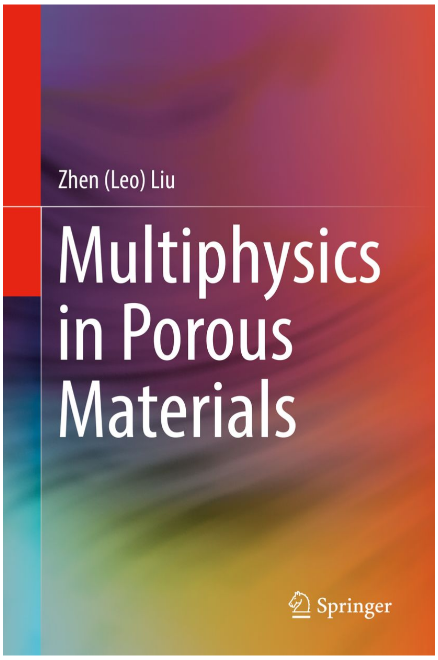

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Zhen (Leo) Liu

Multiphysics in Porous Materials

- • Presents the essential components of multiphysics along with innovative numerical modeling techniques in the context of porous materials
- • Structured for a wide range of readers from those new to the field to experts, instructors, researchers, software developers, and modelers from many scientific and engineering disciplines
- • Organized using a practical approach that combines a logical presentation of theories with illustrative hands-on example problems
- • Reinforces multiphysics concepts with applications demonstrating the use of common software to solve representative problems

This book summarizes, defines, and contextualizes multiphysics with an emphasis on porous materials. It covers various essential aspects of multiphysics, from history, definition, and scope to mathematical theories, physical mechanisms, and numerical implementations. The emphasis on porous materials maximizes readers' understanding as these substances are abundant in nature and a common breeding ground of multiphysical phenomena, especially complicated multiphysics. Dr. Liu's lucid and easy-to-follow presentation serve as a blueprint on the use of multiphysics as a leading edge technique for computer modeling. The contents are organized to facilitate the transition from familiar, monolithic physics such as heat transfer and pore water movement to state-of-the-art applications involving multiphysics, including poroelasticity, thermohydro-mechanical processes, electrokinetics, electromagnetics, fluid dynamics, fluid structure interaction, and electromagnetomechanics. This volume serves as both a general reference and specific treatise for various scientific and engineering disciplines involving multiphysics simulation and porous materials.

Zhen (Leo) Liu

Multiphysics in Porous Materials

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I am dedicating this book to my wife, Ye (Sarah), and my son, Brent. Their understanding and support enabled this work

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Preface

This book started from a course that was first offered in the spring of 2015 at Michigan Technological University. This course was possibly the first one on multiphysics in porous materials worldwide and even likely among the first in the general area of multiphysics. Back at that time, I could not find an appropriate textbook for multiphysics, let alone one with a focus on porous materials. Therefore, I had to develop all the lecture notes and computer labs from scratch. This book was created based on this educational endeavor. Many of the book materials have been tested multiple times via both teaching and learning in that course. In addition, the book has been enriched with materials from several completed and active research projects including cutting-edge studies supported by the US National Science Foundation. In short, the book represents a very implementable and practical learning guide for multiphysics and a path from the basics of multiphysics to advanced research topics.

This book is intended to be a general reference for multiphysics. By now, more than a dozen of books with a title including "multiphysics" can be found. However, they are mostly conference proceedings, introductions to the development of specific multiphysics applications, or summaries on multiphysics in specific areas. A relevant fact is that multiphysics researchers usually tend to focus on the multiphysics applications in their own areas, no matter in the general multiphysics context or in porous materials. There is no effective reference for people to systematically learn about multiphysics, especially to grab a big picture and the basics. This book is presented to fill this gap.

This book is also designed to be a comprehensive introduction to the area of multiphysics in porous materials. Porous materials are an ideal breeding ground of multiphysics due to their multiphase and multicomponent nature. As a result, porous materials are related to most common types of multiphysical phenomena. For example, the coexistence of thermal, hydrological, and mechanical processes is a major interest in geotechnical engineering, hydrogeology, soil science, and petroleum engineering. Particle transport and chemical reactions together with heat transfer and water movement have been extensively studied in environmental engineering, agricultural engineering, and forestry. Electromagnetics, vibration, and acoustics are the primary interest of geophysicists, earthquake engineers, mechanical engineers, and exploratory geologists. Therefore, this book will be a handy tool to researchers and practitioners in these areas involving porous materials, no matter they are new to multiphysics or they want to step into a multiphysics topic out of their home disciplines.

This book is organized in a way to serve readers with different backgrounds and with different levels of knowledge accumulation in multiphysics. For the purpose, this book provides materials that would be essential to obtain a general understanding of the concepts, theories, and implementations of multiphysics. It is believed that multiphysics is an “art” of mathematics, physics, applications, and numerical analysis. Accordingly, the book is organized into five parts: introduction, mathematics, monolithic physics, multiphysics, and numerical analysis. In Part I, a general introduction to the history, state, essence of multiphysics, and its applications in porous materials is offered. The definition, scope, and classification of multiphysics will be given based on the discussions on the existing studies. In Part II, necessary mathematical backgrounds such as tensor and fields, tensor analysis, partial differential equations (PDE), and numerical solution of PDEs are provided. Eight most representative monolithic physical fields are introduced in Part III, each of which is presented as a chapter. Then in Part IV, typical multiphysical processes are introduced. The introduction is made based on the mathematics in Part II and the monolithic physics in Part III. Each multiphysical topic is introduced in the order of background, theory, implementation, and applications. The theory will be discussed in a way that mathematics and physics are integrated. Implementations are demonstrated with a simple but representative example, which is solved using a PDE solver. In Part V, a brief tour will be given to show how to implement a multiphysics model with three typical numerical simulation methods, i.e., finite difference method, finite volume method, and finite element method, using self-developed computer code.

The use of physical fields extends over most science and engineering disciplines, while a discipline or sub-discipline usually primarily deals with one or a few physical fields. This fact makes multiphysics an extremely interdisciplinary topic and poses challenges in enumerating the fields. The eight most common monolithic physical fields introduced in this book are heat transfer (thermo-), pore water movement (hydro-), concentration field (concentro or diffuso/convecto/advecto), stress and strain analysis (mechano-), dynamics (dyno-), chemical reactions (chemo- or chemico-), electrostatics (electro-), and magnetostatics (magneto-). For multiphysics, the following nine most representative topics in porous materials will be discussed: thermomechanics, hydromechanics (static poroelasticity), thermohydromechanics, electrokinetics, electromagnetics, fluid dynamics, hydrodynomechanics (e.g., fluid-structure interaction), thermoelectromagnetics (including Joule heating, dielectric heating, and induction heating), and electromagnetomechanics (e.g., piezoelectricity).

It is my hope that this book can significantly flatten and shorten the learning curve of multiphysics. Usually, it takes many years to pick up the basic concepts, preparation knowledge, and software skills before we can excel in or even get a big picture of multiphysics. Such a multiyear knowledge preparation includes math courses such as partial differential equations and tensor analysis; specialty courses such as mechanics, heat transfer, and electromagnetics; and numerical analysis courses such as finite difference method, finite volume method, and finite element method. As a result, the learning curve for multiphysics is both steep and long. Commercial software such as COMSOL made a great effort at lowering the bar for implementing multiphysics and expediting the process for research and design with multiphysics. However, more advanced use especially that requires an in-depth understanding of multiphysics and bottom-level theoretical and numerical operations still calls for a framework and summary of multiphysics. Based on my 10 years of multiphysics implementations and even more time in knowledge preparation, I want to share the opinion that not all the knowledge in the above courses/subjects are equally needed for understanding and practicing multiphysics. Moreover, it is possible to organize the most relevant and significant knowledge into a book by which people can obtain a smooth and pleasant ride to the kingdom of multiphysics especially for the applications in porous materials. The book is presented and will be continuously improved to show and prove this opinion.

A continuously updated website, multiphysics.us, is available to complement this book. This website provides updated technical details, applications from communities, and networking information for multiphysics and its applications in porous materials.

Houghton, MI, USA Zhen (Leo) Liu

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