The VR Book

Human-Centered Design for Virtual Reality

Jason Jerald, Ph.D.

The VR Book

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NextGen Interactions

ACM Books #8

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ISBN: 978-1-97000-112-9 paperback
ISBN: 978-1-97000-113-6 ebook
ISBN: 978-1-62705-114-3 ePub
ISBN: 978-1-97000-115-0 hardcover
Series ISSN: 2374-6769 print 2374-6777 electronic

A publication in the ACM Books series, #8
Editor in Chief: M. Tamer Özsu, *University of Waterloo*
Area Editor: John C. Hart, University of Illinois

First Edition

10 9 8 7 6 5 4 3 2 1

DOIs

10.1145/2792790 Book
10.1145/2792790.2792791 Preface/Intro
10.1145/2792790.2792792 Part I
10.1145/2792790.2792793 Chap. 1
10.1145/2792790.2792794 Chap. 2
10.1145/2792790.2792795 Chap. 3
10.1145/2792790.2792796 Chap. 4
10.1145/2792790.2792797 Chap. 5
10.1145/2792790.2792798 Part II
10.1145/2792790.2792799 Chap. 6
10.1145/2792790.2792800 Chap. 7
10.1145/2792790.2792801 Chap. 8
10.1145/2792790.2792802 Chap. 9
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This book is dedicated to the entire community of VR researchers, developers, designers, entrepreneurs, managers, marketers, and users. It is their passion for, and contributions to, VR that makes this all possible. Without this community, working in isolation would make VR an interesting niche research project that could neither be shared nor improved upon by others. If you choose to join this community, your pursuit of VR experiences may very well be the most intense years of your life, but you will find the rewards well worth the effort. Perhaps the greatest rewards will come from the users of your experiences—for if you do VR well then your users will tell you how you have changed their lives—and that is how we change the world.

There are many facets to VR creation, ranging from getting the technology right, sometimes during exhausting overnight sessions, to the fascinating and abundant collaboration with others in the VR community. At times, what we are embarking on can feel overwhelming. When that happens, I look to a quote by George Bernard Shaw posted on my wall and am reminded about the joy of being a part of the VR revolution.

> This is the true joy in life, the being used for a purpose recognized by yourself as a mighty one; the being a force of nature . . . I am of the opinion that my life belongs to the whole community and as long as I live it is my privilege to do for it whatever I can. I want to be thoroughly used up when I die, for the harder I work, the more I live. I rejoice in life for its own sake. Life is no "brief candle" to me. It is sort of a splendid torch which I have a hold of for the moment, and I want to make it burn as brightly as possible before handing it over to future generations.

This book is thus dedicated to the VR community and the future generations that will create many virtual worlds as well as change the real world. My purpose in writing this book is to welcome others into this VR community, to help fuel a VR revolution that changes the world and the way we interact with it and each other, in ways that have never before been possible—until now.

Contents

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* Practitioner chapters are marked with a star next to the chapter number. See page 5 for an explanation.

Preface

I've known for some time that I wanted to write a book on VR. However, I wanted to bring a unique perspective as opposed to simply writing a book for the sake of doing so. Then insight hit me during Oculus Connect in the fall of 2014. After experiencing the Oculus Crescent Bay demo, I realized the hardware is becoming really good. Not by accident, but as a result of some of the world's leading engineers diligently working on the technical challenges with great success. What the community now desperately needs is for content developers to understand human perception as it applies to VR, to design experiences that are comfortable (i.e., do not make you sick), and to create intuitive interactions within their immersive creations. That insight led me to the realization that I need to stop focusing primarily on technical implementation and start focusing on higher-level challenges in VR and its design. Focusing on these challenges offers the most value to the VR community of the present day, and is why a new VR book is necessary.

I had originally planned to self-publish instead of spending valuable time on pitching the idea of a new VR book to publishers, which I know can be a very long, arduous, and disappointing path. Then one of the most serendipitous things occurred. A few days after having the idea for a new VR book and committing to make it happen, my former undergraduate adviser, Dr. John Hart, now professor of computer science at the University of Illinois at Urbana–Champaign and, more germanely, the editor of the Computer Graphics Series of ACM Books, contacted me out of the blue. He informed me that Michael Morgan of Morgan & Claypool Publishers wanted to publish a book on VR content creation and John thought I was the person to make it happen. It didn't take much time to enthusiastically accept their proposal, as their vision for the book was the same as mine.

I've condensed approximately 20 years and 30,000 hours of personal study, application, notes, and VR sickness into this book. Those two decades of my VR career have somehow been summarized with six months of intense writing and editing from

January to July of 2015. I knew, as others working hard on VR know, the time is now, and after finishing up a couple of contracts I was finally able to put other aspects of my life on hold (clients have been very understanding!), sometimes writing more than 75 hours a week. I hope this rush to get these timely concepts into one book does not sacrifice the overall quality, and I am always seeking feedback. Please contact me at book@nextgeninteractions.com to let me know of any errors, lack of clarity, or important points missed so that an improved second edition can emerge at some point.

It all started in 1980

I owe much of my pursuit of developing VR systems and applications to my parents. It started at the age of six with an Atari game system that my family couldn't afford but I wanted so badly. For Christmas 1980, I somehow received it. Then in 1986 my mother took away the games in hopes of curing my addiction, which naturally forced me to make my own games (with advanced moving 2D sprites!) on the family's Commodore 64. Here, I taught myself programming and essential software design concepts, such as simple computer graphics and collision detection, which turned out to be quite important for VR development. At that point, she thankfully gave up on trying to cure me. I also owe my father, who connected me with my first internship in the summer of 1992 after my junior year of high school at a design firm where he worked. My job was to deliver plots from the printers to the designers. This did not completely fill my time, and I somehow managed to gain access to AutoCad and 3D Studio R2 (long before today's 3ds Max!). I was soon extruding 2D architectural plans into 3D worlds and animating horrible-looking flat-shaded polygons in the evenings and weekends when nobody was the wiser.

SIGGRAPH 1995 and 1996

After regrettably missing SIGGRAPH 1994, I somehow acquired the conference course notes on creating virtual worlds and other related concepts. Soon afterwards, I discovered the SIGGRAPH Student Volunteer Program and realized that was my ticket to the conference. After realizing what I missed, I was not going to leave the opportunity to chance. I sought out a referral from Dr. John Hart, a professor very heavily involved with SIGGRAPH. He must have given me a solid referral based on my initiative and passion for computer graphics, as I had not yet taken a class from him. John would later become my undergraduate adviser and eventually editor of this book. Both his advice through the years and SIGGRAPH had an enormous influence on my career. In fact, I ended up leading the SIGGRAPH Student Volunteer Program more than a decade later, out of appreciation and respect for its ability to inspire careers in computer graphics.

I was quite fortunate to be accepted to the 1995 SIGGRAPH Student Volunteer Program in Los Angeles, which is where I first experienced VR and have been fully hooked ever since. Having never attended a conference up to that point that I was this passionate about, I was completely blown away by its people and its magnitude. I was no longer alone in this world; I had finally found "my people." Soon afterward, I found my first VR mentor, Richard May, now director of the National Visualization and Analytics Center. I enthusiastically jumped in on helping him build one of the world's first immersive VR medical applications at Battelle Pacific Northwest National Laboratories. Richard and I returned to SIGGRAPH 1996 in New Orleans, where I more intentionally sought out VR. VR was now bigger than ever and I remember two things from the conference that defined my future. One was a course on VR interactions by the legendary Dr. Frederick P. Brooks, Jr. and one of his students, Mark Miné. The other event was a VR demo that I still remember vividly to this day—and still one of the most compelling demos I've seen yet. It was a virtual Legoland where the user built an entire world around himself by snapping Legos and Lego neighborhoods together in an intuitive, almost effortless manner.

Post-1996

SIGGRAPH 1996 was a turning point for me in knowing what I wanted to do with my life. Since that time, I have been fortunate to know and work with many individuals that have inspired me. This book is largely a result of their work and their mentorship.

Since 1996, Dr. Brooks unknowingly inspired me to move on from a full-time dream VR job in the late 1990s at HRL Laboratories to pursue VR at the next level at UNC-Chapel Hill. Once there, I managed to persuade Dr. Brooks to become my PhD adviser in studying VR latency. In addition to being a major influence on my career, two of his books—*The Mythical Man Month* and more recently *The Design of Design*—are heavily referenced throughout Part VI, Iterative Design. He also had significant input for Part II, Perception, especially Chapter 16, Latency, as some of that writing originally came from my dissertation that was largely a result of significant suggestions from him. His serving as adviser for Mark Miné's seminal work on VR interaction also indirectly affected Part V, Interaction. It is still quite difficult for me to fathom that before Dr. Brooks came along, bytes—the molecules of all digital technology—were not always 8 bits in size like they are defined to be today. That 8-bit design decision he made in the 1960s, which most all of us computer scientists now just assume to be an inherent truth, is just one of his many contributions to computers in general, along with his more specific contributions to VR research. It boggles my mind even more how a small-town kid like myself, growing up in a tiny town of 1,200 people on the opposite side of the country, somehow came to study under an ACM Turing Award recipient (the equivalent of the Nobel Prize in computer science). For that, I will forever be grateful to Dr. Brooks and the UNC-Chapel Hill Department of Computer Science for admitting me.

In 2009, I interviewed with Paul Mlyniec, president of Digital ArtForms. At some point during the interview, I came to the realization that this was the man that led the VR Lego work from SIGGRAPH that had inspired and driven me for over a decade. The interface in that Lego demo is one of the first implementations of what I refer to as the 3D Multi-Touch Pattern in Section 28.3.3, a pattern two decades ahead of its time. I've now worked closely with Paul and Digital ArtForms for six years on various projects, including ones that have improved upon 3D Multi-Touch (Sixense's MakeVR also uses this same viewpoint control implementation). We are currently working together (along with Sixense and Wake Forest School of Medicine) on immersive games for neuroscience education funded by the National Institutes of Health. In addition to these games, several other examples of Digital ArtForms' work (along with work from its sister company Sixense that Paul was essential in helping to form) are featured throughout the book.

VR Today

After a long VR drought after the 1990s, VR is bigger than ever at SIGGRAPH. An entire venue, the VR Village, is dedicated specifically to VR, and I have the privilege of leading the Immersive Realities Contest. After so many years of heavy involvement with my SIGGRAPH family, it feels quite fitting that this book is launched at the SIGGRAPH bookstore on the 20th anniversary of my discovery of SIGGRAPH and VR.

I joke that when I did my PhD Dissertation on latency perception for head-mounted displays, perhaps ten people in the world cared about VR latency—and five of those people were on my committee (in three different time zones!). Then in 2011, people started wanting to know more. I remember having lunch with Amir Rubin, CEO of Sixense. He was inquiring about consumer HMDs for games. I thought the idea was crazy; we could barely get VR to work well in a lab and he wanted to put it in people's living rooms! Other inquiries led to work with companies such as Valve and Oculus. All three of these companies are doing spectacular jobs of making high-quality VR accessible, and now suddenly everyone wants to experience VR. Largely due to these companies' efforts, VR has turned a corner, transitioning from a specialized laboratory instrument available only to the technically elite, to a mainstream mode of content consumption available to any consumer. Now, most everyone that is involved in VR technology understands at least the basics of latency and its challenges/dangers, most notably motion sickness—the greatest risk for VR. Even better, ultra-low-latency hardware technologies (e.g., low-persistence OLED displays) that I once unsuccessfully searched the world for (I ended up having to build/simulate my own; the best I did was 7.4 ms of end-to-end latency with tracking and rendering performed at ~1,500 frames per second) are being developed in mass quantities by giants such as Samsung, Sony, Valve, and Oculus. Times have certainly changed!

The last 20 years of pursuing VR have truly been a dream. During that time, I imagined and even seriously considered starting companies devoted to VR, but it was never feasible until recently. Today it is more of a real fantasy than a simple dream, now that VR technology is delivering upon its promise of the 1990s. Describing the feeling is like trying to describe a VR experience. Words cannot do justice as to what it is like to be a part of this VR community and contributing to the VR revolution. Through my VR consulting and contracting firm, NextGen Interactions, I have the privilege of working with some of the best companies in the world that are able to do things that could only previously be imagined. Virtual reality is unlike any technology devised to date and has the potential not only to change the fictional synthetic worlds we make up but to change people's real lives. I very much look forward to seeing what this community discovers and creates over the next 20 years!

Acknowledgments

It would be untrue if I claimed that this book was completely based on my own work. The book was certainly not written in isolation and is a result of contributions from a vast number of mentors, colleagues, and friends in the VR community who have been working just as hard as I have over the years to make VR something real. I couldn't possibly say everything there is about VR, and I encourage readers to further investigate the more than 300 references discussed throughout the book, along with other writings. I've learned so much from those who came before me as well as those newer to VR. Unfortunately, it is not possible to list everyone who has influenced this book, but the following gives thanks to those who have given the most support.

First of all, this book would never have been anything beyond a simple self-published work without the team at Morgan & Claypool Publishers and ACM Books. On the Morgan & Claypool Publishers side, I'd like to thank Executive Editor Diane Cerra, Editorial Assistant Samantha Draper, Copyeditor Sara Kreisman, Production

Manager Paul Anagnostopoulos, Artist Laurel Muller, Proofreader Jennifer McClain, and President Michael Morgan. On the ACM Books side, I'd like to thank Computer Graphics Series Editor John Hart and Editor-in-Chief M. Tamer Özsu.

This book you are reading is very different and much better than initial drafts due to suggestions from great reviewers. Reviewers of the book include Paul Mlyniec (president of Digital ArtForms), Arun Yoganandan (formerly of Digital ArtForms and Disney, now a research engineer at Samsung), Russell Taylor (former professor of computer science at UNC–Chapel Hill, now cofounder of Rheomics and independent consultant at Relia Solve), Beau Cronin (an expert VR neuroscientist at Salesforce, who is writing his own VR book), Mike McArdle (cofounder of the Virtual Reality Learning Experience), Ryan McMahan (professor at University of Texas at Dallas), Eugene Nalivaiko (professor at New Castle University), Kyle Yamamoto (cofounder and game developer at MochiBits), Ann McNamara (professor at Texas A&M), Mark Fagiano (professor at Emory University), Zach Wendt (computer games guru and independent software developer), Francisco Ortega (postdoc fellow at Florida International University and who is writing his own VR book), Matt Cook (emerging technologies librarian at the University of Oklahoma), Sharif Razzaque (CTO of Inneroptic), Neeta Nahta (cofounder of NextGen Interactions), Kevin Rio (UX researcher at Microsoft), Chris Pusczak (project manager at Burnout Game Ventures and SymbioVR), Daniel Ackley (psychologist), my mother, Susan Jerald (behavioral psychologist), and my father, Rick Jerald (CEO of Envirocept).

Additional specific input came from Mark Bolas (professor at the University of Southern California), Neil Schneider (founder of Meant to be Seen and founder/executive director of the Immersive Technology Alliance), Eric Greenbaum (attorney and founder of Jema VR), John Baker (COO of Chosen Realities), Denny Unger (founder and president of Cloudhead Games), Andrew Robinson and Sigurdur Gunnarsson (developers at CCP Games), Max Rheiner (founder and CTO of Somniacs), Chadwick Wingrave (founder of Conquest Creations), Barry Downes (CEO of TSSG), Denise Quesnel (research associate at Emily Carr University of Art and Design, cofounder of the Canadian & Advanced Imaging Society, and cochair of the SIGGRAPH VR Village), Nick England (founder and CEO of 3rdTech), Jesse Joudrey (CEO of VRChat and CTO of Jespionage Entertainment), David Collodi (cofounder and CTO of CI Dynamics), David Beaver (cofounder of the Overview Institute), and Bill Howe (CEO of the Growth Engine Group).

I've been very fortunate to be employed by some amazing organizations and even more amazing bosses that are world-leading experts in VR. These individuals gave me the opportunity to make a career out of what I love doing, and working with them led to much of what is contained within these pages: Richard May of Battelle

Pacific Northwest National Laboratories (now director of the National Visualization and Analytics Center), Michael Papka of Argonne National Laboratories, Mike Daily of HRL Laboratories, Greg Schmidt of the Naval Research Laboratory, Steve Ellis and Dov Adelstein of NASA Ames, Paul Mlyniec of Digital ArtForms, and Michael Abrash at Valve (now at Oculus).

In addition to those listed above, the following individuals have been invaluable as VR advisers/mentors throughout the years: Howard Neely, research project manager at HRL Laboratories and now CEO at Three Birds Systems; Ron Azuma, senior research staff member at HRL Laboratories and now at Intel; Fred Brooks, Henry Fuchs, Mary Whitton, and Anselmo Lastra—all professors at UNC–Chapel Hill; Jeff Bellinghausen, formerly lead engineer at Digital ArtForms and CTO at Sixense, now at Valve; and Amir Rubin, CEO of Sixense.

I also very much appreciate working with the teams at Sixense, Valve, and Oculus. I've been incredibly impressed with the people and their commitment to creating the highest-quality software and hardware, and not just resurrecting VR but raising awareness to levels beyond anything that previously existed.

Others I've had the pleasure of working with who have influenced this book include Rupert Meghnot and his team at Burnout Game Ventures, especially Chris Pusczak of the SymbioVR team; Jan Goetgeluk of Virtuix; Simon Solotko, the Kickstarter guru who marketed some of the biggest VR Kickstarters such as the Virtuix Omni, the Cyberith Virtualizer, and the Sixense STEM; the UNC Effective Virtual Environments team; Karl Krantz of Silicon Valley Virtual Reality, who was the first to pioneer local meetups where his events are duplicated throughout the world; and Henry Velez, founder of the RTP Virtual Reality Enthusiasts, which I now have the privilege of leading.

I've also enjoyed working with literally thousands of volunteers through ACM SIGGRAPH, IEEE VR, and IEEE 3DUI, ranging from student volunteers to the legends of computer graphics and VR. In particular, I'd like to thank the SIGGRAPH conference committees of the last 20 years. Of course, I've also enjoyed working with those outside of conferences, ranging from those in academics to those doing start-ups. Then there are those who have given me invaluable feedback on VR projects, ranging from middle schoolers to VR experts.

I'd especially like to thank Neeta Nahta, my partner in business and life, who comes from a completely different world of sales, financial analysis, and corporate boardrooms. Her input enables me to see VR from a different perspective than most anyone else in the VR community. Seeing VR as a sustainable and profitable business that adds real value to the world will ensure that this time VR is here for good.

I would also like to thank the Link Foundation for supporting me through the Link Foundation Advanced Simulation and Training Fellowship, which helped to fund graduate work in studying and reducing latency. It is certainly an honor to be funded by the foundation started by Edwin A. Link, who built the world's first mechanical flight simulator in 1928 (Figure 3.5), which some consider to be one of the first VR systems, as well as to be among a list of world-leading VR experts who also received the Fellowship. I highly encourage any graduate student readers who have already selected a dissertation topic to apply for the Link Foundation Fellowship ($28,500 to be awarded for 2016). Details are available at http://www.linksim.org.

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Figure 8.2 Based on: Badcock, D. R., Palmisano, S., & May, J. G. (2014). Vision and Virtual Environments. In K. S. Hale & K. M. Stanney (Eds.), *Handbook of Virtual Environments* (2nd ed.). CRC Press.

Figure 8.3 Based on: Coren, S., Ward, L. M., & Enns, J. T. (1999). *Sensation and Perception* (5th ed.). Harcourt Brace College Publishers.

Figure 8.4 Adapted from: Clulow, F. W. (1972). *Color: Its principle and their applications.* New York: Morgan & Morgan.

Figure 8.5 Based on: Coren, S., Ward, L. M., & Enns, J. T. (1999). *Sensation and Perception* (5th ed.). Harcourt Brace College Publishers.

Figure 8.6 Adapted from: Coren, S., Ward, L. M., & Enns, J. T. (1999). *Sensation and Perception* (5th ed.). Harcourt Brace College Publishers.

Figure 8.7 Adapted from: Goldstein, E. B. (2014). *Sensation and Perception* (9th ed.). Cengage Learning.

Figure 8.8 Based on: Burton, T.M.W. (2012) *Robotic Rehabilitation for the Restoration of Functional Grasping Following Stroke*. Dissertation, University of Bristol, England.

Figure 8.9 Based on: Jerald, J. (2009). *Scene-Motion- and Latency-Perception Thresholds for Head-Mounted Displays*. Department of Computer Science, University of North Carolina at Chapel Hill. Used with permission. Adapted from: Martini (1998). *Fundamentals of Anatomy and Physiology*. Upper Saddle River, Prentice Hall.

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Figure 9.5 Courtesy of Galkin Grigory/Shutterstock.com

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Figure 9.8 Adapted from: Mirzaie, H. (2009, March 16). *Stereoscopic Vision*.

Figure 9.9 Adapted from: Coren, S., Ward, L. M., & Enns, J. T. (1999). *Sensation and Perception* (5th ed.). Harcourt Brace College Publishers.

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Figure 12.1 Adapted from: Razzaque, S. (2005). *Redirected Walking*. Department of Computer Science, University of North Carolina at Chapel Hill.

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Figure 15.1 Based on: Gregory, R. L. (1973). *Eye and Brain: The Psychology of Seeing* (2nd ed.). London: Weidenfeld and Nicolson.

Figure 15.2 Adapted from: Jerald, J. (2009). *Scene-Motion-and Latency-Perception Thresholds for Head-Mounted Displays*. Department of Computer Science, University of North Carolina at Chapel Hill.

Figure 15.3 Adapted from: Jerald, J. (2009). *Scene-Motion-and Latency-Perception Thresholds for Head-Mounted Displays*. Department of Computer Science, University of North Carolina at Chapel Hill.

Figure 15.4 Based on: Jerald, J. (2009). *Scene-Motion- and Latency-Perception Thresholds for Head-Mounted Displays*. Department of Computer Science, University of North Carolina at Chapel Hill. Used with permission.

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Figure 20.1 From: Heider, F., & Simmel, M. (1944). An experimental study of apparent behavior. *The American Journal of Psychology, 57*, 243–259. DOI: 10.2307/1416950

Figure 20.2 From: Lehar, S. (2007). The Constructive Aspect of Visual Perception: A Gestalt Field Theory Principle of Visual Reification Suggests a Phase Conjugate Mirror Principle of Perceptual Computation. Used with permission.

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Figure 20.4 Based on: Wolfe, J. (2006). *Sensation & perception*. Sunderland, Mass.: Sinauer Associates.

Figure 20.5 From: Yoganandan, A., Jerald, J., & Mlyniec, P. (2014). Bimanual Selection and Interaction with Volumetric Regions of Interest. In *IEEE Virtual Reality Workshop on Immersive Volumetric Interaction.* Used with permission.

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Figure 26.2 Courtesy of NextGen Interactions.

Figure 26.3 Courtesy of NextGen Interactions.

Figure 26.4 Courtesy of NextGen Interactions.

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Figure 27.1 From: Pausch, R., Snoddy, J., Taylor, R., Watson, S., & Haseltine, E. (1996). Disney's Aladdin: first steps toward storytelling in virtual reality. In *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques* (pp. 193–203). ACM Press. Copyright © ACM 1996. Used with permission. DOI: 10.1145/237170.237257

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Figure 28.2 From: Pierce, J., Forsberg, A., Conway, M., Hong, S., Zeleznik, R., & Miné, M. R. (1997). Image Plane Interaction Techniques in 3D Immersive Environments. In *ACM Symposium on Interactive 3D Graphics* (pp. 39–44). ACM Press. Copyright © ACM 1997. Used with permission. DOI: 10.1145/253284.253303

Figure 28.3 Courtesy of Digital ArtForms.

Figure 28.4 From: Hinckley, K., Pausch, R., Goble, J. C., & Kassell, N. F. (1994). Passive Real-world Interface Props for Neurosurgical Visualization. In *Proceedings of the SIGCHI conference on Human factors in computing systems celebrating interdependence - CHI '94* (Vol. 30, pp. 452–458). Copyright © ACM 1994. Used with permission. DOI: 10.1145/191666.191821

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Figure 28.7 From: Schultheis, U., Jerald, J., Toledo, F., Yoganandan, A., & Mlyniec, P. (2012). Comparison of a two-handed interface to a wand interface and a mouse interface for fundamental 3D tasks. In *IEEE Symposium on 3D User Interfaces 2012, 3DUI 2012 - Proceedings* (pp. 117–124). Copyright © 2012 IEEE. Used with permission. DOI: 10.1109/3DUI.2012.6184195

Figure 28.8 Courtesy of Sixense and Digital ArtForms.

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Figure 31.1 Based on: Rasmusson, J. (2010). The Agile Samurai–How Agile Masters Deliver Great Software. *Pragmatic Bookshelf*.

Figure 31.2 Based on: Rasmusson, J. (2010). The Agile Samurai–How Agile Masters Deliver Great Software. *Pragmatic Bookshelf*.

Figure 31.6 Courtesy of Geomedia.

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Figure 32.2 Based on: Neely, H. E., Belvin, R. S., Fox, J. R., & Daily, M. J. (2004). Multimodal interaction techniques for situational awareness and command of robotic combat entities. In *IEEE Aerospace Conference Proceedings* (Vol. 5, pp. 3297–3305). DOI: 10.1109/AERO.2004.1368136

Figure 32.4 Based on: Daily, M., Howard, M., Jerald, J., Lee, C., Martin, K., McInnes, D., & Tinker, P. (2000). Distributed design review in virtual environments. In *Proceedings of the third international conference on Collaborative virtual environments* (pp. 57–63). ACM. DOI: 10.1145/351006.351013

Figure 33.2 Adapted from: Gabbard, J. L. (2014). Usability Engineering of Virtual Environments. In K. S. Hale & K. M. Stanney (Eds.), *Handbook of Virtual Environments* (2nd ed., pp. 721–747). CRC Press.

Figure 33.3 Courtesy of NextGen Interactions.

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Overview

Virtual reality (VR) can provide our minds with direct access to digital media in a way that seemingly has no limits. However, creating compelling VR experiences is an incredibly complex challenge. When VR is done well, the results are brilliant and pleasurable experiences that go beyond what we can do in the real world. When VR is done badly, not only do users get frustrated, but they can get sick. There are many causes of bad VR; some failures come from the limitations of technology, but many come from a lack of understanding perception, interaction, design principles, and real users. This book discusses these issues by emphasizing the human element of VR. The fact is, if we do not get the human element correct, then no amount of technology will make VR anything more than an interesting tool confined to research laboratories. Even when VR principles are fully understood, the first implementation is rarely novel and almost never ideal due to the complex nature of VR and the countless possibilities that can be created. The VR principles discussed in this book will enable readers to intelligently experiment with the rules and iteratively design toward innovative experiences.

Historically, most VR creators have been engineers (the author included) with expertise in technology and logic but limited in their understanding of humans. This is primarily due to the fact that VR has previously been so technically challenging that it was difficult to build VR experiences without an engineering background. Unfortunately, we engineers often believe "I am human, therefore I understand other humans and what works for them." However, the way humans perceive and interact with the world is incredibly complex and not typically based on logic, mathematics, or a user manual. If we stick solely to the expertise of knowing it all through engineering and logic, then VR will certainly be doomed. We have to accept human perception and behavior the way it is, not the way logic tells us it should be. Engineering will always be essential as it is the core of VR systems that everything else builds upon, but VR itself presents a fascinating interplay of technology and psychology, and we must understand both to do VR well.

Technically minded people tend to dislike the word "experience" as it is less logical and more subjective in nature. But when asked about their favorite tool or game they often convey emotion as they discuss how, for example, the tool responds. They talk about how it makes them feel often without them consciously realizing they are speaking in the language of emotion. Observe how they act when attempting to navigate through a poorly designed voice-response system for technical support via phone. In their frustration, they very well may give up on the product they are calling about and never purchase from that company again. The experience is important for everything, even for engineers, for it determines our quality of life on a moment-by-moment basis. For VR, the experience is even more critical. To create quality VR, we need to continuously ask ourselves and others questions about how we perceive the VR worlds that we create. Is the experience understandable and enjoyable? Or is it sometimes confusing to use while at other times just all-out frustrating and sickness inducing? If the VR experience is intuitive to understand, easily controlled, and comfortable, then just like anything in life, there will be a sense of mastery and satisfaction with "logical" reasons why it works well. Emotion and cognition are tightly coupled, with cognition more often than not justifying decisions that were actually made emotionally. We must create VR experiences with both emotion and logic.

What This Book Is

This book focuses on **human-centered design**, a design philosophy that puts human needs, capabilities, and behavior first, then designs to accommodate those needs, capabilities, and ways of behaving (Norman, 2013). More specifically, this book focuses on the human elements of VR—how users perceive and intuitively interact with various forms of reality, causes of VR sickness, creating content that is pleasing and useful, and how to design and iterate upon effective VR applications.

Good VR design starts with an understanding of both technology and perception. It requires good communication between human and machine, indicating what interactions are possible, what is currently occurring, and what is about to occur. Human-centered design also comes about through observation, for humans are often unaware of their perceptual processes and methods of interacting (at least for VR that works well). Getting the specification of a VR experience is difficult, and rarely does a VR creator do it well for his first few projects. In fact, even VR experts do not perfectly define the project from the start if they are creating a novel experience. A human-centered design principle, like lean methods, is to avoid completely defining the problem at the start and to iterate upon repeated approximations and modifications through rapid tests of ideas with real users.

Developing intuitive VR should not be driven by software/hardware engineering considerations alone (e.g., we need to do much more than figure out how to efficiently display at the highest resolution available based on the most current hardware). A good portion of this book is devoted to how the human mind works in order to help readers create higher-quality VR applications. VR design, however, goes beyond just technology and psychology; VR is intensely multidisciplinary. VR is an incredibly complex challenge and the study, design, and implementation of high-quality VR requires an understanding of various disciplines, including the behavioral and social sciences, neuroscience, information and computer science, physics, communications, art, and even philosophy. When reflecting back upon VR design and implementation, Wingrave and LaViola [2010] point out: "Practitioners must be carpenters, electricians, engineers, artists, and masters of duct tape and Velcro." This book takes a broad perspective, applying insights from various disciplines to VR design.

In summary, this book provides basic theory, an overview of various concepts useful for VR, examples that put the theory and concepts into more understandable form, useful guidelines, and a foundation for further exploration and interaction design for virtual worlds that do not yet exist.

What This Book Is Not

There are more questions about VR than there are answers and the intent of this book is not to attempt to provide all of the answers. VR covers a broad range of imaginary spaces broader than the real world; nobody could possibly have all the answers to the real world, so it is unreasonable to expect to find all the answers for virtual worlds. Instead, this book attempts to help readers build and iterate upon creative answers and compelling experiences. Although this book can't possibly cover all aspects of VR in detail, it does provide an overview of various topics and delves more deeply into those that are most important. References are provided throughout for those wishing to further study concepts of interest.

In some cases, the concepts presented in this book follow well-understood principles or conclusive research (although even conclusive research rarely holds 100% of the time across all conditions). In other cases, concepts are not the "truth" but have been found to be useful in the way we think about design and interaction. Studying theory can be useful, but VR development should always follow pragmatism over theory.

Although there is a brief chapter on getting started (Chapter 36), and there are tips throughout on high- and mid-level implementation concepts, this book is not a step-by-step tutorial of how to implement an example VR system. In fact, this book intentionally contains no code or equations so that all concepts can be understood by anyone from any discipline (references are provided for more rigorous detail). Although researchers have been experimenting with VR for decades (Section 2.1), VR in no way comes close to reaching its full potential. Not only are there many unknowns, but VR implementation very much depends on the project. For example, a surgical training system is very different from an immersive film.

Who This Book Is For

This book is for the entire team that works on a VR project, not just for those who define themselves as designers. It is intended to act as a foundation for anyone and everyone involved with creating VR experiences. The book also is meant to serve as a bridge between academic research and practical advice to a wide range of individuals who wish to build compelling experiences. This includes designers, managers, programmers, artists, psychologists, engineers, students, educators, and user experience professionals so the entire team can have a common understanding and language of VR. Everyone involved with a VR project should understand at least the basics of perception, VR sickness, interaction, content creation, and iterative design. VR requires specialized experts in various disciplines to each contribute in their own unique way, but we each must also know at least a little about human-centered design in order to effectively communicate with teammates and to integrate the various components together into a seamless, quality experience.

How to Read This Book

Readers may wish to read and use this book differently depending on their background, particular interests, and how they would like to apply it.

Newcomers

Those completely new to VR who want a high-level understanding will most appreciate Part I, Introduction and Background. After reading Part I, the reader may want to skip ahead to Part VII, The Future Starts Now. Once these basics are understood, most of Part IV, Content Creation, should be able to be understood. As the reader learns more about VR, the other parts will become easier to digest.

Teachers

This book will be especially relevant to interdisciplinary VR courses. Teachers will want to choose chapters that are most relevant to the course requirements and student interests. It is highly suggested that any VR course take a project-centered approach. In such a case, the teacher should consider the suggestions below for both students and practitioners. An outline for starting a first project, albeit slightly different for a class project, is outlined in Chapter 36, Getting Started.

Students

Students will gain a core understanding of VR by first gaining a high-level overview of VR through Part I, Introduction and Background. For those wishing to understand theory, Part II, Perception, and Part III, Adverse Health Effects, will be invaluable. For students working on VR projects, they should also follow the advice below for practitioners.

Practitioners

Practitioners who want to immediately get the most important points that apply to their VR creations will want to start with the practitioner chapters that have a leading star (⋆) in the table of contents (mostly Parts IV–VI). In particular, they may want to start with the design guidelines chapters at the end of each part, where each part contains multiple chapters on one of the primary topics. Most of the guidelines provide back references to the relevant sections for more detailed information.

VR Experts

VR experts will likely use this book more as a reference so they do not spend time reading material they are already familiar with. The references will also serve VR experts for further investigation. Those experts who primarily work with head-mounted displays may find Part I, Introduction and Background, useful to understand how head-mounted displays fit within the larger scheme of other implementations of VR and augmented reality (AR). Those interested in implementing straightforward applications that have already been built may not find Part II, Perception, useful. However, for those who want to innovate with new forms of VR and interaction, they may find this part useful to understand how we perceive the world in order to help invent novel creations.

Overview of the Seven Parts

Part I, Introduction and Background, provides a background of VR including a brief history of VR, different forms of VR and related technologies, and a broad overview of some of the most important concepts that will be further discussed in later parts.

Part II, Perception, provides a background in perception to educate VR creators on concepts and theories of how we perceive and interact with the world around us.

This part serves as an intellectual framework that will enable the reader to not only implement the ideas discussed in later chapters but more thoroughly understand why some techniques do or do not work, to extend those techniques, to intelligently experiment with new concepts that have a better chance of working without causing human factors issues, and to know when it might be appropriate to break the rules.

Part III, Adverse Health Effects, describes one of the most difficult challenges of VR and helps to reduce the greatest risk to VR succeeding at a massive scale: VR sickness. Whereas it may be impossible to remove 100% of VR sickness for the entire population, there are several ways to dramatically reduce it if we understand the theories of why it occurs. Other adverse health effects such as risk of injury, seizures, and aftereffects are also discussed.

Part IV, Content Creation, discusses high-level concepts for designing/building assets and how subtle design choices can influence user behavior. Examples include story creation, the core experience, environmental design, wayfinding aids, social networking, and porting existing content to VR.

Part V, Interaction, focuses on how to design the way users interact within the scenes they find themselves in. For many applications, we want to engage the user by creating an active experience that consists of more than simply looking around; we want to empower users by enabling them to reach out, touch, and manipulate that world in a way that makes them feel they are a part of the world instead of just a passive observer.

Part VI, Iterative Design, provides an overview of several different methods for creating, experimenting, and improving upon VR designs. Whereas each project may not utilize all methods, it is still good to understand them all to be able to apply them when appropriate. For example, you may not wish to conduct a formal and rigorous scientific user study, but you do want to understand the concepts to minimize mistaken conclusions due to confounding factors.

Part VII, The Future Starts Now, summarizes the book, discusses the current and future state of VR, and provides a brief plan to get started.

PART I

INTRODUCTION AND BACKGROUND

What is virtual reality (VR)? What does VR consist of and for what situations is it useful? What is different about VR that gets people so excited? How do developers engage users so that they feel present in a virtual environment? This part of the book answers such questions, and provides a basic background that later chapters build upon. This introduction and background serves as a simple high-level toolbox of options to intelligently choose from, such as different forms of virtual and augmented reality (AR), different hardware options, various methods of presenting information to the senses, and ways to induce presence into the minds of users.

Part I consists of five chapters that cover the basics of VR.

Chapter 1, What Is Virtual Reality?, begins by describing what VR is at a high level and what it is suitable/effective for. This includes descriptions of different forms of communication that are at the heart of what VR is—communication between the user and a system created by the VR designer.

Chapter 2, A History of VR, provides a history of VR starting with stereoscopes created in the 1800s. The concept and implementation of VR is not new.

Chapter 3, An Overview of Various Realities, discusses forms of reality ranging from the real world to augmented reality (AR) to VR. Whereas the focus of this book is on fully immersive VR, this chapter provides context of where VR fits into the overall picture of related technologies. The chapter also gives a high-level description of various forms of input and output hardware options that can be used as part of AR and VR systems.

Chapter 4, Immersion, Presence, and Reality Trade-Offs, discusses the often-used terms of immersion and presence. Readers may be surprised to learn that realism is not necessarily the goal of VR and there are trade-offs for attempting to perfectly simulate reality, even if reality could be perfectly simulated.

Chapter 5, The Basics: Design Guidelines, concludes this introductory part of the book and gives a small number of guidelines for those looking to create VR experiences.

1 What Is Virtual Reality?

1.1 The Definition of Virtual Reality

The term virtual reality (VR) is commonly used by the popular media to describe imaginary worlds that only exist in computers and our minds. However, let us more precisely define the term. Sherman and Craig [2003] point out in their book *Understanding Virtual Reality* that *Webster's New Universal Unabridged Dictionary* [1989] defines virtual as "being in essence or effect, but not in fact" and 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." Thus, virtual reality is a term that contradicts itself—an oxymoron! Fortunately, the website merriam-webster.com [Merriam-Webster 2015] has more recently defined the full term virtual reality to be "an artificial environment which is experienced through sensory stimuli (as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment." In this book, **virtual reality** is defined to be a computer-generated digital environment that can be experienced and interacted with as if that environment were real.

An ideal VR system enables users to physically walk around objects and touch those objects as if they were real. Ivan Sutherland, the creator of one of the world's first VR systems in the 1960s, stated [Sutherland 1965]: "The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal." We haven't yet come anywhere near Ivan Sutherland's vision (nor do we necessarily want to!) and perhaps we never will. However, there are some quite engaging virtual realities today—many of which are featured throughout this book.

1.2 VR Is Communication

Normally, communication is thought of as interaction between two or more people. This book defines **communication** more abstractly: the transfer of energy between two entities, even if just the cause and effect of one object colliding with another object. Communication can also be between human and technology—an essential component and basis of VR. VR design is concerned with the communication of how the virtual world works, how that world and its objects are controlled, and the relationship between user and content: ideally where users are focused on the experience rather than the technology.

Well-designed VR experiences can be thought of as collaboration between human and machine where both software and hardware work harmoniously together to provide intuitive communication with the human. Developers write complex software to create, if designed well, seemingly simple transfer functions to provide effective interactions and engaging experiences. Communication can be broken down into direct communication and indirect communication as discussed below.

1.2.1 Direct Communication

Direct communication is the direct transfer of energy between two entities with no intermediary and no interpretation attached. In the real world, pure direct communication between entities doesn't represent anything as the purpose is not communication, but it is a side effect. However, in VR, developers insert an artificial intermediary (the VR system that is ideally unperceivable) between the user and carefully controlled sensory stimuli (e.g., shapes, motions, sounds). When the goal is direct communication, VR creators should focus on making the intermediary transparent so users feel like they have direct access to those entities. If that can be achieved, then users will perceive, interpret, and interact with stimuli as if they are directly communicating with the virtual world and its entities.

Direct communication consists of structural communication and visceral communication.

Structural Communication

Structural communication is the physics of the world, not the description or the mathematical representation but the thing-in-itself [Kant 1781]. An example of structural communication is the bouncing of a ball off of the hand. We are always in relationship to objects, which help to define our state; e.g., the shape of our hand around a controller. The world, as well as our own bodies, directly tells us what the structure is through our senses. Although thinking and feeling do not exist within structural communication, such communication does provide the starting point for perception, interpretation, thinking, and feeling.

In order for our ideas to persist through time, we must put those ideas into structural form, what Norman [2013] calls knowledge in the world. Recorded information and data is the obvious example of structural form, but sometimes less obvious structural forms are the signifiers and constraints (Section 25.1) of interaction. In order to induce experiences into others through VR, we present structural stimuli (e.g., pixels on a display, sound through headphones, or the rumble/vibration of a controller) so the users can sense and interact with our creations.

Visceral Communication

Visceral communication is the language of automatic emotion and primal behavior, not the rational representation of the emotions and behavior (Section 7.7). Visceral communication is always present for humans and is the in-between of structural communication and indirect communication. Presence (Chapter 4) is the act of being fully engaged via direct communication (albeit primarily one way). Examples of visceral communication are the feeling of awe while sitting on a mountaintop, looking down at the earth from space, or being with someone via solid eye contact (whether in the real world or via avatars in VR). The full experience of such visceral communication cannot be put into words, although we often attempt to do so at which point the experience is transformed into indirect communication (e.g., explaining VR to someone is not the same as experiencing VR).

1.2.2 Indirect Communication

Indirect communication connects two or more entities through some intermediary. The intermediary need not be physical; in fact, the intermediary is often our mind's interpretation that sits between the world and behavior/action. Once we interpret and give something meaning, then we have transformed the direct communication into indirect communication. Indirect communication includes what we normally think of as language, such as spoken and written language, as well as sign languages and our internal thoughts (i.e., communicating with oneself). Indirect communication consists of talking, understanding, creating stories/histories, giving meaning, comparing, negating, fantasizing, lying, and romancing. These are not part of the objective real world but are what we humans describe and create with our minds. Indirect VR communication includes the user's internal mental model (Section 7.8) of how the VR world works (e.g., the interpretation of what is occurring in the VR world), and indirect interactions (Section 28.4) such as moving a slider that changes an object property, speech recognition that changes the system's state, and indirect gestures that act as a sign language to the computer.

1.3 What Is VR Good For?

The recent surge in media coverage about VR has inspired the public to become quite excited about its potential. This coverage has focused on the entertainment industry, specifically video games and immersive film. VR is a great fit for the entertainment industry and will certainly be the driving force behind VR in the short term. However, what is VR good for beyond entertainment? It turns out VR can have enormous benefit over a wide range of verticals. VR has been successfully deployed in various industries for many years now. Successful applications include oil and gas exploration, scientific visualization, architecture, flight simulation, therapy, military training, theme-park entertainment, engineering analysis, and design review. Using VR in such situations has successfully revealed costly design mistakes before manufacturing anything, reduced time to market by speeding up iterative processes, provided safe learning environments that would otherwise be dangerous, reduced PTSD by gradually increasing exposure to feared stimuli, and helped to visualize large datasets that would be difficult to comprehend with traditional systems.

Unfortunately, to date, VR has largely been limited to well-funded academic and corporate research labs to which few have access. That is all changing with consumer-priced systems now becoming widely available. The VR market is expected to first explode in the entertainment industry but will soon expand significantly in other industries. Education, telepresence, and professional training will likely be the next industries to take advantage of VR in a big way.

Whatever the industry, VR is largely about providing understanding—whether that is understanding an entertaining story, learning an abstract concept, or practicing a real skill. Actively using more of the human sensory capability and motor skills has been known to increase understanding/learning for some time [Dale 1969]. This is in part due to the increased sensory bandwidth between human and information, but there is much more to understanding. Actively participating in an action, making concepts intuitive, encouraging motivation through engaging experiences, and the thoughts inside one's head all contribute to understanding. This book focuses on how to design such concepts into VR experiences.

Figure 1.1 shows Edgar Dale's Cone of Experience [Dale 1969]. As can be seen in the figure, direct purposeful experiences provide the best basis for understanding. As Confucius stated, "I see and I forget. I hear and I remember. I do and I understand." Note this diagram does not suggest direct purposeful experiences should be

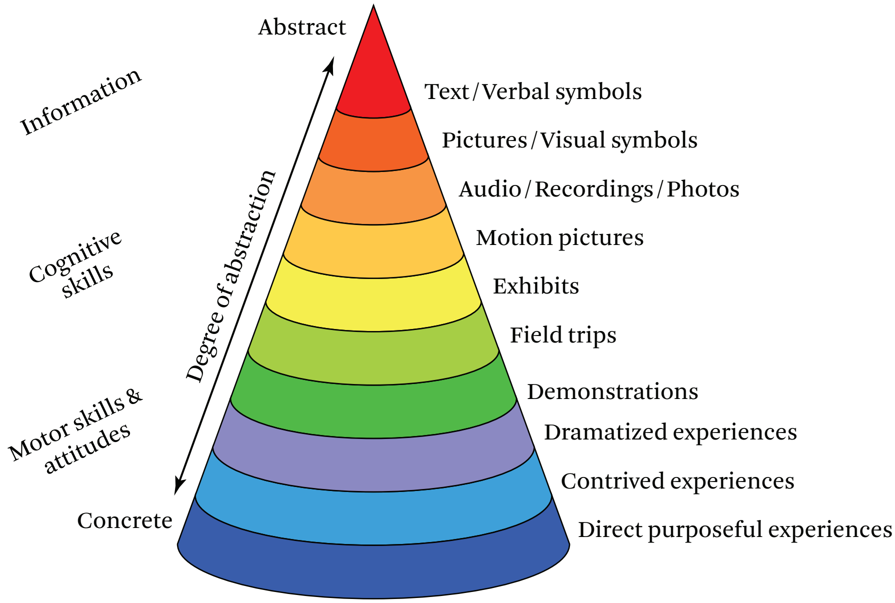

Figure 1.1 **The Cone of Experience. VR uses many levels of abstraction.** (Adapted from Dale [1969])

the only method of learning, but instead describes the progression of learning experience. Adding other indirect information within direct purposeful VR experiences can further enhance understanding. For example, embedding abstract information such as text, symbols, and multimedia directly into the scene and onto virtual objects can lead to more efficient understanding than what can be achieved in the real world.

2

A History of VR

When anything new comes along, everyone, like a child discovering the world, thinks that they've invented it, but you scratch a little and you find a caveman scratching on a wall is creating virtual reality in a sense. What is new here is that more sophisticated instruments give you the power to do it more easily.

—Morton Heilig [Hamit 1993]

Precursors to what we think of today as VR go back as far as humans have had imaginations and the ability to communicate through the spoken word and cave drawings (what could be called analog VR). The Egyptians, Chaldeans, Jews, Romans, and Greeks used magical illusions to entertain and control the masses. In the Middle Ages, magicians used smoke and concave mirrors to produce faint ghost and demon illusions to gull naive apprentices as well as larger audiences [Hopkins 2013]. Although the words and implementation have changed over the centuries, the core goals of creating the illusion of conveying that which is not actually present and capturing our imaginations remain the same.

2.1 The 1800s

The static version of today's stereoscopic 3D TVs is called a stereoscope and was invented before photography in 1832 by Sir Charles Wheatstone [Gregory 1997]. As shown in Figure 2.2, the device used mirrors angled at 45° to reflect images into the eye from the left and right side.

David Brewster, who earlier invented the kaleidoscope, used lenses to make a smaller consumer-friendly hand-held stereoscope (Figure 2.3). His stereoscope was demonstrated at the 1851 Exhibition at the Crystal Palace where Queen Victoria found it quite pleasing. Later the poet Oliver Wendell Holmes stated ". . . is a surprise such as no painting ever produced. The mind feels its way into the very depths of the picture." [Zone 2007]. By 1856 Brewster estimated over a half million stereoscopes had been sold [Brewster 1856]. This first 3D craze included various forms of the stereoscope,

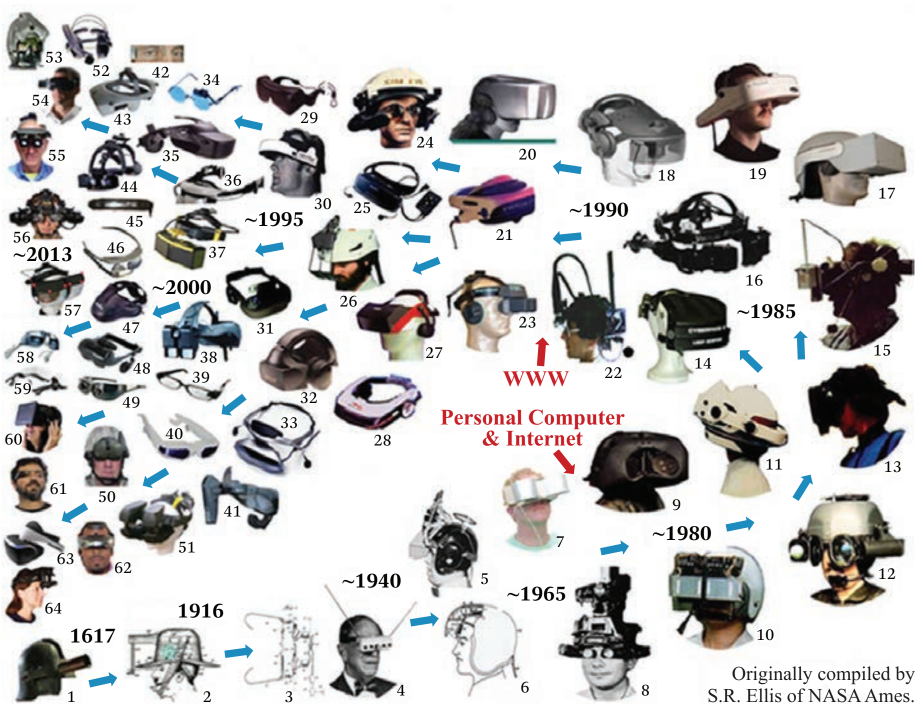

Figure 2.1 **Some head-mounted displays and viewers over time.** (Based on Ellis [2014])

including self-assembled cardboard versions with moving images controlled by the hand in 1860 [Zone 2007]. One company alone sold a million stereoscopic views in 1862. Brewster's design is conceptually the same as the 20th century View-Master and today's Google Cardboard. In the case of Google Cardboard and similar phone-based VR systems, a cellular phone is used to display the images in place of the actual physical images themselves.

Many years later, a 360° VR-type display known as the Haunted Swing was shown at the '95 Midwinter Fair in San Francisco, and is still one of the most compelling technical demonstrations of an illusion to this day. The demo consisted of a room and large swing that held approximately 40 people. After the audience seated themselves, the swing was put in motion and as the swing oscillated, users felt motion similar to being in an elevator while they involuntarily clutched their seats. In fact, the swing hardly moved at all, but the surrounding room moved substantially, resulting in the sense of self-motion (Section 9.3.10) and motion sickness (Chapter 12). The date was not 1995, but was 1895 [Wood 1895].

Figure 2.2 **Charles Wheatstone's stereoscope.**

Figure 2.3 **A Brewster stereoscope from 1860.** (Courtesy of The National Media Museum/Science & Society Picture Library, United Kingdom)

It was also in 1895 that film began to go mainstream; and when the audience saw a virtual train coming at them through the screen in the short film “L’Arrivée d’un train en gare de La Ciotat,” some people reportedly screamed and ran to the back of the room. Although the screaming and running away is more rumor than verified reports, there was certainly hype, excitement, and fear about the new artistic medium, perhaps similar to what is happening with VR today.

2.2 The 1900s

VR-related innovation continued in the 1900s that moved beyond simply presenting visual images. New interaction concepts started to emerge that might be considered novel for even today’s VR systems. For example, Figure 2.4 shows what is a head-worn gun pointing and firing device patented by Albert Pratt in 1916 [Pratt 1916]. No hand tracking is required to fire this device as the interface consists of a tube the user blows through.

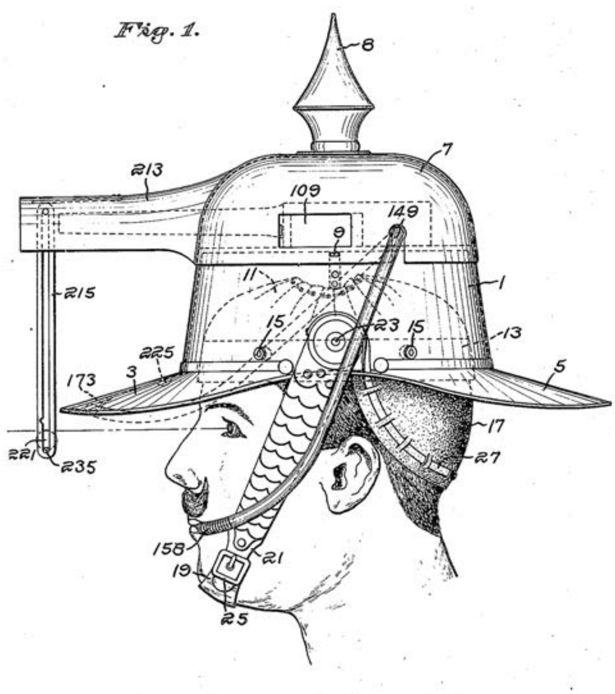

Figure 2.4 **Albert Pratt’s head-mounted targeting and gun-firing interface.** (From Pratt [1916])

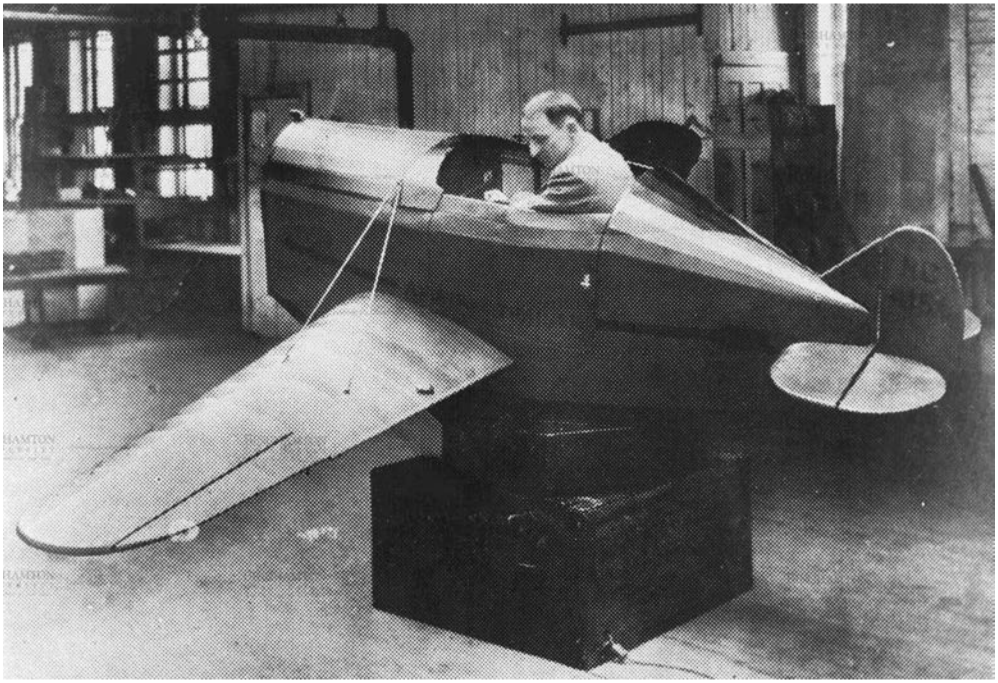

Figure 2.5 **Edwin A. Link and the first flight simulator in 1928.** (Courtesy of Edwin A. Link and Marion Clayton Link Collections, Binghamton University Libraries' Special Collections and University Archives, Binghamton University)

A little over a decade after Pratt received his weapon patent, Edwin Link developed the first simple mechanical flight simulator, a fuselage-like device with a cockpit and controls that produced the motions and sensations of flying (Figure 2.5). Surprisingly, his intended client—the military—was not initially interested, so he pivoted to selling to amusement parks. By 1935, the Army Air Corps ordered six systems and by the end of World War II, Link had sold 10,000 systems. Link trainers eventually evolved into astronaut training systems and advanced flight simulators complete with motion platform and real-time computer-generated imagery, and today is Link Simulation & Training, a division of L-3 Communications. Since 1991, the Link Foundation Advanced Simulation and Training Fellowship Program has funded many graduate students in their pursuits of improving upon VR systems, including work in computer graphics, latency, spatialized audio, avatars, and haptics [Link 2015].

As early 20th century technologies started to be built, science fiction and questions inquiring about what makes reality started to become popular. In 1935, for example,

Figure 2.6 ***Pygmalion's Spectacles* is perhaps the first science fiction story written about an alternate world that is perceived through eyeglasses and other sensory equipment.** (From Weinbaum [1935])

science fiction readers got excited about a surprisingly similar future that we now aspire to with head-mounted displays and other equipment through the book *Pygmalion's Spectacles* (Figure 2.6). The story opens with the words "But what is reality?" written by a professor friend of George Berkeley, the Father of Idealism (the philosophy that reality is mentally constructed) and for whom the University of California, Berkeley, is named. The professor then explains a set of eyeglasses along with other equipment that replaces real-world stimuli with artificial stimuli. The demo consists of a quite compelling interactive and immersive world where "The story is all about you, and you are in it" through vision sound, taste, smell, and even touch. One of the virtual characters calls the world Paracosma—Greek for "land beyond-the-world." The demo is so good that the main character, although skeptical at first, becomes convinced that it is no longer illusion, but reality itself. Today there are countless books ranging from philosophy to science fiction that discuss the illusion of reality.

Perhaps inspired by *Pygmalion's Spectacles,* McCollum patented the first stereoscopic television glasses in 1945. Unfortunately, there is no record of the device ever actually having been built.

In the 1950s Morton Heilig designed both a head-mounted display and a world-fixed display. The head-mounted display (HMD) patent [Heilig 1960] shown in Figure 2.7 claims lenses that enable a 140° horizontal and vertical field of view, stereo

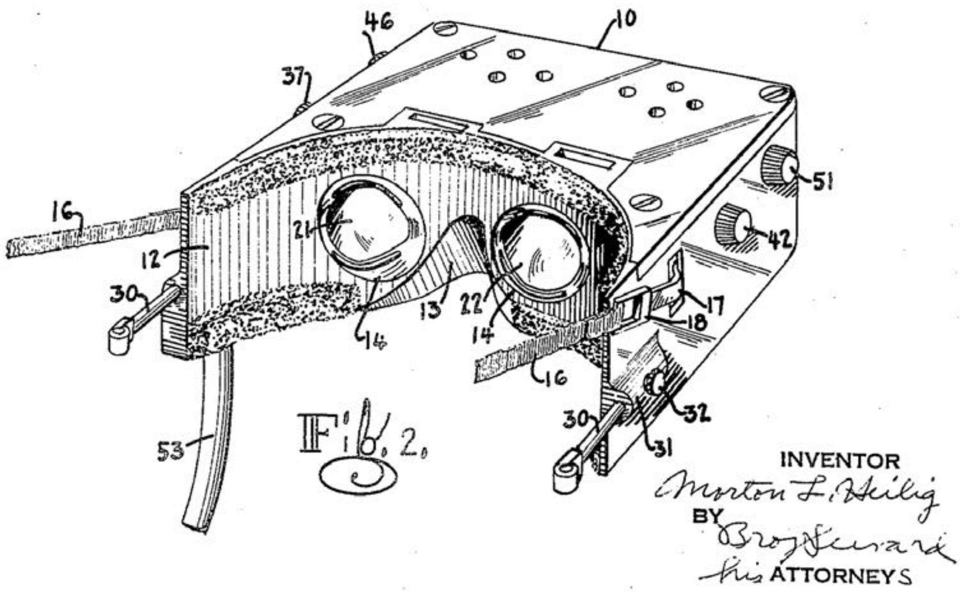

Figure 2.7 **A drawing from Heilig's 1960 Stereoscopic Television Apparatus patent.** (From Heilig [1960])

earphones, and air discharge nozzles that provide a sense of breezes at different temperatures as well as scent. He called his world-fixed display the Sensorama. As can be seen in Figure 2.8, the Sensorama was created for immersive film and it provided stereoscopic color views with a wide field of view, stereo sounds, seat tilting, vibrations, smell, and wind [Heilig 1992].

In 1961, Philco Corporation engineers built the first actual working tracked HMD that included head tracking (Figure 2.9). As the user moved his head, a camera in a different room moved so the user could see as if he were at the other location. This was the world's first working telepresence system.

One year later IBM was awarded a patent for the first glove input device (Figure 2.10). This glove was designed as a comfortable alternative to keyboard entry, and a sensor for each finger could recognize multiple finger positions. Four possible positions for each finger with a glove in each hand resulted in 1,048,575 possible input combinations. Glove input, albeit with very different implementations, later became a common VR input device in the 1990s.

Starting in 1965, Tom Furness and others at the Wright-Patterson Air Force Base worked on visually coupled systems for pilots that consisted of head-mounted displays

Figure 2.8 **Morton Heilig's Sensorama created the experience of being fully immersed in film.** (Courtesy of © Morton Heilig Legacy)

(Figure 2.11, left). While Furness was developing head-mounted displays at Wright-Patterson Air Force Base, Ivan Sutherland was doing similar work at Harvard and the University of Utah. Sutherland is known as the first to demonstrate a head-mounted display that used head tracking and computer-generated imagery [Oakes 2007]. The system was called the Sword of Damocles (Figure 2.11, right), named after the story of King Damocles who, with a sword hanging above his head by a single hair of a horse's tail, was in constant peril. The story is a metaphor that can be applied to VR technology: (1) with great power comes great responsibility; (2) precarious situations give a sense of foreboding; and (3) as stated by Shakespeare [1598] in *Henry IV*, "uneasy lies the head that wears a crown." All these seem very relevant for both VR developers and VR users even today.

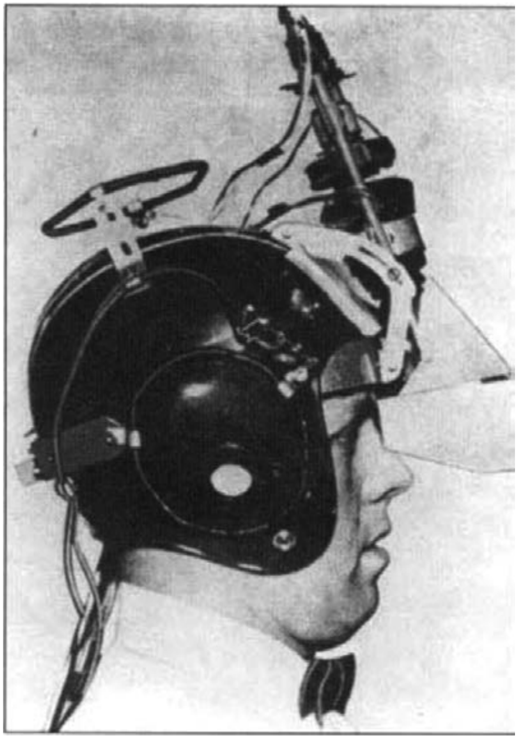

Figure 2.9 **The Philco Headsight from 1961.** (From Comeau and Brian [1961])

Dr. Frederick P. Brooks, Jr., inspired by Ivan Sutherland's vision of the Ultimate Display [Sutherland 1965], established a new research program in interactive graphics at the University of North Carolina at Chapel Hill, with the initial focus being on molecular graphics. This not only resulted in a visual interaction with simulated molecules but also included force feedback where the docking of simulated molecules could be felt. Figure 2.12 shows the resulting Grope-III system that Dr. Brooks and his team built. UNC has since focused on building various VR systems and applications with the intent to help practitioners solve real problems ranging from architectural visualization to surgical simulation.

In 1982, Atari Research, led by legendary computer scientist Alan Kay, was formed to explore the future of entertainment. The Atari research team, which included Scott Fisher, Jaron Lanier, Thomas Zimmerman, Scott Foster, and Beth Wenzel, brainstormed novel ways of interacting with computers and designed technologies that would soon be essential for commercializing VR systems.

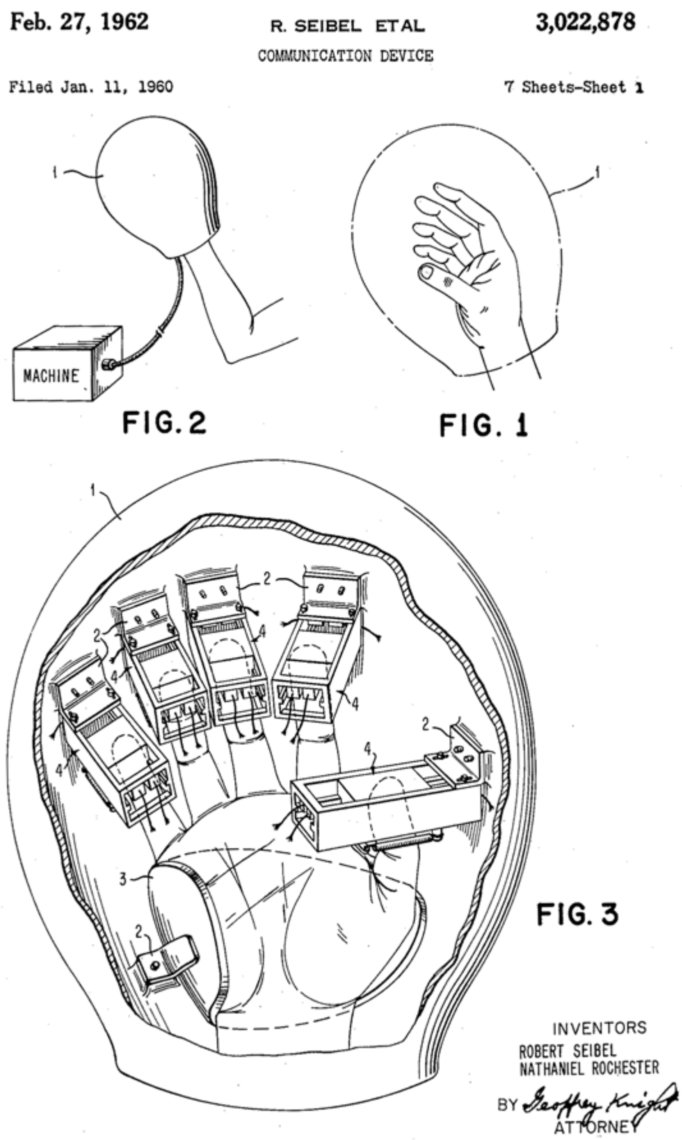

Figure 2.10 **An image from IBM's 1962 glove patent.** (From Rochester and Seibel [1962])

Figure 2.11 **The Wright-Patterson Air Force Base head-mounted display from 1967 (courtesy of Tom Furness) and the Sword of Damocles [Sutherland 1968])**

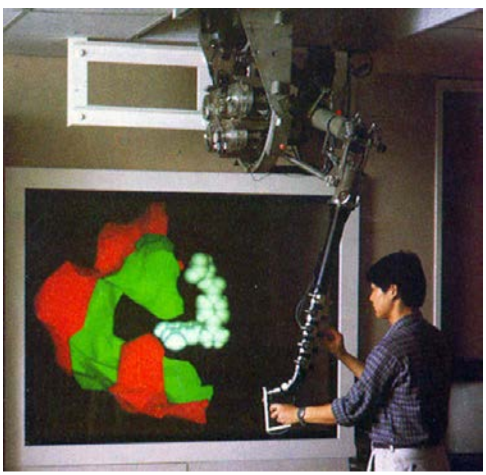

Figure 2.12 **The Grope-III haptic display for molecular docking.** (From Brooks et al. [1990])

Figure 2.13 **The NASA VIEW System.** (Courtesy of NASA/S.S. Fisher, W. Sisler, 1988)

In 1985, Scott Fisher, now at NASA Ames, along with other NASA researchers developed the first commercially viable, stereoscopic head-tracked HMD with a wide field of view, called the Virtual Visual Environment Display (VIVED). It was based on a scuba diver's face mask with the displays provided by two Citizen Pocket TVs (Scott Fisher, personal communication, Aug 25, 2015). Scott Foster and Beth Wenzel built a system called the Convolvotron that provided localized 3D sounds. The VR system was unprecedented as the HMD could be produced at a relatively affordable price, and as a result the VR industry was born. Figure 2.13 shows a later system called the VIEW (Virtual Interface Environment Workstation) system.

Jaron Lanier and Thomas Zimmerman left Atari in 1985 to start VPL Research (VPL stands for Visual Programming Language) where they built commercial VR gloves, head-mounted displays, and software. During this time Jaron coined the term "virtual reality." In addition to building and selling head-mounted displays, VPL built the Dataglove specified by NASA—a VR glove with optical flex sensors to measure finger bending and tactile vibrator feedback [Zimmerman et al. 1987].

VR exploded in the 1990s with various companies focusing mostly on the professional research market and location-based entertainment. Examples of the more well-known newly formed VR companies were Virtuality, Division, and Fakespace. Existing companies such as Sega, Disney, and General Motors, as well as numerous universities and the military, also started to more extensively experiment with VR technologies. Movies were made, numerous books were written, journals emerged, and conferences formed—all focused exclusively on VR. In 1993, *Wired* magazine predicted that within five years more than one in ten people would wear HMDs while traveling in buses, trains, and planes [Negroponte 1993]. In 1995, the *New York Times* reported that Virtuality Managing Director Jonathan Waldern predicted the VR market to reach $4 billion by 1998 [Bailey 1995]. It seemed VR was about to change the world and there was nothing that could stop it. Unfortunately, technology could not support the promises of VR. In 1996, the VR industry peaked and then started to slowly contract with most VR companies, including Virtuality, going out of business by 1998.

2.3 The 2000s

The first decade of the 21st century is known as the "VR winter." Although there was little mainstream media attention given to VR from 2000 to 2012, VR research continued in depth at corporate, government, academic, and military research laboratories around the world. The VR community started to turn toward human-centered design with an emphasis on user studies, and it became difficult to get a VR paper accepted at a conference without including some form of formal evaluation. Thousands of VR-related research papers from this era contain a wealth of knowledge that today is unfortunately largely unknown and ignored by those new to VR.

A wide field of view was a major missing component of consumer HMDs in the 1990s, and without it users were just not getting the "magic" feeling of presence (Mark Bolas, personal communication, June 13, 2015). In 2006, Mark Bolas of USC's MxR Lab and Ian McDowall of Fakespace Labs created a 150° field of view HMD called the Wide5, which the lab later used to study the effects of field of view on the user experience and behavior. For example, users can more accurately judge distances when walking to a target when they have a larger field of view [Jones et al. 2012]. The team's research led to the low-cost Field of View To Go (FOV2GO), which was shown at the IEEE VR 2012 conference in Orange County, California, where the device won the Best Demo Award and was part of the MxR Lab's Open-source project that is the precursor to most of today's consumer HMDs. Around that time, a member of that lab named Palmer Luckey started sharing his prototype on Meant to be Seen (mtbs3D.com) where he was a forum moderator and where he first met John Carmack (now CTO of Oculus VR) and formed Oculus VR. Shortly after that he left the lab and launched the Oculus Rift Kickstarter. The hacker community and media latched onto VR once again. Companies ranging from start-ups to the Fortune 500 began to see the value of VR and started providing resources for VR development, including Facebook, which acquired Oculus VR in 2014 for $2 billion. The new era of VR was born.

3 An Overview of Various Realities

This chapter aims to provide a basic high-level overview of various forms of reality, as well as different hardware options to build systems supporting those forms of reality. Whereas most of the book focuses on fully immersive VR, this chapter takes a broader view; its aim is to put fully immersive VR in the context of the larger array of options.

3.1 Forms of Reality

Reality takes many forms and can be considered to range on a virtuality continuum from the real environment to virtual environments [Milgram and Kishino 1994]. Figure 3.1 shows various forms along that continuum. These forms, which are somewhere between virtual and augmented reality, are broadly defined as "mixed reality," which can be further broken down into "augmented reality" and "augmented virtuality." This book focuses on the right side of the continuum from augmented virtuality to virtual environments.

The **real environment** is the real world that we live in. Although creating real-world experiences is not always the goal of VR, it is still important to understand the real world and how we perceive and interact with it in order to replicate relevant functionality into VR experiences. What is relevant depends on the goals of the application. Section 4.4 further discusses trade-offs of realism vs. more abstract implementations of reality. Part II discusses how we perceive real environments in order to help build better fully immersive virtual environments.

Instead of replacing reality, **augmented reality** (AR) adds cues onto the already existing real world, and ideally the human mind would not be able to distinguish between computer-generated stimuli and the real world. This can take various forms, some of which are described in Section 3.2.

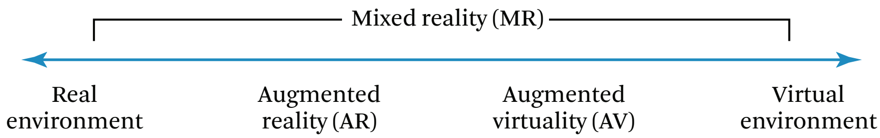

Figure 3.1 **The virtuality continuum.** (Adapted from Milgram and Kishino [1994])

Augmented virtuality (AV) is the result of capturing real-world content and bringing that content into VR. Immersive film is an example of augmented virtuality. In the simplest case, the capture is taken from a single viewpoint, but in other cases, real-world capture can consist of light fields or geometry, where users can freely move about the environment, perceiving it from any perspective. Section 21.6 provides some examples of augmented virtuality.

True **virtual environments** are artificially created without capturing any content from the real world. The goal of virtual environments is to completely engage a user in an experience so that she feels as if she is present (Chapter 4) in another world such that the real world is temporarily forgotten, while minimizing any adverse effects (Part III).

3.2 Reality Systems

The screen is a window through which one sees a virtual world. The challenge is to make that world look real, act real, sound real, feel real.

—Sutherland [1965]

A **reality system** is the hardware and operating system that full sensory experiences are built upon. The reality system's job is to effectively communicate the application content to and from the user in an intuitive way as if the user is interacting with the real world. Humans and computers do not speak the same language so the reality system must act as a translator or intermediary between them (note the reality system also includes the computer). It is the VR creator's obligation to integrate content with the system so the intermediary is transparent and to ensure objects and system behaviors are consistent with the intended experience. Ideally, the technology will not be perceived so that users forget about the interface and experience the artificial reality as if it is real.

Communication between the human and system is achieved via hardware devices. These devices serve as input and/or output. A transfer function, as it relates to inter-

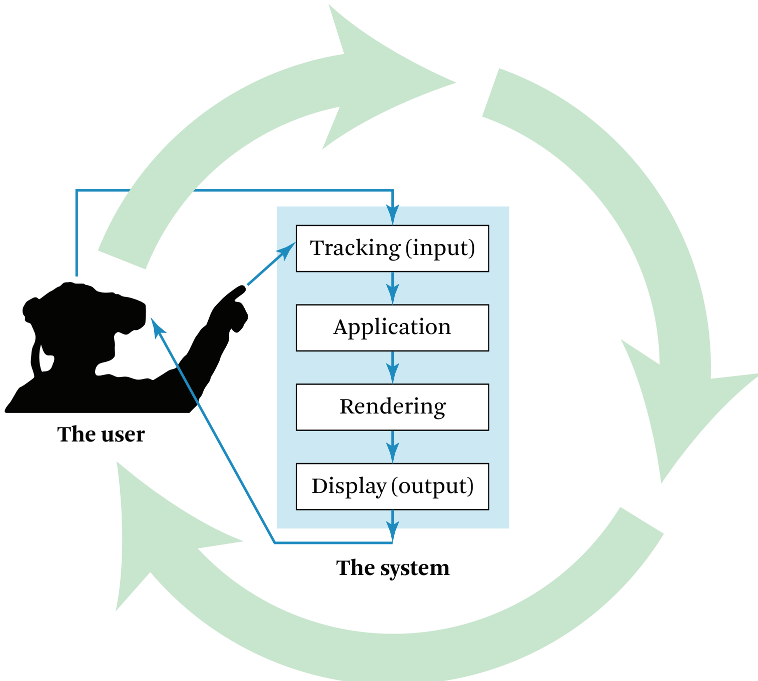

Figure 3.2 **A VR system consists of input from the user, the application, rendering, and output to the user.** (Adapted from Jerald [2009])

action, is a conversion from human output to digital input or from digital output to human input. What is output and what is input depends on whether it is from the point of view of the system or the human. For consistency, input is considered information traveling from the user into the system and output is feedback that goes from the system back to the user. This forms a cycle of input/output that continuously occurs for as long as the VR experience lasts. This loop can be thought of as occurring between the action and distal stimulus stages of the perceptual process (Figure 7.2) where the user is the perceptual process.

Figure 3.2 shows a user and a VR system divided into their primary components of input, application, rendering, and output. **Input** collects data from the user such as where the user's eyes are located, where the hands are located, button presses, etc. The **application** includes non-rendering aspects of the virtual world including updating dynamic geometry, user interaction, physics simulation, etc. **Rendering** is the transformation of a computer-friendly format to a user-friendly format that gives the illusion of some form of reality and includes visual rendering, auditory rendering (called auralization), and haptic (the sense of touch) rendering. An example of rendering is drawing a sphere. Rendering is already well defined (e.g., Foley et al. 1995) and other than high-level descriptions and elements that directly affect the user experience the technical details are not the focus of this book. **Output** is the physical representation directly perceived by the user (e.g., a display with pixels or headphones with sound waves).

The primary output devices used for VR are visual displays, speakers, haptics, and motion platforms. More exotic displays include olfactory (smell), wind, heat, and even taste displays. Input devices are only briefly mentioned in this chapter as they are described in detail in Chapter 27. Selecting appropriate hardware is an essential part of designing VR experiences. Some hardware may be more appropriate for some designs than others. For example, large screens are more appropriate than head-mounted displays for large audiences located at the same physical location. The following sections provide an overview of some commonly used VR hardware.

3.2.1 Visual Displays

Today's reality systems are implemented in one of three ways: head-mounted displays, world-fixed displays, and hand-held displays.

Head-Mounted Displays

A **head-mounted display** (HMD) is a visual display that is more or less rigidly attached to the head. Figure 3.3 shows some examples of different HMDs. Position and orientation tracking of HMDs is essential for VR because the display and earphones move with the head. For a virtual object to appear stable in space, the display must be appropriately updated as a function of the current pose of the head; for example, as the user rotates his head to the left, the computer-generated image on the display should move to the right so that the image of the virtual objects appears stable in space, just as real-world objects are stable in space as people turn their heads. Well-implemented HMDs typically provide the greatest amount of immersion. However, doing this well consists of many challenges such as accurate tracking, low latency, and careful calibration.

HMDs can be further broken down into three types: non-see-through HMDs, video-see-through HMDs, and optical-see-through HMDs. **Non-see-through HMDs** block out all cues from the real world and provide optimal full immersion conditions for VR. **Optical-see-through HMDs** enable computer-generated cues to be overlaid onto the visual field and provide the ideal augmented reality experience. Conveying the ideal augmented reality experience using optical-see-through head-mounted displays is extremely challenging due to various requirements (extremely low latency, extremely accurate tracking, optics, etc.). Due to these challenges, **video-see-through HMDs** are

Figure 3.3 **The Oculus Rift (upper left; courtesy of Oculus VR), CastAR (upper right; courtesy of CastAR), the Joint-Force Fighter Helmet (lower left; courtesy of Marines Magazine), and a custom built/modified HMD (lower right; from Jerald et al. [2007]).**

sometimes used. Video-see-through HMDs are often considered to be augmented virtuality (Section 3.1), and have some advantages and disadvantages of both augmented reality and virtual reality.

World-Fixed Displays

World-fixed displays render graphics onto surfaces and audio through speakers that do not move with the head. Displays take many forms, ranging from a standard monitor (also known as fish-tank VR) to displays that completely surround the user

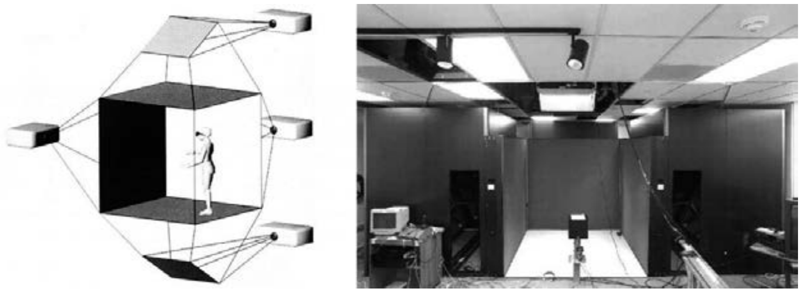

Figure 3.4 **Conceptual drawing of a CAVE (left). Users are surrounded with stereoscopic perspective-correct images displayed on the floor and walls that they interact with. The CABANA (right) has movable walls so that the display can be configured into different display shapes such as a wall or L-shape.** (From Cruz et al. [1992] (left) and Daily et al. [1999] (right))

(e.g., CAVEs and CAVE-like displays as shown in Figures 3.4 and 3.5). Display surfaces are typically flat surfaces, although more complex shapes can be used if those shapes are well defined or known, as shown in Figure 3.6. Head tracking is important for world-fixed displays, but accuracy and latency requirements are typically not as critical as they are for head-mounted displays because stimuli are not as dependent upon head motion. High-end world-fixed displays with multiple surfaces and projectors can be highly immersive but are more expensive in dollars and space.

World-fixed displays typically are considered to be part virtual reality and part augmented reality. This is because real-world objects are easily integrated into the experience, such as the physical chair shown in Figure 3.7. However, it is often the intent that the user's body is the only visible real-world cue.

Hand-Held Displays

Hand-held displays are output devices that can be held with the hand(s) and do not require precise tracking or alignment with the head/eyes (in fact the head is rarely tracked for hand-held displays). Hand-held augmented reality, also called indirect augmented reality, has recently become popular due to the ease of access and improvements in smartphones/tablets (Figure 3.8). In addition, system requirements are much less since viewing is indirect—rendering is independent of the user's head and eyes.

3.2.2 Audio

Spatialized audio provides a sense of where sounds are coming from in 3D space. Speakers can be fixed in space or move with the head. Headphones are preferred for a fully immersive system as they block out more of the real world. How the ears and

Figure 3.5 **The author interacting with desktop applications within the CABANA.** (From Jerald et al. [2001])

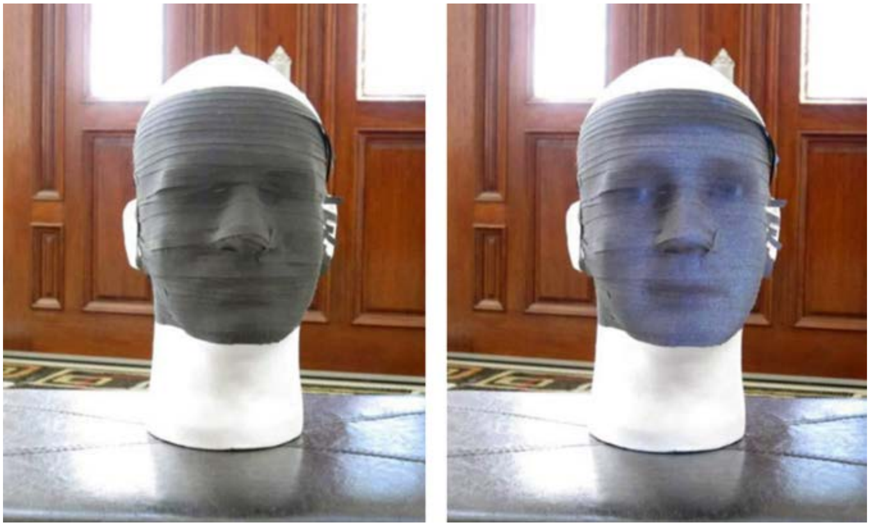

Figure 3.6 **Display surfaces do not necessarily need to be planar.** (From Krum et al. [2012])

Figure 3.7 **The University of Southern California's Gunslinger uses a mix of the real world along with world-fixed displays.** (Courtesy of USC Institute for Creative Technologies)

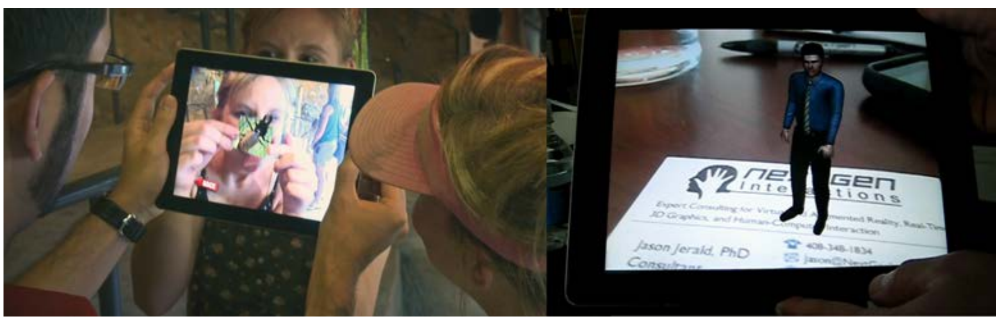

Figure 3.8 **Zoo-AR from GeoMedia and a virtual assistant that appears on a business card from NextGen Interactions.** (Courtesy of Geomedia (left) and NextGen Interactions (right))

brain perceive sound is discussed in Section 8.2. Audio more specific to how content is created for VR is discussed in Section 21.3.

3.2.3 Haptics

Haptics are artificial forces between virtual objects and the user's body. Haptics can be classified as passive (static physical objects) or active (physical feedback controlled by the computer), tactile (through skin) or proprioceptive force (through joints/muscles), and self-grounded (worn) or world-grounded (attached to real world). Many haptic systems also serve as input devices.

Passive vs. Active Haptics

Passive haptics provide a sense of touch in VR at a low cost—one simply creates a real-world physical object and matches that object to the shape of a virtual object [Lindeman et al. 1999]. These physical objects can be hand-held props or larger objects in the world that can be touched. Passive haptics increases presence, improves cognitive mapping of the environment, and improves training performance [Insko 2001].

Touching a few objects with passive haptics can make everything else seem more real. Perhaps the most compelling VR experience to this day is the legendary UNC-Chapel Hill Pit demo [Meehan et al. 2002]. Users first experience a virtual room that includes passive haptics made from Styrofoam blocks and other real-world material to match the visual VR environment. After touching different parts of the room, users walk into a second room and see a pit in the floor. The pit is quite compelling (in fact, heart rate increases) because everything else they have touched up to this point has physically felt real, thus users assume the pit is physically real as well. There is an even more startling response from many users when they put their toe over the virtual ledge and feel a real ledge. What they don't realize is the physical ledge is only a 1.5 inch drop-off compared to the visual pit that is 20 feet deep.

Active haptics are controlled by a computer and are the most common form of haptics. Active haptics have the advantage that forces can be dynamically controlled to provide a feeling of a wide range of simulated virtual objects. The remainder of this section focuses on active haptics.

Tactile vs. Proprioceptive Force Haptics

Tactile haptics provide a sense of touch through the skin. Vibrotactile stimulation evokes tactile sensations using mechanical vibration of the skin. Electrotactile stimulation evokes tactile sensation via an electrode passing current through the skin.

Figure 3.9 shows Tactical Haptics' Reactive Grip technology, which provides a sense of tactile feedback that is surprisingly compelling, especially when combined with fully immersive visual displays [Provancher 2014]. The system utilizes sliding skin-contact plates that can be added to any hand-held controller. Translational motions and forces are portrayed along the length of the grip by moving the plates in unison. Opposing motion and forces from different plates creates the feeling of a virtual object wrenching within the user's grasp.

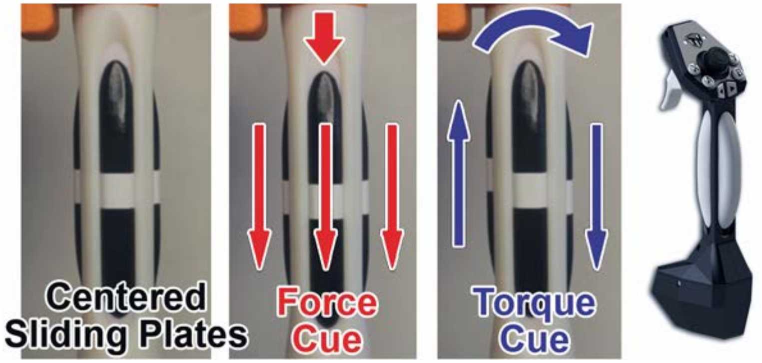

Figure 3.9 **Tactical Haptics technology uses sliding plates to provide a sense of up or down force as well as rotational torque. The rightmost image shows the sliding plates integrated into the latest controller design.** (Courtesy of Tactical Haptics)

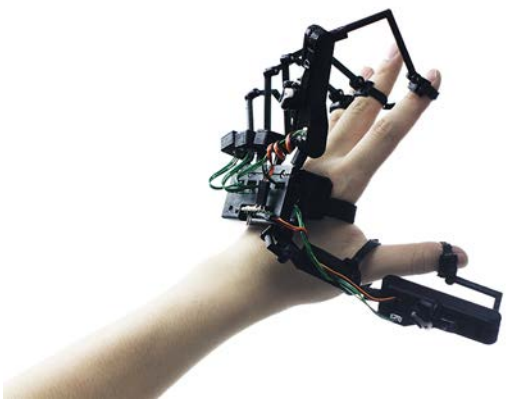

Figure 3.10 **The Dexta Robotics Dexmo F2 device provides both finger tracking and force feedback.** (Courtesy of Dexta Robotics)

Proprioceptive force provides a sense of limb movement and muscular resistance. Proprioceptive haptics can be self-grounded or world-grounded.

Self-Grounded vs. World-Grounded Haptics

Self-grounded haptics are worn/held by and move with the user. The forces applied are relative to the user. Gloves with exoskeletons or buzzers are examples of self-grounded haptics. Figure 3.10 shows an exoskeleton glove. Hand-held controllers are also examples of self-grounded haptics. Such controllers might be simply a passive

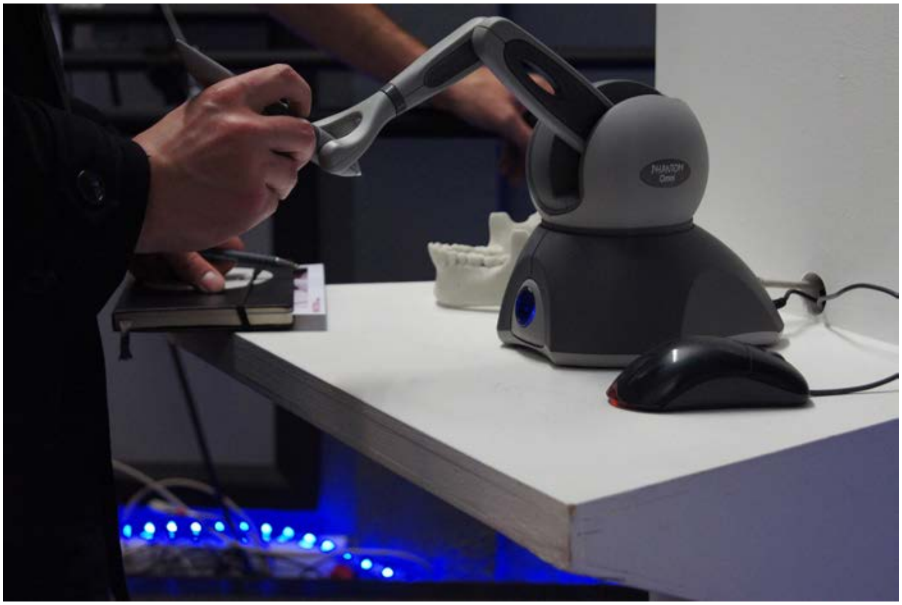

Figure 3.11 **Sensable's Phantom haptics system.** (Courtesy of INITION)

prop that acts as a handle to virtual objects or might be rumble controllers that vibrate to provide feedback to the user (e.g., to signify the user has put his hand through a virtual object).

World-grounded haptics are physically attached to the real world and can provide a true sense of fully solid objects that don't move because the position of the virtual object providing the force can remain stable relative to the world. The ease of which the object can be moved can also be felt, providing a sense of weight and friction [Craig et al. 2009].

Figure 3.11 shows Sensable's Phantom haptic device, which provides stable force feedback for a single point in space (the tip of the stylus). Figure 3.12 shows Cyberglove's CyberForce glove that provides the sense of touching real objects with the entire hand as if the objects were stationary in the world.

3.2.4 Motion Platforms

A **motion platform** is a hardware device that moves the entire body resulting in a sense of physical motion and gravity. Such motions can help to convey a sense of orientation, vibration, acceleration, and jerking. Common uses of platforms are for racing games, flight simulation, and location-based entertainment. When integrated well with the

Figure 3.12 **Cyberglove's Cyberforce Immersive Workstation.** (Courtesy of Haptic Workstation with HMD at VRLab in EPFL, Lausanne, 2005)

rest of a VR application, motion sickness can be reduced by decreasing the conflict between visual motion and felt motion. Section 18.8 discusses how motion platforms can be used to reduce motion sickness.

Motion platforms can be active or passive. An **active motion platform** is controlled by the computer simulation. Figure 3.13 shows an example of an active motion platform that moves a base platform via hydraulic actuators. A **passive motion platform** is controlled by the user. For example, the tilting of a passive motion platform might be achieved by leaning forward, such as used with Birdly shown in Figure 3.14. Note active and passive as described here are from the point of view of the motion platform and system. When describing motion from the point of view of the user, passive implies the user is passively along for the ride, with no way to influence the experience, and active implies the user is actively influencing the experience.

3.2.5 Treadmills

Treadmills provide a sense that one is walking or running while actually staying in one place. Variable-incline treadmills, individual foot platforms, and mechanical tethers

Figure 3.13 **An active motion platform that moves via hydraulic actuators. A chair can be attached to the top of the platform.** (Courtesy of Shifz, Syntharturalist Art Association)

Figure 3.14 **Birdly by Somniacs. In addition to providing visual, auditory, and motion cues, this VR experience provides a sense of taste and smell.** (Courtesy of Swissnex San Francisco and Myleen Hollero)

Figure 3.15 **The Virtuix Omni.** (Courtesy of Virtuix)

providing restraint can convey hills by manipulating the physical effort required to travel forward.

Omnidirectional treadmills enable simulation of physical travel in any direction and can be active or passive.

Active omnidirectional treadmills have computer-controlled mechanically moving parts. These treadmills move the treadmill surface in order to recenter the user on the treadmill (e.g., Darken et al. 1997 and Iwata 1999). Unfortunately, such recentering can cause the user to lose balance.

Passive omnidirectional treadmills contain no computer-controlled mechanically moving parts. For example, the feet might slide along a low-friction surface (e.g., the Virtuix Omni as shown in Figure 3.15). A harness and surrounding encasing keeps the user from falling. Like other forms of non-real walking, the experience of walking on a passive treadmill does not perfectly match the real world (it feels more like walking on slippery ice), but can add a significant amount of presence and reduce motion sickness.

3.2.6 Other Sensory Output

VR largely focuses on the display component, but other components such as taste, smell, and wind can more fully immerse users and add to a VR experience. Figure 3.14

shows Birdly by Somniacs, a system that adds smells and wind to a VR experience. Section 8.6 discusses the senses of taste and smell.

3.2.7 Input

A fully immersive VR experience is more than simply presenting content. The more a user physically interacts with a virtual world using his own body in intuitive ways, the more that user feels engaged and present in that virtual world. VR interactions consist of both hardware and software working closely together in complex ways, yet the best interaction techniques are simple and intuitive to use. Designers must take into account input device capabilities when designing experiences—one input device might work well for one type of interaction but be inappropriate for another. Other interactions might work across a wider range of input devices. Part V contains multiple chapters on interaction with Chapter 27 focusing exclusively on input devices.

3.2.8 Content

VR cannot exist without content. The more compelling the content, the more interesting and engaging the experience. Content includes not only the individual pieces of media and their perceptual cues, but also the conceptual arc of the story, the design/layout of the environment, and computer- or user-controlled characters. Part IV contains multiple chapters dedicated to content creation.