INTERDISCIPLINARY TOOLS AND TOPICS IN CHEMICAL EDUCATION

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The role of interdisciplinary course content, as well as the incorporation of methods, tools and materials from other disciplines, in the teaching of chemistry is considered. Special attention is given to inclusion of interdisciplinary materials into introductory university level courses. Organization of the introductory course around interdisciplinary topics has many advantages; it permits a stronger emphasis on concept-based learning, promotes active learning by students and has greater appeal because of the closer relationships of course content to students' interests. Alternatives to traditional course content and methods of teaching are discussed.

Keywords: interdisciplinary tools; chemical education.

In recent years the economies of the major industrial nations have been subject to great stresses. Competitive pressures are great; the need to reduce costs in manufacturing, to become more efficient, has grown. At the same time, the extraordinary collapse of the the cold war standoff between east and west has resulted in less research and development related to military and national security goals. One consequence of these changes in the major industrial nations has been a searching reexamination of the role of scientific research, and the place of science and technology in the formulation of national policy. In the United States the value of curiosity-driven research, uncoupled from specific societal goals such as economic competitiveness or improved treatment of diseases, has been called into question.

The examination of the roles of fundamental research in sciences and engineering, with the accompanying stronger focus on effectiveness and application to specific problems, has led to a greater emphasis on interdisclinary approaches to research. Further, the changing character of the sciences themselves has also prompted a greater interest in interdisciplinarity. The development of powerful new experimental methods and the growth of computing and communications technologies have also contributed. At the same time, many obstacles exist to the formation of interdisciplinary initiatives.

The incorporation of intersdisciplinary content into educational programs reflects the status of interdisciplinary activities more generally, and is stimulated or dampened by the same sorts of forces. In this paper I wish to consider the state of interdisciplinary activities in chemical education, examining on the one hand the incorporation of interdisciplinary topics into the curriculum, and on the other, the use of teaching tools, methodologies and insights borrowed from other disciplines.

ASPECTS OF INTERDISCIPLINARITY

It is useful at the outset to consider the relationship of chemistry to other disciplines. Figure 1 illustrates the place of chemistry in terms of level of abstraction, or fundamental character. Mathematics provides the abstract, formal framework in terms of which models of nature can be constructed. Physics provides the fundamental laws of nature in terms of which we can interpret observations. Chemistry in turn deals with the observations and models for fundamental chemical processes, and the physical processes that underlie these. The other basic sciences, in their turn, depend on the principles of physics and chemistry for development of the underlying basis of each discipline.

While chemistry "feeds" the various science and engineering disciplines that focus on particular aspects of nature, it also receives from other sciences a host of useful tools, materials and methods, through technological development. Examples include lasers, charge-coupled detectors, high performance ceramics and computer software programs.

THE INTERFACES OF CHEMISTRY

Because chemistry interfaces with so many other disciplines, it is aptly referred to as "The Central Science". To give some flavor of the nature of these interfaces, it is useful to discuss a few examples at some length.

• **Molecular Biology** - The relationship of chemistry to the exciting developments in molecular biology is of special importance. Molecular biology is a clear extension of chemical principles and practice to a particular class of substances, those present in living systems. The character of this interface is evident from the areas of coverage recently announced[1] for a new journal, Chemistry and Biology: natural and designed molecules as probes of cellular pathways; structure and function studies for drug design; molecular recognition in biological systems; cell signaling; molecular control of gene expression; biological catalysis; molecular basis of evolution; the biology of highly reactive species; protein folding; biosynthetic pathways; new methods for generating ligand diversity. Developments such as the polymerase chain reaction, catalytic antibodies, and the understanding of the role of reverse transcriptase represent examples of essentially chemical contributions to biology.

• **Environment** - Chemistry plays many important roles in understanding and coping with some of the most important problems in the environmental sciences. Obvious examples include the depletion of stratospheric ozone, formation and distribution of the so-called "greenhouse" gases that contribute to

* Conferência apresentada na 17ª Reunião Anual da SBQ, em Caxambu (Maio, 1994).

global warming, pathways for distribution and eventual depletion of polychlorinated hydrocarbons, formulation of less polluting gasolines, and the technologies of waste disposal.

• **Engineering** - Many aspects of engineering rely heavily on chemistry. These include the development of new electronic materials, in which chemical vapor deposition, molecular beam epitaxy and other essentially chemical processes are central to formation of microelectronic devices. The "packaging" of such devices is also largely a chemical problem, requiring materials to serve as insulators and conductors, heat sinks and support structures. The development of optical fibers of the quality demanded for modern optoelectronic applications has been a triumph of chemical technology. In the construction industries, chemistry is central to the development of new cement and concrete formulations. High technology glass materials are very important to the construction of large scale, high-rise structures. High performance polymers and plastics are employed in construction, in the manufacture of automobiles and many appliances.

These few examples serve to make the point that chemistry is vital to the development of many other fields of science and technology. In fact, many of the people working in these fields are chemists. This brings us to the question of how the central role of chemistry in the sciences and technology influences, or should influence, the students we teach.

WHOM DO WE TEACH?

Interdisciplinary considerations in chemical education at the university level begin with the introductory courses offered to entering students, and extend throughout the student's educational experience, including the education of pre-doctoral, Ph.D. candidates. However, the challenges of incorporating interdisciplinary materials into the curriculum are perhaps greatest at the introductory level, where there is the greatest diversity among students in terms of career goals and prior training. The organization of university-level instruction varies from one nation to another, but the pathways via which students acquire their training in chemistry are broadly similar. My comments reflect my experience with the system of college and university organization characteristic of the United States.

The introductory course may enroll students whose career goals are any of the following:

• Chemistry, chemical engineering or a closely related field.
• A science field with a strong chemical content, such as life sciences, environmental sciences or materials sciences.
• A field of engineering or technology, in which chemistry may play a significant, though not dominant, role.
• A field other than one of the science or engineering disciplines, in which chemistry may not play any role.

It is sometimes possible to provide separate course offerings for students with closely related career goals. For example, there may be a special course for the well-prepared students in curricula that demand a strong chemical background. Similarly, engineering or pre-medical students may be placed in separate courses. Even when this is possible, however, there is likely to remain the need to teach introductory chemistry to large numbers of students with diverse backgrounds and career interests. The challenge in such courses is to motivate students to learn, and to present material that is relevant to their present and likely future needs and interests. Clearly, these two goals are not independent. The question for our discussion then becomes: can an emphasis on interdisciplinary topics add value to the course and assist in achieving our goals? Before we attempt to answer this question, we must first define what is meant by the term, "interdisciplinary material". For our purposes it is perhaps sufficient to say that it refers to course content that alludes specifically to the relevance and utility to another field of information, materials or methods characteristic of a discipline. This rather simplistic definition does not address the sometimes difficult issues of whether a particular topic properly belongs to one discipline or another.

WHY INTRODUCE INTERDISCIPLINARY MATERIAL?

There are several reasons why interdisciplinary materials are appropriate for inclusion in chemistry courses, particularly at the introductory level. As indicated above, a major challenge in introductory courses is to motivate students to learn. For many students a major barrier to learning is the fact that the course content with which they are presented is not only unfamiliar, but also lacks connections with the students' own experiences. Interest in the material presented can be heightened considerably by employing examples to which students can readily relate. For example, in discussion of acidic and basic solutions, applications of the principles to household products, soil science and water treatment can serve to add interest.

The use of materials drawn from other disciplines can also serve as the most effective means of conveying understanding of a principle. In addition, the introduction of interdisciplinary materials can provide the student background that will be useful in further studies. For example, the use of material drawn from polymer chemistry to illustrate concepts ranging from van der Waals forces to non-crystalline solids to molecular geometry could provide engineering and life sciences students with insights useful in later course work.

One of the most important, though often-neglected goals of introductory science courses is to prepare students, regardless of their career interests, for citizenship. In a continually evolving and complex technological society, the capability of general citizens to appreciate the roles of science and technology in society is becoming increasingly important. The ability of a people to make informed decisions about socially important topics such as acid rain, waste disposal, water pollution and many other issues involving risk assessment will increasingly determine the future courses of national and international policies. The introduction of broadly interdisciplinary materials dealing with such matters, and the inculcation of modes of reasoned thought with respect to sensitive issues, should be one of our goals as educators.

HOW CAN INTERDISCIPLINARY TOPICS BE INTRODUCED?

If it can be agreed that the introduction of interdisciplinary materials into introductory chemistry courses is a desirable goal, the question then becomes one of how it can be achieved. The most direct approach is to retain the traditional organization and content, while somehow incorporating interdisciplinary topics. Such topics can be employed as a means of exemplifying principles. For example, the use of zeolites as catalysts in the cracking of hydrocarbon feedstocks is important from an environmental point of view, because it permits formation of higher octane, lower-polluting gasoline formulations. In addition, the catalysts permit extraction of more gasoline and other useful components from a barrel of crude oil, lessening dependence on imported oil. Zeolites and their roles as catalysts can be discussed at several points in the course, in connection with such topics as ionic structures, gas kinetic theory and van der Waals forces, acid-base chemistry and structures and shapes of organic molecules.

A second example is stratospheric ozone depletion. This very important and timely topic can be discussed in connection with gas kinetic theory, equilibrium, catalysis, and photochemistry, to name the most obvious traditional topics. In using interdisciplinary topics in this way, the difficult part is to introduce the topic in sufficient detail so that the particular application at hand can be understood, but not to allow the interdisciplinary topic itself to dominate. Over time, by revisiting the topic several times as relevant principles are discussed, the student comes to see various aspects of it.

A second method for introducing interdisciplinary material is to incorporate it into exercises and problem sets. Exercises that are based on realistic circumstances are inherently more interesting than those that simply ask the student to follow a prescribed algorithmic procedure. On the other hand, students generally find "word problems", in which they must extract the essential question from a verbal description, the most difficult type of problem to solve. Thus, while interdisciplinary content in problems and exercises is desirable, it is by no means an easy matter to incorporate it in a substantive way.

A third approach is to include interdisciplinary materials in laboratory exercises. The opportunities for incorporating familiar materials in demonstrating principles are plentiful, but the development of successful experiments is time-consuming and difficult.

A fourth approach is to tie the chemistry course to larger societal concerns and interesting applications through outside readings. Many daily newspapers, as well as various magazines, special TV shows, museum shows and the like provide oppourtunities for linking chemistry to other disciplines. As an example, Table 1 shows a listing of a small fraction of topics bearing on chemistry that appeared over a one-year period in the New York Times.

Using standard procedures for obtaining copyright permission, such materials can be reproduced locally for student use. In each case the topic provides an opportunity to discuss the underlying principles, and to illustrate the application of chemistry to an interesting system.

While all of these various means are attractive in themselves, most teachers of introductory courses fail to make use of most opportunities to introduce interdisciplinary materials. The reasons for this are several; among them is the fact that the teacher may not be well-informed about the background associated with a given topic. Unless the material is spelled out fairly explicitly in the introductory text chosen for the course, it is necessary for the teacher to prepare and distribute supplementary materials. The amount of interdisciplinary materials in the most widely used texts has increased recently, but it is not always organized so that teacher or student can readily refer to it at any given stage in the course.

Perhaps the largest impediment to more extensive use of interdisciplinary topics is the feeling that there is not sufficient time in the course, that the introduction of such topics would require the omission of other topics deemed to be very important or essential. The issue of course content, and the conflicting demands in the introductory courses for achieving goals which, if not in conflict, are at least competing, is presently generating a new wave of critical analysis of the introductory courses, indeed of the entire undergraduate chemistry curriculum.

Table 1. Chemistry-related Science Topics from the New York Times

Windows for Energy-efficient Buildings
Iron Levels in the Blood; Connection to Heart Risk
Fullerene Carbon in a Mineral
Space Age Composites
DDT and Pancreatic Cancer
Conversion of Wood to Fuels
Reduction of NO Emissions from Power Plants
Use of Clays to Trap Strontium-90
Chiral Compounds as Drugs
NO as a Biological Messenger
Superconductivity of "Buckyballs"
Titanium Anchors in Joint Repairs

WHAT ARE OUR GOALS?

To help resolve the conflicting demands related to content and direction of introductory chemistry courses, it is important to consider what goals we should have for the students in these courses. These goals are numerous, because the students have diverse backgrounds and career interests. There are, however, several important desirable outcomes that are more or less independent of the student's particular orientation.

- **Concept Mastery** - Mastery of the concepts on which the course is based is the foundation on which all other desirable outcomes rest. By mastery of a concept is meant first that the student has a clear physical understanding of a particular phenomenon; that is, he or she can give a reasonably accurate account of what happens when a weak acid is dissolved in water, or a piece of ignited sodium is placed in a chlorine atmosphere. Secondly, the student can relate that account to a chemically relevant model for what occurs; that is, can describe the process in terms of atomic and molecular level processes.
- **Familiarity with the Vocabulary** - It is important that students acquire a sufficient chemical vocabulary to permit them to speak in chemical terms. Students must know the distinction between cation and anion; between chloride ion on the one hand and molecular chlorine on the other. When students have difficulties in distinguishing between different chemical names, the problem is often that they lack a clear conceptual understanding of what distinguishes various substances.
- **Capacity for Problem-solving** - The introductory chemistry course is typically laden with materials related to problem-solving. Numerical problems abound: stoichiometry problems of all kinds, gas law problems, weak acid-base equilibria, solubility product problems, all manner of problems involving electrochemistry, and so on. Much of the emphasis on problem-solving involves training students to carry out algorithmic procedures. They learn to recognize a problem as belonging to a certain type. Having learned (or memorized) the algorithm for solving that type of problem, they insert the given numerical data into the appropriate equations and solve.

It may be doubted whether learning such skills has an important present value; it almost certainly has no lasting qualities. While teachers may take heart from the ability of their students to perform various such prescribed problem-solving skills on an examination, a fundamental understanding of the problem on the student's part has usually not been tested. The alternative to an emphasis on manipulative skills is to concentrate on conceptual mastery, on understanding at the qualitative level of the concepts that underlie the problem.

- **Ability to Relate Principles to Observed Phenomena** - Once conceptual mastery has been achieved, it is likely to be retained for a much longer time than any procedural skills that are not regularly practiced. The ability to see how the concepts, once understood, can be applied to understanding everyday phenomena is a further skill that can be enhanced through practice in an introductory course. Why might a farmer or homeowner distribute lime on the land? Why might the level of PCB's in the eggs of herring gulls be a thousand times higher than the level in the lake near which the nest is built? The use of interdisciplinary material provides many opportunities to reason through the connections between observed pheonomena and the underlying chemical principles.

RESTRUCTURING OF THE INTRODUCTORY COURSE

The recognition that the traditional general chemistry course is not serving the broad range of students who come to it as well as it should has led to several initiatives toward restructuring of introductory courses. Some of the initiatives are based on new understandings of how students learn, and involve major alterations in the format of the course. The traditional lecture, in which the lecturer is in the active stance of presenting materials to students, who in turn are more or less passive recipients, has increasingly been called into question. While great lecturers can inspire students and impart important insights, the most usual role of the lecturer is to define the content of the course. Further, while many lecturers today are employing computer technology to enrich the lecture experience (vide infra), the great majority have not moved beyond the technology of the chalk board and the demonstration bench.

Alternatives (or additions) to the traditional lecture format are based on the concept of active learning[2-4]. Students learn best when they play an active role in the learning process. Their learning should be purposeful and personal to them. They must feel that it is important for them to learn, and must have a certain level of confidence that they can learn. Related to this is the idea that cooperative learning has great benefits for many students. While very gifted students may be thought to have no need for cooperative learning activities, even these students may benefit from the opportunity to teach other students, thus testing their own understanding of the materials.

In many successful experimental programs student are encouraged to study together in coherent groups, to engage in collaborative problem-solving, and to teach one another. In an experiment underway at Rensselaer Polytechnic Institute, physics, mathematics and chemistry courses are taught in a studio format.5 The traditional lecture room is replaced by a studio with about 30 workstations, each of which can support two students. When working with their workstations the students face toward the walls of the room. The teacher is centered in the room, able to monitor student activities, offer brief introductory explanations and serve as a consultant as students learn with and from each other and directly from learning materials. Through the workstations the students have access to a hypermedia-like environment that incorporates online textbook materials, video and audio tape materials, and software for graphics, data acquisition, data analysis, spreadsheet and workprocessing. While it might at first appear that such a course would be prohibitively expensive to operate, the claim is made that costs are comparable with those required to operate large enrollment courses with traditional formats. Student reactions are generally extremely positive.

Many of the new developments in approaches to teaching chemistry are a consequence of a second and important aspect of interdisciplinarity in chemical education: the impact of other disciplines on the methods and tools used to teach chemistry.

IMPACTS OF COGNITIVE PSYCHOLOGY ON CHEMICAL EDUCATION

An increased awareness of the findings of cognitive psychology, and advances in neurosciences, have in recent years had an influence on chemical educators' views of how learning occurs and how best to present materials to students. While these influences are not widespread among academic chemists, they have begun to have significant impact on the teaching of chemistry in many leading institutions in the United States.

Many advances in cognitive sciences and in the neurosciences have informed our understanding of how students learn, and under what conditions they can learn best. One finding that is strongly supported by the results of basic biological studies with animals is that early learning is very important. The implications of these findings for our educational systems, and particularly for the fates of those disadvantaged persons who do not receive intellectual stimulation early in life, are immense.

The influence of B. F. Skinner's views of behavioral psychology held sway for many years in determining the approaches to studies of how students learn, and what they learn. On the other hand, in more recent years the role of conceptual understanding, derived in part from the thinking of Piaget,6 have held sway. Today, cognitive pyschologists focus on the central role of how students construct conceptual frameworks consisting of ideas of how the world works, and use these meanings to interpret the observable world[7-9]. When a student displays an inability to solve certain types of problems, it is nearly always the case that he or she is operating from a conceptually flawed mental representation. In this view of how a student learns, it is important that the student be guided to "seek explicit conceptual linkages between relevant knowledge that he/she already has and new knowledge being presented."9 Rote memorization of definitions and of algorithmic procedures for solving numerical problems do not represent meaningful learning when a fundamental understanding of the underlying concepts is lacking.

ALTERNATIVE FORMATS FOR THE INTRODUCTORY CHEMISTRY COURSE

The results from cognitive psychology and experiments with alternative learning formats present opportunities to develop new approaches to introductory chemistry courses that emphasis conceptual understanding, and which are based on course content that is broadly interdisciplinary. In such courses there is more time to concentrate on conceptual understandings, as opposed to development of algorithmic problem-solving skills. The "studio" format described above is one of the new approaches to large enrollment introductory courses that is currently receiving attention.

An approach that permits the natural presentation of chemistry in terms of interdisciplinary materials is the applications-oriented or topics-oriented format. In this formulation of the introductory course the lecture format may or may not be retained; the major innovation is to organize the course content around topics rather than a seriatim approach to principles and traditional descriptive materials. The list of topics must be carefully chosen so that in discussing them the student is exposed to the essential principles and descriptive materials. A topics list might, for example, include stratospheric ozone; acid rain; sources of energy; physical properties of familiar plastics; applications for batteries, including electric vehicles and heart pacemakers; variation in PCB's in the Great Lakes over the past 20 years.

As each topic is presented and analyzed, the underlying principles necessary for its understanding are uncovered and discussed. For example, discussion of stratospheric ozone, and depletion of the ozone layer might proceed as follows: After painting a broad-brush picture of earth's atmosphere and the place of stratospheric ozone in it, the properties of gases (compressibility, diffusion, kinetic energy), the impact of solar radiation on atmospheric constituents, gas kinetic theory of reactions, the concept of catalysis and other principles necessary to having a clear understanding of the system are brought into the discussion as needed. The properties of the atmosphere, such as the distinction between troposphere and stratosphere, would need to be explained. Photochemical principles would need to be discussed. (It is worth noting that very little photochemistry is discussed in the traditional introductory chemistry course, despite the enormous importance of photochemical processes.) Concepts are employed as tools for understanding a discrete physical system with observable but complex properties, and not learned simply for their own sake. As the course progresses, a particular concept may be brought into the discussion in several lights, thus enriching the student's understanding of it.

The topics-oriented course is not an easy one to teach. No textbook exists to serve up the factual descriptive materials on the various topics. Rather, the text serves as the reference source for the student in learning the principles, to be dipped into as needed rather than read seriatim. The teacher's primary role is to guide the student's learning, but providing the raw materials regarding the topics to be covered, and guiding the analysis of the complex system in terms of the underlying principles. One of the most challenging aspects of the topics-oriented course is to properly test the students' command of the materials. The type of concept mastery sought, as opposed to rote memorization of facts and problem-solving procedures, does not lend itself well to the multiple-choice testing so common in large enrollment courses. Rather, analytic discussion of a posed problem, with an essay-type response, is more appropriate. The use of computer-based testing offers the possibility of posing a complex problem, then allowing the student to respond to various questions about it, some of them possibly requiring numerical analysis.

APPLICATIONS OF COMPUTER TECHNOLOGIES IN CHEMICAL EDUCATION

As indicated in the Introduction, chemical education can be interdisciplinary not only in terms of course content, but also in terms of the methods and tools borrowed from other disciplines as aids in teaching. Most important among these are computer-based tools. Table 2 lists many of the ways in which computing and computer-related tools are involved in modern chemical education.

***Table 2.** Applications of Computers and Computer-based Tools in Chemical Education.*

- Computer-aided Instruction
  - Reinforcement of lecture materials
  - Pre-laboratory exercises
  - Replacement for laboratory experiments
  - Reference materials
  - Drill work with problem-solving
  - Testing of conceptual mastery
- Computer Aids for Lecture
  - Slide sequences, chemical art
  - CD-ROM sources of figures, video sequences
- Laboratory-based Computing
  - instrument control
  - data acquistion
  - data analysis
- Molecular Modeling
  - molecular mechanics-based programs
  - spatial aspects of molecular structure, isomerism
- Productivity Tools
  - word processing
  - analysis and graphing
  - statistics
  - symbolic mathematics
  - electronic mail, bulletin boards
- Literature Searching
  - on-line searching of chemical literature
  - CD-ROM based bibliographic materials

All of these various applications of computing to chemical education, which extend from the most elementary courses to the advanced, are becoming of increasing importance. Computers are increasingly available to students, either because they can afford to have their own, or because they are available through the institution. Collectively, computer-based tools have the effect of promoting cooperative learning among students, more independently of the instructor than in the past.

INTERDISCIPLINARITY IN GRADUATE CHEMICAL EDUCATION

Our discussion of interdisciplinary in chemical education would not be complete without some consideration of what is happening at the graduate level. It goes without saying that tools and technics developed in other fields are freely borrowed in chemical research as rapidly as the opportunities for their exploitation become evident. Thus, the most advanced lasers, synchrotron light sources, ultra high vacuum techniques for the study of surfaces, advanced workstations and new computational software have been incorporated into many chemical research laboratories.

The problem areas chosen for study by chemists have also become much more manifestly interdisciplinary in recent years. For a long time interdisciplinary research and scholarship was regarded with general suspicion, on the grounds that it lacked the rigor and standards that the discipline itself required of its practitioners. That suspicion was itself often grounded in a lack of appreciation of the aims of the interdisciplinary work, and an inability to evaluate its significance. In fields such as chemistry, in which individual faculty members traditionally maintain independent research programs, and are held accountable for the originality and significance of their research achievements, the multi-investigator mode characteristic of interdisciplinary work was often at odds with the prevailing norms. Further, it must be admitted that some interdisciplinary initiatives in the past failed to adhere to high standards of scholarship, and lacked an appropriate focus.

In recent years in the United States, the move toward a greater level of interdisciplinary activity has been generated by the federal government's policies of research support, in which larger scale, multi-investigator programs have increased in importance. The National Science Foundation has a program of Science and Technology Centers and Engineering Research Centers, funded at multi-million dollar levels over periods of from 5 to 10 years. In such centers, collaborative research in support of larger research goals is expected. Such Centers have been established in areas such as superconductivity, microelectronics, polymers, nanolithography, DNA sequencing and many others. Large scale centralized facilities also promote interdisciplinary organization. For example, the Advanced Photon Source at Argonne National Laboratory, which will become operational later in this decade, has prompted many interdisciplinary initiatives to secure the necessary resources to gain access to one of the beam lines.

Research facilities with accompanying organizational structure that have been designed to promote broadly-based interdisciplinary research have not yet appeared in large numbers, but notable examples exist. The Beckman Institute for Advanced Science and Technology at the University of Illinois, Urbana-Champaign is a noteworthy example. It is the largest and most broadly based interdisciplinary organization existing within a university setting anywhere. The building has about 34,000 m^2 gross area, and supports a total of more than 700 personnel. The Beckman Institute was made possible by a generous grant from Arnold and Mabel Beckman, and through funds provided by the state of Illinois. It is highly interdisciplinary,

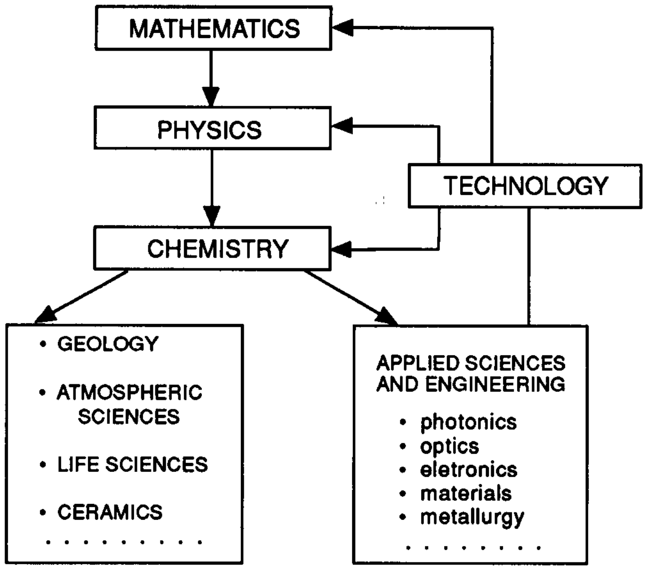

***Figure 1.** Relationship of Chemistry to other science and engineering disciplines.*

embracing physics, chemistry, the life and behavioral sciences and engineering. Its mission, broadly speaking, is the study of "intelligent systems", whether these be naturally occuring or artificial, living or man-made, from the molecular level to that of entire organisms or systems. Chemistry faculty are well-represented in the Institute, but no one discipline has a commanding share of the personnel or space.

The Beckman Institute is an integral part of the University of Illinois. The faculty who have appointments there all have their primary appointments in departments of the University, and continue to maintain teaching and other obligations in those departments. The faculty have all or some part of their research programs in the Institute. They receive various kinds of basic infrastructure support from the Institute, but must rely on obtaining outside funding for their research, just as in departments.

The faculty in the Institute are organized into several research groups, each of which may be highly interdisciplinary in itself.The broad range of research interests in the Institute is clear from the listing of the various research groups shown in Table 3. The Institute is organized to encourage interdisciplinary interactions between faculty members, graduate students and postdoctoral personnel. For example, a special competition is offered each year to provide support for graduate students who formulate a proposed Ph.D. thesis project that involves the active participation of two faculty mentors from different groups.

An organization such as the Beckman Institute offers faculty,

***Table 3.** Interdisciplinary Research Groups in the Beckman Institute.*

Cognitive Science
Neurobiology
Biophysical Systems
Advanced Chemical Systems
Biomolecular Electronics
Submicron Structures
Field-Responsive Polymers
Complex Systems
Image Formation and Analysis
Advanced Devices and Circuits
Computational Electronics
VLSI Theory and Design
STM; nanolithography
photonic systems
Artificial Intelligence

postdoctoral and graduate students an opportunity to work closely with colleagues from other departments. The limitations of physical separation are overcome, but more importantly, the atmosphere is one that encourages and rewards cross-departmental and cross-collegial interactions. The success of the Beckman Institute depends critically on its acceptance by the disciplinary departments and colleges. Fortunately, to date the Institute has enjoyed very productive and mutually beneficial relations. The Beckman Institute represents one direction that may signal the wave of the future for promoting interdisciplinary research and scholarship. It remains to be determined how the movement toward a more strongly interdisciplinary stance in both teaching and research will affect the organization and culture of the research university.

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