Virtual Reality

Virtual reality (VR) is a powerful technology that promises to transform our lives. This balanced and interdisciplinary text blends key components from computer graphics, perceptual psychology, human physiology, behavioral science, media studies, human–computer interaction, optical engineering, and sensing and filtering, showing how each contributes to engineering perceptual illusions. Steven LaValle draws on his unique experience as a teacher, researcher, and co-creator of the Oculus Rift to demonstrate how the best practices and insights from industry are built on fundamental principles. Topics include media history, geometric modeling, optical systems, displays, eyes, ears, low-level perception, neuroscience of vision, graphical rendering, tracking systems, interaction mechanisms, audio, evaluating VR systems, and mitigating side effects. Students, researchers, and developers will gain a clear understanding of timeless foundations and new applications, enabling them to make innovative contributions to this growing field as scientists, engineers, business developers, and content makers.

Steven LaValle is Professor of Computer Science and Engineering at the University of Oulu and Professor of Computer Science at the University of Illinois at Urbana-Champaign. He was an early founder and chief scientist of Oculus VR, where he developed patented tracking technology for consumer VR and led a team of perceptual psychologists to provide principled approaches to virtual reality system calibration, health and safety, and the design of comfortable user experiences. He has also served as Vice President and Chief Scientist of VR/AR/MR at Huawei. He has conducted research for over three decades, publishing over 150 articles and two books, *Planning Algorithms* and *Sensing and Filtering*.

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For my family, Anna, Alexander, Ethan, Rose, and Petri

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Preface

The Rebirth of Virtual Reality

Virtual reality (VR) is a powerful technology that promises to change our lives unlike any other. By artificially stimulating our senses, our bodies become tricked into accepting another version of reality. Virtual reality is like a waking dream that could take place in a magical cartoon-like world or could transport us to another part of the Earth or universe. It is the next step along a path that includes many familiar media, from paintings to movies to video games. We can even socialize with people inside of new worlds, which could be real or artificial.

At the same time, VR bears the stigma of unkept promises. The hype and excitement has often far exceeded the delivery of VR experiences to match it, especially for people without access to expensive laboratory equipment. This was particularly painful in the early 1990s when VR seemed poised to enter mainstream use but failed to catch on (outside of some niche markets). Decades later, we are witnessing an exciting rebirth. The latest technological components, mainly arising from the smartphone industry, have enabled high-resolution, low-cost, portable VR headsets to provide compelling VR experiences. From 2014 onward, this has mobilized leading technology companies to invest billions of dollars into growing a VR ecosystem that includes art, communication, entertainment, enhanced work productivity, and social interaction. At the same time, a new generation of technologists is entering the field with fresh ideas. Online communities of hackers and makers, along with college students around the world, are excitedly following the rapid advances in VR and are starting to shape it by starting new companies, working to improve the technology, and making new kinds of experiences.

The whole ecosystem is growing at a steady pace, while some particular use cases such as industry training are rapidly expanding. A current challenge is to introduce advanced hardware that is not simply derived from other markets. The greatest need for innovation is in visual displays that are particularly designed for VR. Distinctions with other technologies such as augmented reality (AR) and mixed reality (MR) are becoming less significant as the technology progresses because they can all be handled by the same or similar devices. At the time of writing, the relatively new term extended reality (XR) has become popular to represent this unification; however, this book will refer to these as variations of VR.

The Intended Audience

The book grew out of material for an undergraduate course on VR that I introduced at the University of Illinois in 2015. I have never in decades of teaching seen students so excited to take a course. We could not offer enough slots to come even close to meeting the demand. Therefore, the primary target of this book is undergraduate students around the world. This book would be an ideal source for starting similar VR courses at other universities. Although most of the interested students have been computer scientists, the course at the University of Illinois has attracted students from many disciplines, such as psychology, music, kinesiology, engineering, medicine, and economics. Students in these other fields come with the most exciting project ideas because they can see how VR has the potential to radically alter *their* disciplines. To make the course accessible to students with such diverse backgrounds, I have made the material as self-contained as possible. There is no assumed background in software development or advanced mathematics. If prospective readers have at least written some scripts before and can remember how to multiply matrices together, they should be ready to go.

In addition to students who are studying VR in university courses, this text is also targeted at developers in industry, hobbyists on the forums, and researchers in academia. The book appears online so that it may serve as a convenient reference for all of these groups. To provide further assistance, there are also accompanying materials online, including lecture slides (prepared by Anna Yershova LaValle) and recorded lectures (provided online for free by NPTEL of India).

Why Am I Writing This Book?

I enjoy teaching and research, especially when I can tie the two together. I have been a professor and have taught university courses for over two decades. Robotics has been my main field of expertise; however, in 2012, while on a sabbatical in Oulu, Finland, I started working at Oculus VR a few days after its Kickstarter campaign. I left the university and became their chief scientist, working on head tracking methods, perceptual psychology, health and safety, and numerous other problems. I was struck by how many new challenges arose during that time because engineers and computer scientists (myself included) did not recognize human perception problems that were disrupting our progress. I became convinced that for VR to succeed, perceptual psychology must permeate the design of VR systems. As we tackled some of these challenges, the company rapidly grew in visibility and influence, eventually being acquired by Facebook. Oculus VR is largely credited with stimulating the most recent rebirth of VR [111].

I quickly returned to the University of Illinois with a new educational mission: teach a new generation of students, developers, and researchers the fundamentals of VR in a way that fuses perceptual psychology with engineering. Furthermore, this book focuses on principles that do not depend heavily on the particular technology of today. The goal is to improve the reader's *understanding* of how VR systems work, what limitations they have, and what can be done to improve them. One important component is that even though technology rapidly evolves, humans who use it do not. It is therefore crucial to understand how our sensory systems function, especially when matched with artificial stimulation. The intent is to provide a useful

foundation as the technology evolves. In many cases, open challenges remain. This book does not provide the solutions to them, but instead supplies the background to begin researching them.

Online Materials

Pointers to additional materials, including lecture videos and slides, are available online at the following link:

`http://lavalle.pl/vr/`

Suggested Use

This text may be used for a one-semester course by spending roughly one week per chapter, with the exception of Chapter 3, which may require two weeks. The book can also be used to augment other courses such as computer graphics, interfaces, and game development. Selected topics may also be drawn for a short course or seminar series.

Depending on the technical level of the students, the mathematical concepts in Chapter 3 might seem oppressive. If that is the case, students may be advised to skim over it and jump to subsequent chapters. They can understand most of the later concepts without the full mathematical details of Chapter 3. Nevertheless, understanding these concepts will enhance their comprehension throughout the book and will also make them more comfortable with programming exercises.

Lab Component

From 2015, we have used high-end consumer VR headsets on PCs with graphics cards that were specifically designed for VR. Development on many other platforms is possible, including all-in-one VR headsets, but one must be careful to ensure that the performance requirements for projects and exercises are met by the particular choice of platform. For software, almost all students develop VR projects using Unity 3D. Alternatives may be Unreal Engine and CryEngine, depending on their level of technical coding skills. Unity 3D is the easiest, because knowledge of C++ and associated low-level concepts is unnecessary. Students with strong programming and computer graphics skills may instead want to develop projects "from scratch," but they should be aware that implementation times may be much longer.

Acknowledgments

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I am grateful to the College of Engineering and Computer Science Department at the University of Illinois for their support of the course. Furthermore, Oculus/Facebook has generously supported the lab with headset donations. I am also grateful to the Indian Institute of Technology (IIT) Madras in Chennai, India, for their hospitality and support while I taught a short version of the course. I also appreciate the efforts of my colleagues at the University of Oulu, who in 2018 recruited me and supported me in building the Perception Engineering Laboratory, which investigates fundamental VR issues. Most of the thanks goes to Timo Ojala and the Center for Ubiquitous Computing. Finally, I am extremely grateful to the hundreds of students who have served as test subjects for the course and book while they were under development. Their endless enthusiasm and questions helped shape this material.

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