science with the liberal arts mission of the college, are welcoming to science students and the entire college community, foster collaborations, provide opportunities for formal and informal learning, and incorporate new technologies for learning. This chapter will outline the inclusive planning process from the viewpoint of one faculty member who was chosen to shepherd the process from initial planning through choosing architects, designing learning and shared spaces, and value engineering along with a reflection on whether the PKAL vision has been realized in the design of the new Math, Science and Technology building at Mount Saint Mary College.

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I should have seen it coming, but I didn’t. And then it was done. I was the faculty member chosen to shepherd our new Math, Science and Technology Center. What did that mean? What was this new role of “shepherd”? And why me?

It shouldn’t have taken me by surprise. We had been discussing the possibility of renovating or replacing our old laboratory facilities for years, and I was an active participant in those discussions. And it wasn’t just discussions; we had met with consultants, engineers, and designers and had come to the conclusion that we could not renovate our existing facilities; we had to build new ones. This chapter will chronicle our ten year journey from thinking about new science laboratories to moving in to our new Kaplan Family Mathematics, Science and Technology (MST) Center addition to Aquinas Hall.

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In the Beginning…

Our journey began in 1997 with an internal review of our facilities, which had been in place for almost forty years. Those 37 years had been good ones for Mount Saint Mary College (MSMC), which had grown from the first graduating class of 32 women to a coeducational college with 47 undergraduate programs, three graduate programs, and over 2000 students. However, the years had not been kind to the science laboratories, which had been a home away from home for our science students (approximately 5% of the graduating class) and a training ground for hundreds more prospective nurses (approximately 20% of graduates) learning about the science behind their craft.

Not only were the facilities old, worn, and aesthetically displeasing, but more importantly, they were no longer adequate for the needs of the Division of Natural Science. Ventilation was limited to four laboratory hoods that worked only marginally and the cross breeze generated by opening windows and doors. Upon opening the stairwell door to the science floor in Aquinas Hall, one was often met with the stench of the autoclave or the sweet smell of organic solvents, neither of which enticed students to go near the science laboratories. Chemical storage was limited to a closet (unventilated of course) that housed a large metal still, all of our chemicals, and a flammable safety cabinet which, when opened, released fumes that could knock you out. The lack of adjacent prep rooms did not allow us to use our laboratories efficiently for multiple courses, but the limited number of laboratory spaces required multiple courses to be taught in each room. More significantly, our teaching methods had outgrown our learning spaces. Cooperative team learning could not take place in old laboratories that had long benches with high reagent shelves between them, and students could not present their findings to the rest of the class with this laboratory configuration. It was time to find solutions.

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Three important first steps were taken in this initial assessment phase:

1. attending Project Kaleidoscope facilities conferences
2. working with a consultant to get a professional assessment of our options
3. visiting other schools' renovated laboratories and speaking with their faculty liasons

An MSMC team consisting of an administrator (Associate Academic Dean), a faculty member (Chair of the Division of Natural Sciences) and a facilities supervisor attended facilities workshops in 1998 and again in 2003, sponsored by Project Kaleidoscope (PKAL) (*1*), now the Learning Spaces Collaboratory (LSC) (*2*). These workshops advanced the idea of collaborative planning of STEM (Science, Technology, Engineering and Mathematics) spaces based on research into how students learn. The team returned with great ideas for moving forward.

Our work with PKAL led us to a consultancy program supported by the W. M. Keck Foundation. Through this program, we were able to bring consultants to campus to help us formulate our own strategic initiatives that would bring us closer to resolving our facilities concerns. In addition, the consultancy made general and curricular recommendations which fed into the facilities recommendations. These recommendations included identifying short and long term curricular goals, defining student outcomes more explicitly, experimenting with active learning strategies, sharing our pedagogical initiatives across campus, using student feedback to assess changes, and incorporating math and science across the curriculum. Their facilities recommendations led us to develop a multi-year plan which included:

1. establishing a timeline for moving forward
2. generating a campus-wide master facilities plan based on a study of current and projected programs
3. commissioning a mechanical engineering consultant to assess the existing facilities and the options of renovation versus new construction
4. designing a prototype lab space for collaborative and active learning
5. assessing the new prototype lab space
6. looking outside the college for inspiration in innovative laboratory design by touring new facilities elsewhere
7. making science visible and welcoming to students

Faculty members in the Division of Natural Science visited five other colleges to tour laboratories that were recently renovated or were in the process of renovation. This was an important step in our process, allowing us to consider multiple options for laboratory design and giving us feedback, not only about what worked, but also about what did not work. For instance, installing ice machines in hallway closets for easy access by all of the science laboratories seemed like a great idea, but after speaking to faculty members who used this design, we found out that the ice machines generated so much heat in these small spaces that the ice melted. We were gathering useful information.

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On the PKAL Model and Being a Shepherd…

Project Kaleidoscope is a community of Science, Technology, Engineering and Mathematics (STEM) stakeholders that provides resources for advancing STEM learning for all students on undergraduate campuses (*1*). Since 1989, and now under the umbrella of the Association of American Colleges and Universities (AAC&U), it has provided resources to support the transformation of undergraduate STEM teaching and learning. PKAL publications, workshops, and conferences support the development of strong STEM programs, active learning pedagogies for science, STEM leadership development, and innovative learning space design. PKAL's work focusing on facilities planning continues through the Learning Spaces Collaboratory (LSC).

In facilities design, the PKAL/LSC model calls for active participation of the entire college community in designing learning spaces that:

1. promote active student learning
2. integrate science with the liberal arts mission of the college
3. are welcoming to the entire college community
4. make science visible and attractive
5. foster collaborations
6. provide opportunities for formal and informal learning
7. integrate new learning technologies

In this model, the planning of new learning spaces should be a collaborative effort led by a Building Advisory Committee with members from the administration, facilities management and faculty. Although PKAL recommendations called for a steering committee of three or four people in order to facilitate efficient decision making, our steering committee was considerably larger, consisting of seven members:

1. Chair, Division of Mathematics and Computer Science
2. Chair, Division of Natural Science
3. Vice President for Academic Affairs
4. Vice President for Facilities and Operations
5. Vice President for College Advancement
6. Vice President for Planning, Research and Information Systems
7. Vice President for Finance and Administration.

The steering committee was charged with making the hard decisions of scope, program and budget, selecting and collaborating closely with the architects, providing the College's vision to the design, and meeting continually throughout the process of design and building.

The PKAL vision of planning new learning spaces also recommends assigning a faculty member to "shepherd" the process. This Faculty Shepherd works with architects and college stakeholders to ensure that the process is open and inclusive, that programmatic needs are being met, and that all voices are heard. As the new

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Chair of the Division of Natural Science, I became the Faculty Shepherd. I was expected to balance the needs of my Division with those of the entire College, the vision of the steering committee, and the resentment of the rest of the campus who wondered why we would get a new building and what was the consequence to them.

Moving Forward…Choosing an Architect

The first order of business for the steering committee was to choose an architect. During this architectural review, we invited nine architectural firms, chosen for their interest in and work on similar projects, to present their vision for a new science building. The steering committee members considered each architect according to the following criteria:

1. history of completing projects on time and within budget
2. integration of the new facility with programmatic needs
3. incorporation of interactive spaces for students and faculty
4. experience in designing scientific buildings
5. currency of relevant experience
6. work done at comparable institutions
7. aesthetic considerations

After each committee member ranked the architects, the steering committee met to discuss the merits of each, along with the costs, fees, and other budgetary considerations. This may have been the most important meeting of the steering committee, one that set the course for the entire venture. It was imperative for us to choose an architectural firm that understood our vision and mission, that knew how to guide us in designing our laboratories around our teaching needs, and that would be willing to work closely with faculty to realize the PKAL vision of teaching and learning. Although budget was a consideration, more important was the ability of the architect to transfer our needs into a vision for transforming the campus. It was clear that choosing EYP Architecture and Engineering was the right decision when, shortly after we began the process of siting our new facility, the Senior Design Principal Architect stopped the meeting with a revelation of how we could use the new building project to tie together all constituencies of the College. By siting the building as an addition to the front of the existing Aquinas Hall, we could create a community gathering space in front of the existing theater, make mathematics, science and technology more visible, and provide formal and informal learning and gathering spaces that would serve everyone on campus. In the months that followed, we were able to see the vision that he sketched at that meeting realized through the skill and talent of his firm. It is critical to spend the time, and perhaps even the extra money, to choose the right architect for your project.

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Building Consensus

In order to include the entire campus in the process and ensure transparency, a number of advisory committees and working groups were formed. Each group met independently with the architects and the Faculty Shepherd to provide their input. Working groups were formed for each academic Division that would be affected by the new building or renovation of existing spaces: the Divisions of Natural Science, Mathematics and Computer Science, Business, and Nursing.

A Building Advisory Committee (BAC) was formed to represent the entire college constituency. It met periodically to get updates about the progress of the building design, provided suggestions and recommendations, and disseminated information to the rest of the college. This BAC was composed of the Faculty Shepherd, representatives from every academic division on campus (not just those directly affected by the building and renovation), the Director of Information Technology, the Director of Operations, the Director of Plant Operations, the Library Director, two alumni, and two students. This large group of seventeen people was not a decision-making body but worked in an advisory and dissemination capacity to ensure that everyone knew how the project was progressing.

In addition to the Steering Committee, the Building Advisory Committee, and the working groups, other committees were formed to consider specific aspects of the new building. A Classroom Committee composed of the IT director and two faculty members met with the architects to design flexible classrooms and computer labs. A Furniture, Fixtures, and Equipment (FF&E) group met to discuss paint colors, furniture design and patterns. An Aesthetics Committee concerned themselves with the beauty of the spaces, including the artwork or murals to be included in the new and renovated spaces.

The campus community and the public were kept informed about the ongoing development and construction of the new MST Center via a website, which contained the project description, schedule and plans. The website also contained construction newsletters (Hard Hat Happenings and Construction Flash Notices) and construction progress photos.

As Faculty Shepherd, I scheduled meetings of each working group or advisory committee with the architects, sometimes with subsets of faculty discussing the architectural and engineering design room-by-room. Not only did I arrange meeting times around faculty schedules and reserve rooms, I also sat in on every meeting to ensure that decisions made by one committee were available for consideration by others. It was also important that someone (the Faculty Shepherd) was aware of all of the decisions being made to guarantee that each one was addressed by the architects. It made for long days and detailed discussions but ensured that the building was designed to fit the needs of those who would be using the spaces: faculty and students.

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Steps of Architectural Design

Although the choice of the architect was critical to the ultimate success of our project, the hard work was about to begin. We first developed a wish list of what we would want in new math and science facilities. Generating our wish list was a great exercise in imagining our ideal campus with formal and informal learning spaces for everyone, including a maximum number of labs and even an astronomical observatory on the roof, without the realities of budget and space. A programming study was commissioned to look at what our program looked like, coordinating it with our mission statement and our wish list of what we would like to see in the new building. The programming study would tell what types and sizes of space we would need for the next ten to twenty years.

In reconciling our wishes with programming and budgeting considerations, the realities of budget and space became our realities. Each phase of architectural design was followed by a "Pricing and Cost Reconciliation" phase, causing us to re-examine our priorities and realign our expectations with our mission and goals. This was the most difficult and contentious part of the process as we made decisions about scope and scale through negotiation and consensus within our steering committee and with the architects and engineers involved in designing the building. It fell to me, as Faculty Shepherd, to represent the faculty viewpoint in these negotiations and communicate these decisions to the stakeholders, a job that would have been difficult to do if I had not been involved in all of the previous stakeholder meetings.

The architects developed a detailed timeline for our project (Figure 1) that kept everyone informed about the phases of the design, what was happening at any point in time, and how the project would proceed to meet our completion deadline. This timeline was reviewed at each Steering Committee meeting to see how we were meeting its goals. It seemed like an aggressive plan, but it turned out to be right on target. We met each deadline for the completion of the construction and renovations.

The first phase of the architectural design, after the programming study and site selection, was Schematic Design. Schematic Design is a "roughing in" of generalized spaces for specific programmatic needs. It establishes where specific elements will be located in relationship to each other in the new building. Where will the biology labs be located relative to the chemistry laboratories or the computer labs? How will they be connected to each other and to the outside? How will people and materials flow through the space? Where will offices be located relative to the classrooms and labs? In this phase, it is important to think about the space needs of each type of lab, the logical placement of things like storage and prep rooms relative to each laboratory space, and the programmatic requirements to be achieved by the new spaces. Our initial Schematic Design included extra elements, such as a board room with a view of the campus, which were removed during the subsequent "Pricing and Cost Reconciliaton" phase. You can see in Figure 2 that the Schematic Design defines spaces only in a general way with no detail. The idea here is to look for adjacencies, not detailed plans.

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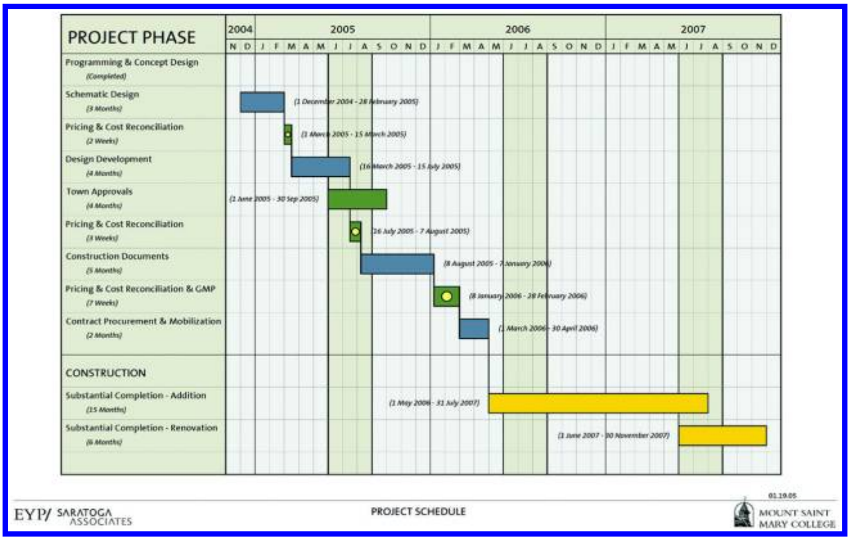

Figure 1. Timeline provided by architectural firm for completion of project phases. (Reproduced with permission from reference (3). Copyright 2005 EYP.).

Determining a generalized scheme of space utilization may sound like the easiest part of the process, but finding a way to hear all voices and develop a plan that was acceptable to everyone, took some negotiation. For instance, siting faculty offices was an issue about which there was a wide range of ideas. A number of faculty members in the science division wanted offices adjacent to the labs to facilitate supervision of research students. Faculty from the Division of Mathematics and Computer Science preferred a centrally located office suite for all faculty. The architects wanted a unified vision so they could design each floor of the building symmetrically. As Faculty Shepherd, it was important to communicate the wishes of each group to the others and help everyone come to a consensus about how to proceed. In the end, office suites were designed for each floor, a model that has turned out to be a great asset for enhancing faculty-faculty, faculty-student, and student-student interactions.

Schematic Design is followed by Design Development (DD), where the details of each space are enumerated, including the materials to be used in construction, HVAC (heating, ventilation and air conditioning) systems, and specific details about each room, such as, locations of cabinetry, fume hoods, sinks, and electrical outlets. The nitty gritty of the details for each room was worked out in exhaustive 1½ hour meetings between the architects and individual faculty or small working groups who could advise the architects how each space would be used for teaching and learning. In this stage of design, the Faculty Shepherd must mediate between the faculty, who may have definite ideas about how a room should be designed, and the architects, who bring to the table a working knowledge of regulations, spacing requirements and current trends in lab design. The Faculty Shepherd must also help faculty think about how each room will be used, what pedagogies will be employed, and what instrumentation will be needed. They must then be encouraged to trust the expertise of the architects to design the spaces in a way that meets all of these expectations.

Figure 2. Schematic Design of second floor of Aquinas Hall addition. (Reproduced with permission from reference (3). Copyright 2005 EYP.).

Details, such as numbers of hoods and benches, were only the beginning of the DD process. We also discussed at length: bench heights, expected location of equipment, benchtop materials, flat or raised edges on the benches, sink locations, knee spaces, wall storage, microscope storage, markerboard location, water purity needs, soap and paper towel locations, drain boards, services such as compressed air, central vacuum, gases, steam, power requirements for benches and for equipment, compressed gas cylinder locations, data outlet locations, exhaust requirements, wall storage, cabinet doors, special item storage, flammable storage, ventilation, acid-base storage, waste collection, emergency provisions, and gas shut-off valve locations. The increased level of detail of this phase can be seen in Figure 3. As Faculty Shepherd, I spent hours at the end of Design Development pouring over architectural plans to ensure that the vision formulated and decisions made in all of our meetings were translated into the architectural design.

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Figure 3. Design Development schematic for 2nd floor of Aquinas Hall addition. (Reproduced with permission from reference (3). Copyright 2005 EYP.).

With Design Development comes the costing of materials for the project, leading to a total cost of the project, the Guaranteed Maximum Price (GMP). At this point, cost reconciliation began in earnest, and Value Engineering (VE) was used to bring costs into alignment with budget. Value Engineering is the process of minimizing the cost of the project by looking carefully at the specifications of the design to determine opportunities for efficiency without reducing the performance or quality of the project. Value Engineering of our new addition reduced the number of fume hoods in the organic chemistry laboratory, the number of electrical outlets and air nozzles on student benches, and reduced the size of the addition by 20 feet. VE completely eliminated a loading dock upgrade. It was a time for hard decisions about what was necessary versus what was optimal and how we could provide cost-efficient facilities to our students without sacrificing the quality of their learning experience. Because many of these decisions required immediate resolution, faculty input into these decisions rested mainly on the Faculty Shepherd, who had extensive knowledge of why prior decsions had been made and how these VE changes would affect the design vision of the faculty who would be using the new spaces.

My work as Faculty Shepherd did not end at the building planning stage. Even after the building was completed, I spent a large amount of time attending to the details of what was included in the building and making sure that our expectations were met, everything worked, and feedback from all stakeholders was heard. I worked closely with the construction management team to share information and work out all of the finishing details from balance lockdowns, to furniture needs, to HVAC issues.

Are We There Yet?

Have we met our goals? In a word, YES. Our new 50,000 gross square foot (gsf) addition and 12,500 gsf renovation was completed on time and under budget. More importantly, our goals for the new MST Center, which closely matched those of Project Kaleidoscope for new science facilities, were met. We had the institutional transformation we had been hoping for. What were the lessons we learned from this process, and what worked for us in designing our new teaching and learning spaces? Our lessons learned can be aligned with the PKAL vision for teaching laboratories. This vision includes providing spaces for active student learning, making science visible and inviting, integrating the sciences with the liberal arts mission of the college, fostering collaborations, providing opportunities for formal and informal learning, and incorporating new technologies for learning. Here's how have we met each of these goals and realized the PKAL vision for science facilities.

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STEM Facilities Should Promote Active Student Learning

Our computer labs were designed by the classroom committee to be flexible enough to support collaborative group learning. From the furniture to the electrical services, everything was designed with flexibility and student learning in mind. Our laboratory designs are open enough for lecture and lab to be taught in one room, and they often are. Collaborative student learning is the norm in our freshman courses for science majors, and the laboratory configurations allow that to happen seamlessly. Students can easily move from working in their groups at the bench, to using a fume hood, to presenting their findings to the class. Even the location of prep rooms next to each lab space allows us to prepare for the next laboratory activity without impacting those that are already in session. These adjacent prep rooms can also be used to allow student projects to continue over time without impacting or being impacted by subsequent lab classes. We also planned for the installation of microscope cabinets in the preparatory area next to each lab so that other faculty could use them without disrupting an ongoing lab section.

STEM Facilities Should Integrate STEM with the Liberal Arts Mission of the College

As reflected in its motto "Doce Me Veritatem" (Teach Me the Truth), Mount Saint Mary College is committed to the intellectual and personal growth of its students. This includes learning outside of the classroom. Our new building contains space for independent student research in the sciences: a flexible research lab with two fume hoods, electrical utilities in the floor, and movable lab benches so that many different types of research can be carried out in the same room. This is a luxury that was not available in our old science facilities. As a result of this new space, the Division of Natural Science requested strategic funding for students to be paid to do research with a faculty mentor during the summer. Very quickly this became a college-wide program, encouraging research across the campus. In addition to science students working with faculty mentors, students have been working with faculty from the Divisions of Nursing, Arts and Letters, Business, Social Science, and Education. Without the impetus of research facilities in the sciences, this Summer Undergraduate Research Experience (SURE) program would not be thriving as it is today.

STEM Facilities Should Be Welcoming to All Students and Should Make Science Visible

The initial idea of building an addition on the back of the building was quickly discarded as the idea of putting science front and center took over our thinking. The science and math labs are in the flow of student foot traffic to the career center, the library, the parking lots, the lecture hall, and the dining hall. A new atrium attracts students to meet and study together and provides spaces for students to meet faculty. Our new café provides gathering spaces for students and faculty right outside of the computer labs. Science labs have glass in the doors so that students can see science being done. Labs along the corridors (the Developmental Biology Lab, the Research Lab, and the Instrumentation Lab) have glass windows to make science visible to students passing through the building. All of our laboratories are ADA (Americans with Disabilities Act) compliant so that all students have access to hands on science learning.

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STEM Facilities Should Foster Collaborations and Provide Opportunites for Formal and Informal Learning

The atrium space connecting the old building to the new addition has become a an informal gathering space for students between classes but is also a formal gathering space for celebrations and receptions. Poster presentations of student research are held in the atrium every semester, and outside symposia have also used the space to bring together students and faculty to discuss their work. Other informal gathering spaces are spread throughout the building, allowing students to meet and study together. Even spaces that were designed with programmatic purposes, such as conference rooms, have been taken over by students studying together. Our office suites were designed with an open area surrounded by faculty offices. These open areas have become gathering areas for students to study together, meet with faculty, or provide peer tutoring. The science office is used for peer tutoring four days each week well into the evening hours. It is a lively place where you will often find faculty collaborating with other faculty, faculty meeting with students, students tutoring other students, or students meeting up with their friends between classes.

STEM Facilities Should Incorporate New Technologies for Learning

Our MST building has many technological enhancements to promote student learning in math, science and technology. In addition to four computer laboratories, a networking lab was designed to allow students to learn about computer networks without disrupting existing MSMC computer networks.

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Every classroom and laboratory has computer projection capability and state of the art video equipment. Every biology lab is also equipped to project from a microscope. Laptop computers are available in each lab for data collection and analysis, with software available so that data can be projected from anywhere in the room from any computer. Our laboratories are equipped with selected "red plug" outlets that are connected to generator power so that sensitive instruments and refrigerated materials can be safeguarded. State of the art systems for monitoring the pH of wastewater from the labs, for providing reverse osmosis water to laboratory faucets, and house vacuum to the labs also provide students with safe and modern laboratory facilities. In addition, our new instrumentation lab has provided the space and utilities necessary for new equipment to make our students' laboratory experiences reflect the state of laboratories they will see upon graduation.

Lessons of a Faculty Shepherd

The role of Faculty Shepherd requires a number of skills that may not be immediately obvious. Of course, the Faculty Shepherd should have a stake in the outcome of the new building, but to be successful, one needs much more than a desire to have a great new building.

A successful Faculty Shepherd should have good organizational skills. Collaborating with multiple committees, working groups, architects, engineers and construction managers requires the Faculty Shepherd to bring various groups of people together to meet, working around the schedules of all involved. Each of these meetings will come to conclusions that will affect the outcome of the building, so each of these decisions should be clearly delineated and documented.

A successful Faculty Shepherd should have a meticulous attention to detail. Each of the decisions made by the various committees and working groups must be monitored in order to ensure that they come to fruition. Architectural plans must be scrutinized carefully to make sure that details are not omitted: which cabinets must be lockable? Where will the electrical outlets be located? Are the "red plug" outlets that are connected to a back-up generator in the appropriate locations? Are there enough sinks? Where will the projection equipment be located? Are there enough special chemical storage locations (flammable, acid/base, waste)? Are the fume hoods the correct size? Are there enough drawers for student materials? These are decisions that can only be made by those who will be using the space and not by the architects. To ensure that the vision of the faculty becomes the reality of the new teaching space, the Faculty Shepherd must be continually and watchfully guarding that vision.

A successful Faculty Shepherd should have the ability to communicate and build consensus without enmity. This ability should extend to the entire campus community and to those from outside the campus who will be helping you to realize your goals. It will not matter how detail oriented and impeccably organized you are if colleagues, architects and construction managers cringe when they see you coming. Collegiality is necessary to get everyone to share the vision of what your new building should be.

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Not only must the Faculty Shepherd have the appropriate skills to be successful, but the design process must also have a number of attributes to ensure maximum effectiveness. All stakeholders should be included in the process of developing the vision for the new building. It is important that everyone who may be affected by the addition of the new building to the campus is consulted. This includes those who will be using the labs and classrooms, those who will be using the shared spaces, as well as those who will be charged with maintaining the facilities. Even those who were simply interested in the aesthetics of the campus formed a committee to make sure that the new spaces were aesthetically pleasing and fit with the style of the campus. A necessary component of a successful process is inclusive collaboration coupled with consensus and compromise. Not everyone will agree on all aspects of the design, and all ideas will not be incorporated into the final design, due to budget and space considerations, but allowing everyone to have a voice in the vision for the building will foster buy-in and give everyone a stake in the success of the building. The ability to bring everyone to a consensus through discussion and compromise is essential to keeping the vision alive through a difficult cost reconciliation discussion. As this process proceeds, it is essential that the status of the project is clearly communicated to the college community. Transparency of the process and project is essential to keeping everyone moving forward.

In summary, inclusivity, transparency, collaboration and consensus-building are all essential elements for a successful building project, and it is up to the Faculty Shepherd to employ all of the skills necessary to make it happen.

Acknowledgments

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Chapter 3

Leveraging Collaborations, Conversations, and Experimentation To Create an Interdisciplinary Science Facility

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New and renovated spaces provide opportunities for inquiry and learning in Regents Hall of Natural and Mathematical Sciences at St. Olaf College. A long planning process (~1992-2008) serendipitously allowed user groups time to develop a coherent and compelling mission and vision. Cross-disciplinary dialogue and clearly articulated principles, fostered by bringing all the constituencies to the planning table, resulted in collaborations that yielded efficiencies in design and operations. Partnerships with campus facilities personnel permitted design element experiments in our old spaces, which served as a means of piloting learning spaces for the new facility. This experimentation allowed us to test flexible lab designs, alternatives to current practices, and the adoption of a green chemistry curriculum. Ultimately, we were able to construct a facility tailored to the curriculum we were trying to deliver.

St. Olaf College is a private liberal arts college of about 3000 students located in Northfield, MN. The chemistry department is part of the Faculty of Natural Sciences and Mathematics (FNSM), which consists of about 60 faculty members in the departments of biology, chemistry, physics, psychology, and the department of mathematics, statistics, and computer science. All St. Olaf students are required to complete two courses in science. About 40% of each graduating class completes

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a major in science or mathematics. Over the last three years we have graduated an annual average of 61 B.A. chemistry majors.

Regents Hall of Natural and Mathematical Sciences consists of a 195,000 gross square foot new natural science building and an 18,000 gross square foot renovated mathematical sciences building connected by an 8,000 gross square foot link. The natural sciences and link portions of Regents Hall, housing biology, chemistry, physics, and psychology, opened in Fall 2008; the renovated mathematical sciences building, including mathematics, statistics and computer science, opened in Fall 2009. Regents Hall is also home to interdisciplinary programs in biomolecular science and neuroscience. Regents Hall contains seven tiered classrooms, eleven flat-floored classrooms, eight seminar rooms, four computational rooms, 26 teaching labs, 13,000 square feet of student-faculty research space, and an 8,000 square foot science library with individual and group study spaces. Unlike many science facilities, Regents Hall is organized by common functions and shared resources (equipment, instruments, and infrastructure) rather than by department. Chemistry occupies spaces found on two floors and in two wings of the facility, with neighbors that bridge to areas of the biological sciences. More details on the building design can be found elsewhere (*1–3*).

This chapter focuses on the design, construction and operation of Regents Hall of Natural Science. Throughout the project, we learned lessons that influenced the choices made in the final design. Our decisions were informed by 1) inviting a wide range of professionals to the *planning teams*; 2) establishing a common *mission and vision* for the facility; 3) *experimenting with space, operations and curricular approaches* in our old building; and 4) *promoting cross-disciplinary conversations* to break down departmental barriers and enhance efficiencies. We have also assessed the impact of our designs on student and faculty experiences in the new space.

Planning Teams

In order to create a facility that achieves objectives of a diverse group of users while meeting broad institutional aspirations, a diverse and committed planning and building team is needed. The team structure for Regents Hall was two-fold: a Design Team and an Oversight Team. The latter established fiscal strategy, monitored fund raising, blended building design and college priorities, and approved any changes in the scope of the project. The Oversight Team was comprised of major leadership positions at the college (Advancement, Facilities, Treasurer, Registrar, Provost/Dean, Assistant Provost) and the Faculty Shepherd. The Design Team did the majority of the project work and represented users, design/engineering professionals, facilities professionals, and the building trades. The Design Team was charged with matching the programmatic vision to the fiscal strategy advanced by the President and the Oversight Team and regularly communicating with the FNSM faculty about evolving plans. The Assistant Vice President for Facilities and the Faculty Shepherd were members of both the Oversight Team and the Design Team. Timely communication of feedback and exchange of ideas between the two teams occurred through these common members. Decision-making involving changes in project scope were expressed through written memoranda exchanged between the two teams.

Major user groups, including faculty, students and staff, comprised the campus membership of the Design Team. One faculty representative was drawn from each of the participating departments. Initially, the department representatives were the chairs. Over the roughly ten-year planning and construction timeline, shown in Table 1, other faculty replaced these individuals for the chemistry and psychology departments. In other departments, individuals continued to serve on the Design Team after completing service as chair. The department representatives made the commitment to: 1) attend and participate in as many meetings as possible; 2) provide clear, concise and regular communication with their department constituencies, including the distribution of meeting minutes; 3) bring honest feedback, candor and questions to their work; and 4) work to achieve the maximum benefit to all stakeholders. None of these individuals received release time or extra compensation for their work.

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Table 1. Brief Timeline for Regents Hall Complex

1992-1994	Users begin conversations
Oct 1998	Project Kaleidoscope Consultants Visit 1
1999	Feasibility Study and Department Visions
2000-2002	Initial Design
Jun 2002	Project Kaleidoscope Consultants Visit 2
2004-2006	Revised Design
Dec 2006	Break Ground
Feb 2007	Begin Regents Natural Science Construction
Jun 2008	Begin Regents Mathematical Sciences Renovations
Sep 2008	Regents Hall of Natural Science opens
Sep 2009	Regents Hall of Mathematical Sciences opens

Student participation on the Design Team was vitally important. Three student members, all of whom joined the group as sophomores (Fall 2005), made a three-year commitment to the project. The students brought the perspective from the student body and reminded others on the team how the building would function outside the typical daily work schedule.

The Faculty Shepherd chaired the Design Team. During the planning phase of the project, the leadership changed a few times. The leader was either a senior faculty member or the Associate Dean for the Natural Sciences and Mathematics. In order to provide continuity across the decade-long process, former Faculty Shepherds continued service after leadership transitions. Once the Design Team began working on building design (approximately 2004, see Table 1), one individual remained Faculty Shepherd. The Assistant Vice President for Facilities played a major role in supporting facility related experimentation and research as work moved from planning into design and subsequently into construction. The Design Team size was dynamic as it moved through these same phases, increasing membership to include the construction manager, major subcontractors and campus facilities personnel. St. Olaf chose to pursue a design-build strategy so that real-time budget estimating would inform the Design Team's work and deliver a project within fiscal targets. The leadership teams for this project were endorsed by our second consultancy (June 2002, see Table 1), and the two-fold team structure was important for maintaining the attention of the institution's senior leadership.

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Mission and Vision

When undertaking a project as large as Regents Hall, we found it was essential to take time to articulate a vision for the future that is informed by the mission(s) of the users. In addition to insuring a building that meets the needs and intentions of its inhabitants, a shared mission and vision assisted in fundraising, marketing, and design efforts.

As a result of our first consultancy (October 1998, see Table 1), we began our feasibility study with each department developing a vision for the future. The chemistry department emphasized a desire to have well designed, adaptable spaces to attract and meet the needs of future students and faculty. In particular, the department singled out a vision for spaces that supported and augmented on-going innovative, interactive, and hands-on approaches to learning. We envisioned learning occurring in classrooms, laboratories, research spaces, support spaces and social spaces. We sought an environment that would be welcoming to chemistry majors and non-majors, faculty, staff, and visitors.

The existing facility, with fixed-in-place features, posed challenges to the design and implementation of group learning and open-ended, inquiry-based experiences. We were eager to implement inquiry-based laboratory experiences that would supplant traditional approaches and encourage student participation in research related endeavors. In a departure from department-focused thinking, the chemistry faculty recognized future research was likely to be increasingly collaborative and interdisciplinary in nature, augmenting traditional areas of chemical inquiry; consequently, the department advocated for the design and organization of spaces around general themes and functions rather than specific projects or traditional areas. To promote interactions between individuals from different disciplinary backgrounds, we sought to include elements that brought people together in informal settings. These efforts led to chemistry faculty office and research labs located in three areas of the building: analytical chemists were collocated with evolutionary biologists and ecologists on the west wing of the fourth floor, biochemists were intermingled with molecular biologists, microbiologists and geneticists on the east wing of the third floor, and organic and inorganic chemists were located on the west wing of the third floor. Teaching labs used primarily by chemists are located in these same locations. One lab, designated "General Science," is used by different departments as needs dictate.

Synthesis of the vision statements from all five departments led to a description of the entire facility's programs using recurring themes and ideas. While it took time for these ideas to develop and to be embraced by the user groups, their importance was paramount. The common vision led to organizing the facility by function and shared resources rather than by department. The overall feasibility and initial design studies resulted in a series of institution honoring, program grounded, future looking principles used to guide the planning and design process moving forward. The principles, shown in Table 2, became known as the *Seven I's*. Whenever the Design Team generated new ideas, considered design elements or questioned a course of action, these principles were used as an internal check. The principles enabled overarching goals to come into focus as illustrated by this excerpt from the Design Team project vision:

> A St. Olaf science education must […] engage students in meaningful scientific inquiry, exposing them to the grammar and form of investigation from formulation to observation to interpretation to communication. A science education at St. Olaf must also include the practice of scientific integration, emphasizing multiple levels of scientific understanding and broader connections with the other liberal arts. Within the inspiring and inviting confines of the new Regents Hall Complex, our creative and energetic faculty will provide a highly visible program of 21st century science and mathematics, engaging students in the interdisciplinary, investigative, interactive, and innovative learning necessary to train the next generation of scientists, physicians, engineers, and mathematicians.

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Table 2. Guiding Principles of the Seven I's

Interdisciplinary	How does the design preserve rigorous exploration of the current disciplines while enhancing interdisciplinary inquiry, teaching and learning?
Investigative	How does the design promote the expression of our investigative approaches to science and math?
Interactive	How does the design promote the interactive nature of modern science (student-student, student-faculty and faculty-faculty)?
Innovating	How does the design accommodate the technological and pedagogical innovations of modern science education and adapt to emerging educational strategies and technologies?
Interconnected	How does the design show the interconnections between the sciences and other distinctively St. Olaf strengths? How does the design reinforce awareness of the interconnectivity of physical space and linkages beyond the building envelope?

Continued on next page.

Table 2. (Continued). Guiding Principles of the Seven I's

Inviting	How does the design invite students, faculty, staff and visitors to explore the space, encourage them to linger and inspire them to work and learn?
Integrity	How does the design model the integrity we seek, honor the environment in which it resides and reflect the college's continued commitment to environmental stewardship? It must also allow the faculty to fulfill the charge of the college mission statement to: 1) stimulate students' critical thinking and moral development; 2) encourage students to be seekers of truth, leading lives of unselfish service to others, and; 3) challenge students to be responsible and knowledgeable citizens of the world.

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Experimenting with Space, Operations, and Curricular Approaches

A common mistake in facility planning is to arrive at a design that over emphasizes the limitations of the current facility – a natural first response to perceived deficiencies – rather than to examine how design components address your mission and vision. Designing a facility that fits the mission is similar in many ways to backward course design (*4*). In addition to using the abilities of architects and laboratory design professionals, we implemented three strategies to help us determine the design strategies that were aligned with our objectives: 1) We leveraged our propensity for scientific and educational inquiry to *experiment* with ideas in the form of pilot projects in our old spaces; 2) We *investigated* the current "state of the art" by visiting other institutions with newly built science facilities, seeking input from consultants, and teaching courses focused on building materials; 3) We *partnered* with one another, with students, and with our campus facilities professionals to explore alternative designs to our current facility.

Experiments in Space

The teaching labs in our old building were characterized by fixed benches with modestly functional sinks located throughout the labs. We envisioned building new, flexible laboratory spaces that allowed for re-configuration. Since we had no experience teaching in that type of lab, we wanted to renovate one of our existing labs to mimic our intentions in the new facility. Removal of fixed benches in an introductory chemistry lab permitted us to explore the idea of moveable, variable height tables, location of sinks around the lab periphery, delivery of equipment and apparatus via bin systems, and dropping electrical utilities from the ceiling. Student and faculty feedback was positive about the openness moveable tables provided; however, many did not support utility drops from above due to sightline issues.

We discovered that students, especially short and tall ones, appreciated adjustable tables; however, few instructors took the time to make adjustments to the table heights. Once a table height was set, few if any, sought to change it. Additionally, the large size of the table, 3 ft x 8 ft, made it difficult to reconfigure the table arrangement without assistance. This feedback suggested that we use a movable table with a smaller footprint at a single ADA acceptable height, 2.5 ft x 6 ft x 34 in. Our colleagues in biology and physics conducted experiments with different sized movable tables (4 ft x 4 ft x 36 in and 3 ft x 6 ft x 34 in) and drew similar conclusions.

Table 3. Areas of Laboratory Spaces Shown in Figure 2

Letter	*Space name or description*	*Area (ft^2)*
a	Synthesis lab	1440
b	Main stockroom	1700
c	NMR, GC-MS	430; 450
d	Synthesis research	630; 400; 605
e	Advanced synthesis lab	830
f	Introductory chemistry lab	1560; 1270
g	Biochemistry, molecular and cell biology lab	1320
h	Physical chemistry lab	1275
i	Freezers & ice machine	160
j	Walk-in cold room	125
k	Centrifuges and gel imaging	380
l	Tissue culture	305
m	Media preparation & autoclave	315
n	Biomolecular life sciences research	3000

Perimeter sinks worked very well for lab activity clean up and maintenance; however, we saw a major backlog stemming from the limited access to deionized water (six sinks, two DI taps). This helped us make decisions about distributing deionized water to each major sink location in the new facility.

To experiment with alternatives to student lab drawers, which would not be available with movable table workstations, we piloted a bin system for distributing equipment to students. Students, faculty, and staff liked using bin systems in part because it was easy to identify missing items and replace worn or ineffective apparatus. Our centrally located stockroom allowed for quick replacement of bins between lab periods. While the bin system worked well for a single lab room, faculty and staff expressed concern about using the bin approach for multiple labs. As a test, the department moved to a bin system for the entire first year curriculum in the old facility. Through this approach, we identified bottlenecks in the process

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and refined our approach to utilize a carted bin delivery system, shown in Figure 1a, for the introductory laboratories. The bin approach did not work as well in the synthesis laboratory, so we elected to include a stock of commonly used glassware (e.g., flasks, condensers, funnels) in this lab.

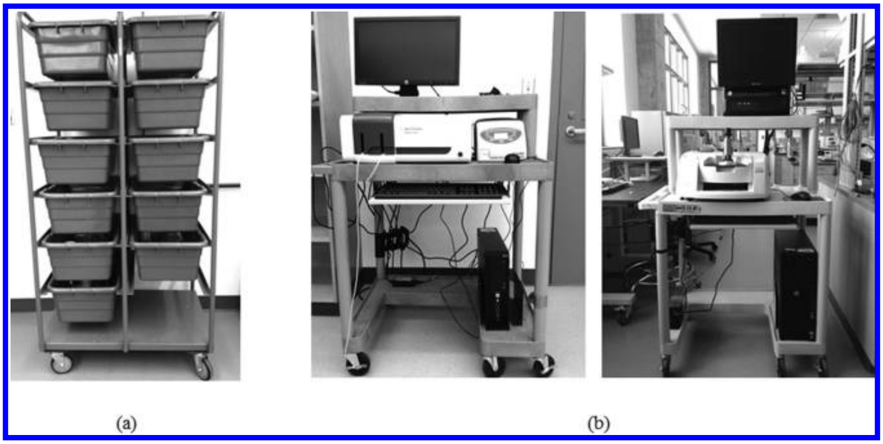

Figure 1. Mobile systems used to supply equipment and instruments to teaching laboratories. (a) plastic tote box truck used in introductory and synthesis labs; (b) UV/VIS (left) and FT-IR (right) carted instruments.

Through our pilot projects, we partnered with our colleagues in campus facilities. When possible, these experiments coincided with the needs of newly hired faculty; in other cases, campus facilities staff supported work aimed to inform the design of new facilities. This forward thinking approach allowed the College and Design Team to explore new cabinetry configurations, natural linoleum flooring, different colored chemical resistant work surfaces, tables with electrical from floor boxes, and different mounting configurations for electrical access at the work surface.

One of the major complaints of the old facility was that the interior labs showcased four concrete block walls with no visual connectivity to other spaces, let alone the outdoors. A small number of internal windows were added to a few spaces to explore aspects of visual connectivity and its impact on worker productivity and sense of safety.

Locating Stockroom and Instrumentation

In our prior facility, the stockroom was located adjacent to most of the teaching labs and research space was next to faculty offices. Since it was impossible to have the stockroom adjacent to all the teaching and research labs spread over three wings of the building, we eventually decided that it was more important to have the stockroom near to our highest volume laboratories: the introductory and synthesis labs. These lab courses have approximately 350 and 110 students, respectively, enrolled per semester. Other laboratories with lower student enrollments were located further away from the stockroom. These ideas resulted in a layout for

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the introductory chemistry and synthetic efforts of the department, represented in Figure 2. The stockroom, (b) in Figure 2, is located across the corridor from the synthesis lab (a) and down the hall from the two introductory chemistry labs (f). The physical chemistry (h) and biochemistry (g) labs are also shown in Figure 2; Table 3 contains the areas associated with each of the spaces (*5*).

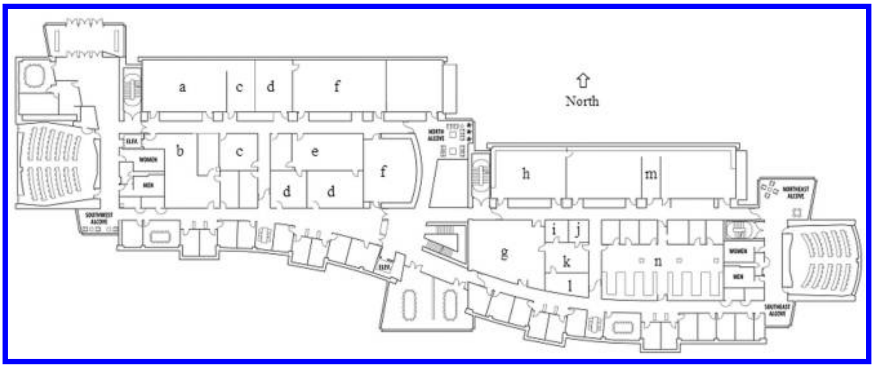

Figure 2. 3rd Floor layout of Regents Hall showing relationship of laboratory related spaces to one another and organization of activities according to shared functions and equipment rather than department. Faculty/staff offices and small seminar rooms are scattered along the south wall. Synthetic chemistry comprises the focus of the west wing (left). Note the proximity of the spaces: a) synthesis teaching lab; b) main stockroom; c) NMR & GC-MS; d) synthesis research; e) advanced synthesis teaching lab and f) first year labs. The biomolecular life sciences are located in the east wing (right). The spatial highlights include: g) biochemistry/cell/ molecular biology lab; h) physical chemistry lab; i) -80 C freezers/ice machine, j) walk-in cold room, k) centrifuges & imaging, l) tissue culture, m) media prep & autoclave, and n) collaborative research space with small dedicated technical spaces along its north wall. Unlabeled rooms along the north side of the building are computational spaces or spaces for genetics and microbiology labs.

We continued to place a high value on the relative location of faculty offices and research laboratories. This is largely out of concern for laboratory safety and supervision of undergraduate collaborators. In Figure 2, the faculty offices are located at the south (lower) portion of the building. Research spaces (labeled d and n) are primarily across the hall from faculty offices.

A parallel conversation took place regarding a dedicated instrument room. The prior facility no longer had an instrument room; the space had been previously renovated into a computational facility. At that time, many instruments were placed onto carts and, when not in use, stored in a secure hallway space reconfigured as a mobile instrument garage. An example of two such instrument carts are shown in Figure 1b. Other equipment was redistributed to spaces in which the equipment was used regularly. Our success with carted instruments led the department to not create a centralized instrument room in the new facility; instead, the carted instruments were distributed in spaces where they were most often used or in spaces developed for temporary instrument parking.

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Certain instruments and equipment require dedicated space due to size, safety, noise, maintenance, and traffic issues. For example, Figure 2 shows dedicated space for the NMR, GC-MS and large freezer systems (see spaces labeled c, g and k). We elected to place other major equipment in locations that permit the greatest use or as part of a blending of purpose between research and teaching laboratories. For example, a MALDI-TOF mass spectrometer, located in a faculty/student research lab, is used by both introductory integrated chemistry-biology students (*6*) and by instrumental analysis students.

Green Chemistry

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When we were first considering building design, the chemical profession emphasized engineering controls as a means to address chemical exposure risks. The department initially supported this direction, planning to incorporate 2.5 to 3 feet of fume hood space per student in our teaching laboratories. After a colleague participated in a National Science Foundation funded green chemistry workshop at the University of Oregon, the department began discussing the green chemistry approach and whether such a path was possible at St. Olaf College. This consideration occurred at a critical juncture in the facility planning process, the middle of the initial design phase after our feasibility study (2000-02). Since our decision about adopting a green chemistry approach to the curriculum potentially had significant impact on building design and costs, we wanted to experiment and pilot our ideas as soon as possible. Within two years, green chemistry experiments were introduced into our synthesis teaching lab, and a major grant funded project was underway to infuse a green chemistry approach into the first three years of our chemistry laboratory curriculum (*7–12*). Our synthesis lab, typically taken concurrently with organic chemistry, incorporates organic and organometallic reaction systems. We detail the impacts of our movement to green chemistry on the design and operation of chemistry facilities in Chapter 4.

In addition to the "greening" of our laboratory program, we also created opportunities for students to partner with us to explore potential materials for the new building. In one of our general education courses, students did open-ended projects to assess the environmental impact of various interior building components, such as carpet, carpet adhesives, concrete sealants, interior latex paint, floor tile, casework, lab benchtops, ceramic tile, restroom partitions, and windows. Students used the Environmental Impact Questionnaire (*13*) from the Minnesota Sustainable Building Guide as an organizational tool for their investigations. College decision-makers, including Design Team members, attended student poster presentations and reviewed their reports and recommendations. Some consequences to the project arising from these classes include facilities personnel installing carpet squares campus-wide in new or renovation projects, the Design Team developing questions for casework vendors regarding sustainable practices, and faculty ordering and testing samples of lab bench materials.

Taken together, our efforts to create a building that maximizes environmental stewardship and social responsibility led to Regents Hall becoming the first academic wet lab facility to achieve a LEED Platinum rating from the United States Green Building Council (*14*, *15*).

Enhancing Interdisciplinary Activities

We also discussed how space needs change over the course of a faculty career. We recognized that needs for dedicated laboratory space ebb and flow throughout a research career. The Design Team questioned the model of a specific number of square feet per full-time equivalent positions (*16*),especially after seeing spaces sitting dormant at various institutions around the country. In order to match programmatic vision with fiscal reality, we needed to explore models of individual and shared research spaces.

Two student-faculty research lab models encapsulate the cross-section of thinking within the chemistry department. The first model was developed in partnership with faculty engaged in chemical synthesis. The ability to grow and shrink group sizes and make use of resources located in nearby synthesis-related laboratories was highly valuable. The resulting design, Figure 2 c-e, reveals a mixture of dedicated and shared research labs adjacent to the advanced synthesis lab. As a research group grows, activities can expand into the advanced synthesis lab (e) and later contract back into an adjacent research lab (d). Additionally, this design facilitates conversation and collaboration between research teams. The synthesis faculty anticipated that up to two faculty members could share larger (~ 600 sq ft) research spaces, and a single dedicated research lab (400 sq ft) was devoted to faculty projects with special needs, such as synthesis of UV/VIS sensitive organometallic species.

The second research lab model, represented in Figure 2n, uses a large open space for complementary biomolecular science research. Each faculty-student team is assigned a U-shaped space between benches and use dedicated smaller spaces (~125 square foot rooms along the north edge of n) for targeted activities, such as laser-light scattering, radioisotope work, small-scale chemical synthesis, fluorescence spectroscopy or work with microorganisms. In this model, all faculty and students collaborate to operate in the space and are supported by the adjacent support spaces (Figure 2 g, i, j, k l, m). This space has fostered cross-project collaborations and consultations ever since the building opened. The benefits of spatial and equipment efficiency and collegial interactions has more than offset concerns about the need for dedicated research space for every faculty member. We are able to model the collaborative aspects of the profession for our students while being professionally productive.

Assessment

One advantage of a long planning phase is that we had an opportunity to assess our laboratory spaces in a pre/post study. In Spring 2008, the last semester we were teaching in the old building, and in Spring 2009, the first spring in the new building, we conducted a survey of all students enrolled in first- or second-year lab courses in biology, chemistry, physics and psychology. The study, detailed elsewhere (*2*),

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asked students for responses on a Likert scale (strongly agree….strongly disagree) to eleven statements about their experience in the laboratory.

We had three goals for this study. First, we wanted to see whether having visible connectedness in the laboratories influenced student perceptions of interdisciplinarity. Second, we wondered whether having many windows into and out of the laboratories resulted in students feeling uncomfortable working in the laboratory environment. Finally, we wanted to assess the learning environment in the old building with that in the new building.

Student responses to most of the statements in our survey were statistically significantly more positive in 2009 in comparison with 2008. Students were between three and eighteen times more likely to respond positively to the statements in 2009 than they were in 2008. In particular, students were four times more likely to agree that departments are organized in a way that helps students appreciate what happens in laboratories in other disciplines and three times more likely to indicate that the organization of departments in the building helps them appreciate what happens in lab in other disciplines. These results suggest that we are achieving our goal of promoting interdisciplinarity through our building design.

Students were eighteen times more likely to be satisfied with the number of windows to the hallway in the new building than the old. The old building had narrow (six inch wide) windows in the doors, while the new building has large panes of glass in the doorways. Some labs (see Figure 2 f and g) have a wall of windows to the central atrium in addition to the door windows. Curiously, students in the two environments had no difference in their response to the statement: *External activities during my lab sessions interfere with my ability to focus on my laboratory work.* From these results, we conclude that our students do not suffer from a fishbowl effect in the labs with large windows to interior spaces, nor are they distracted by outdoor activities while in lab.

We included several statements about student attitudes toward lab in an effort to assess the learning environment. Students were eighteen times more likely to agree that they enjoy the physical ambiance of the laboratory in the new building than in the old building. They were six times more likely to agree that they like coming to this laboratory for lab in the new building and fifteen times more likely to think the lab was well designed. Taken together, our results show that the overall environment for student learning is enhanced in our new building.

Conclusion

Our experience working together across disciplines to develop a vision for 21st century science at St. Olaf College led to a building that is truly interdisciplinary in layout and function. We had the luxury of time in our long planning period and were able to develop a shared vision among the departments, conduct experiments to try out our ideas before committing to them in the new facility, and assess student attitudes toward their science laboratories. As a result, we have a building that builds community among the users, includes flexible space for classes and labs, and is welcoming to the college community.

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Chapter 4

Case Study Approach to Green Chemistry Impacts on Science Facility Design and Operations: Regents Hall of Natural Sciences at St. Olaf College

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Regents Hall of Natural Sciences at St. Olaf College exemplifies the substantial impacts green chemistry exerts in the design and operation of STEM related learning spaces. The principles of green chemistry align well with the guiding principles for facility construction, and they offer users and design teams opportunities to redesign and rethink systems. This case study reveals qualitative and quantitative deliverables associated with an implemented green chemistry laboratory curriculum. Feedback between building vision, mission and green chemistry yielded substantial energy and cost savings, attention to safety, design simplicity, open sight lines, low ambient ventilation noise and an inviting feel in the built laboratory facility.

In 2009, Doxsee published a chapter in the *ACS Symposium Series* describing the potential of green chemistry to permit broad access to chemical experimentation in facility independent ways (*1*). Furthermore, he posited that institutions and learners experience broad benefits from a green curriculum, specifically calling attention to issues of safety and cost savings. This chapter is not meant to provide a comprehensive review of green chemistry. It explores the impacts of green chemistry on facility design using a case study approach coupled to the framework suggested by Doxsee. Regents Hall of Natural Sciences at St. Olaf College serves as the subject of the case. While the design of the Regents

In Innovations and Renovations: Designing the Teaching Laboratory; O'Connell, L.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2013.

Hall chemistry laboratory spaces were informed by a department commitment to pilot and implement a green chemistry focused lab program, we explore the influence of green chemistry in the broader context of STEM education facilities and operations. We express, in qualitative and quantitative ways, the impacts of green chemistry on 1) chemical safety related to chemical procurement, storage and wastes; 2) engineering controls; 3) laboratory layout and design; and 4) costs, including energy and operations.

Regents Hall of Natural and Mathematical Sciences consists of a 195,000 square foot new natural science building and an 18,000 square foot renovated mathematical sciences building connected by an 8,000 square foot link. The natural sciences and link portions of Regents Hall, housing biology, chemistry, physics, and psychology, opened in Fall 2008; the renovated mathematical sciences building, including mathematics, statistics and computer science, opened in Fall 2009. Interdisciplinary programs in biomolecular science and neuroscience also call Regents Hall home. The facility contains seven multi-level classrooms, eleven flat-floored classrooms, eight seminar rooms, four computational rooms, 26 teaching labs, 13,000 square feet of student-faculty research space, and an 8,000 square foot science library with individual and group study spaces. Unlike many science facilities, Regents Hall is organized by common functions and shared resources (equipment, instruments, and infrastructure) rather than by department. Chemistry occupies spaces found on two floors and in two wings of the facility, with neighbors that bridge to areas of the biological sciences. A description of how other facility-related decisions were informed by a wide range of professionals, the development of a common mission and vision, experimenting with space in our old building and promoting cross-disciplinary approaches to enhance efficiencies can be found in this volume, Chapter X (*2*). Additional details on the building design can be accessed elsewhere (*3–6*).

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Green Chemistry

Green chemistry represents a philosophical shift in the practice of chemical science to broader systems thinking. At its core, green chemistry is resource management and pollution prevention at the molecular level. Formally, green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances (*7*). In practice, green chemistry encourages a critical focus on the hazard component of the risk equation.

Risk = the <u>probability</u> that <u>exposure</u> to a <u>hazard</u> leads to some undesired <u>outcome.</u>

In short, risk = f(exposure, hazard).

As such, green chemistry requires scientists and engineers to examine the life-cycle impacts of the chemicals and chemical processes used to study natural phenomena, manufacture new materials and create commercial goods. It calls practitioners to make strategic choices using this broad set of information. Reframing chemical questions into life-cycle-systems-thinking is similar to looking at the operation or design of a building as a complex system - a living organism that achieves multiple goals through optimization (*8*, *9*). Green chemistry taps scientific creativity, interdisciplinary approaches and innovation to pursue the design and discovery of the next generation of chemicals and materials so that they augment what we mean by performance and value to include multiple environment and human health outcomes.

In making a commitment to green chemistry, the St. Olaf College chemistry faculty recognized the need to develop this kind of mindset in its graduates and in its operations. The chemical literature is filled with calls for a shift in chemical thinking to address substantive challenges, such as, improvements to chemical water treatment (*10*), expansion of green polymers and packaging (*11*), and changes to analytical methodology (*12*, *13*). Shulte (*14*) argued that green chemistry bridges occupational safety and health to sustainability. Recently, Andraos and Dicks (*15*) conducted a comprehensive review of effective green chemistry practices in higher education. They note a series of green chemistry payoffs and identify areas for improvement in teaching and research that parallel experiences of the St. Olaf faculty and student learning mentioned by Doxsee (*1*).

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Green Chemistry and Facility Planning

Visionary teams connect green chemistry to facility operation and the planning processes for new or renovated science facilities. The organizational construct of the Regents Hall design team and the development of the project principles are detailed in Chapter X (*2*). The return of a colleague from a National Science Foundation (NSF) green chemistry workshop at the University of Oregon initiated a major shift within the St. Olaf College chemistry department. Workshop participants performed sophisticated synthetic transformations without the need of resource-intensive fume hoods or other kinds of specialized ventilation. Immediately our colleague pitched the idea of moving to a green chemistry focus in our synthesis laboratory as a way to cope with aging and unreliable infrastructure. Others quickly recognized the potential of green chemistry in other parts of the curriculum, and an externally funded effort was soon underway to pilot green chemistry in the first three years of the laboratory curriculum.

Crossover participation between the green chemistry team and Regents Hall design team formed a critical bridge. The colleague involved with the green chemistry workshop was one of the former facility planning project Faculty Shepherds. A second member of the green chemistry team served on the facility design team as the chemistry department representative during the last four years of design and construction. Their presence and work allowed green chemistry ideas and pilot project results to move into facility planning deliberations, and the facility planning questions fed back into their green chemistry work. Connecting green chemistry outcomes to the mission and vision of the facility formed another key component in making the feedback system work effectively. The guiding principles for the Regents Hall complex were known as the *Seven I's*, and they are shown in Table 1. Whenever the Design Team generated new ideas, considered design elements or questioned a course of action, these principles were used as an internal check; to be adopted, options generally had to address at least three of the seven principles.

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Table 1. Guiding Principles of the Seven I's

Interdisciplinary	How does the design preserve rigorous exploration of the current disciplines while enhancing interdisciplinary inquiry, teaching and learning?
Investigative	How does the design promote the expression of our investigative approaches to science and math?
Interactive	How does the design promote the interactive nature of modern science (student-student, student-faculty and faculty-faculty)?
Innovating	How does the design accommodate the technological and pedagogical innovations of modern science education and adapt to emerging educational strategies and technologies?
Interconnected	How does the design show the interconnections between the sciences and other distinctively St. Olaf strengths? How does the design reinforce awareness of the interconnectivity of physical space and linkages beyond the building envelope?
Inviting	How does the design invite students, faculty, staff and visitors to explore the space, encourage them to linger and inspire them to work and learn?
Integrity	How does the design model the integrity we seek, honor the environment in which it resides and reflect the college's continued commitment to environmental stewardship? It must also allow the faculty to fulfill the charge of the college mission statement to: 1) stimulate students' critical thinking and moral development; 2) encourage students to be seekers of truth, leading lives of unselfish service to others, and; 3) challenge students to be responsible and knowledgeable citizens of the world.

Green chemistry strongly coupled to a number of these guiding principles: interdisciplinary; investigative; innovating; and integrity. The ability to ascertain the hazard characteristics of a material relies on different sets of knowledge – physical, biological, and chemical - coming together in a way that moves beyond the disciplines. In order to infuse green chemistry into the laboratory, we investigated what others had previously contributed to green chemistry education. We mapped green chemistry principles onto the first three years of the chemistry laboratory program (Table 2). Then we undertook faculty-student collaborations to develop and pilot green chemistry learning experiences in our old facility; we call this innovation (*16–21*). Integrity is captured by the broad green chemistry vision at St. Olaf College: to prepare the next generation of chemical explorers to be sensitive to the impact the chemical profession has on the local and global environments; to apply creative problem solving skills to issues related to building a sustainable, just, global society; and to ask questions, seek answers, engage others and act responsibly. Overall, green chemistry provided the chemistry department and design team with opportunities to rethink and redesign. It helped the teams think broadly about systems, educational goals and what it means to do good chemistry.

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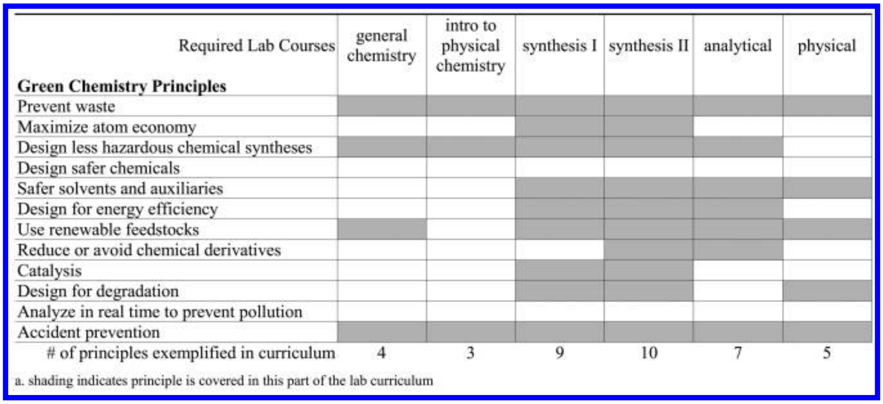
Table 2. Distribution of Green Chemistry Principles across the Lab Curriculum[a]



Required Lab Courses	general chemistry	intro to physical chemistry	synthesis I	synthesis II	analytical	physical
Green Chemistry Principles						
Prevent waste	▨	▨	▨	▨	▨	▨
Maximize atom economy			▨	▨		
Design less hazardous chemical syntheses	▨	▨	▨	▨	▨	
Design safer chemicals						
Safer solvents and auxiliaries			▨	▨	▨	▨
Design for energy efficiency			▨	▨	▨	
Use renewable feedstocks	▨		▨	▨	▨	▨
Reduce or avoid chemical derivatives				▨	▨	
Catalysis			▨	▨		
Design for degradation			▨	▨		▨
Analyze in real time to prevent pollution						
Accident prevention	▨	▨	▨	▨	▨	▨
# of principles exemplified in curriculum	4	3	9	10	7	5

a. shading indicates principle is covered in this part of the lab curriculum

The teams discovered synergies between the green chemistry principles and the credits used in the Leadership for Energy and Environmental Design (LEED) program of the United States Green Building Council (USGBC). LEED is a third party analysis tool developed to address building lifecycle issues and to recognize best-in-class building strategies. To be certified in one of four levels, building projects must satisfy prerequisites and earn points (credits) based on design and construction decisions (*22*). Many of those design points dovetail with green chemistry concepts. For example, in the LEED Materials & Resources section, the use of locally sourced materials and high recycled content relates to waste prevention and the use of renewable feedstocks, green chemistry principles 1 and 7. Energy efficiency in chemical reactions (principle 6) connects to the LEED Energy and Atmosphere credits. LEED credits associated with indoor chemical/pollutant source control and low-emitting materials map onto the design of safer chemicals, solvents and auxillaries (principles 4 & 5). The effectiveness of these synergies was recognized when Regents Hall of Natural Science became the first academic wet lab facility to achieve a LEED Platinum rating (*23*, *24*).

Impacts: Chemical Procurement, Storage, and Wastes

Waste prevention undergirds many of the green chemistry principles. In the practice of chemical education, many people may be responsible for the cycle of chemical procurement, storage, waste accumulation and disposal. In order to enhance communication among those charged with executing a hazardous material information system, renovations or new construction creates an opportunity for synergistic arrangement of spaces and personnel. Figure 1 shows the case in Regents Hall; the biology and chemistry department stockroom managers play prominent roles in managing chemical materials and share an office immediately adjacent to the large service stockroom and chemical storeroom. The chemical hygiene officer occupies an office located across the hall from this stockroom; consequently, the three principal players involved in hazardous material management are in close proximity to one another. This small team collectively manages chemical storage and waste accumulation locations throughout the building. The primary chemical storage and waste accumulation area is located adjacent to the building's loading dock; this arrangement facilitates transfers into and out of the facility. Recessed floors in this area will contain chemical spills of a variety of magnitudes. Computer network access and power is located immediately outside the storage spaces so that databases related to inventory and waste management can be readily accessed, updated and shared.

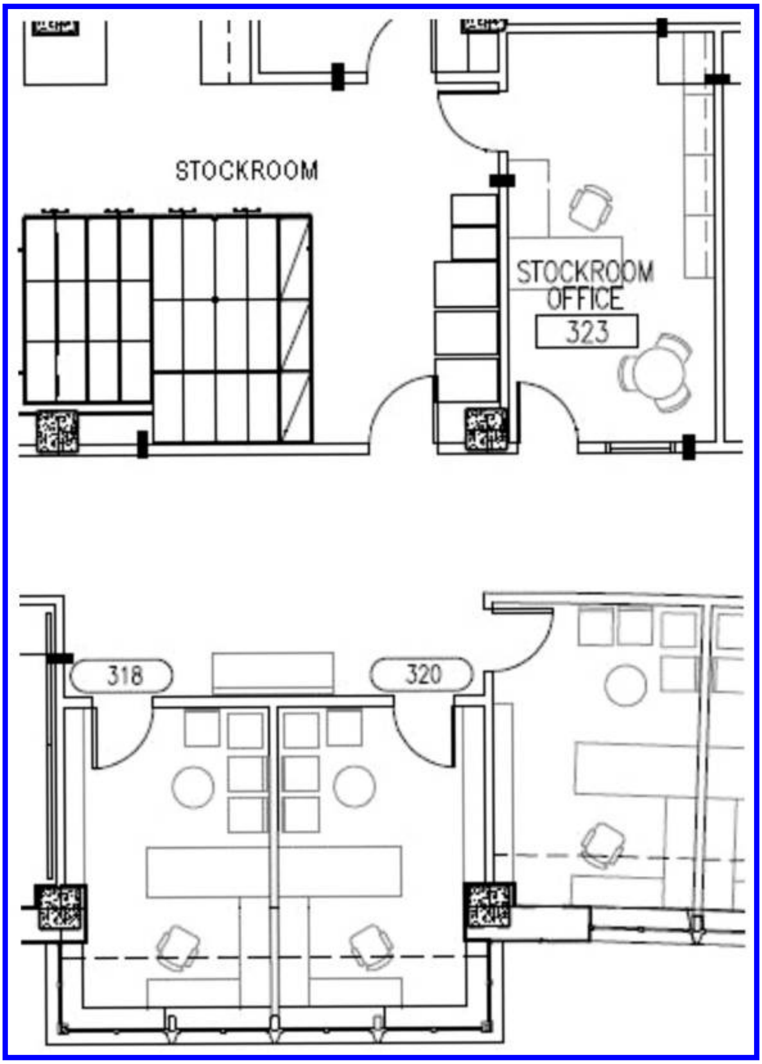


Figure 1. Proximity of personnel responsible for chemical procurement, storage and wastes. Biology and Chemistry stockroom managers share an office (323) located near the Chemical Hygiene Officer (318) and connect to the main service stockroom.

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Beginning in 2004-05, St. Olaf College implemented a new waste management system, and the chemical synthesis faculty piloted green chemistry laboratory experiments. The total liquid hazardous waste generated by the synthesis laboratory course decreased by over 30 percent in the three year pilot (Table 3). The amount of hazardous waste generated depends on the characteristics of the chemical processes, the number of students enrolled and the proficiency under which those enrolled carry out their work. In an effort to minimize variation in hazardous waste generation from fluctuations in student numbers, waste outputs were normalized by the respective annual enrollments. The amount of hazardous waste generated per student decreased by more than 20 percent over the three year pilot period, highlighting the effectiveness of green chemistry in waste prevention.

Table 3. Hazardous Waste Generation in Synthesis Laboratory Green Chemistry Pilot

Academic Year	*Annual enrollment*	*Haz waste (L/yr)*	*Per capita waste (L/student yr)*
2004-2005	290	103	0.36
2005-2006	300	95	0.32
2006-2007	248	70	0.28

Impacts: Engineering Controls and Layouts

At the time of our initial facility design, the chemical profession emphasized engineering controls as a means to address the risk of chemical exposure, including development of ductless chemical fume hood systems (*25*) and alternative fume hood designs (*26*). The chemistry department initially supported this direction, planning to incorporate 2.5 feet of fume hood space per student in our teaching laboratories. Poor product yields and difficult physical manipulations associated with microscale synthesis and sporadic operation of aging constant volume chemical fume hood infrastructure fueled this vision. Concerns about the acquisition and installation costs of the alternative fume hood designs and the life cycle impacts of filters used in ductless hoods led the department to pursue more traditional fume hood designs. The chemical sciences and facilities managers would certainly benefit from additional life cycle analysis of newer ductless fume hoods and their filtration systems.

The success of collaborative undergraduate research in forwarding green chemistry development in the curriculum (*16–21*) led to a change in the way the design team looked at engineering controls for managing risk associated with chemical use. If we could effectively teach the practice of chemistry without large numbers of functional fume hoods in our old facility, why not examine how that would carry into a new facility? The design team proposed the removal of

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one-third to one-half of the originally planned fume hoods. The architects and users recognized this change would mean additional flexibility in the layout of the laboratories as the sizes of the air handling systems decreased. Facilities personnel and the project engineers identified initial cost savings and recurrent savings to operations. Users began to think of laboratory spaces as dual function learning environments, having the potential to serve as both classroom and laboratory. The impacts of green chemistry on learning space design mentioned by Doxsee - design simplicity, open sight lines, low ambient ventilation noise, an inviting feel, and a productive work environment - became manifest (*1*, *3*, *4*).

The removal of nearly forty percent of the chemical fume hoods yielded the benefits highlighted in Table 4 and in Figures 2-5. Most notable is the footprint formerly associated with a chemical fume hood, now available for reassignment. We calculated this footprint as the area of the fume hood plus an additional work zone extending out four feet from the fume hood. The work zone allows traffic to move safely past users at the fume hood. For standard 36 inch deep 4-ft, 6-ft, and 8-ft fume hoods, this yields 28, 42 and 56 ft^2 of assigned floor space, respectively. When summed together, the total space available for reassignment in Regents Hall was 1700 ft^2. When compared to our 315 ft^2 laboratory design module, this represented 5.4 laboratory design units – very substantial space! In addition to floor space, fume hoods occupy wall space. We calculated a 'wallprint' using the distance from the former hood work surface (34 inches) upward to a 7 ft reference line the architectural team set for wall installations. Approximately 1300 ft^2 of wall space became available for other uses.

Table 4. Floor and Wall Space Gained by Reduction in Fume Hood Numbers

Timepoint	*# hoods*	*% decrease*	*floor*[a]	*wall*[b]
Initial facility plan	88			
Constructed facility plan	53	39.8	1700	1300

[a] Floor space now available for other uses (ft^2).

[b] Wall space now available for other uses (ft^2).

The availability of 3,000 ft^2 of assignable wall and floor space leads to substantial design flexibility and an open character to the laboratories, as illustrated in the layouts and photographs exhibited in Figures 2-5. The introductory chemistry labs (Figures 2 and 3) demonstrate exceptional sight lines, and an entire wall of windows provides views to the outside. Movable lab tables with edge mounted electrical strips powered through floor boxes allow for different interior spatial arrangements and promote dual uses. The space may house an integrated class/lab experience for up to 32 students or host a class when laboratory activities are not underway. Water, both tap and deionized, as well as space for small, dedicated equipment is available around the periphery. Infrastructure for projection technologies is available above the ceiling tiles.

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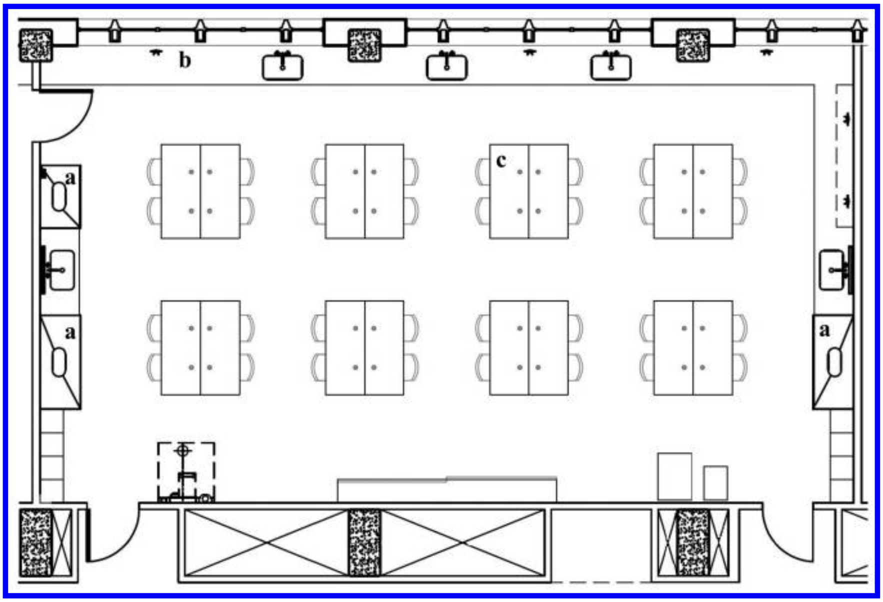

Figure 2. Laboratory layout for general chemistry. (a) Two six foot and one four foot hoods occupy interior walls, (b) exterior wall comprised of large windows and counter space for small equipment, and (c) moveable tables powered from floor boxes occupy the interior.

Figure 3. Introductory chemistry laboratory space that emphasizes green chemistry. Small equipment and sinks are located around the periphery while movable lab tables occupy the interior and allow for different configurations.

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Sophomores typically explore organic and organometallic chemical synthesis in our curriculum. Figures 4 and 5 display the design of our synthesis teaching lab. Similar in many ways to the introductory lab in hood configuration and sight lines, this lab space uses fixed benches to allow additional storage of synthetic products and intermediates. Work with high hazard materials is moved out of the sophomore level synthesis labs and into advanced laboratories and collaborative spaces for undergraduate research and inquiry. *These latter space categories were designed with the 2.5 linear feet of hood access per user in mind and preserved the ability to employ chemical approaches where no substantive green chemistry alternative exists currently.*

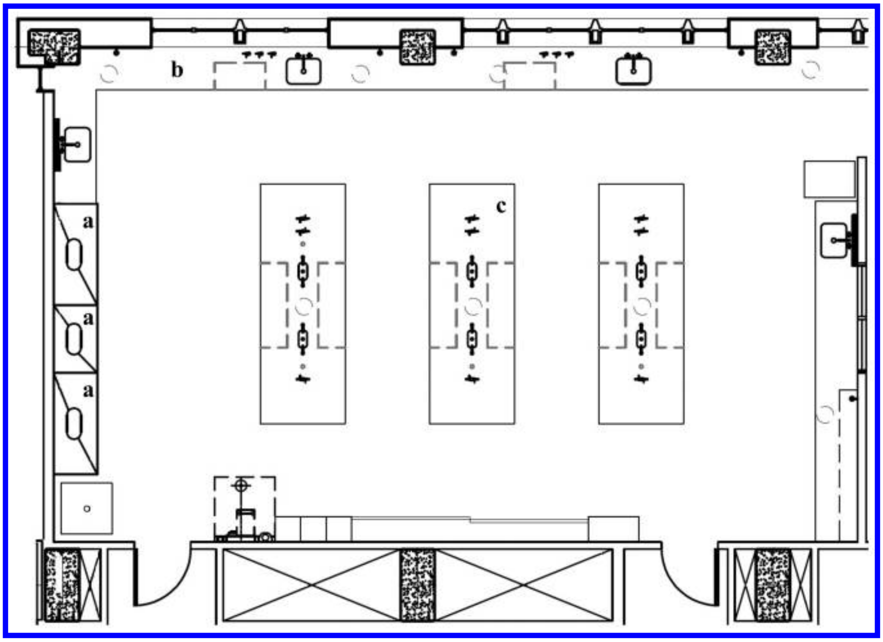

Figure 4. Laboratory layout for chemical synthesis. (a) Two six foot and one four foot hoods occupy one interior wall, (b) exterior wall comprised of large windows, and (c) fixed lab benches provide work surfaces and storage.

Fewer fume hoods allowed engineers to decrease the mechanical footprint required to condition and move air through the laboratories. Attention to chemical containment permitted the project to establish performance benchmarks for fume hoods at 50-60 ft/min linear velocities rather than at the much higher velocities used in our previous facility. The emphasis on hood performance (containment) and costs led the design team away from alternative hood designs. Considerations of the 24 hour, weekly, monthly and annual duty cycles of the lab spaces and fume hoods permitted us to create a user selectable standby status for hoods not in use. All of these factors further decreased the noise associated with laboratory air exchanges and assisted the project in meeting both the college's building requirements and LEED criteria. Most surprising was the discovery that the heating, ventilation, and air conditioning (HVAC) loads in our laboratories

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shifted from a fume hood dominated system to one determined by thermal energy released by people and the laboratory equipment. To some degree, the laboratory spaces in chemical sciences began to resemble laboratory spaces used in the biological sciences.

Figure 5. Students doing green chemistry in the sophomore level synthesis laboratory. Note the sight lines, fume hoods, windows, storage, and work areas present.

Impacts: First Costs and Operating Costs

Any time a large scale project has an infrastructure dependent system removed from the plans, substantial financial savings follow. Our construction manager calculated the average costs associated with each chemical fume hood at approximately $40,000, including the purchase of the hood, ductwork, controls, electrical, plumbing, etc. (*27*). Removal of the 35 hoods as a result of green chemistry commitments yielded a first cost savings of $1.4 million; this represents 2.2 percent of the total project costs. This money was leveraged and reinvested into the project to meet sustainability metrics.

Additional savings are realized from facility operations. It costs roughly $1000 to $1500 annually to operate each fume hood in the climate of Minnesota, and the reduction in the number of fume hoods translates into $35,000-50,000 saved in annual operations. Further energy savings result from a cascade air distribution system that employs glycol heat recovery loops and a low-flow variable air volume (VAV) laboratory exhaust system. Separate lab and public air supplies create the cascade air system in the facility. Outside air, conditioned using heat recovered from the glycol coils in the laboratory exhausts, is first passed through the classrooms, public and office spaces then returned and mixed with fresh air at the air handlers feeding the laboratory spaces. The mixing of returned air from the public side with fresh air preconditions the outside air to the 55 °F distribution temperature as it is sent to the laboratory spaces. If needed, a steam fed reheat coil supplements the VAV boxes to reheat the air when it reaches the desired space. Above an outdoor air temperature of -12 °C (10 °F), the effectiveness of this coupled heat recovery, air cascade system minimizes the steam heat supplied from the college's central plant.

Overall building performance, as measured by electrical energy use, has exceeded our expectations. The DOE-2 building energy models (*28*) suggested that if the facility was simply constructed to the Minnesota building code, annual energy use was estimated at 8.9 million kWh. Pursuit of design strategies incorporated into the facility predicted energy use at 4.9 million kWh. The first two years of operations posted energy use at 2.7 million kWh and 2.2 million kWh, respectively, as systems were optimized. This represents energy savings of 75 percent over the code requirements and almost 50 percent over the model with the design elements included. This highlights what integrated planning coupled to green chemistry can yield. According to St. Olaf College Assistant Vice President of Facilities, "We are operating at one-third the predicted costs." (*24*).

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Impacts: Students and Staff Productivity and Perspectives

A nearly decades long planning process allowed the Design Team to strategically experiment with old spaces, frequently seek user perspectives, and assess laboratory spaces in a pre/post study. Results of that work (*3*, *4*) suggest a strong relationship between student perception, learning experiences, and the design of spaces in which the learning occurs. Increased student numbers in biology (10%), chemistry (45%) and physics (100%) suggest an inviting learning space and may reflect a broader appeal of the sciences. Since the 2008-09 opening of Regents Hall, the number ofsenior chemistry majors increased from an average of 42 to 61. Similarly, the physics department observed a substantial increase in majors from 12-15 per year into the upper 20s. These observed increases were explicitly excluded from facility planning due to budgetary and other institutional constraints. We are uncertain about the specific factors contributing to the student interest; however, our assessments reflect that the overall environment for student learning is enhanced in Regents Hall.

Conclusion

Our experience in the design, construction and operation of Regents Hall of Natural Sciences at St. Olaf College showed the substantial impacts green chemistry has on the design and operation of STEM related learning spaces. The principles of green chemistry aligned well with the guiding principles for facility construction, and they offered the users and design team opportunities to redesign and rethink systems. Energy and cost savings, attention to safety, design simplicity, open sight lines, low ambient ventilation noise and an inviting feel were delivered in this facility. As a result, we have a building that supports green chemistry, includes flexible learning spaces, exemplifies thoughtful stewardship of resources, and welcomes all to engage in STEM learning.

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Chapter 5

Pressure Point: Balancing the Competing Demands of Chemistry Lab Design

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A number of pressures and challenges affect the construction or renovation of teaching laboratories, including safety, space utilization, and energy efficiency. This chapter will examine the options lab owners have for finding a balance among those factors, by analyzing the pros, cons, and expected savings and/or concessions, and will give examples of ways to creatively use lab space to meet program goals.

Introduction

Today's chemistry labs face a number of competing pressures. While safety must always come first, education and research institutions are committing to increasingly stringent energy conservation goals, making the balance between modern research and environmentally sensitive design difficult to achieve. For each lab construction project, the project team—from the designers to the users—must assess the needs and uses of the lab, including the intended teaching philosophy, to determine the priorities that will guide all design decisions. But by first identifying non-negotiable safety factors, space needs, and the lab's sustainable design goals, the team can better assess the design options that will help strike that balance between form and function. Rather than step through every code, feature, and consideration in a lab's design, this chapter provides a general discussion of some of those factors and how they influence design choices.

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Safety

When planning chemistry teaching laboratories, safety is at the top of the decision making hierarchy—as it should be! Safety considerations impact many decisions throughout the design process. International building codes, fire codes, and other standards govern the presence of the requisite safety features of a lab, from walls, doors, and windows, to safety showers and eye wash stations, to fire extinguishers and other safety-related equipment. These features are incorporated into every lab and are predetermined, non-negotiable features of its design.

Hazardous Materials

A safety requirement that has less predictable implications on the design of a lab is the storage and containment of hazardous materials. Building and fire codes set quantity limits for several categories of hazardous materials, including combustible liquids, flammable gas, flammable liquid, unstable reactive, water reactive, corrosive, highly toxic, toxic, etc. Specific quantities of chemicals in each category are permitted to be used and stored in a "control area," which may be an entire building, a floor in a building, or multiple areas on a floor.

This is where design decisions particularly come into play. Control areas are separated by fire-rated construction, and the quantity of chemicals, number of control areas, and fire rating requirements vary based on their location. The International Building Code (IBC) permits the highest number of control areas with the greatest quantity of chemicals on the at-grade floor of a building. As you ascend or descend from the at-grade floor, the number of control areas, and the chemical quantities permitted within them, are reduced. For example, the IBC (*1*) permits four control areas on the at-grade floor, with 100% of the allowable quantity of chemicals and one-hour fire separation walls, meaning walls must be constructed to withstand fire for at least one hour. The fourth floor, however, is limited to two control areas with just 12.5% of the allowable quantity of chemicals and two-hour fire separation walls. These requirements are generally based on the emergency response time necessary to access the hazardous material. The quantities of chemicals allowed in these areas can be increased if the building is equipped throughout with an automatic sprinkler system and/or the chemicals are stored in approved storage cabinets and containers.

Rooms created for the storage of hazardous materials can be part of a control area, an entire control area themselves, or, if needed, constructed as "high hazard" rooms. Building codes have specific requirements for high hazard storage rooms, including separate exhaust systems. At Cornell University's Physical Sciences Building, multiple high hazard rooms were created on the upper floors of the building to increase the hazardous material storage capacity for the flexible research labs located on those floors. Some highly hazardous materials have even more specific code requirements, such as Class 4 oxidizers (hydrogen peroxide, perchloric acid solutions, etc.), which must be stored in dedicated hazardous materials storage cabinets.

Building codes also have requirements for the containment of chemical spills, which can include containing not only spills from the largest chemical vessels,

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but also sprinkler discharge water for a specific period of time. This can be a substantial amount of water to contain and has significant design implications, such as the need for curbs around entire rooms with ramps at the doors.

Lab users, safety officers, and facilities personnel must work together with the lab design team to establish the needs for managing chemicals to ensure that the building's design appropriately accommodates them. Once that design becomes a reality, the responsibility for managing those hazardous materials belongs to the lab users. Although each project is unique, generally the process for developing a hazardous materials strategy includes the following steps:

1. Identify and quantify the hazardous materials that are needed.
2. Have industrial hygienists and/or chemists categorize the materials into the code-designated categories. Lab planners can provide the hazardous categories as described in the codes.
3. Determine where the hazardous materials are needed in the building and in what quantities.
4. Using control areas, storage strategies, etc., determine a safe and realistic approach that accommodates present and future needs.

The planning team needs to discuss the details of chemical dispensing and chemical waste management as well. Chemicals and other supplies should move as efficiently and safely as possible from the time they leave the delivery truck, to storage, prep, use, and disposal. Prep areas should be convenient to the labs and adjacent to storage rooms, where possible. "Parking areas" for chemical transport carts should be allotted in the prep rooms and the teaching labs to avoid carts in aisles. Often fume hoods within the labs are designated for chemical dispensing and for chemical waste collection.

Safe Design

With these requirements satisfied, a number of other laboratory design features are beyond the scope of building codes but still have a significant impact on safety, including:

People Flow

Safety can be compromised when areas become overly congested or inefficient. The project team needs to walk through the steps that students will undertake on a typical day and identify these areas. For example, students will gather before class to study, organize, and prepare. An area dedicated to this function will help avoid the unsafe practice of sitting on the floor in the corridors outside the labs. Additionally, a large group of students waiting near the balances to weigh chemicals is inefficient and a safety concern. Particular attention should also be paid to the distance between counters in the lab. A distance of at least 5 feet should be provided in areas where students work back-to-back to accommodate circulation between the students.

Sight Lines

Good sight lines can be achieved in general chemistry labs by locating traditional fume hoods at the perimeter of the lab and utilizing fume-extraction-type exhaust devices at the student stations in the center of the lab. Achieving good sight lines in organic and advanced chemistry teaching labs can be more challenging due to the higher number of fume hoods typically needed. In some situations, the fume hoods can still be located at the perimeter of the lab, as shown in Figure 1. In cases where windows reduce perimeter availability, fume hoods can be located in the middle of the lab in a way that creates "work zones," as shown in Figure 2. Glass fume hoods may be applicable in these instances.

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Figure 1. Fume hoods are reserved for the perimeter in this chemistry lab at John Tyler Community College. (photo courtesy of Philip Beaurline). (see color insert)

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Figure 2. Glass fume hoods are used to facilitate visibility in a chemistry lab at Delaware County Community College. (photo courtesy of Jeffrey Totaro). (see color insert)

Views into Labs

Views into labs can reduce the amount of visitor traffic, add natural daylight, and increase visibility in the event of an emergency. Window locations and treatments, such as blinds, must be carefully planned to minimize distractions to the students and instructors.

Student Belongings

Student book bags and coats should be stored away from the student workstations for safety reasons. Generally, students prefer to be able to see their belongings, making the area inside the main entry to the lab a good place for such storage. If located outside the lab, a more secure means of storage, such as lockers, will be needed. Designs that incorporate laptops above the work surface can save valuable bench space for experimentation.

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Selection of Fume Hoods and Exhaust Devices

Traditional fume hoods have long been the standard for chemistry laboratories, but they are not the only solution. As noted in the ANSI/AIHA standard for laboratory ventilation, “In many cases, an enclosing hood (e.g., glovebox, biosafety cabinet, ventilated enclosure) or a local exhaust hood (snorkel, tight fitting canopy hood, or specially designed hood) may provide as good or better control and require less volumetric flow” (*2*). Movable arm fume extractors connected to the building exhaust system at the ceiling are being used at Nazareth College, as shown in Figure 3.

Figure 3. Fume extractors at Nazareth College are movable. (photo courtesy of Tim Wilkes Photography). (see color insert)

Organic and advanced teaching labs typically use greater quantities of hazardous substances, and traditional fume hoods are often required. The proper selection and placement of these fume hoods can increase capability, according to Tracy Halmi, a chemistry lecturer at Penn State Behrend. “With our new lab layout, increased ventilation and proper fume hood selection, we no longer have to limit ourselves and can safely conduct a broader range of experiments in the labs,” she says.

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Space Planning

While safety concerns dictate many aspects of a laboratory design, the spatial arrangement of the teaching laboratory must also reinforce the specific teaching goals of the institution it serves. While the common theme of learner engagement has been at the forefront in the STEM fields for many years, the fact remains that the means of achieving this goal varies widely and reflects the diversity of institutions, students, and faculty. Because of this diversity, the range of solutions for a teaching lab type can vary from large "ballroom" facilities designed for hundreds of students to smaller facilities designed to fit the needs of a single faculty member and a handful of students.

In the context of such wide variations, it is helpful to understand the design of the laboratory as a reflection of the "clustering" of laboratory activities. A number of indicators help identify what might make sense for any given institution and its pedagogical approach:

1. Target student/instructor ratios
2. Target section/team sizes
3. Scale and/or mode of experimentation
4. Degree of "interdisciplinarity"
5. Degree of flexibility
6. Modes of instruction

Considering student/instructor ratios, one finds a remarkable level of similarity across institutions. Dictated by convention, as well as common accreditation standards, these ratios generally stay around 1:24 (reaching as low as 1:12, where the second instructor is a TA). While the specific ratio achieved may vary, it has important implications for the planning of the space.

Specifically, the inclusion of lecture-based content in a lab class implies the ability for students to see a common teaching wall and to interact with the instructor. This approach to teaching is very different from the team-based, project-based approach that forms the foundation of most curricula. Invariably, both must be accommodated, and the specific means of accommodating this essential cluster of activities yields a broad range of solutions.

Solutions vary from the inclusion of multiple teaching walls at the perimeter of labs, like those at Penn State Behrend (see Figure 4), to smaller laboratories in which a smaller student population can quickly alternate focus from team-based activities at the bench to instructor-based activities at the "front" of the room, such as at McMaster University (see Figure 5). In other cases, such as at Harrisburg University of Science and Technology and Carnegie Mellon University, the lecture-based activities are deliberately separated from but adjacent to the laboratory.

The variations not only reflect a difference in attitude regarding the ideal class size, but also variations in attitudes regarding the role of interdisciplinary inquiry and overall laboratory flexibility. At McMaster University, for example (Figure 5), students work on team-based projects, which deliberately draw upon a wide array of physical and biological sciences. The eight-person tables in

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these labs reinforce the breakdown of the class into eight-, four-, and two-person groups. Providing "parking spaces" for equipment carts, as well as recessed utilities, the tables maximize flexibility, enabling quick set-up and take down for discipline-specific equipment. Supported by an adjacent hood room and a dedicated instrument/set-up area with an attendant, the suite enables teams to work at both macro and micro scales and offers access to a full set of experimental operations. (See example floor plans in Figure 6.) Importantly, it does so without sacrificing the laboratory sight lines, thus supporting constant interaction between student teams and the instructor. All of these design decisions are, of course, also observant of the Americans with Disabilities Act (ADA), with the moveable benches, low sinks, and other features that are now inherent in any design process.

Figure 4. A teaching wall lines one end of this lab at Penn State's Behrend Campus. (photo courtesy of Denmarsh Photography). (see color insert)

On the other end of the spectrum, the organic chemistry labs at Carnegie Mellon have a bench configuration that seeks to encourage the formation of small gathering areas within the lab. Thus, while the lab houses as many as 70 students, each with easy access to a dedicated hood area, it is divided into a series of neighborhoods and "pods," as shown in Figure 7. Supported by multiple TAs and instructors, this arrangement supports group instruction in mid-lab, but functions equally well for the one-to-two-person teams one typically finds in organic chemistry instruction. Like at the facility at McMaster, the laboratory has adjacent support spaces – in this case, an instrumentation room and chemical distribution area. Rolling carts enable the "parking" of equipment adjacent to student stations, creating opportunities for longer-term use of the equipment in association with student projects, further enhancing the overall flexibility of the space. These arrangements are examples of the degree to which the integration of technology has begun to influence laboratory design. Solutions range from the “parking” of expensive testing apparatus adjacent to student benches to the integration of laptops and/or shared monitors at the desktop, as shown in Figure 8.

Figure 5. McMaster University labs provide flexibility for team-based work and central instruction. (see color insert)

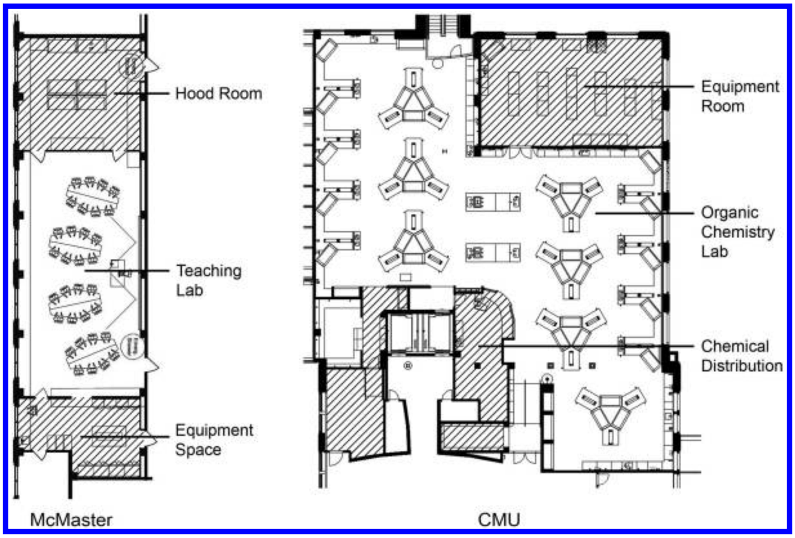

Figure 6. Suites designed to cluster support spaces with teaching laboratories, as in these example floor plans, enable more flexibility for student project work.

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Figure 7. A "pod" station at an organic chemistry lab at Carnegie Mellon University. (photo courtesy of Ed Massery). (see color insert)

Figure 8. Marist College chemistry teaching labs fully integrate technology into the lab bench. (photo courtesy of Denmarsh Photography). (see color insert)

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These examples indicate the degree to which any lab must be considered in the context of an entire suite of activities and teaching styles and objectives (i.e., the various ways of achieving the adjacency of lecture and hands-on modes, or of supporting student projects in the context of large-scale instruction). Adjacent equipment and support spaces can enable increased flexibility. In addition, given the pressure to improve learning outcomes and to provide a wider array of students the ability to learn "on their own terms," many institutions now consider adjacent "learning commons" to be an essential component of the laboratory suite. These spaces range from open seating areas and work tables in close proximity to TAs and faculty, to facilitated learning spaces in which student teams pursue project work outside of the lab but overseen by TAs. Learning commons offer a means of extending laboratory effectiveness and help create the cohesive learning communities that underlie successful STEM programs.

Indeed, some institutions, such as the University of Maryland, Baltimore, have begun to require the use of these spaces as a prerequisite to earning academic credit for laboratory coursework. This approach has the advantage of reinforcing course content and improving outcomes, while simultaneously decreasing the burden on regularly scheduled spaces for credit-bearing activities. Such innovations are driven by the demands of increased enrollments, coupled with the need to more effectively engage an increasingly diverse student body.

These trends, combined with the explosion of good online content, hint at the potential for a paradigm shift in the planning of STEM learning environments and associated curricula – one in which the clustering of activities will occur in both the virtual and physical world. In this model, the clustering of learning and facilitated support venues near the laboratory environments will give faculty the flexibility they need in order to adapt to the demands of students immersed in new modes of interaction, without sacrificing the quality of the laboratory experience.

Sustainable Design Principles

With these shifts in how an institution approaches its lab space, sustainable design becomes yet another pressure on the already full design plate. But a more energy-conscious design can be achieved, primarily by focusing on a lab's ventilation and plumbing systems.

Ventilation

Considering that a typical fume hood exhausting 1,200 cubic feet of air per minute, 24 hours per day, consumes more energy than an average house, the most significant impact a lab's design can have on energy conservation stems from the design of air supply and exhaust systems for fume hoods. A variety of options exist for fume hoods and similar equipment, including basic fume hoods, energy efficient or "high performance" fume hoods, ductless fume hoods, and fume extractors. The fume hood selected for a lab is directly related to the controls systems of the building, meaning a solid assessment of the costs, benefits, and function of each type of fume hood is critical to ensuring the system as a whole functions as efficiently as possible.

Basic Fume Hoods

Basic fume hoods are available in a variety of types and sizes. If extensive lab work will occur in the fume hood (such as in an organic/synthetic chemistry lab), a 6-, 7-, or 8-foot fume hood can reasonably accommodate two students simultaneously (Figure 9 shows these longer fume hoods). Ideally, once operational and safety concerns have been met, the smallest fume hood should be selected to minimize the amount of ventilation air required. The ventilation requirement generally increases at the same rate as the fume hood size, so an 8-foot fume hood will require approximately 33% more ventilation air as compared to a 6-foot fume hood.

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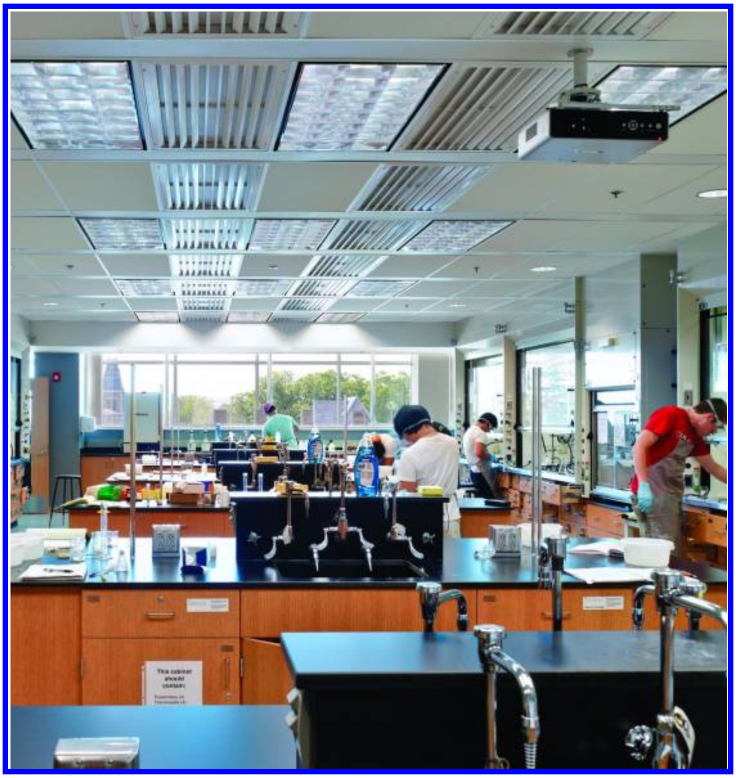

Figure 9. Two students can share 7-foot fume hoods at organic chemistry labs in Cornell University's Physical Sciences Building. (photo courtesy of Jeffrey Totaro). (see color insert)

High-Performance Fume Hoods

High-performance (once called “low flow”) fume hoods were developed with energy efficiency in mind. The interior cabinet configurations are aerodynamically designed and, as a result, less ventilation air is required to maintain a safe working environment. The high-performance fume hoods tend to be larger (particularly deeper) and more expensive. A cost/benefit analysis should be completed to determine if the proposed energy savings will offset the higher sales price.

Ductless Fume Hoods

Ductless fume hoods rely on sophisticated filters to clean the exhaust air before it is re-introduced into the laboratory. While a fan is still required to move the contaminated air through the filters, energy is conserved by avoiding the need to recondition the air since it remains in the laboratory. The cost of a ductless fume hood exceeds the cost of a ducted fume hood, but that cost is offset by eliminating the need for fume hood exhaust ductwork. Laboratory supply and exhaust air systems are still required to maintain the minimum air-change rates described above. Ductless fume hoods should not be used for:

- laboratory work in which chemicals of different types are repeatedly used
- unknown chemicals or to contain byproducts of reactions for which the characteristics are unknown
- multiple chemical processes where the mix of chemicals could cause hazardous reactions in the filter
- certain chemicals and processes with high levels of concentrations and/or emissions

Fume Extractors

Fume extractors, or snorkels, require less ventilation than fume hoods, but they can only be used with nontoxic noxious and annoying materials. These devices are not intended to be used with hazardous substances due to their unreliable capture characteristics as compared with a fume hood.

Supply Air

Supply air for laboratory ventilation is required to be 100% outside air. The amount of ventilation air required and energy consumed to deliver, heat and cool, humidify and dehumidify, and filter the air is directly related to the number of fume hoods in the laboratory. The energy can be reduced if energy from the exhaust air is transferred to the supply air upon entering the building. A variety of systems exist, but the most efficient is a heat wheel, also known as a thermal wheel, rotary heat exchanger, rotary air-to-air enthalpy wheel, or heat recovery wheel.

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Heat wheels have been used for many years in a variety of research and healthcare facilities. The advantage of a heat wheel is its ability to transfer sensible as well as latent energy for heating or cooling. There is some concern that the supply air will be contaminated by the exhaust air since portions of the heat wheel come into contact with both. However, manufacturers of the devices note the molecular structure of that portion of the wheel makes the possibility of contamination minimal. SEMCO LLC's EXCLU-SIEVE wheel, for example, utilizes a 3Å molecular sieve desiccant coating to limit the risk of desiccant cross-contamination, which would otherwise cause a portion of the exhaust air pollutants to be transferred, along with the water vapor, to the fresh air stream.

One disadvantage of the heat wheel is the requirement to consolidate all supply and exhaust ductwork in a side-by-side configuration for the heat wheel to work. Depending on the size of the facility, these ducts may be substantially large. Although not insurmountable, their collocation does pose some architectural and mechanical design challenges.

Reducing the energy needed to power the fans for conveying supply air is another way to conserve energy in a lab. A common technique to reduce this fan power energy is to reduce the amount of supply air delivered to the laboratory when it is unoccupied. Dual-technology (infrared and motion) occupancy sensors are commonly used to determine when a laboratory is unoccupied, prompting the system to reduce the amount of ventilation (and exhaust air). The quantities of each are restored when an occupant is identified by the occupancy sensor. Occupancy sensors can also be connected to the fume hood sash so that it will automatically close when the lab is unoccupied.

An additional option for reducing supply and exhaust air utilizes sensors that periodically monitor the quality of the lab's air. When hazardous materials are not present, the supply and exhaust air is reduced. The limitation of this system lies in the sensor types, which must be selected based on the anticipated hazardous materials that will be used in a lab. This system may be appropriate for an instructional lab where predictable hazardous materials will be used. As is the case with all options that have the potential to create unsafe conditions in the event of a system failure, the institution's Environmental Health and Safety representative should be consulted prior to their inclusion in the lab's planning, design, and construction.

While effective at reducing energy, there are some concerns about the quality of the laboratory air if the amount of ventilation air is reduced prior to the laboratory's occupancy. An alternative is to allow the temperature of the air to rise in an unoccupied lab while in cooling mode and lower if in heating mode. This technique has been proven to be more effective in reducing energy than adjusting the ventilation amounts and allows the amount of supply or exhaust air delivered to the laboratory to remain constant. For example, the HVAC controls at Cornell's Physical Sciences Building were designed to allow the temperature of the air to rise in an unoccupied lab while in cooling mode and lower if in heating mode without changing the amount of ventilation air. This technique has reduced the building's energy usage by almost 4%.

Another innovative way to reduce fan power energy is to circulate supply air through a simplified supply air duct system that minimizes size transitions and

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bends. Duct size transitions are typically used when less supply air is required, such as at the end of the duct run. The supply air ducts transition to smaller sizes, and less sheet metal is required. However, each transition element creates a restriction in the duct that increases the static pressure and increases the fan power needed to deliver the supply air. A supply air duct that retains the same cross section from the beginning to the end will require less fan power than a duct that has several size transitions. By retaining the same duct size, additional supply air can be made available to spaces at the end of the duct run. Although additional sheet metal is required, the value of the added flexibility can offset the small additional cost.

A final innovative way to reduce supply air energy costs is through the use of a single air supply system rather than separate systems for laboratory and non-laboratory uses. Since non-laboratory spaces do not require 100% outside air, separate systems have traditionally been designed for laboratory and non-laboratory spaces. However, a small percentage of the air provided to non-laboratory spaces is ultimately exhausted, which is offset by a small percentage of outdoor air delivered to the non-laboratory spaces.

Alternatively, a lab building could employ a single system that serves both laboratory and non-laboratory spaces. The air from the non-laboratory spaces that is normally recirculated is re-introduced into the air system as is the air that is normally exhausted from the non-laboratory spaces. The 100% outside air for laboratory spaces is therefore made up of pre-conditioned outside air from the recirculated, non-laboratory air and unconditioned outside air. The air from the laboratory spaces continues to be 100% exhausted. The result is a simpler single air supply system that provides much higher-quality ventilation air (a sustainable principle) to non-laboratory spaces and that takes advantage of the pre-conditioned air delivered to the non-laboratory spaces. The small cost premium associated with the larger air handling system is offset by the flexibility to allow any non-laboratory space to be converted into a laboratory space without significant ventilation system changes (and significant costs).

Exhaust Air

It was common in the past to provide a separate exhaust duct from fume hoods and laboratories to separate exhaust fans on the roof. Today, shared exhaust plenums often serve multiple fume hoods since it is now understood that the amount of dilution air commonly introduced into the exhaust air system reduces the possibility of undesirable reactions to within acceptable limits. Separate exhaust ducts continue to be required for fume hoods in which radioactive materials or perchloric acid is used.

Even with the acceptance of larger plenum-style exhaust ductwork, changing the horizontal exhaust duct size along its length with transition pieces remains a common strategy to reduce the amount of sheet metal used. However, like the supply air ductwork, every transition piece and bend creates additional resistance (static pressure) that results in higher exhaust fan power. A different solution for reducing that fan power is to reduce or eliminate size transitions and organize the

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horizontal exhaust duct runs to minimize bends. While there is a small cost to add more exhaust duct sheet metal, that cost can be easily recouped in the flexibility the system allows for adding or moving fume hoods to any location along the horizontal exhaust duct run.

Plumbing

Several common chemistry lab practices needlessly use clean water, such as using water aspirators that employ clean water to create a vacuum or rotary evaporators that use clean water for cooling. In the past, vacuum systems have included a central pump or many decentralized vacuum pumps with dedicated vacuum piping. Often the vacuum pumps would be contaminated when proper vacuum-trap protocols were not followed. An innovative alternative is to take advantage of the Venturi effect by using compressed air to create vacuum pressures of up to 28" of mercury or less. These readily available generators require a source of compressed air in order to function but require no electricity. Rather than use clean water for cooling, closed loop chillers or water baths and water pumps can recirculate ice water through a condenser on a rotary evaporator, conserving water and costs.

Other Utility Services

While the ventilation and plumbing systems of a lab offer the most opportunity for improving its environmental efficiency, some adjustments can be made to the typical utility networks to further support conservation goals. As mentioned, replacing water aspirators with vacuum generators that use compressed air saves water and eliminates a separate piping system and associated vacuum pumps.

The elimination of a central vacuum pump is consistent with the general trend for decentralized vs. centralized lab services. Central systems require regular inspection and maintenance on the common or shared “trunk” portion as well as the dedicated or “branch” parts of the distribution system. Utilizing multiple dedicated vacuum pumps, compressed air pumps, and/or specialty gas sources results in the elimination of the trunk portion of the distribution system, reducing inspection and maintenance costs and reducing the possibility of contamination caused by leaks.

Natural gas represents an additional lab service that many academic institutions are eliminating from their chemistry teaching labs, partially due to the potential liability associated with this flammable gas. Heating mantles, hot plates, and other lab equipment are available to replace Bunsen burners. Some academic institutions use steam to provide a heating source, but this system generally requires frequent maintenance.

Finally, occupancy sensors should be considered for all lab lighting to reduce electrical use. While earlier occupancy sensors were less reliable and had the potential for being a safety hazard, current dual-technology (infrared and motion) detectors are more reliable.

Conclusion

When it comes to trends in laboratory design, the "trend" is that each institution approaches it differently, perhaps emphasizing collaboration in one design, individual or small team research in another, and energy efficiencies somewhere else. By first considering the ultimate goals of the curriculum and the style of teaching employed, one can provide the guardrails for the design philosophy which, with a little ingenuity, can certainly accommodate the safety and sustainability measures that the modern teaching laboratory now requires.

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Chapter 6

Renovating Four General Chemistry Laboratory Rooms at the University of Nebraska-Lincoln

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Four General Chemistry laboratory rooms were renovated at the University of Nebraska-Lincoln over the span of one year and at a cost of \$1.6 million. The rooms were designed in conjunction with the development of a new laboratory curriculum that aims to teach methodological proficiency and critical thinking. Assessments were developed to determine the effect of the renovated space and the new curriculum on student learning, student attitudes, student retention, and teaching assistant evaluations. The most significant result was that students retained positive attitudes toward chemistry due to the interventions. Two key ideas that led to the final room design were the elimination of assigned desk drawers and a scheduling change that allowed students to enroll in any laboratory section. The rooms were designed to be flexible for students, teaching assistants, staff, and instructors. Student-student and student-TA interactions are enhanced by the student bench design, linkage of monitors to each bench, improved sightlines, and improved safety features.

In Innovations and Renovations: Designing the Teaching Laboratory; O'Connell, L.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2013.

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Four Renovated General Chemistry Laboratory Rooms

Four general chemistry laboratory rooms at the University of Nebraska-Lincoln (UNL) were renovated in 2011 at a cost of $1.6 million (Figure 1). UNL is the state's largest and oldest research university with over 24,000 enrolled students. The project was launched in late December 2010, and construction was completed shortly before the beginning of Spring 2012 semester. The rooms incorporate many new concepts for chemistry teaching labs and were designed to be flexible for students, teaching assistants, staff, and instructors. The bench design and improved sightlines foster student-student and student-TA interactions while increasing lab safety.

Figure 1. Island benches in the renovated general chemistry laboratory room, Spring 2012. The doghouse (small raised platform) in the center of each island bench has eight electrical outlets and two vacuum ports. Each bench has an HDMI connection to a wall-mounted large-screen monitor. Photo courtesy HDR Architecture © 2012 HDR Inc.

Student Features

The rooms were designed to enhance student learning in several ways. Four students work at each island bench. The octagonal shape of the bench top allows them to work on their apparatus while looking at their partner. The proximity to a second pair of students invites conversation and the natural tendency to keep tabs on each other's progress. There are no chairs or stools because standing people can reach farther (*1*). People are also more alert and react quicker when they are standing, which also promotes safety. At the center of the bench's broad unencumbered surface is a doghouse (small raised platform) with eight electrical outlets and two vacuum lines. This allows nearly all of the procedures to be performed at the bench and reduces the need to transport materials. During the semester, students learn that each of the six island tables is connected to one of the wall-mounted large-screen monitors with a high-definition multimedia interface (HDMI) port. At the end of certain experiments, they are encouraged to share their results with the class via this connection.

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Safety Features

The strong light and clear sightlines are safety features. The transparent fume hoods allow students in adjacent rooms to be aware of, but not distracted by, the activity next door. There is a door between the adjacent rooms for quick access in case it is needed. To ensure a cleaner work area, the trash receptacles are located at both ends of the room. To ensure a drier, safer work area, the sinks were also placed at the two ends of the room rather than next to the island benches. There are numerous cubby holes located along the room perimeter in which students can store their backpacks or jackets.

Features for the Teaching Assistants

Each room is outfitted with a TA station. At the beginning of the period, all six wall-mounted large-screen monitors are controlled by the teaching assistant, who uses a short set of PowerPoint slides to introduce the goal and to administer the safety quiz. The TA can use the flex camera to demonstrate some aspect of that day's apparatus or method and has the capability to access the internet to show a relevant video. The island benches are situated far enough from one another that the TA can easily make his or her way around the room while remaining aware of the general activity. If the reagents run short during the week, the TA can use the computer to send a text or email to a staff member rather than send a student to the stockroom, as we have done until now.

Features for the Staff

There are maple cabinets along the perimeter, each filled with trays containing a different week's apparatus. On Monday, a staff member transfers that week's apparatus to the island benches. On Friday, the apparatus is returned to the cabinets. There is a reagents table located near one of the doors for easy access throughout the week. Its broad surface holds materials that will be consumed during the week.

Energy-Saving Features

Despite being brightly lit, the light fixtures do not generate excessive heat because the room is fitted with low-energy fluorescent bulbs in which the light is sent downward by hundreds of glass panes placed perpendicular to the light bulbs. The light is also ambiently reflected downward by the white ceiling clouds that also absorb sound, give visual interest by resembling graphene, and hide the

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mechanical duct socks above. The duct socks quietly deliver substantial amounts of air to the room. There are sound and motion sensors on the ceiling to shut off the lights when no one is present for 30 minutes. If the lights are off when you enter, they will automatically turn on, although there is also a set of light switches for fine control. To save even more energy, the windows are covered in UV film and outfitted with electronically controlled shades.

The 1970 Laboratory Room Design

The renovated rooms are such a conceptual departure from the previous laboratory rooms that it is fruitful to consider the original design. Hamilton Hall accommodates all functions of the Chemistry Department at the University of Nebraska-Lincoln. It was built in 1970 to handle the rapid growth in the number of faculty and students that occurred throughout the 1960s. The second, third, and fourth floors house all chemistry teaching laboratory rooms (Figure 2), plus the Chemistry Resource Center, two preparatory rooms, the Undergraduate Instrumentation Center, a former library that now serves as a large storeroom, a former glass shop, and a variety of rooms for ordering and storing chemicals, glassware, and disposables. In the past decade, the building's entire infrastructure of heating, ventilation, air conditioning, and electricity was renovated. While these improvements were taking place, it became apparent that the three undergraduate teaching laboratory floors were past due for renovation.

Figure 2. Teaching Lab Room after 40 years of continuous use. The student in the foreground is reading a burette attached to a rod, which is connected to a shelf that divides the bench in half. There are two small blackboards for instruction between the windows. Photo by UNL Chemistry Department.

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According to our architects, a typical teaching laboratory is designed for 15 years of use. Although our chemistry teaching laboratories at UNL have been maintained as best as possible, they have not been renovated since they were constructed in 1970. Their design reflects the expectations of the era in which they were built. Every enrolled student was assigned a drawer of glassware so they learned responsibility and became familiar with individual pieces. In the event something broke, the student paid a replacement fee. Each general chemistry lab room had enough drawers to handle a maximum of eight sections of 24 students, which is no longer sufficient for our student load. Over the years, the ever-increasing equipment footprint has also reduced the maximum section size to 20 or 22 students per room. Whenever a lab curriculum update required a change in drawer contents, student workers were hired to change hundreds of drawers in multiple rooms.

The original general chemistry laboratory rooms consisted of two full benches down the middle of the room plus two half benches along each side (Figure 2). All rows were perpendicular to the windows, which were not shaded. The students worked side-by-side. The shelf down the middle of each bench housed piping and electricity. Each student's space had spigots for air, nitrogen, steam, and natural gas, a single electrical outlet, and was adjacent to a deep sink. The nitrogen and steam sources were capped over the years due to excessive leakage. The shelf contained a channel to which metal rods could be secured for attachment of clamps. The shelf also prevented students from seeing each other and the teaching assistants. There were no specific places for trash cans, waste containers, coats, or personal items. Over the years, the TAs learned to communicate with the students by writing notes in chalk on the bulk head of the hoods. Associated with each lab room was a smaller equipment room where students transformed their samples into data. Although we began our renovation discussions by listing the problems associated with the original space, nearly all of the assumptions and choices made to create the 40-year-old design were reconsidered by the time we reached the final design for the renovation.

Funding, Planning, and Vision

The most important factors that led to our ability to develop a highly functional design in such a short time period were: 1. assembling a small, focused team, 2. two site visits to innovative and recently renovated laboratories, 3. the serendipitous availability of a new and nearly complete general chemistry lab curriculum developed by a colleague, 4. the decision to create a laboratory pool whereby students could enroll in any lab section independently of their lecture section, and 5. the decision against assigning lab drawers. Our discussions about laboratory design iteratively reconsidered our choices from the following perspectives: 1. a safe environment, 2. students ability to learn, 3. the teaching assistant's ability to communicate with students, 4. the staff member's access to and maintenance of the lab space, 5. the instructor's ability to update experiments, and 6. infrastructure so the space is bright, quiet, and low in energy demands.

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Funding, Goals, and Assessment

The design phase took three months, beginning immediately after the department received word the renovation was being funded in late December 2010. An amount of $1.6 million was provided to renovate four rooms for use by General Chemistry 1 students. Separate funds provided $75,000 for audio-visual and other instructional technologies. Additionally, the department and college spent over $75,000 to purchase new equipment, including enough Vernier Labquest units and attachments for every student.

The department chose to renovate four rooms on one wing of the second floor because it is one flight of stairs from the ground floor and because it houses the Chemistry Resource Center, where TAs are on duty to answer questions.

Coupled to the renovation, the Associate Vice Chancellor requested a plan for pedagogical improvements and a plan to assess the impact the room renovation has on student learning. Fortunately, Professor Eric Malina was developing a new General Chemistry laboratory curriculum. The first part of each experiment is highly structured to develop proficiency with an instrument or protocol. The second part is driven entirely by students working in pairs who are given a problem to solve—they must develop the protocol, make the measurements, and analyze the results. The primary goal of Malina's new laboratory curriculum is to develop critical thinking skills, which are linked to increased motivation, attitude, and retention (*2*).

Professor Marilyne Stains devised an assessment protocol to measure the impact of the new space on learning. The assessment began in Fall 2011 in our unrenovated rooms (to compare the existing curriculum with the pilot of the new curriculum), then continued in Spring 2012 in our newly renovated rooms (when everyone was using the new curriculum), and concluded in Fall 2012 after the space had been used for one full year. One of our controls was to assess students in General Chemistry 2 carrying out the existing curriculum in unrenovated rooms. The most important assessments were of student critical thinking skills (ACT College Assessment of Academic Proficiency Exam, CAAP Exam), student attitudes toward chemistry (Attitude toward the Subject of Chemistry Inventory, ASCI) (*3*, *4*), and the impact of the laboratory environment on student learning (Science Laboratory Environment Inventory, SLEI) (*5*). We also assessed course retention, midterm exam performance, percentage of students earning D, F, and Withdrawal grades in the course (%DFW), formative feedback about the teaching assistants, and overall evaluation of teaching assistants, as all of these are routinely collected by the department every semester.

Although there has been a great deal written about the integration of instructional technology in the classroom (*6*), there is scant literature about the impact of lecture or seminar rooms on learning and none on laboratory rooms. At the Massachussetts Institute of Technology, physics students showed deeper conceptual learning in classrooms designed for a collaborative, active learning approach that was enhanced by visualizations, desktop experiments, Web-based assignments, a personal response system, and conceptual questions coupled with peer discussions (*7*). At the University of South Carolina, physics and calculus students showed deeper conceptual learning, better attendance, and

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higher retention when they engaged in collaborative learning in spaces designed to foster such interactions (*8*). It was not established, however, whether the effects observed at MIT and USC were due to new pedagogy or new rooms because both were changed simultaneously. Arguably the only published evidence concerning the impact of a room on science learning is from the University of Minnesota, after they constructed seminar/lecture rooms designed to foster student-student and student-faculty interactions (*9*). In this study, instructor and time of day were controlled such that only the meeting space varied between a traditional classroom and a room designed for active learning and collaboration. The results showed that students in the active-learning classroom outperformed expectations based on their ACT scores, while students in the traditional classroom performed almost exactly as predicted. At UNL, we had enough time to plan an effective program of assessments for both our new space and our new curriculum to disentangle the two factors.

Developing a Vision

The Lab Renovation Team consisted of 1. Vice Chair Mark Griep and Business Manager Dodie Eveleth from the Chemistry Department, 2. Associate Vice Chancellor Lance Pérez from the Office of Academic Affairs, 3. a Project Manager contracted from outside the University, and 4. Architects Chris Ertl and David Hinsley from HDR Inc. The Team held meetings every other week for the period of one year. At key moments, Griep sought the advice and approval of other department members. Pérez identified the freshman chemistry laboratory rooms as a critical feature in need of renovation and managed the project on behalf of the Chancellor and Senior Vice Chancellor for Academic Affairs. Pérez also manages campus instructional technology and was responsible for introducing ideas about using wall-mounted large-screen monitors to foster student communication during the lab period. The Project Manager was responsible for ensuring the project met the requirements set down by University Facilities, conformed to the architect's design, and kept on schedule and on budget. He led the biweekly progress meetings with the Team and the Construction Leaders. The architects were chosen because they specialize in undergraduate science laboratory design.

The visits to recently renovated labs were critical to the project's success. Each department we visited was very happy to show their renovated lab rooms, discuss how they developed their design, and share how they use the rooms. They were also willing to describe features that had been roadblocks or that had not quite worked out or had not been fully considered. In January 2011, a group of us visited the University of Iowa's Department of Chemistry to view their laboratory rooms, which were renovated in conjunction with the rest of their building in 2007. A few weeks later, some of us visited Creighton University's Department of Chemistry laboratory rooms, which were renovated by HDR in about 2008. In early February 2011, some of us toured the UNL Department of Physics, a new building completed in Fall 2010.

A great deal of information was learned from these visits, but several observations proved especially critical to our design. 1. An octagonal work space significantly enhances collaboration. 2. Do not assign drawers to students.

Instead, lay out each experiment's apparatus at the beginning of the week for the students to use throughout the week. This allows students to begin working almost immediately. Clean up is also quicker, although it must be closely monitored by the TA. With less glassware in play every week, breakage is significantly reduced. 3. Install cubby holes around the periphery for backpacks and coats to prevent tripping during the lab period. 4. Keep frequently used equipment on the desktop near the students.

In our earliest design meetings, we coupled the findings from our visits to the idea that the bench top should be as clear as possible to give the largest possible workspace. Even so, our key idea was to create a space that was flexible and adaptable for all users now and into the future. The architect was diligent in exploring all avenues. For instance, one design that was rejected, even though it would be flexible and adaptable, was to install variable-height benches on wheels with electrical and other connections that dropped from the ceiling, as they do in engineering laboratories. We also opted against installing computer stations and water service at each bench. We decided to move the sinks to the periphery and reduce their numbers, which forced us to add two vacuum lines to each island. We decided to store balances and other equipment in the cabinets and to place them on the benches only during the weeks they would be used. We decided to incorporate the electronic probeware systems into our new curriculum. Since everything was becoming more electronic, we wanted sufficient numbers of electrical outlets. While discussing the need for clean sightlines to enhance safety and that we would no longer assign drawers to the students, Ertl hit upon the idea of relegating all material to the shelves in the cabinets along the periphery. Without drawers beneath, the benches became islands at which the students would work.

For the teaching assistants, we designed a TA station with computer, flex camera, and adjacent whiteboard. Instead of installing a projector and screen, Pérez suggested sending the images to monitors located around the room. We settled upon one monitor near each bench. The next suggestion was to give students a way to share their data via the monitors, which led to the installation of HDMI ports at each bench.

Our building design requires us to store and prepare chemicals in the preparatory room located down the hall; consequently, we placed a reagents table near one of the doors in each room. Within each room's cabinets, we planned to store the apparatus for all experiments. University Facilities worked separately with the architects to incorporate low-decibel air flow technology, low-energy but high-intensity lighting, automatic light intensity adjustments, and key card access to the rooms.

After all the key design elements were in place, the architects generated a three-dimensional image of the new design (Figure 3). This image helped visualize the plan prior to its final approval, and it was used in the press release announcing that the renovation would be complete in nine months.

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Figure 3. Three-dimensional rendering of Island Bench Laboratory Room Design, Spring 2011. It shows the relationship between lighting, flooring, cabinetry, and bench tops. The six island benches give an open feeling to the room, the ceiling clouds absorb sound and reflect light, the monitors along the perimeter allow communication with and between students, and the transparent hoods allow two adjacent rooms to keep tabs on each other. Image was prepared by HDR Architecture © 2011 HDR Inc.

The Lab Pool Schedule

The idea to switch to a lab pool system came from a consideration of long-range room usage throughout the building. In a lab pool, students from any lecture section can enroll in any laboratory section. While the site visits and the earliest design discussions were taking place, it was necessary to devise a wide range of plans: an interim lab room usage plan; a long-range renovation plan for all undergraduate laboratory rooms; and usage plan for other rooms throughout the building. Since courses are scheduled nine months in advance, it meant developing a schedule for lab sections in the rooms being renovated. Before this could be done, however, the new rooms had to be entered into the system, which led to a discussion about room numbering and labeling.

The Department had never considered using the lab pool system before, and it was necessary to describe its merits and demerits before it could be implemented. For the student, the biggest advantage of a lab pool is more choice when setting up a schedule. The idea to switch to a lab pool came from the decision not to assign drawers to students. Without assigned lab drawers, the number of sections per room is limited by scheduling conflicts and the efficiency of turnover between

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sections, not by drawer allocations. Another advantage of the lab pool is that no matter how many sections are scheduled in each room, there is only a need for one or two pieces of equipment to every bench. In our case, four rooms times six benches means a total of 24 balances and 48 hot plates.

Four rooms of 24 students can comfortably handle just over 1000 students when there are 11 sections per week (Table 1). One hour was scheduled between the first and second period because it is an hour of great activity throughout the building. No lab sections are offered on Monday morning because they would overlap with the first lectures of the week. Experience indicates it is most desirable for lab content to follow behind the lecture content. Monday mornings are now reserved for delivering the reagents to the lab rooms. No lab sections are offered Thursday evening because we have common general chemistry midterm exams from 6:00 PM to 9:00 PM on four different Thursdays throughout the semester. No lab sections are offered on Friday afternoon because it overlaps with our departmental seminar series, and we encourage attendance by all graduate students, about half of whom are TAs. Friday afternoons are now the time for the staff to exchange the apparatus on each island bench. During Spring 2012, when the rooms were used for the first time, the four Wednesday morning and two Friday morning sections filled the slowest. This allowed us to continue to schedule makeup labs during these less-populated sections.

Table 1. Lab Pool Schedule for 11 Sections/Week

Period	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*
830-1120	Prep	X	X	X	X
1230-320	X	X	X	X	Prep
400-650	X	X	X	Exams	

Prep indicates room preparation time, which is scheduled during periods when it is not desirable to schedule lab sections. Exams indicates no labs are scheduled at this period because it conflicts with the multi-section mid-term Chemistry Exams.

Table 2. Dense Lab Pool Schedule for 16 Sections/Week

Period	*Mon*	*Tue*	*Wed*	*Thu*	*Fri*
830-1120	Prep	X	X	X	X
1130-220	X	X	X	X	X
230-520	X	X	X	X	Prep
530-820	X	X	X	Exams	

The abbreviations are the same as in Table 1.

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UNL's goal is to increase undergraduate enrollment by 30% by 2017, so a dense lab pool schedule was also developed (Table 2). When there are 16 sections per week, four rooms of 24 students can handle just over 1500 students. This can be accomplished within a 12-hour time frame by scheduling four three-hour lab sections per day, each separated by ten-minute turnovers. As we switch to the dense schedule, we will need to train TAs to manage their students so they complete their work before the period has ended. Such changes and skills will be communicated to the TAs during the Fall pre-semester TA training week.

Construction, Completion, and Celebration

The biweekly meetings of the team with the construction leaders were another important component to the success of the project. As work proceeded, the construction crew and architects encountered issues that were best dealt with by the team. Having firm deadlines led to solutions of many issues that could easily have become roadbloacks.

When the work was completed shortly before Spring 2012 semester, the Chemistry Department hosted a launching party. It was our first look at the completed rooms, and we had a big turnout from faculty, staff, students, and key administrators. Since then, tours of the space have been given to the Chancellor and Board of Regents, the university advisors from across campus, and visitors from the Committee on Institutional Cooperation. Everyone agrees the space looks spectacular. The Department has also been happy to discover that our renovated laboratory rooms are now part of the campus tours for prospective students and their parents.

Assessing the Impact of Rooms and Curriculum

Guidance for our assessment can be found in the goals of Project 2061, in which the American Association for the Advancement of Science describes the "knowledge, skills, and attitudes all students should acquire as a consequence of their total school experience" (*10*). Project 2061 acknowledges that a scientifically literate population must have a positive attitude toward science if the U.S. is going to continue to promote and use science to solve the issues we face. They argue that a science curriculum should simultaneously enhance content knowledge, laboratory skills, and student attitudes. Any one of these without the other two would indicate the student is unlikely to engage in scientific thought or inquiry in the future.

Our assessment of the new curriculum and renovated rooms covered five areas: student attitudes toward chemistry, student attitudes toward the laboratory environment, student retention, student cognition, and the teaching assistant experience. We have also noted an increase in the number of entering freshmen chemistry majors that may be attributed to the renovated laboratory rooms. There is not enough space in this chapter to cover all the results, thus only a few are highlighted below.

Professor Stains assessed student attitudes using two tools—the Attitude toward the Subject of Chemical Inventory (ASCI; (*3*), (*4*)) and the Science Laboratory Environment Inventory (SLEI; (*5*)). Both were offered to all students taking General Chemistry 1 and 2 for three consecutive semesters. To prevent survey fatigue, students were randomly assigned to take either the ASCI or SLEI in the second week of the semester. They were then tracked to take the same survey during the second to last week of the semester.

During Fall 2011, a comparison between students who carried out the established curriculum versus those who piloted the new curriculum was completed. All lab sections during that semester took place in unrenovated rooms. This was also the semester during which lab pool scheduling was in place, so the effect of enrollment in different lecture sections was eliminated. In Spring 2012, the renovated lab rooms were used for the first time by General Chemistry 1 students. Data collected in this semester allowed us to assess the difference between students taking the new curriculum in the renovated rooms versus the unrenovated rooms of the previous semester. In Fall 2012, entering freshman were using the new rooms for the first time, and the curriculum assessment was a control for students in the Fall versus Spring semesters. During all three semesters, data was also gathered on students taking the General Chemistry 2 laboratory course in unrenovated rooms. The interesting question was whether student attitudes about chemistry or their lab environment would change when they moved from renovated space in General Chemistry 1 to unrenovated space in General Chemistry 2, with the control being those students who took both in unrenovated rooms.

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Student Attitude toward Chemistry

The Attitude toward the Subject of Chemistry Inventory is the most widely used attitudinal instrument in chemistry (*3*). It was recently re-validated for college students and reduced from 20 responses to 8 (*4*) and then aggregrated into two categories—intellectual accessibility and emotional satisfaction. Although we administered the original 20-question version, only the two most robust categories are summarized here.

The impact of the new curriculum in the existing classrooms was assessed in Fall 2011. In total, 776 General Chemistry 1 students completed at least one attitude survey, and 561 surveys were valid for pre- and post- analysis. In the pre-semester ASCI survey, students taking the existing or new curricula reported an overall neutral response to emotional satisfaction (52.2% with 1.6% SEM from those using the existing curriculum, 52.6% with 1.6% SEM from those using the new curriculum). Students using the new curriculum reported somewhat higher intellectual accessibility, although not statistically significant (45.7% with 1.8% SEM for the existing curriculum, 48.3% with 1.8% SEM for the new curriculum). When their scores were compared to their post-semester surveys, students taking the existing curriculum showed 3.2% less emotional satisfaction ($t(126)=2.023$; $p<0.05$) and 4.9% less intellectual accessibility ($t(126)=2.721$; $p<0.01$). In contrast, students taking the pilot curriculum decreased by only 2.2% and 3.2% in those same categories, however, this was not statistically significant (t(103)=1.204; p>0.05 and t(103)=1.830; p>0.05). Therefore, the new inquiry-based curriculum is better at maintaining positive chemistry attitudes. This observation was repeated in subsequent semesters.

Student Attitude toward the Laboratory Environment

Laboratory work is arguably the most effective way to learn all aspects of the scientific method: observation, hypothesis development, experimental design, data collection, data analysis, and interpretion. At UNL, science laboratory work is also how the majority of students meet their general education requirement to learn “The Scientific Method” (called Achievement-Centered Education Student Learning Outcome 4).

The SLEI survey assesses student perceptions of their laboratory environment. It asks students to evaluate their Actual and Preferred environments by answering 35 items, each on a 5-point Likert scale. The responses are aggregated into five categories: cohesiveness (students know and support each other), open-endedness (laboratory activities emphasize open-ended approaches to experimentation), integration (laboratory activities are integrated with lecture and recitation), rule clarity (how strongly laboratory behavior is guided by formal rules), and material environment (laboratory and equipment are adequate). Only the material environment results are discussed here.

In Fall 2011 in the unrenovated rooms, the Science Laboratory Environment Inventory results showed no statistical difference between students who were using the existing or new curriculum, and those who were taking General Chemistry 2. They reported that the environment they were experiencing had slightly above average material environment (score of 3.42 on a 1 to 5 scale, where 3 means indifference and 4 means they want it or have it). When comparing actual with preferred environments, all students in the unrenovated rooms wanted a mere 8% more material environment but much larger changes in the other categories, such as integration, rule clarity, student cohesiveness, and open-endedness. The surprising result was that the material environment was *the least important* component of the environment inventory for students who were working in the unrenovated rooms with well-used equipment and old glassware.

During the next two semesters, all General Chemistry 1 students followed the new curriculum in the renovated laboratory rooms, whereas the General Chemistry 2 students carried out the existing curriculum in existing rooms. We expected the strongest test of the environment would be those students who took General Chemistry 1 in Spring 2012 followed by General Chemistry 2 in Fall 2012. There were 75 valid SLEI responses for those students who attended both General Chemistry 1 and 2 in this sequence. In this comparison, the General Chemistry 1 students reported the material environment as above average (3.87 out of 5; the highest value for any of the five survey components) at the end of the semester, whereas General Chemistry 2 students rated their material environment as average by the end of the semester (3.17 out of 5; t(74)=11.387, p<0.001). The difference in the two scores was the largest we observed for any parameter in our study, indicating a very strong preference for the renovated material environment.

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Critical Thinking

The ACT College Assessment of Academic Proficiency (CAAP) Science exam was used to assess students' science reasoning skills over the course of the room renovations. The CAAP exam was given to both General Chemistry 1 and 2 students during each of three semesters (Fall 2011, Spring 2012, and Fall 2012). The exam was implemented during the first and last week of the semester in Spring 2012 and Fall 2012, but only during the last week in Fall 2011. Statistical comparisons of raw scores and gain scores were performed between the following groups: General Chemistry 1 in unrenovated rooms with old curriculum, General Chemistry 1 in unrenovated rooms with pilot of new curriculum, General Chemistry 1 in renovated rooms with new curriculum, and General Chemistry 2 students in unrenovated rooms. No statistical differences were found in mean raw scores or gain scores between all groups (data not shown). However, when groups were divided by motivational levels (self-reported on CAAP exam), statistical differences were found between students reporting higher, same, and lower motivational levels within and across groups (data not shown). While the analysis does not indicate significant gains in student science reasoning due to either the new curriculum or the renovated rooms, the lesson learned was critical: for any assessment to be valid, the students must be motivated to perform well on that assessment. Our five bonus points for taking the CAAP exam, regardless of performance, did not motivate sufficient numbers of students for the data to be a valid.

Teaching Assistant Experience

Our expectation was that students would be more frustrated by the inquiry-based experiments than the older, canned experiments, but that they would grow to appreciate them with experience. As such, it was expected that the teaching assistant evaluations would suffer since their role was to guide them through inquiry experiences rather than to tell them what they should do next.

The teaching assistant experience was measured by end-of-semester overall instructor evaluation (OIE) scores and by TA interviews. When the curriculum was piloted in Fall 2011, select TAs were asked for formative feedback throughout the semester. This allowed us to incrementally improve the experience for the remainder of the week's sections.

In Fall 2011, the TA OIE scores averaged 3.9 for the 10 sections of pilot curriculum and averaged 3.7 for the 17 sections of existing curriculum. Likewise, the eight TAs for General Chemistry 2 averaged 3.7. Similar results were observed in subsequent semesters. Since the typical standard deviation each semester is 0.6 for the TA OIEs, we concluded the curriculum has little influence on the teaching assistant evaluations.

Undergraduate Recruiting

Prospective chemistry majors who request to visit the department are given a tour of the Chemistry Resource Center, the Undergraduate Instrumentation Center, and one of our large stadium-style multi-media lecture halls. For the past few years, we did not show them the undergraduate teaching laboratory rooms because of their poor condition. In the year since the renovations, it has become our tour highlight, and anecdotal evidence indicates it has been very favorably received. In addition, UNL Office of Admissions has added the renovated rooms to the campus tour for all prospective students and their parents.

As mentioned previously, we already anticipate an increase in the number of entering freshman chemistry majors. Based on the number of students already accepted for Fall 2013, we expect there will be more than 40 entering freshman, compared to the 24±9 student average over the past ten years. Since total UNL undergraduate enrollment has varied less than 2% over the past three years, the 66% increase in entering chemistry majors is significant. Our analysis of recruitment data indicates that two-thirds of entering freshman chemistry majors had visited campus and toured the facilities.

Future Renovations

Based on the successes described above, the Department was funded to renovate the remainder of the second floor. Four more laboratory rooms, which will accommodate all other freshman courses, and the preparatory room were completed by Spring 2013. The Chemistry Resource Center will be complete in Summer 2013.

Conclusion

Over the period of one year, we were able to design and renovate four laboratory rooms for General Chemistry 1. The renovated rooms met our goals of enhancing the student learning experience and greatly increasing the flexibility for changes in the future. Assessments indicate that the renovated rooms have a positive impact on student attitudes.

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Chapter 7

From Concept to Construction: The New Science Pavilion at Saint Vincent College

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At Saint Vincent College, we have recently completed a roughly 10-year project to significantly overhaul our entire science facility. The Dupré Science Pavilion consists of a new central building surrounded by three newly renovated wings integrated seamlessly into the structure. In this chapter, we discuss our goals for the project and how we endeavored to achieve them through the design process. One of the main goals was to encourage interdisciplinary engagement of students and faculty from across the sciences. We present a variety of examples illustrating how this and our other design goals have been implemented in our laboratories and elsewhere in the facility.

Background of the Facilities

Saint Vincent College is a Catholic, Benedictine, liberal arts college in rural western Pennsylvania with about 1700 undergraduate and 200 graduate students. By 2002, it was recognized among the science faculty that the current science center, built in the late 1960's and housing Chemistry, Biology, Physics and Computer Science, was desperately in need of renovation or replacement. There were several ways in which the infrastructure was archaic and significantly deteriorated, which negatively impacted the safety and health of the occupants and the overall learning environment as well. Specific examples include: 1. The infrastructure needed significant repair to address the many leaks throughout the facility in classrooms, laboratories and offices, which were unsightly, costly

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to repair and hazardous to the instruments. 2. The electrical supply to the laboratories was inadequate; circuit breakers would often trip during high demand experiments. 3. The outdated air handling system did not provide adequate ventilation. For example, faculty offices contained hoods as part of a mini-research lab provided for each faculty member. Unfortunately, it was essential that these hoods be turned on if chemicals were being vented up hoods in other laboratories in the facility. This situation was in the least uncomfortable and at the worst dangerous.

The ~40-year-old structure did not give faculty the flexibility to engage in innovative pedagogies in the classroom and laboratories (see Figure 1). In this structure, there was a central Commons building, which contained three large classrooms, a large amphitheater (both indoor and outdoor) and the planetarium in the basement. The laboratories and offices of Chemistry, Biology, Physics and Computer Science were found in separate buildings around the outside of the science center, as indicated in the figure.

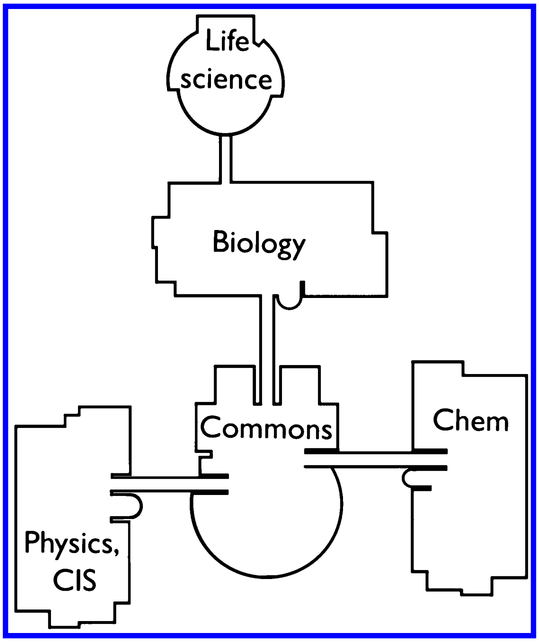

Figure 1. Original layout of science center with separate buildings for the sciences.

At the turn of the millennium, there was a great interest among faculty to adopt more student-centered active learning style pedagogies in the classroom and in the laboratories. However, the existing classrooms were designed to accommodate large lectures and were full of tablet-arm desk chairs that did not readily permit students to work in groups. The laboratories were designed for large numbers of students to work individually on “verification” type experiments. Prime examples

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were the General and Organic Chemistry teaching laboratories, which had capacity for 32 students each, although safety considerations and ACS requirements limited the number of students in each lab to no more than 24. The labs were cramped with lab furniture and contained long benches with reagent racks down the middle, both of which prevented students from moving around or working in conjunction with others.

In contrast, student-centered active learning pedagogies typically involve students working in groups, discussing ideas and not merely copying notes off the board. In a guided inquiry laboratory, students need to discuss ideas for conducting the laboratory experiment and to negotiate interpretations of the results they obtain. The layout of the classrooms and laboratory spaces did not allow for these types of learning strategies.

Hallmarks of Benedictine Learning

A significant guiding principle in the development of a new science center was the Benedictine nature of Saint Vincent College. The Association of Benedictine Colleges and Universities (*1*) has identified 10 Hallmarks of a Benedictine education. This list includes three items that have been particularly relevant to the educational mission of the sciences: Community, Hospitality and Stewardship. Thus the aging science facility, which became less hospitable as the years went on, contrasted sharply with the mission and values of the college. The faculty in the sciences, as in the rest of the college, strove to create an environment where all felt welcome, and all were challenged to work together to solve problems posed by their courses and their instructors. Further, the science faculty wanted to encourage and support informal interactions between faculty and students, which are important to fostering a sense of community. The design of the classrooms and laboratories, and indeed the layout of the science center as a whole, seemed to be structured more to keep constituents separated (e.g., students vs. faculty, biology vs. chemistry, lecture vs. laboratory.) In the early 2000's, the faculty and administration recognized that a significant construction and/or renovation project had to occur so that we could move forward with the styles of teaching and learning that matched the needs of the students and the mission of the college.

History of the Renovation Process

The structure of the dialogs that resulted in the planning for the new facilities began in the 1990's as "Science Brown Bag" meetings. During this time, the faculty from Chemistry, Biology and Physics met to discuss issues relevant to the sciences as a whole. These issues included interdisciplinary grant-seeking, core curriculum reform, and other interdepartmental topics related to teaching and research. By Fall 2002, when the Boyer School of Natural Science, Mathematics and Computers (NSMC) was established, it was clear that those discussions needed to focus on planning for a new science center. The Brown Bag format proved to be an ideal structure for bringing the faculty together to develop a list of needs for a new facility; this list was generated in November, 2002. Unfortunately, the nascent school had no Dean at this time, so the faculty put further planning on hold until one was hired.

During 2002 and 2003, members of Saint Vincent College attended two Project Kaleidoscope (PKAL) workshops (*2*). The purpose of attending these meetings was to learn about PKAL's approach to both facility renovation and overall improvement in STEM (science, technology, engineering and mathematics) education. PKAL worked to shape undergraduate STEM learning environments in order to attract students to STEM fields and to inspire them to persist and succeed in science and technology. This organization explored "what works" in shaping spaces that support 21st century STEM learning. That is, they strove to improve the process by which science facilities were built and renovated. Their proposed process centered on involving all stakeholders in planning for construction and renovation, which was revolutionary in the late 1980's when they began their work. By the time we began planning for our renovation and construction in the early 2000's, it was routine for architects to consult with faculty, staff and administrators before designing their new buildings. This change in perspective was due in large part to the work of PKAL.

In addition to these workshops, PKAL consultants came to Saint Vincent in 2005 and again in 2006 to help us move forward with the planning process. There was a faculty workshop in fall 2005 to renew the process for collecting ideas from the faculty for new facilities. By this time, a school Dean was in place who could move the process forward.

In July 2004, the first Dean of the Boyer School of Natural Science, Mathematics and Computers was hired. One of the major goals of the new Dean was to develop plans for constructing and renovating a new science center. A proposal for new facilities was drawn up in the fall based on the mission of the five departments in the school. An advisory board made up of members outside of Saint Vincent was created, as was a steering committee made up of faculty, staff, and administrators at Saint Vincent College. Thus, from the beginning of the planning process, input was obtained from a range of individuals both inside and outside of the college.

One of the first major steps in the construction effort was to determine if the current facilities were sufficiently robust to be renovated or whether completely new construction would be required. In 2006, the architectural firm selected to make this assessment determined that the old buildings were strong enough for renovation. They also made a preliminary recommendation for the renovation.

Another major step was to visit other colleges that had recently renovated or reconstructed their facilities. This was carried out by faculty, administrators and members of the advisory board during the 2006-2007 academic year. It was an essential early step for this diverse group of stakeholders to learn about different structures, and the strengths and weaknesses of those structures, from the people currently using them. This provided Saint Vincent with two crucial pieces of information. First, these visits gave us first-hand ideas of facilities that would be appropriate and not appropriate at Saint Vincent. Second, it allowed us to view the actual work of architects up close, which greatly helped us to directly evaluate different architectural firms.

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During 2007-2008, an architectural firm was selected (MacLachlan, Cornelius & Filoni) and planning sessions were begun. These planning sessions typically involved the general architect, the lab architect and groups of faculty members from different disciplines. Each of the planning sessions involved faculty with similar interests, not just members of individual departments. For example, one set of planning sessions involved environmental faculty from chemistry and biology, and another involved the biochemist (from chemistry) and the microbiologist (from biology). This structure allowed for constructive interdisciplinary dialogs that resulted in facilities that were optimized for all departments.

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Design Philosophy

In October 2006, the Boyer School created a "vision" document, a major portion of which was devoted to the attributes of a new facility. In the document, we proposed that facility enhancements would translate the School of NSMC into a model environment that supports interdisciplinary teaching and research; fosters faculty-student collaboration and cooperative student learning; promotes scientific inquiry and active student learning; accommodates computer networking and the continued integration of technology in the curriculum; and addresses critical infrastructure and safety concerns. As such, the proposed plan was consistent with the hallmarks of a Saint Vincent education and reflected the current thinking about best practices in undergraduate science education endorsed by groups such as PKAL (*3*) and the National Research Council (*4*, *5*). In addition, the new facility was designed to create a distinctive identity for the School, foster an enhanced sense of community among faculty, students, and staff, and provide an aesthetically-pleasing and environmentally-conscious architectural design that is welcoming and inviting to all, embodying the Benedictine tenets of community, hospitality, and stewardship of the natural world.

Throughout the planning sessions with the architects during 2007-2008, we kept these overarching design principles in mind. Our plans came to fruition during the 2008-2009 academic year, when fundraising began and the initial demolition was started. In the following four years, construction and renovation were carried out according to the plans drawn up during 2007-2008. The results of these discussions are described in the sections below.

Structure of Dupré Science Pavilion

The original layout of the Science center at Saint Vincent College consisted of a central "Commons" building surrounded by three outer buildings for Physics (and Computing Science), Biology and Chemistry. To walk from one of the outer buildings to the Commons or another building, one either traversed narrow bridges connecting the second floors of each building or walked outside across a parking lot or up and down steep concrete ramps.

The design adopted for the new facility involved demolishing the old Commons building and replacing it with a completely new central building that connected the three outer buildings more intimately (see Figure 2). The overall structure was reimagined. Instead of maintaining the disciplines in separate buildings with bridges connecting one building to another, faculty and labs with similar interests are located near each other regardless of department. One result is that faculty and labs are not simply grouped by the separate departments of Biology, Chemistry, Physics and Computer Science, but rather by areas of interest. Therefore the buildings (which are now wings of a single structure) are labeled according to location: North, South, East and West. For example, faculty with interests in molecular and cell biology and biochemistry are located on the second floor, with offices and research labs in the North building and teaching labs in the South building. Environmental Science faculty from the Biology and Chemistry departments have offices and labs on the first floor of the North building.

The Commons building in the old structure contained an amphitheater, three classrooms and the planetarium (tucked away in the basement) and no laboratories. In addition, the front of the Commons building had a large amphitheater but no obvious front entrance. One entered the Commons through the side doors facing the outer building or a small set of doors off to the side. In the new structure (see Figure 3), there is a clearly marked front entrance to the atrium, which is welcoming and heavily used.

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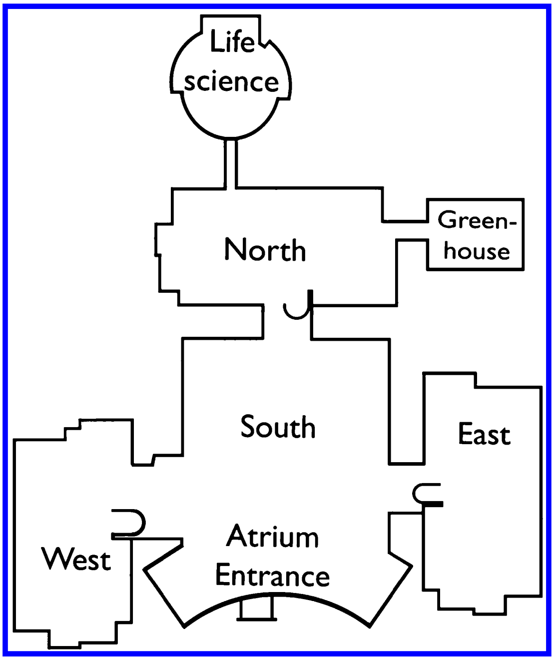

Figure 2. Current layout of Dupré Science Pavilion. The South building, which contains several large labs, an atrium and a front entrance, is all new construction. The outer buildings have been completely renovated.

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More importantly, the new central building ("South") is the largest building in the complex and contains the teaching and research labs that have the greatest infrastructure needs and a planetarium prominently displayed in the front atrium. While the former Commons served to separate the three science buildings, this new South structure brings the outer buildings together with spacious two-story connectors. Also, because the South building has so many teaching and research labs, as well as a spacious atrium for students to gather, it is probably the most heavily used portion of the pavilion. The atrium has been a pleasant surprise for all users. It contains many areas and alcoves with tables, chairs and couches where groups of students from across campus meet to study and work on group projects. Indeed, the campus choirs find it to be one of their favorite places to practice. This space nicely exemplifies how the design of the facilities adheres to the Benedictine principles of hospitality and community.

Figure 3. The front of the Dupré Science Pavilion showing the atrium and the main entrance.

An important change to the Dupré Pavilion is the inclusion of the Math Department. Although the Boyer School consists of the five departments of Biology, Chemistry, Physics, Mathematics and Computing and Information Science, only four of the departments were present in the old structure. The Mathematics department was located on the other end of campus. The presence of all five departments in the pavilion has resulted in more frequent interactions (both intentional and accidental) among these departments. One concrete example of that enhanced interaction is the recent development of an Engineering

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Science major, which involved faculty from Chemistry, Physics and Mathematics. Although many examples of interactions among the five departments exist, we focus this chapter on the portions of the pavilion that explicitly involve the Chemistry Department.

The laboratories for the Chemistry Department are found on the second floor of the two-story Dupré pavilion along with Biology (micro- and cell biology), Mathematics, and Computing and Information Science, as shown in Figure 4. The regions for each department are labeled in the figure. The first floor of the Dupré pavilion (not shown) houses laboratories and offices for organismal biology, the Environmental Science Program and the Physics Department, as well as the chemical stockroom (for all departments) and most of the classrooms.

In the next few sections of the chapter, we give examples of how different portions of the complex were designed to meet the teaching and research needs in the areas of chemistry, biochemistry and microbiology, and environmental science. We intend to show not only how the complex provides state of the art facilities appropriate to each discipline, but also how it adheres to the Benedictine principles of community, hospitality and stewardship of the environment.

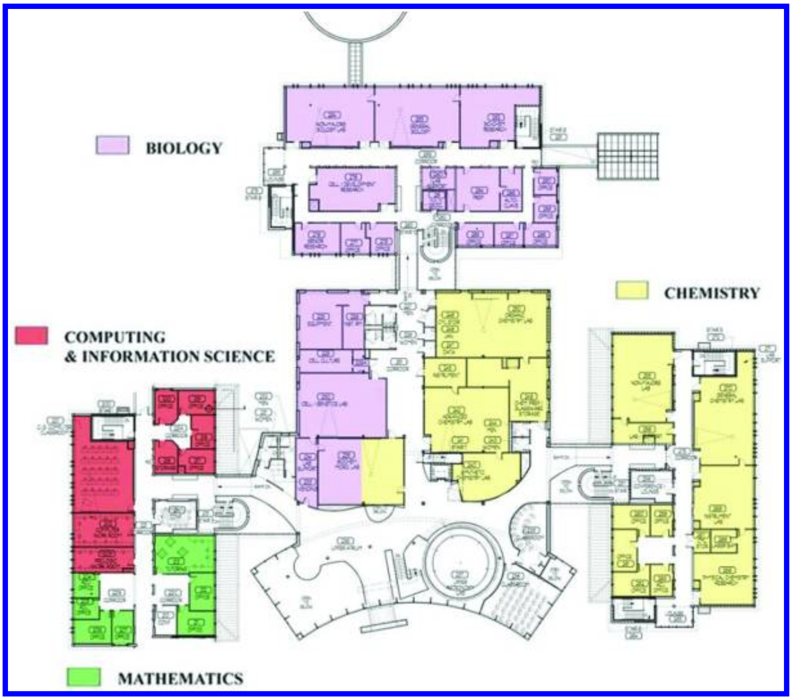

Figure 4. Schematic structure of Dupré Science Pavilion, second floor. The laboratories and offices are color-coded by academic department.

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Organization of Chemistry Laboratory Spaces

The laboratories that are used primarily for chemistry courses are on the second floor in the South and East buildings (see Figure 4). The laboratories in the new South building are the ones that require the greatest fume hood and laboratory air ventilation. These labs include the Organic teaching lab, an "Advanced" lab used by sophomores through seniors for analytical, physical and other laboratory courses, and our "Synthetic" research laboratory (see the labs labeled Organic, Adv and Synth in Figure 5). The Synthetic research laboratory is one of two main student research laboratories for Chemistry majors and is designed for organic and inorganic synthesis. The other lab (labeled Phys Anal. in Figure 5) is designed for physical and analytical research. In addition, there are research labs for Biochemistry and Environmental Chemistry majors, which are described in the relevant sections below.

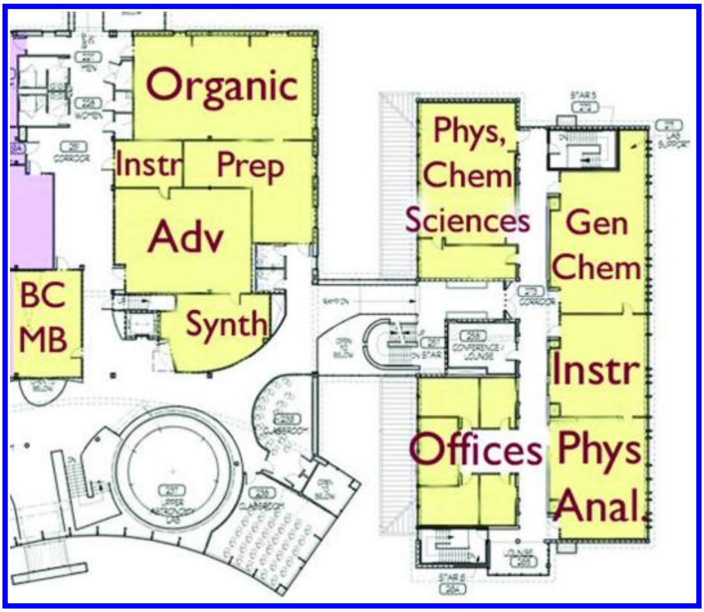

Figure 5. Schematic structure of East building and the eastern portion of the South building, second floor.

Designing adequate research space in these new facilities was critical for the science faculty because senior research is required of all science students. In Chemistry, the students propose a research project of their own choosing in their junior year and carry out the research in their senior year. This curriculum format required us to build state-of-the-art lab spaces that could adequately accommodate all of our seniors. One of these labs, the Synthetic Research lab, contains plenty of hood space and a glove box for conducting both inorganic and organic syntheses. It is located (as is the Organic teaching lab) near a small instrument room containing FTIR and NMR spectrometers for routine analysis (the Instr lab on the left side of Figure 5). Also located nearby is the chemical prep room, labeled "Prep" in

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Figure 5. The Physical/Analytical research lab is located in the East building adjacent to our main instrument lab so that students may readily access both labs. In the former science facility, each professor had his or her own lab, which was used for teaching and research. This resulted in keeping students apart, especially as they progressed in their college career. The current structure allows for greater interaction among students working on different research projects, which enhances their learning experience.

The Organic lab is large (1500 square feet) and contains a central “dry” area, with tables for students to sit and work, surrounded by a series of hoods where students conduct their reactions (see Figure 6). The outer hoods are transparent, allowing good visibility anywhere in the lab. This design also ensures the best use of students’ time. At the beginning of a lab session, students may gather at the tables to discuss the upcoming experiment. During the lab period, if students are waiting for a reaction to occur in the hood, they can go to a table to interpret spectra or prepare for other parts of the experiment. Additionally, because the small instrument lab with the FTIR and the NMR spectrometers is adjacent to and visible from the Organic lab, students may work at the central tables while waiting for an instrument, without wasting time standing in line for an instrument to become available.

Figure 6. The Organic laboratory with tables on the left and hoods on the right.

The other reason for the proximity of the Organic, Advanced and Synthetic labs is to enhance visibility of science among the students who work in these areas. Students may readily pass through or by these rooms without concern for safety and can observe what happens in these labs. In addition, students in one of the teaching labs may use resources (e.g, a Schlenk line) in the Synthetic research lab. Likewise, synthetic research students may need hood space or other resources from

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one of the teaching labs. This overlap results in accidental interactions of students in the various courses and in research. This interaction allows the students early in their college careers to see the types of research going on by the upper level students.

Adjacent to or nearby all of these labs is our central laboratory preparation room (Prep in Figure 5). This central location does not simply allow for ready access to the labs by the staff; it also allows students to readily find equipment they may need if it is not in their lab. In the former structure, students and faculty needed to wander from room to room to look for particular pieces of equipment. They can now readily find what they need in this centrally located prep room. This allows for greater independence on the part of students and less down time during the lab period.

In the East building, a short walk from the labs in the South building, is our main Instrumental lab (see Figure 7). Students who prepare solutions or chemicals in a teaching or research lab elsewhere can easily take their materials to this accessible laboratory. This lab is centrally located and has windows to the hallway, which allow other students to see the types of analyses that are done in the lab. It also has the unintended consequence of allowing students and faculty to find each other readily. In fact, students using the instruments have the autonomy to work on the instruments by themselves without feeling isolated from the professors if they do need assistance. Further, students conducting research are visible to faculty and students passing by, who become curious about their project and stop in.

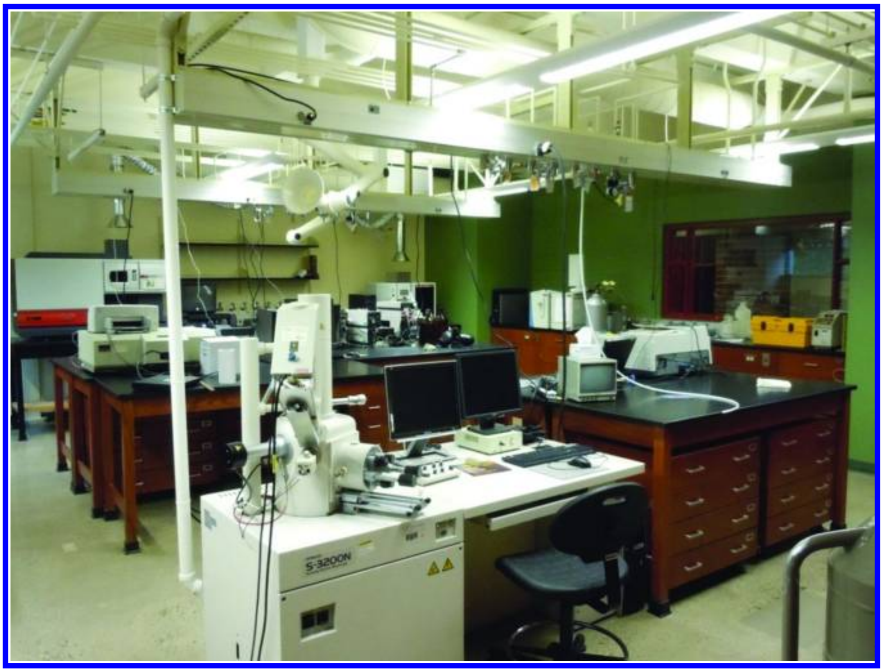

Figure 7. The main Instrumental laboratory with movable benches and drawers and a window to the hallway on the right.

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The Physical/Analytical research lab is located next to the Instrumental lab. It is designed to maximize flexibility so that various research projects can be conducted there. It contains an isolatable laser bay to keep laser light out of the rest of the lab and to allow complete darkness if needed for delicate optical experiments. The laser facility is used for both teaching and research and is connected to the main Instrumental lab to ensure that students may readily access both labs.

Physical and Chemical Sciences Laboratory

The Physical and Chemical Sciences Laboratory (Phys, Chem Sciences in Figure 5) is a multi-purpose laboratory serving both majors and non-majors. Among the various non-majors courses taught in that lab is our Chemistry of Cooking course, for which this lab is ideal (*6*). The design of the laboratory has two distinct advantages over the old facilities. First, the room dimensions, the placement of student seating, and incorporation of instructional technology (including a Promethean Board) allow for both lecture and laboratory activities in the same space. Second, the addition of a kitchenette at one end of the lab consisting of a range, dishwasher, refrigerator, and sink, along with locking cabinets for storage of equipment designated as food safe, has allowed for the incorporation and development of new activities (see Figure 8). Both of these factors have greatly enriched our Chemistry of Cooking course, which has been offered for non-majors students since 2007.

Figure 8. Closeup of the kitchenette at the end of our Physical and Chemical Sciences laboratory.

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The latest iteration of the course, taught during the spring semester of 2013, utilizes an integrated lecture/laboratory format. Instead of meeting for three 50 minute sessions three times a week with a 3-hour laboratory period once a week, students now meet for 2-hour sessions three times a week. Since all the sessions are held in the same space, there is greater flexibility for mixing content presentation, group problem solving exercises, and hands-on laboratory investigations. This is a much better use of instructional time and keeps students engaged in the material and motivated to come to each session. Attendance in the course has already improved. Under the old course structure, students were more likely to have a casual absence if all they were missing was a lecture. Now, most sessions have a laboratory component that cannot be made up. In addition, most of these sessions involve the consumption of food, which is only possible because of the kitchenette. Student comments from the initial offerings of the course frequently mentioned the lack of actual eating and cooking in the course. With the addition of food safe equipment and appliances, the laboratory activities are much more germane to practical cooking. For example, a number of the lab activities have students compare the characteristics of food prepared via different cooking methods (i.e. saucepan, pressure saucepan, microwave, etc.). While students used Bunsen burners and beakers in the past, they now use actual pots and pans on the stovetop, which helps them make better connections to their daily lives. Furthermore, a small toaster oven is no substitute for a full gas range that allows for more student groups to actually bake and compare the inner texture of dough balls prepared using different recipes and protocols. It is also safe to taste most of the experiments. In fact, the incorporation of subjective observations along with objective measurements (and how the two differ) is a nice additional course outcome.

Biochemistry/Microbiology Laboratories

An important example of the interdisciplinary efforts at teaching and research is the joint Biochemistry/Microbiology teaching and research laboratories (see Figure 9). The collaboration between the biochemist (in the Chemistry Department) and the microbiologist (in the Biology Department) started well before they met with the architects to design the biochemistry/microbiology teaching and research labs. Both faculty members had research projects where two-dimensional electrophoresis was an important experimental technique, so they had been sharing reagents and equipment for a few years prior to their involvement in the design process. In addition, several biochemistry students had completed senior research projects that involved working with bacteria, where the microbiologist had been an important resource person. So there was a pre-existing relationship of trust and respect in place when the planning meetings with the architects began. The two faculty members always met jointly with the architects to plan out the teaching and research labs; each faculty member came to the meetings with topics and ideas that had been raised in their respective departments.

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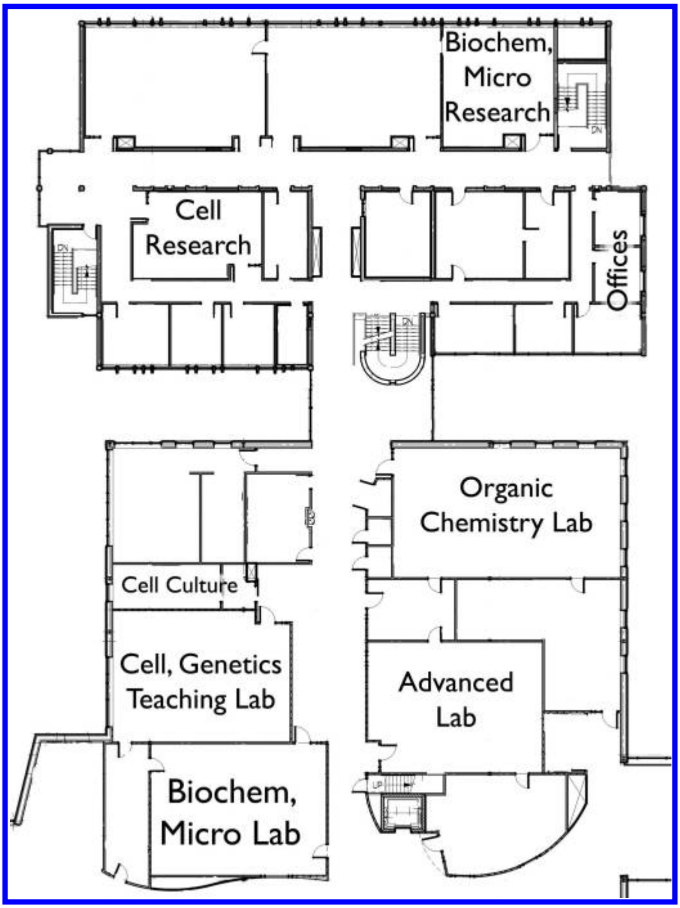

Figure 9. Layout of the North and South buildings showing the location of the Biochemistry/Microbiology teaching and research labs and the offices of the faculty teaching in those labs. The cell biology labs and two chemistry labs are shown for reference.

The biochemistry/microbiology teaching and research labs are located in separate areas of the Science Center. The teaching lab (which can hold 24 students) is in the South wing, next to the Atrium and quite visible from that space (see Figure 10). This lab is also next to the cell/developmental biology teaching lab and just across the hall from the advanced chemistry and synthetic chemistry labs. In addition, there is a small prep room that is shared by and adjacent to the biochemistry/microbiology and cell/developmental biology teaching labs. Our hope is that the proximity of so many labs will encourage informal interactions between students in different upper level chemistry and biology courses. There is also an informal gathering space next to these labs that is used by students in our courses and other courses as a socializing and study area outside of classes. In contrast, the research lab - which can hold 6-7 students at any single time - is in the North wing, much closer to the offices of the two faculty members.

While there is an informal gathering space near the research lab, it is significantly smaller than the one near the teaching lab and can only accommodate one or two students. There were several factors that contributed to the physical separation of the two labs. The biology department had a strong desire for research labs to be situated near their faculty offices, which are located in the North building. In addition, there was a desire to utilize the "new" space in the South building so that as many students as possible came through this area. As a result, many of the biology (and chemistry) teaching labs ended up in the South wing, while the corresponding research labs ended up in the North building.

Figure 10. The Biochemistry/Microbiology lab with a window to the atrium.

The biochemistry/microbiology teaching lab has six stand-alone square benches, each with space for four students to work. The tables do not have reagent shelves. We agreed on this configuration since it provided a large surface area for students to do microbiological work and did not hamper anything that would have been done in a biochemistry lab experiment. Each table has a vortexer since these are frequently used in both lab courses. The lab also includes a small chemical fume hood and a small biological safety hood. Equipment is arranged in the lab through a combination of separate and shared areas. Examples of separate areas include space (cabinet and drawers) to store microbiology equipment like plate counters and spreaders. Shared areas include a space for electrophoresis experiments as well as equipment used by both lab courses – shakers, microcentrifuges, and micropipettors. We share common refrigerators – one in the lab and one in the prep room – but try to keep our respective supplies on separate shelves simply to minimize any confusion or the accidental disposal of a solution that is still in use.

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We also worked with the architects to decide where certain features, such as sinks and the hood, should be placed in the lab. Both faculty agreed that we wanted multiple sinks around the periphery of the lab, so there are four sinks that students can use. Each sink also has a separate fixture for "house distilled" water. Once the construction of the lab was actually finished, both faculty members worked together to decide on specific locations for larger equipment, such as orbital shakers and a microwave, that we agreed should be placed so that they did not block the ability of Science Center visitors to look inside the lab.

The biochemistry/microbiology research lab uses a similar design of shared and separate space (Figure 11). Because this lab is smaller than the teaching lab, the benches were installed in a different configuration with two short benches along the west wall and a longer bench placed in a north-south orientation on one side of the lab near the entrance (orthogonal to the shorter benches). Both faculty members agreed that the shorter benches would work well as shared work spaces for things like electrophoresis. The long bench is set up so that one side is primarily used for microbiology work, and the other side is used for biochemical experiments. There is one area along the back (north) wall that is set up for students (regardless of which faculty member they are working with) to be able to sit and record information in a lab notebook or laptop computer. The architect's design for the room included a small alcove on the other side of the biological hood; we agreed that we would reserve this area for more specialized setups – e.g. an incubator set at 55°C to grow a particular microbe requiring high temperatures – that we did not want to have occupying space in the main part of the lab.

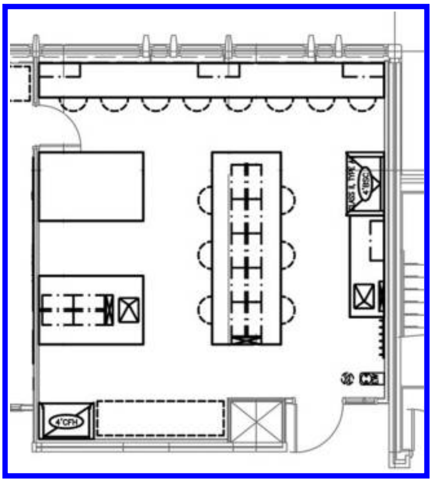

Figure 11. Diagram of the Biochemistry/Microbiology research lab.

A year into using both the teaching and research labs, we are beginning to see how we might want to rearrange some things and perhaps add some equipment. For example, we recently moved the location of the satellite waste accumulation area; we have talked about moving the location of the orbital shakers; and we have decided to purchase additional vortexers that would be used solely in the research

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lab. Many of these ideas have developed in informal conversations that are much more frequent because the offices of both faculty members are in the same cluster.

Environmental Wing

The environmental science wing is located on the first floor of the renovated North Building. As shown in Figure 12, it consists of a teaching lab, two research labs, a storage room for lab equipment and collections, a field equipment room (with a mud room), and a computer controlled greenhouse. The entire wing has provided a home for environmental science that was not present in the old building. In the former building, environmental science classes were held in the chemistry and biology departments. In addition, the offices for the chemistry and biology faculty who teach environmental courses are located in a suite down the hall from the labs. This proximity encourages collaboration among the environmental faculty and makes it easier to discuss the environmental science program. Since the move to the new space, environmental faculty have jointly obtained two small grants for developing energy curriculum materials.

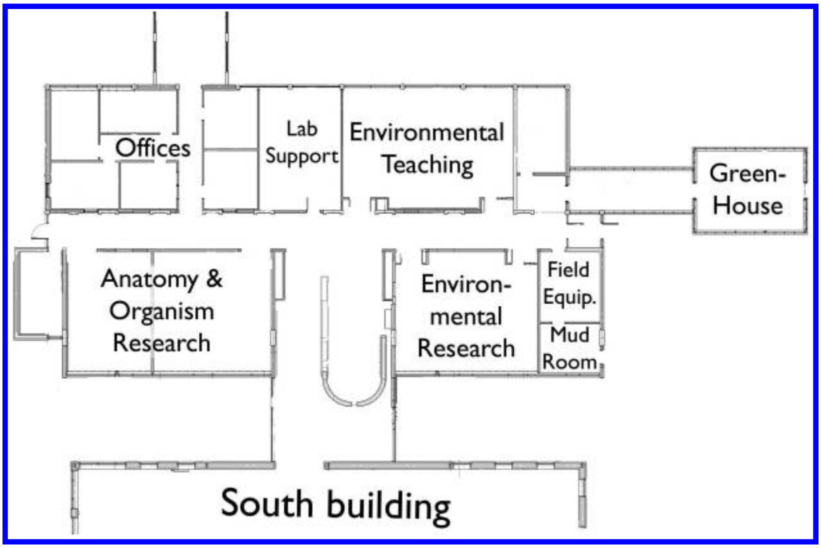

Figure 12. Layout of the first floor of the North Building showing the environmental teaching and research labs.

The design of the environmental wing involved the collaboration between an environmental chemist and an ecologist from the biology department. Both faculty teach environmental science courses and advise environmental research students. They met regularly with the architects to design the shared spaces. While there was some cooperation between these faculty members prior to the renovation, the process of designing the space and the subsequent sharing of laboratories has enhanced their collaboration. The program has a definite identity now that it is separate from the chemistry and biology departments.

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The teaching lab is an interdisciplinary space shared by environmental science classes and biology/ecology classes. One advantage of this space is that it is close to equipment storage that is used by these classes, which reduces the need for duplication of equipment in different departments. It also includes lab equipment designed for dirty field samples, such as stainless steel sinks. Another advantage of the space is that it serves as both a classroom and a lab with group seating and projection equipment. This makes it possible to teach integrated lecture/laboratory classes in the same space.

In designing the environmental wing, we wanted a mud room (see Figure 13) – a place with a door to the outside into which you could bring dirty field equipment without dragging all the dirt through the halls and labs. The architects were initially skeptical, but they helped us design a wonderful addition to the environmental wing. The mud room has a high pressure hose that will reach outside, a large stainless steel sink with deep basins and sprayer faucets. It has a drain in the concrete floor. There is also a wall for hanging hip boots and sampling nets. It is the perfect spot to clean off the dirt from field work without contaminating the labs. In the old space, the boots were stored in the basement, the field meters were in the biology and chemistry labs, and the sampling equipment was split between labs and a storage room near our wetlands. It was difficult to keep track of the equipment.

Figure 13. Field equipment room, which is adjacent to the mud room.

The dedicated environmental research laboratories are a welcome addition to the new pavilion. Senior research is an integral part of the environmental science curriculum and is a requirement for all students majoring in environmental science.

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In the past, senior research students had to share space with upper level laboratory courses in chemistry and biology. This made it difficult to set up equipment and run experiments over long time periods. Environmental science students now have two dedicated research laboratories, one for environmental science/ecology research and the other for wildlife/ornithology research. These labs provide a home for the senior research students who are focusing on environmental research; with multiple projects in the same space, there is a sense of camaraderie among the seniors. The research labs are close to the equipment storage, mud room, and the greenhouse, so research students have ready access to these spaces.

As would be expected in any renovation, there are a few difficulties. In the teaching lab, there can be as many as six different lab classes sharing the space in the fall semester. This makes scheduling difficult and prep time limited. Most other lab spaces in the science center either house multiple sections of the same class or only a few different lab classes in a semester. In the research lab, the space is tight, however, and it may be difficult for all the senior projects to fit into the labs. Luckily, many environmental research projects are conducted in the field and several are done over the summer. This staggering of research time should help to accommodate all the projects.

LEED Certification and Environmental Stewardship

According to the U.S. Green Building Council (*7*), LEED (Leadership in Energy and Environmental Design) is a voluntary, consensus-based, market--driven program that provides third-party verification of green buildings. The Dupré Science Pavilion achieved LEED gold certification by improving the quality of the site, reducing water and energy consumption, using materials that reduced the impact on the environment and providing a healthy and safe work environment for faculty and students. The following items are a few of the ways that the construction project achieved LEED status.

1. The site was designed to replace an existing 40-year-old structure within the same general footprint by minimizing the disturbance of new areas and reusing much of the existing building shell. The old Boyer School Commons building was demolished, crushed and recycled into the new construction access road. Over 4,000 tons (roughly 90% of the construction waste) was diverted from landfills and recycled or reused.
2. Energy efficiency was enhanced through the use of a geothermal heating and cooling system, which takes advantage of the fact that the ground maintains a nearly constant temperature between 50° and 60°F (10° and 16°C). To heat and cool the Dupré Pavilion, 283 wells were dug in a field 100 yards behind the pavilion at a depth of 255 feet. The geothermal system is capable of pumping 1,800 gallons per minute and recovering approximately nine million BTU per hour from the earth. Engineers estimate that this system will result in a savings of at least 30% over a conventional heating/cooling system.

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3. To reduce the electrical demand of the pavilion, 111 solar panels (generating up to 22kW of power) were placed on the roof of the atrium, which was oriented to optimize use of the solar panels. The southern exposure of the glass also provides a great deal of natural light into the atrium.

Because LEED certification is a significant and concrete way to exhibit the Benedictine hallmark of stewardship, we wished to incorporate the LEED certification into our classes. Nine academic courses are now incorporating additional topics regarding environmental sustainability with specific details associated with the building project. These courses include General Biology Lecture and Laboratory, Advanced Environmental Chemistry and Materials Science and Engineering.

Assessment and Conclusion

To summarize our original goals, we wanted to build a facility that supports interdisciplinary teaching and research; fosters faculty-student collaboration and cooperative student learning; promotes scientific inquiry and active student learning; accommodates computer networking and the continued integration of technology in the curriculum; and addresses critical infrastructure and safety concerns. To determine how successful the building design has been at achieving our goals, we surveyed students and faculty to gauge their reaction to the facility. We summarize their comments here and list some recommendations for others based on those comments.

The students and faculty find the complex to be spacious and welcoming; students now come up to the science center willingly and even eagerly. There are plenty of places for students and faculty to meet comfortably. The laboratory spaces are organized well and provide flexibility for teaching different courses. In fact, we have been able to try some courses in different laboratories to see which room works the best. At the same time, there is enough specialization in the laboratories (e.g, the kitchenette in the Physical and Chemical Sciences lab) to provide individualized space for different courses. The layout of the laboratories (especially the Organic lab) allows for more collaborative discussions. For labs that do not contain tables for sitting, there are seminar rooms nearby where students can gather and work on calculations or other lab-related work. The laboratories have prep rooms adjacent or nearby, which allows for more seamless transition between lab experiments and less clutter in the labs themselves. The only complaint that we have heard from students is that most labs do not have stools for sitting (an intentional safety decision by the chemistry faculty.)

As with any construction project, there are items that could be improved. With the great attention paid to laboratory space in this complex, there has been less attention paid to classroom and office space. Consequently, there is little room for growth in these areas. While there is plenty of space available for storage, the organization of that space is not optimized to be effective. Although the atrium has many areas for students to meet, there are very few electrical outlets for laptop

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computers, although wireless is available throughout the facility. Finally, there is less interdepartmental cooperation than initially envisioned. However, this too can change with time as faculty learn to take full advantage of the new facilities.

Based on our experiences with the new facility, there are some general recommendations that we believe will benefit others. First of all, we committed more time to planning than to the actual demolition and construction, which worked very well. This is especially true because of the many meetings needed to have everybody's voice heard in the planning process. It is also critical, especially when the project involves renovation of existing buildings, to plan the phasing carefully so that it accommodates the ongoing academic calendar and minimizes the disruption to the students. In addition to these scheduling complexities, it is important to maintain the morale of those students who experience the construction headaches without being able to use the final product. When constructing a new facility, one should plan for added equipment and maintenance costs. It was initially intended that our project budget would include equipment for the labs and a maintenance budget to accommodate the expanded facility, but the costs of the construction itself swallowed up the budget. We have been able to obtain grants for equipment since the facility came online, but those have been necessarily more piecemeal than organizing a more comprehensive equipment procurement strategy.

Overall, we have found that the aesthetically-pleasing and environmentally-friendly Dupré Pavilion is welcoming and inviting, embodying the Benedictine tenets of hospitality and stewardship of the natural world. We have also found that the facility helps to foster an enhanced sense of community among faculty, students, and staff, and that it provides a distinctive identity for the Boyer School of Natural Science, Mathematics and Computers at Saint Vincent College.

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Chapter 8

Design of Cooperative Learning Laboratories

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A building renovation at the University of New Hampshire provided the opportunity to redesign the general chemistry laboratory rooms with an emphasis on the creation of more interactive laboratory space and a more efficient use of space given constrained financial resources. After two years of use, what has been gained by and what has been learned from the new lab design is coming into focus.

Introduction

The General Chemistry program at the University of New Hampshire (UNH) has, over the past several years, redesigned laboratory exercises to emphasize cooperative inquiry learning. Laboratory exercises incorporate data sharing between individual students and/or groups of students. Laboratory procedures include specific prompts for in-class discussions with written follow-ups. A recent building renovation at UNH provided the opportunity to redesign laboratory rooms to include the interactive lab space that would foster these cooperative activities. Two years of use of these renovated rooms has illuminated the consequences of our new design.

Construction Logistics and Timeline

The Chemistry department at UNH was faced with design limitations due to economic constraints. We were limited to a renovation within the footprint of the outside walls with little additional space added. No money was allocated for more energy efficient windows. Original windows remained.

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UNH started the renovation of the Parsons Science building in 2010, at the beginning of the downturn of the economy. Initially, the renovation was to be postponed, but the money had already been allocated. The contractors, architects and construction companies made the case that $1 million could be saved by going ahead rather than waiting. Their arguments were: construction crews would have work so employees could be kept on; materials would be less expensive if purchased earlier; and construction crews who remained on the job were the senior workers who could handle the intense schedule and demanding work of a renovation within a partially occupied building.

The renovation process was separated into four phases corresponding to four sections of the chemistry building in order to minimize the temporary displacement of chemistry staff. Everyone was relocated once; only one professor was relocated twice. Initially, the general chemistry labs on the first floor and organic teaching labs on the second floor (above the general chemistry labs) were to be completed during the final phase; however, the order of the phases was changed in order to minimize the disruption of the laboratory schedule in the spring and summer semesters. Construction of the general chemistry and organic labs was moved to Phase 1. Below in Figure 1is a simple floor plan of the building, which consists of two floors. Both floors were renovated at the same time. Renovation of the teaching labs on the first and second floors was moved from Phase 4 to Phase 1. Renovation of another wing was pushed back from Phase 1 to Phase 2 while the construction crew focused on the general and organic teaching labs.

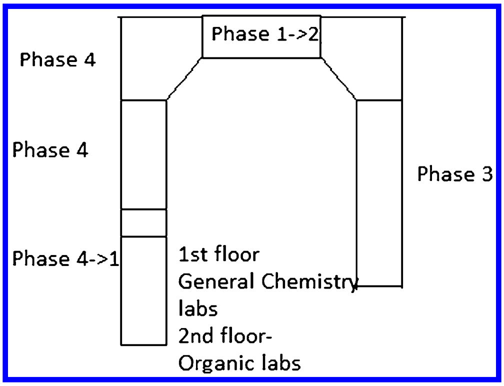

Figure 1. Floor plan of the Parsons Science Building showing phases of construction.

Laboratory classes were stopped two weeks early in the spring of 2011, and we moved back to the renovated spaces one week before classes began in late August. Two crews of 50 people on 10 hour shifts worked 6 days per week. We ran both general chemistry and organic labs during summer school, utilizing old labs to be renovated in the last phase of construction, by running morning and afternoon lab periods in one lab rather than conducting concurrent morning lab periods.

Another benefit of the economic downturn was that the construction company had the time to carefully plan the work because their staff was not thinly spread between jobs. We worked very closely with the architects [architect's address:

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EYP, Independence Wharf, 470 Atlantic Ave., 7th Fl., Boston, MA 02210] and contractors [construction company's address: Gilbane Construction, 7 Jackson Walkway, Providence, RI 02903], and we had a fantastic manager for the department, a detail person, who fought for the wishes of the chemistry staff and faculty.

Problematic Aspects of Original Laboratory Room Design

Each of our four original labs had three long benches, with the teaching boards at one end and the hoods at the other (see Figure 2).

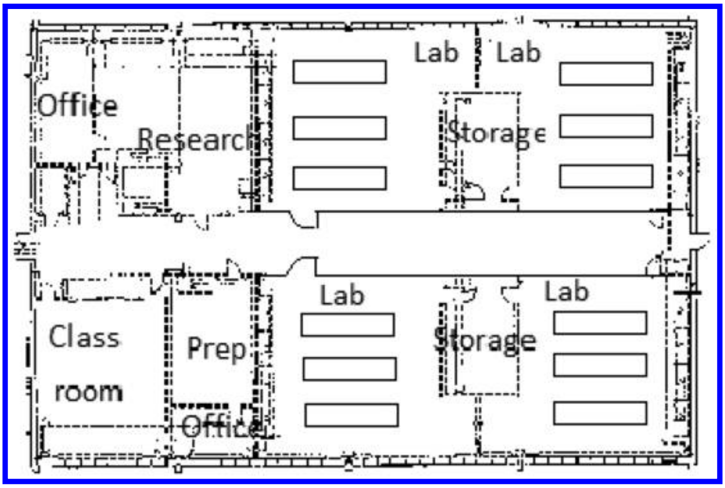

Figure 2. Old design of General Chemistry labs.

One similar lab, shown in Figure 3, had four benches running across the lab rather than lengthwise. In both types of labs, four computers per bench sat on an elevated platform (the computers were in storage when the photo was taken but the shelves for the computers are visible). The keyboards were held on a slanted lip off the platform, and the large CRT monitors and CPUs were situated on the platform. This design lessened the danger of splattering water and chemicals on the keyboard, but it did not allow a clear line of sight between each student and the instructor. Also, visibility of the blackboards by the students was poor. It was difficult to give a pre-lab lecture or lead discussions with the class.

Computers were placed on raised benches—2 per side of each bench. Hoods are at the end of benches on left.

No stools were available. Students stood during pre-lab discussion and throughout the lab period. While students should stand while working at the bench for reasons of mobility and safety, standing is tiresome and awkward when significant writing is required.

Traffic flow in these labs was poor. Students had to walk past others to get to the hoods or to access the balances at the far end of the lab. Eight students shared a hood, and all the hoods were at one side of the lab, creating a traffic jam when hoods were used.

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Figure 3. Old General Chemistry Lab.

Each lab room had its own storage area in a separate room in addition to a main stockroom/prep lab. Supplies specific to each lab exercise were located in each storage room, resulting in redundant storage of the same articles. This area was not accessible to the students, so materials to be laid out for each experiment were gathered from multiple storage locations instead of one central location. Taking inventory of multiple storage rooms was cumbersome and time-consuming.

Rationale for Lab Layout Modifications

In our general chemistry program prior to the renovation, we had created interactive lab activities involving discussion among students. Because we wanted to continue using this new instructional format, we sought lab space that facilitated quality interaction between students. Our students needed to be able to talk as partners or as a group and yet still be able to work independently.

As we entered the design phase, we had to decide logistics for the types of lab activities we wanted to do. Would the students work independently, in pairs, or in larger groups? Would the students need to easily interact? How often would they use the hood versus work at their lab bench? How often would they need vacuum or gas? How often would they use computer data acquisition? How many computers should each lab have? Where did we want to locate the computers and sinks? Would students stand or sit? Would students have assigned drawers or share drawers?

An early step of the design process consisted of visits to newly renovated or newly constructed labs. Before locking into a plan, viewing many alternatives helped us to formulate our own plan. It would have been easiest to duplicate the

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current design. Lab procedures would not need to be adjusted and changes in materials and setups would not be necessary. But would the new lab spaces meet the needs of future laboratory instruction? The viewing of other laboratory designs enabled us to consider new and very different options.

New Stockroom Design

The design chosen was an adaptation of one seen at the University of Massachusetts Amherst, where the central hallway becomes the stockroom with all labs radiating from that center (see Figure 4).

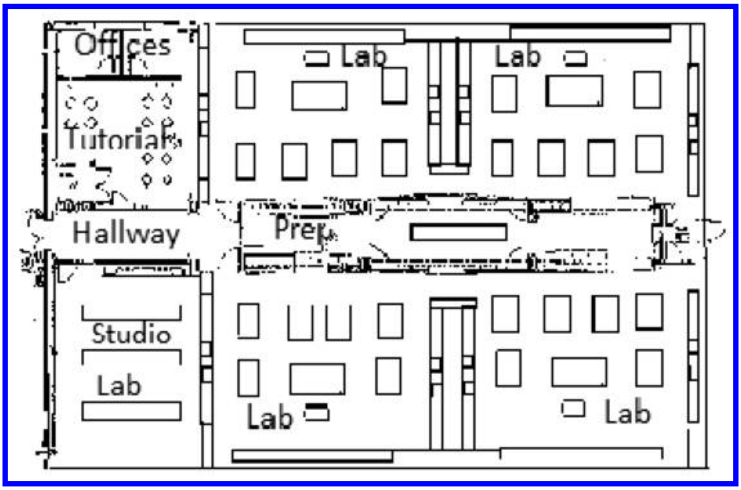

Figure 4. New design of General Chemistry labs.

With this design, one common storage and preparation space replaces four previous spaces, providing us with 30% more usable space for lab preparation. This common space is easily accessible to all introductory chemistry labs—a two-semester course for chemistry and life sciences, a one-semester engineering chemistry course, a one-semester lower level introductory chemistry course, and a chemistry course for non-science majors. At the end of the hallway is the door to the stockroom, which replaced the central hallway, as shown in Figure 5. Entrances to the labs are on either side of the central door. In the foreground, a door to a studio laboratory is shown on the right and a door to professors' offices and a computer lab/study area is shown on the left. An anticipated disadvantage was that students had to walk through one classroom to get to the furthest classrooms, but this proved not to be a problem. All students enter the labs at the same time through two doors, however the far labs exit at the other end of the wing, so students do not need to walk through a classroom upon exiting.

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Figure 5. Hallway and entrances to General Chemistry labs and stockroom.

Materials unique to each experiment are stored in bins in the prep room shown in Figures 6-8. In many cases, these bins are used for multiple courses.

Figure 6. General Chemistry Stockroom.

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Figure 7. Storage bins.

Figure 8. Chemical storage in stockroom.

Many of the chemicals used in the various general chemistry lab experiments are the same. With the centralization of lab preparation and storage, the space necessary for chemical storage is minimized. Also, this centralization provides for easy access to necessary supplies and chemicals and easy collection of waste. There is a two-way "pass-through" hood to each teaching lab that enables waste collection and chemical distribution to occur directly from the stockroom, without interruption of the lab exercise. The only difficulty with this hood has been the maintenance of proper air balance between the labs and the prep room when the sash is being raised from both sides. There has been a learning curve on its use.

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New Teaching Lab Design

A detailed design of the teaching labs is shown below in Figure 9.

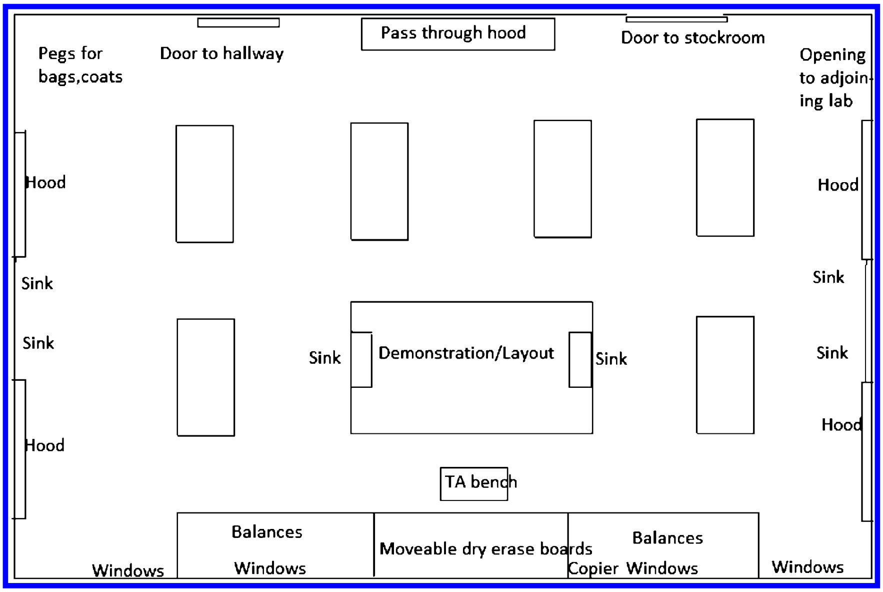

Figure 9. Renovated lab.

By removing the storage rooms between the labs on either side of the hallway, the overall length of the labs increased from 36 to 44 feet. The original windows remained unchanged. In order to allow light into the room, sliding dry erase boards were mounted above a set of storage drawers that runs along the wall (see Figure 10), a feature observed at Worcester Polytechnic Institute. These drawers and cupboards contain storage space for supplies—stir/hotplates, paper, model kits, extra beakers and glassware, etc. Each 30 x 44 foot lab has six benches around a demonstration/ distribution bench. Each 42 x 66 inch bench has two computers shared by two pairs of students (Figure 11).

All students in a location share the same glassware, eliminating the need to assign drawers. This freed up considerable lab space. Students are charged a lab fee of $90/semester as part of their tuition to cover glassware replacement and supplies and chemicals. In the old labs, each student location had four drawers (96 drawers/lab), which was decreased later to two drawers/station (48 drawers/lab). After the renovation, with our students almost always working in pairs, we decreased this further to one drawer per pair of students, so now there are just twelve drawers per lab.

I have since learned of a design where all drawers designated to students were eliminated in the general chemistry labs. In retrospect, this approach might have been advantageous. Without individual student responsibility for drawers, the equipment becomes disorganized. We have tried different approaches to control this problem, and elimination of the drawers is probably the best. Placing appropriate glassware out for a week's lab experiment is simple and eliminates the continuous checking of the lab drawers. It is easy to see that glassware is returned clean and ready for the next lab period. Inventory of common storage is simpler than overseeing closed drawers. In addition, a large amount of space is freed in the labs. Without drawers at a bench, students can get their legs under benches without sitting sideways or hitting the drawers.

Figure 10. Demonstration/Distribution bench with sliding boards in background.

Items used occasionally, such as ring stands, clamps, stir plates, stir/hot plates, hotplates, and test tube racks, are in common storage in each lab room rather than at each bench. Students learn where these items are stored within the lab and collect and return the items to their common storage location, placing more of the responsibility of lab setup on the students. Because space is no longer needed for assigned drawers, more room is left for common storage. This facilitates quick inventory of equipment and allows rearrangement, if needed.

Student lab benches surround a large multi-purpose bench, which is used for demonstrations and for the distribution of materials not found in their drawers (Figure 10). This bench is easily visible and accessible to all students, and it is easy to keep track of items and see that they are returned clean.

The instructor stands behind the demonstration/distribution bench and has excellent visibility of the students and vice versa. Students can easily see the dry erase boards for information and during the pre-lab presentation. The vertically sliding dry erase boards double the writing space, allow for hidden board material, provide access to additional bench space behind the boards, and can be moved to allow natural light to enter through the windows. This design maintained the original windows and light in the room since replacement of windows was not part of the renovation.

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Figure 11. Student lab bench, student hood, and sink.

Since our lab exercises require significant writing and data workup during the lab period, the new lab was equipped with stools. The benches have an overhang at either end so the stools can be pushed under the benches and students can sit. At night, the last students place the stools on the benches for sweeping. Computer CPUs are suspended under the benches, and electrical lines are fed through holes in the bench tops.

No mockup was made of the benches, nor did we have flat screen monitors until close to move in. Once in place, there were several unanticipated surprises. The bench height of 33.75 inches is the standard throughout the building but feels too low to work comfortably while standing. Even with the monitors in the highest position, the monitor is below eye level while standing, and it is awkward to operate the mouse on the bench surface from a standing position. The monitors occupy more space on the benches than anticipated, which makes the bench surface smaller than is necessary to accommodate both computers and work space. With stools at a height of 23.5 inches, students' eyes are level with the monitor when they sit. Monitor arm mounts at that time cost several hundred dollars per bench, so instead the monitors were positioned at their highest height and placed directly on the bench without investing in constructing additional shelves or purchasing monitor mounts (Figure 11). However, since students prefer to sit when the monitors are in the low position, the monitors have now been moved to a shelf in the middle of the bench, as shown in Figure 12. These new shelves were found throughout the renovated space and were not being used for any specific purpose. Will raising the monitors result in more students standing during data acquisition? If not, is the problem the position of the mouse and keyboard?

It was hoped that students would stand in front of the drawers to work at the bench during experiments and sit at the ends of the benches, where there is an overhang, only during data workup, to search the Internet and for computer-based labs. The electrical outlet for hotplates and peripheral equipment was placed at

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the ends of the benches so as not to be in front of the students in their work area. Because the monitors have been low, students have preferred to sit on the ends of the benches during the experiment with the electrical cords and outlets in front of them. For safety reasons, an alternative would have been to place an electrical stanchion in the center of each bench. Even with an overhang at the ends of the benches, the clearance for legs is not enough for comfort.

Figure 12. Lab bench with shelf for monitor.

Sitting rather than standing creates an informal attitude in the lab. This is beneficial since students are comfortable and can discuss what they are doing. Our labs are written to promote discussion with one's partner, but sometimes they feel too comfortable and students become inattentive to their lab work.

A water source was not placed at each bench due to the proximity of the computers. Instead, there is a designated sink a few steps away—two sinks between the hoods on either side of the room (Figure 13) and sinks at both ends of the demonstration/distribution bench (Figure 11). This alleviates any splashing from the faucet onto the keyboard or screen. The work surface is thus increased in the absence of gas, vacuum, and water on the lab benches.

A true mock-up of the lab bench, along with any anticipated equipment to be used on the bench, should be constructed as part of the design process. Are you going to have stools? Is the height correct? Where are your electrical lines? Do you have enough electrical outlets for all equipment with a couple to spare? Where will students place their feet? Where will they place their notebooks and hands when working the mouse? What is the traffic flow to the sink, hood, and balance? Is the height of drawers sufficient for all of the glassware you intend to put in the drawers? The original drawers were not large enough. This problem was caught in time and the drawer height was modified.

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Figure 13. Sinks on periphery of lab.

Exhaust Hoods

Hoods are very expensive, and our renovation was kept to a tight budget. We reviewed the number of times the hoods are used and the ways in which they are used in the general chemistry curriculum and could not justify the cost of a hood for every four students (6 hoods per room). In the old labs, we had four hoods in each room, and this number has been maintained in the new labs. The pass-through hood to the prep room can be used as an additional student hood, when necessary. The pass-through hood is intended for chemical distribution and waste collection and can be accessed without interruption of a class.

Each bench is a few steps away from a hood. With only four hoods (or five hoods if the pass-through hood is included), each table does not have its own designated hood. This can be awkward but was a necessary compromise because we needed the wall space between the hoods for water and sinks.

Gas

Anticipated use of gas versus the cost of plumbing for natural gas was evaluated. For many of our lab procedures, heat is supplied by hot plates. A flame is used only for flame drying, flame tests and in a few other limited ways. Considering the cost to plumb gas lines, the limited use of gas, and potential problems with corroding lines (one reason for this renovation), it was decided that small butane burners would be more cost effective. Stand-alone torches are now standard in many industries. We settled on a versatile portable butane burner that can be used upright or at a slant to prevent material from falling into the flame. The butane canisters are relatively inexpensive ($4.85 each), and it is easy to refill the burners, dispose of the canisters, and move the burners within the lab as needed. Gas burners are used in the hoods only. Without gas plumbed on the benches, fire danger to the computers is eliminated.

Group Work

Most experiments are performed in pairs, and teamwork and discussion are encouraged throughout the experiments. Our lab experiments focus on concept development and allow time for students to stop, think, and discuss. Procedures are written with embedded questions that are to be discussed between partners. Boxing is used around the question as a prompt for discussion. The students record their discussion in their lab notebooks with similar boxing. Most often these boxed discussions provide the source material for their post lab questions.

The following is an example of an embedded question in a qualitative investigation to develop the concept of equilibrium. In the laboratory exercise, students have mixed iron(III) and thiocyanate ions to prepare iron (III) thiocyanate. Additional iron(III) is added, resulting in a darker solution as more iron(III) thiocyanate is formed. In a traditional Le Chatelier's Principle laboratory exercise, students perceive that the reaction goes to completion with the formation of iron(III) thiocyanate. The boxed questions force them to think about the changes in concentrations of all the species.

- If no Fe^{3+} was left, would you have been able to make more $FeSCN^{2+}$? When you made the complex, did the reaction go to completion?
- Draw the above reaction progress diagram a second time. Add a dashed line to the diagram of the addition of SCN^-. Diagram the reaction process for the other species as a new equilibrium is reached.
- You will now have more SCN^- than at the time of the addition. But what about the final concentration of Fe^{3+}? $FeSCN^{2+}$?

This type of discussion with their partner is time consuming and involves significant writing, which is one reason the decision was made to provide stools.

In the report, questions referring to data or the procedure are shared with a partner and answered in a paired portion of the report, since students share data and graphs. Questions requiring analysis and interpretation are answered individually. The entire report must be turned in at the same time so the individual portions can be graded simultaneously in an attempt to minimize and detect "cheating."

Having benches of four students and two computers allows for multiple configurations of student groups for data collection. One experiment in particular utilizes groups of four students—the boiling point lab. The students at a bench analyze the boiling points of one assigned series of four organic chemicals: alkanes, alkenes, bromoalkanes, primary alcohols, secondary alcohols. Each student at that bench analyzes one chemical from their assigned series. Data is collected using a Vernier thermistor and data acquisition system. Each group then plots the data for the four chemicals in their series, discusses the reason for the trend observed and relates it to molecular mass and structure. All groups share

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their graphs with each other in Excel. Differences in boiling points lead to a class discussion of differences in intermolecular forces for the various series.

Another experiment that utilizes groups of four is the thermochemistry lab. The students at one bench weigh out four different masses of sodium chloride and dissolve the salt while recording the temperature change. At the same time, another group of students does the same for calcium chloride and another for ammonium chloride. Data are shared, and each group of students plots the data on one graph and compares and discusses their observations.

In some exercises, all students analyze different samples that contribute to a data set. For example, an acid-base experiment consists of five modules that have been laid out on the demonstration/ distribution bench—exercises to investigate acid concentration, acid strength, pH of commercial products, what is a buffer, and what is a salt. All data are shared and posted on Blackboard.

For many lab exercises, materials are placed in the middle of the lab benches and chemicals are easily shared among four students without movement in the lab. This was difficult with the previous lab lay-out, a long bench where the computers blocked access and visibility.

One lab exercise that has adapted well to the new lab design is an investigation of light, where students use spectroscopes and the SpectroVis Plus spectrophotometers with a fiber optic cable to provide the spectra of natural light, light-emitting diodes, vapor discharge lamps, and fluorescent light. A carousel for vapor discharge tubes with a port that locks the fiber optic cable in the correct position is available from Vernier Software & Technology. One of these has been purchased for each lab. This example illustrates that additional equipment was needed to accommodate groups of four in the new lab configuration. When choosing a different lab organization than previously used, additional costs for new equipment for the new layout need to be anticipated.

Summary

In spite of unanticipated consequences, the new design is a definite improvement from the previous one. Laboratory exercises involving group work are easily implemented. The most positive aspects are the six benches of four students each, the central demonstration/distribution bench, and the elimination of water from the benches. The bench size could have been increased slightly and height of the bench increased an inch. The main problem has been the position of the monitor below eye level and the position of the mouse. Hopefully, the students will choose to stand during the experiments now that the monitors have been raised. Shared drawers result in no ownership of care for a drawer, thus elimination of drawers entirely should be considered. A critical analysis of the renovation has been discussed but, in conclusion, the ability to do group work has been satisfactorily enhanced, which was the primary pedagogical goal of the renovation.

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Chapter 9

Building Flexibility for the Undergraduate Chemistry Laboratory

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The theme of this chapter from Wheaton College is flexibility. The Department of Chemistry occupies the third floor of the new Mars Center for Science and Technology, opened in August 2011. All teaching laboratories on the floor are described, with primary focus on the "Superlab". The Superlab is an interconnected series of four rooms comprised of a Seminar Room, an HVAC (heating, ventilation and air conditioning) Intensive Laboratory, a less-HVAC Intensive Laboratory and an Instrument Room. All of the department's upper level laboratories are taught in the Superlab, shared by as many as four different courses in any given semester. The process of planning, as well as the benefits and challenges of using, such a shared space are discussed. Additionally, flexibility has been incorporated into the design of the laboratory space for the introductory courses, so that experiments can be carried out by individuals or in collaborative teams of two to four students.

Introduction

Wheaton College is a residential, liberal arts college of 1750 students located in Norton, MA. Wheaton was founded in 1834 as a female seminary and chartered as a four-year liberal arts college in 1912. The College became coeducational in 1988. The College mission is to provide a transformative liberal arts education for intellectually curious students in a collaborative, academically vibrant residential community that values a diverse world.

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On September 23, 2012, Wheaton College cut the ribbon (in the form of an inflatable strand of DNA) on the new Mars Center for Science and Technology. That ceremony marked the culmination of over a decade of planning and preparation. Many years of work produced a natural light-filled state-of-the-art LEED (Leadership in Energy and Environmental Design) Gold Certified building housing the science programs. The $46 million dollar project was the most ambitious building project in the history of the College. In this chapter, we describe the process leading up to the building's design, with emphasis on how divisional and departmental goals helped shape its features. Further, we detail the Chemistry Department's spaces in the facility and highlight how we have incorporated flexibility into our laboratories. Finally, we provide some insights gleaned from the experience and offer suggestions for others embarking on a new science facility construction project.

The Old Facility

The previous Science Center, whose lower floor was renovated as part of this project, was built and first occupied in 1967 and had been slated for major renovation or replacement for more than a decade. Although innovative in its original design, it had become outdated both in the ways it was unable to meet modern pedagogical goals and in the practical aspects of outdated building mechanical systems. The floor plan, with each department on distinct floors in a "pancake" manner, was not effective toward encouraging collaborations between departments, and the physical placement of the building was such that it isolated the science division from the rest of the campus. Students who did not major in one of the sciences could literally spend four years at Wheaton and almost never step foot in the building.

In the Department of Chemistry, almost every teaching laboratory space was identical. For example, the Organic Chemistry laboratory was a carbon copy of the General Chemistry laboratory, each having the same number of fume hoods and the same fixed bench configuration. The specific needs of distinct courses were not taken into consideration. This particular design feature was meant to allow for flexibility in teaching a variety of courses, as there were no course-specific features in the laboratory rooms; the thought at the time was that a given course could be taught in any one of the laboratories. While such a notion of flexibility can be important, at a minimum there must be differences in the rooms for safety considerations. In addition, the sight lines throughout the spaces were poor as large shelf structures stood atop the benches, preventing visibility across the laboratory.

Initial Planning Process

Planning and execution of the new building took place in three distinct phases; this start-and-stop mode was necessitated first by an internal college change in administration, with consequent delay of fundraising, and then because of the global financial downturn of 2008. In the end, the long planning times served us well, as they allowed careful communication among all the science departments and with the architects. The lack of continuity, however, also meant that the same material was reviewed multiple times, often with different participating parties.

Beginning in 2001, faculty and staff from the Science Division, working with Einhorn Yaffee and Prescott, Architects and Engineers (EYPAE), engaged in initial conversations at the request of then College President Dale Rogers Marshall. The charge to the Science Center Planning Committee (SCPC) from the President affirmed the college commitment to strengthening the sciences, enhancing scientific literacy for all students, and increasing the percentage of students majoring in the sciences. The President further asked the SCPC to advise her on programmatic priorities for the departments in the Science Division.

The Preliminary Planning and Feasibility Study consisted of several parts, including a review of existing conditions, an internal program review and goal setting by the entire science and mathematics division and by individual departments, and finally, the development of a wish list for the new facility. For this latter planning, we were asked to "think outside the box." As this chapter will describe in a later paragraph (although our thinking here is counter-intuitive), the exercise of planning in the absence of realistic limitations does not in fact encourage creative and collaborative solutions to the numerous questions posed by the construction of a new building. It is more useful to allow financial constraints to be understood and reconciled from the earliest stages of planning.

EYPAE conducted an extensive review of the state of the existing Science Center. It came as no surprise that the building's mechanical systems were deemed to have exceeded their useful lifetimes, and new plumbing, electrical, and HVAC systems were needed. Additionally, the existing spaces did not accommodate the needs of a modern and changing science curriculum, and the physical environment hampered the full utilization of the facility. Temperature and humidity control were almost nonexistent, and the fixed configuration in the laboratory benches made collaborative learning nearly impossible. A modern vivarium for work with animals and improved observation facilities for Astronomy needs were also long overdue. Given that the college knew well that the building needed both renovation of some spaces and full replacement of others, minimal investment in repairs and upgrades had been made to the existing Science Center since the early 1990s.

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Shared Goals for the Mars Center for Science and Technology

As a result of this Preliminary Program and Feasibility Study, clear and shared goals were developed that served us well in all subsequent phases. The shared goals stemming from these discussions, initially articulated in a report to the College President and Board of Trustees in October of 2002, are described below. The new building shall:

1. Be Attractive and Interactive

The building should draw students in and make them want to stay. It should be a destination of choice with commons and study spaces not available elsewhere on campus. It should showcase work in the building and encourage students to participate in the projects they see.

2. Promote and Showcase Student/Faculty Research

Research in the sciences at Wheaton must be highly visible as it is a fundamental component of the educational mission of the Natural Science Division. The building must include appropriate research facilities for all science disciplines as student/ faculty research spaces ***are*** teaching spaces. These should receive the same prominence as traditional classrooms and teaching laboratories.

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3. Celebrate Connections

The sciences are highly collaborative. Connections among students, between students and faculty, and between Science Center departments are a necessity. Connections with disciplines outside of the sciences, as part of the Wheaton Curriculum, should also be encouraged by design features in the building.

4. Be Responsible

The building must be flexible enough to address current needs and be designed to easily adapt over its lifespan to meet the future needs of inevitably changing and expanding programs. It must be as green as possible, including consideration of long-term energy costs, environmentally friendly materials and minimal impact on the surrounding ecosystem.

Chemistry Department Goals for the Mars Center for Science and Technology

The faculty and staff in the Chemistry Department developed a set of goals specific to our program and students. The Chemistry goals mirror the overall project goals but place them in a more discipline-specific context.

The building should be designed to help our students acquire the knowledge and skills needed to understand our chemical world and to investigate its complexities. The building should therefore include:

1. Research laboratories to foster students' creativity and channel their interests toward productive independent research in preparation for graduate school or technical employment.
2. Readily accessible support spaces to allow integration of state-of-the-art instrumentation and computing at all levels of the curriculum.
3. Common spaces to foster a sense of community within the department as students and faculty work together to solve chemical problems.

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During this first planning phase, faculty and staff were encouraged to "dream big" and "think outside the box" with respect to the types of spaces envisioned for the new facility. The faculty took up this task with enthusiasm. After all ideas and ambitious intentions were gathered and organized, we arrived at a project that represented approximately double the national average of square feet per faculty member (and thus double the price) for the departments involved. The size and scope of such a project was clearly *not* feasible, and many rounds of reductions and cuts became necessary. Looking back on this phase of the building process, we would urge other institutions to use caution. While it is important to dream and think outside the box, we believe it is also critically important to have "the box" be as well defined as possible. This definition could be in terms of square footage or even total dollar cost.

Starts, Stops, and Building Construction

Shortly after the Preliminary Planning and Feasibility Study was completed, both the College President and Provost at Wheaton entered retirement. After two years of searches, both positions were filled, and President Ronald Crutcher took the helm of the college. Additional time was needed before the new administration could undertake fundraising for the project; thus, several years passed before the new science center construction could take center-stage in the priorities of the College Trustees and Administration. Nevertheless, with renewed enthusiasm and a great flurry of activity, the faculty took on the task of planning at the detailed level, once the overall size and capacity of the building had been defined. A careful and consensual preliminary building plan was in place by the summer of 2007.

Numerous architectural firms submitted preliminary proposals, and three firms were interviewed for the position of Project Architect. Ultimately, Einhorn Yaffe Prescott (EYP) was chosen during the 2007-08 academic year. The need for an owners' representative to oversee the day-to-day construction was recognized shortly thereafter, and the RISE group was chosen for this purpose in 2008. While the groundbreaking ceremony took place with great excitement in October of 2008, the national and global financial downturn made it impossible to procure the financing needed to begin construction of the building. The project was put aside for yet one more disappointing time.

Nevertheless, one year later, with encouragement and continued financial commitment from our major donors and with the ever-urgent educational needs of the Science Division looming, the project resumed.

The total project consisted of the construction of a new three-story building (77,325 square feet) to house Biology, Chemistry and Neuroscience (part of Psychology) and renovation of the first floor of the existing science building (24,375 square feet) to house the departments of Mathematic and Computer Science, and Physics and Astronomy. The building project includes 14 teaching laboratories, 23 faculty/student research laboratories, 40 faculty offices, and 13 student study rooms. In addition, the new building houses a Greenhouse, an Observation Deck and a Café as well as numerous student study spaces and informal gathering areas throughout the building. An outdoor classroom and a courtyard with boulders representing the geological history of the region were also

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part of the project. The construction portion of the project was completed between May 2010 and the end of January 2012. The new construction was occupied in the fall of 2011 by the departments of Biology, Chemistry and Psychology (Neuroscience faculty) and the renovated space occupied in the spring of 2012 by Physics and Astronomy, and Mathematics and Computer Science.

At the successful completion of the project, we are delighted to find that the initial goals of the Division have been met and exceeded in the actual spaces. Some features, designed by the architects, had not even been included in our dreams. The green roof that fronts the building allows efficient use of energy in the common space (the Spencer Café) that lies underneath it. Wheaton's Astronomy program, located on the roof, provides an excellent vantage point for stargazing and observation of the night skies. The college greenhouses are positioned well, so as to maximize exposure to sunlight. And, most importantly perhaps, the use of large interior glass partitions promotes visibility for student and faculty work. These have allowed our wishful intention "to put science at the center" to become our daily lived reality. This is for good reason, as the sciences are critical not only for the future of the College but also for our world.

One of the shared goals for the project was sustainability. From the earliest days of planning, the faculty and the College were committed to constructing a facility with the intention of applying to the U.S. Green Building Council for LEED certification. In fact, these efforts resulted in the awarding of the LEED Gold certification to the Mars Center, an accomplishment the College was particularly proud to achieve.

The Chemistry Department

At Wheaton College, the Department of Chemistry occupies the entire third floor of the new Mars Center for Science and Technology. Additionally, there are two research laboratories, two faculty offices and a small instrument room on the second floor dedicated to chemistry. The overall floor plan for Level 3 is depicted in Figure 1. The teaching laboratories lie along the south face of the building, the research laboratories lie along the north face of the building, and the support spaces (prep room, instrument room and storage room) are located in the central part of the floor. All faculty and staff offices are grouped together at the east end of the building. This general layout is also found on the lower two levels of the building, which house the Biology Department and the faculty members in Neuroscience (part of the Psychology Department). The Central Stockroom for chemicals, glassware, and small equipment, as well as the Vivarium and the Café, are located on Level 1 of the building. The Greenhouses and Observation Deck are located on Level 4, the roof level.

There are three main teaching laboratory spaces in the Mars Center for the Chemistry Department. They are the Chemistry Superlab, the Organic Chemistry Laboratory and the General Chemistry Laboratory. Each of these laboratory spaces will be described in some detail with respect to the main design features, including the flexibility of the spaces, the sight lines and the relationship of the spaces to one another.

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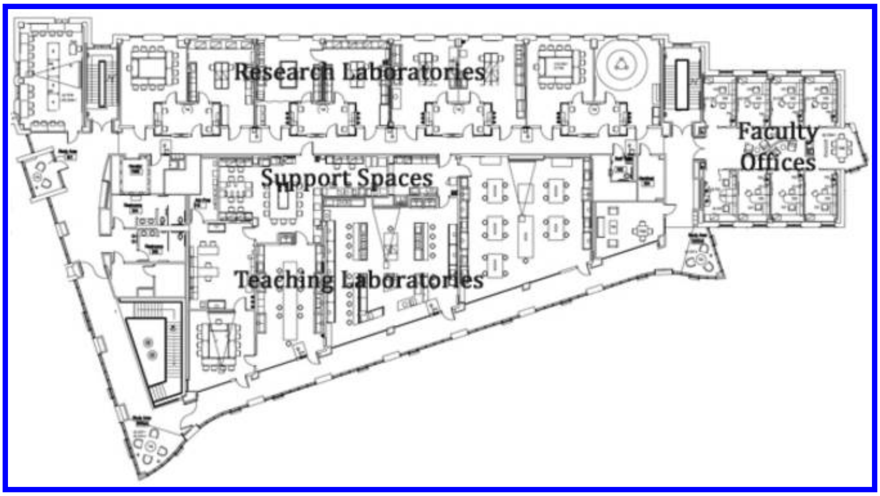

Figure 1. Level 3 floor plan of Mars Center for Science and Technology.

The Chemistry Superlab

One of the first major decisions that the Chemistry Department had to make concerned the way that space would be handled for all the upper level courses: Inorganic Chemistry, Chemical Thermodynamics, Quantum Chemistry, Advanced Organic, and Instrumental Analysis. In the old facility, each course had dedicated laboratory space. It was clear, for numerous reasons, that this would be neither possible nor necessary in the new Mars Center. These reasons included the initial cost of construction for individual spaces and the high cost of running and maintaining spaces normally used only one or two times each week. Such a pattern of use was not sustainable either financially or from an environmental standpoint. We clearly needed to think differently.

Many discussions took place among faculty and staff in chemistry and with the project architects concerning possible ways to accommodate the needs of upper-level courses. The first decision made by the faculty was that the laboratories for all these courses would be capped at ten students per section.

Next, we carefully examined all the experiments in each of the upper level courses to look for commonalities. Indeed, we saw several distinct patterns emerge from this process. Many experiments, in various courses, required a highly HVAC intensive teaching space. Others had minimal HVAC requirements but rather required that experimental apparatus be set up for multiple weeks at a time. Another theme that emerged was the need for a seminar room accessible for all courses. This space would be used for pre-lab lectures and also for students to sit and analyze data on computers separate from the direct laboratory environment. Finally, ready access to and a more seamless incorporation of instrumentation was desired in all upper level courses.

The notion of the Chemistry Superlab emerged during the course of the discussions described above. The Superlab, comprising approximately 2500 total square feet, is a series of four connected, shared rooms that readily accommodate the laboratory sections for all the upper level courses and can additionally facilitate more effective incorporation of computing and instrumentation into these courses. The Chemistry Superlab consists of a Seminar Room, an HVAC Intensive Laboratory, a less HVAC Intensive Laboratory and a large Instrument Room, Figure 2. This series of spaces has been shared by as many as four different courses in a given semester, but it is dedicated to a single course on each day of the week. In the fall of 2012, for example, Advanced Organic occupied the space on Mondays, Inorganic on Tuesdays, while two sections of the course on Thermodynamics used the Superlab on Wednesdays and Thursdays.

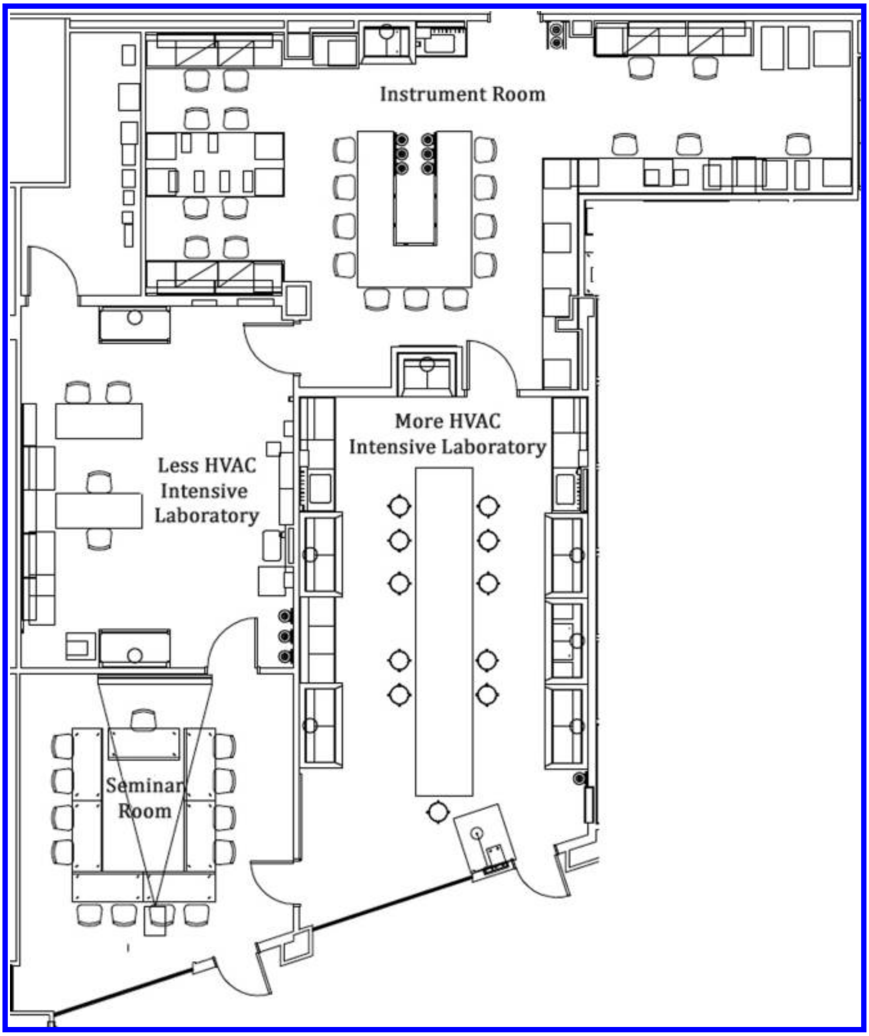

Figure 2. Chemistry Superlab consisting of a Seminar Room, an HVAC intensive laboratory, a less HVAC intensive laboratory and Instrument Room.

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The relationship of the rooms in the Superlab to one another was of critical importance. The Seminar Room has direct access to both the HVAC Intensive and the less HVAC Intensive laboratories. Additionally, both of these laboratories open directly to the Instrument Room. This arrangement allows for seamless movement of students between and among the various spaces as needed to carry out experimental work effectively.

The HVAC Intensive laboratory has five student fume hoods and one prep/ dispensing hood placed along the outside walls with one large bench in the middle of the room. This arrangement provides good sight lines and ready student access to both hood space and open bench space, depending on the needs of the individual experiment. A panoramic view of the HVAC Intensive Laboratory is shown in Figure 3. Access to the Instrument Room is at the back of the laboratory and access to the Seminar Room is near the front.

The less HVAC Intensive laboratory has only two fume hoods, one placed at each end of the room. This room is used primarily for the Thermodynamics and Quantum Chemistry courses. Clear bench space and movable tables were deemed most important for this space as these courses often have experimental apparatus assembled at the beginning of the semester that remains in place for many weeks as students rotate through the various experiments. Again, there is direct access to the Instrument Room at the back of the laboratory, and access to the Seminar Room is near the front.

Figure 3. Panoramic photo of the HVAC intensive laboratory. (see color insert)

The Instrument Room houses virtually all the major instruments owned by the department. These include HPLC, IR Microscope, scanning UV/Vis, Diode Array UV/Vis, FTIR, GC with FID/TCD, GC/MS, TOC, Polarograph and NMR as well as five analytical balances. We believe it is critical that these instruments are gathered in one well organized space and that it is centrally located so it can be accessed for both teaching and research purposes. There are eleven areas we call "Instrument Zones". Each Instrument Zone consists of approximately ten linear feet of bench space. This is sufficient to house one instrument and the associated computer hardware while still leaving two to three feet of bench space for sample

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preparation. Each zone also has one or two drawer-over-cabinet storage areas and a large knee space to accommodate two people sitting in chairs. The single fume hood in the Instrument Room serves both as a place to prepare samples and for general room ventilation. The U-shaped bench, open at one end in the middle of the room, was placed intentionally so the gas tanks for the GCs and TOC are readily accessible but also out of the main traffic area in the room, Figure 4. The only major instruments not housed in this space are the Flame and Graphite Furnace AA and the Fluorimeter.

Figure 4. Photo of Instrument Room depicting three instrument zones on the U-shaped bench in the middle of the room with gas tanks at the center. (see color insert)

Organic Chemistry Laboratory

The laboratory space occupied by Organic Chemistry, 1450 square feet, is the most highly specialized room in the entire Mars Center facility, Figure 5. This room was designed specifically for the traditional two-semester Organic Chemistry sequence and is typically used every afternoon and one or more evenings a week, depending on the semester. For example, in the spring of 2013, there were six laboratory sections using the space on Monday afternoons and evenings, Tuesday afternoons and evenings as well as Wednesday and Thursday afternoons. At Wheaton, the laboratory experience in Organic Chemistry, normally taken in the spring of a student's first year, represents the first time when chemistry students work individually on their experiments. A number of important issues had to be addressed in the Organic Chemistry Laboratory, including adequate hood space for 16 students, good sight lines, and space for equipment specific to organic chemistry.

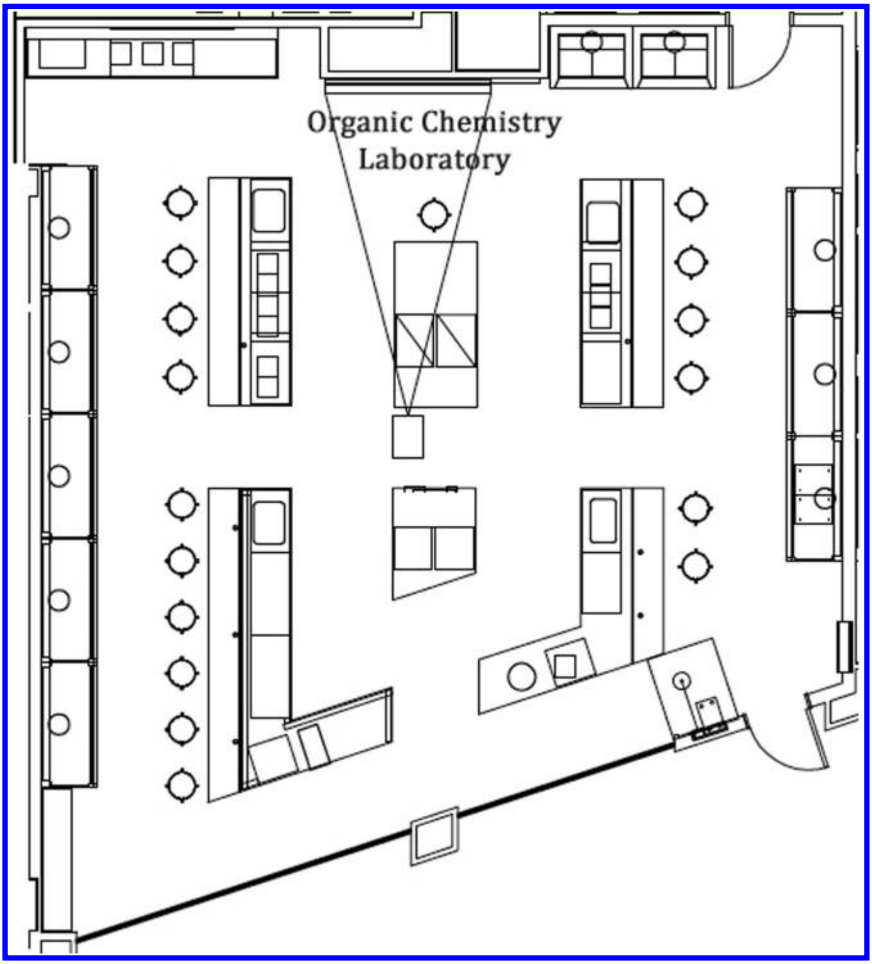

Figure 5. Organic Chemistry Laboratory.

In the Organic Laboratory, eight student fume hoods and two prep/dispensing hoods are again placed along the outside walls of the room. This leaves the large interior portion of the room with no visible obstructions to sight lines, Figure 6. Each student has three linear feet of hood space in which all experimental work is carried out and three feet of bench space immediately behind for notebooks, instructions and the like. All other equipment, such as balances, melting point apparatus and rotary evaporators, is placed on benches toward the middle of the room. Sinks are also at the ends of each of the middle benches. This arrangement allows for good work flow as students taking masses or using rotary evaporators do not interfere with students still working at the hoods.

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Figure 6. Panoramic photo of the Organic Chemistry Laboratory. (see color insert)

General Chemistry Laboratory

The General Chemistry Laboratory, 1450 square feet, presented a different set of challenges. On a weekly basis, this room needed to accommodate 120 or more students in the Chemical Principles course and at the same time had to accommodate the foundation course in Analytical Chemistry, as well as potentially serve additional courses on an as-needed basis, Figure 7.

In General Chemistry, five student hoods and two prep/dispensing hoods are again moved to the outside walls of the room. In this room, a single student hood is shared by two pairs of students in Chemical Principles or two to three students individually in the foundation Analytical course. Again, the large portion of the laboratory in the middle has unobstructed sight lines, Figure 8. Much of the experimental work in this laboratory is done at the benches rather than in the hoods. Each student bench is designed to accommodate a maximum of four students. In the Chemical Principles course, the bench is used by two pairs of students, with one pair working on each of the long sides. In the Analytical course, the bench is used by two or three students working individually.

The large energy use and potential for noise generated by the intensity of the HVAC systems in all the teaching laboratories were of concern to chemistry faculty and the College. Working with the architects, we were able to solve these issues in an acceptable manner. The energy usage was addressed in part by operating only the prep/dispensing hoods in the teaching laboratories on a 24 hours per day basis. These hoods provide sufficient turnover of the air for general room exhaust. All student fume hoods are on switches so they can be turned on when needed and left “off” (minimal flow) when not in use. This plan greatly reduces the energy usage for all laboratory spaces. The noise generated from the air flow when all hoods are in use was attenuated through the use of large cross section ducts and with the addition of baffles at the air inlets in the rooms.

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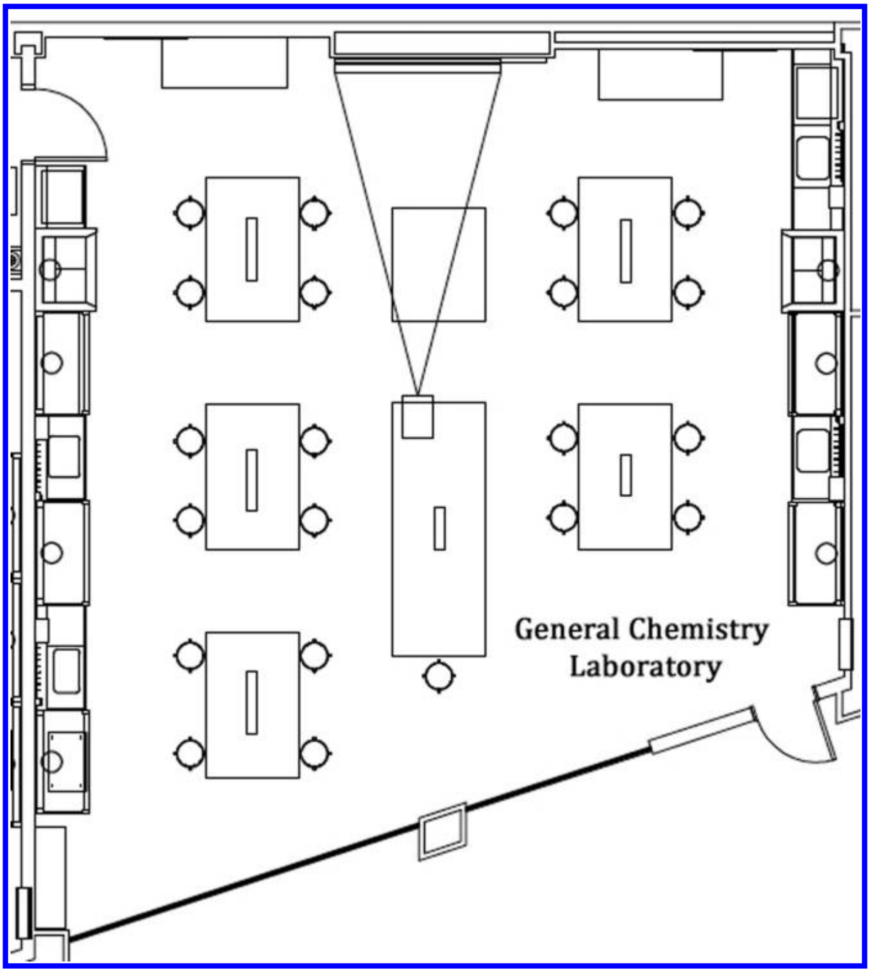

Figure 7. General Chemistry Laboratory.

Figure 8. Panoramic photo of the General Chemistry Laboratory. (see color insert)

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Conclusions

The Mars Center for Science and Technology project at Wheaton College was more than ten years in the making from initial planning to occupancy. There were times when the planning seemed hopeless and when wishes seemed unattainable. The development of both shared and chemistry department specific goals early in the planning process was critical as they helped guide decisions that were made during the other stages of planning and construction.

A thorough review of all chemistry courses, and in particular the laboratory exercises associated with each course, required us to think creatively about how to organize and design the laboratory spaces needed to teach our courses effectively. This process led to the development of the Superlab, a space that houses the laboratories for all our upper level courses. Thinking creatively about how best to accomplish commonly-derived goals, within realistic financial and space limitations, more accurately describes our successful process of planning a building, as opposed to less fruitful processes that allowed for “dreaming big” or “thinking outside the box”.

Finally, the new Mars Center has already accomplished its goal of “Bringing Science to the Center” at Wheaton College. The commonly used phrase “If you build it, they will come” is being realized on a daily basis in the chemistry department, as we have seen substantial increases in student enrollment in all four introductory courses. Additionally, non-science students are often seen studying or socializing in one of the many student common spaces in the Mars Center. We strongly encourage others at any of the various stages of a project such as this to keep a positive attitude and to realize that wonderful teaching and research spaces are waiting at the finish line.

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Chapter 10

Taking Center Stage: Tomorrow's Chemistry Teaching Laboratory

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This chapter explores current trends in chemistry teaching laboratory design and examines, through case studies, the role the design process plays in *setting the dial* appropriately with respect to each of these trends in order to support the pedagogical needs of an institution while creating the highest quality laboratory environment. Among the trends explored are interdisciplinary collaboration, project-based learning, teaching laboratory as research laboratory, transparency, flexibility, energy and sustainability. Collectively, these trends are shaping the design of tomorrow's teaching laboratory in diverse ways but with trajectories that are remarkably similar.

Introduction

When the Merkert Chemistry Center opened on Boston College's Chestnut Hill campus in the fall of 1991, it was regarded as "a model for chemistry departments nationwide and as a standard of laboratory innovation and excellence" (*1*). The 109,000-square-foot building contained state-of-the-art research and teaching laboratories, multi-purpose and computer classrooms, specialized research facilities and shared instrumentation to support organic chemistry, chemical biology, and physical chemistry.

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Indeed, the design of the chemistry teaching laboratories reflected the current thinking of the time for higher education teaching laboratories throughout the country. The labs were sized to accommodate 16 to 18 students working in pairs, for safety and resource sharing, around centralized island benches. Fume hoods and the necessary lab services were dispersed evenly throughout the lab on both the island benches and along the perimeter walls. However, the Merkert Center can also be seen as standing on a tipping point in chemistry teaching lab design. Its fume hoods were not the full-sized opaque elephants typically seen in chemistry teaching laboratories, but rather smaller bench-top canopy hoods with glass sides aimed at achieving some level of visual transparency and community space within the lab, however modest. A chalkboard along a primary teaching wall also hinted at a shift towards in-lab lectures as opposed to (or perhaps to supplement) the standard model of chemistry education comprised of separate and discreet classroom and laboratory components. Despite these attributes, the teaching laboratories no longer serve as an exemplary model of chemistry teaching laboratory design due to advancements in chemistry education.

Interestingly, at the time of the Merkert Center construction, there was a curious outlier in the available prototypes of chemistry teaching laboratories already exhibiting these same spatial qualities of transparency and orientation towards a primary teaching wall: the organic chemistry teaching lab module.

The familiar “Orgo” module, shown in Figure 1, is a teaching lab of approximately 1,200 square-feet (30’x40’) sized for 18 students seated along tall L-shaped counters in a bullpen configuration around a lower centralized equipment area. Fume hoods and often the majority of fixed lab services are located around the perimeter of the room, leaving the bench space dry for in-lab data collection, computation and analysis. The room has ample clearances and uninterrupted sight lines to a primary teaching wall with marker boards and overhead projectors for presentations. Seated at the counters, students have direct eye contact with the instructor and one another in a seminar-style setting. When working in the perimeter fume hoods directly behind them, students’ work is easily observed by the instructor who can see into every fume hood. Close proximity of a student’s fume hood to his or her bench space and workflow minimizes the need for traffic in front of the fume hoods and improves safety.

Recent trends in chemistry education and teaching laboratory design are, in many ways, reinforcing the attributes of the organic chemistry teaching module and further advancing its characteristics across the spectrum of chemistry disciplines. For institutions looking to embark on new or renovated chemistry teaching lab programs, *setting the dial* appropriately with respect to each of these trends in order to support the pedagogical needs of the institution is a critically important step in creating the highest quality laboratory environment.

Looking ahead, these trends in chemistry teaching and laboratory design illustrate a larger and more fundamental shift toward labs with an *evacuated center*, a highly flexible, technology enabled teaching/work zone in the center of the lab, with fume hoods and other fixed lab services pushed to the periphery.

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Figure 1. College of Wooster, Severance Chemistry Building: Organic teaching laboratory with bullpen configuration and perimeter fume hoods. Payette, Architect Image Credit: © Timothy Hursley. (see color insert)

Interdisciplinary Collaboration

While interdisciplinary collaboration has been common practice in the scientific community since the early 20th century (*2*), its impact on teaching laboratory design is accelerating at a rapid pace as institutions shift from traditional departmental silos to interdisciplinary theme-based research and education. As a result, the teaching laboratory, historically hidden away from the social hub and activity center of a building, is taking center stage. Science is increasingly placed *on display* along primary circulation routes and with direct access to lobbies and major public spaces as a reflection of the cross-pollination occurring within the sciences, as shown in Figure 2. With a comparatively high cost-per-square-foot, the teaching laboratory is also being leveraged as a showcase of an institution's commitment to science education and is serving as a tool for recruitment and retention.

Interdisciplinary collaboration is also creating learning opportunities outside the boundaries of the traditional teaching laboratory. Shared lounges and break-out spaces with informal teaching walls can serve as strategically located

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nodes of interaction, bringing various faculty and student groups together. Similarly, interactive displays in social spaces enable building occupants and visitors to engage directly with the work being undertaken in the laboratories.

Figure 2. Princeton University, Frick Chemistry Laboratory: Science is on display with views into the introductory chemistry teaching laboratories from the atrium. Payette, Architect, in collaboration with Hopkins Architects, Design Architect Image Credit: © Warren Jagger Photography. (see color insert)

Teaching Laboratory as Research Laboratory

Laboratory-oriented teaching methods found their start in 1824 in the academic teaching laboratory of chemist Justus von Liebig (b. 1803-d. 1873), where the teaching model was a version of the apprenticeship process (*3*). Novice students learned under the direct supervision of Liebig's assistants, who acted as mentors to the younger students. The assistants "worked on original problems, turning in a report each morning on their progress the day before. These reports were discussed by Liebig with the various students in planning their future work." Liebig was, indirectly, active in the formal training of the novice students by inventing equipment and procedures that permitted students to perform analyses more efficiently in research-based procedures aimed at methodically advancing the breadth and understanding of chemistry at the time.

The Liebig model – the training of students to produce research quality data – is again a topic of discussion for chemistry education at the graduate and, increasingly, undergraduate levels. Its methods are seen as synergistic with the rise

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in project-based learning, discussed below, and laboratory design is responding by creating teaching laboratories that more closely exhibit the characteristics of research laboratories. This response can be seen in the undergraduate teaching spaces of Princeton University's Frick Chemistry Laboratory, shown in Figure 3.

Within the new 268,000 square-foot building, seven identical teaching laboratories are located on the ground level visible from the atrium. All labs are structured around workgroups of up to 18 students, each with an individual hood to best emulate the research experience. The student-to-fume hood ratio of 1:1 is extraordinary in an undergraduate teaching environment and expands the range of curriculum while instructing students in safe laboratory practice. The laboratories, shown in Figure 4, are designed around a central island bench for shared instrumentation, sink and emergency eyewash, surrounded by an array of fume hood alcoves. The full glass fume hood enclosure ensures visibility by the professor for safety and maintains the transparency of these fume hood intensive labs. The central bench also serves as a space for note taking during pre-lab instruction. A marker board at one end of the central bench allows notes from the pre-lab session to lift vertically out of the way for access to a dispensing alcove, while leaving the notes available for reference during the lab period.

Figure 3. Princeton University, Frick Chemistry Laboratory: Introductory chemistry teaching laboratory with individual fume hoods per student and open passages between lab modules. Payette, Architect, in collaboration with Hopkins Architects, Design Architect Image Credit: © Warren Jagger Photography. (see color insert)

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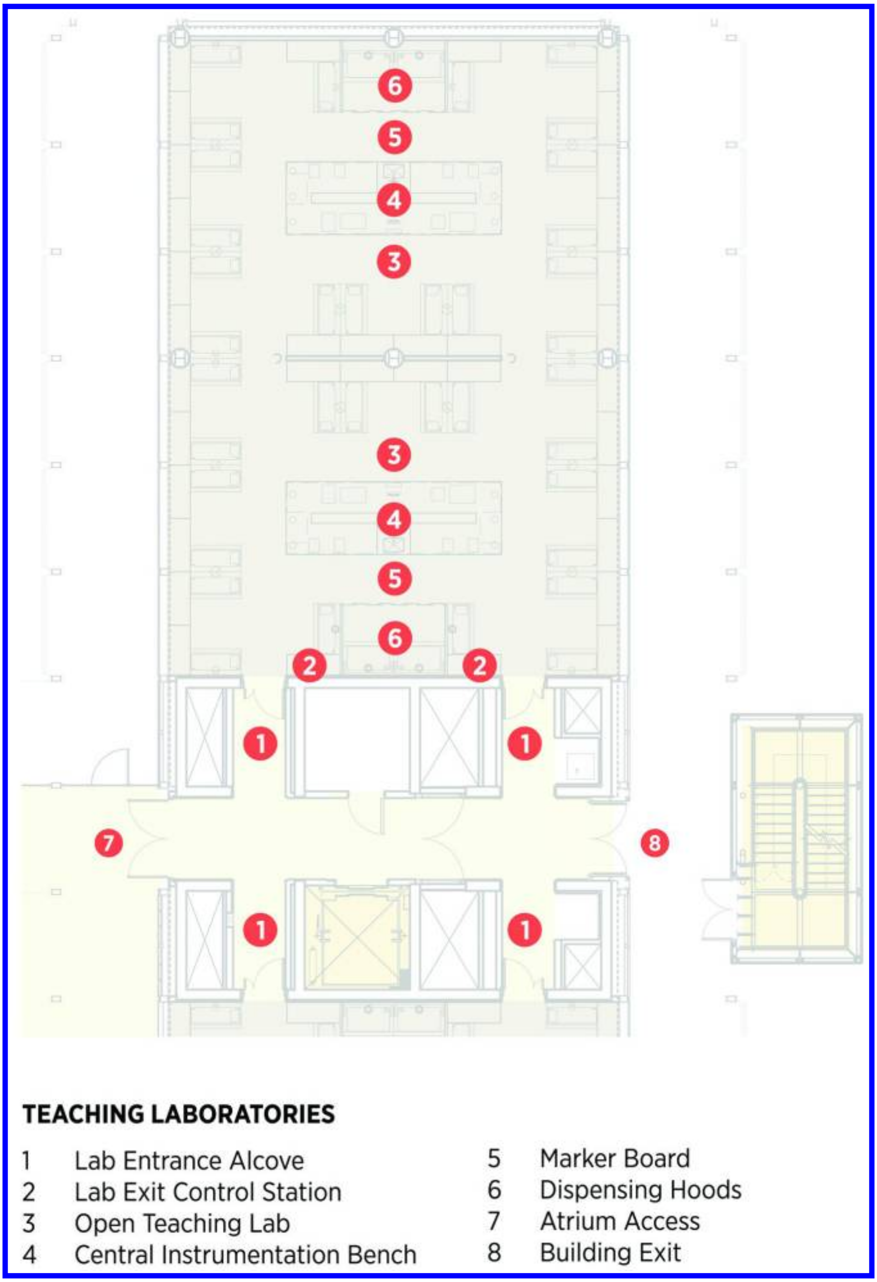

Figure 4. Princeton University, Frick Chemistry Laboratory: Perimeter fume hood alcoves are located around a shared centralized equipment bench. Payette, Architect, in collaboration with Hopkins Architects, Design Architect Image Credit: © Payette. (see color insert)

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Transparency and Flexibility

Modern teaching labs have a greater emphasis on instrumentation and integrated computational set-ups than ever before. Teaching labs, in general, and chemistry teaching labs, in particular, are less reliant on bench-top apparatus with more emphasis placed on under-hood experiments. This transformation poses challenges to visual transparency, safety, and an open and collaborative learning environment.

The design of the Brandies University Carl J. Shapiro Science Center responded to this challenge by creating open suites of teaching laboratories. Within the new building, students in chemistry and biology teaching labs learn in close proximity to the chemistry and biology research functions. A collection of informal interaction spaces and general purpose classrooms located strategically throughout the project serve to bring students, instructors, and researchers together, providing students with direct exposure to the scientific research. Flexible casework can be modified to suit a range of teaching styles, and labs are outfitted with the latest technology, including projection systems and large format flat panel monitors.

The chemistry teaching laboratory functions as a single open lab, or *suite*, along the entire south façade of the building, subdivided through building geometry and low height partitions, with transom windows into General, Honors, and Organic Chemistry programs. Ten teaching modules with teaching assistant stations, separate teaching walls, and projection capabilities accommodate a total of 112 students in groups ranging from 10 to 16.

Within the laboratories, shown in Figure 5, a high degree of spatial transparency, primary and secondary circulation paths, and a flexible casework system configured into island benches enable the size of the programs to change over time and help ensure a safe laboratory environment, which is critical given that 45 of the building's 70 fume hoods are located on this floor. In addition to transparency between labs, transparency between inside and outside is heightened through the clever use of glass-backed fume hoods located along the perimeter walls. The glass fume hoods enable abundant natural light to enter the laboratories while framing views to the exterior. These types of high-quality environments are increasingly valued compared to the dark, drab and anonymous labs common before the end of the 20th century.

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Figure 5. Brandeis University, Carl J. Shapiro Science Center: Chemistry Teaching Laboratory: Distinctive daylight and views uncharacteristic in chemistry teaching laboratories. Payette, Architect Image Credit: © Warren Jagger Photography. (see color insert)

Super Labs

The concept of the laboratory teaching suite creates project-based places for students and strengthens the interactions between students and faculty. At the University of Massachusetts, Amherst Integrated Sciences Building, this concept was paramount. Within the University's chemistry department, introductory chemistry courses serve laboratory sections of up to 160 students. In these sections, the University sought to establish a ratio of 16 students per teaching assistant. A particular challenge in these areas was to allow observation of the entire group by the professor while maintaining intimate environments conducive to instruction in smaller groups. An innovative chemistry suite design, shown in Figure 6, uses ten 16-person modules to create an entire floor that is simultaneously a huge "superlab" and a collection of seminar-like lab "clusters." This arrangement allows an instructor to rotate between modules (like a doctor doing rounds), without ever leaving the lab space. Grouping students in smaller clusters gives them the feeling of being in an intimate environment, reducing distractions and improving learning. Five lab modules are arranged on each side of the building with support space occupying all of the area in between, as shown in Figure 7. The arrangement offers students access to instrumentation, prep space and the chemical stock room directly from the teaching laboratory, resulting in a highly efficient layout where the entire floor is usable space. The superlab's utililization of repetitive lab modules promotes safety and enables greater flexibility in how the laboratories are programmed and operated.

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Figure 6. University of Massachusetts, Amherst, Integrated Sciences Building: Sixteen person chemistry teaching module with open passage to adjacent modules. Payette, Architect Image Credit: © Warren Jagger Photography. (see color insert)

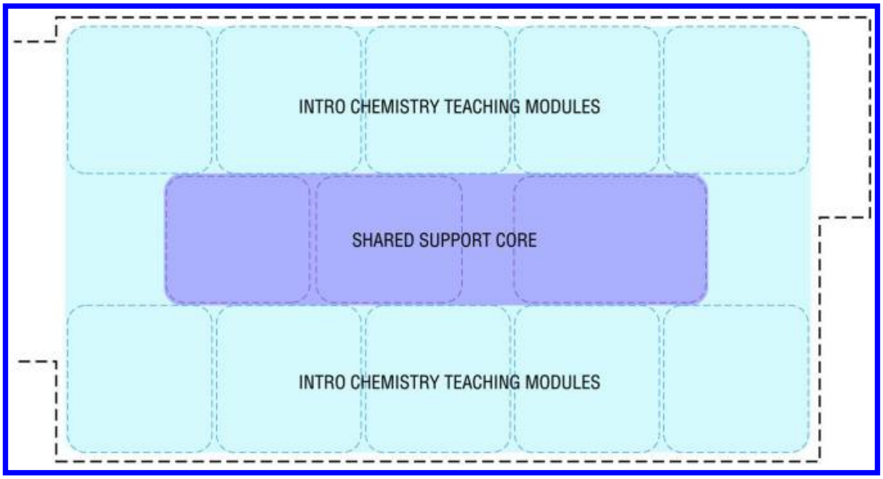

Figure 7. University of Massachusetts, Amherst, Integrated Sciences Building: Continuous adjacent laboratory modules with a centralized shared support core create a superlab of chemistry teaching. Payette, Architect Image Credit: © Payette. (see color insert)

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Organic Chemistry as a Model for General Chemistry

Recently, Boston College has undertaken a renovation of the chemistry teaching laboratories in the Merkert Chemistry Center. While innovative at the time of their opening in 1991, the labs have fallen into decline and are no longer aligned with the pedagogy of the University, which supports a strong relationship between instructors, teaching assistants and students. The 6,500 square-foot renovation project includes two general chemistry teaching labs as well as a shared lab for general and analytical chemistry. Two primary goals were established for the project. First, increase the lab capacity from 18 to 22 or 24 students per lab in order to serve both current and near-term projected chemistry enrollment. Second, replace the bench top canopy hoods with perimeter fume hoods at a ratio of two students per fume hood in order to fundamentally improve sight lines and transparency within the labs while simultaneously embracing *laboratory as classroom* with focus directed towards a primary teaching wall.

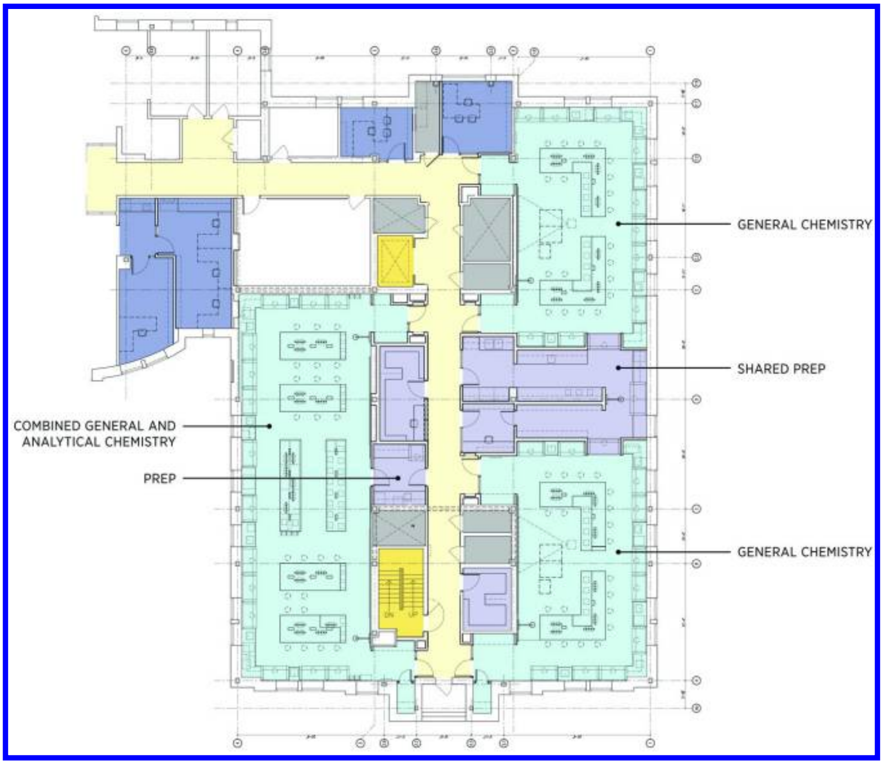

Figure 8. Boston College, Merkert Hall Chemistry Teaching Lab Renovation: General chemistry teaching laboratories utilize an organic chemistry model while the shared lab is calibrated for both general and analytical chemistry. Payette, Architect Image Credit: © Payette. (see color insert)

After several iterations, the design team, working in close collaboration with the chemistry faculty, discovered that the most appropriate layout for the renovated general chemistry teaching labs is the traditional organic chemistry module with perimeter fume hoods and students seated in a bullpen configuration around an open, shared equipment area, as shown in Figure 8. Sinks and lab services are located around the perimeter with some lab services also on the island lab benches. Each of the two general chemistry labs has a capacity of 20 students. The shared lab is optimized for analytical chemistry, while not impeding its use as a third general chemistry lab, and has a capacity of 24 students. Linear island benches within the large lab are arranged in two clusters of 12 students with an expanded shared equipment zone in the center. In both types of labs, demonstration style fume hoods were selected with glass backs and sides due to the intensity of fume hoods within each lab and the necessity in their perimeter configuration of being, at times, located in front of the building's existing windows. The transparent fume hoods help maximize the openness of the labs while optimizing perimeter space, maintaining a strong connection to the exterior and enabling as much natural light into the space as possible.

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Generic Laboratories

Modern scientific instruction is driving the way we think about the design of teaching environments for the sciences. Inquiry-based learning offers "hands on experiences" for the students. Often, this means more sections with fewer students per section. This new paradigm, along with the ongoing growth in science enrollment, requires teaching laboratory spaces to be highly flexible and multi-purposed.

When Middlebury College began planning for its new McCardell Bicentennial Hall science complex, it analyzed its existing 1960's era science facilities for adequacy and determined that no intervention or renovation could meet the needs for the type of new facility imagined. After reviewing enrollment trends, Middlebury committed to bring together all of the science disciplines, including biology, chemistry and biochemistry, physics, geology, psychology and geography in a new building. The goal of the project was to blur the boundaries between these departments for the design and use of both research and teaching space and to bring learning to the forefront in the classroom and in the laboratory.

The solution takes the idea of a flexible and multi-purposed laboratory to the extreme by creating wholly *generic* laboratories which can be utilized in many different configurations, as shown in Figure 9, depending on the subject matter, class size and individual preference of the instructor. Each 1,000 square-foot (36' x 28') lab is coupled with a 350 square-foot (12' x 28') support room. Flexibility is idealized with fixed fume hoods, sinks, and lab services located around the perimeter of the room and movable epoxy-topped tables in the center with recessed floor boxes for electrical power and telecommunications. The tables can be arranged in a seminar format, horseshoe, square or back-to-back configuration to support various modes of student interaction and teaching pedagogy including lecture, seminar, computer lab, and project-based learning. Chalkboards are provided on multiple walls to enhance the flexibility of the various configurations.

Figure 9. Middlebury College, McCardell Bicentennial Hall: Generic laboratory can be utilized in many different configurations to maximize flexibility. Payette, Architect Image Credit: © Jeff Goldberg/Esto. (see color insert)

Energy and Sustainability

This is a particularly advantageous time for the design and renovation of chemistry teaching laboratories. In recent years, architects and engineers have been designing laboratories with a vastly different energy profile than the previous generation of science buildings. Many emerging technologies are being tested and implemented in an effort to create highly sustainable environments for scientific teaching and research without compromising flexibility or performance. Important in the design of any teaching laboratory today is the discussion, understanding, and calibration of these technologies in a manner most appropriate for the specific project.

Low Energy Heating Ventilation and Air Conditioning (HVAC)

A common HVAC strategy in research laboratories is the use of a Variable-Air-Volume (VAV) system, which provides supply air at a constant temperature but varies the air flow rate to meet the rising and falling heat gains or losses within the thermal zone served. While the use of a VAV system helps lower the volume of outside air needed to properly ventilate research labs, teaching labs pose a different

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challenge. Because teaching labs are only occupied during scheduled lab periods, their utilization can be as low as 30 hours per week. A common strategy for efficiently operating these spaces is the use of two-position, constant volume fume hoods where the instructor is responsible for turning *off* the hoods at the end of the lab session while ensuring there are no chemicals remaining in the fume hoods. Typically, any chemical-dispensing fume hood(s) within the teaching laboratory are left *on* with a flow of exhaust air to ventilate the chemicals that remain.

In chemistry teaching laboratories with a central open student area and perimeter fume hoods and services, such as in the bullpen configuration of the organic chemistry teaching laboratory, an effective design for the HVAC system supplies the fresh air at very low velocity through a ceiling supply plenum (often through a perforated ceiling) above the center of the room, as shown in Figure 10. The supply air is drawn toward the lab's perimeter and exhausted through the fume hoods, keeping the students and sensitive lab equipment free from contaminated air. The low velocity supply reduces noise, providing better room acoustics and allowing in-lab discussions between students and the instructor. When combined with the use of energy-efficient low-flow fume hoods, this approach can result in decreased energy use with smaller ductwork and considerable cost savings.

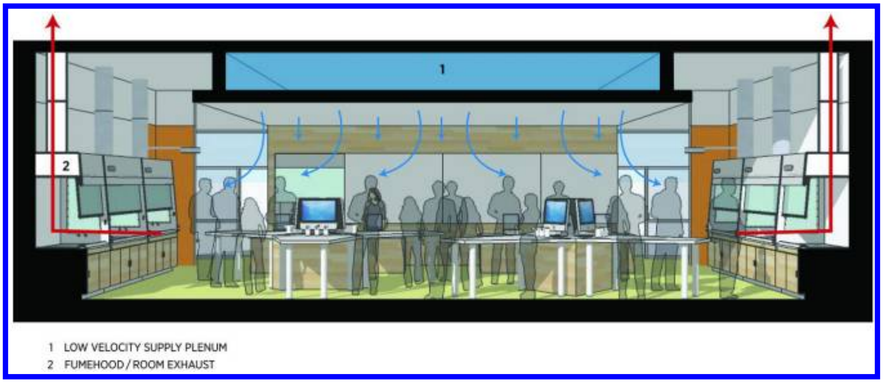

Figure 10. HVAC Diagram: Low volume supply air is distributed through a ceiling plenum over the central teaching area and exhausted through the perimeter fume hoods. Payette, Architect Image Credit: © Payette. (see color insert)

Trends in Laboratory Lighting

High efficiency lighting systems, like LEDs, coupled with advanced lighting controls and supplemented by daylight, can provide a dramatic reduction in lighting energy usage. Smart lighting strategies are proving to generate less heat in the space and are far more energy efficient to operate. Ceilings within the lab can be an integral component of the lighting/daylighting strategy. For example, reflective ceilings or ceiling "clouds" can be coupled with light fixtures, providing a mix of both direct and indirect light to enhance the performance of the light fixtures and enabling a more even distribution of light levels throughout the space,

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as shown in Figure 9. This solution can reduce the typical laboratory lighting configuration by 50%, benefiting first costs, operating costs and maintenance. In addition, with light levels consistent throughout the space, furniture and casework arrangements can be more flexible.

Green Chemistry

In academic institutions across the country, courses incorporating green chemistry concepts are becoming more prevalent and influencing the design of teaching laboratories. "Green chemistry is the use of chemistry for pollution prevention. More specifically, it is the design of chemical products and processes that are environmentally benign. Green chemistry encompasses all aspects and types of chemical processes that reduce negative impacts to human health and the environment" (*4*). This methodology enables the teaching laboratories to have a higher student-to-fume hood ratio than more traditional laboratory practices. At Bridgewater State University, for example, where the chemistry teaching laboratories are organized to support green chemistry, this ratio is 8:1 (eight students per fume hood) and enables fewer fume hoods to be located on the side walls of each teaching laboratory, creating a highly flexible zone in the center with access to exterior views and daylight, as shown in Figure 11. In addition to reduced exposure to potentially dangerous chemicals and improved transparency through the reduction in fume hood density, laboratories which embrace green chemistry see significant energy savings.

Figure 11. Bridgewater State University, Science and Mathematics Center: The sixteen person chemistry teaching laboratory supports project-based learning with students organized in clusters of four with one fume hood per cluster. Payette, Architect Image Credit: © Warren Jagger Photography. (see color insert)

Project-Based Learning

Student achievement in the sciences is directly linked to teaching methodology, and an awareness of this link is leading to a rise in project-based

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learning as a means of enhancing science curricula. This teaching method is characterized by authentic investigation, the production of an end product, collaboration among peers, and the use of technology to support the process of inquiry. In project-based learning environments, “students are engaged as active participants in the learning process, setting their own learning goals and forging meaningful relations through their experiences as they investigate real-world issues” (*5*).

Teaching laboratories in which project-based learning is utilized must be uniquely tailored to the method of inquiry. At Bridgewater State University, project-based learning laboratories are sized for 16 students working collaboratively in clusters of 4 students, as shown in Figure 11. This is reinforced through the arrangement of island benches. Often in such laboratories, the furniture is mobile to enable reconfigurations, and the labs exhibit a high level of technology integration and multiple teaching walls. In some instances, the instructor can select that content from any student’s workstation (or laptop) be displayed on an overhead projector or teaching wall monitor for view by the entire class during presentations or discussion of analysis and findings (*6*).

Active Learning Laboratories

In recent years, rapid progress in communication technology and an emphasis on an active learning pedagogy have been changing the learning environments in higher education. Student-centered design and the deep integration of technology are key factors in a process that not only enhances the learning experience within the teaching laboratory, but potentially turns all campus spaces into a learning environment (*7*).

The central goal in designing such spaces is to give students and instructors choices to learn and to teach in an easily adaptable, resource deep and attractive environment. This comprehensive approach not only addresses the teaching laboratory proper but also the informal soft spaces that may be adjacent to the laboratory, such as lounges, cafes, break-out collaboration zones and even exterior landscape spaces.

In active learning classrooms and laboratories, such as the one shown in Figure 12, conventional lecture format is increasingly complemented and replaced with a new pedagogy that encourages independent, group, and peer-to-peer learning. Moving away from teacher-centered models, the new student-centered approach emphasizes collaborative, project-based, and hands-on learning. Rather than “places of instruction,” the future role of higher education can be characterized as “places to produce learning” that emphasize critical thinking and complex problem solving. This paradigm shift is fueled by both a better understanding of the diverse range of learning styles, which has been informed by research in education, and by a growing demand for a flexible, creative and highly skilled workforce.

The consequences of this new paradigm on the design of teaching laboratories include: flexible spaces that can be easily reconfigured to support different modes of instruction; provision of spaces for team based learning; de-emphasized classroom front "teaching wall" in favor of universal distribution of projection surfaces and whiteboards; dedicated wireless networks to allow students to control large screen displays, including video-conferencing; integrated use of personal portable devices to participate in class activities; and potential collocation of teaching laboratories with an adjacent large group learning space, such as a Technology Enabled Active Learning (TEAL) classroom. A unique characteristic of certain TEAL classrooms, which could influence teaching laboratory design, is their organization around groups of three – often, three groups of three students each, for a total of nine students, per cluster. The grouping of three students is seen as a way to promote discussion and debate more successfully than pairs of students, which can deteriorate into non-productive leader-follower relationships thereby limiting discovery.

Figure 12. Georgetown University, Regents Hall Science Center: In a student-centered, technology-enabled active learning laboratory, the instructor serves more as moderator than lecturer. Payette, Architect Image Credit: © Robert Benson Photography. (see color insert)

Looking Ahead

If the trends in chemistry teaching laboratory design, discussed above, were plotted on a map and connections made between projects exhibiting similar trends, the result would likely resemble the route map of a large international airline, a seemingly incomprehensible starburst of complexity. Upon closer inspection, however, there appears to be an underlying pattern to the trends, with modern teaching laboratories likely to exhibit multiple trends rather than one or two. The case studies evaluated reinforce this and illustrate how the trends are

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often synergistic rather than exclusionary. Collectively, these trends are shaping the design of tomorrow's teaching laboratory in diverse ways but with trajectories that are remarkably similar, resulting in laboratories with an *evacuated center*, a blank stage upon which anything is possible. The center of the teaching laboratory is becoming a highly flexible, technology-rich learning environment with more fluid boundaries and configurations. Infrastructure, such as fume hoods and fixed laboratory services, rings the perimeter, facilitating and providing technical support to the activities in the center.

Imagine the next generation of the chemistry teaching laboratory, Figure 13. The lab is sized for 18 to 24 students working in a project-based setting in teams of three students grouped around flexible, if not mobile, casework that can be easily reconfigured to suit a variety of teaching and learning styles. Power and ethernet connections are located in recessed floor boxes, as are any table mounted laboratory services, via quick-disconnect fittings. A primary teaching wall provides cohesiveness to the laboratory, reinforcing the space as a classroom. However, teaching is also made multi-directional, even student-driven, through increasingly wireless technologies as well as large display monitors at each workstation around which groups of students can cluster. Media is bi-directional and can be both *pushed* from the primary teaching wall to each workstation for reference during experiments or analysis and *pulled* from each workstation to the primary teaching wall for group discussion, review of findings, and student presentations. Equipment is shared and centralized on mobile tables and base cabinets, which serve to maintain storage capacity in the more open and transparent laboratory. A support core accessed via pass-through dispensing fume hood(s) can be shared between multiple labs to further an institution's teaching flexibility and support multi-disciplinary collaboration. Safety remains paramount with multiple laboratory entrances, dedicated storage for student coats and backpacks with a clear threshold between the storage area and the lab proper, and clearly identifiable and redundant safety stations each incorporating an emergency shower/eyewash, first-aid, and emergency shut offs for power and gas. Fume hoods, sinks, and fixed laboratory services are strategically located around the perimeter, supporting the laboratory activities through efficient workflow while not impeding the amount of natural light entering the lab nor the lab's connection to the exterior. The fume hoods are also an integral link to the teaching laboratory's HVAC system with low-volume supply air distributed through a perforated plenum and exhausted through the fume hoods.

While this idealized modern teaching laboratory may not suit the unique needs of each academic institution looking to embark on a new or renovated project, an understanding and calibration of the trends shaping the modern chemistry teaching laboratory are fundamental to the creation of a high quality learning environment and the success of any project. In this way, tomorrow's chemistry teaching laboratory, like the Liebig-model teaching/research laboratory of the 19th century or the organic chemistry module of the 20th century, can be seen on a continuum of developing strategies for the rapid advancement of chemistry education.

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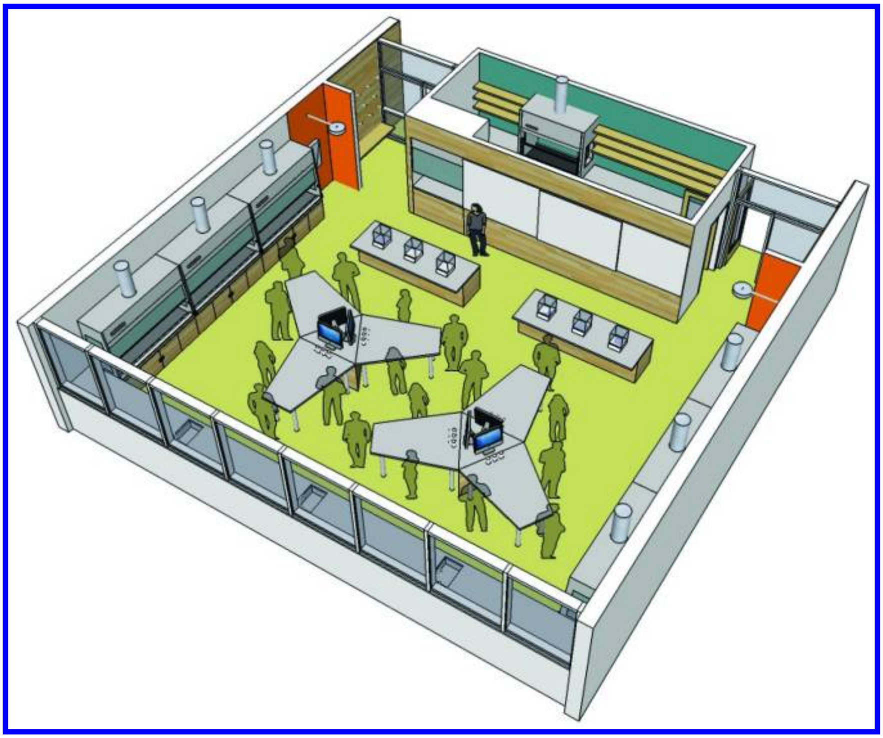

Figure 13. The Modern Chemistry Teaching Laboratory: Trends in teaching laboratory design point towards a technology-rich laboratory with a highly flexible center and fixed services located around the perimeter. Payette, Architect Image Credit: © Payette. (see color insert)

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