Second Edition

William R. Sherman
Alan B. Craig

UNDERSTANDING VIRTUAL REALITY

Interface, Application, and Design

Foreword by Mark Bolas

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MORGAN KAUFMANN

The Morgan Kaufmann Series in Computer Graphics

Understanding Virtual Reality

INTERFACE, APPLICATION, AND DESIGN

Second Edition

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Dedicated to Sheryl and all those who followed with love

Dedicated to my mother Mary Craig, the grand supporter
of all my endeavors

About the Authors

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William R. Sherman is a member of the Indiana University Advanced Visualization Lab, where he leads efforts in scientific visualization and virtual reality. He also teaches undergraduate and graduate courses on VR and visualization, which he has done for two decades, including at the University of Nevada, Reno (UVR), and at the University of Illinois at Urbana–Champaign (UIUC).

Previously he founded the Center for Advanced Visualization, Computation and Modeling (CAVCaM) at the Desert Research Institute (DRI), where he led the VR and visualization efforts, including overseeing the installation of a FLEX CAVE-style VR system as well as a six-sided CAVE system. Prior to DRI, he led the virtual reality effort at the National Center for Supercomputing Applications (NCSA) at UIUC, working with the Electronic Visualization Lab to install and operate the second CAVE VR system.

He has authored several book chapters and papers on the topics of scientific visualization and virtual reality, and has organized and led "bootcamps" on immersive visualization in collaboration with the Idaho National Lab and Kitware Inc. Sherman is the architect of the FreeVR VR integration library. He has attended every single IEEE Virtual Reality Conference since 1995, and was chair of the 2008 Conference.

Alan B. Craig, Ph.D.
Independent Consultant, Inventor, Musician, Author, Scientist, Teacher

Dr. Alan B. Craig is an independent consultant in virtual reality, augmented reality, visualization, and high-performance computing. Prior to this role, he contributed much to these fields during his 30-year career at the University of Illinois at Urbana–Champaign (UIUC) as a Research Scientist at the National Center for Supercomputing Applications (NCSA) and as Senior Associate Director for Human–Computer Interaction at the Institute for Computing in Humanities, Arts, and Social Science (I-CHASS). Among his other consulting roles, he is currently engaged with the Extreme Science and Engineering Discovery Environment (XSEDE).

Dr. Craig has been called upon to speak as an expert in VR and AR at countless worldwide events and continues to speak at various venues. He has taught classes related to VR and AR online as well as on-site at universities, companies, and high school campuses. Dr. Craig has worked with government and industry entities regarding VR and AR applications.

He has been interviewed by numerous publications, television, and news outlets.

In addition to *Understanding Virtual Reality* (with William R. Sherman) he also authored *Developing Virtual Reality Applications* (with William R. Sherman and Jeffrey D. Will) and *Understanding Augmented Reality*.

Additionally, he has written multiple book chapters and articles. He has developed many virtual reality and augmented reality applications in content areas ranging from archeology to zoology. He also teaches and advises on related topics. His primary focus has been on the use of virtual reality and augmented reality in educational applications and his work centers on the continuum between the physical and the digital.

He holds three patents.

Foreword

Our lives are spent in a mixed reality that integrates the real and the virtual—a reality in which much of our day is filled with synthesized experiences, to the point that "real" reality may be experienced less than "virtual" reality. We are often more engaged with our phones than with our physical environment.

I believe that mixed reality has the potential to reinvent our economy, tread lightly on the environment, and enable more satisfying creation, collaboration, and communication. With people texting each other across the dinner table and children confused when "pinch-to-zoom" does not work on the pages of a paper magazine, that may seem a foolhardy belief. But only because we have not opened ourselves up to the potential of a medium that frees us from the constraints of the physical world yet simultaneously keeps us perceptually grounded in our bodies.

We are in the middle of a transition from the industrial to the informational. Our mind-numbing life of email and web forms is a vestige of bygone thinking. We now must explore the perceptual, cognitive, and emotional power of the experiences that are possible in this new world, and study how the heart, mind, and body can joyfully inhabit the virtual realm.

In 1992 (the same year I met Alan and Bill), I wrote "*the designer must abandon the physical environment of everyday perception and the characteristics of other media in order to completely embrace the nature and character of virtual environments.*" I find this to be ever more important as the field progresses: Surrealism is essential in virtual environment design because of its counterintuitive ability to enhance the feeling of presence while transcending reality.

The psychologist J.J. Gibson posited that humans make sense of an environment by first modeling what is there, and then what it affords and enables us to do. That is how I think of this book. It goes beyond typical cursory descriptions of virtual reality—those that simply describe the surface of the medium—to consider structure and context. It dives below the surface to look at the topic from multiple

angles: historical, perceptual, technical, artistic. In doing so, it gives the reader a feeling not just for what the medium is, but what can be done with it.

That is a wise approach, because we are not at a point yet where anyone can truly describe what virtual reality is. It is far too powerful to know the course it will take—and that is what makes it so exciting to be a creator in the medium. That said, we are beginning to discover some of its boundaries, and I appreciate that Bill and Alan emphasize that virtual reality experiences are inherently co-created between developer and participant. It enables the *finding* of story more than the *telling*.

Similarly, the book does not attempt to serve as a textbook with neat answers in the back. Rather, it enables readers by providing a framework upon which to base their own explorations and experiments. I am happy to introduce this guidebook on our travels together to discover the nature of a new reality.

Mark Bolas
Bellevue, Washington

Preface

Introduction to the Second Edition

This edition of *Understanding Virtual Reality* has been a long time in the making [and as it happens, comes out on the 50th anniversary of Ivan Sutherland's first working head-mounted display (HMD)]. Recognizing that the technology used to create immersive experiences would continually evolve, our goal for the first edition was to discuss topics in as era-agnostic/technology-agnostic a manner as possible. To a large degree we feel we were successful in that regard.

The last line of the first edition of this book reads: "*What we (early VR developers) are developing now is the future. We need to be prepared for a future built on what we are doing today.*" And while that was mostly true, now we are riding a bigger wave, one that we don't control, but we can still steer a course through, and make our contributions.

Much of what we anticipated in the "Future" chapter of the first edition (Chapter 9) has come to pass—perhaps even bigger than we might have imagined even as we began our revisions 5 years ago. We did not anticipate such a rapid proliferation of smartphones and tablets in this timeframe, and especially their contribution to virtual reality (VR). We did not expect an entirely "new" method of position tracking to take off, and indeed two new technologies emerged: the Vive Lighthouse tracking system and the SLAM inside/out tracking method, which scans the world and then detects movements relative to what is now known about the world. Indeed, while working on what might have been an incremental update to the first edition, we were struck by the wave of smartphone-VR/Oculus Kickstarter, and then the 2016 release of three consumer HMDs (Oculus CV-1, HTC Vive, and Sony PlayStation-VR). Thus, as the new landscape began to take shape, we ended up doing a much more significant update than planned. (At the moment, we don't see another *huge* disruptive wave like this, but then you never know!)

We were also quite surprised to discover that one of the participants in our VR demonstrations held at the Illinois State Capitol in 2000, an Illinois state senator, went on to become rather famous—see Fig. 8.11D. (And if you look closely at Fig. 7.5, or preferably color plate 23, of our first edition, you will see him wearing the tracked glasses for our drunk driving simulator created for Allstate Insurance.)

As usual, the VR community rides the coat-tails of games and the game industry. VR development got a great boost when GPU cards brought new rendering capabilities for computer games, and it got another boost from smartphone technology, both in the small, flat, high-resolution displays, but also from the IMU inputs (GPS, tilt, compass, etc.), as well as the computing. And, then, when the component prices were low enough, from gaming enthusiasts who backed the funding of the Oculus HMD.

Learning about virtual reality covers a lot of topics spanning a large swath of computer science, engineering, perceptual psychology, art, physics, and storytelling. Certainly teaching virtual reality has changed, and for the better. In the past, we might offer the students a lab in a research building at the edge of campus (or even off campus) housing the one VR display that students could share time with researchers, be it a CAVE-style system or an HMD. After the introduction of the widely available Google Cardboard (which, in our case, Google provided free holders for two semester's worth of students), it was now possible for students to conveniently develop and test VR experiences. Later, as universities deployed labs with multiple HMDs in multiple public spaces (including libraries), students could now make use of the full 6-DOF VR experience in their work. In addition, teaching VR has changed in that more accessible software toolkits are now available with the emergence of the integration of game engines with VR, perhaps most notably, Unity.

Yet overall, the concept of virtual reality as a medium is the same. There are still the same design criteria that existed in the past, though we may know a little more about what works under particular circumstances than before.

The examples shown in this edition are a mix of new and old. When we could find good modern examples, we did; but when older examples still best exemplified some concept, then they were retained. New interfaces and representations have begun to coalesce, but perhaps not on the best options, and some good ideas have fallen by the wayside, but need to be explored further. Since the publication of the first edition we published another book (*Developing Virtual Reality Applications*), which looks at many examples (some now historical) that

had good ideas, which should be considered when developing the next generation of experiences. Additionally, Alan Craig has written a book titled *Understanding Augmented Reality* that focuses specifically on AR.

What This Book Is

The aim of this book is to explore the use of virtual reality as a means of sharing information and experiences among people—as a medium of human communication. We have sought to provide a comprehensive overview of the medium of virtual reality, including the technology required to produce the physically immersive effect and the interface design necessary to provide useful and meaningful content.

Research in VR is turning the corner from being focused primarily on technology to an increasing focus on what can be done using VR—content is now driving the application. The earlier focus on technology wasn't because researchers lacked interest in what could be done with the emerging medium, but because the technology itself was lacking in many ways. Researchers like Fred Brooks at the University of North Carolina at Chapel Hill aimed their work at usable applications, but recognized that significant advances would be required in the fields of computer graphics, display, and tracking devices among others, and thus were compelled to extend their research in all these directions.

As the required technology has become widely available and of adequate quality, the medium of virtual reality has become a feasible tool for accomplishing research, and not just a topic of research for its own sake. Beginning in the late 1980s and early 1990s, enough technological advancement had taken place that more centers of research (in business and academia) could afford to experiment with VR. Now we have reached the point of technology being inexpensive enough not only for larger research facilities, but for the mass market as well. Thus, using and creating VR content has become largely cost-effective at the consumer level. This book explores what is required to develop virtual reality applications for real-world uses in areas such as science, industry, art, education, and medicine.

Much like the entertainment industry has driven the development of computer graphics, so movies, arcades, and the home entertainment market have been among the first to exploit the commercial possibilities of VR. These forces are what are helping bring prices into a reasonable range for more widespread application. Among some niche audiences, many viable scientific, industrial, medical,

educational, and artistic applications have already emerged. Indeed, many examples are taken from real-world VR applications, ranging from science, manufacturing, business, medicine, education, sports, arcade entertainment, art, and the military.

Our goal in writing this book is to provide a comprehensive volume on the medium of virtual reality, how it can be used, and how to create compelling virtual reality applications. Our coverage of this new medium also briefly examines its origins, what comprises a VR system, and the methods of interfacing human participants with virtual worlds. While we briefly discuss the types of virtual reality systems and the differences between them, we avoid going into great detail on the hardware technology—advances in technology are too rapid to be covered in depth in this volume, and there are other resources available for obtaining this information. The most current, detailed information is generally found at conferences, tradeshows, and online.

What This Book Is Not!

This book is not a tutorial on how to implement a VR system with today's technology. We presume that the readers of this book will be approaching VR on a content level. The goal is to have a book which will be useful beyond the technologies of today. There are many resources available for those who need to learn the ins and outs of low-level VR device interfacing.

Neither does this book cover the programming aspects of virtual reality or computer graphics. Rather, the focus is on issues of content, interaction, system integration, and usability. On the other hand, this book has been successfully utilized as a text in VR programming courses through integration with other VR programming resources.

Whenever possible, we will try to aid the reader in acquiring factual, practical information and in separating the pragmatic from the gimmicky. VR has been accused of being merely a technological novelty, something overly promoted by the press into a false sense of importance. While there is some truth to VR being hyped in the press, the authors believe (and hopefully demonstrate in the chapters that follow) that VR is a useful emerging medium, one that cannot be ignored. Astute readers will recognize the power of the new medium and work to harness it in ways that are constructive in their own applications.

Who This Book Is For

This book is intended to be of interest to anyone with a forward-looking view—those in business, as well as scientists, engineers, educators, and artists—who want to go beyond the hype and learn about how VR is being applied to solve problems today. The target reader is technically knowledgeable but may be unaware of how to apply VR to their particular area of interest.

This book is also intended to be useful as a textbook in a course on virtual reality. It is an appropriate text for graduate or undergraduate courses on VR aimed at providing a broad background in VR systems and content. The collegiate audience includes students from a variety of disciplines, ranging from computer science, engineering, psychology, medicine, education, science and the arts. Indeed, to a large degree, VR developers need to be jacks of all trades, or at least jacks of many trades, who team up with others with complementary skills.

Further, this book is designed to be a useful source of information for anyone who wonders whether VR can benefit them, whether as a tool to explore information and convey ideas or to develop a full virtual reality application. Often VR conjures up the limited notion of games and complicated science. To investigate how virtual reality can be applied in a variety of fields, we examine general virtual reality interface techniques in Part II, and overall design in Part III.

How to Use This Book

The first part of this book (Part I) is intended to give the reader the terminology and background required to understand the application of VR. The chapters in the middle (Part II) focus on technical issues, interaction techniques, content choice, and representation concerns that require attention when designing VR applications. In this second edition we now include a chapter (3) on the aspects of the human user that play significant roles in how a VR application is personally experienced. The concluding chapters (Part III) explore the issues that come into play when designing VR experiences, and explore the classifications of those experiences with a look at the experiences from the past that we can learn from. The final chapter concludes with a look at both where the future may lie for virtual reality systems and applications, as well as a look back to how our predictions in the first edition fared.

You can think of the three parts of the book as:

- Part I—The "What" of VR;
- Part II—The "How" of VR; and
- Part III—The "Why," "How-to" (or "How-best-to"), and "What's to come?" for VR.

To gain an understanding of the basics of the field and what has been done with virtual reality in a variety of application areas, the reader may well read this book from cover to cover. However, usage of this book can be tailored to a variety of different university-level courses. A technically oriented course may focus less on the initial chapters, which emphasize VR as a communication medium, and more on the technical and systems chapters (Part II); a media studies course, or any source where the interest is primarily at the content level, may de-emphasize the technical issues of VR systems, and focus instead on the usage of virtual reality (Parts I and III). A VR programming course can touch on the technology and usability aspects of this book, in particular by taking advantage of the additional online material we provide at www.understandingvirtualreality.com.

In the first edition of this book, we included a collection of appendices, each providing an in-depth look at a particular VR experience. Those will now be available on the website.

How to Help Us Improve This Book

Of course, as VR and AR/MR (and thus "XR") continue to develop both as media and through the underlying technologies, there are bound to be new concepts that aren't covered by the material in this book (like SLAM tracking was for the first edition of this book). Beyond that, research continues on how humans interact with technology, and how experiences can be improved to meet the participant where they are. Thus at some point a third edition of this book will be warranted. As such, we certainly would welcome input from any readers of this book, and in particular anyone teaching a course on VR/AR/MR/XR. (We already envision splitting at least one of the chapters which has became rather large, but due to time constraints chose to leave as a single chapter in this edition.)

Quirks of Authorship

VR is a medium that can only truly be experienced live, and it can be difficult to understand certain concepts without prior familiarity with the medium. Thus, in keeping with the visual nature of VR, we use a considerable number of photographs, screenshots, and diagrams to enhance the text. The reader may notice that many of our images utilize the *CAVE* VR system. We did this because it is easier to witness a participant interacting in a virtual reality experience in a stationary VR display and because a *CAVE* system was at our ready disposal.

However, we have also used many head-based systems and recognize that they are the most appropriate display choices in many circumstances. So our discussion of display technologies attempts to strike a good balance between stationary and head-based displays (HBDs). Accordingly, we also include several photographs of head-based display systems.

As indicated, it is not the objective of this book to provide a detailed look at today's rapidly changing technology. We hope the information presented here will continue to be of use when today's hardware is suitable for display in a museum as the object on display rather than the means of display. There are already many useful sources of information covering the intricacies and implementations of current VR technology.

Because there is no set standard for how to implement genderless singular pronouns in the common usage of English, we include our choice as one of our quirks. We have chosen to use *they/them*, etc. as our solution. We think this works the best, and much like *you/your*, etc. were once used only in plural situations (vs. *thy/thine*, etc.), it is certainly possible for *they/them*, etc. to make the same leap. Here we boldly offer the precedent found in the works of William Shakespeare, William Caxton, and Jane Austen.

Threads

Who doesn't like to have fun? One additional "quirk of authorship" is the handful of recurring themes (allusions, or perhaps "running gags") we include that refer to elements of popular, classical, or even VR-specific culture from our part of the world—themes such as: *Moby Dick*, *The Muppets*, *Portal* (i.e., the virtual world of *Portal*), the *Crayoland* VR world, The Who, and finally appearances of colleagues and family in many of the photos herein (and yes, "running gag" is a reference to "*The Muppet Movie*," so that's one!). We have surprisingly few references to

Seinfeld and Monty Python. We give a special hat-tip to a 1994 episode of Saturday Night Live which included a spoof commercial on "Virtual Reality Books," which featured *Moby Dick*, thus beginning our inclusion of allusions.

Acknowledgments From the First Edition

A large number of people have contributed to the creation of this book (starting with the first edition). The first contribution was from Audrey Walko, who put us in contact with Mike Morgan (founder of Morgan Kaufmann Publishing) and thus initiated our journey. Another early contribution was provided by Mary Craig, who transcribed portions of our first drafts from dictation.

Ideally, we would like to individually acknowledge each person who has shown and discussed with us their virtual reality work, including hosting us during our visits to many VR facilities around the world. Our initial focus was on how virtual reality has been applied to a wide variety of disciplines and topic areas. Thus, our authorial journey began with an exploration of as many virtual reality applications as we could find, experience, and discuss with the creators. Our discussions with the people responsible for more than 50 virtual reality applications have certainly helped shape our view of what is involved in creating a good VR experience.

As the book progressed and expanded to include material on the medium of virtual reality, it became unwieldy, and we elected to remove much of the material we wrote about existing VR applications from that particular publication. [Indeed, most of our material on those VR applications became the content for our book "*Developing Virtual Reality Applications*."] Also, portions of that effort remain in the images used to exemplify many concepts (and in the first edition in the four appendices). Thus we acknowledge many of our contributors directly in the captions. However, it is our ongoing goal to acknowledge individually the many people whose generosity we encountered in our initial surveys, by working to make much more of that material available.

Of course, there are many people who literally shared their virtual reality work with us by allowing us to run their applications at our facility. Again, their generosity is most amply evident through our use of many of these applications in our photographs of how various VR techniques are implemented, and we acknowledge these individuals in the photograph captions. We would like to especially thank Dave Pape for directly or indirectly making many of the *CAVE* applications available and for allowing us to use the *Crayoland* House, which we transplanted into many example scenarios.

We would also like to acknowledge the many people we have had the opportunity to collaborate with at NCSA. Certainly this includes all the people who've done visualization work at NCSA with a special mention of those involved in the visualization group representation project. The representation project introduced us to a lot of the underlying concepts of visualization, including perception, presentation, mapping, semiotics, and cognition. Even when our day-to-day tasks keep us focused on technology, our primary aim is to use technology for the purposes of communication and to gain insight. We hope we have been able to present some of the concepts explored during those insightful sessions in such a way as to make them accessible to the reader.

NCSA had also provided us ample opportunity to work with research scientists interested in pursuing visualization, and sometimes VR, as tools for investigating their science. Our work has also put us in contact with businesses interested in putting VR to use, as a manufacturing design tool, promoting safety, and visualizing retail data. We worked with professors who provided novel teaching environments through the medium of virtual reality. NCSA management contributed through their support of the NCSA virtual reality facilities, beginning with a FakeSpace *BOOM*, VPL, and Virtual Research HMDs, and a single screen projected display in 1991, to the *CAVE* that we then used on a regular basis, but was ultimately retired. Also, NCSA's collaboration with the Electronic Visualization Lab (EVL) at the University of Illinois at Chicago, then headed by Tom DeFanti and Dan Sandin, remains a great source of information, technology, and inspiration through the years.

Given the number of iterations through which this book progressed, it is not surprising that we have a large number of reviewers to thank for their comments. In alphabetical order, they include Colleen Bushell, Toni Emerson, Scott Fisher, George Francis, Kurt Hebel, Andy Johnson, Mike McNeill, Robert Moorhead, Carla Scaletti, Steve Shaffer, Audrey Walko, and Chris Wickens. Three reviewers in particular provided us with detailed comments for several of the chapters; Bill Chapin, Rich Holloway, and Holly Korab. And there have been a few anonymous reviewers whom we would like to thank just as much for pushing the book to be better than it might have been.

We would also like to thank Mike Morgan and his crew at Morgan Kaufmann— in particular, our editor Diane Cerra, series editor Brian Barsky, and Belinda Breyer. Mike and Diane had the patience to allow us to iterate over the design and implementation of various aspects of the book as we honed in on the current product. Belinda's contributions included a complete review and edit of the book to help make sure all the necessary information was included and ordered for readers new to the field.

We would like to thank Beverly M. Carver for developing many of the line drawings. We would also like to thank Yonie Overton for helping us further shape the prose and for overseeing the design and production process. Her efforts helped make the final product better.

And finally, we would like to thank our families: Bill's wife Sheryl, who took on more of the home load and was supportive through the marathon this book became. And Cindy and Danielle for behaving as best as kids can be expected to for Mom, even though Dad wasn't around as much as he or they would have liked. And Theresa for waiting to arrive long enough for us to get the final edits completed. And Alan's friends and family for encouragement and expertise in any number of technical areas.

Acknowledgments for the Second Edition

Once again, a large number of people have contributed to the creation of this book. We first thank the reviewers of our proposal to update this book: Christoph Borst, Torsten Kuhlen, and Ryan McMahon, not just with the encouragement to produce the new edition, but also with thoughtful comments on where improvements could be made. We also owe our thanks, and perhaps apologies, to Jesse Schell from whom we first learned about the Gartner Hype Curve, and had further discussions. His acknowledgment in the first edition had been in the form of a footnote, but when the book layout choice to exclude footnotes was adopted, his credit was not transferred to the Preface.

We also had great conversations with many VR practitioners, including Mary Whitton, Jason Jerald, and Richards Skarbez (especially when working on the Presence section); and also John Stone who provided considerable insight into the world of modern GPU rendering. Additionally, Carla Scaletti of Symbolic Sound Corp. provided information and review regarding audio generally and audio specifically in virtual reality.

As with the first edition, this book has been greatly enhanced through our working relationship with our colleagues and collaborators. Now, not just at NCSA, but at the Desert Research Institute (DRI), I-CHASS, and Indiana University. And, of course, we have now visited approximately 100 VR labs around the world, plus we can now easily download VR experiences directly to our personal VR systems!

And for a second time, we acknowledge the great, and often heroic contributions of Beverly M. Carver for her help with the 2D diagrams, many of which needed to be updated, and as we lost some of the original files, had to be recreated

from scratch. Once again there are many who contributed images for this book, and their contributions are provided in the corresponding captions. Images appearing without credit, are generally those that we created—except for most of the 2D diagrams by Bev. Thus, screenshots of purchased and open applications, 3D worlds created in Unity and Iris Inventor, and the 2D illusions created in Py-cairo, were created by ourselves semianonymously (except for this attribution here). For some reason, we did give ourselves credit for our photographs.

Also to the teams at Elsevier/Morgan Kaufmann, including Todd Green and then Meg Dunkerley who signed us up for the second go-round, along with Amy Invernizzi; and then with Ana Garcia, and the production team, including Punithavathy Govindaradjane and Sandhya Narayanan. As with the first edition, it was a long process, and we thank them for persevering with us, and pushing us across the finish line.

And finally, to our families: Bill's wife Sheryl, who again did more driving and more homework help, etc. while Bill spent evenings and nights writing, editing, and emailing. And to the kids, now a longer list: Cindy with Josh, Danielle, Theresa, Thomas, and Anthony, along with a few more: Gracie, Nora, and Andrew, who occasionally wandered into Grandpa's study to provide some comic relief. To Bill's parents, Robert and Kathleen, who probably remember when my fifth-grade book project on the solar system started to get out of hand. And, Alan's friends and family, too numerous to mention.

PART I

What Is Virtual Reality?

Chapter 1 begins with our description of what is meant by *virtual reality* (VR). We begin with the dictionary definitions of *virtual* and *reality* and consider how these individual words combine to describe a unique means of human communication. We go on to define other key terms and offer a brief history of the origins of VR.

Chapter 2 examines how knowledge about previously existing media can be applied to the medium of virtual reality and looks at the media from which VR has evolved. We compare the characteristics of virtual reality with other media for human communication and explore how VR is used to convey models of virtual worlds.

Introduction to Virtual Reality

Human history is marked by a progression of media used to convey and experience ideas. One of the most recent steps in this progression is the use of virtual reality (VR). Recorded history begins with people painting on cave walls to express the happenings of the hunt and sharing stories to chronicle the history of a community or tribe. It was the importance of communication that raised the storyteller to a position of high esteem within a community.

The first cave paintings transcend the physical experience they depict (Fig. 1-1). These paintings were a primitive medium for conveying the artist's concept. They were a method for communicating ideas, useful facts, and events among people. Viewers then superimposed their own interpretations on the painter's manifested expression.

Starting with the first pigment spread on cave walls, new technologies have developed and evolved, leading in turn to new media (Fig. 1-2) Along the way, humans have explored ways to utilize each new medium to best express their ideas. Virtual reality is a new medium brought about by technological advances in which much experimentation is taking place to find practical applications and more effective ways to communicate.

FIGURE 1-1 *Cave paintings were an early medium for storytelling. A virtual world could be conveyed from one person to another via the technology of pigment on stone. (Image courtesy of Benjamin Britton.)*

Defining Virtual Reality

As the medium of virtual reality matures, different people and groups of people have different ideas and different points of view about what it encompasses. Those less familiar with the field may have slightly different interpretations. The definition we use in this book reflects what is generally meant by practitioners and scholars of the field of VR—which is not always how the term has been used by marketing departments and the mass media.

Webster's New Universal Unabridged Dictionary [1989] defines *virtual* as "being in essence or effect, but not in fact." This usage has been applied to earlier concepts in computing; for example, when a computer system requires more RAM (primary storage) than is available, memory is expanded *virtually* by use of disk storage (secondary, cheaper storage). The resultant, seemingly enlarged RAM capacity is referred to as *virtual memory*.

What is meant by *reality* is more complicated, and trying to define it completely can result in complex philosophical discussions. *Webster's* defines reality as "the state or quality of being real. Something that exists independently of ideas concerning it. Something that constitutes a real or actual thing as distinguished from something that is merely apparent." To simplify things for our purposes, let's say it is a place that exists and that we can experience.

Five Key Elements of the Virtual Reality Experience

The key elements in experiencing virtual reality—or any reality for that matter—are *the virtual world*, *immersion*, *interactivity,* as well as *the people on the creating and receiving sides of the medium*.

Key Elements 1 and 2: The Participants and the Creators

Chapter 2 focuses on what it means for VR to be a medium—a means of communication between people. So two key elements of any VR experience are those people.

Indeed, probably *the most* important element to any VR experience is the participant(s). All the magic of VR happens in the mind of the participants, hence, every VR experience is different for each of them, because each brings their own capabilities, interpretations/background/history, and thus experiences the virtual world in their own unique way.

Imagination
Dance
Music
Storytelling (oral tradition)
– BEGIN RECORDED HISTORY –
Cave painting
Written language
Sculpting (e.g., totem poles)
Musical notation
Books (hand written)
Books (printing press)
Newspapers (periodical information)
Telegraph
Photography
Stereoscope (Whetstone)
Stereo photography
Animated images
Motion pictures (mass visual presentation)
Telephone
Radio
Recorded audio
Television (mass visual presentation)
Digital computer (ENIAC)
Flight simulation
Computer graphics (sketchpad)
First HMD (Sutherland)
Video games
Picture phone
Video teleconferencing
Internet (telnet, ftp, sockets, etc.)
Color frame buffers for computers)
Computer graphics animation
Networked computer discussion forums (USENET) etc.
Stereo computer graphics
Interactive computer graphics
MUDs, etc.
Immersive Interactive computer display (ie. VR)
Augmented Reality
The CAVE (theater-like VR venue)
The World Wide Web
Physical Video Games (DDR, Wii, Kinect)

FIGURE 1-2 *From painting cave walls to sharing computer-generated images on the screens of a virtual CAVE and beyond, the history of humankind has been marked with a progression of new media.*

Note that while this book focuses on participants that are humans, VR experiences can be created for (and experienced by) nonhuman participants. For example, experiments have been designed with "participants" as varied as fish [Hughes 2013], cockroaches, and praying mantises [Nityananda et al. 2016] (Fig. 1-3).

FIGURE 1-3 *In experiments to determine the ability of praying mantises to use stereopsis to measure distance, beeswax is used to affix anaglyphic filters over the insect's eyes. (Because praying mantises have poor red vision, filters are colored with blue and green hues.) (Image courtesy of Newcastle University, UK.)*

The second key element then is the person or team that designs and implements the application and system as a created work to be experienced by the participant(s). We avoid calling this person/team the author for reasons discussed in Chapter 2, but rather think of them as "creators," "composers," or "developers" of the work. This book is primarily intended for people interested in creating applications and systems that can be engaged as a VR experience. We generally differentiate between what we call the "application" (or the work) versus the "experience" because the experience is actually created as a team effort between participants and creators, even though in general they will have never met, whereas what we call the "application" is the combination of the VR system along with specific code, concepts, and models presented to participants to aid them in their experience. These ideas are sufficiently important that we will delve deeper into them in Chapter 2.

Key Element 3: Virtual World

A virtual world is the content of a given medium. It may exist solely in the mind of its originator or be manifested in such a way that it can be shared with others. A *virtual world* can exist without being displayed in a *VR system* (i.e., an integrated collection of hardware, software, and content assembled for producing VR experiences)—much like play or film scripts exist independently of specific instances of their performance. Such scripts do in fact describe virtual worlds. Let's carry the analogy further. We can refer to the script of a play as merely the description of a play. When that description is brought to life via actors, stage sets, and music, we are *experiencing* the play's virtual world. Similarly, a computer-based virtual world

is the description of objects within a simulation. When we view that world via a system that brings those objects and interactions to us in a physically immersive, interactive presentation, we are experiencing it via *VR*.

> **Virtual world: (1)** an imaginary space often manifested through a medium. **(2)** a description of a collection of objects in a space and the rules and relationships governing those objects.

Key Element 4: Immersion

Considering the user must be *immersed* within some other, alternate reality, an admittedly simplistic definition of VR might be:

> **Virtual reality:** Immersion into an alternate reality or point of view.

But what does this mean? Where do you go to get immersed into an alternate reality or POV? What in fact *is* an alternate reality or POV? According to our simple definition, a medium qualifies if its participants are able to perceive something other than what they would have without an external influence. This definition acknowledges the possibility of perceiving something besides the world you are currently living in in two ways: you can either perceive an alternate world or the normal world from another POV.

An alternate world might be a representation of an actual space that exists elsewhere, or it could be a purely imaginary environment. Alternate worlds are often created in the minds of novelists, composers, and other artists and creative individuals.

Imagine for a moment that you are empowered with the magical ability to live in a world other than the one you currently inhabit. You are given new powers, objects have different properties, perhaps there is no gravity. Other human and nonhuman beings inhabit this space. Space may or may not exist in the same way it does in our universe. Perhaps the shortest distance between two points is not a straight line. Is such a scenario possible?

If you are able to imagine such a place then indeed, it is possible. Imagination is where virtual worlds begin and how numerous virtual worlds are experienced. The power of imagination can allow us to dwell where we choose, when we choose, and with whom we choose. We are limited only by what we can imagine and our ability to communicate it.

FIGURE 1-4 *Ideas can be manifested and conveyed in powerful ways through media such as novels and movies. ((A) © Hallmark Entertainment Distribution, LLC. All rights reserved. (B) Reprinted by permission of Citadel Press/Kensington Publishing Corp., www.kensingtonbooks.com, © 1985 by Douglas Brode. All rights reserved.)*

We often desire to manifest the ideas of our imagination into some *medium*. By doing so, we are able to share our world with others and to partake in the creations of others. A novel, for instance, can take us to exotic places and into a life other than our normal daily existence, as can motion pictures, radio, television, and animation (Fig. 1-4). However, each of *these* media produces only one-way communication: from creator to audience. The point of view (POV) is preselected. The dialog is predetermined. The outcome of the story is preordained. However, each member of the audience will likely have a different reaction, perhaps in ways unexpected by the creator.

Depending on a writer's ability to envelop the reader into the world of the story—through a realistic, or at least self-consistent representation of the story-world, referred to as *mimesis*—a novel might qualify as an alternate world that *immerses* the reader. Perhaps you have found yourself empathizing with the characters in a radio, motion picture, or television show. Your *suspension of disbelief* makes the content of these media seem real. None, however, provide direct interaction between the viewer or listener (the recipient) and the world. Furthermore, these media often present their worlds from a third person POV.

Yet the major difference between these experiences and VR is that they only engage the participants at the mental level. Whereas, in VR the effect of entering the world begins with *physical*, rather than mental, immersion. Because physical immersion is a necessary component of VR, our simple definition is not specific enough as many other media fall within its parameters.

Physical and Mental Immersion

Thus, the term *immersion* can be used in two ways: mental immersion and physical (or sensory) immersion. In discussions of most media, "being immersed" generally refers to an emotional or mental state—a feeling of being involved in the experience. In the medium of VR, however, we also refer to physical immersion as the property of a VR system that replaces or augments the stimuli to the participant's senses.

The state of being mentally immersed is often referred to as having "a sense of presence" within an environment. Unfortunately, there is not yet a common understanding of precisely what each of these terms means, how they relate to one another, or how to differentiate between them. (We have found one book in which chapters written by different authors give exactly the opposite definitions for immersion and presence.) Let's define what *we* mean by these three terms and how they are used in *this* book.

> **Immersion:** sensation of being in an environment; can be a purely mental state or can be accomplished through physical means: physical immersion is a defining characteristic of VR; mental immersion is a principal goal of most media creators.

> **Mental immersion:** state of being deeply engaged; suspension of disbelief; involvement.

> **Physical immersion:** bodily entering into a medium; synthetic stimulus of the body's senses via the use of technology; this does not imply all senses or that the entire body is immersed/engulfed.

We will generally use the terms *mental immersion* and *physical immersion* to discuss these phenomena. However, the VR community has also embraced the term *presence* (probably because of prior use of the term *telepresence*) to represent this concept. In this context it may be more precise to say "*sense of presence*," which is how we will generally express this concept.

> **Presence:** short for sense of presence; being mentally immersed.

Unlike more traditional media, VR allows participants to select their vantage point by positioning their body and to affect events in the virtual world. These features help to make the reality more compelling than static, third-person media experiences.

The participant's feeling as though they can exert control into the virtual world is referred to as their sense of "*agency*" within the world (Fig. 1-5). More will be said about presence, agency, and related topics in Chapter 3.

Without getting into a philosophical discussion of what reality is, we will consider that there can be more than the reality we experi-ence firsthand with our unaided senses. We refer to the latter as *physical reality*. *Imagined reality* refers to the experiences we have in our thoughts and dreams or that we experience secondhand in novels, films, radio, and so on. In imagined reality, we imagine ourselves within the world presented through the medium—also known as the *diegesis*. The diegesis of a world presented through a medium includes places and events that are not directly presented but are implied to exist or to have occurred. VR is the medium through which we can use our physical scenes to experience an imagined reality; that is, we use less of our imagination during the experience and rely more on the imagination of the content creator. In other words, VR is a medium that allows us to have a simulated experience approaching that of physical reality. VR also allows us to purposefully reduce the danger of physical reality and to create scenarios not possible in the real world. We will discuss diegesis as well as mimesis further in the "Verisimilitude" section of Chapter 6.

Sensory feedback is critical to physical immersion, and thus to VR. The VR system provides direct sensory feedback to participants based on their physi-cal position. In most cases, it is the visual sense that receives feedback, although VR environments do exist that display (perhaps exclusively) haptic (touch) expe-riences, sound experiences, and so on. Achieving immediate interactive feedback requires the use of a high-speed computer as a mediating device.

In order to base the sensory output of the VR system on the position of the participant, the system must track their movement. A typical VR system will track the head of the participant and at least one hand or an object held by the hand. Advanced systems may track many of the major body joints. There are a variety of

FIGURE 1-5 *The ability to affect the world (exert your will onto the world), gives a person agency and helps them to accept the world as real. (Photograph by William Sherman.)*

technologies that can be used by a VR system to perform tracking. These technologies are described in Chapter 4. A good definition is:

> **Position tracking:** the computerized sensing of the position (location and/or orientation) of an object in the physical world—usually including one or more parts of the participant's body.

Key Element 5: Interactivity

For VR to seem authentic, it should respond to user actions. Thus, another necessary component in the full definition of VR is *interactivity*. Interactivity comes more readily with the addition of the computer to the equation. Alternate realities supported by computers include games, computer simulations of natural and unnatural phenomena, and flight simulation.

It should be noted that computer graphics are not required for any of these alternate realities. The classic computer games *The Oregon Trail* (the very original version), *Adventure*, and *Zork* (originally called *Dungeon*; see Fig. 1-6) render their worlds via text descriptions. Each world responds to commands typed by the player, giving the player the sense of being involved. Within these imaginary worlds, players interact with objects, characters, and places in them. The medium of authored, text-based interactive worlds is now generally referred to as *interactive fiction* (IF).

The ability to affect a computer-based world describes one form of interactivity. Another form is the ability to change one's viewpoint within a world. Interactive fiction can be defined in terms of the user/player's ability to interact with a world by changing locations, picking up objects and setting them down, flipping switches, and so on. VR is more closely associated with the ability of the participant to move physically within the world, obtaining a new vantage point through movements of the head. IF and VR may be defined by one particular form of interaction,
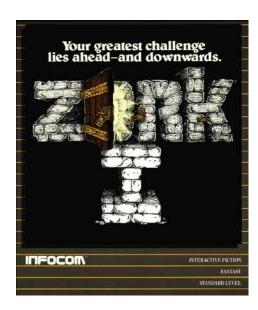
FIGURE 1-6 *The digital computer provided a platform for new media. By allowing a participant to interact with a story delivered as text by a computer program, interactive fiction provides a powerful communication mechanism. Zork was one of the first commercially successful interactive fiction programs. Recognizing the power of the medium and the creativity of the consumer, Infocom, Inc. showed a human brain in their advertising and boasted: "We stick our graphics where the sun don' t shine!" (Image courtesy of Infocom, Inc.)*