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Introduction

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Stephen's remarkable combination of boldness, vision, insight and courage have enabled him to produce ideas that have transformed our understanding of space and time, black holes and the origin of the universe.

James B. Hartle

To celebrate Stephen Hawking's 60th birthday, a workshop and symposium were held in Cambridge at the Centre for Mathematical Sciences. About two hundred colleagues, collaborators and former students, as well as younger researchers, gathered from around the world for a critical evaluation of the subjects to which Stephen has contributed with such distinction, and to assess the prospects for the future. This volume contains articles based on the lectures delivered at this remarkable event.

The title for these proceedings is adapted from Stephen's inaugural lecture as Lucasian Professor of Mathematics, 'Is the end in sight for theoretical physics?' The contributors here revisit many of the central questions raised in that lecture and which have motivated Stephen throughout his career. The recurring themes of particular importance include the endeavour to unify quantum theory with gravity and, specifically, its application to black hole evaporation, the issue of spacetime singularities and whether there was a beginning in time, and the problem of setting the special initial conditions which led to our habitable universe. We have grouped the workshop articles in this volume under eight headings, which we briefly review below; they roughly reflect the chronological order of the fields to which Stephen has contributed and in which he continues to work. The volume begins however, as the conference ended, with popular lectures from the final one-day symposium aimed at a more general audience.

1.1 Popular symposium

For any world class scientist a sixtieth birthday is sufficient cause to celebrate, but for Stephen Hawking there are particular reasons to mark the event, not just due to his personal triumph over disability but also his unique contribution to the popularization and dissemination of fundamental ideas about physics and the universe. Few could be unaware of the singular phenomenon of *A Brief History of Time*, with over ten million copies in print and now translated into 45 languages (nor is this unique, for example, with sales of *The Universe in a Nutshell* already exceeding 1.5 million). It seemed appropriate, therefore, to hold a much larger event with public lectures given by some of the foremost scientific popularizers of the present day, including Stephen himself. This symposium received worldwide media attention and BBC recordings of the event were broadcast later as a series of programmes entitled *The Hawking Lectures*.

These popular articles begin with Martin Rees, the Astronomer Royal, providing a cogent overview of our present understanding of the universe, a picture that Stephen has influenced so profoundly. Jim Hartle, Stephen's key collaborator in developing the 'no boundary' proposal for the origin of the universe, then addresses broad questions about the search for a unified

Fig. 1.1. Stephen Hawking arriving for the popular symposium which was attended by over 600 participants and attracted media interest from around the globe. [*Photograph Michael Hall*]

Fig. 1.2. Stephen Hawking at his 60th Birthday Symposium. [*Photograph Michael Hall*]

theory of everything. The challenges to be faced in such a marriage between classical general relativity and quantum mechanics is the theme continued by Roger Penrose. Next, Kip Thorne takes us on a journey from the golden age of black hole theory to the exciting prospect today of testing these theoretical predictions using a new generation of gravitational wave detectors. Finally, Stephen concludes with an account of his personal odyssey, 'sixty years in a nutshell', beginning as a Cambridge graduate student determined to tackle the big questions in cosmology. A measure of his ongoing commitment to this quest is apparent from the fact that he wrote and delivered this lecture while recovering from a broken leg, sustained less than two weeks before the conference.

1.2 Spacetime singularities

Stephen first came to the attention of the wider scientific world for his work with Roger Penrose showing that if classical general relativity is correct and certain energy conditions hold, then singularities are almost inevitable both at the beginning of the universe at the Big Bang and during the gravitational collapse inside black holes. These results were extremely influential in cosmology, as George Ellis reviews in the first

of the articles in this section. He worked with Stephen to show from the cosmic microwave background that the conditions of the theorems actually hold in our universe. He also offers a masterly account of an approach to the relativistic theory of cosmological perturbations that was originally pioneered by Stephen (it prefigures articles on cosmology in the final section of the book).

The issue of closed timelike curves is another topic to which Stephen has devoted considerable attention. Classically according to general relativity it seems that they are quite possible, a point made forcibly by Kurt Goedel. However, Stephen has proposed a *chronology protection conjecture* whereby closed timelike curves are forbidden by quantum field theoretic effects. Matt Visser surveys the current evidence for the conjecture and provides a critical assessment of future prospects.

Of the classical energy conditions, the dominant energy condition is the most useful. It implies the positive mass theorem and, as pointed out by Stephen when he named it, according to classical theory it forbids the creation of matter *ex nihilo*. Brandon Carter reviews the proof. Finally, Roger Penrose points out that the singularity theorems also hold in higher dimensions and raises the question of the theoretical significance of Kaluza–Klein theory. It is interesting to note that the singularity theorems gave a powerful impetus to the search for a quantum theory of gravity because they show that classical general relativity is an incomplete theory. The obviously attractive direction in which to complete it is by passing to some quantum version. This argument is quite independent of the many other motivations for quantizing gravity such as providing a consistent marriage between quantum theory and spacetime physics or unifying gravity with the other forces of nature.

1.3 Black holes

The singularity theorems are inextricably tied up with the development of the theory of black holes and, indeed, it was from this direction that Stephen entered the field. At that time we had Werner Israel's theorem on static black holes and Brandon Carter's work on axisymmetric black holes. The main aim was to demonstrate a complete 'No Hair' or uniqueness theorem showing that the exterior of a black hole is characterized only by its mass and angular momentum. Stephen made a pivotal contribution here by giving an argument that stationary black holes must be axisymmetric, thus complementing Carter's work. About the same time he showed that the area of the event horizon cannot decrease, a fact which has come to play an essential part of our understanding of black hole thermodynamics.

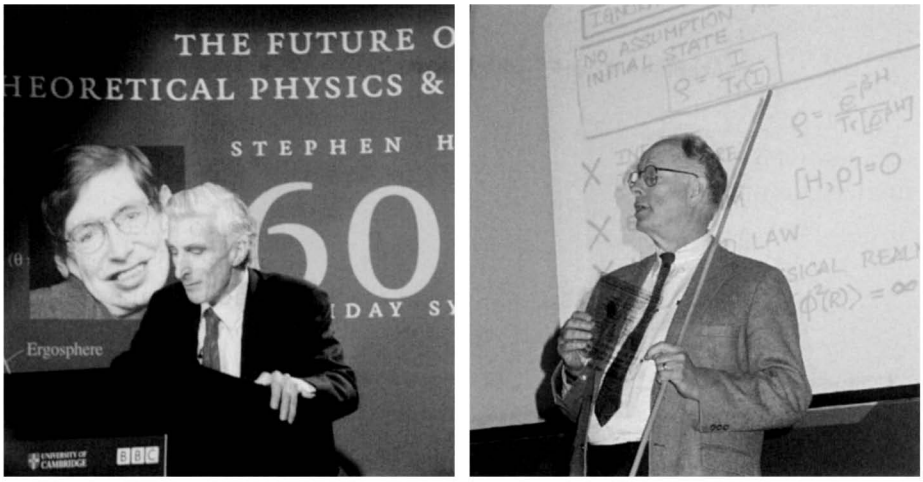

Fig. 1.3. Martin Rees (left) speaking at the popular symposium and Jim Hartle (right) at the scientific workshop. [*Photographs Anna Żytkow*]

Werner Israel reviews some of this history and how he now views the problem of black hole singularities. Martin Rees points out that nowadays black holes are commonplace in astrophysics and are beginning to be used as probes of relativistic gravity, offering the exciting prospect of testing Einstein's theory in the fully non-linear regime.

One of Stephen's most striking early physical predictions, made before his work on the event horizon and its symmetry, was the possibility that very small black holes may have formed in the early universe and that they may still exist as fossil relics of the Big Bang. Bernard Carr gives a historical overview of the development of the theory of such primordial black holes and how they may also be used as experimental or observational probes for exotic physics. In many ways primordial black holes resemble very heavy elementary particles. Simon Ross describes how this similarity extends to the possibility of black hole pair creation in strong external fields. Steve Giddings concludes this section by noting that if theories with 'large' extra dimensions are correct then we should be able to make them in accelerators, a truly awesome prospect for the future.

1.4 Hawking radiation

Stephen's work on primordial black holes led him, using quantum field theory, to his most famous discovery, their thermal radiation. This raises many deep puzzles, as he has strenuously and repeatedly insisted. Among them are whether black holes can evaporate completely or must they

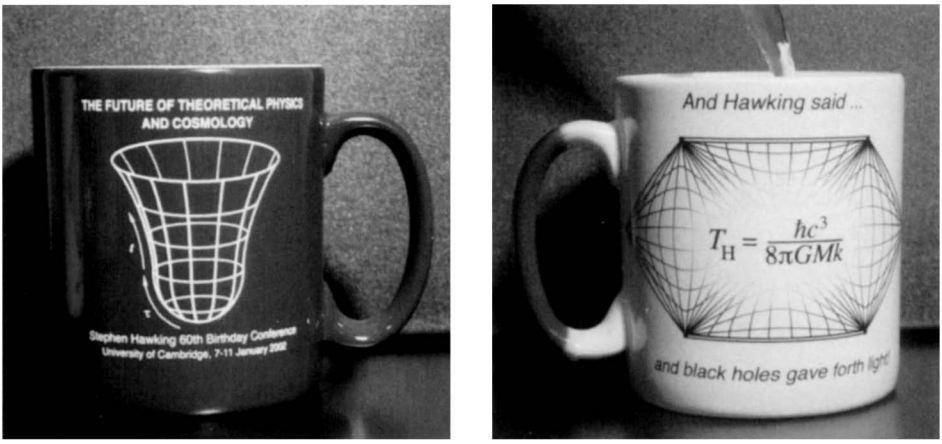

Fig. 1.4. In use, the black conference mug (left) transforms into white (right), revealing the Hawking temperature. [*Photographs Stefanie Wikner*]

leave relics? If the former case is true, what has happened to any conserved quantum numbers? Perhaps black hole evaporation processes and their virtual counterparts will violate any global conservation law. More puzzling still: what happens to quantum coherence during this process. Put in more popular if less helpful terms: where does all the information go?

Many of these problems cannot be solved within semiclassical general relativity and nowadays many theorists seek in string theory the answers to these puzzles. Malcolm Perry tells us what it has told us about black holes. Joe Polchinski extends the discussion to include M Theory. Gary Horowitz turns the topic around and tells us how strings can be made of black holes. Finally in this section, Lenny Susskind records his own personal journey from crisis and paradigm shift to holography.

1.5 Quantum gravity

Applying quantum mechanics to black holes might be thought to be jumping the gun if one does not yet have a quantum theory of gravity. Nevertheless one has to start somewhere. One approach much favoured by Stephen is the path integral, using a Feynman sum over positive definite metrics and Gary Gibbons describes how this may be used to elucidate many aspects of black holes, cosmology and the AdS/CFT correspondence. A key ingredient of this approach is the evaluation of functional determinants and Ian Moss reviews Stephen's suggestion that zeta function methods be used for this purpose. The article by Chris Isham, who sadly could not be

present at the workshop, comes at the subject from the opposite direction pointing out that deep logical pre-conceptions may require modification. Following this, Abhay Ashtekar, who was also unable to attend, considers the changes in our geometrical notions that quantum gravity may entail. Whatever the answer to these questions, one of the things we ought to get out of a quantum theory of gravity is some account of topology change. It may be that concepts like the topology of space or of spacetime make no sense in the final formulation except as an approximate description. Nevertheless, we can try to work in a 'top-down' manner from what we know to what we don't know. Fay Dowker describes what we can expect if we retain as much of the spacetime picture as we can using Morse metrics.

1.6 M theory and beyond

In the quest for a complete quantum theory of gravity, many hopes are pinned at present on a combination of ideas from string theory and supergravity often called M theory. The idea is that the five ten-dimensional superstring theories and eleven-dimensional supergravity should be thought of as limiting forms of a single overall structure whose precise form is at present unknown. All six theories, often envisaged as the vertices of a hexagonal space of theories, are linked by a web of dualities taking for example one theory at weak coupling to another at strong coupling or even more dramatically an eleven-dimensional theory to a ten-dimensional theory.

In his article, Ed Witten tells us about the past of string theory and how it was built up, perturbatively bit by bit, unlike general relativity: complete and beautifully-formed like Venus born from the waves. Given this unexpected turn of events he declines to make too many predictions about its future, arguing that if he had tried to do so in the past he would not have been very successful. The future may be dark and uncertain but the past is not so. David Gross and Michael Green highlight the achievements of string theory in very accessible articles. Paul Townsend describes the origin of the mysterious 'M' name and how it arose from considering membranes rather than strings.

One of the most astonishing achievements of this synthesis is the idea that supergravity in five dimensions can tell us about Yang-Mills theory in four dimensions. This is the famous AdS/CFT correspondence. Nick Warner describes how this works in practice and Chris Pope relates it to the search for metrics of special and exceptional holonomy. A striking feature of both articles is the extent to which work carried out for an entirely different purpose now takes on a new significance. Is there perhaps a lesson here for the future?

1.7 De Sitter space

The similarities between the cosmological event horizon in de Sitter space and the absolute event horizon of a black hole spacetime have long been a subject of fascination. Put in its simplest terms, black holes are regions into which one is attracted by gravity and the absolute event horizon marks the point of no return. If the cosmological constant is non-zero, as astronomers now tell us it may be and cosmologists that it probably was in the past, then we have not only to contend with Newton's universal law of gravitation but also with de Sitter's universal law of repulsion, in other words, with anti-gravity. Things are now turned inside out and every observer is surrounded by their own cosmological event horizon whose properties, including thermodynamic, closely resemble those of black holes, a point made by Stephen and Gary Gibbons long ago.

Raphael Bousso describes more recent ideas about this connection, including a formulation of the idea of holography originally proposed by Gerard t'Hooft and by Lenny Susskind, which roughly speaking implies that degrees of freedom are associated with the boundary rather than the bulk of a region of spacetime. Raphael insists that the boundary should be lightlike.

An unresolved problem here is that, unlike anti-de Sitter space, it is hard to relate de Sitter space to string theory and M theory because

Fig. 1.5. Workshop participants transfixed by a lecture on Euclidean quantum gravity. [*Photograph Anna Żytkow*]

to do so would be to violate the strong energy condition used in the Hawking–Penrose theorems and satisfied by almost all known forms of matter (except scalars with positive potentials). Andy Strominger tries to do just that and Renata Kallosh carries the discussion forward to show how extended supergravity theories are compatible with a de Sitter term and what cosmological features arise when supersymmetry is broken.

1.8 Quantum cosmology

Perhaps Stephen's most daring intellectual project has been his work on quantum cosmology and his famous proposal, developed with Hartle, that the universe has no boundary. It is motivated by the simple fact that it is not sufficient to know the dynamical laws that govern the universe, one must also specify its initial state. Jim Hartle provides a global view of what this means in practice in the context of fundamental theory and semiclassical approximations to quantum gravity. Don Page, another of Stephen's longstanding collaborators, provides his own account of the Hartle–Hawking wavefunction of the universe and how to calculate its predictions in some specific cases. Alex Vilenkin brings an alternative perspective to quantum cosmology that is not always entirely in accord with Stephen's. He concludes by arguing for the genericity of eternal inflation which may make it difficult to distinguish between competing theories of initial conditions. Quantum mechanics raises many interpretational problems of its own, as Bryce De Witt makes clear. In quantum cosmology one must add the problem of time, as Jonathan Halliwell points out, and which he tackles using the decoherent histories approach. Peter D'Eath describes what special features supersymmetry brings to a discussion of quantum cosmology.

1.9 Cosmology

Stephen began working in cosmology just before the discovery in 1965 of the cosmic microwave background (CMB). The field has since emerged from a metaphysical backwater into a truly quantitative science, a process dramatically accelerated over the last decade by the discovery and study of primordial fluctuations in the CMB. It is these observations which appear to be remarkably consistent with those predicted by inflation. The idea of the quantum origin of these inflationary fluctuations, in which Stephen played such a key role, is reviewed by Alan Guth, focusing especially on the famous 1982 Nuffield workshop in Cambridge during which their amplitude was pinned down. He then discusses the observational evidence for inflation, before turning to the implications of eternal inflation. This

work suggests that even an inflationary epoch cannot avoid a singularity in the past and thus a beginning in time. Paul Shellard reviews the observational prospects for cosmology, concentrating on the role of the cosmic microwave sky in testing inflation and other early universe models. He also considers the computational effort necessary if theoretical cosmology is to keep pace with rapidly improving observations.

The endeavour to place the standard cosmology within the framework of fundamental theory has led to the concept of braneworlds, in which our universe becomes a three-dimensional membrane (or brane) within some higher dimensional space. A controversial variant of these models, in which the branes move and collide, is presented by Neil Turok as a possible alternative to inflation. Andrei Linde mounts a robust defence of the conventional viewpoint. Finally, Pierre Binetruy reviews the present status of the brave new world of branes, borrowing his title from one of Stephen's recent papers on the subject. He discusses how cosmology is modified by these extra dimensions and the potential observational signatures that might reveal their presence.

1.10 Postscript

In the short space of an introduction like this, it is not easy to summarize the enormous impact of Stephen's contributions in so many areas from cosmology to black holes to quantum gravity. It seems far better to let the articles in this volume speak for themselves in tribute of his profound influence. However, one can be left in no doubt that Stephen is a physicist of the first class, drawn, in Kip Thorne's words, 'from that small handful who repeatedly make the breakthroughs that shape research in their fields for many years'.

Stephen's close colleagues and former students have enjoyed the special privilege of knowing him personally and seeing his work at first hand. As a mentor, we are deeply indebted to him for the example he has set. He strikes at the heart of a problem using his incisive physical intuition and, out of complex mathematics, he distils the essential geometric concepts. As a friend, we have daily seen with our own eyes his unparalleled courage and his sheer determination in the face of such grave disability. He has identified what he can do well, in fact, exceptionally well, and he gets on with his life and work with such impish good humour that it is difficult to believe that he has now reached the ripe old age of sixty!

So is the end in sight for theoretical physics and cosmology? Well, who are we to presume when Stephen and so many others at the conference have exercised such wise caution in their predictions. However after a meeting like this we cannot resist voicing the optimistic sentiment that