RESEARCH CORPORATION FOR SCIENCE ADVANCEMENT
Cottrell Scholar Award Application
EDUCATIONAL PROPOSAL

Thermodynamics for the 21st Century: Timely Upgrade of a 19th Century Model

Motivation: A rift has opened between undergraduate chemical thermodynamics and contemporary challenges in chemistry. The current presentation of undergraduate thermodynamics had matured at the turn of the 20th century and pedagogy is geared towards the challenges of the 19th century. That is why undergraduate thermodynamics books are replete with heat engines, pistons, cylinders, and gas laws as means of explanation. Unfortunately, this leads many students, and even professionals, to think of thermodynamics as irrelevant to the modern age. “Physical chemistry is about studying viscosity of gases.” “We do not study thermodynamics. We do nanotechnology.” These are two anecdotes from a chemistry graduate, and a professor at a high-caliber research university respectively. I argue that in the age of nanotechnology, thermodynamics is even more relevant than before.

The difficulty of teaching thermodynamics is very well known, as is evident by a continuous stream of research in chemical education[1-4]. A particular line of debate is in the two approaches of teaching the subject, the classical and the statistical mechanics approach. I argue for a balance between the two lines, where classical concepts are bolstered by statistical arguments. Regardless of which line of reasoning the central ideas of thermodynamics is built on, student interest on a large scale is often not engaged unless **connections to practical and modern day challenges** are made. From my personal experience in teaching the subject, in a large class of 60-80 students there are at most 5-6 students who are impressed by the pure theoretical elegance of the subject. That is despite my best efforts in emphasizing the theoretical structure from several angles with ample historical reference to the 19th century architects of thermodynamics. The majority often ask, either openly or in their mind, **“why are we learning this?”** They often have aspirations in synthetic chemistry, materials sciences, engineering, biology, or medicine. It is increasingly important to emphasize that thermodynamics is not merely a rite of passage to a degree, but a practically useful set of tools serving a wide variety of sciences.

Proposed Work

The central goal of the proposed work is to provide pedagogical tools for thermodynamics with reference to systems that are more relevant to modern challenges without sacrificing the fundamentals of the subject. For example, an important contemporary challenge is solar light harvesting, which mirrors the 19th century technological problem of increasing the efficiency of the heat engines. Bringing this problem to the center-stage will make learning relevant for a wider audience. The proposed work has two components, **insertable modules** and **collaborative concept maps** that are described in detail below.

Insertable Modules

Chemical education research has shown the effectiveness of contextualization of concepts[2], where the relevance of the concepts to tangible problems are brought to light. Classical thermodynamics, which is often considered an unpalatable[3] and dry subject, can greatly benefit from this contextualization. Towards this goal, the proposal aims to introduce **“bite-size” small modules** that could be inserted within a regular thermodynamics syllabus to make the material relevant to modern challenges and more exciting to the students (figure 6). Each module will be a set of resource files that will be made publicly available on a website for use by educators and students alike. The proposed approach has the following advantages:

- It is not an imposing and demanding overhaul of the current syllabi used by educators. They are relatively small, modular modifications of an already existing syllabus. Thus they are **likely to be accepted and adapted** by a wide range of educators.
- They provide context for the otherwise abstract concepts. An earnest attempt will be made to highlight the technological, economical, and environmental relevance of the concepts.
- The work of producing the modules is **not burdened on one person or one group**. The modules will be shared on a website managed by the PI and will accept contributions from registered users. The contributed modules will be subject to scrutiny prior to posting. Users will be able to provide feedback and share their experiences of using it.

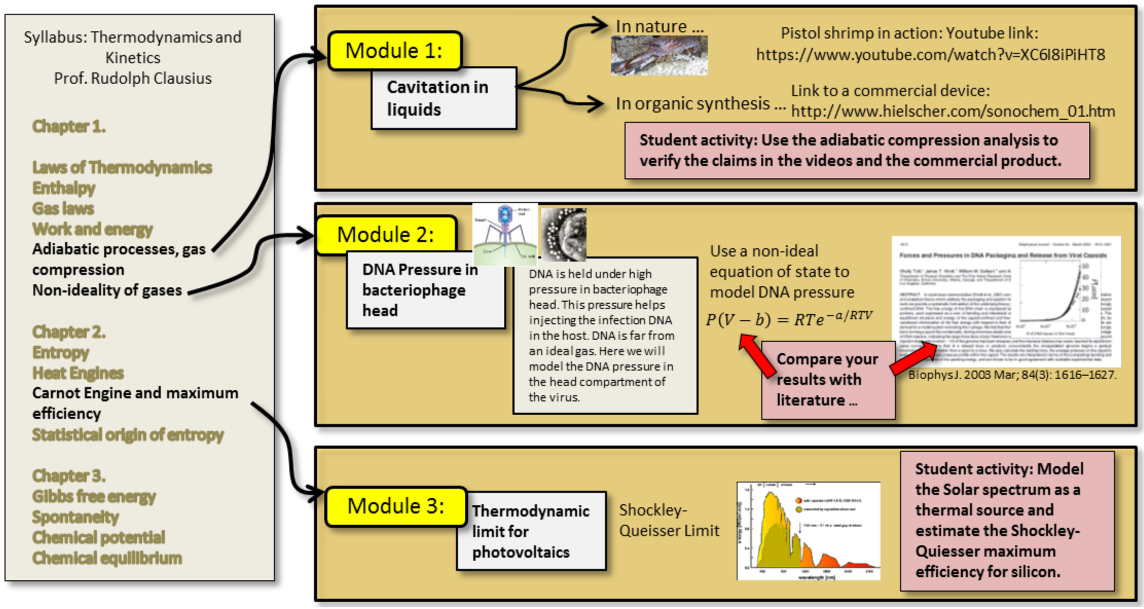


Figure 6. Diagram showing representative features of a few insertable modules and the place where they may be inserted in an existing syllabus. The modules will be made available for use by educators and students, and will contain student activities, pictures, external links, literature, and more.

Each module will be presented in the form of a **zip file** and will contain all or some of the following contents:

- A brief description of the topic and its relation to the main theme of the course.
- Manifestations of the concept in natural or artificial cases.
- Economic, environmental, or social significance of the phenomena, if applicable.
- Relating the phenomena to the material in the class and suggesting ways for calculating quantitative aspects of the phenomena.
- Scientific literature and/or link to literature.
- Pictures, and videos, and/or links to videos.
- Links to manifestation of the phenomena in commercial products.
- Student activities, using the models learned in the course, often in the form of estimating the validity of claims in the literature or commercial products, or other resources.
- Matlab or Mathematica programs to simulate the phenomena.

The users will be able to download the files, provide comments, critique, and feedback. Figure 6 lists only a few representative modules. Other potential modules to kick-start the project are as follows: storing wind power under the ocean, Stirling engine for solar energy harvesting, the Joule-Thomson effect and environmentally friendly refrigerants, harvesting energy from the junction of fresh water and sea water, surface adsorption and gas sensing, desalination of sea water for drinking, which are all relevant to modern challenges.

Collaborative Concept-to-Application Maps

The efficacy of concept maps in teaching chemistry is established through years of chemical education research[5]. Physical chemistry, in particular thermodynamics and kinetics, is often perceived as a collection of loosely held concepts and equations. Although the three laws seem to form a foundation for the subject, often tracking the origin of an observed phenomenon (for example boiling point elevation) to the three laws is unclear to the students. A little while into the course, students often find themselves dealing with several disparate and seemingly unconnected concepts. Concept maps are ideal solutions to this problem.

In this work, we extend the use of concept maps to organize not only the concepts, but also show the relation of concepts to applications. This will answer every student's persisting question of **"why are we learning this?"** A representative concept map is shown in figure 7. The concept maps will have the following features:

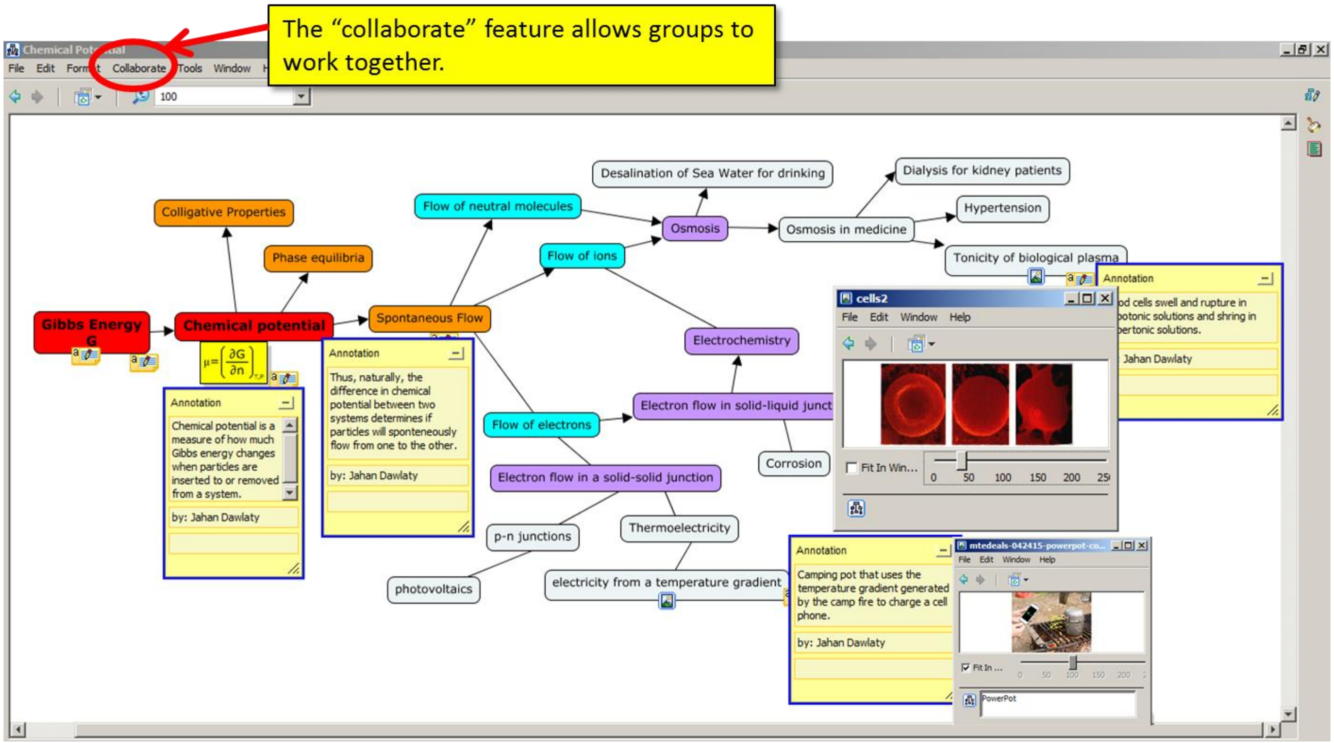


Figure 7. The interface of the freely available concept map software CMAP that will be used for the proposed work. The concepts maps can be developed and used both individually and as a group. Videos, pictures, annotations, and external links can be included. The map above highlights the phenomena that are derived from the concept of chemical potential, which is often found too abstract and uninteresting by students.

- The maps will be prepared using free concept map software. CMAP is an ideal free software option (http://cmap.ihmc.us/) and is already used for educational purposes. This **will not pose any financial burden** on educators and students.
- The software already allows collaborative projects, where several people can work on the same map (see figure 7). Thus a small group (e.g. a class) or a more expansive group (e.g. a group of educators in several institutes) can all work together to create and enhance concept maps.
- The map files will be disseminated through a website that is managed by the PI. The PI will contribute maps to the website, and just like the insertable modules project discussed above, registered users will also contribute their maps. Thus the work of preparing the content will be **shared within a community** of scholars and educators. I have already begun nucleating such a community from 5-6 personal contacts involved in teaching physical chemistry who are at a similar stage of career as me.
- The maps will support pictures, videos, external links, annotations, and equations. The map files can be exported in other forms for use with other teaching platforms.
- The maps will emphasize how an otherwise unappealing concept forms the foundation of practical applications and technologies. As an example, figure 7 shows how the concept of chemical potential is necessary to understand phenomena as varied as dialysis, and thermoelectricity. Of course, to make the connection clear, the links between concepts will be supported by annotations, equations, and external links.

Concept maps are not a replacement for lectures or textbooks. They are a supporting tool. While they encourage independent learning, their power is truly harnessed in the hands of an educator. They are intended to supplement lectures by the participating community.

Only a few publicly available CMAPs for thermodynamics exist. While they are a great start, they are often isolated, small-scale, not linked to applications, and prepared by a single individual. The proposed work is very distinct from these efforts, since it is focused on concept-to-application connections and intends to unleash the collective knowledge of a community of users.

ASSESSMENT PLAN:

There will be two layers of assessment to evaluate the efficacy of the proposed approaches.

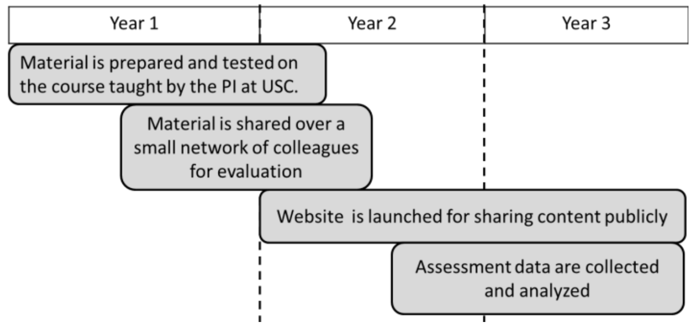


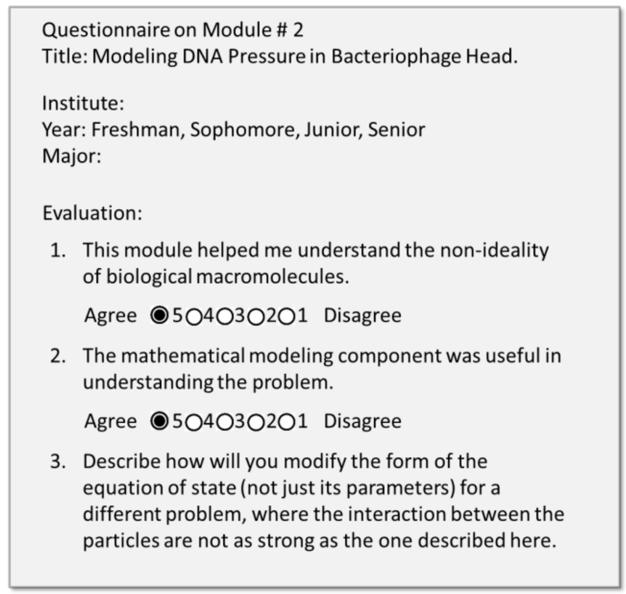
Figure 8. Timeline of activities in the proposed project.

<u>Indirect Assessment:</u> Since the material (both insertable modules and concept-to-application maps) will be made available publicly on a website, the following parameters can be directly tracked.

- Number of downloads of a given module.
- Comments from the users, including on their experiences on how the module or the concept map worked in their classrooms.
- A numerical score (1-5) given by the users to the module.

All of the above data evaluate of the material from the perspective of the educators. While it is correlated to student learning, it is not built on direct student responses.

<u>Direct Assessment:</u> To get the feedback of students, questionnaire forms (in the electronic format) will be made available either as part of the material (e.g. included as an extra file in the package) or as an online page. The students can fill in the forms tailored to each module. This will assess whether the module was successful or not. Students can comment separately on the scientific benefit of the module (whether it helped them learn), and the technical delivery (whether the material was organized and presented well). Furthermore, direct scientific questions will be included, to find out if the self-perception of learning correlates with the capability to extend and apply the material to new cases. An example of an evaluation form is shown in figure 9.


Questionnaire on Module # 2
Title: Modeling DNA Pressure in Bacteriophage Head.

Institute:
Year: Freshman, Sophomore, Junior, Senior
Major:

Evaluation:

1. This module helped me understand the non-ideality of biological macromolecules.

   Agree ◉5○4○3○2○1 Disagree

2. The mathematical modeling component was useful in understanding the problem.

   Agree ◉5○4○3○2○1 Disagree

3. Describe how will you modify the form of the equation of state (not just its parameters) for a different problem, where the interaction between the particles are not as strong as the one described here.

Figure 9. An example of an evaluation form with representative questions, in particular questions that contrast self -evaluation (question 1) with a more challenging extension of the concept (question 3) are emphasized.

Identify departmental or institutional colleagues who might play a role in this educational endeavor (as mentors, collaborators, etc.) as appropriate and describe the role they will play.

Prof. Stephen Bradforth:
In our department, Prof. Bradforth has pioneered the use of several forms of technology in teaching, including use of course websites, and clickers. He has provided advice on teaching, choosing class materials, and much more. He has taught thermodynamics and kinetics in the past and can provide essential scientific and technical advice. He is a previous Cottrell Scholar and my dedicated mentor both on research and teaching fronts.

Prof. Hanna Reisler:
Prof. Reisler has over 30 years of experience in teaching at USC. She has provided practical guidance to me in my first years at USC with teaching methods, grade distributions, dealing with special cases and exceptions, time management, and more. Since she has decades of experience, she has a good intuition for what works in a classroom and what does not. I will benefit from her experience and candid critique on this front.

Prof. Chi Mak:
Prof. Mak has taught thermodynamics and kinetics before. As a practitioner of statistical mechanics, he brings special insight into the materials. I have used his previous notes as a foundation to structure and formulate my course materials. I anticipate that he will critique my work from the scientific point of view.

Dr. Bruno Herreros:
Dr. Herreros is the director of instructional computing in our department. Although he will not prepare the material proposed in this work, the PI will benefit from his technical advice on preparing a system of managing and disseminating the material.

References for the Educational Proposal

1. T. M. Hamilton, Thermodynamics for Visual Learners, J. Chem. Educ., 80, 1425, (2003)
2. J. Holman et. al. Thermodynamics in Context: A Case Study of Contextualized Teaching for Undergraduates, J. Chem. Educ., 81, 373, (2004).
3. L. S. Bartell, Stories to Make Thermodynamics and Related Subjects More Palatable, J. Chem. Educ., 78, 1059 (2001)
4. T. J. Zielinski, et. al. Teaching Chemistry in the New Century: Physical Chemistry, J. Chem. Educ., 78, 1173 (2001)
5. B. L. Earl, Concept Maps for General Chemistry, J. Chem. Educ., 84, 1788 (2007)
6. J. S. Francisco, et. al. Assessing Student Understanding of General Chemistry with Concept Mapping, J. Chem. Educ., 79, 248 (2002).