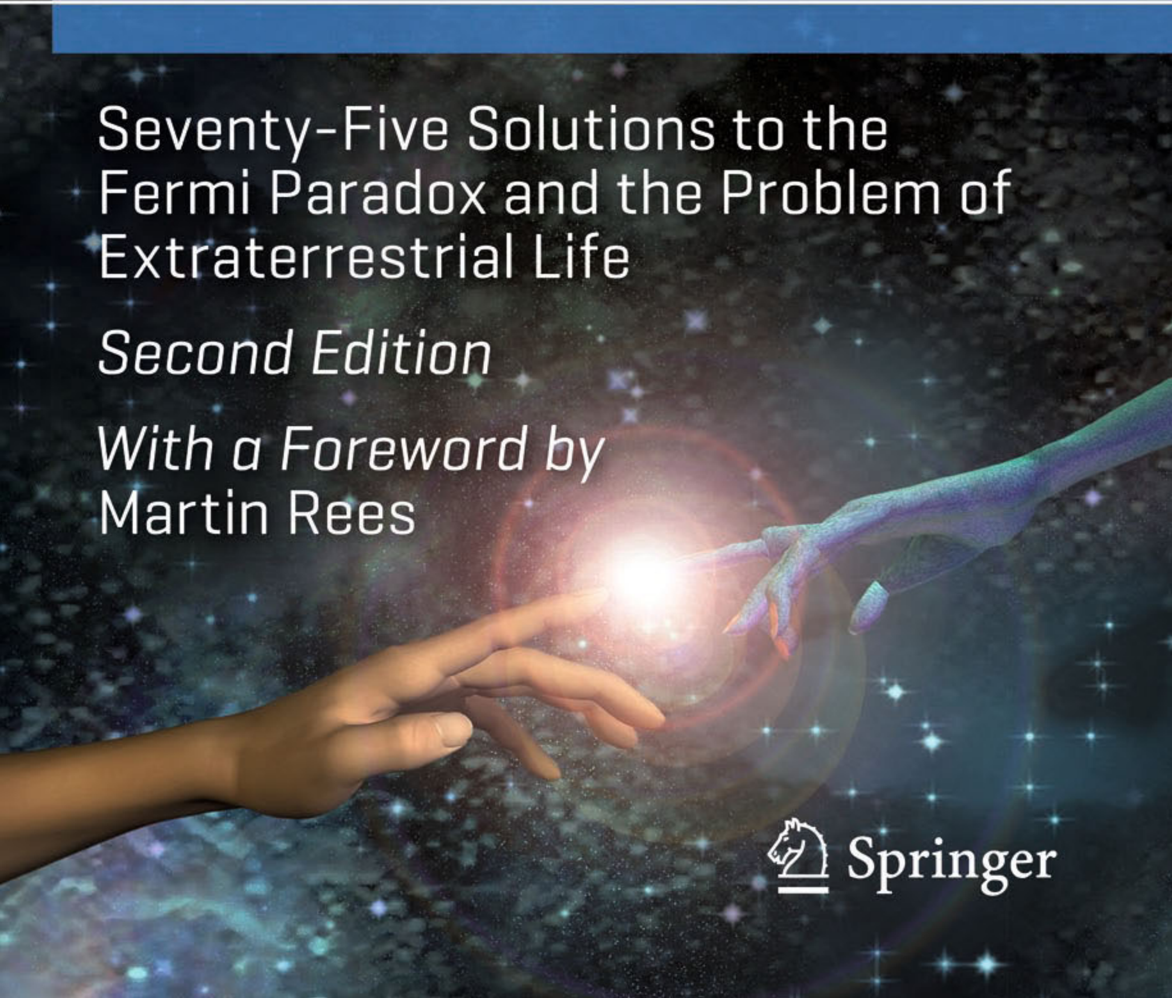
Stephen Webb

If the Universe Is Teeming with Aliens ... Where Is Everybody?

Seventy-Five Solutions to the Fermi Paradox and the Problem of Extraterrestrial Life

Second Edition

With a Foreword by
Martin Rees



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- Consciousness and mind manipulation

Stephen Webb

If the Universe Is Teeming with Aliens . . . WHERE IS EVERYBODY?

Seventy-Five Solutions to the Fermi Paradox and the Problem of Extraterrestrial Life

Second Edition

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To Heike and Jessica

Foreword

"Are we alone in the universe?" is one of the oldest and most universal questions. For a century or more it has stimulated brilliant science fiction—and it's now incentivizing real science and exploration. But we still lack evidence—indeed we know too little to say whether intelligent aliens are likely or unlikely to exist. That's why we need all the arguments that can be mustered. And that's why this book will be such a stimulus to all enquiring minds.

There may be simple organisms on Mars, or remnants of creatures that lived early in the planet's history; and there could be life, too, in the ice-covered oceans of Jupiter's moon Europa, or Saturn's moon Enceladus. But few would bet on this; and certainly nobody expects a complex biosphere in such locations. For that, we must look to the distant stars—far beyond the range of any probe we can now construct.

Prospects are here far brighter. In the last twenty years (and especially in the last five) the night sky has become far more interesting, and far more enticing to explorers, than it was to our forebears. Astronomers have discovered that many stars—perhaps even most—are orbited by retinues of planets, just like the Sun is. These planets aren't generally detectable directly. Instead, they reveal their presence by effects on their parent star that can be detected by precise measurements: small periodic motions in the star induced by an orbiting planet's gravity, and slight recurrent dimmings in a star's brightness when a planet transits in front of it, blocking out a small fraction of its light.

There is special interest in possible "twins" of our Earth—planets the same size as ours, orbiting other Sun-like stars, on orbits with temperatures such that water neither boils nor stays frozen. The Kepler spacecraft has identified many of these, and we can confidently infer that there are billions in our Galaxy.

Within twenty years the next generation of telescopes will image the nearest of these planets. Will there be life on them? We know too little about how life began on Earth to lay confident odds. What triggered the transition from complex molecules to entities that can metabolize and reproduce? It might have involved a fluke so rare that it happened only once in the entire Galaxy. On the other hand, this crucial transition might have been almost inevitable given the "right" environment. We just don't know—nor do we know if the DNA/RNA chemistry of terrestrial life is the only possibility, or just one chemical basis among many options that could be realized elsewhere.

Furthermore, even if simple life is widespread, we can't assess the odds that it evolves into a complex biosphere. And, even it did, the outcome might anyway be unrecognizably different. I won't hold my breath, but the SETI programme is a worthwhile gamble—because success in the search would carry the momentous message that concepts of logic and physics (if not consciousness) aren't limited to the hardware in human skulls.

Moreover, it might be too anthropocentric to limit attention to Earth-like planets. Science fiction writers have other ideas—balloon-like creatures floating in the dense atmospheres of Jupiter-like planets, swarms of intelligent insects, nanoscale robots etc. Perhaps life can flourish on planets flung into the frozen darkness of interstellar space, whose main warmth comes from internal radioactivity (the process that heats Earth's core). There could even be diffiuse living structures floating freely in interstellar clouds; such entities would live (and, if intelligent, think) in slow motion, but perhaps come into their own in the far future—like the "Black Cloud" envisaged by my Cambridge mentor Fred Hoyle.

No life would survive on a planet whose central Sun-like star became a giant and blew off its outer layers. Such considerations remind us of the transience of inhabited worlds (and life's imperative to escape their bonds eventually). We should also be mindful that seemingly artificial signals could come from super-intelligent (though not necessarily conscious) computers, created by a race of alien beings that had already died out.

Maybe we will one day find ET. On the other hand, this book offers 75 reasons why SETI searches may fail; Earth's intricate biosphere may be unique. That would disappoint the searchers, but it would have an upside: it would entitle us humans to be less "cosmically modest". Moreover, this outcome would not render life a cosmic sideshow. Evolution may still be nearer its beginning than its end. Our Solar System is barely middle aged and, if humans avoid self-destruction, the post-human era beckons. Life from Earth could spread through the Galaxy, evolving into a teeming complexity far beyond what we can even conceive. If so, our tiny planet—this pale blue dot floating in space—could be the most important place in the entire Galaxy, and the first interstellar voyagers from Earth would have a mission that would resonate through the entire Galaxy and perhaps beyond.

This debate will continue for decades. And Stephen Webb has condensed, within just one highly entertaining book, a fascinating cornucopia of arguments and speculation that will enrich the debate. We should be grateful to him.

Martin Rees, Astronomer Royal

Preface to the Second Edition

I'd like to thank Chris Caron of Springer, both for his suggestion that I should update *Where Is Everybody?* and for his encouragement throughout the painful process of updating. I'm pleased that the second edition of the book will appear in Springer's Science & Fiction series, the brainchild of Chris and his colleague Angela Lahee, because any discussion of the Fermi paradox sits at that stimulating intersection between science and science fiction. A dozen years after the publication of the first edition I believe even more strongly that Fermi's question is one of the most pressing problems in science, but it remains the case that SF authors have contributed at least as much to the debate as professional scientists.

I've discussed the Fermi paradox with too many people over the years to mention them all by name, but I would particularly like to thank Milan Ćirković, Mike Lampton, Colin McInnes, Anders Sandberg, David Waltham and Willard Wells for sharing ideas, papers and manuscripts with me.

And of course I must thank Heike and Jessica, who make all this worthwhile.

Stephen Webb
Lee on the Solent, July 2014

Preface to the First Edition

This book is about the Fermi paradox—the contradiction between the apparent absence of aliens, and the common expectation that we should see evidence of their existence. I was fascinated by the paradox when I first met it, some 17 years ago, and it fascinates me still. Over those years, many authors (too many to mention here, though their names appear in the reference list at the back of this book) have enthralled me with their writing about the paradox. Their influence upon this work will be clear. I have also discussed the paradox with many friends and colleagues; although they are too numerous to mention individually, I am indebted to them all.

Several people have contributed directly to the writing of this book, and I would like to take this chance to thank them. Clive Horwood of Praxis, and John Watson of Springer, have been very supportive of the project; the book would not have been completed had it not been for their advice and encouragement. (I would also like to thank John for sharing his favoured resolution of the paradox over an enjoyable working lunch.) Stuart Clark provided many useful comments on an early draft of the manuscript; Bob Marriott caught several errors and solecisms in a later draft (Bob also sent me a list of 101 resolutions of the paradox—75 of which I agree with); and I am extremely grateful to Steve Gillett for putting me right on many scientific points. (I am, of course, responsible for those errors that remain.) Several authors and organizations kindly gave permission to reproduce figures; I am particularly grateful to thank Lora Gordon, Geoffrey Landis, Ian Wall, Susan Lendroth, Reinhard Rachel, Heather Lindsay and Merrideth Miller for help in obtaining suitable figures. I would like to thank David Glasper, for sharing his recollections of a childhood incident that affected us both. Finally, of course, I would like to thank my family—Heike, Ron, Ronnie, Peter, Jackie, Emily and Abigail—for their patience. I spent time writing that I should instead have shared with them.

Stephen Webb
Milton Keynes, July 2002

Contents

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Where *Is* Everybody?

There is something beguiling about paradox. The visual paradoxes of Maurits Escher's prints never fail to entice the eye. Poems such as Robert Graves' *Warning to Children*, which play with the paradox of infinite regress, make the head spin. Paradox lies at the heart of Joseph Heller's *Catch-22*, one of the 20th century's greatest novels. My favorite paradox, though, is that of Fermi.

I first came across the Fermi paradox in the summer of 1984. I had just graduated from Bristol University, and I should have spent the summer months studying Aitchison and Hey's *Gauge Theories in Particle Physics*—required reading before I started postgraduate studies at Manchester University. Instead, I spent my time enjoying the sunshine on the Bristol Downs, studying my favorite reading matter: *Isaac Asimov's Science Fiction Magazine*. As is the case with many people, SF sparked my interest in science. It was through reading the works of Isaac Asimov,[1] Arthur Clarke and Robert Heinlein and watching films such as *Forbidden Planet* that I became enamored with science. Two thought-provoking science-fact articles appeared in successive issues[2] of *Asimov's* that year. The first, by Stephen Gillett, was simply entitled *The Fermi Paradox*. The second, a forceful rebuttal by Robert Freitas, was entitled *Fermi's Paradox: A Real Howler*.

Gillett argued in the following way. Suppose, as the optimists believed, that the Galaxy is home to many extraterrestrial civilizations. (To save typing, I shall often refer to an extraterrestrial civilization as an ETC.) Then, since the Galaxy is extremely old, the chances are good that ETCs will be millions or even *billions* of years in advance of us. The Russian astrophysicist Nikolai Kardashev proposed a useful way of thinking about such civilizations. He argued that we could classify ETCs in terms of the technology they possessed, and he devised a 3-point scale for measuring the potency of that technology. A Kardashev type 1 civilization, or KI civilization, would be comparable to our own: it could employ the energy resources of a planet. A KII civilization would be far beyond our own: it could employ the energy resources of a star. A KIII civilization could employ the energy resources of an entire *galaxy*. According to Gillett, then, most ETCs in the Galaxy would be of a KII or KIII type. Now, everything we know about terrestrial life tells us that life has a natural

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tendency to expand into all available space. Why should extraterrestrial life be any different? Surely ETCs would want to expand from their home world and out into the Galaxy. But—and this is the key point—a KII or KIII civilization should be able to colonize the Galaxy in a few million years. The Galaxy should be *swarming* with technologically advanced civilizations. They should already be here! And yet we see no evidence that ETCs exist. Gillett called this the Fermi paradox. (I learned why Fermi's name is attached to the paradox a few months later, when Eric Jones published a Los Alamos preprint describing the origins of the paradox; but more of this later.) For Gillett, the paradox pointed to a chilling conclusion: humankind is alone in the universe.

Freitas thought this was all hogwash. He compared Gillett's logic to the following argument. Lemmings breed quickly—about 3 litters per year, with each litter containing up to 8 offspring. In just a few years the total mass of lemmings will be equal to the mass of the entire terrestrial biosphere. The Earth must be swarming with lemmings. And yet most of us see no evidence that lemmings exist. Have *you* ever seen a lemming? The "Fermi paradox" line of reasoning would lead us to conclude that lemmings don't exist—yet, as Freitas pointed out, this would be absurd. More interestingly, he pointed out that the lack of evidence for ETCs isn't particularly strong: if small artificial probes were parked in the Asteroid Belt, say, or larger probes in the Oort Cloud, then we'd have essentially no chance of detecting them. Besides, he argued that the logic behind the so-called paradox is faulty. The first two steps in the argument are: (i) if aliens exist, then they should be here; (ii) if they are here, then we should observe them. The difficulty is those two "should"s. A "should" is not a "must" and therefore it's logically incorrect to reverse the arrow of implication. (In other words, the fact we haven't observed them doesn't allow us to conclude they aren't here, so we can't conclude they don't exist.)

Until we obtain some new information that can help us resolve a paradox, people are free to follow differing lines of reasoning. This is, after all, what makes paradox so interesting. In the case of the Fermi paradox, the stakes are so high (the existence or otherwise of alien intelligence) and the experimental input to the argument is so sparse (even now, we can't be sure ETCs aren't here) that arguments often become heated. In the Gillett–Freitas debate, I initially sided with Freitas. The main reason was sheer weight of numbers: there are perhaps as many as 400 billion stars in the Galaxy, and as many galaxies in the universe as there are stars in the Galaxy. Ever since the time of Copernicus, science has taught us there's nothing special about Earth. It followed, then, that Earth couldn't be the sole home to intelligent life. And yet . . .

Gillett's argument stuck in my mind. I'd been reading about cosmic wonders since I was a child. The Galaxy-spanning civilization of the *Foundation* trilogy, the astroengineering wonders of *Ringworld*, the enigma of the vessel in

Fig. 1.1 The first image of Earth taken from the surface of another planet: this photograph was taken in March 2004 by the Mars Exploration Rover Spirit. Earth is just about visible on a computer screen; the limits of printing technology mean you might not be able to see it here. Earlier, in 1990, Voyager 1 sent back a photograph of Earth taken from much further away—a distance of about 6 billion kilometers. In Carl Sagan's words, Earth appeared as a pale blue dot. When contemplating the insignificance of the piece of rock we inhabit, and the billions of similar rocks that must be out there, it's difficult to believe we might be alone in the universe. (Credit: NASA)

Rendezvous with Rama—all these were part of my mental furniture. And yet where *were* these marvels? The imaginations of SF writers had shown me hundreds of possible universes, but my astronomy lecturers had made it clear that so far, whenever we look out into the real universe, we can explain everything we see in terms of the cold equations of physics. Put simply, the universe looks dead. The Fermi question: where *is* everybody? The more I thought about it, the more the paradox seemed to be significant.

It seemed to me the paradox was a competition between two large numbers: the plethora of potential sites for life versus the vast age of the universe.

The first number is simply the number of planets with suitable environments for the development of life. If we adopt the Principle of Mediocrity, and assume there's nothing special about Earth, it follows there are many millions of suitable environments for life in the Galaxy (and many billions of environments in the universe). Given so many potential seeding grounds, life should be common. This argument goes back at least as far as the 4th century BC when Metrodorus of Chios wrote that "a single ear of wheat in a large field is as strange as a single world in infinite space".

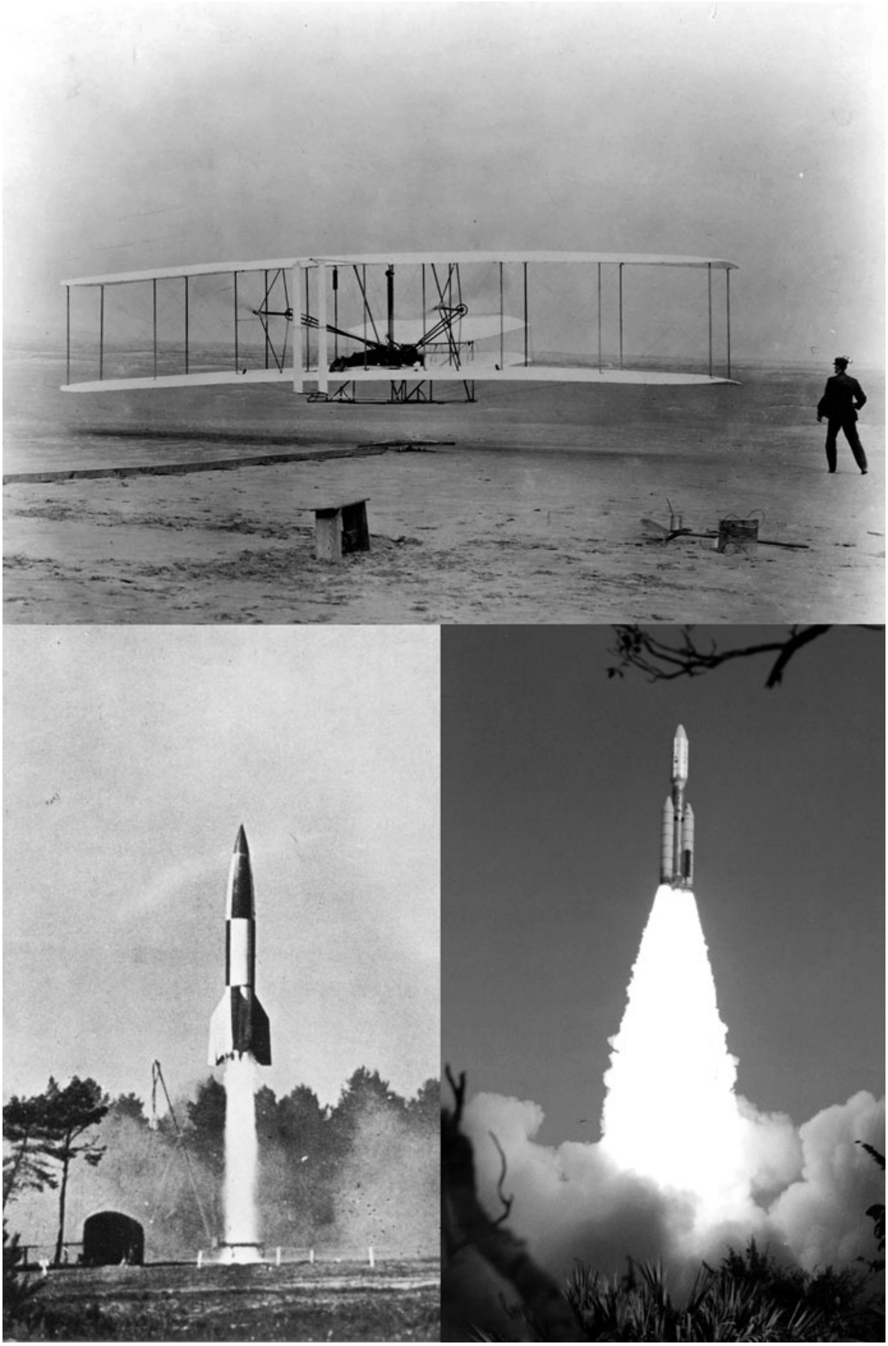

Fig. 1.2 *Top*: Orville Wright at the controls in 1903. *Bottom left*: a rocket fired from a launchpad in Germany in 1945. *Bottom right*: the launch of Voyager 1 in 1977. Immense technological progress in less than a century. What will our craft look like in a thousand years? (Credit: *top*—USAF; *bottom left*—Crown Copyright 1946; *bottom right*—NASA)

Table 1.1 In the Universal Year we compress 13.8 billion years into 365 days. On this timescale, an individual's lifespan is a fraction of a second. Jesus lived about 4.6 seconds before midnight on 31 December and the dinosaurs died out in the early hours of 30 December

Real time	Time in a Universal Year
70 yrs	0.16 s
100 yrs	0.23 s
437 yrs	1 s
1000 yrs	2.3 s
2000 yrs	4.6 s
10 000 yrs	23 s
100 000 yrs	3 mins 50 s
1 million yrs	38 mins 20 s
2 million yrs	1 hr 16 mins 40 s
10 million yrs	6 hr 23 min 20 s
100 million yrs	2 days 15 hr 53 min 20 s

The second number is now known with astonishing precision: the latest cosmological measurements[3] tell us the universe is 13.8 billion years old (give or take 37 million years). To evoke a feeling for such a large time span, it's usual in these discussions to compress the entire history of the universe into some standard interval. In this case, I'll compress the current age of the universe into a standard Earth year: in other words, the "Universal Year" compresses the entire history of the universe into 365 days. On this timescale, a second of real time corresponds to 437 years; in the Universal Year, western science begins about 1 second before midnight on 31 December. In 1903, the Wright brothers developed powered flight; less than four decades later a German V-2 rocket became the first object to achieve suborbital flight; about three decades after that, in 1977, Voyager 1 was launched on a Titan rocket and has now reached the edge of interstellar space. Within a typical person's lifespan, humans went from being an essentially Earthbound species to one capable of launching a craft that will eventually reach the stars. And yet that span of time represents just the final 0.16 seconds of the Universal Year. Even the entire history of our species takes up much less than 1 hour of the final day of the Universal Year. On this scale, however, the earliest ETCs could have originated in the early summer months. If the colonization of the Galaxy can take place in the equivalent of a few hours, then one would expect one or more of the advanced technological civilizations to have long since completed the job. Even if they all took some path other than colonization, wouldn't we at least expect to hear some evidence of their presence? But the universe is silent. The paradox might not logically *prove* aliens don't exist, but surely Fermi's question is worth some of our attention.

I wasn't the only one who found the Fermi paradox interesting. Over the years, many people have offered their resolutions to the paradox, and I developed the habit of collecting them. Although there's a fascinating range of answers to the question "where is everybody?", they all fall into one of three classes.

First, there are answers based around the idea that somehow extraterrestrials are (or have been) here. This is probably the most popular resolution of the paradox. Certainly, belief in intelligent extraterrestrial life is widespread. Polls repeatedly and consistently suggest that the majority of Americans believe flying saucers exist and are buzzing around Earth; the proportion of Europeans holding that belief seems to be smaller, but is nevertheless high.

Second, there are answers suggesting ETCs exist, but for some reason we've not yet found evidence of their existence. This is probably the most popular category of answer among practicing scientists.

Third, there are answers purporting to explain why humankind is alone in the universe, or at least in the Galaxy; we don't hear from extraterrestrial intelligence because there *is* no extraterrestrial intelligence.

In 2002 I published the first edition of this book. It contained discussions of 50 solutions to the Fermi paradox that I'd collected over the years, organized into the three classes mentioned above. Why, a dozen years later, do I feel there's a need for a second edition of the book? After all—and I don't believe this will come as a surprise to anyone—there's still no hard evidence for the existence of extraterrestrial intelligence. Well, although we have no definitive answer to the question "Where *is* everybody?", scientists have made tremendous progress in better understanding the relevant inputs to many of the proposed solutions. Over the past dozen years scientists have learned much about exoplanets, about planetary dynamics, about the limits to life . . . we've even learned more about the genesis of the first proposed solution to the paradox ("They are here and they call themselves Hungarian"). Thus many discussions in the first edition are now rather dated. There's also the fact that various new solutions have been proposed in recent years. A duodecennial update therefore seems appropriate.

The first edition of the book contained one or two light-hearted solutions. I've decided to keep these, and even add a couple more, but this is not to imply that the Fermi paradox need not be taken seriously. I believe that the Great Silence is becoming ever-more deafening. With each search that turns up negative, with each year that passes without scientists finding some evidential trace of extraterrestrial activity in the mountains of data captured by our telescopes, the paradox gains in strength. I believe that Fermi's question is becoming one of the most important in all of science—right up there with questions to do with the nature of consciousness and the unification of our physical theories.

Exponential Notation The book uses exponential notation. If you're unfamiliar with the notation, all you need to know is that it's a convenient method for handling very large and very small numbers.

In this book I always use 10 as a base and so, in essence, the exponent counts the number of zeros following the 1. Multiplying numbers together using this notation is simple: just add the exponents. For example:

$$100 = 10 \times 10 = 10^2$$

and

$$1000 = 10 \times 10 \times 10 = 10^3.$$

Division is just as easy: subtract one exponent from another. For example:

$$1000 \div 10 = 10^{3-1} = 10^2 = 100.$$

For numbers less than unity, the exponent is negative. A negative exponent gives the same value as the reciprocal of its matching positive exponent. Thus:

$$10^{-2} = \tfrac{1}{10^2} = \tfrac{1}{100} = 0.01$$

and

$$10^{-3} = \tfrac{1}{10^3} = \tfrac{1}{1000} = 0.001.$$

Using exponential notation we can write, for example, 1 million as 10^6 and 1 billionth as 10^{-9}. This is useful in science, where we routinely deal with very large and very small numbers. Using exponential notation we can discuss the number of stars in the universe (there are about 10^{22} of them) or the mass of an electron (which is about 10^{-36} kg) without resorting to unwieldy phrases such as "a thousand billion billion" or "a trillion trillion trillionth".

The purpose of this book, then, is to present and discuss 75 proposed solutions to Fermi's question. The list of solutions isn't intended to be exhaustive; rather, I've chosen them because they are representative or because I think they possess some feature that's particularly interesting. The solutions come from scientists working in several widely separated fields, but also from SF authors; in this topic, authors have been at least as industrious as academics, and in many cases they have anticipated the work of professional scientists.

The outline of the book is as follows.

Chapter 2 gives a brief biography of Fermi, focusing on his scientific achievements. I then discuss the notion of paradox and present a brief discussion of the history of the Fermi paradox.

Chapters 3–5 present 74 of my favorite solutions to the paradox. Not all of them are independent, and sometimes I revisit a solution in another guise, but all of them have been seriously proposed as answering Fermi's question. I arrange the answers according to the three classes mentioned above. Chapter 3 discusses 10 proposals based around the idea that ETCs are or were here. Chapter 4 discusses 30 answers based around the idea that ETCs exist, but we've yet to find evidence of them. Chapter 5 discusses 24 solutions of the paradox based around the idea that we are alone. There's a logic to the arrangement of the various discussions, but I hope the sections are all self-contained enough to allow readers to "dip into" the book and pick out solutions that particularly interest them. In the discussions I try to be as even-handed as possible, even if I disagree with the solution (which I often do).

Chapter 6 contains the 75th solution: my own view of the resolution of the paradox. It's not a particularly original suggestion, but it summarizes what I feel the Fermi paradox might be telling us about the universe in which we live.

This is followed by a chapter of notes and suggestions for further reading. The material discussed in this book covers various subjects, ranging from astronomy to zoology, so the references in the final chapter are necessarily wide in scope. They range from SF stories to popular science books to primary research articles published in scholarly journals. Many readers might encounter difficulties in accessing the more specialized references, but I hope they will at least find it possible to use this chapter to discover related information on the Web.

The book is specifically aimed at a popular audience. One of the beauties of the Fermi paradox is that it can be appreciated without the need for any mathematics beyond an understanding of exponential notation. It follows that anyone can present a resolution of the Fermi paradox; you don't need to have years of scientific and mathematical training behind you to contribute to the debate. I hope that a reader of this book might devise a solution that no-one else has thought of. If you do—please write to me and share it!

2
Of Fermi and Paradox

Before considering the merits of the various proposed solutions to the Fermi paradox, this chapter presents some of the background. I first give a short biography of Enrico Fermi himself, focusing on just a few of his many and varied scientific accomplishments. I mention only those contributions to science that I refer to in later sections of the book. I ignore, for example, his contribution to cosmic ray physics: Fermi was the first to propose a realistic model for explaining the origin of the high-energy particles that bombard Earth from space. This work is honored by the naming of NASA's satellite mission for investigating cosmic rays—the *Fermi Gamma-ray Space Telescope*. Indeed, Fermi's scientific achievements were so numerous that the *Fermi Space Telescope* is only the latest in a variety of things named after him. Fermilab, in Batavia, IL, is one of the world's leading centers for particle physics; the element with atomic number 100, which was first synthesized in 1952 in a hydrogen bomb explosion, is called fermium (Fm); the typical length scale in nuclear physics, 10^{-15} m, is called the fermi; 8103 Fermi is a main-belt asteroid and Fermi is a large crater on the far side of the Moon; several members of the Enrico Fermi Institute at Chicago University have won Nobel prizes. For more details of Fermi's life, both inside and outside science, I recommend the interested reader to the biographies of Fermi listed in the References.

I then discuss the notion of paradox, and briefly look at a few examples from various fields. Paradox has played an important role in intellectual history, helping thinkers to widen their conceptual framework and sometimes forcing them to accept quite counterintuitive notions. It's interesting to compare the Fermi paradox with these more established paradoxes.

Finally, I discuss how the Fermi paradox itself—where *is* everybody?—came into being. It's worth noting that some people argue that this is neither a paradox nor is it Fermi's. Nevertheless, we shall see that Fermi's question can be cast into the shape of a formal paradox (if you feel the need to do so) and I explain how Fermi's name came to be attached to a paradox that is older than many people believe.

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The Physicist Enrico Fermi

It is no good to try to stop knowledge from going forward. Ignorance is never better than knowledge.

Enrico Fermi

Enrico Fermi was the most complete physicist of the last century—a world-class theoretician who carried out experimental work of the highest order. No other physicist since Fermi has switched between theory and experiment with such ease, and it's unlikely that anyone will do so again. The field has become too large to permit such crossover.

Fermi was born in Rome on 29 September 1901, the third child of Alberto Fermi, a civil servant, and Ida DeGattis, a schoolteacher. He showed precocious ability in mathematics,[4] and as an undergraduate student of physics at the Scuola Normale Superiore in Pisa he quickly outstripped his teachers.[5]

His first major contribution to physics was an analysis of the behavior of certain fundamental particles that make up matter. These particles—such as protons, neutrons and electrons—are now called *fermions* in his honor. Fermi showed how, when matter is compressed so that identical fermions are brought close together, a repulsive force comes into play that resists further compression. This fermionic repulsion plays an important role in our understanding of phenomena as diverse as the thermal conductivity of metals and the stability of white dwarf stars.

Soon after, Fermi's theory of beta decay (a type of radioactivity in which a massive nucleus emits an electron) cemented his international reputation. The theory demanded that a ghostly particle be emitted along with the electron, a particle he called the *neutrino*—"little neutral one". Not everyone believed in the existence of this hypothetical fermion, but Fermi was proved correct. Physicists finally detected the neutrino in 1956. Although the neutrino remains rather intangible in terms of its reluctance to react with normal matter, its properties play a profound role in present-day astronomical and cosmological theories.

In 1938 Fermi was awarded the Nobel prize for physics, partly in recognition of a technique he developed to probe the atomic nucleus. His technique led him to the discovery of new radioactive elements; by bombarding the naturally occurring elements with neutrons, he produced more than 40 artificial radioisotopes. The award also recognized his discovery of how to make neutrons move slowly. This might seem a minor point but it has profound practical applications, since slow-moving neutrons are more effective than fast neutrons at inducing radioactivity. (A slow neutron spends more time in the

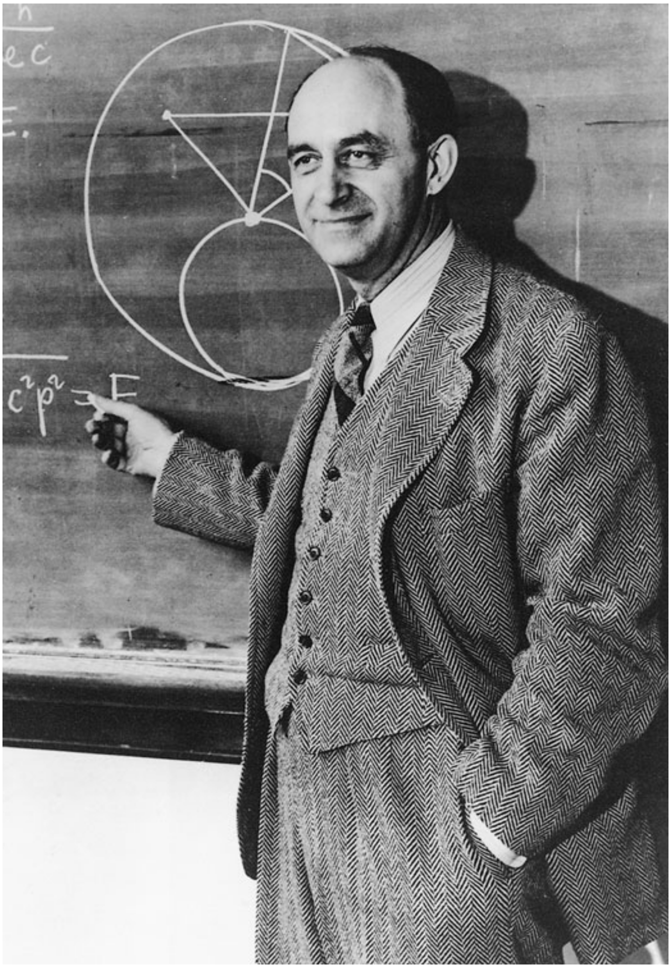

Fig. 2.1 This photograph of Enrico Fermi lecturing on atomic theory appears on a stamp released by the US Postal Service on 29 September 2001 to commemorate the hundredth anniversary of Fermi's birth. (Credit: American Institute of Physics Emilio Segré Visual Archives)

neighborhood of a target nucleus, and so is more likely to interact with the nucleus. In a similar way, a well-aimed golf ball is more likely to sink into the hole if it's moving slowly: a fast-moving putt can roll by.) This principle is used in the operation of nuclear reactors.

News of the award was tempered by the worsening political situation in Italy. Mussolini, increasingly influenced by Hitler, initiated an anti-Semitic campaign. Italy's fascist government passed laws that were copied directly from the Nazi Nuremberg edicts. The laws didn't directly affect Fermi or his two children, who were considered to be Aryans, but Fermi's wife, Laura, was Jewish. They decided to leave Italy, and Fermi accepted a position in America.

Two weeks after arriving in New York, news reached Fermi that German and Austrian scientists had demonstrated nuclear fission. Einstein, after some prompting, wrote his historic letter to Roosevelt alerting the President to the probable consequences of nuclear fission. Citing work by Fermi and colleagues, Einstein warned that a nuclear chain reaction might be set up in a large mass of uranium—a reaction that could lead to the release of vast amounts of energy. Roosevelt was concerned enough to fund a program of research into the defense possibilities. Fermi was deeply involved in the program.

Fermi Questions Fermi's colleagues were in awe of him for his uncanny ability to see straight to the heart of a physical problem and describe it in simple terms. They called him the Pope because he seemed infallible. Almost as impressive was the way he estimated the magnitude of an answer (often by doing complex calculations in his head). Fermi tried to inculcate this facility in his students. He would demand of them, without warning, answers to seemingly unanswerable questions. How many grains of sand are there on the world's beaches? How far can a crow fly without stopping? How many atoms of Caesar's last breath do you inhale with each lungful of air? Such "Fermi questions" (as they are now known) required students to draw upon their understanding of the world and their everyday experience and make rough approximations, rather than rely on bookwork or prior knowledge.

The archetypal Fermi question is one he asked his American students: "How many piano tuners are there in Chicago?" We can derive an informed estimate, as opposed to an uninformed guess, by reasoning as follows.

First, suppose that Chicago has a population of 3 million people. (I haven't checked an almanac to see whether this is correct; but making explicit estimates in the absence of certain knowledge is the whole point of the exercise. Chicago is a big city, but not the biggest in America, so we can be confident that the estimate is unlikely to be in error by more than a factor of 2. Since we have explicitly stated our assumption we can revisit the calculation at a later date, and revise the answer in the light of improved data.) Second, assume that families, rather than individuals, own pianos and ignore those pianos belonging to institutions such as schools, universities and orchestras. Third, if we assume that a typical family contains 5 members, then our estimate is that there are 600,000 families in Chicago. We know that not every family owns a piano; our fourth assumption is that 1 family in 20 owns a piano. We thus estimate there are 30,000 pianos in Chicago. Now ask the question: how many tunings would 30,000 pianos require in 1 year? Our fifth assumption is that a typical piano will require tuning once per year—so 30,000 piano tunings take place in Chicago each year. Assumption six: a piano tuner can tune 2 pianos per day and works on 200 days in a year. An individual piano tuner therefore tunes 400 instruments in 1 year. In order to accommodate the total number of tunings required, Chicago must be home to 30,000/400 = 75 piano tuners. We want an estimate, not a precise figure, so finally we round this number up to an even 100.

As we shall see later, Fermi's ability to grasp the essentials of a problem manifested itself when he posed the question: "where *is* everybody?"

Physicists had many questions to answer before they could build a bomb, and it was Fermi who answered many of them. On 2 December 1942, in a makeshift laboratory constructed in a squash court under the West Stands of the University of Chicago stadium, Fermi's group successfully achieved the first self-sustaining nuclear reaction. The reactor, or pile, consisted of slugs of purified uranium—about 6 tons in all—arranged within a matrix of graphite.

The graphite slowed the neutrons, enabling them to cause further fission and maintain the chain reaction. Control rods made of cadmium, which is a strong neutron absorber, controlled the rate of the chain reaction. The pile went critical[6] at 2:20 PM, and the first test was run for 28 minutes.

Fermi, with his unmatched knowledge of nuclear physics, played an important role in the Manhattan Project. He was there in the Alamogordo desert on 15 July 1945, just 9 miles away from ground zero at the Trinity test. He lay on the ground facing in the direction opposite the bomb. When he saw the flash from the immense explosion he got to his feet and dropped small pieces of paper from his hand. In still air the pieces of paper would have fallen to his feet, but when the shock wave arrived, a few seconds after the flash, the paper moved horizontally due to the displacement of air. In typical fashion, he measured the displacement of the paper; since he knew the distance to the source, he could immediately estimate the energy of the explosion.

After the war, Fermi returned to academic life at the University of Chicago and became interested in the nature and origin of cosmic rays. In 1954, however, he was diagnosed with stomach cancer. Emilio Segré, Fermi's lifelong friend and colleague, visited him in hospital. Fermi was resting after an exploratory operation, and was being fed intravenously. Even at the end, according to Segré's touching account, Fermi retained his love of observation and calculation: he measured the flux of the nutrient by counting drops and timing them with a stopwatch.

Fermi died on 29 November 1954, at the early age of 53.

Paradox

These are old fond paradoxes, to make fools laugh i' the alehouse.

William Shakespeare, *Othello*, Act II, Scene 1

Our word paradox comes from[7] two Greek words: *para* meaning "contrary to" and *doxa* meaning "opinion". It describes a situation in which, alongside one opinion or interpretation, there's another, mutually exclusive opinion. The word has taken on a variety of subtly different meanings, but at the core of each usage is the idea of a contradiction. Paradox is more than mere inconsistency, though. If you say "it's raining, it's not raining" then you've contradicted yourself, but paradox requires more than this. A paradox arises when you begin with a set of seemingly self-evident premises and then deduce a conclusion that undermines them. If your cast-iron argument proves it must be raining, but you look and see that it's dry outside, then you have a paradox to resolve.

Fig. 2.2 A visual paradox. This impossible figure is a Penrose triangle. It's named after Roger Penrose, a British mathematician who devised it in the 1950s. (It was first created even earlier, in 1934, by the Swedish graphic artist Oscar Reutersvärd.) The illustration appears to show a three-dimensional triangular solid, but the triangle is impossible to construct. Each vertex of a Penrose triangle is in fact a perspective view of a right angle. Artists such as Escher and Reutersvärd delighted in presenting visual paradoxes. (Credit: Tobias R.)

A weak paradox or *fallacy* can often be clarified with a little thought. The contradiction usually arises because of a mistake in a chain of logic leading from premises to conclusion. For example, beginning students of algebra often construct "proofs" of obviously untrue statements such as $1+1 = 1$. Such "proofs" usually contain a step in which an equation is divided by zero. This is the source of the fallacy, since dividing by zero is inadmissible in arithmetic: if you divide by zero you can "prove" anything at all. In a strong paradox, however, the source of a contradiction is not immediately apparent; centuries can pass before matters are resolved. A strong paradox has the power to challenge our most cherished theories and beliefs. Indeed, as the mathematician Anatol Rapoport once remarked:[8] "Paradoxes have played a dramatic part in intellectual history, often foreshadowing revolutionary developments in science, mathematics and logic. Whenever, in any discipline, we discover a problem that cannot be solved within the conceptual framework that supposedly should apply, we experience shock. The shock may compel us to discard the old framework and adopt a new one."

Paradoxes abound in logic and mathematics and physics, and there's a type for every taste and interest.

A Few Logical Paradoxes

An old paradox, contemplated by philosophers since the middle of the 4[th] century BC and still discussed, is that of the liar paradox. Its most ancient attribution is to Eubulides of Miletus, who asked: "A man says he is lying; is what he says true or false?" Whichever way one analyzes the sentence, there's a contradiction. The same paradox appears in the New Testament. St. Paul, in his letter to Titus, the first bishop of Crete, wrote: "One of themselves, even a prophet of their own, said the Cretans are always liars." It's not clear whether Paul was aware of the problem in his sentence, but when self-reference is allowed paradox is almost inevitable.

One of the most important tools of reasoning we possess is the sorites. In logicians' parlance, a sorites is a chain of linked syllogisms: the predicate of one statement becomes the subject of the following statement. The statements below form a typical example of a sorites:

all ravens are birds;
all birds are animals;
all animals require water to survive.

Following the chain we must logically conclude: all ravens need water to survive.

Sorites are important because they allow us to make conclusions without covering every eventuality in an experiment. In the example above, we don't need to deprive ravens of water to know that doing so would cause them to die of thirst. But sometimes the conclusion of a sorites can be absurd: we have a sorites paradox. For example, if we accept that adding one grain of sand to another grain of sand doesn't make a heap of sand, and given that a single grain doesn't itself constitute a heap, then we must conclude that no amount of sand can make a heap. And yet we see heaps of sand. The source of such paradoxes lies in the intentional vagueness[9] of a word such as "heap". Another paradox—Theseus' paradox—hangs on the vagueness of the word "same": if you restore a wooden ship by replacing each and every plank, is it the same ship? Politicians, of course, routinely take advantage of these linguistic tricks.

In addition to sorites, we all routinely employ induction—the drawing of generalizations from specific cases—when reasoning. For example, whenever we see something drop, it falls *down*: using induction we propose a general law, namely that when things drop they *always* fall down and never up. Induction is such a useful technique that anything casting doubt on it is troubling. Consider Hempel's raven paradox.[10] Suppose an ornithologist, after years of field observation, has observed hundreds of black ravens. The evidence is enough for her to suggest the hypothesis that "all ravens are black". This is the standard process of scientific induction. Every time the ornithologist sees a black raven it's a small piece of evidence in favor of her hypothesis. Now, the statement "all ravens are black" is logically equivalent to the statement "all non-black things are non-ravens". If the ornithologist sees a piece of white chalk, then the observation is a small piece of evidence in favor of the hypothesis that "all non-black things are non-ravens"—but therefore it must be evidence for her claim that ravens are black. Why should an observation regarding chalk be evidence for a hypothesis regarding birds? Does it mean that ornithologists can do valuable work whilst sat indoors watching television, without bothering to watch a bird in the bush?

Another paradox in logic is that of the unexpected hanging, wherein a judge tells a condemned man: “You will hang one day next week but, to spare you mental agony, the day that the sentence will be carried out will come as a surprise.” The prisoner reasons that the hangman can’t wait until Friday to carry out the judge’s order: so long a delay means everyone will know the execution takes place that day—the execution will not come as a surprise. So Friday is out. But if Friday is ruled out, Thursday is ruled out by the same logic. Ditto Wednesday, Tuesday and Monday. The prisoner, mightily relieved, reasons that the sentence can’t possibly take place. Nevertheless, he’s completely surprised when the executioner leads him to the gallows on Thursday! This argument—which also goes under the name of the “surprise examination paradox” and the “prediction paradox”—has generated a huge literature.[11]

A Few Scientific Paradoxes

Although it’s often fun, and occasionally useful, to ponder liars, ravens and condemned men, arguments involving logical paradoxes too frequently—for my taste at least—degenerate into a discussion over the precise meaning and usage of words. Such discussions are fine if one is a philosopher, but for my money the really fascinating paradoxes are those that can be found in science.

The twin paradox, which involves the special relativistic phenomenon of time dilation, is perhaps one of the most famous. Suppose one twin stays at home while the other twin travels to a distant star at close to the speed of light. To the stay-at-home twin, his sibling’s clock runs slow: his twin ages more slowly than he does. Although this phenomenon is contrary to common sense, it’s an experimentally verified fact. But surely relativity tells us that the traveling twin can consider himself to be at rest? From *his* point of view, the clock of the earthbound twin runs slow; the stay-at-home twin should be the one who ages slowly. So what happens when the traveler returns? They can’t both be right. It’s impossible for both twins to be younger than each other! The resolution of this paradox is easy: the confusion arises from a misapplication of special relativity. The two scenarios aren’t interchangeable because it’s only the traveling twin who accelerates to light speed, decelerates at the half-way point of his journey, and does it all again on the trip back. Everyone can agree that the stay-at-home twin undergoes no such acceleration. So the traveler ages more slowly than the earthbound twin; he returns to find his brother aged, or even dead. An extraterrestrial visitor to Earth would observe the same phenomenon when it returned to its home planet: its stay-at-home siblings (if aliens have siblings) would be older or long-since dead. This behavior is certainly contrary to our experience, but it's not a paradox—rather, a sad fact of interstellar travel.[12]

The so-called firewall paradox is of much more recent vintage than the twin paradox. It was first proposed in 2012,[13] and since then a storm of papers have attempted to resolve the underlying riddle. As of the time of writing, no one has managed to douse the firewall; it remains a troubling issue for theoretical physics. The paradox arises because of an apparent contradiction between the predictions made by three fundamental theories of physics: quantum theory, general relativity and complementarity.

Quantum theory is our best theory of the physical processes that happen in nature. It's a probabilistic theory, which means that it doesn't predict what will definitely happen; rather, it gives the *probability* that some particular event will happen. Quantum theory thus only makes sense if the probabilities of all the different outcomes to an event add up to 1. If you add up the probabilities for all possible outcomes and find that the result is 0.8 or 1.3—or *any* value except 1—then the result is nonsensical. It follows that information in quantum theory can't be lost and it can't be cloned: if information somehow disappeared or could somehow be copied then probabilities wouldn't add up to 1 and the result would be nonsense.

General relativity, which is our best theory of gravity, is a classical rather than a quantum theory. In other words it gives a definite prediction for the outcome of an event rather than a range of probabilities for different possible outcomes. General relativity describes gravity in terms of the warping of spacetime, and one of its predictions is that when the warping of spacetime becomes intense enough a black hole can form. A black hole is a region of space where not even light itself travels fast enough to escape the grip of gravity. Surrounding a black hole is an event horizon, a "surface of no return". If you are outside the event horizon then it's always possible, if only in principle, to leave the vicinity of the black hole; fall over the event horizon, however, and any attempt to leave the black hole will inevitably end in failure. It's important to note that according to general relativity you wouldn't notice anything special as you passed the event horizon; there's no sign marking the boundary in space beyond which lies a black hole. The usual analogy is with a rowing boat on a river with an increasingly fast current that culminates in a weir. The river contains a point of no return, beyond which the muscle power of any rower will fail to overcome the current. If the boat passes the point of no return then its fate is sealed: it will be carried over the weir. But nothing in the river marks that point of no return, and the boat can drift quite peacefully past that point without noticing anything has changed. It's the same with the event horizon surrounding a black hole.

In the mid-1970s, Stephen Hawking introduced the black hole information paradox to physics. Hawking showed that black holes do in fact radiate: quantum effects close to the surface of the event horizon mean that particles can