

Contents

Preface ix

Part I REALITY'S ARENA

1. Roads to Reality 3
Space, Time, and Why Things Are as They Are
2. The Universe and the Bucket 23
Is Space a Human Abstraction or a Physical Entity?
3. Relativity and the Absolute 39
Is Spacetime an Einsteinian Abstraction or a Physical Entity?
4. Entangling Space 77
What Does It Mean to Be Separate in a Quantum Universe?

Part II TIME AND EXPERIENCE

5. The Frozen River 127
Does Time Flow?
6. Chance and the Arrow 143
Does Time Have a Direction?
7. Time and the Quantum 177
Insights into Time's Nature from the Quantum Realm

Part III SPACETIME AND COSMOLOGY

- | | |
|---|-----|
| 8. Of Snowflakes and Spacetime
<i>Symmetry and the Evolution of the Cosmos</i> | 219 |
| 9. Vaporizing the Vacuum
<i>Heat, Nothingness, and Unification</i> | 251 |
| 10. Deconstructing the Bang
<i>What Banged?</i> | 272 |
| 11. Quanta in the Sky with Diamonds
<i>Inflation, Quantum Jitters, and the Arrow of Time</i> | 304 |

Part IV ORIGINS AND UNIFICATION

- | | |
|--|-----|
| 12. The World on a String
<i>The Fabric According to String Theory</i> | 327 |
| 13. The Universe on a Brane
<i>Speculations on Space and Time in M-Theory</i> | 376 |

Part V REALITY AND IMAGINATION

- | | |
|---|-----|
| 14. Up in the Heavens and Down in the Earth
<i>Experimenting with Space and Time</i> | 415 |
| 15. Teleporters and Time Machines
<i>Traveling Through Space and Time</i> | 437 |
| 16. The Future of an Allusion
<i>Prospects for Space and Time</i> | 470 |
| <i>Notes</i> | 495 |
| <i>Glossary</i> | 537 |
| <i>Suggestions for Further Reading</i> | 543 |
| <i>Index</i> | 545 |

P r e f a c e

Space and time capture the imagination like no other. For good reason. They form the arena of reality, the vast cosmos. Our entire existence—everything we do, think, feel—takes place in some region of space during some interval of time. Science is still struggling to understand what space and time are. Are they real physical entities or simply useful ideas? Are they fundamental, or do they emerge from more basic principles? Does it mean for space to be empty? Does time have an arrow, flowing inexorably from past to future? What experience would indicate? Can we manipulate space and time? In this book, we follow three hundred years of passionate scientific inquiry, seeking answers, or at least glimpses of answers, to some of the most important questions about the nature of the universe.

Our journey also brings us repeatedly to another, more fundamental question, as encompassing as it is elusive: What *is* reality? Can we have access to the internal experiences of perception? Can we be sure they truly reflect an external world? We have long recognized this problem. Filmmakers have popularized it with story lines involving artificial worlds, generated by computer graphics and virtual stimulation that exist solely within the minds of the viewers. And physicists such as myself are acutely aware of the limits of what we can observe—matter evolving on the stage of space and time. We can do little to do with the reality, if any, that's out there. Nevertheless, these observations are all we have, we take them seriously. We construct the framework of mathematics as our guides, not unaided intuition or unrelenting skepticism, and seek the simplest, most elegant theories capable of explaining and predicting the results of past and future experiments. This severely restricts the theoretical possibilities. In this book, for example, we won't find a hint that I'm