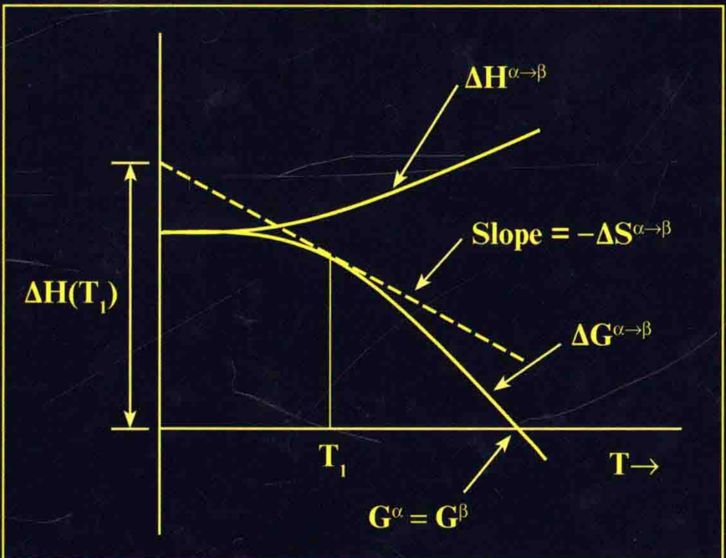
Introduction to the THERMODYNAMICS OF MATERIALS

SIXTH EDITION



David R. Gaskell
David E. Laughlin

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MATERIALS SCIENCE

Introduction to the THERMODYNAMICS OF MATERIALS

Maintaining the substance that made *Introduction to the Thermodynamic of Materials* a perennial best seller for decades, this Sixth Edition is updated to reflect the broadening field of materials science and engineering. The new edition is reorganized into three major sections to align the book for practical coursework, with the first (Thermodynamic Principles) and second (Phase Equilibria) sections aimed at use in a one semester undergraduate course. The third section (Reactions and Transformations) can be used in other courses of the curriculum that deal with oxidation, energy, and phase transformations. The book is updated to include the role of work terms other than PV work (e.g., magnetic work) along with their attendant aspects of entropy, Maxwell equations, and the role of such applied fields on phase diagrams. There is also an increased emphasis on the thermodynamics of phase transformations and the Sixth Edition features an entirely new chapter 15 that links specific thermodynamic applications to the study of phase transformations. The book also features more than 50 new end of chapter problems and more than 50 new figures.

- Features a new chapter on thermodynamics and phase transformations
- Reorganized into 3 major sections—Thermodynamic Principles, Phase Equilibria, and Reactions and Transformations of Phases in order to match the book to course curricula.
- Includes more than 50 new figures, more than 50 new end of chapter problems, and many short answers added to new problems at the end of the book.
- Includes in each chapter a new section titled "Concepts and Terms Introduced in This Chapter" following the summary section as well as a new sections called "Qualitative Example Problems" and "Quantitative Example Problems."
- Updated solutions manual available for qualifying adopting professors.
- Written as the definitive introduction to thermodynamic behavior of materials systems, it presents the underlying thermodynamic principles of materials and their plethora of applications.
- Offers excellent coverage of chemical thermodynamics.

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Introduction to the Thermodynamics of Materials

Sixth Edition

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The Laws of Thermodynamics

- **0th Law**
  Introduces the thermodynamic intensive variable of temperature ($\boldsymbol{T}$)
- **1st Law**
  Conservation and conversion of energy
  Defines extensive thermodynamic state variable of internal energy ($\boldsymbol{U}$)
  $d\boldsymbol{U} = \delta q - \delta w'$
- **2nd Law**
  Defines the extensive thermodynamic state variable of entropy ($\boldsymbol{S}$)
  $d\boldsymbol{S}_{universe} \geq 0$
- **3rd Law**
  For systems in internal equilibrium, sets the zero of entropy at the minimum in temperature (0K) and at the minimum in internal energy

The Three *TdS* Equations

$$TdS = c_v dT + \frac{T\alpha}{\beta_T} dV$$

$$TdS = c_p dT - TV\alpha dP$$

$$TdS = c_v \frac{\beta_T}{\alpha} dP + \frac{c_P}{\alpha V} dV$$

Fundamental Equations (extensive) for Magnetic Materials

$$dU' = TdS' - PdV' + V'\mu_0 \mathcal{H} dM + \Sigma\mu_i dn_i$$

$$dH' = TdS' + V'dP - V'\mu_0 M d\mathcal{H} + \Sigma\mu_i dn_i$$

$$dA' = -S'dT - PdV' + V'\mu_0 \mathcal{H} dM + \Sigma\mu_i dn_i$$

$$dG' = -S'dT + V'dP - V'\mu_0 M d\mathcal{H} + \Sigma\mu_i dn_i$$

Maxwell Relations for Single Component

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P$$

Introduction to the Thermodynamics of Materials

Sixth Edition

Dedication

Grandchildren are the crown of the aged.

(Proverbs 17:6)

Sadie, Gabe, Rowan, Sawyer, Ramona, Adam, Charlie, Astrid, and Reuben.

The LORD bless you … and may you (also) see your children's children.

(Psalm 128:5ff.)

Preface

In preparing this new edition, I have endeavored to retain the substance of the previous five editions while adding some flavors of my own. These additions are ones which reflect my research interests (in magnetism and phase transformations) and are also relevant to current materials science students. Additions to this book include the role of work terms other than *P-V* work (e.g., magnetic work), along with their attendant aspects of entropy, Maxwell relations, and the role of such applied fields on phase diagrams. Also, there is an increased emphasis on the thermodynamics of phase transformations. These topics are sprinkled throughout the text, and an entirely new chapter (Chapter 15) has been included which collects specific thermodynamic applications to the study of phase transformations. To make the agreed-upon deadline for the manuscript, other potential changes remain on my computer. Perhaps they will see the light of day in the seventh edition!

The text is written for undergraduate materials science students and can be utilized by materials-related graduate students who have not taken such a course in their undergraduate studies. It has been more than 40 years since I used the first edition of the text when teaching my first class in thermodynamics at Carnegie Mellon University. I also used the text in the mid-1990s in several summer school classes on thermodynamics at CMU. Experience makes me aware that it is impossible to make it through the entire text in a one-semester course. In this edition, I have divided the book into three sections. I suggest that at least the first section ("Thermodynamic Principles") and as much as possible of the second section ("Phase Equilibria") be included in a one-semester undergraduate course. The third section ("Reactions and Transformations") can make its way into other courses of the curriculum that deal with oxidation, energy, and phase transformations.

This author is well aware of the rise of computational materials science and the need for computational thermodynamics in such courses. I consider this text a prerequisite for any course that utilizes the computational methods of thermodynamics: one should not compute what one does not understand!

I acknowledge the continual support of my family, especially my wife Diane, who has been very patient over the years with my excursions to my study in preparation for lectures, often on weekends! All of my students have been helpful in so many ways over the years of teaching and research. My former student Dr. Jingxi Zhu is especially thanked for help with the proof reading of several chapters. For nearly twenty years I have had the benefit of collaboration and friendship with Prof. Michael McHenry with whom I have taught magnetic materials classes in which thermodynamics has played a major role. Lastly, I acknowledge my long friendship with Prof. William A. Soffa of the University of Virginia for countless discussions and learning sessions on topics relevant to thermodynamics, magnetism, phase transformations, as well as the history and philosophy of science. I hope that he has learned at least half as much from me as I have from him.

I count it a privilege to produce the sixth edition of Gaskell's *Thermodynamics*, some 4 years after David's death. May the text continue to train materials students well in the basics of thermodynamics.

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Postscript: Typographical errors enter thermodynamics books at an alarming rate. There is a Web site for this text https://www.crcpress.com/product/isbn/9781498757003 and on it will be a list of typos. Please feel free to send me any that you find. Send all typos to Gaskell.Laughlin@gmail.com.

Authors

David R. Gaskell received a BSc in metallurgy and technical chemistry from the University of Glasgow, Scotland, and a PhD from McMaster University, Hamilton, ON. Dr. Gaskell's first faculty position was at the University of Pennsylvania, where he taught from 1967 to 1982 in metallurgy and materials science. In 1982, he was recruited at the rank of professor by Purdue University, West Lafayette, IN, where he taught until 2013. During Dr. Gaskell's career, he served as a visiting professor at the National Research Council of Canada, Atlantic Regional Laboratory, Halifax, NS (1975–1976), and as a visiting professor at the G. C. Williams Co-operative Research Centre for Extraction Metallurgy, in the Department of Chemical Engineering, University of Melbourne, Australia (1995). He also held a position during his sabbatical in Australia as a visiting scientist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Clayton, Victoria. Dr. Gaskell authored the textbooks *Introduction to Metallurgical Thermodynamics*, *Introduction to the Thermodynamics of Materials*, and *Introduction to Transport Phenomena in Materials Engineering*.

David E. Laughlin is the ALCOA Professor of Physical Metallurgy in the Department of Materials Science and Engineering of Carnegie Mellon University (CMU), Pittsburgh, PA, and also has a courtesy appointment in the Electrical and Computer Engineering Department. He was the principal editor of *Metallurgical and Materials Transactions* from 1987 to 2016. David is a graduate of Drexel University, Philadelphia, PA (1969), and the Massachusetts Institute of Technology, Cambridge, MA (1973). He is a fellow of the Minerals, Metals and Materials Society (TMS), an honorary member of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), and a fellow of ASM International. He is also the recipient of several CMU awards for teaching and research excellence and was named a distinguished scientist of the TMS Electronic, Magnetic and Photonic Materials Division. He has authored more than 400 technical publications in the field of phase transformations, physical metallurgy, and magnetic materials, has been awarded 12 patents and has edited or coedited seven books, including the fifth edition of *Physical Metallurgy*.

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