A COURSE TO EXAMINE CONTEMPORARY THERMODYNAMICS*

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"OUR VISION OF nature is undergoing a radical change toward the multiple, the temporal, and the complex." These are the opening words of the preface to *Order Out of Chaos* by Ilya Prigogine and Isabelle Stengers [1]. Many instructors of engineering thermodynamics would probably agree that there is little evidence of anything "radical" going on in regards to the content of the typical undergraduate courses in thermodynamics. Engineers are taught basic thermodynamic principles with which they can eventually enter the world of industry and enjoy meaningful technical careers. These principles as presented in the various textbooks on the subject have undergone little change in the recent past. This in itself is not necessarily bad, for many have recognized that this thermodynamic "toolkit" with which we are equipping our students (or, as H. G. Jones calls them, "thermodynamic plumbers" [2]) is really a powerful collection of ideas and methodologies. Keeping within the narrow confines of chemical or mechanical engineering, students often fail to realize just how powerful their thermodynamic "toolkits" can be. For example, anyone who is aware of recent developments

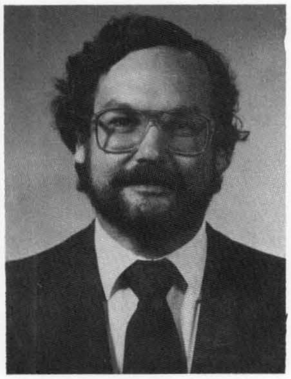

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TABLE 1
Course Outline

I. An introduction to philosophy of science
   - A. Logic, reasoning processes, and logical fallacies
   - B. Scientific method
     - Inductivism
     - Falsification
     - Other methods
   - C. Theories, hypotheses, *etc.*

II. Entropy and its many forms
   - A. The second law and its historical and scientific basis
   - B. Forms of entropy
     - "Steam engine" entropy
     - Statistical entropy
     - Informational (Shannon) entropy
     - Others (*e.g.*, "negentropy")
   - C. Irreversibility and its implications

III. Contemporary thermodynamic concepts and related topics
   - A. Time and time's arrows
   - B. "Brussels school" concepts and theories
   - C. Bifurcation and catastrophe theory
   - D. Cybernetics, synergetics, systems theory, and related theories
   - E. Fractals
   - F. Non-Western viewpoints

IV. Thermodynamic analysis in other disciplines
   - A. Biology
     - First law: Does it apply?
     - Second law: Does it apply?
   - B. Psychology, social sciences, *etc.*

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in the application of thermodynamic concepts knows that there have been many exciting developments in such diverse fields as psychiatry, biology, and social science. Thermodynamicists are providing new insights into these fields—fields which many scientists previously thought were not amenable to thermodynamic "intrusions." Most engineering students are unaware of this. They think thermodynamics is something confined to heat engines and not much more.

Even when the discussion is confined to more technical matters of physical science, students are often unaware of the recent advances in thermodynamics. Most of them leave with their Bachelor of Science degrees, never having heard of such things as "dissipative structures" and having received only limited exposure to the general field of irreversible thermodynamics. "Catastrophies" may be associated more with test performance rather than with a powerful analytical tool. In many ways, their knowledge of thermodynamics may be more reflective of the closed system close-to-equilibrium mentality of the past.

Finally, their understanding of very basic concepts such as entropy and the second law is often poor. As one person lamented, "One of the most highly developed skills in contemporary Western civilization is dissection: the split-up of problems into their smallest possible components . . . we often forget to put the pieces back together again" (A. Toffler in [1]). Indeed, many professors have noted that engineering students probably work harder than other students, but may not possess sufficient critical analytical skills or *philosophical* abilities. This is not all that surprising, given the pragmatic or empirical nature of engineering "science." We teach students how to work problems, often resorting to "black box" strategies, but rarely do they get to sit back and just "think," particularly in a more qualitative philosophical sense.

With these things in mind, we developed a course which would give students a chance to critically think about and otherwise analyze the contents of their thermodynamic "toolkits." In addition, the students would be exposed to recent developments in thermodynamics and related topics, including attempted applications to fields other than the physical sciences. Finally, students were exposed to the general field of philosophy of science in an attempt to stimulate further development of their critical skills.

COURSE OBJECTIVES AND OUTLINE

The course was organized to achieve four broad objectives:

- **To critically discuss and analyze fundamental thermodynamic concepts such as entropy**
- **To expose the student to contemporary thermodynamic concepts such as those put forth by the "Brussels group" and to related topics such as bifurcation theory**
- **To critically discuss attempted applications of the above objectives to other fields, particularly to the life sciences**
- **To introduce the student to the field of philosophy of science, including logic and scientific method.**

Table 1 presents the course outline. The course was run in a seminar fashion to encourage student discussions. During the first offering of the course, the books presented in Table 2 were utilized, and

TABLE 2
Books Utilized in the Course

Required Texts

- *Time's Arrows*, by R. Morris: Simon & Schuster, New York, 1985
- *Order Out of Chaos*, by I. Prigogine, I. Stengers; Bantam Books, Toronto, 1984
- *The Systems View of the World*, by E. Laszlo; George Braziller Inc., New York, 1972
- *An Introduction to Catastrophe Theory*, by P. T. Saunders; Cambridge University Press, New York, 1980

Referenced Texts *(Texts which were referred to repeatedly during the course.)*

- *The Tao of Physics*, by F. Capra; Shambhala, Berkeley, 1975
- *Entropy*, by J. D. Fast; Gordon & Breach, New York, 1968
- *Against Method*, by P. Feyerabend; Thetford Press Limited, Thetford, 1978
- *The Structure of Scientific Revolutions*, by T. S. Kuhn; University of Chicago Press, Chicago, 1970
- *Conjectures and Refutations: The Growth of Scientific Knowledge*, by K. R. Popper; Harper & Row Publishers, Inc., New York, 1965
- *Entropy: A New World View* , by J. Rifkin; Viking Press, New York, 1980
- *The Tragicomical History of Thermodynamics 1822-1854*, by C. Turesdell; Springer-Verlag, New York, 1980
- *Catastrophe Theory*, by A. Woodcock, M. Davis; E. P. Dutton, New York, 1978

numerous journal articles were discussed. A list of the more useful journal articles is presented in Table 3. While the course was basically run by myself, I found that the presentation of scientific method by an actual philosopher of science to be particularly effective.

The typical assignment was to read the assigned materials and be prepared to discuss them but there were also several assignments which required some library work. For example, students were instructed to find specific examples of the application of catastrophe theory and present them to the class. Overall grading was based on a consideration of in-class participation (reflecting preparation), the written assignments, and performance on a comprehensive final exam.

TABLE 3
Selected Journal Articles Utilized in the Course

- "Equilibrium, Entropy, and Homeostasis: A Multidisciplinary Legacy," by K. D. Baily; *Systems Res.* 1, 1984; 25-43
- "The Theory of Open Systems in Physics and Biology," by L. von Bertalanffy; *Science,* III, 1950; 23-29
- "Life, Thermodynamics, and Cybernetics," by L. Brillouin; *Am. Scientist,* 37, 1949; 554-568
- "Entropy and Disorder," by J. M. Burgers; *Brit. J. Phil. Sci.,* 5, 1954; 70-71
- "The Interdisciplinary Study of Time," by J. T. Fraser; *Ann. NY Acad. Sci.,* 138 (art. 2), 1967; 822-847
- "Entropic Models in Biology: The Next Scientific Revolution?" by D. P. Jones; *Persp. Biol. Med.,* 20, 1977; 285-299
- "Order and Irreversibility," by P. Kroes; *Nature and System,* 4, 1982; 115-129
- "Gibbs *vs.* Shannon Entropies," by R. L. Liboff; *J. Stat. Phys.,* 11, 1974; 343-357
- "Maxwell Demon and the Correspondence Between Information and Entropy," by R. P. Poplavskii; *Sov. Phys. Usp.,* 22, 1979; 371-380
- "Time's Arrow and Entropy," by K. Popper; *Nature,*207, 1965; 233-234
- "Can Thermodynamics Explain Biological Order?" by I Prigogine; *Impact Sci. Soc.,* 23, 1973; 151-179
- "Should Irreversible Thermodynamics be Applied to Metabolic Systems?" discussion forum; *Trends Biochem. Sci.,* 7, 1982; 275-279
- "Entropy, Not Negentropy," by J. A. Wilson; *Nature,* 219, 1968; 535-536

DISCUSSION

On the first day, I gave a simple quiz that consisted of two parts: 1) define the words *entropy, time, order,* and *stability;* 2) define *hypothesis, law,* and *theory,* and outline how you would prove a given hypothesis. The answers to the first part were rather poor. In fact, blanks appeared with an alarming frequency. Answers to the second part were typically inductive in nature—"go run experiments." Following the quiz, students readily admitted their personal embarrassment over their performances. But while a few egos may have been bruised, students for the most part had a clearer understanding of the importance of the class objectives. A point had been made.

Further in-class discussion on the nature of entropy revealed the usual associations with *order* and *chaos.* Others have written on this superficial understanding as expressed by "naive" students (for example, see [3]). All students challenged the idea that movement further and further away from equilibrium could possibly lead to the creation of stable structures. Again, it was clear that the students' basic understanding of the thermodynamic fundamentals was narrow and shallow.

The typical class consisted of some initial lecturing, usually outlining the basic ideas associated with the assigned readings and sometimes presenting historical perspectives. Most of the class time was devoted to free-style discussions. A key to this sort of format is to maintain several opinions for a while and not to converge on a "right" answer (if there even is one) too quickly. In fact, sometimes there may be several tenable explanations (for example, what is time?) and the students are left to make up their own minds.

I found it was a good strategy to present the philosophy of science topics first. It provided a framework for later critical discussions. Questions such as, "Is it a testable hypothesis?" or, "What logical fallacy is being committed?" could be posed more intelligently. The main scientific method lecture was presented by a philosopher of science. This proved to be a good move since it gave the students a chance to see that philosophers might actually have something of value to offer engineering students. Also, students found the discussion on various scientific methods (*e.g.,* inductivism, falsification, *etc.*) to be very stimulating.

I also tried to present conflicting views whenever appropriate. The article "Gibbs vs. Shannon Entropies" (see Table 3) is an example of this. The forum-style article "Should Irreversible Thermodynamics be Applied to Metabolic Systems?" (see Table 3) is another example. In general, a fair presentation of the strong points *and* the weak points of a given viewpoint should always be made.

The books *Time's Arrows* and *Order Out of Chaos* were excellent choices. I currently plan to use the book *What is This Thing Called Science* [4] as the third principle text the next time the course is offered. It is a good overview of recent topics in scientific method. However, there are probably other available books that could also serve this purpose. The remaining topics in Table 1 can be handled with lecture notes and relevant journal articles.

I judged this course to be effective based on several observations. First, the same quiz previously given on the first day was also given near the end of the class, and needless to say, the answers were much more satisfactory. In fact, students felt they did not have enough time to respond completely. Second, the students themselves seemed to feel more confident of their understanding of thermodynamics. While there may have been periods of confusion (probably a good sign) during the semester, students generally emerged on a firmer basis. Finally, several students stated that they planned to continue their self-education in the topics they were exposed to during the course.

ACKNOWLEDGEMENTS

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3. Johnstone, A. H., J. J. MacDonald, and G. Webb, "Misconceptions in School Thermodynamics," *Phys. Educ.*, **12** (4), 248-251, 1977
4. Chalmers, A. F., *What Is This Thing Called Science?*, University of Queensland Press, St. Lucia, Queensland, 1986 ❐

DISCUSSION: The reviewers of this paper presented some interesting comments of their own. We feel their views deserve consideration and present them here for our readers' information

Review #1:

Although I have serious reservations about the course described by Lee, I am not inclined to recommend rejection of his manuscript. Thus, while I may deplore his poor taste (...applications of thermodynamics to problems in psychiatry and social science? Why not throw in psychohistory and social Darwinism as well? and... [exposure to] philosophy of science in an attempt to stimulate...critical skills. He apparently has had much better experiences with philosophers of science than I), he has taught the course and so does have something to report.

If there is a single "fault" to the plan, it is Lee's strategy of bolstering students' admittedly inadequate understanding of a well-defined subject (thermodynamics) by exposing them to ideas about other topics, namely, the philosophy of science (a discipline that is itself disdained by many knowledgeable scientists and scientific historians for whom I have great respect), Prigogine's dissipative structures stuff, and the pseudo-scientific applications of thermodynamic terminology to psychiatry and social science. That last one really gets me. These are interesting items, perfectly suitable for dinner table conversation, but unlikely to advance the understanding of thermodynamics. Still, I doubt that it can hurt...and it is comforting to see that the "simple quiz"...doesn't include the Mumbo Jumbo. If the course enhances the students' understanding of these terms and concepts, then it probably is worthwhile. I would opt for more attention to these and less for the topics about which I already have vented my spleen. Finally, a course that attempts to cover so many complex topics surely must be superficial: how do students discuss whether irreversible thermodynamics should be applied to metabolic systems...without a thorough grounding in irreversible thermodynamics?

In summary, I recommend that the manuscript be published so that others can judge for themselves whether this or a related course should be included in their own curricula.

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Review #2:

I agree with the author that many undergraduates do not develop a good understanding of thermodynamics, especially of the Second Law. There are several reasons for this, including hasty exposure and emphasis on routine and mechanized problem solving, overloading with other courses, etc. The cure, in my opinion, is emphasis on critical understanding, more interesting problems and more substantial injection of statistical thermodynamics.

As for irreversible thermodynamics of the Prigogine fame, this reviewer believes that the subject is practically useless to chemical engineering. The only contribution that irreversible thermodynamics has made to our discipline stems from the Onsager relations which provide a framework for constitutive transport relations. Applications to social sciences or medicine are best tackled by more experienced workers and not by the undergraduates who struggle with basic physics and chemistry.

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