SIXTH EDITION

Heat and Mass Transfer

FUNDAMENTALS & APPLICATIONS

YUNUS A. ÇENGEL | AFSHIN J. GHAJAR

Mc Graw Hill Education

HEAT AND MASS TRANSFER

FUNDAMENTALS & APPLICATIONS

Quotes on Ethics

Without ethics, everything happens as if we were all five billion passengers on a big machinery and nobody is driving the machinery. And it's going faster and faster, but we don't know where.

—Jacques Cousteau

Because you're able to do it and because you have the right to do it doesn't mean it's right to do it.

—Laura Schlessinger

A man without ethics is a wild beast loosed upon this world.

—Manly Hall

The concern for man and his destiny must always be the chief interest of all technical effort. Never forget it among your diagrams and equations.

—Albert Einstein

To educate a man in mind and not in morals is to educate a menace to society.

—Theodore Roosevelt

Politics which revolves around benefit is savagery.

—Said Nursi

The true test of civilization is, not the census, nor the size of the cities, nor the crops, but the kind of man that the country turns out.

—Ralph W. Emerson

The measure of a man's character is what he would do if he knew he never would be found out.

—Thomas B. Macaulay

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HEAT AND MASS TRANSFER: FUNDAMENTALS AND APPLICATIONS, SIXTH EDITION

This book is printed on acid-free paper.

1 2 3 4 5 6 7 8 9 LWI 21 20 19

ISBN 978-0-07-339819-8 (bound edition)
MHID 0-07-339819-5 (bound edition)

ISBN 978-1-260-44002-7 (loose-leaf edition)
MHID 1-260-44002-8 (loose-leaf edition)

Executive Portfolio Manager: *Suzy Bainbridge*
Product Developer: *Heather Ervolino*
Marketing Manager: *Shannon O'Donnell*
Content Project Managers: *Jane Mohr, Samantha Donisi-Hamm, and Sandy Schnee*
Buyer: *Susan K. Culbertson*
Design: *Egzon Shaqiri*
Content Licensing Specialist: *Shawntel Schmitt*
Cover Image: ©*Ivan Smuk/Shutterstock*
Compositor: *SPi Global*

Library of Congress Cataloging-in-Publication Data

Names: Cengel, Yunus A., author. | Ghajar, Afshin J., author.
Title: Heat and mass transfer : fundamentals and applications / Yunus A. Cengel, University of Nevada, Reno, Afshin J. Ghajar, Oklahoma State University, Stillwater.
Description: Sixth edition. | New York, NY : McGraw-Hill Education, [2020] | Includes bibliographical references and index.,
Identifiers: LCCN 2018052611| ISBN 9780073398198 (alk. paper) | ISBN 0073398195 (bound edition) | ISBN 9781260440027 (loose-leaf edition) | ISBN 1260440028 (loose-leaf edition)
Subjects: LCSH: Heat–Transmission. | Mass transfer.
Classification: LCC TJ260 .C38 2020 | DDC 621.402/2–dc23 LC record available at https://lccn.loc.gov/2018052611

mheducation.com/highered

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Yunus A. Çengel is Professor Emeritus of Mechanical Engineering at the University of Nevada, Reno. He received his B.S. in mechanical engineering from Istanbul Technical University and his M.S. and Ph.D. in mechanical engineering from North Carolina State University. His areas of interest are renewable energy, energy efficiency, energy policies, heat transfer enhancement, and engineering education. He served as the director of the Industrial Assessment Center (IAC) at the University of Nevada, Reno, from 1996 to 2000. He has led teams of engineering students to numerous manufacturing facilities in Northern Nevada and California to perform industrial assessments and has prepared energy conservation, waste minimization, and productivity enhancement reports for them. He has also served as an advisor for various government organizations and corporations.

Dr. Çengel is also the author or coauthor of the widely adopted textbooks *Thermodynamics: An Engineering Approach* (9th ed., 2019), *Fluid Mechanics: Fundamentals and Applications* (4th ed., 2018), *Fundamentals of Thermal-Fluid Sciences* (5th ed., 2017), and *Differential Equations for Engineers and Scientists* (1st ed., 2013), all published by McGraw-Hill. Some of his textbooks have been translated into Chinese, Japanese, Korean, Thai, Spanish, Portuguese, Turkish, Italian, Greek, French and Basq.

Dr. Çengel is the recipient of several outstanding teacher awards, and he received the ASEE Meriam/Wiley Distinguished Author Award for excellence in authorship in 1992 and again in 2000. Dr. Çengel is a registered Professional Engineer in the State of Nevada, and he is a member of the American Society of Mechanical Engineers (ASME) and the American Society for Engineering Education (ASEE).

Afshin J. Ghajar is Regents Professor and John Brammer Professor in the School of Mechanical and Aerospace Engineering at Oklahoma State University, Stillwater, Oklahoma, and an Honorary Professor of Xi'an Jiaotong University, Xi'an, China. He received his B.S., M.S., and Ph.D. degrees, all in mechanical engineering, from Oklahoma State University. His expertise is in experimental heat transfer/fluid mechanics and the development of practical engineering correlations. Dr. Ghajar has made significant contributions to the field of thermal sciences through his experimental, empirical, and numerical works in heat transfer and stratification in sensible heat storage systems, heat transfer to non-Newtonian fluids, heat transfer in the transition region, and non-boiling heat transfer in two-phase flow. His current research is in two-phase flow heat transfer/pressure drop studies in pipes with different orientations, heat transfer/pressure drop in mini/micro tubes, and mixed convective heat transfer/pressure drop in the transition region (plain and enhanced tubes). Dr. Ghajar has been a Summer Research Fellow at Wright Patterson AFB (Dayton, Ohio) and Dow Chemical Company (Freeport, Texas). He and his co-workers have published over 200 reviewed research papers. He has delivered numerous keynote and invited lectures at major technical conferences and institutions.

He has received several outstanding teaching, research, advising, and service awards from the College of Engineering at Oklahoma State University. His latest significant awards are the 75th Anniversary Medal of the ASME Heat Transfer Division "in recognition of his service to the heat transfer community and contributions to the field," awarded in 2013. He received the ASME ICNMM 2016 Outstanding Leadership Award, which recognizes a person whose service within the ICNMM (International Conference on Nanochannels, Microchannels, and Minichannels) is exemplary. He also received the 2017 Donald Q. Kern Award "in recognition of his outstanding leadership in the field of heat exchangers and two-phase flow, book and archival publications, and service to the academic and industrial professionals." Dr. Ghajar is a Fellow of the American Society of Mechanical Engineers (ASME), Heat Transfer Series Editor for CRC Press/Taylor & Francis, and Editor-in-Chief of *Heat Transfer Engineering,* an international journal aimed at practicing engineers and specialists in heat transfer published by Taylor and Francis.

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PREFACE

BACKGROUND

Heat and mass transfer is a basic science that deals with the rate of transfer of thermal energy. It is an exciting and fascinating subject with unlimited practical applications ranging from biological systems to common household appliances, residential and commercial buildings, industrial processes, electronic devices, and food processing. Students are assumed to have an adequate background in calculus and physics. The completion of first courses in thermodynamics, fluid mechanics, and differential equations prior to taking heat transfer is desirable. However, relevant concepts from these topics are introduced and reviewed as needed.

OBJECTIVES

This book is intended for undergraduate engineering students in their sophomore or junior year and as a reference book for practicing engineers. The objectives of this text are

- To present the *basic principles* and *equations* of heat transfer.
- To show numerous and diverse real-world *engineering examples* to help students develop the intuition they need to correctly apply heat transfer principles in engineering.
- To develop an *intuitive understanding* of heat transfer by emphasizing the physics and physical arguments.

It is our hope that this book, through its careful explanations of concepts and its use of many practical examples and figures, helps students to develop the skills they need to bridge the gap between gaining knowledge and confidently applying that knowledge.

In engineering practice, an understanding of the mechanisms of heat transfer is becoming increasingly important since heat transfer plays a crucial role in the design of vehicles, power plants, refrigerators, electronic devices, buildings, and bridges, among other things. Even a chef needs an intuitive understanding of heat transfer in order to cook the food "right" by adjusting the rate of heat transfer. We may not be aware of it, but we already use the principles of heat transfer when we seek thermal comfort. We insulate our bodies by putting on heavy coats in winter, and we minimize heat gain by radiation by staying in shady places in summer. We speed up the cooling of hot food by blowing on it and keep warm in cold weather by cuddling up and thus minimizing our exposed surface area. That is, we already use heat transfer whether we realize it or not.

PHILOSOPHY AND GOAL

This text is the outcome of an attempt to have a textbook for a practically oriented heat transfer course for engineering students. The text covers the standard topics of heat transfer with an emphasis on physics and real-world

applications. This approach is more in line with students' intuition and makes learning the subject matter enjoyable.

The philosophy that contributed to the overwhelming popularity of the prior editions of this book has remained unchanged in this edition. Our goal has been to offer an engineering textbook that

- Communicates directly with tomorrow's engineers in a *simple yet precise* manner.
- Leads students toward a clear understanding and a firm grasp of the *basic principles* of heat transfer.
- Encourages *creative thinking* and development of a *deeper understanding* and *intuitive feel* for heat transfer.
- Is *read* by students with *interest* and *enthusiasm* rather than being used as a guide to solve problems.

Special effort has been made to appeal to students' natural curiosity and to help them explore the various facets of the exciting subject area of heat transfer. The enthusiastic response we received from the users of prior editions—from small colleges to large universities all over the world—indicates that our objectives have largely been achieved. It is our philosophy that the best way to learn is by practice. Therefore, special effort is made throughout the book to reinforce material that was presented earlier (in each chapter as well as in material from previous chapters). Many of the illustrated example problems and end-of-chapter problems are comprehensive and encourage students to review and revisit concepts and intuitions gained previously.

Yesterday's engineer spent a major portion of his or her time substituting values into formulas and obtaining numerical results. However, now formula manipulations and number crunching are being left mainly to the computers. Tomorrow's engineer will have to have a clear understanding and a firm grasp of the *basic principles* so that he or she can understand even the most complex problems, formulate them, and interpret the results. A conscious effort is made to emphasize these basic principles while also enabling students to see how computational tools are used in engineering practice.

NEW TO THE SIXTH EDITION

One of the primary changes in the sixth edition of this text is the effective use of full color to enhance the learning experience of students and to make it more enjoyable. Another significant change is the inclusion of a new section in Chap. 1 on Engineering Codes and Standards (C&S). A knowledge of heat and mass transfer, along with adherence to the relevant codes and standards, allow engineers to analyze, design, and build components and systems to function within the design conditions. Throughout the text, as appropriate, example problems and end-of-chapter problems related to engineering codes and standards have been presented to introduce this concept to tomorrow's engineers. The third important change has been in Chap. 4 where the graphical representation of the one-dimensional transient conduction solutions (Heisler charts) have been eliminated, and the emphasis has been placed on the solution with more accurate approximate or exact analytical expressions. Other important changes have been the addition of five new sections or subsections: "Aerogel—A Remarkable Superinsulating Material," "Equation Solvers," and

"Accuracy, Precision and Significant Digits" to Chap. 1, "General Solutions for Simultaneously Moving Plates and Fluids" to Chap. 7, and "Analogies Between Momentum and Heat Transfer in the Transition Region" to Chap. 8.

We have also incorporated 20 new solved example problems in the text, modified over 450 of the existing end-of-chapter problems, and added over 150 new end-of-chapter problems. A significant number of the new problems are on the concept of Engineering Codes and Standards (C&S). All the popular features of the previous editions have been retained, while new ones have been added. Updates and changes for clarity and readability have been made throughout the text.

ENGINEERING CODES AND STANDARDS (C&S) PROBLEMS

A recent study done by ASME Vision 2030 Project reveals that almost 50 percent of engineers in their early careers are unfamiliar with engineering codes and standards. As companies and manufacturers are expanding operations globally, there is a greater interest in harmonizing codes and standards across jurisdictions and disciplines. The need for engineers to have the knowledge about codes and standards is growing, and having this knowledge allows engineers to innovate and manufacture competitive products. In the subject of heat and mass transfer, there are several engineering codes and standards that are relevant. These codes and standards have been issued and published by professional associations, such as the ASME and the ASHRAE, and standards organizations, such as ASTM International, ANSI, and the ISO. The Engineering Codes and Standards (C&S) concept is first introduced in Chap. 1. The engineering C&S concept complements the Prevention through Design (PtD) concept that was introduced in the fifth edition of this book to emphasize safety in designs. The example problems and end-of-chapter problems in each chapter not only offer perspectives on interesting real-world applications but also introduce the concepts of engineering C&S to tomorrow's engineers so they may influence a change in the culture toward a greater emphasis on codes and standards. The knowledge of heat and mass transfer, along with adherence to the relevant codes and standards, allow engineers to analyze, design, and build components and systems to function within their design conditions.

CONTENT CHANGES AND REORGANIZATION

With the exception of the changes already mentioned, several updates and changes for clarity and readability have been made in the text. In this edition, we have introduced 20 new example problems and over 600 new and modified end-of-chapter problems. The noteworthy changes are summarized here for those who are familiar with the previous edition.

- In Chap. 1, four new sections or subsections have been added: "Aerogel—A Remarkable Superinsulating Material" by Dr. Ann M. Anderson of Union College, "Engineering Codes and Standards (C&S)" by Dr. Clement C. Tang of the University of North Dakota, "Equation Solver," and "Accuracy, Precision and Significant Digits." Also, the Topic of Special Interest on "Thermal Comfort" has been expanded.
- In Chap. 3, the section on "Bioheat Transfer Equation" has been expanded.

- In Chap. 4, the graphical representation of the one-dimensional transient conduction solutions (Heisler charts) have been eliminated, and the emphasis has been placed on the solution with more accurate approximate or exact analytical expressions. Based on the input we have received from instructors, very few students use the graphical representations of the one-dimensional, transient conduction solutions (Heisler charts); most prefer to solve the approximate or exact analytical expressions. In addition, all the example problems using the graphical solution have been updated.
- In Chap. 7, a new subsection on "General Solutions for Simultaneously Moving Plates and Fluids" has been added. In addition, new equations for the flat plate average Nusselt number with unheated starting length for laminar and turbulent flows have been added. We have also updated Table 7-1 with several additional correlations for noncircular geometries.
- In Chap. 8, a new subsection on "Analogies Between Momentum and Heat Transfer in the Transition Region" has been added. Also, we have updated/expanded internal forced convection heat transfer correlations in laminar, transitional, and turbulent flows.
- In Chap. 10, the coverage of the Topic of Special Interest on "Non-Boiling Two-Phase Flow Heat Transfer" has been expanded.
- In Chap. 11, the coverage of the Topic of Special Interest on "The Human Cardiovascular System as a Countercurrent Heat Exchanger" has been expanded.
- In Chap. 13, the section on view factors was updated. We have also updated and added a few view factor relations.

LEARNING TOOLS

EMPHASIS ON PHYSICS

A distinctive feature of this book is its emphasis on the physical aspects of the subject matter in addition to mathematical representations and manipulations. The authors believe that the emphasis in undergraduate education should remain on *developing a sense of underlying physical mechanisms* and a *mastery of solving practical problems* that an engineer is likely to face in the real world. Developing an intuitive understanding should also make the course a more motivating and worthwhile experience for the students.

EFFECTIVE USE OF ASSOCIATION

An observant mind should have no difficulty understanding engineering sciences. After all, the principles of engineering sciences are based on our *everyday experiences and experimental observations.* Therefore, a physical, intuitive approach is used throughout this text. Frequently, *parallels are drawn* between the subject matter and students' everyday experiences so that they can relate the subject matter to what they already know. The process of cooking, for example, serves as an excellent vehicle to demonstrate the basic principles of heat transfer.

SELF-INSTRUCTING

The material in the text is introduced at a level that an average student can follow comfortably. It speaks *to* students, not *over* students. In fact, it is *self-instructive.* The order of coverage is from *simple* to *general.* That is, it starts with the simplest case and adds complexities gradually. In this way, the basic principles are repeatedly applied to different systems, and students master how to apply the principles instead of how to simplify a general formula. Noting that principles of science are based on experimental observations, all the derivations in this text are based on physical arguments, and thus they are easy to follow and understand.

EXTENSIVE USE OF ARTWORK

Figures are important learning tools that help the students "get the picture," and the text makes effective use of graphics. It contains more figures and illustrations than any other book in this category. This sixth edition of *Heat and Mass Transfer: Fundamentals & Applications,* features an enhanced art program done in four colors to provide more realism and pedagogical understanding. Further, a large number of figures have been upgraded to become three-dimensional and thus more real-life. Figures attract attention and stimulate curiosity and interest. Most of the figures in this text are intended to serve as a means of emphasizing some key concepts that would otherwise go unnoticed; some serve as summaries.

LEARNING OBJECTIVES AND SUMMARIES

Each chapter begins with an *Overview* of the material to be covered and chapter-specific *Learning Objectives.* A *Summary* is included at the end of each chapter, providing a quick review of basic concepts and important relations, and pointing out the relevance of the material.

NUMEROUS WORKED-OUT EXAMPLES WITH A SYSTEMATIC SOLUTIONS PROCEDURE

Each chapter contains several worked-out *examples* that both clarify the material and illustrate the use of the basic principles in a context that helps develop student's intuition. An *intuitive* and *systematic* approach is used in the solution of all example problems. The solution methodology starts with a statement of the problem, and all objectives are identified. The assumptions and approximations are then stated together with their justifications. Any properties needed to solve the problem are listed separately. Numerical values are used together with their units to emphasize that numbers without units are meaningless, and that unit manipulations are as important as manipulating the numerical values with a calculator. The significance of each example's result is discussed following the solution. This methodical approach is also followed and provided in the solutions to the end-of-chapter problems, available to the instructors.

A WEALTH OF REALISTIC END-OF-CHAPTER PROBLEMS

The end-of-chapter problems are grouped under specific topics to make problem selection easier for both instructors and students. Within each group of problems are:

- ***Concept Questions,*** indicated by "C," to check the students' level of understanding of basic concepts.

- ***Prevention through Design Problems,*** designated by the icon PtD. These problems introduce the concepts of PtD to the minds of tomorrow's engineers whereby they may influence a change in culture toward more emphasis on safe designs.
- ***Engineering Codes and Standards Problems,*** designated by the icon C&S. These problems introduce the concepts of C&S to engineering students. The knowledge of heat and mass transfer, along with adherence to the relevant engineering codes and standards, allow tomorrow's engineers to analyze, design, and build components and systems to function within the design conditions.
- ***Computer-Oriented Problems,*** designated by the icon  . These problems are comprehensive in nature and are intended to be solved with a computer, using appropriate software.
- ***Review Problems*** are more comprehensive in nature and are not directly tied to any specific section of a chapter—in some cases they require review of material learned in previous chapters. These problems are placed under the heading "Review Problems."
- ***Fundamentals of Engineering (FE) Exam Problems*** are designed to help students prepare for the *Fundamentals of Engineering* exam, as they prepare for their Professional Engineering license. These are *multiple-choice problems,* and they are intended to check the readers' understanding of fundamentals and to help them avoid common pitfalls. These problems are placed under the heading "Fundamentals of Engineering (FE) Exam Problems."
- ***Design and Essay Problems*** are intended to encourage students to make engineering judgments, to conduct independent exploration of topics of interest, and to communicate their findings in a professional manner. These problems are placed under the heading "Design and Essay Problems."
- ***Problems Designated by an "E"*** are in English units, and SI users can ignore them.

Several economics- and safety-related problems are incorporated throughout to enhance cost and safety awareness among engineering students. Answers to selected problems are listed immediately following the problem for convenience to students.

USE OF COMMON NOTATION

The use of different notation for the same quantities in different engineering courses has long been a source of discontent and confusion. A student taking both heat transfer and fluid mechanics, for example, has to use notation Q for heat transfer in one course and for volume flow rate in the other. In this text, we have made a conscious effort to minimize this conflict by adopting the familiar thermodynamic notation $\dot{V}$ for volume flow rate, thus reserving the notation Q for heat transfer. This type of effort has been made in all the other engineering texts by lead author Yunus Çengel. We think that both students and instructors will appreciate this effort to promote a common notation.

A CHOICE OF SI ALONE OR SI/ENGLISH UNITS

In recognition of the fact that English units are still widely used in some industries, both SI and English units are used in this text, with an emphasis on SI. The material in this text can be covered using combined SI/English units or SI units alone, depending on the preference of the instructor. The property tables and charts in the appendices are presented in both units, except the ones that involve dimensionless quantities. Problems, tables, and charts in English units are designated by "**E**" after the number for easy recognition, and they can be ignored by SI users.

TOPICS OF SPECIAL INTEREST

Most chapters contain a real-world application, end-of-chapter optional section called "Topic of Special Interest" where interesting applications of heat transfer are discussed. Examples include *Thermal Comfort* in Chap. 1, *Heat Transfer Through Walls and Roofs* in Chap. 3, *Microscale Heat Transfer* in Chap. 6, *Transitional Flow in Tubes* in Chap. 8, *Heat Transfer Through Windows* in Chap. 9, *Non-Boiling Two-Phase Flow Heat Transfer* in Chap. 10, *Human Cardiovascular System as a Countercurrent Heat Exchanger* in Chap. 11, and *Heat Transfer from the Human Body* in Chap. 13. The topics selected for these sections provide intriguing extensions to heat transfer, but they can be ignored without a loss in continuity.

IMPORTANT HEAT TRANSFER TERMS

Through the chapters, when an important key term or concept is introduced and defined, it appears in **red** boldface type.

CONVERSION FACTORS

Frequently used conversion factors and physical constants are listed at the very end of the book for easy reference.

NOMENCLATURE

A list of the major symbols, subscripts, and superscripts are also listed at the very end of the book for easy reference.

SUPPLEMENTS

The following supplements are available to the users of the book.

TEXT WEBSITE

Visit the website for several instructor resources including Lecture PowerPoints, the text's images in PowerPoint form, Solution's Manual, and helpful web links for students.

THREE ONLINE APPLICATION CHAPTERS

The application chapters "Cooling of Electronic Equipment" (Chap. 15), "Heating and Cooling of Buildings" (Chap. 16), and "Refrigeration and Freezing of Foods" (Chap. 17) are available via the text website.

ACKNOWLEDGMENTS

We would like to acknowledge with appreciation the contribution of new sections, problems, and the numerous and valuable comments, suggestions, constructive criticisms, and praise from the following contributors, evaluators, and reviewers:

John P. Abraham
University of St. Thomas

Ann M. Anderson
Union College

C. Thomas Avedisian
Cornell University

Antonette Cummings
University of Wisconsin-Platteville

Ranjan Ganguly
Jadavpur University, India

Kamel Hooman
University of Queensland, Australia

Mehmet Kanoglu
University of Gaziantep, Turkey

Sunwoo Kim
University of Alaska

Josua P. Meyer
University of Pretoria, South Africa

Ehsan Moallem
Oklahoma State University

David A. Rubenstein
Stony Brook University

Clement C. Tang
University of North Dakota

Roman Voronov
New Jersey Institute of Technology

Wei Yin
Stony Brook University

Their contributions and suggestions have greatly helped to improve the quality of this text.

Special thanks are due to Dr. Clement C. Tang of the University of North Dakota for his help with developing new example problems and end-of-chapter problems for the new section on Engineering Codes and Standards in this edition.

We also thank those who were acknowledged in the first to fifth editions of this book, but are too numerous to mention again here. The authors are also grateful to Dr. Mehmet Kanoglu of University of Gaziantep for his valuable contributions in editing and updating the solutions manual for this edition of the text. We also would like to thank our students and instructors from all over the globe, who provided plenty of feedback from students' and users' perspectives.

Finally, we would like to express our appreciation to our wives, Zehra Çengel and Homa Ghajar, for their continued patience, understanding, and support throughout the preparation of the sixth edition of this text.

Yunus A. Çengel
Afshin J. Ghajar

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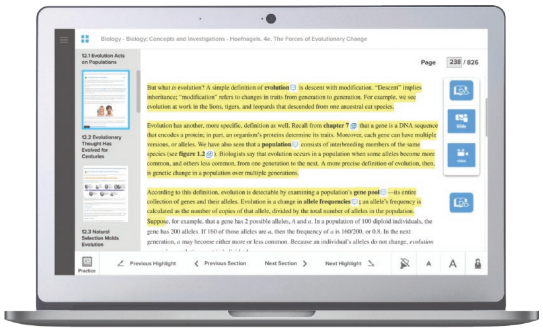

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