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978-1-107-47741-4 - The Wonders of Light
Marta García-Matos and Lluís Torner
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THE WONDERS OF LIGHT

Discover the spectacular power of light with this visually stunning celebration of the multitude of ways in which light-based technologies are shaping our society.

Be inspired by state-of-the-art science
Sixteen beautiful, straightforward chapters demonstrate the science behind the fascinating and surprising ways in which light can be harnessed and used, from displays, solar cells, and the internet to advanced quantum technologies.

Be dazzled by brilliant color
Dramatic design and radiant color illustrations bring cutting-edge science and ground-breaking innovations to life, clearly explaining the fundamental principles behind them.

Be part of something bigger
Featuring a foreword by Nobel Laureate and former US Secretary of Energy, Steven Chu, this book has been published in association with ICFO - The Institute of Photonic Sciences to celebrate the 2015 International Year of Light. It will enthrall anyone interested in the developments of science, technology and human civilization that have been made possible by light.

Marta García-Matos is a physicist, mathematician and writer working at the outreach division of ICFO - The Institute of Photonic Sciences.

Lluís Torner is the Founding Director of ICFO - The Institute of Photonic Sciences. He is a Fellow of the European Physical Society, the European Optical Society, and the Optical Society of America.

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FOREWORD

Steven Chu
Stanford University
Nobel Laureate
Former US Secretary of Energy (2009–2013)

We are visual beings, and qualities such as "insight" and "vision" describe our understanding well beyond sensory inputs. The ability to extend our sight beyond our eyes gives deeper meaning to the observation of Yogi Berra, the great American philosopher of the 20th century: "You see a lot by just watching."

Visible light is a small sliver of a huge spectrum that includes radio waves with energies as low as 2×10^{-13} eV (48 Hz) used to communicate with submarines, to cosmic gamma rays with energies in excess of 300 GeV (7×10^{25} Hz). Maxwell's equations, written in 1862, predicted that radio waves, infrared radiation, and visible light are different forms of electromagnetic waves. In the ensuing 150 years, we discovered X-rays and gamma rays, and subsequently realized that these forms of energy are also part of the electromagnetic spectrum.

With the development of Quantum Mechanics in the 1920s, we discovered that the energy of these waves cannot be dialed down arbitrarily, but there exists a fundamental "graininess" to light: the photon. An electromagnetic wave of frequency ν is composed of particles of light with energy $E_{min} = \hbar\nu$, where Planck's constant h is a universal constant of Nature. Light can display both particle and wave properties. Remarkably, Maxwell's equations predicted that photons with energies less than 10^{-13} eV to greater than $3 \times 10^{+11}$ eV all move at the same speed in vacuum. This prediction, yet to be contradicted by experiment, is one of the wonders of light.

Marta García-Matos' and Lluís Torner's *Wonders of Light* presents a delightful smorgasbord that illustrates how light continues to redefine our daily lives. The chapter "Lighting" reminds us how artificial light liberated us from darkness (and boredom) and protected us from predators; rapidly advancing technology is allowing us to create light that mimics the changing hues of sunlight during the day. The chapter "Displays" shows how light enhances our ability to visualize. All of these technologies rest on recent stunning advances in the chapter "New Materials."

Our ability to image the microscopic world down to the atomic level helps us understand and combat "Virus Attacks." The chapter "Focus" describes recent advances in the effective resolution of optical microscopy that are able to circumvent the limits imposed by the Uncertainty Principle of Quantum Mechanics. "Optogenetics" speaks of powerful new ways of stimulating neurons in fully functioning animals that are leading to a deeper understanding of the brain, and will soon find applications in pain control and neuronal disorders.

Part of the wonder of light is that it can be used in applications that demand wildly different properties. Light can be extremely "Sharp" for precise laser surgery and destruction of selected cells. It can be "Gentle," and used to cradle and move individual cells and biomolecules. While intense beams of light can heat matter to temperatures that mimic the center of the Sun, it can be used to create "Cold" more than a billion times colder than the temperature of the most remote corners of our universe. Lasers can be utilized in

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seemingly diametrically opposite applications. They can be ultra-stable clocks that detect a deviation of less than one second over the lifetime of the universe or, alternatively, be used to take ultra-"Fast" snapshots of changes in the electrons of atoms, molecules, and materials. During this time, the atomic motion appears frozen. While a laser beam is synonymous with a straight-line path, and more generally the path that minimizes the transit time between two points in space and time, the chapter "Random Walks" introduces the reader to the manner in which we exploit light when it travels in media that scatter and absorb the photons.

Advances in science and technology do not require an intuitive understanding of the underlying phenomena. The chapters "Privacy" and "Riddles" discuss applications of quantum states connected to each other in ways far removed from human experience. Nevertheless, we used Quantum Mechanics to invent the transistor, the laser, and more recently, quantum computing and quantum cryptography. Over the past half a century, we have learned to live in peaceful co-existence with a wildly successful theory that still defies human intuition. "Connected" shows how we use light to transmit information at staggering rates. While we routinely communicate with people half-way around the world in a blink of an eye, we have no mechanical insight as to how light travels in vacuum. All that remains of the mechanical model Maxwell used to arrive at his equations are the equations: like the Cheshire Cat in *Alice in Wonderland*, the body of the cat disappears and all that remains is its smile. Massive particles, electrons, atoms, molecules also have wave-like properties, but today there is a debate as to whether the quantum phase frequency ν, given by $E = mc^2 = \hbar\nu$, that appears in our most general theory of Quantum Mechanics is measurable in principle.

The Wonders of Light also discusses how light will help us transition to a sustainable world. Because of our ability to exploit fossil energy, a growing number of people keep their homes warm in the winter, cool in the summer, and lit at night. Many of us go to the local market in cars with the power of over a hundred horses and fly across continents in wide-body airplanes with the power of a hundred thousand horses. The Sun is ultimately the source of this energy. What took Nature hundreds of millions of years to create in coal, oil, and natural gas, we are using up in hundreds of years.

Long before we run out of fossil fuels, there is another danger. The carbon emissions used to generate the equivalent of more than a billion horses working continuously have created significant climate-change risks. The overwhelming consensus among climate scientists is that the Earth is warming up due to the burning of fossil fuels, and we need to drastically reduce carbon emissions by mid-century. To accomplish this task, we must convert massive amounts of sunlight energy into electricity. The chapter "Catch that Energy!" describes how the technology is racing ahead. A wonder and necessity of light is its role in providing a clean source of energy necessary to protect us from dire peril.

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All Advisors listed at the end of each chapter

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ABOUT THE BOOK

"The sun shone, having no alternative, on the nothing new." Samuel Beckett's acclaimed opening words for *Murphy* appear to be somehow pessimistic. Yet actually, quite often, a distinctive control over light beams puts forward a path to the new. This book takes a glance over some of those paths.

Exploring the natural phenomena around us and across the Universe; pushing the limits of our understanding of Nature; and using the knowledge acquired to diagnose and cure disease, and to create devices and machines that make life safer, healthier, and more fulfilling is a program that many, throughout history, have found as captivating as compelling. Advancing such programs requires tools, which must be more and more sophisticated as the limits of knowledge move farther from our own scale and intuition. Really small or really large things, as well as really fast or really slow events, are particularly challenging, as neither our senses nor our ordinary gadgets are equipped to tackle them. We need powerful tools and technologies to enter such territories. The farther we aim to reach, the higher the performances that our toolkit must deliver.

Light is one of these wonderful tools. It is ubiquitous and universal, and can be outstandingly accurate and precise. During the past decades we have learnt not only how to generate and control light in exquisite ways – especially since the invention of the laser half a century ago – but also how to transmit it and display it in ways that used to be the realm of science fiction and novels.

As a result, light-based technologies are, literally, everywhere. And what is available today is just the beginning.

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The book consists of sixteen chapters of the same length and structure, each addressing a particular scientific and technological challenge in which some of the multifaceted existing light–matter interactions take a leading role. Readers can go through the chapters following any order they want. Each chapter opens with a short story that aims at motivating a context in which the overall challenge to be addressed has an impact. A brief description of the science and technology of light involved in the solution follows, supported by a set of graphic illustrations and complemented with a technical glossary and suggestions for further reading. Chapters are intended to be self-contained.

We avoided an introductory chapter reviewing the properties of light. Instead, we chose to spread the technical and scientific content through the different chapters, picking up properties only as they were relevant for the different applications.

The first part of the book addresses a wealth of accomplishments that require the finest control of light in order to push fundamental limits of experimental science: achieving the coldest temperatures, just billionths of billionths of a degree over absolute zero; resolving the smallest structural details, at the scale of a billionth of a meter; or filming the fastest processes ever recorded, such as the electronic transitions in chemical reactions that take millionths of billionths of a second.

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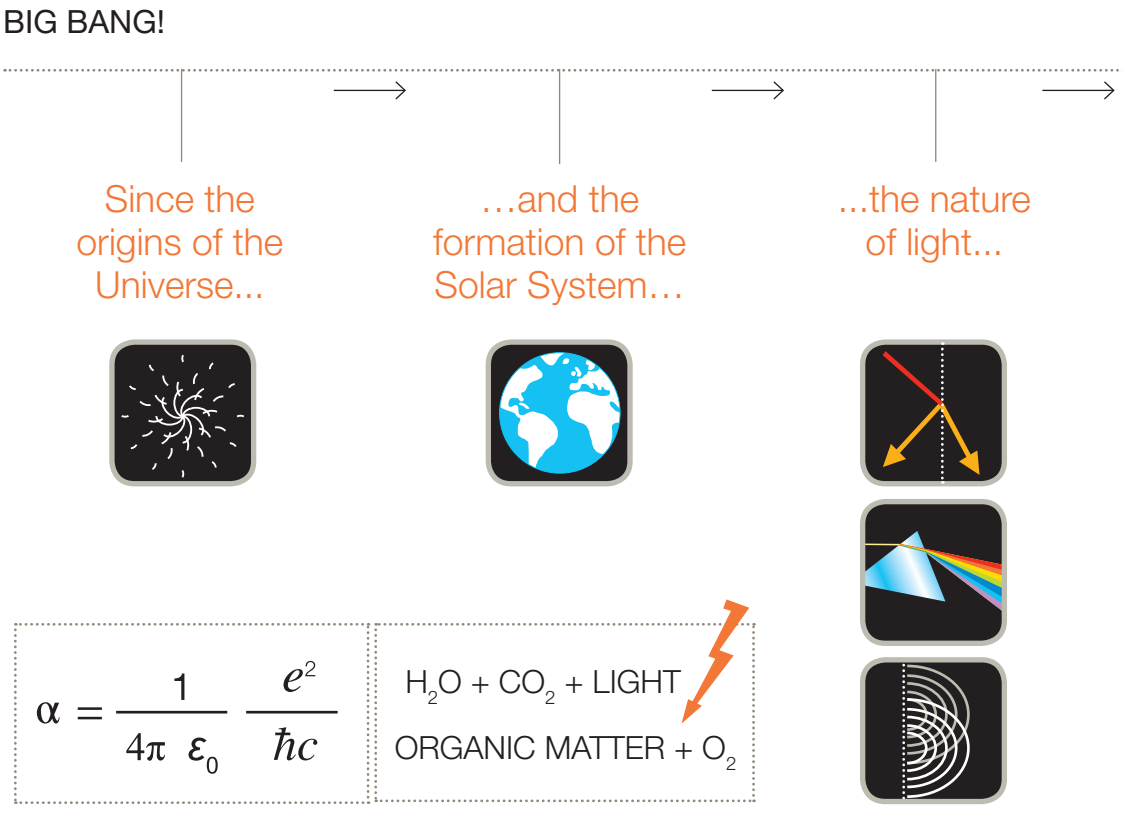
The second part deals with understanding technologies and applications that have a central impact in our life style and in the way current civilization is shaped. We address applications in health and life sciences, global communications, new materials, renewable energy, lighting sources, consumer gadgets, and futuristic technologies, such as quantum computing. Unfortunately, we had to omit many other applications, in the hope that the material presented here motivates readers to search for more.



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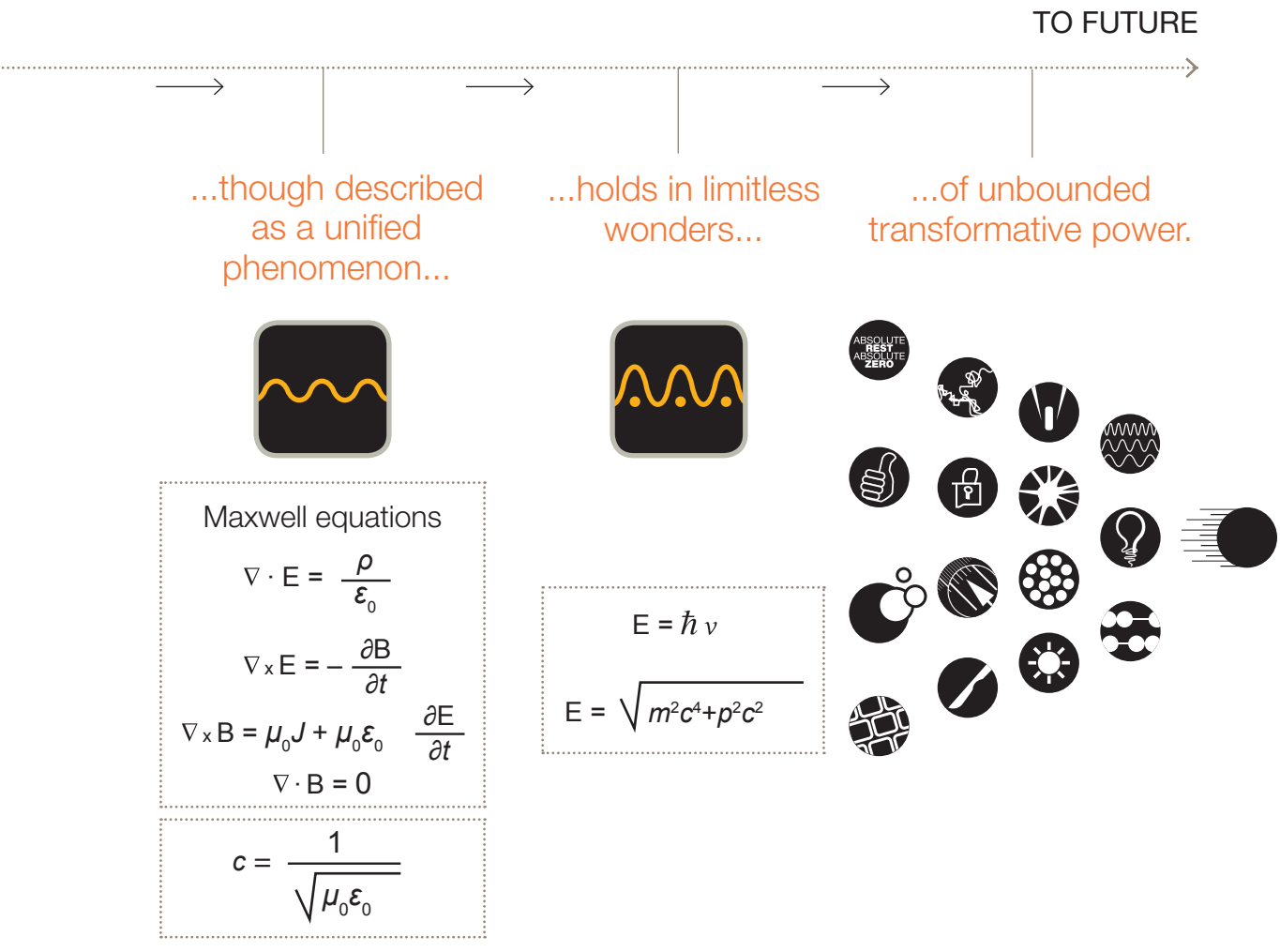
The science and technology of light has reached a point in which, under the proper conditions, it can be used to direct the exact energy and information we want to the exact point in time and space we need. This is the principle behind an emergent technology, often known as photonics, already shining in a wealth of ordinary situations, but which promises to get in through every and many more cracks in the years to come.



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