ant") components is akin to the recognition that variation in biological form results from both indeterministic and deterministic components ("chance and necessity") (*6*).

Given its significance, this research program should be generating far more interest in the ecology and evolution fields than we see at present. So far, the trends have been evaluated mainly across diverse species, but have yet to be shown across individuals within a species, or within individuals as they grow. By placing individuals in ecological conditions where they are likely to confront allometric constraints, experiments have the potential to verify the existence of the constraints where they act (that is, at the level of the individual plant). In addition, key assumptions of this theory remain to be confirmed. For example, does wood density really remain constant during the ontogeny of the plant? As such data become available, we will be able to subject allometric models to the scrutiny they deserve.

If the new theory proves robust, the implications are both practical and profound. Given the great difficulty in measuring roots, sound theoretical predictions of below-ground biomass will be of great practical value. One timely application will be in large-scale biomass models that predict how much carbon plants sequester from the atmosphere (*7*, *8*). In these cases, scaling rules can provide functional forms and boundary predictions of total biomass for seed plants in virtually every type of terrestrial ecosystem. Allometric theory also provides a foundation for appropriate measures of growth, to compare ecological performance among plants of different sizes. These measures could replace the standard "relative growth rate" (RGR), which implicitly ignores nonphotosynthetic tissue in the underlying assumption of exponential individual growth.

At the very least, the theory of allometry has been rejuvenated and its horizons greatly expanded. More optimistically, we may begin to see at organismal scales some of the synthesis of the physical and biological sciences that has been so apparent and powerful at the molecular level. We can even envision mechanistic links with macroecological and evolutionary models of community structure and abundance (*9*, *10*). And when we next walk in the forest, we can see anew how the physical processes necessary for life explain the similarities (and differences) in form between a diminutive forest herb and the redwood tree that towers above it.

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PERSPECTIVES: COSMOLOGY

Tales of Singularities

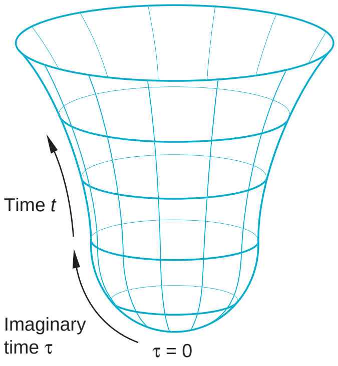
G. W. Gibbons and E. P. S. Shellard

To celebrate Stephen Hawking's 60th birthday, a workshop and symposium were held in Cambridge from 7 to 11 January 2002 (*1*). The title of the meeting, "The Future of Theoretical Physics and Cosmology," was taken from Hawking's inaugural lecture in 1979 as Lucasian Professor (the chair of Isaac Newton and Paul Dirac). Colleagues, collaborators, and former students took stock of what has been achieved in fundamental physics since Hawking began his career and considered the future of the subject.

George Ellis (University of Cape Town) recalled that Hawking began working in cosmology just before the discovery in 1965 of the cosmic microwave background (CMB)—primordial light reaching us from all directions in the sky. The burning issue at that time was whether the universe had a beginning. Was it in a steady state of exponential expansion or did it originate in a Big Bang, a singular state where the known laws of physics break down and the curvature of space becomes very high or infinite?

The CMB data clearly favored the Big Bang, bearing evidence of a time when our universe was much hotter and denser than it is now. Using the singularity theorems of Roger Penrose, Robert Geroch, and Hawking, George Ellis and Hawking showed that the classical equations of general relativity require a singularity in our universe's past unless one invokes some unusual form of matter, which in effect antigravitates.

Current observations suggest that the situation is more complicated. There is strong evidence that during its first fraction of a second, the universe underwent a period of exponential expansion or inflation. And there is good (although not yet conclusive) evidence that today, the expansion of the universe is accelerated by antigravitating "dark energy" (also called quintessence). Does this mean that the singularity theorems may not apply and that the universe may not have had a beginning? Not according to Alan Guth (MIT) and Alex Vilenkin (Tufts University), who showed that even an everywhere expanding universe filled with antigravitating material cannot be extended infinitely into the past.



Out of nothing. Hawking's no-boundary proposal links imaginary and real time in one extended spacetime called an instanton. In effect, the instanton describes the creation of the universe from nothing.

Guth recalled another meeting in Cambridge some 20 years ago, when the quantum fluctuations produced during inflation were discussed and characterized. Hawking played a leading role in these discussions. The latest CMB observations are providing the first observational indications that inflationary fluctuations provided the primordial seeds around which galaxies and other structures in the universe formed. The NASA Microwave Anisotropy Probe (MAP) satellite is now scanning the cosmic microwave sky and many other experiments and surveys are under way. These studies will yield a wealth of observational data on the early universe, allowing a more detailed search for the theoretically predicted signatures of inflation.

Ambitious cosmological theories about the origin of the universe, such as Hartle and Hawking's no-boundary proposal (see the first figure), will increasingly run the gauntlet of these discriminating observational tests. Theoreticians must match the quality of the observations with the accuracy of their predictions. This process will require massive computational effort using,

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for example, COSMOS (the UK national cosmology supercomputer), of which Hawking is principal investigator.

The observational hints of an inflationary past present important challenges and pointers for the future of theoretical physics. The simplest mathematical model exhibiting inflationary behavior is called de Sitter space-time. In this model, the universe contains no matter but only a positive cosmological constant and expands exponentially forever. However, calculations of inflationary fluctuations use semiclassical approximation schemes based on quantum field theory in this fixed space-time, and it remains unclear how this simple limit can emerge from a more fundamental quantum gravitational theory. Indeed, as Andy Strominger (Harvard University) pointed out, it is difficult to even find a place for de Sitter space itself.

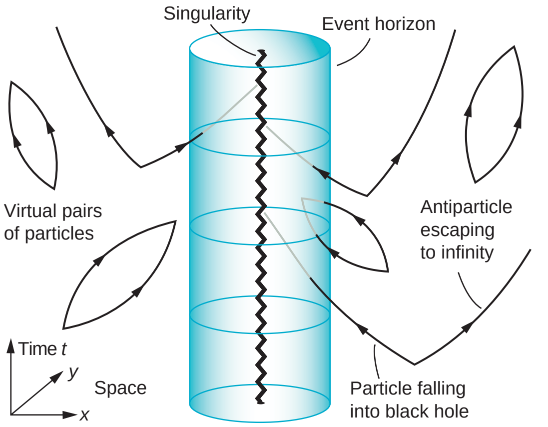
Directly analogous challenges exist in black hole physics (see the first figure). The Penrose and Hawking theorems imply that, classically, a singularity must develop inside black holes. Werner Israel, Brandon Carter, Hawking, and others have demonstrated that the exterior of such a black hole is characterized uniquely by its mass and angular momentum. Israel (University of Victoria) reviewed the theoretical evidence that the interiors of black holes may also undergo a rapid expansion, which he calls mass inflation.

Martin Rees (Cambridge University) reminded us of the growing observational evidence for enormous black holes in the center of many galaxies. Kip Thorne (California Institute of Technology) discussed the quest to detect black holes directly through the gravitational waves they emit. The next generation of laser interferometers, such as the Laser Interferometer Gravitational Wave Observatory (LIGO), should be able to characterize the properties of black holes as they merge with sufficient accuracy to measure the areas of their event horizons (the gravity fields of the black holes where space-time is so bent that light cannot escape) and test Hawking's area law for the final black hole.

Gravitational wave astronomy will open up a new window on the universe, potentially lifting the CMB veil 300,000 years after the Big Bang to reveal violent processes as far back as the Planck epoch (the instant after the beginning of the universe's expansion when the cosmic matter density was so high that gravitational force acted as strongly as the other fundamental forces on the subatomic scale).

A tremendous theoretical impetus to quantum gravity came from Hawking's discovery that black holes emit black body radiation with a characteristic and universal temperature that, in the simplest case of nonrotating and spherically symmetric (Schwarzschild) black holes, depends only on their mass. In the early 1970s, Hawking, Hartle, Gibbons, and Perry showed that this universality and the consequent universal thermodynamic behavior of black holes owe their origins to the behavior of the space-time of black holes in imaginary time. All physical qualities are periodic in imaginary time, with the inverse period giving the temperature.

However, these results posed deep puzzles. Bekenstein and Hawking showed that black holes have an entropy proportional to the area. How can one understand this entropy in terms of the numbers of some underlying quantum microstates, just as one does in ordinary physics? Hawking radiation (see the second figure) leads to the evaporation and disappearance of black holes. Does quantum mechanics break down during this process? Most exciting of all, as discussed by Bernard Carr (Queen Mary and Westfield College, London), can one hope to find observational evidence for evaporating black holes?



Escape from a black hole. Hawking's most famous discovery was that pairs of particles are created near a black hole. One member falls inside and the other escapes to infinity as Hawking radiation.

These questions are not restricted to the physics of black holes. If the universe expands fast enough, as it must have done in the past if the theory of inflation is correct, then it will have an event horizon outside which things are expanding so rapidly that causal contact is lost with the interior. This cosmological horizon behaves very similarly to an "inside out" black hole. In particular, it has a temperature and an entropy, and according to inflationary theory, the resulting quantum/thermal fluctuations eventually grew into galaxies.

No proper understanding of these questions can be achieved without quantizing gravity because classical general relativity breaks down at very short distances. As the talks at the meeting confirmed, quantum gravity is still a contentious subject, but enormous progress has been made over the past few years. Many, although by no means all, researchers in the field now feel that the most promising ideas fall under the heading of "M-theory," a quantum theory that goes beyond superstring theory and deals with membranes as well (*2*). M-theory is as yet imperfectly formulated, but it is beginning to provide answers to the questions posed above. For example, Malcolm Perry (Cambridge University) reviewed the progress made in understanding the entropy of black holes with ideas from M-theory.

Further reasons for confidence in M-theory and also in the techniques of Euclidean quantum gravity are the extraordinary recent theoretical successes reported by Nick Warner (University of Southern California) of the AdS/CFT correspondence, which allows calculation of the properties of gauge particles, such as the gluons binding quarks in nuclei, in terms of gravitational fields in Anti-de Sitter space (a variant of de Sitter space used in inflation). This correspondence has strongly influenced cosmological models in which our universe is envisaged as a three-dimensional surface or three-brane moving in a higher dimensional space-time (*2*). The study of such exotic cosmological models is in its infancy and remains extremely controversial, as was clear from the talks of Neil Turok (Cambridge University) and Ande Linde (Stanford University). Nevertheless, one may confidently predict that they will be energetically pursued in the years to come.

Theorists will continue to work on M-theory and its consequences for cosmology. However, Edward Witten (Institute for Advanced Study, Princeton) was not prepared to venture a more detailed 10-year prognosis. Having reviewed progress over the previous two decades, he was well aware that his earlier predictions would not have done any justice to the directions in which the field had developed. As Hawking summed up in the final talk of the meeting, "It has been a glorious time to be alive, and doing research in theoretical physics. Our picture of the universe has changed a great deal in the last 40 years" (*3*). Even Hawking made no firm prophecy about the surprises ahead.

References and Notes

1. It is not possible to summarize all that was discussed at the meeting here. For more details, see the comprehensive conference Web site (www.damtp.cam.ac.uk/user/hawking60) and the proceedings, which will be published by Cambridge University Press later this year.
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3. Hawking's lecture, "60 years in a nutshell," is available at www.bbc.co.uk/science/space/spacepeople_az/hawkinglecture.shtml.