# Equilibrium as a Conceptual Framework for an Integrated, Synergistic Introductory Course in Chemistry and Physics

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**Abstract**

Teachers of introductory chemistry face the reality of outdated curricula and decreased student interest. The retention rates of students in the sciences remain troubling and the need to revisit course content and teaching methods has become increasingly apparent. A more general course framework developed on the principles of scientific teaching and active learning with relevant examples will perhaps allow students to embrace both chemistry and physics as relevant and inextricably linked disciplines. The present article proposes an integrated curriculum of chemistry and physics at the introductory level, based on the overarching conceptual framework of equilibrium with a focus on energy, topics of high relevance usually addressed in a more advanced course.

**Introduction**

The advent of scientific teaching[1] has raised important questions related to the way people learn and how best to provide training to our students for an uncertain future.[2] A deeply inspirational article from Whitesides *et al.* (2011)[3] calls for a change in chemistry coursework "to include the hard parts" (the role of solvent in chemistry, the importance of thermodynamics in biochemistry, the centrality of mathematics to the study of networks, the subtlety of catalysis and systems of coupled catalysts), as well as 'non-science' subjects — especially economics and corporate finance and manufacturing — useful in generating practical technologies. However, teachers of chemistry may not be qualified or willing to speak on these topics. Given this real challenge, how does one meet the task of a widespread need for interdisciplinarity? We need to find the common ground and teachers must be willing to blur the lines of their professional identity.

One of the central tenets of scientific teaching[1] is structure. A teacher must set clear learning goals and have clear learning objectives. Choosing an adequate interdisciplinary learning goal for the course is a possible solution to the problem. Corresponding assessments would also be required for this approach to succeed.

Combining physics and chemistry at the intro level, but not only, has several advantages, namely that the concepts reinforce each other and students get more interested. Equilibrium would make a good conceptual framework for teaching such an integrated course. Equilibrium lets us talk about all of forms energy and their transfer from one form to another, as a deviation from an equilibrium state. We believe a deeper student understanding will arise from  a multidisciplinary approach addressing these problems.

Against the backdrop of an uncertain energy future,[4-6] the increased collaboration in multi-disciplinary energy research has become a reality. As such, non-traditional, energy-focused careers for traditionally trained chemists are emerging. Consequently, the current monochromatic view of introductory chemistry training is likely insufficient to recruit and *retain* the scientists of tomorrow, for example in the emerging area of alternative energy. Current introductory chemistry courses cover few energy-related topics at a fundamental level and provide little context for energy problems. These concepts should ideally emerge at an early enough stage to entice and create interest in energy related careers. However, such energy topics cannot be covered without the adequate introductory training in physics.  Recent advances in the fields of green and sustainable chemical transformations for energy applications underscore the issue of relevant formal training in both chemistry and physics at all levels of instruction. In the vein of sustainability-driven education, Scott Cummings[7] from Kenyon College, Ohio has recently put forth a description of a course geared towards instruction in solar energy.

The area of physical chemistry and chemical physics is very well developed in both coursework and at a research level. Courses like chemical kinetics and quantum chemistry are usually requirements for an undergraduate curriculum in chemistry. Although covered in introductory chemistry classes, in-depth courses in these topics are geared toward the self-selecting group of students who have already decided to pursue science as their career option.

The goal of this work is to propose a conceptual framework that would allow for a deep understanding of equilibrium concepts in physics *and* chemistry and relate them with energy transfer at a fundamental level.

*How* we teach is a second facet of the problem. Oftentimes, a starting assistant professor assigned to teach a course has not received any formal pedagogical training, and with limited teaching experience, struggles to find his or her own teaching momentum. Active-learning, as a tool of scientific teaching, has been shown to have a positive effect on long-term retention.[8] Deeply rooted in cognitive science, aspects of efficient pedagogical instruction like group work to address diversity, activities like flipped classrooms, concept mapping, think-pair-share, student dyads and so forth have been increasingly embraced by the modern chemistry classroom. The changes are now propagating.[1,9,10]

**The Case for Physics and Chemistry in an Integrated Course: Historical Context**

In 1977, Kuhn[11] described the philosophy and evolution of disciplines from the general integrated natural sciences into specific scientific domains with distinct and, at times, disjointed conceptual frameworks. Almost 30 years before, a report from the New England Association of Teachers[12] highlighted in J. Chem. Educ. by J. Hoag asks the question whether chemistry should come before or after physics and whether the areas of overlap could lead to an integrated curriculum. This hypothesis was associated with a comprehensive list of areas of overlap and comments regarding the teaching of specific topics. For example, the Hoag writes, “in the section about electricity […] the student, whether taking chemistry or physics, needs not only know the definitions of Ampere, Volt, Ohm, Watt and Joule, but needs considerable practice in the use of these electrical quantities.” The author thus makes the case for teaching physics and ends the commentary with the question, “Why not let the physicists teach their own subject matter first?”

The concept of teaching chemistry and physics as an integrated introductory course is not new and has been a topic of interest for several decades of education research.[13-15] How to achieve integration has been extensively discussed. An adequate curriculum overlap between the two disciplines is desired, [16] but, at a fundamental level, an adequate framework upon which to develop these overlapping topics is still missing.

Taber[17] specifically takes the view that in the context of current technological advancements and training of upcoming professionals, chemistry and physics are not necessarily distinct disciplines and as such, synergistic formal training would be useful. Aikenhead[18] however, points out an obstacle arising from an integrated curriculum: the professional identity of the teacher and departmental affiliation. As noted before, he makes the point that as chemists, we are expected to teach "chemistry" and as a consequence, material pertaining to a physics curriculum requires the chemist to blur the lines of an apparently immutable professional identity and to overcome the obstacle of different conceptual frameworks. The label of "chemistry" and the subsequent material to be covered is a difficult obstacle to overcome.

In a commentary related to efforts in the US in the 1970s towards curriculum integration,[18] it was pointed out that "integration for the sake of integration itself is a futile innovation. It tends to be artificial, arbitrary, idiosyncratic, highly abstract, and therefore, not relevant for most pupils." It is thus necessary to have a specific goal in mind and has to be relevant to the student's life.

Making the case for interdisciplinarity in a science curriculum, Taber[17] addresses the "*re*-production of culture (be that science or any other aspect)" as a factor in decrease in creativity. This raises the issue of a necessary joint and novel conceptual framework. In recent years, the interfaces of physics/biology and chemistry/ biology have given rise to new fields of scientific interest and, as such, courses addressing these fields have emerged.

**Equilibrium as a Conceptual Framework for Chemistry and Physics**

Toomey and Garofalo[19] provide their readers with a refined sequence of units in a fully integrated chemistry and physics course employing energy-related concepts as a guiding principle. They comment on successful removal of course content in favor of a deeper understanding, rather than pulling the equations "out of the hat". They also report that doing qualitative presentations before quantitative presentations leads to better student performance.

As students, the concept of equilibrium is usually perceived loosely in distinct chemistry and physics courses only at a rather advanced level and is especially emphasized in heavily-theoretical statistical mechanics courses. Although the sequence of material was new in the work of Toomey and Garofalo,[19] the disjoined conceptual framework of the two disciplines was still maintained. The purpose of this article is to propose equilibrium as a synergistic Physical and Chemical conceptual framework to overcome interdisciplinary barriers. Rather than covering a traditional sequence of materials, a scientific learning-based approach is desirable, with emphasis on the overall learning goal of conveying methods of understanding and analyzing energy transfers as systems achieving an equilibrium condition. In response to the thoughts of Hoag on whether chemistry or physics should come first,[12] we suggest the concepts could be presented at the same time.

This framework is amenable to all equilibrium types such as: mechanical, thermal, chemical, radiative, and acoustic equilibrium and their underlying basic scientific concepts. Table 1 summarizes the learning goals and possible topics to be addressed in the proposed synergistic course. We provide a large list of topics, which can then be downsized to a smaller list, once specific learning goals are set.

For each of the units, the summative assessment would be provided in full prior to the introduction of the unit. This way, as the student becomes comfortable with the material presented, he or she can then build on the conceptual framework necessary to reach the clearly stated learning goals.

In the proposed course, after the introduction of mechanical equilibrium and kinetic and potential energy, these concepts can be developed across the further units. The unit on electromagnetism further introduces the concept of point charge and potential by presenting the equilibrium conditions and deviations from it. The notion of charge and electrostatic equilibrium is then built upon in the introduction of atomic particles and molecules. The students can then be guided to relate the topics with a discussion of chemical transformations vs. physical transformations.

After covering the balancing of chemical reactions and chemical equilibrium, the notion of redox-balancing and redox-equilibrium can follow. At this point, the introduction of chemical potential, the electrochemical series and relation with Gibbs free energy transformation can be made. The following unit of thermodynamics can tie in with the previous unit by introducing thermodynamic balancing of chemical reactions, equilibrium concepts like enthalpy, entropy and free energy and non-equilibrium concepts like pV work. The material then progresses to approach radiative equilibrium with an introduction to radiation. Optics can then be described. The students can then tie these concepts in with the redox chemistry discussion from unit 3 and the discussion of interaction of molecules with radiation directly focusing in topics of photochemistry and spectroscopy. Acoustic equilibrium will then revisit the concept of a wave and develop on the elasticity concepts of Unit 1 (Table 1) while tying in the concept of elastic potential energy, sound and seismology.

Even at the introductory level, topics related to interactions of different types of energy and chemical processes can be developed at each step to describe more advanced topics such as: mechanochemistry (chemical reactions caused by input of mechanical energy), magnetochemistry (the basics of analytical methods of probing of equilibrium electronic and nuclear states of atoms and molecules), and electrochemistry (analytical methods and chemical reactions caused by input of electricity). For the unit on thermodynamics an extension to a discussion of Transition State Theory would deepen the understanding of the topics.[20] The study of radiative equilibrium, an introduction to photochemistry, microwave reactions, solar cell structure, function and limitations, and introduction to heat transfer can be tied in with the unit on thermodynamics. Lastly, the unit on acoustics can be accompanied by aspects of sound wave-triggered chemical reactions.

Such a course will make use of a series of refined teaching tools developed through Physics Education Research (PER) which can be used to refine our understanding of chemical processes.[21] An example of such a tool is the University of Colorado Boulder “phet” series of inquiry-based learning experiences.[22] Recently, the simulations are also covering topics related to chemistry, including atomic structure, molecular structure, acid/base solutions, atomic interactions, and balancing chemical equations.

To illustrate the structure of one of the teaching units, we describe a possible lesson plan for Unit 3, which revolves around the summative assessment and gaining the necessary knowledge to be able to provide a solution for it. (*See the Supporting Information for specific details*) The students will be presented with a situation in which they are stranded on Venus, where their water reserves are held at 80°C. They have to use their basic knowledge of how electrochemical cells work to devise a plan to return home. They are provided with a series of available elements and the necessary voltage for the spaceship to take off. The students need to use their knowledge of the Nernst Equation and the electrochemical series, as well as Kirchoff’s laws to answer the questions, thus achieving a better understanding of the application of both chemical and physical concepts.

We propose a series of group-based summative assessments for the rest of the units as well. For Unit 1, the summative assessment will consist of a group-based project describing the physical properties of Lagrange points and explicit description of the equilibrium condition. Summative assessment for Unit 2 will rely on an interactive phet.colorado.edu project, asking the student to independently explore circuits in series and parallel using the online construction kit and report on the findings. An example summative assessment for Unit 4 (thermodynamics) will rely on a group project with the goal of comparing similarities and differences between a hydrogen fuel cell from a standard internal combustion engine from a chemical reactions perspective, as well as energy efficiencies and environmental and technological limitations. In the same vein, a research project on fuel octane ratings will allow the student to discover the chemical basis of gasoline quality rating. Similarly, for the unit of radiative equilibrium, two summative assessment group projects are proposed. One deals with energy conservation and asks the students to read a popular science article and discuss whether they think the universe is "leaking" energy. Moreover, a second project will ask them to explain errors in temperature measurements by relating such measurements and their errors with radiative heat transfer. The unit on acoustic equilibrium will again have a two-project summative assessment. The students will be asked to discuss how earthquakes work and to research the nature of musical notes.

Heeding the challenge that Whitesides *et al.*[3] put forth, equilibrium was chosen because it covers a broad spectrum of STEM disciplines. If the topic of the current course were not restricted to chemistry and physics, the conceptual framework of equilibrium could be tied in with chemical biology concepts like the equilibrium of unfolding proteins or RNA,[23] and could be used to describe stagnant population growth as genetic equilibrium (heavily reliant on statistics),[24] and even homeostasis[25] (an organism's ability to maintain a stable internal environment) to name two examples.

Outside of the traditional boundaries of natural science curricular areas, a Nobel Prize for Economics was awarded to Prof. John C. Harsanyi (Berkeley), Dr. John F. Nash Jr. (Princeton) and Prof. Dr. Reinhard Selten (Rheinische Friedrich-Wilhelms-Universität) in 1994 for their groundbreaking analysis of Economic Equilibrium derived from mathematical models of strategic interactions developed by the field of Game Theory. As such, in a distant future, an equilibrium course can perhaps even be related to economics in an integrated fashion, no longer restricted to the disciplinal boundaries.

## Conclusion

This article provides a launching platform for further discussions and ideas in the development of a synergistic physics and chemistry course to allow us to "Get practical"[3] and engage more students in science learning by providing a broader perspective. The modern ideas to address the *how and what to teach* aspect of the problem are becoming more and more available and one can only look forward to an "exciting yet uncertain future."[2]

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**Table 1.** Topics and learning goals amenable to a fully integrated chemistry/physics course framed around equilibrium.

| | *Type of Equilibrium* | *Learning Goal: Equilibrium Condition* | *Basic Topics* | *Energy Concepts* | *Summative Assessment* | *Advanced Chemistry Applications* |
|---|---|---|---|---|---|---|
| **1** | **Mechanical** | $\sum_{all}\vec{F}=0^{a}$ | **Force, Velocity, Speed, Momentum, Conservational Laws, Collisions, Elasticity, Hooke's Law, Law of Universal Attraction, Orbits, Centrifugal, Centripetal Forces** | **Kinetic and Potential Energy** | **Determination of an Optimal Location For of a Space Station: Lagrange Points Project** | **Mechanochemistry** |
| **2** | **Electromagnetic** | ***No motion of charge in a conductor*** <br> ***Earnshaw's [b] theorem*** | **Point Charge, Field, Gauss's Law, Current, Potential, Resistance, Capacitance, Dielectrics, Power, Ohm's Law, Kirchoff's Law (DC Circuits), Magnetic Field, Magnetic Forces, Inductance, Alternating Current, Electromagnetic Waves, Electromagnetic Spectrum** | **Electrostatic Potential Energy** | **"Phet" based project** | **Magnetochemistry** <br> **Spectroscopy** |
| **3** | **Chemical** | $k_f / k_b = 1^{c}$ | **Chemical Composition of Matter, Atomic Particles, Atoms, Molecules, Periodic Table, Moles, Concentration, Inter and Intramolecular Forces (Bonding), Chemical Equations, Equilibrium Constants, pH scale, Redox Equilibrium, Intro to Free Energy, Nernst Equation, Electrochemical Series, Galvanic and Electrolysis Cells, Electromotive Force, Fuel Cells** | **Chemical Potential Energy** | **Electrochemical solution to being stranded in outer space[d]** | **Electrochemical Devices (Fuel Cells and Batteries): Types and Practical Limitations** |
| **4** | **Thermodynamic** | *Min ΔG, max S [e]* | **State Functions, Ideal Gas Law, Energy, Work, Heat, Heats of Formation, Heats of Chemical Reactions, Le Chatelier's Principle, Hess's Law, Combustion, Entropy, Gibbs Free Energy, Temperature, Spontaneity of a Chemical Process, Phase Equilibrium** | **Heat, Work, Chemical Potential Energy Revisited** | **Fuel cell vs. engine,** <br> **Fuel Octane Rating Project** | **Determination of Bond Energies, Calorimetry, Transition State Theory** |
| **5** | **Radiative** | $\Delta H = 0^{f}$ | **Wave- Particle Duality, Black Body Radiation, Optics, Interference, Diffraction, Specific Radiative Intensity, Stokes-Helmholtz Reciprocity Principle, Kirchhoff's Law of Thermal Radiation, Intro to Heat Transfer** | **Solar Energy, Heat** | **Is the Universe Leaking Energy? Discussion of red-shift[26]** <br> **Temperature Measurement Errors Project: Radiative Heat Transfer Project** | **Photochemistry** <br> **Solar Cells: Types and Design Limitations** <br> **Microwave Chemistry** <br> **Spectroscopy Revisited** |
| **6** | **Acoustic** | $PdV = 0^{g}$ | **Sound Pressure, pV Work, Velocity, Rarefraction/Comprression, Hooke's Law revisited, Acoustic Wave Equation, Propagation, Snell's Law, Coupled Oscillators, Resonance, Cavitation, Natural Frequencies, Timbre, Human Frequency Range, Seismology** | **Elastic Potential Energy** | **Earthquake Energy Project** <br> **Musical Notes Project** | **Sonochemistry** |

*a.* Sum of all acting forces acting on a system at equilibrium is null. *b.* Stable stationary equilibrium is not possible for a collection of point charges with only an external applied electric field. *c*. At chemical equilibrium, the rate of a forward chemical reaction equals the reverse. *d.* Teaching material in the supporting information e. For a system in thermodynamic equilibrium, the Gibbs free energy change of the system (ΔG) is minimized, whereas the Entropy is maximized (S). *f.* Radiative exchange equilibrium "any two bodies or elements of bodies selected at random exchange by radiation equal amounts of heat with each other."[27] *g.* Elastic potential energy is stored in a cube of acoustic material at equilibrium.[28]

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