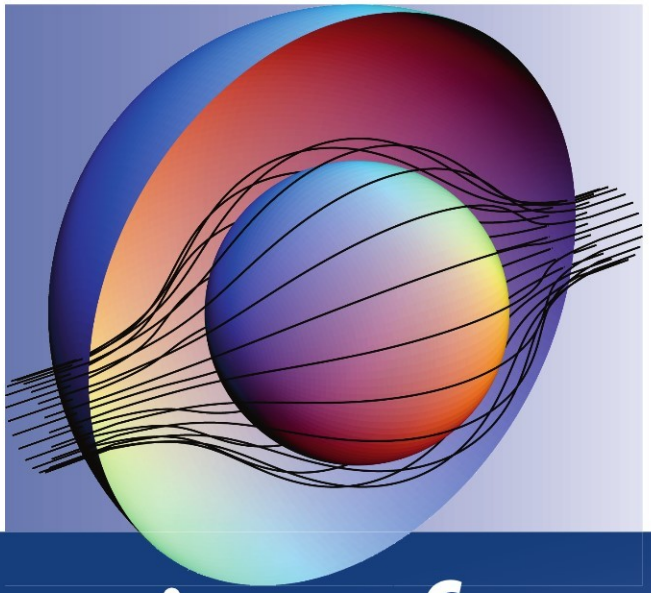
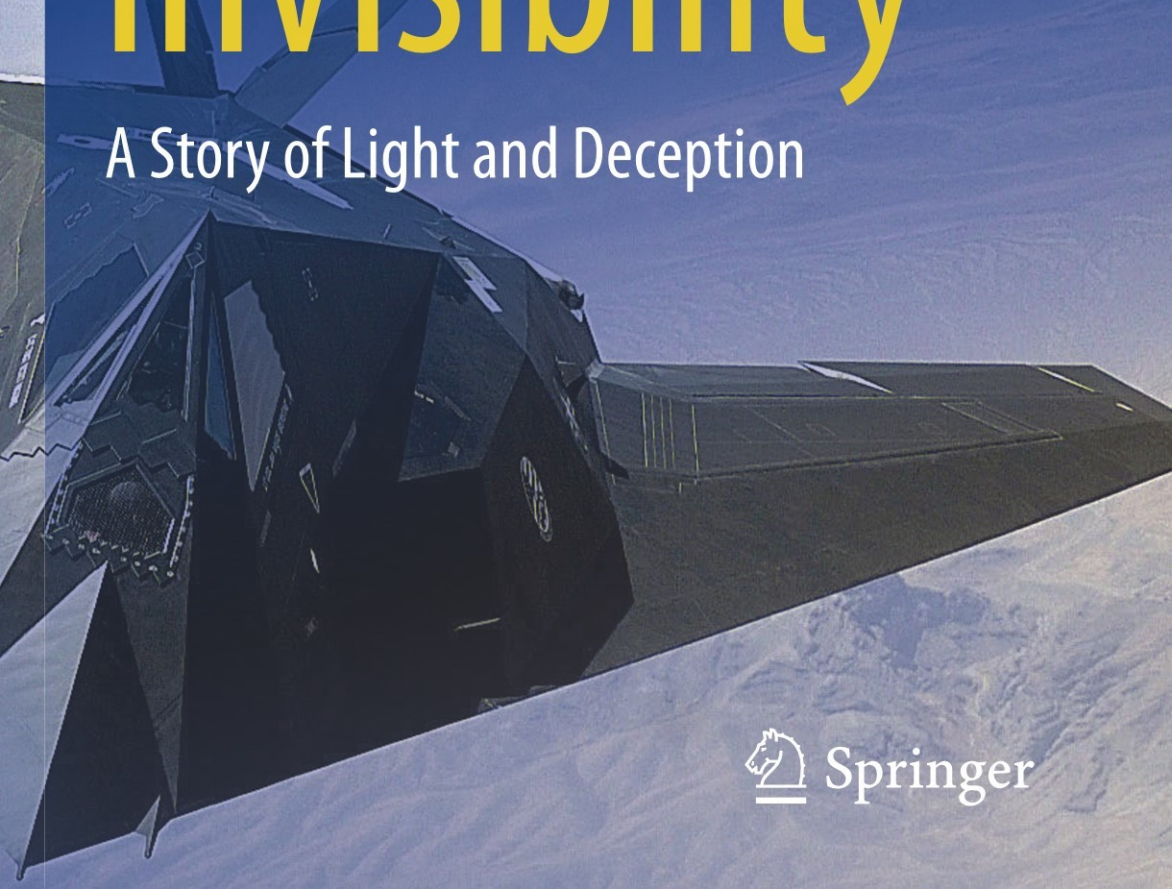




The Physics of Invisibility

A Story of Light and Deception



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Martin Beech
University of Regina
Regina, SK, Canada
martin.beech@uregina.ca

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*This book is for Gael with many thanks
for showing me the stars from New Zealand.*

About the Author

Martin Beech is Professor of Astronomy at Campion College, The University of Regina in Saskatchewan, Canada. He has written numerous research articles on topics ranging from meteor physics, Martian meteorites, stellar structure and evolution, cosmology, the history of science and mathematical number theory. He lives in Regina with his more than visible wife, a brother-in-law, five dogs (*a.k.a.* The Five Pugs of the Apocalypse) and three cats – there are times when he certainly wishes he could be invisible.

Introduction

The second worst joke in the world begins with the question, “When is a door not a door?” The answer to this conundrum, of course, is, “when it is ajar.” The logician might at first wince at this dreadful play on words, but then in learned tones continue that a door is not a door, of course, if one cannot see it in the first place, or if it is camouflaged to look like something else.

Well, the joke, as we first warned, is the second worst joke in the world, and the logician’s rejoinder is no more amusing, but at least there can be little argument with the fact that if you can’t see something then it is impossible to name it, and if it looks like something else then the naming will be wrong. For, indeed, we live in a world of names and light. Through an incredible act of evolution our eyes bring the light from the surrounding world to the rods and cones attached to our retinas, and there a photochemical reaction transforms the laid-out vista, a real and inverted vista at that, into a series of electrochemical pulses that our brain can, somehow, transform into a mind’s-eye view. Reality turned into light, into chemistry, into synaptic pulses, into virtual inner seeing – what an incredible transformation our view of the world truly is.

It is by this remarkable chain of transformations that we see and thereby recognize and name the objects around us. Indeed, the world is given permanence by naming: a door is a door and nothing else – unless, of course, it is ajar, or if it cannot be seen. We make sense of the world and its stability by seeing and interpreting the images that are presented to us, and we take dominion over the world by giving names to those objects that don’t change their form from one moment to the next. By the act of seeing, and through the action of naming, the world makes sense to us – well, some of the time. And yet, the Belgian surrealist painter René Magritte also reminds us of “The Treachery of Images” (Fig. 1) and how the mind’s-eye can be so easily fooled. Not least with respect to context can we be hoodwinked, but our perception of reality can also be misdirected and manipulated – what we think we see is not necessarily what occurred or was actually there. Indeed nature, long ago, learned that survival is all about blending into the background and looking like something else. Camouflage, after all, is about the art of melding into invisibility. So let’s ask the question again: “When is a door not a door?” Answer: When it looks



Fig. 1 “The Treachery of Images,” by René Magritte, oil on canvas painted 1928/29. This picture does not show a pipe. What we see in this image is, in fact, the image of an image of a painting of an object called a pipe



Fig. 2 *Cnemaspis Neangthyi* – a new species of gecko discovered in the rocky foothills of the Cadamon Mountains of Cambodia in 2007. The gecko’s surface texture and coloring is a superb camouflage match to the background rock. Image courtesy of Lee Grismer, La Sierra University, California

like a brick wall. Likewise, “When does a gecko not look like food?” Answer: When it looks like a piece of rock (Fig. 2).

Without light all is lost. If we cannot see an object we cannot name it, and it is invisible to our senses – it becomes a mystery and at best a shadow-form devoid of meaning. For all this, however, the world is full of impossible images; not least among these are the shimmering mirages on a deep blue sky, turning distant sailing



Fig. 3 Two of the very first experimental cloaking devices. These disks can mask from view (at microwave wavelengths) any object placed within their central core (Image courtesy of D. Smith, Duke University)

ships into airborne galleons, or the diaphanous glow of Pepper's Ghost, the phantasm that haunts many a thespian stage. Reality, for so it would seem, is mercurial and ever changing, and what we think we see may be nothing more than an imagined chimera – as French author and diarist Anaïs Nin so aptly wrote, “We don't see things as they are, we see things as we are.”

There are many, many ways in which an object can be made invisible, and some of them, as we shall see, appear to fall under the banner of magical. This is the magic of science, of course, rather than the magic of wishful thinking or the miraculous act in which something happens beyond the laws of physics and normality. Science is, indeed, a hard task master, but fortunately it has not stifled the free ranging nature of literary imagination – for certainly, both ancient and modern writings are rich with the ideas of magic, invisibility and the miraculous. The desire to walk unobserved through the world and to command invisibility at will is a power that many humans may have wished for, but as Chap. 1 reveals it is a power that no one person should have unrestricted access to. But this being said, we now live in a world where the technology to make solid objects invisible to outside detection does exist. It is a reality, and we assuredly do live in an age of miracles and wonders (Fig. 3). These fledgling devices will change the world and the way in which we see it – or don't see it, as the case may be.

The world is revealed to us by seeing, and there is both fear and desire in the thought of invisibility. It would, indeed, be the strangest sight we ever saw if something disappeared before our eyes. And yet, our waking world is full of familiar invisible entities. The flow of electricity along a bare metal wire, the gravity that keeps us grounded, the air we breathe, the bacteria and viruses that make us ill, the X-rays that reveal our broken bones, the time that measures our days, and the radio signals that keep us connected – all are invisible to our visual senses, and yet they surround us and we don't give them a second thought.

Not only this, we also explain the very world in terms of entities we cannot see. The atoms that make up this page and the chair you are sitting on – even you – are so minutely small that to our everyday senses they are not just invisible, they verge on the non-existent. Indeed, the famous Austrian physicist and logical positivist philosopher Ernst Mach (as recently as a century ago) denied the very existence of atoms because no one could observe them. And yet, the modern theory of the atom is one of the most successful and most cherished of all scientific accomplishments.

Not only do we humans give names and permanency to those objects that can be seen, we also provide names and existence to entities that we cannot sense at all. Invisible doesn't necessarily mean out of sight and out of mind. "Vision," in the intellectual sense, Jonathan Swift reminds us, "is the art of seeing what is invisible to others."

To understand what it is that we see, we must first understand light itself, and in this era of nascent cloaking devices this also means that we must know how to control light and make it move according to our desires. But what is light? This is one of the questions that will be answered in Chap. 2. Before this, however, in Chap. 1 our attention will be directed towards a brief review of what invisibility has historically meant to society, scientists and philosophers, and we shall look at a few of the simpler invisibility-making ruses. In Chap. 3 we begin to explore some of the ways in which light can be manipulated and how some more complex forms of invisibility are achieved. Chapter 4 delves deeper into the question of light as a manifestation of electromagnetic radiation, while Chap. 5 turns to issues relating to the direct manipulation of light via metamaterial substrates (Fig. 3).

Much of the physics of invisibility seems magical and often downright impossible, but in the world of scientific exploration there are many different levels of magic and impossibility. Perhaps, however, as physicist Michio Kaku has explained in his highly entertaining book *The Physics of the Impossible* (Anchor Books, 2009), there are three basic levels of impossibility. Type I impossibilities encompass those ideas that are presently impossible to realize, but the way to make them possible is at least known in principle – in other words they do not contradict any known physical principles. Type II impossibilities are those that are currently impossible, and it is not clear how they might be made possible in the future either technically or theoretically. And, finally Type III impossibilities constitute those processes that are impossible because they violate one or more of the known laws of physics – so-called perpetual motion machines fall under this category, for example, because they violate the known (and fully agreed upon) laws of thermodynamics.

Making an object invisible to all wavelengths of light is presently a Type I impossibility – since, as we shall see in later chapters, it is already possible to make an object invisible at selected wavelengths of electromagnetic radiation. The final construction of a fully flexible, all wavelengths of light invisibility cloak is perhaps a few decades away. At issue are not fundamental questions of theoretical physics but rather questions relating to technology development and fabrication methods. For all this, however, there are many ways of making something disappear, and a few of the more recent ideas hover tantalizingly in the borderline realm separating Type II impossibilities from those of Type III. The fun, of course, will be in finding out exactly which side of the borderline they do reside upon. The physics of invisibility is a new, dynamic and exciting field of research, and we shall surely marvel at what we may see, or more appropriately not see, as the near-term future unfolds.

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Chapter 1

Of All Things Visible and Invisible

*O world invisible, we view thee,
O world intangible, we touch thee,
O world unknowable, we know thee,
Inapprehensible, we clutch thee.*

Francis Thomson (1859–1907)

It is incredible. Out of all the epochs of human history we find ourselves alive in the era in which magic is truly manifest. This wizardry is no hocus-pocus, however, but resides in the marvelous new technologies that can make a solid object disappear from view. That such knowledge and engineering skills exist is a triumph of human ingenuity, but, for all this, we must ask of this new innovation, where will it take us? Indeed, the desire to control our visibility has deep and dark roots that stretch back to the very beginnings of human antiquity. Some reflection seems entirely appropriate, therefore.

How, for example, did the idea of controlled invisibility inspire our distant ancestors, and how have such ancient dreams permeated our modern culture? Indeed, through numerous novels, plays, films, and more recently television programs, invisibility, in its many different guises, has been exploited as a fruitful plot theme. For invisibility has been, and continues to be, a rich literary vein to examine and explore. It has it all; ranging from the philosophical, the historical, the ethical, the artistic, the mythical, and sometimes the downright bizarre. Indeed, as we shall see, the history of invisibility is a strange and wonderful one, and it has, on occasion, preoccupied the minds of some of humanity's greatest thinkers.

We live in the corporeal world; the things we see and sense have substance and form. We need these perceptions of reality to function, and yet for all this the desire to become invisible, at one's own command, is a craving as ancient as humanity is old. We can all probably think of times when we have wished to be unseen, to be a fly on the wall – an invisible interloper with the ability to eavesdrop and secretly see what others are up to. And yet, the power of invisibility is a double-edged sword. It is both a blessing and a curse. To the lonely of heart, to see and be unseen is an

unbearable grief, but to every spy and despot it is a wanton desire. Indeed, throughout recorded history the pitfalls and ethical challenges that would attach to the gift of becoming invisible have been debated and written about. Let us see, therefore, some of these ancient and venerable musings.

Ancient Mythology

Rising from the abyssal depths of legend we first encounter controllable invisibility through the Helm of Haydes. Wrought by subtle craft and skillful hand this helm was the secret weapon wielded by the Lord of the Underworld. Indeed, it proved of critical advantage in the Titanomachy – the divine war between the Olympian and Titan gods of old. The Helm had the power to make its wearer invisible, and Haydes used it to slip into the Titan camp and thereby destroy their weapons, ushering in the victory of the Olympian gods. Invisibility, it would seem, is not just the desire of mortals but also the weapon of ancient deities.

A magical cap, *tarnhelm* (literally meaning magic helmet), also appears in Norse mythology, and Wagner's orchestration of the *Ring of the Nibelungen* includes reference to its ability to make the wearer invisible. More than this, however, *tarnhelm* can also work to change the form of the wearer as well as transport them to distant places instantly – a powerful device indeed. J. R. R. Tolkien in his famous tale *Lord of the Rings* also makes use of such a magical helmet, via the English equivalent name of *dermhelm*. In this case the shield-maiden Éowyn adopts the name of the helm in her disguise as a male warrior. In Tolkien's application the wearer is not made physically invisible, but their outward persona is transformed.

More than simply existing as a transformative agent, however, there is a cost attached to the employment of an invisible cloak. Indeed, unfettered access to such a device will ultimately warp the moral compass of even the most innocent of users. The Greek philosopher Plato understood this well, and in Chap. 2 of his masterpiece *Republic*, written circa 370 B.C., he recounts the mythical story of the Ring of Gyges – a magic ring that gave the wearer the ability to become invisible. The story concerns a lowly shepherd who, after an intense rainstorm, finds that an underground chasm has opened up close to the location of his flock. Entering the chasm he discovers inside a bronzed horse statue. Cut into the side of the hollowed-out horse are windows, and within the statue's interior is the naked body of a giant dead man. The strange corpse has but one adornment, and that is a golden ring, which the shepherd, perhaps not unsurprisingly, takes.

Purely by accident the shepherd discovers the power of the ring, and he immediately thereafter arranges with his villagers to become a delegate to the king's palace. The corruption of the ring appears to act immediately upon the shepherd, who once inside the palace sets about seducing the king's wife. The shepherd then kills the king and claims the throne for himself. It is a veritable rags to riches story for the shepherd, but one that costs him his humanity. Indeed, this is undoubtedly the idea that Plato intends the story to portray. In Robin Waterfield's recent translation

of the *Republic*, we read “There is no one... who is iron-willed enough to maintain his morality and find strength of purpose to keep his hands off what doesn’t belong to him, when he is able to take whatever he wants...without fear of being discovered.” Plato’s story of the Ring of Gyges is short, taking about a page of text to tell, but it is full of deep-searching questions. How, indeed, would anyone, whether from the ancient past or the present day, behave if they had the power to make themselves invisible?

Where are the limits beyond which no invisible mortal should go? For Plato, there appeared to be no limits. Eventually any device that could render its owner invisible upon command would fully corrupt that owner, sending him or her into a descending spiral of moral defeat and debauched behavior. The temptations would be just too great, and no one would be able to stave off the inner conflict for very long. At heart this is also the message in J. R. R. Tolkien’s *Lord of the Rings*. The Ring, with its associated ability to turn its wearer invisible, is ultimately overpowering, all-consuming and morally corrupting. Indeed, no long-term good can come from it at all. It is a power that no human (or elf or dwarf) should ever have unfettered access to.

Unseen Beasts

While invisibility will bestow great power on the user, it will automatically instill great fear into those who lack such ability. Writers and film makers have long realized this latter fear, and at the core of many a horror story is an unseen, shape-shifting, invisible monster. Indeed, we fear the unseen and even the dark – because, of course, when it is dark our visible senses fail us, and we are blind to our surroundings.

The thought of being stalked by unseen monsters intent upon our destruction is universally disturbing. The invisibility in this case gnaws at our innermost, primordial fears. This was the very premise, for example, in the climactic scenes of the movie *The Silence of the Lambs* (Orion Pictures, 1991). Here the hero FBI cadet investigator is stalked in the darkness, deprived of sight, and left facing an invisible enemy who uses night vision goggles to stalk his victim. Ultimately it is sound that gives the location of the invisible villain away. Here, in fact, is one of the enduring problems of practical invisibility: how to see your surroundings when you can’t actually be seen and how to remain fully undetectable. A similar story line is developed in the classic science fiction film *Forbidden Planet* (MGM, 1956), where the invisible manifestation of a long-extinct civilization’s consciousness terrorizes a team of investigators on planet Altair IV. The unseen monster, the Id, is eventually revealed when it tries to move through a defensive force field.

Ex-U.S. military chemist turned fantasy writer Sterner St. Paul Meek (1894–1972) highlighted this same invisibility problem in his short story *The Cave of Horror*. Published in the January 1930 issue of *Astounding Stories of Super-Science*, this horror tale concerns the discovery of a giant but invisible frog (ah, the days of innocent monsters) in the Mammoth Caves of Kentucky. While invisible to human eyes