

# THE KAVLI PRIZE

SCIENCE PRIZES FOR THE FUTURE

- ASTROPHYSICS
- NANOSCIENCE
- NEUROSCIENCE



## The Norwegian Academy of Science and Letters

*Honorary President H.M. King Harald V*

The Norwegian Academy of Science and Letters has since 2003 awarded the Abel Prize for outstanding scientific work in the field of mathematics. The prize amount is NOK 6 million (approx. EUR 750,000 or USD 1 million).

In 2005 the Academy signed an agreement with the Kavli Foundation and the Norwegian Ministry of Education and Research to jointly sponsor and award The Kavli Prize in astrophysics, nanoscience and neuroscience. Each of the prizes will carry a cash award of USD 1 million. The Kavli Prize will be awarded for the first time in 2008, and then every two years.

### **The Academy**

The Norwegian Academy of Science and Letters, founded in 1857, is a non-governmental, nation-wide, and interdisciplinary body which embraces all fields of learning.

The main purpose of the Academy is the advancement of science and scholarship in Norway. It provides a national forum of communication within and between the various learned disciplines, and it represents Norwegian science vis-à-vis foreign academies and international organisations.

The Academy fulfils these functions by initiating and supporting research projects, by organising meetings and seminars on topics of current interest, by publishing scientific and scholarly works, and by participating in and nominating representatives to various national and international scientific bodies. The Academy also has international scientific co-operation agreements with sister academies in the Baltic States, Poland, Hungary, France and Great Britain.

The Academy represents Norwegian research internationally in the “International Council for Science” (ICSU), including its many sub-organisations, and in the “Union Académique Internationalé” (UAI), the “European Science Foundation” (ESF) and “ALLEA” (All European Academies).

### **Members**

The Academy has 219 ordinary seats for Norwegian members and 183 additional seats for foreign members. The Academy is divided into two divisions, one for the natural sciences and one for the humanities and social sciences. Including members over 67 years of age, there are 830 members.

# THE KAVLI PRIZE SCIENCE PRIZES FOR THE FUTURE

The prizes will emphasise the science of the greatest physical dimensions of space and time, the science of the smallest dimensions of systems of atoms and molecules, and the science of the most complex systems, especially living organisms.



## **The Kavli Prize in Astrophysics**

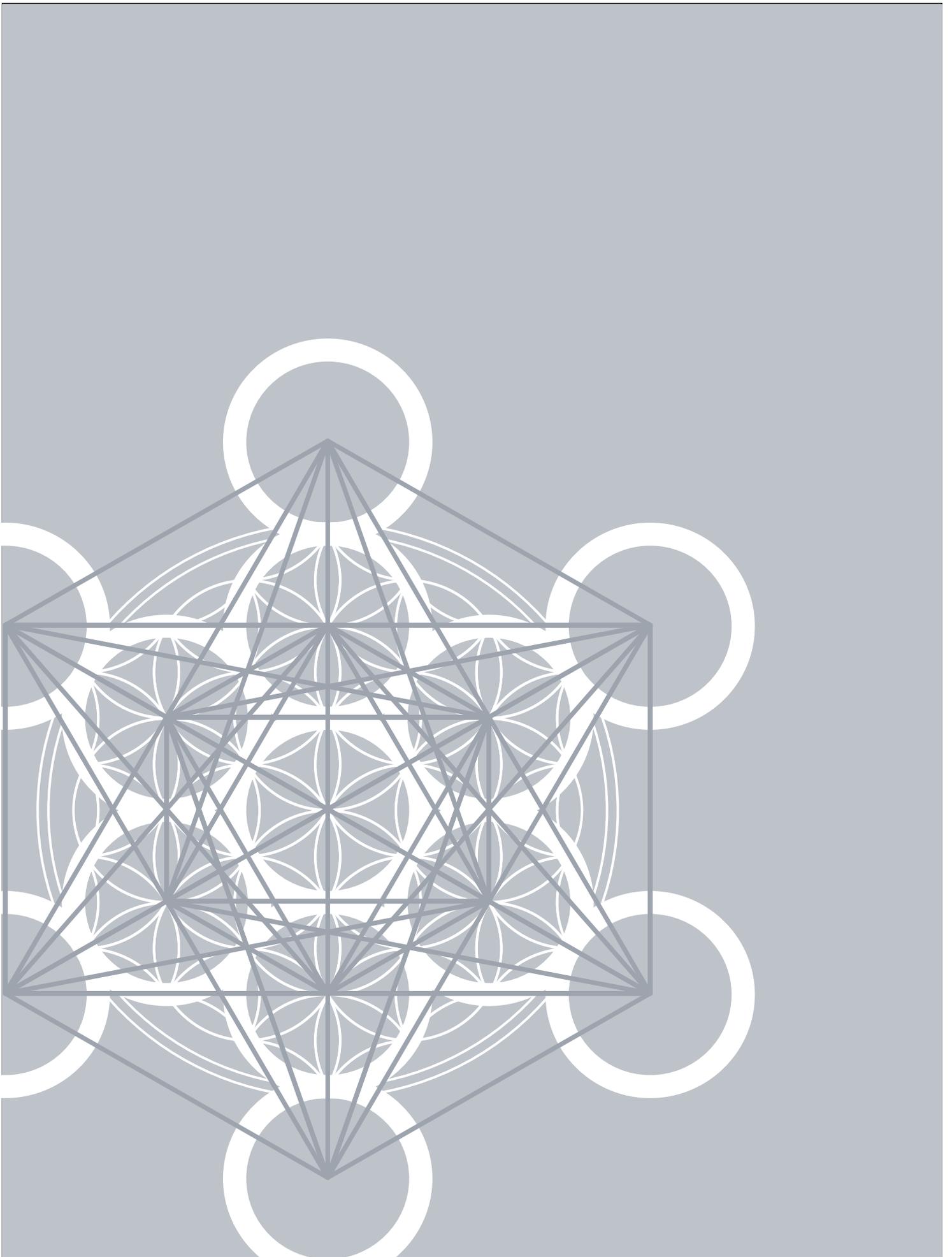
will be awarded for outstanding achievement in advancing our knowledge and understanding of the origin, evolution, and properties of the universe, including the fields of cosmology, astrophysics, astronomy, planetary science, solar physics, space science, astrobiology, astronomical and astrophysical instrumentation, and particle astrophysics.

## **The Kavli Prize in Nanoscience**

will be awarded for outstanding achievement in the science and application of the unique physical, chemical, and biological properties of atomic, molecular, macromolecular, and cellular structures and systems that are manifest in the nanometre scale, including molecular self-assembly, nanomaterials, nanoscale instrumentation, nanobiotechnology, macro-molecular synthesis, molecular mechanics, and related topics.

## **The Kavli Prize in Neuroscience**

will be awarded for outstanding achievement in advancing our knowledge and understanding of the brain and nervous system, including molecular neuroscience, cellular neuroscience, systems neuroscience, neurogenetics, developmental neuroscience, cognitive neuroscience, computational neuroscience, and related facets of the brain and nervous system.



# A S T R O P H Y S I C S

Only in the last century did scientists really begin to understand the physics of the cosmos.

Putting eyes to telescopes and pencils to paper, 20th century observers and theorists were the first to grasp the vastness of space and glimpse the diversity of its contents. The points of light rotating overhead at night, those explorers discovered, are to the cosmos as a cover to a book. And the book turned out to be an elaborate mystery story; full of peculiar characters and surprising plot twists, with the ending still unwritten.

Today's scholars of the nighttime sky tell a story of a universe incomprehensibly huge. Once misjudged to be a fixed sphere of stars encircling the sun and planets, the cosmos is now a ballooning expanse of space populated by billions and billions of galaxies, each containing billions and billions of stars. The galaxies aggregate in intricate clusters, forming great walls that envelop vast voids. Light from the most distant galaxies reaches Earth only after a transit time of billions of years.

And day after day, the universe grows bigger. Galactic clusters recede from one another at rapid speeds as the space separating them expands. Permeating all the intervening space is a faint glow of cosmic radiation, the apparent remnant heat from a cataclysmic explosion – the Big Bang – that burst the universe into existence almost 14 billion years ago.

**So much is known; much more is not.** Today's astronomical explorers seek answers to several deep questions about

Despite their great success in realms small and large, quantum theory and general relativity have left scientists in the dark about several fundamental issues.

## The Search for Answers in a Dark Universe

For one thing, astronomers cannot say what the universe is mostly made of. Add up all its mass and energy, and the stars and gases built from ordinary matter account for a mere four percent of it. Almost 25 percent or so seems to be some form of matter, but too dark to be directly viewed, and not of any sort ever found on Earth. The rest – 70 percent of the cosmos or more – masquerades as an invisible (or “dark”) energy field, exerting a repulsive force on space itself.

“Dark energy has the remarkable feature of having negative pressure,” says Rocky Kolb, of the Kavli Institute for Cosmological Physics at the University of Chicago. “This drives the universe to accelerate – to expand with an ever increasing expansion velocity.”

Identifying the true nature of dark energy and dark matter is the prime directive guiding the pursuits of 21st-century astrophysicists and cosmologists. But besides dark energy, space contains a menagerie of other exotic objects and phenomena taxing the human mind's explanatory powers.

Some stars explode, for instance, brightly enough to momentarily outshine an entire galaxy. Such explosions, called supernovae, underlie many astrophysical mysteries. Many such explosions leave behind dense

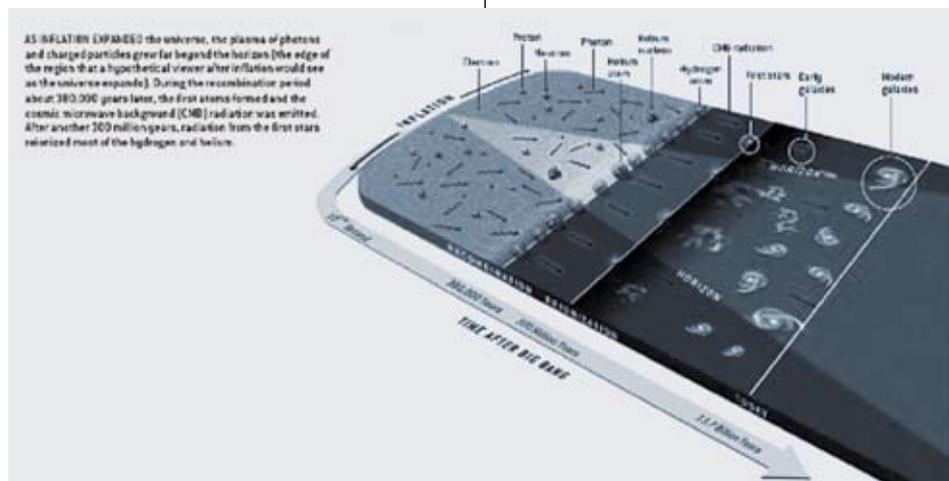


Figure 1. Timeline of the Universe illustrating the expansion of the universe following the big bang and subsequent formation of atoms, stars, galaxies and clusters of galaxies. (Image by Wayne Hu, Scientific American).

the nature of space, the astrophysical objects it contains, and the universe's composition, history and future. Guiding this quest are the 20th century's grandest theoretical accomplishments: quantum mechanics and Einstein's theory of general relativity. Quantum theory specifies the ground rules for explaining matter's basic particles and the forces acting between them, while general relativity governs the large-scale behavior of the cosmos, describing gravity, space and time.

cinders called neutron stars, packing a mass of several suns into a ball the width of a small city. Neutron stars often beam radio signals through space as they rotate, like a lighthouse, enabling earthbound astronomers to record data for testing their theories.

After a very massive star blows itself up, the remnant may be denser than a neutron star – so dense, in fact, that it collapses under its own mass, crushing itself into nothingness and leaving behind its gravity. The result is a black hole – a cosmic sinkhole with gravity concentrated so strongly that any object entering within its boundary remains forever trapped. On its journey into black hole oblivion, however, matter heats up and emits streams of radiation that signal the black hole's presence to the outside world.

Black holes, neutron stars and all other known forms of matter cannot account for what astronomers see through their telescopes. Galaxies spin with speeds exceeding the limits implied by their mass. And galaxy clusters hang together more closely than possible unless some invisible glue binds them together. An additional source of gravity, matter unseen (and therefore called dark) must exist to hold the universe together, so to speak, and sculpt its majestic structure.



Figure 2. This computer-generated image shows the simulated distribution of dark matter in a galaxy cluster formed in the universe with dark energy. The clumps are locations where galaxies form. (Courtesy of Andrey Kravtsov)

But what could that dark matter be? Physicists who understand atoms, and the particles from which atoms are made, say known forms of matter could not supply the galactic glue. Limits on the density of ordinary matter can be calculated based on the way atoms were cooked up in the big bang from a hot primordial soup of quarks and electrons. Such calculations show that matter made from particles familiar on Earth makes up a small fraction of the matter in space.

Physicists theorize, however, that other sorts of particles exist, perhaps “superparticles,” much more massive than those making Earthly matter. In several underground laboratories around the world, physicists attempt to capture such particles as they stream through space – so far without success, but still with hope.

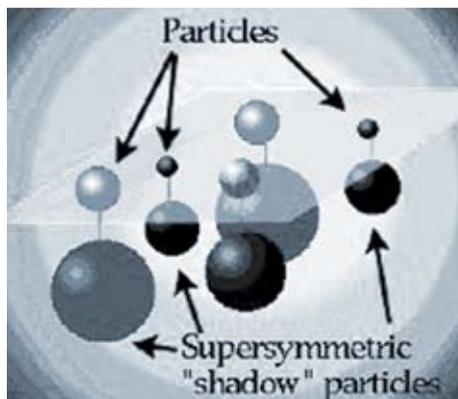


Figure 3. Supersymmetry theories postulate that the two types of particles found in our universe (bosons and fermions) cannot exist without each other. According to supersymmetry, for each type of fermion which exists, there must also exist a boson with many of the same properties - known as its superpartner. In many supersymmetric theories, the lightest superpartner particle is stable and weakly interacting, making it a good candidate for the dark matter of our universe. (Courtesy of Dan Hooper)

Efforts to detect the presence of superparticles in the cosmos has led to the development of a new field of study called particle astrophysics. “There’s a growing recognition now in the whole community that particle astrophysics is a legitimate part of particle physics,” says Josh Frieman, also of the Kavli Institute for Cosmological Physics in Chicago.

That new field has forged close ties between astrophysicists and physicists working at particle colliders, where known bits of matter are smashed together in hopes of producing particles never before seen. If they can’t be caught in flight through space, perhaps dark matter particles can be created in colliders. And producing the particles in colliders would offer additional benefits.

“Everybody hopes that they’ll detect dark matter directly in some underground detector,” says Frieman, “but to really learn about what that particle is, we need to see it produced in a collider so we can really probe its properties.”

### Einstein Revisited

Even more perplexing than dark matter is dark energy. Einstein anticipated something like it, adding a term to his equations that describes a constant energy residing in the vacuum of space, everywhere of equal strength at all times.

Einstein abandoned that idea, but modern cosmologists have revived it, in light of compelling evidence that the universe expands at an accelerating rate. In fact, quantum theory suggests that such a “vacuum energy” should indeed be present, everywhere in space. But calculations predict a density vastly exceeding the observed amount. In fact, the amount of vacuum energy predicted by theory would blast the universe apart so fast that no structure would form – meaning no stars, no planets and no people.

Obviously that prediction is wrong. Consequently some physicists question whether dark energy really exists, suggesting that the accelerating expansion of space reflects large-scale deviations from the law of gravity. If so, Einstein’s general theory of relativity needs to be modified. Others believe the dark energy is a cosmic fluid that alters its strength over time, unlike the constant vacuum energy foreseen by Einstein.

Observers continue to seek more data from space that might resolve the dark energy mystery. Meanwhile, theorists seek guidance from the mathematics of general

relativity and quantum mechanics. But these two pillars of physics, the 20th century's greatest theoretical achievements, seem fundamentally incompatible. Many experts believe that understanding dark energy must await a theory that unifies quantum physics with Einstein's gravity, tying up the remaining loose ends in the cosmic story.

One leading candidate, known as string theory, has been thoroughly explored for the past two decades, so far without ultimate success. But many experts believe string theory's mathematical power, once fully understood, will be great enough to conquer all the problems of the cosmos.

"There is very much a sense that we are discovering something, that there is some structure out there which unites gravity and quantum mechanics in some unique way, and we haven't yet discerned its full form," says string theorist Joe Polchinski, of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara.

String theory conceives matter's basic particles to be tiny bits of vibrating string, called superstrings. Strings vibrating in different modes represent different basic particles, sort of like the way a violin string can produce various musical notes. String theory's math makes sense, though, only if space possesses more than three dimensions – perhaps as many ten. Such extra dimensions go unnoticed, string theorists have proposed, because they are so small, on the size scale of the strings themselves. And a string is smaller than an atom as an atom is smaller than the solar system.

### **Are There Countless Universes?**

While string theory was originally explored in the realm of particle physics, theorists have more recently studied its implications for cosmology. Its most astounding cosmological consequences stem from the possibility that the extra dimensions of space might be bigger than previously believed. Large dimensions would remain invisible because matter and light are stuck like glue to 3-D space. Gravity, however, would be free to travel through other dimensions. If large dimensions actually exist, the visible universe might be just one of many 3-dimensional bubbles (or

"branes," short for membranes) floating in a higher dimensional space. If so, new possibilities emerge for explaining dark matter and dark energy.

Sometimes advertised as a possible "theory of everything," string theory might provide a recipe for all the basic properties of nature, including a precise specification of how dense the dark matter should be. But some theorists believe that string theory will tell a different story – that in fact, the amount of dark energy in the cosmos cannot be precisely specified by any theory. In fact, some versions of string math suggest, dark energy could exist in any possible amount, taking on different values in different realms of reality. These "realms" might even be parallel universes, independent bubbles of space blown into existence by other big bangs.

Perhaps, this view implies, the universe that humans inhabit is only one among countless others, each with a different dark-energy density. Humans find the amount of dark energy in this universe to be small because that's the amount that is compatible with life existing in the first place.

Such reasoning relies on what is known as the anthropic principle, the idea that the properties of the universe must be hospitable to life, because otherwise we wouldn't be around to discuss it. Anthropic reasoning is bitterly opposed by many physicists who regard it as giving up on the grand goal of finding a final theory that specifies the properties of the universe in every detail. But others say permissible solutions for cosmic mysteries must not be prejudged, and solving the deep problems of the cosmos may require radical revisions in the way scientists think.

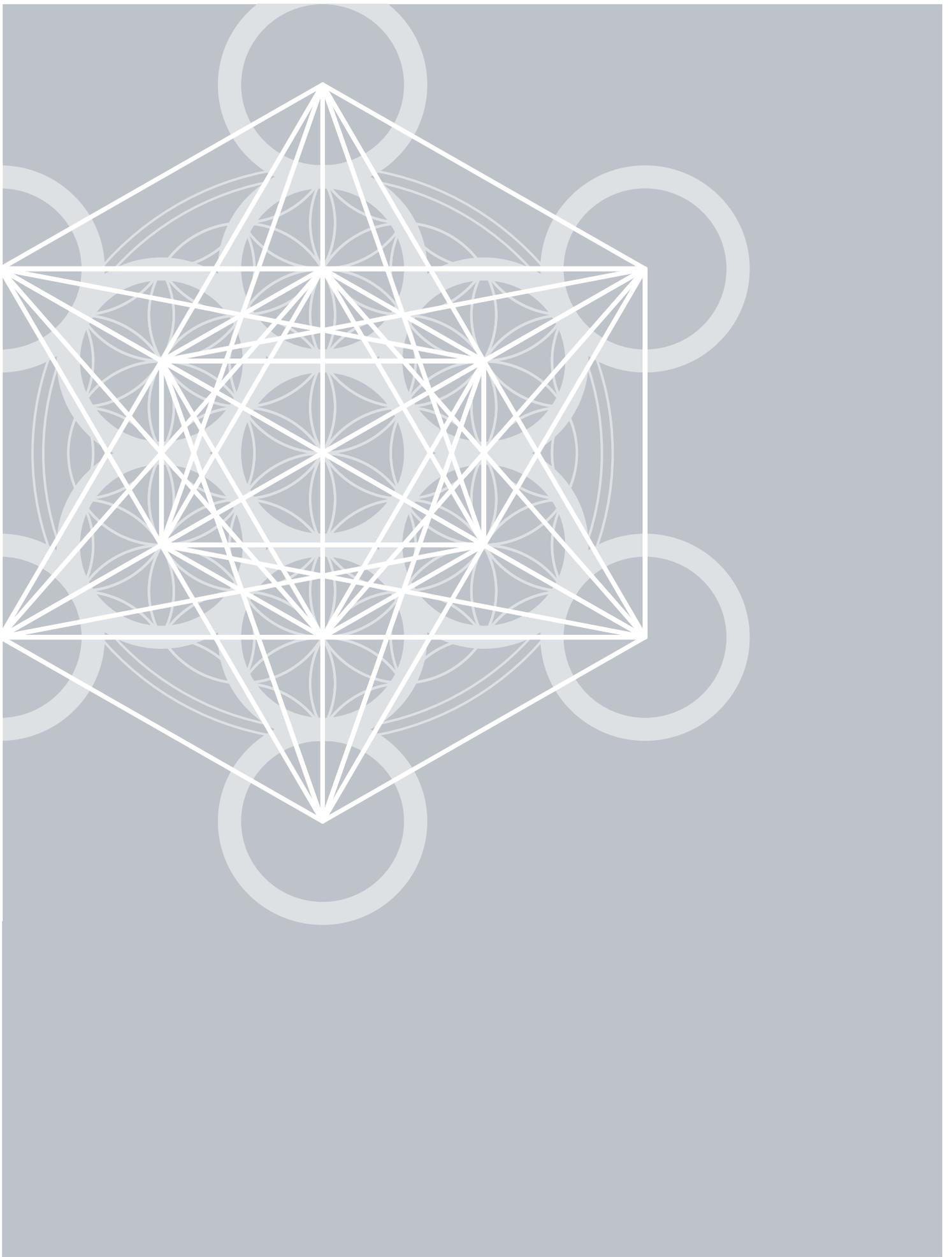
In that sense the situation sounds similar to that of a century ago, when astronomers realized that the Milky Way galaxy, home to sun and Earth, was not the entire universe, but only one of billions of "island universes" or separate galaxies. Today the prospect exists that the known universe is only one of many others, too, and the very definition of "universe" needs rethinking.

Whether such a profound rewriting of the book of the cosmos is in order will await the outcome of further explorations by today's astrophysicists and cosmologists.

In any case, resolving today's paradoxes will no doubt produce profound scientific advances, just as quantum mechanics and general relativity emerged from efforts to solve the mysteries of a century ago.

"We're faced with tremendous questions, and often real advances come when you're faced with big problems," says Kolb. "And I think the problems that we're faced with now, as we begin the 21st century, are as fundamental as the problems that we faced in the 20th century that led to quantum mechanics and general relativity."

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# NANOSCIENCE

Nanoscience and nanotechnology have captured the public imagination, but they are desperately hard to pin down. They seem to embrace everything from biomedicine to rocket science and computer technology.

Some futurologists forecast that nanotechnology could bring doom to humankind, while others that it could be our savior. According to some accounts its impact won't really be felt for decades; others point out that it has reached the marketplace already. In movies and novels such as *Spiderman II* and *Prey*, nanotechnology serves as a *deus ex machina* for whatever technological plot device is required, in contrast to which the commonly known consumer applications that today boast of their use of nanotech seem almost bathetic: sun creams and stain-resistant trousers.

So what's the real deal? What are the nanoscientists up to, and should we fear or welcome it?

## The Big Impact of the Nano World

Perhaps the one thing anyone who has heard of nanotechnology knows is that it deals with very small stuff. To most scientists, nanoscience and nanotechnology are about doing science and technology with objects that measure no more than a few hundred nanometers in one or more dimensions: very thin sheets or fibers, or tiny blobs of material. This is the "nanoscale": a nanometer is a millionth of a millimeter, and it's about the size of some big single molecules such as the protein enzymes in our bodies. A red blood cell is about six thousand nanometers across and a human hair typically 20,000-100,000 nanometers. So yes, nanotech works with small stuff indeed, generally invisible to the naked eye.

As you might imagine, it is very hard to get a grip on things this tiny to mold or cut them into shape, then put them where we want them. So what's the point of making stuff at such a Lilliputian scale? There are several answers, depending on your aims. In computer science and information technology, the incredible advances in computer power over the past few decades have come largely from making the transistors of microelectronic circuits ever smaller. Now millions of them can be carved on a single silicon chip. We can have more computing power in our kettles than was on board the first Apollo missions. Using nanotechnology, the speed and power of computers will continue to increase. In fact, nanotech may supply the

only means for the computer industry to continue meeting the public expectation that next year's machines will be smaller and lighter while being even brainier.

One of the benefits of nanoscience in medicine is that it lets us make interventions at the natural size scale of living cells themselves, rather than trying to affect what these cells do using clumsy instruments that are much bigger. Nanoparticles – lumps of material just a few nanometers wide – can be attached to proteins or other molecules to watch how they move around the cell; for example, acting as labels that glow when light is shone onto them. These particles and other nanoscale structures can be designed to pass through the bloodstream and latch onto invaders ranging from viruses to malignant cells, such as those that cause cancer, then perhaps releasing drugs or heat to kill them. And sensors that use nanotechnology could detect substances in our bodies at far smaller concentrations than is currently possible – maybe as tiny implants offering a continuous, highly sensitive readout of our state of health.

Nanotechnology might allow us to design the properties of new materials from the bottom up; for example, making super-strong fibers or materials that adapt to their environment or when damaged heal themselves. It promises better and cheaper ways of harvesting sunlight for energy, or detecting and eliminating pollutants in water and air. It seems that just about every field of science stands to gain something from working at the nanoscale. Ultimately, a mastery of matter that lets us build things at the scale of atoms and molecules means, in principle, we can do it more efficiently and cleanly, with less

waste of materials and energy. And it means we can measure things more sensitively, design properties and functions with more versatility, and start mimicking some of the clever things that nature achieves with her own "natural nanotechnology."

## How We Began Moving Atoms

All this promise has appeared on the technological horizon within the past two decades or so. Although the word "nanotechnology" was coined in 1974, it didn't mean very much until, the following decade, the tools were invented that made it possible to look into and manipulate the nanoworld. As early as 1959 the physicist Richard Feynman described a visionary goal of moving atoms about one by one. He had no idea how to do it or even if it would ever be possible; but in the early 1980s, scientists at IBM's laboratories in Zürich, Switzerland devised an instrument called the scanning tunneling microscope (STM). This let researchers "see" atoms individually.

It soon became clear that the STM could do more – the extremely fine needle tip that it uses to "feel" atoms could also be used to pick them up and push them around on a surface. In 1991, researchers at IBM's Almaden laboratories in California used the STM to write their company logo using just 35 atoms of the element xenon, arranged on a metal surface. Each letter was just five nanometers (nm) tall. Five years later, IBM researchers at Zürich made a "molecular abacus" by using the STM's needle tip to shift a row of 10 soccer ball-shaped carbon molecules (C<sub>60</sub>), one at a time



Figure 1: The molecular abacus. (Courtesy of Jim Gimzewski, University of California at Los Angeles)

The STM and related microscopes are one of the key enabling technologies that have let nanotech flourish. But making nanoscale structures atom-by-atom this way is a very slow process. One solution, also developed at IBM Zürich, is using many needle tips to manipulate the material. The so-called “Millipede” is an array of thousands of such tips – the latest version has 4000 of them – that work in parallel to modify a material at the nanoscale. Each tip is individually controllable and the plan is to use them to write information into plastic films. This will be done much as it is for today’s CDs and DVDs – by creating little bumps on the surface – but at much smaller scales so that more information can be stored in the same amount of space. The Millipede tips don’t move single atoms; they create little indentations where they have been heated up to melt the plastic. Each dimple is 10 nm across, so that 200 billion of them can be stored in a square inch of plastic film, like a kind of miniaturized Braille.

## Packing Information with Molecules

This is a reminder that information technology is one of the biggest driving forces behind nanotechnology. With data packed more densely, you can start to imagine DVDs containing whole libraries of movies, or digital cameras that never run out of space to hold snapshots. Researchers in California have used nanotechnology to make a memory device that packs 160,000 memory elements into a space no bigger than the surface of a white blood cell, and the information isn’t held in switches made from silicon, as in normal silicon chips, but in switchable molecules. Designed by chemist Fraser Stoddart, who holds the Fred Kavli Chair in Nanosystems Science at the University of California, Los Angeles, and his co-workers, these molecules are called “rotaxanes” because they are shaped like wheels or hoops threaded on an axle. Each axle holds a single hoop, which can shuttle between two different positions when a voltage is applied to the molecule. This shuttling triggers a change in the electrical current that passes through the molecule from end-to-end. That’s just like the switching of a transistor, which allows binary information – a string of 1’s and 0’s, corresponding to the switch being “on” or “off” – to be recorded in an array.

In this new device, a layer of rotaxane molecules is sandwiched between two sets of silicon or titanium wires arranged in parallel rows, with the upper and lower sets of rows crossing at right angles to make a square grid. At each crossing point of two wires, the molecules in between can be switched by applying voltages to the wires, so each of these junctions forms a memory element where a 1 or 0 can be recorded. The wires are just a few tens of nanometers wide, which is about ten times smaller than the narrowest wires in today’s commercial silicon chips (Figure 2). The researchers hope this array can provide a non-volatile memory, which means that the information it holds doesn’t evaporate as soon as the power is turned off. If such memories could be used in computers, they’d have no need to boot up each time you switched them on – they’d be ready in an instant, just as you left them.

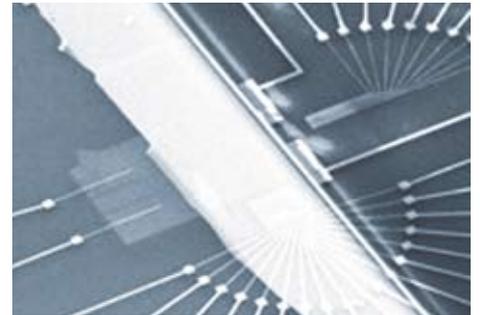
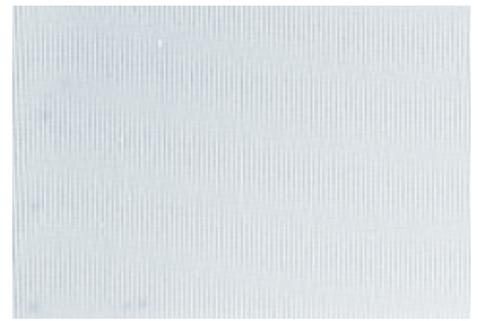


Figure 2: On the left, a memory made from a crossbar array of nanowires, with a thin layer of switchable molecules sandwiched between them. In the close-up on the right, the lower layer of wires running from right to left is just about visible. (Courtesy of James R. Heath, California Institute of Technology)

## The Promise of Nanotubes

Information technology isn’t just about big memories. Computer circuits also have to be able to process information, which again they do today using transistors carved from silicon. But the current carving techniques can’t easily make devices smaller than about 100 nm or so, which is why some researchers think that nanotechnology could enable further miniaturization by letting the devices be built from the bottom up – from atoms and molecules – instead of making them by top-down engraving of silicon. One of the most promising approaches is to make transistors from objects called carbon nanotubes, which are tubes of pure carbon just a few nanometres across, with walls one atom thick. Each nanotube is basically a single tubular molecule, and some of them are semiconducting, like silicon – which means they can be used to make electronic devices such as transistors that are much narrower than those currently made from silicon (Figure 3). The challenge now is to ensure that nanotube transistors are reliable and robust enough for use in commercial circuits, and to arrange them just how we want them.

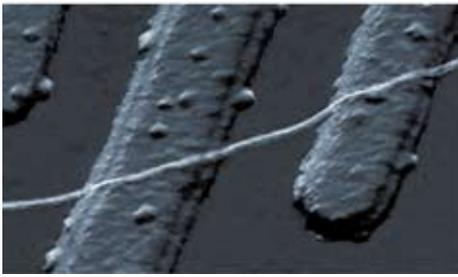


Figure 3: A transistor made from a single carbon nanotube (blue). (Courtesy of Cees Dekker, Delft University of Technology)

Carbon nanotubes are also remarkably stiff and strong – in effect, they are the ultimate carbon fiber. They are already being used as stiffeners, replacing conventional carbon fibers in products such as tennis rackets and golf clubs, although they remain expensive to make. And they could supply the ideal “girders” for building nanoscale structures and machines: for example, nanotubes with walls made of several concentric layers can act as sleeve-and-axle bearings for rotors, or as extendable nanoscale arms that will lengthen like telescopes. Ultrafine needles made from nanotubes can puncture cell walls without damaging them to deliver drugs

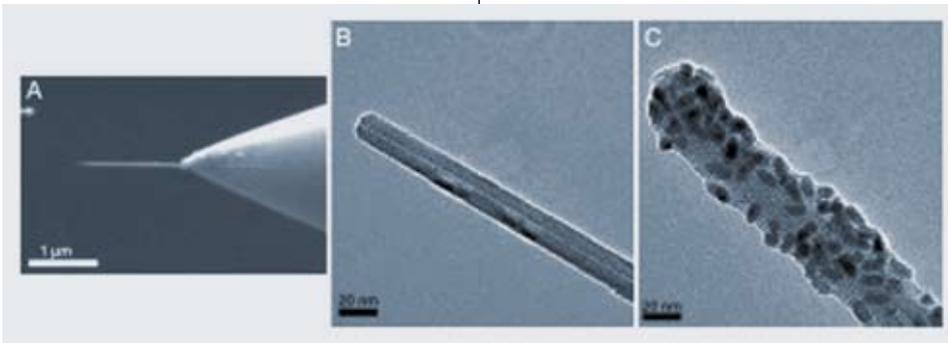


Figure 4: A carbon nanotube nanoinjector. A. The nanotube attached to a needle tip. B. A close-up of the nanotube, showing its concentric layers. C. The nanotube coated with nanoparticles for injecting into a cell. (Source: From X. Chen et al., *Proc. Natl Acad. Sci. USA* 104, 8218-8222 [2007]. Copyright National Academy of Sciences, 2007.)

### Illuminating Molecules

Medical science is expected to be another of the main beneficiaries of nanoscience and nanotechnology. Nanoparticles have been developed by Chad Mirkin and his colleagues at Northwestern University in Illinois to serve in highly sensitive detection systems for particular kinds of DNA or proteins – for example, to look for specific genes in a patient’s blood. The metal nanoparticles have surfaces coated with molecules that latch onto the biomolecules being studied, which binds the nanoparticles into clusters. These clusters scatter light, rather like the grains of silver in an exposed photographic film, and so a solution of nanoparticles changes color or darkens, offering a quick and convenient “readout” for diagnosing the presence of the biomolecules. The Northwestern researchers have used this method to produce commercially available biosensor devices.

Nanoscience pioneer Jim Heath, a member of the Kavli Nanoscience Institute at the California Institute of Technology, believes that arrays of nanowires like those used in the “crossbar” memory device

above can also serve as highly sensitive biosensors, since their electrical conductivity may change when biomolecules become stuck to their surface. These arrays can be made small enough to examine the contents of individual cells, and they might detect substances such as proteins that signal cancer at far lower concentrations than is currently possible. This would allow incipient cancers to be detected much sooner, making their treatment more likely to succeed.

Some of the tools that have been developed for manipulating and investigating objects at the nanoscale have become immensely valuable for studying the “nanomechanics” of living systems. The atomic force microscope, a relative of the STM in which

a needle tip is used to measure forces acting at the nano- and molecular scales, has been used to study how individual biomolecules change shape – for example, when a single protein (a chainlike molecule) is pulled out from its normal, crumpled-up shape into a stretched-out strand. This can provide understanding of how proteins take on the highly specific shapes that are crucial to their biological function, or how biomaterials made from proteins, such as elastic tissues, muscle or silk, achieve their resilience. Another valuable tool for biomolecular nanoscience is a technique called laser trapping (or optical tweezers), in which nanoscale objects are “held” by intense, finely focused laser beams. Because of an interaction between the object’s electron clouds and the strong electromagnetic field of the light, the object gets pulled towards the brightest part of the laser spot. This supplies a way of dragging molecules and nanoparticles around, and has even been used to tie a knot in the long-chain protein actin by using optical tweezers to tug on two microscopic beads at each end (Figure 5).



Figure 5: Tying a knot in the protein actin. By using optical tweezers to manipulate the ends of the molecule, the chain is curled into a hoop and threaded on itself. (Source: Y. Arai et al., *Nature* 399, 446 [1999], used by permission of the author.)

### Unraveling the Fabric of Life

One of the most dramatic conjunctions of nanoscience and biology comes from the realization that the fabric of life – DNA – is also an ideal material for nanoengineers. DNA is a long, chainlike molecule that encodes genetic information in its chemical structure, and this enables two molecular strands to stick together in the famous double helix – the sticking secure only if the information on one strand “matches” that on the other. So techniques for making DNA artificially, with arbitrary sequences of information in a strand, can

be used to program specific strands to stick together in complex shapes. Using this idea, researchers have made nanoscale objects such as cubes and other geometric cages from DNA, as well as grids and ladders. Paul Rothemund at the California Institute of Technology has invented a scheme for programming DNA strands to assemble themselves into just about any flat shape you like, from smiley faces to maps of the world, all measuring just a few nanometers across (Figure 6). DNA tags could also be attached to other nanoscale objects so that they can assemble themselves into organized structures such as electronic circuits.

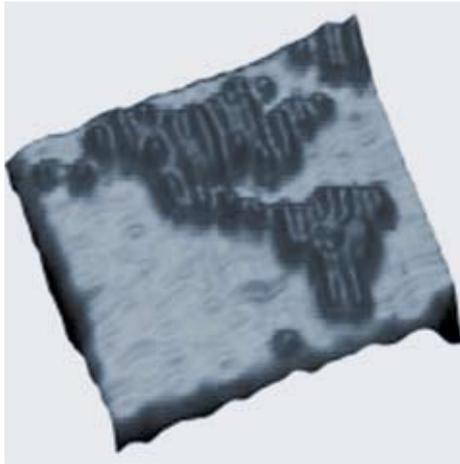


Figure 6: Nanoscale map made from folded strands of DNA. (Courtesy of Paul Rothemund, California Institute of Technology)

This shows how nanotechnology can profit from exploiting some of the tricks that biology uses for making living organisms – in particular, using self-assembly of “programmed” molecules to create structures that are far more complicated than those we could hope to make “by hand.” These tricks might ultimately provide nanotechnological devices and structures that make copies of themselves (replicate), pass on information and perhaps qualify as genuinely living things.

This might sound alarming, and it’s true that such possibilities carry dangers and ethical responsibilities, along with great promise. At this stage, however, the principal potential dangers of nanotechnology hinge more on the question of whether nanoparticles could pose health risks if they get into the body. Their chemical behavior can be quite different from that of larger chunks of the same substance, so we can’t assume that what’s non-toxic

at the everyday scale remains safe at the nanoscale. We don’t yet know enough about such risks, or about how nanoparticles might be transported around the body or the environment. This is now an active area of nanotech research and it’s a priority to find out more, although the initial indications are there is no urgent cause of alarm about nanoparticle toxicity.

Like any new technology, nanotech offers both benefits and risks. But the balance probably depends much more on how we elect to use it, than on anything intrinsic to the technology itself. The choice, in other words, is ours.

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#### Further reading

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*Understanding Nanotechnology – a collection of articles from Scientific American*. Warner, 2002.

# NEUROSCIENCE

**One of the strangest and most wondrous things in the universe is the wrinkled lump in every person's head: the human brain. Weighing about three pounds for the average adult, within the brain are 100 billion neurons that give us the ability to see, smell and move, as well as think, weep, talk and read. Furthermore, all we experience and remember – in essence, every little thing that makes us who we are – is rooted in the neocortex, the seat of the “thinking” brain.**

Understanding how such a miracle is possible is the vast mission of the relatively young field of neuroscience.

In the past few decades, researchers have learned much about the fundamental workings of the brain, with tremendous gains in knowledge about the molecules that make it run. Scientists identified genes for receptor proteins that detect smell and taste. They determined that the stuff of memories is, literally, a cascade of biochemical changes at the connections, or synapses, between neurons. And belying an old view that the nervous system is hardwired from birth, experts found that its cells retain some capacity to adapt and reorganize in response to experience.

Now armed with the human genome and a combination of cutting-edge genetic methods and brain imaging techniques, lab scientists are exploring the neural circuitry of living animals in ways they could likely have never dreamed of 20 years ago. Rather than scrutinizing one or two neurons at a time, they aim to study how networks or systems of the cells function to influence behavior. Such efforts promise to bridge the gap between studies of the cognitive powers of the mind – traditionally the turf of psychologists and linguists – and investigations of the physical brain by neurobiologists.

“We’re at the point now... where we can put together these two disciplines and understand the mind in terms of the operations of the nerve cells in the brain,” says Nicholas Spitzer, co-director of the Kavli Institute of Brain and Mind at the University of California, San Diego.

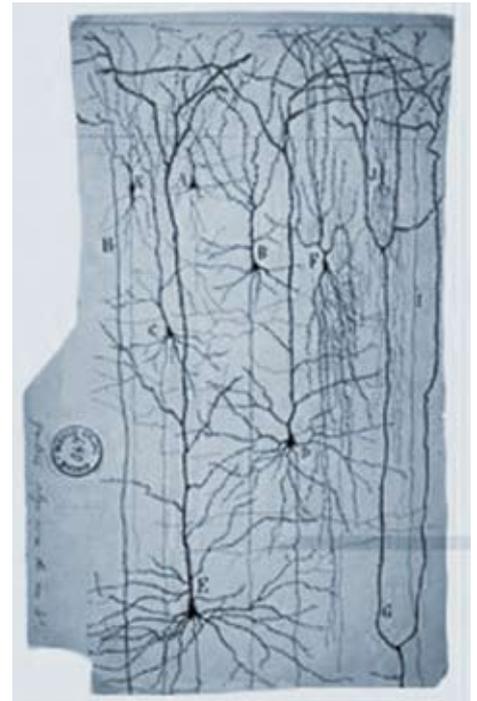
Truly fathoming how the whole nervous system functions will ultimately require building powerful computer simulations that can predict the behavior of millions to billions of neurons working together. The budding subspecialty of computational neurobiology is thus “a hugely important domain for the future,” says David Van Essen, president of the Society for Neuroscience and a researcher at Washington University in St. Louis, Missouri.

Researchers will no doubt be busy for years to come before they can pull together a unifying theory that explains the miracle of the brain. But step-by-step, they’re making headway in many areas, including these developments on several fascinating fronts.

## Mapping the Neural Wilderness

Neuroscientists need a diagram of the brain’s internal wiring, but mapping neural circuits isn’t easy. The human neocortex houses dozens of types of neurons, all intimately intertwined. Each nerve cell is like a tree, with a head of fine branches – known as dendrites – that receive messages from several hundred to thousands of neighbors, and with a complex array of roots that pass the signals on to other cells across synapses. Small wonder that 1906 Nobel laureate Santiago Ramon y Cajal famously described the cerebral cortex as an “impenetrable jungle.” But modern-day researchers can finally see how to survey that wilderness, with some nifty genetic tools.

“We still have to hack through some vines here and there, but we have sharper machetes now,” says neuroscientist Edward Callaway of the Salk Institute for Biological Studies in La Jolla, California. He and colleagues have invented a method that should make it possible for the first time to pick any cell in the cortex of a lab animal and then label “every single neuron in the brain that connects to exactly that one cell,” he says.



*Figure 1. Early image of stained pyramidal neurons by 1906 Nobel laureate Santiago Ramon y Cajal.*

Using a clever set of genetic tricks, Callaway’s team modified a rabies virus so that it can invade only a brain cell of a pre-selected type and move across its synapses to infiltrate all cells linked to it. But the microbe is prevented from then

spreading further. Because the virus is also engineered to produce green fluorescent protein, the scientists can see under a microscope all the glowing-green neighbors that the original brain cell (or group of cells) directly talks to.

In addition, neuroscientists are mastering the art of turning neurons on and off, which will also help with tracing circuits. The standard means of activating nerve cells is to gently zap them with an electrode, but that stimulates all cells in the area. Research labs have devised a number of ingenious ways of genetically introducing molecular switches into neurons that can control their activity more precisely. Lately, neuroscience circles have been abuzz over one new breakthrough technique in particular: photo-sensitive proteins, called channelrhodopsin-2 and halorhodopsin, that can trigger neurons to respectively fire or shut down within milliseconds when exposed to light.

Stanford University investigators and their collaborators created transgenic mice that produce channelrhodopsin throughout their brains, without ill effect. The researchers quickly scanned with blue light over huge regions of an anesthetized rodent's exposed brain; then, using electrodes, they monitored responses triggered in other areas. With this strategy, says Stanford bioengineer and psychiatrist Karl Deisseroth, scientists "can start to map circuitry much faster than you could before." In this case, they examined a key neural pathway involved in processing smells.

In another study, Deisseroth's team applied the method less intrusively by sending blue light through a very thin optical fiber inserted into the cortex of a lightly sedated mouse. The light pulses turned on certain motor neurons (which were engineered to carry channelrhodopsin), causing the animal's whiskers to twitch. In the future, Deisseroth would like to study brain cell types that might be overactive or underactive in depression and autism.

Similarly, neuroscientist Karel Svoboda and colleagues at Cold Spring Harbor Laboratory in New York, and the Howard Hughes Medical Institute's Janelia Farm campus in Ashburn, Virginia, have used channelrhodopsin to trace the long neurons that link the two sides of the mammalian brain through the structure known

as the corpus callosum. By turning on or off parts of a neural loop and watching what happens, researchers hope to learn how specific complex circuits influence an animal's behavior. The light-activated methods, Svoboda says, "will make a new kind of neurobiology possible."

### Tracing the Deep History of the Brain

Approximately two million years ago, the brain capacity of our ancient forebears began greatly increasing, eventually culminating in a brain that today is roughly three times larger than that of a chimpanzee, our closest evolutionary cousin. How that transformation happened, and how we acquired our impressive cognitive abilities, is a mystery that touches on the core of what made us human. Lately, scientists have been gleaning fresh clues from studying genetic data troves and the anatomy of primate brains at the cellular, molecular and genetic levels.

Using computer algorithms, researchers have compared the whole genomes of humans, chimps, rodents and other animals, and identified several hundred regions containing DNA differences that may have played a role in human evolution. Because periodically arising genetic changes are what drive evolution, our DNA is a historical record of deep ancestral secrets.

For instance, biologists at the University of California, Santa Cruz have identified 202 human DNA segments that underwent rapid changes in the 6 to 7 million years since the human and chimp lineages diverged from a common ancestor. Most of those regions aren't genes that code for proteins; instead, they are sequences that appear to regulate when or where certain genes turn on in the body – and some of those genes may be involved in neuro-development.

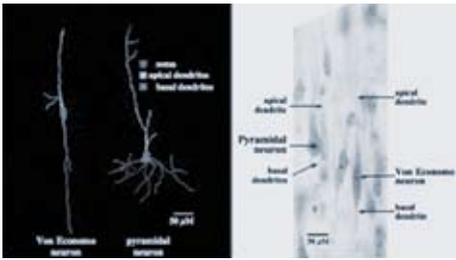
In lab experiments, the research team found that one DNA region, named HARI, is active in Cajal-Retzius neurons, which organize the initial formation of the neocortex. Although that discovery is exciting, the scientists have much to learn about HARI's function in the brain before reaching any conclusion about its potential role in human evolution, says computational biologist Katherine Pollard, who now works at the University of California,

Davis.

Indeed, understanding the early development of the cerebral cortex is another important source of information for deciphering possible mechanisms of how evolution built a bigger and more intricate brain. "We want to figure out how it was done, and the secret is in individual cells, in how they behave during embryonic development," says Pasko Rakic, director of the Kavli Institute for Neuroscience at Yale University. Working at the molecular and genetic level, his lab has been studying how neurons born deep inside the brain, including Cajal-Retzius and pyramidal cells, know exactly where to go as they migrate upward to form the six layers of the neocortex.

Everyone thought the Cajal-Retzius cells were the earliest neurons of the cortex, but Rakic and his colleagues reported last summer that a previously unrecognized type of brain cell emerges even sooner, in 31-day-old human embryos. Rakic hypothesizes that these "predecessor neurons" also guide the organization of the cortex and instruct other precursor cells how much to multiply. The scientists didn't observe the predecessor cells in rodents and are now planning to search for and study them in monkeys.

So far, very little is known about how neuroanatomy differs between people and other primates. But neuroscientists have found that the brains of great apes – which includes humans, chimps and gorillas – evolved a completely new kind of neuron that is absent in monkeys and baboons. More plentiful in people than chimps, these large spindle-shaped cells (called Von Economo neurons) lie in only two locations of the cortex that appear to play a role in social cognitive functioning. Patients with a dementia that destroys these neurons often behave in socially inappropriate ways, says neurobiologist John Allman of the California Institute of Technology in Pasadena.



*Figure 2. Large, spindle-shaped Von Economo neurons have a simple arrangement of two dendrites extending from the top and bottom of the cell body (soma) – unlike the more complex pyramidal neurons of the cortex. Scientists theorize the spindle cells are part of the human brain circuitry involved in social awareness. (Courtesy of John Allman)*

Meanwhile, while it is relatively straightforward to identify potential genes underlying human brain evolution, the difficult next step is comparing what those genes actually do in people versus other primates, says neuroscientist Todd Preuss of the Yerkes National Primate Research Center at Emory University in Atlanta. Preuss and his associates are investigating a gene that codes for a protein named thrombospondin 4, which seems to spur neurons into building new synapses. Analyses of gene expression patterns in brain tissue samples revealed that the human cortex makes six times as much of the protein than the chimp brain does. Other experiments have detected the extra thrombospondin in human brains clustering in the spaces where a neuron's synapses lie. Preuss speculates that our neurons are sculpting and resculpting connections at a faster rate than brain cells in our closest evolutionary relatives do. All of this supports neuroscientists' view that the extraordinary talents of the human brain don't arise merely from its bigness; there's something special about the way it's wired.

### **From Molecules to Memory**

Without the brain's knack for remembering, you would have no learning and no autobiography, crafting who you become. Our memories are what make us each unique, says neurobiologist Roger Nicoll of the University of California, San Francisco. "What identifies you is nothing other than storage of events and places and people." Fifty years ago, psychologists reported that

an epilepsy patient, H.M., could no longer make new memories after surgeons removed part of his brain, including the hippocampus. Since then, neuroscientists have detailed the basic, initial biochemical steps that convert perceptions of the world into permanent recollections of facts and occurrences. "It's absolutely incredible how far we've come," says Nicoll.

The main action happens at the connections between neurons. In the first hour of memory formation, neurotransmitters are released, receptors congregate and the signals that cross the synapse are boosted. Most scientists believe that ultimately, it is an overall persistent strengthening of synaptic activity that lays down a long-term memory.

Support for that idea comes from a decades-old observation that, when hippocampal cells are rapidly bombarded with electrical zaps, neurons on the receiving end of the stimulated cells' synapses respond with a long-lasting jump in firing activity. But the theory that this so-called long-term potentiation (LTP) underlies real-life memory encoding has been tough to prove.

Last year, however, two separate research labs finally reported detecting LTP in learning rodents. Other intriguing news came from SUNY Downstate Medical Center in Brooklyn, New York. Researchers there suspect that an enzyme called protein kinase Mzeta helps to maintain LTP after the first hour, so that long-term remembrance can be forged. And in fact, in a startling experiment, when they blocked that enzyme in the hippocampi of rats, the animals' LTP activity in response to electrical stimulation disappeared – and the rats forgot an electric shock-avoiding behavior they had just learned a day or even a month before. "The memory was erased and, as far as we could tell, never came back," says Downstate neurologist Todd Sacktor.

Like Sacktor, many scientists are now focusing on later stages of memory formation. In people, as years pass, the hippocampus is apparently no longer needed to sustain a recollection, which instead becomes embedded in neurons distributed across the neocortex. Scientists know little about this consolidation process. Studies of patients with brain damage have conflicted over whether lesions in the hippo-

campus wipe out recent memories but spare old ones – or completely empty the memory banks.

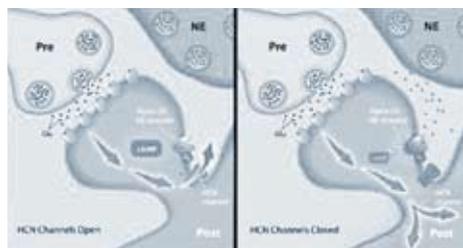
A recent careful analysis of eight amnesia patients by Larry Squire, a neuroscientist at the University of California, San Diego and the Veterans Affairs San Diego Medical Center, helps clarify the issue. If damage is only within the hippocampus, Squire and colleagues determined, patients had trouble recalling events from the past five years, but older memories survived. With bigger lesions stretching into nearby brain areas, the amnesia extended back 30 to 50 years – yet early childhood memories remained. That supports the notion that the hippocampus and adjacent structures are not lasting repositories of memory, Squire says.

However, if the damage reaches into the lateral temporal lobe, then even the oldest autobiographical memories vanish, suggesting this brain area is essential to the permanent storing of memories. Squire is further exploring the consolidation process by temporarily inactivating the hippocampus in rats – with the anesthetic lidocaine – at different times points after learning.

On another front, neurobiologists are unraveling the molecular underpinnings of working memory, the mental scratchpad that makes it possible to retain a phone number long enough to dial it. Working memory depends on a network of cells, housed in the brain's prefrontal cortex, that all trigger each other to fire persistently to hold onto that number. Recent research has shown that certain molecules, called HCN channels, control whether this neural network is functioning. The channels are like tiny gates in a neuron's cell membrane that let charged molecules flow through.

When the channels are open, they weaken the ability of a neuron to receive information from other cells, and thus disconnect the circuit, says Amy Arnsten, a neurobiologist at the Kavli Institute of Neuroscience at Yale. But in monkey experiments, various drugs that shut down the HCN channels enhanced the network's activity. One such drug, a blood-pressure medication called guanfacine, improved the performance of rats as they used working memory to navigate a maze. Arnsten is now working with a pharmaceutical

firm to develop the drug for treating attention deficit hyperactivity disorder.



**Figure 3.** A model illustrating how HCN channels on PFC spines can gate information coming into the neuron based on the level of cAMP in the spine compartment. Under conditions of high cAMP production, the open probability of HCN channels is increased, and incoming information would be shunted due to reduced membrane resistance. When cAMP production is inhibited by  $\alpha$ A adrenoceptor stimulation near the HCN channels, the channels close and allow information to pass into the cell. (Courtesy of Amy Arnsten, Yale University)

### The Inexplicable Lightness of Being

Some of life's secrets seem so amorphous and incomprehensible as to defy any attempt at inquiry. Such is the great riddle of consciousness. Where does it come from? How can electrical buzzings of physical brain cells produce nonphysical sensations of pain or the emotion of savoring the redness of a rose? What accounts for the conscious and the inherently private state of being you?

Although it is obvious to researchers that consciousness arises from the brain, for many years the "C word" was not to be mentioned in respectable scientific company because it seemed too subjective to study. In the 1990s, however, Nobel laureates Gerald Edelman and the late Francis Crick began pushing for serious biological investigations. Crick and Caltech neuroscientist Christof Koch argued the problem could be tackled by breaking it down into smaller research questions.

One intriguing approach has been to ask how the mind becomes conscious of certain information while apparently ignoring other stimuli that bombard the senses. For instance, it's well known that if one of your eyes is presented with a photo of, say, a house while the other eye sees a photo of a face, the two images do not blend. You

alternately perceive only either picture for a few seconds each – even as each retina "sees" the same image all the while. A similar effect happens while gazing with both eyes at an outline of a 3-D cube, which flips between facing leftward and rightward. Such optical illusions are called bistable visual patterns.

In numerous experiments with monkeys (or epilepsy patients undergoing neurosurgery), scientists have inserted electrodes to monitor the brain's responses to a bistable image. Neural areas that initially process visual data fire constantly, showing no differences when conscious perception shifts from one image to the other. But something interesting happens in the



**Figure 4.** In the Eye of the Beholder Optical illusions are a useful tool for investigating the neural mechanisms that govern aspects of perception and consciousness as a viewer sees and interprets an image in different ways. For instance, the Necker cube, Schroeder staircase, and folded card (panel A) can each be perceived as having two separate 3-D orientations. In a phenomenon known as binocular rivalry, if a different picture (panel B) is presented to each of your eyes, you will alternately perceive either the face or the checkerboard, not a fusion of both. (Adapted with permission from Elsevier, Leopold D.A. and Logothetis N.K. [1999] *Trends in Cognitive Sciences*, 3, pp. 254-264)

higher visual processing regions. When perception switches, roughly half the neurons in the middle temporal area – and nearly all neurons in the inferotemporal cortex – display changes in activity, says David Leopold, a neurophysiologist at the National Institute of Mental Health in Bethesda, Maryland.

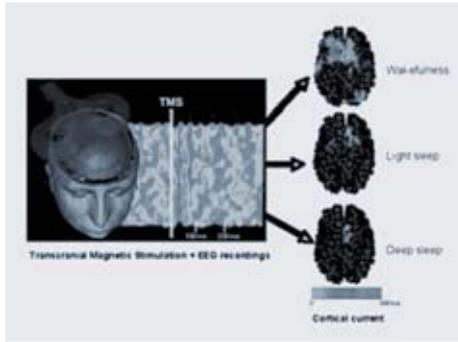
Such findings supported the idea that a subset of brain cells – which Crick and Koch called "neuronal correlates of consciousness" – are specialized to relay selective visual signals to the mind's awareness. But a follow-up report in 2007 by Leopold and associates at the Max Planck Institute in Germany challenges that notion. They monitored middle-temporal neurons in two monkeys that viewed four different bistable patterns. Disappointingly, says Leopold, there was no single fixed subset of brain cells that responded as the monkeys' perceptions oscillated for each pattern. Rather, across all four visual stimuli, 70 to 90 percent of the neurons modulated during at least one perceptual shift. In each situation, he says, vetoing one image in favor of allowing another image to reach conscious awareness requires that a network of visual areas react in a different way.

Opinions still differ over whether the results detract from the theory of neuronal correlates of consciousness. Either way, scientists need a stronger understanding of how different visual areas work together in forming perceptions, Leopold says.

A different tack for exploring consciousness is through sleep studies. Neurons are active during slumber, yet if you are roused from an early, dreamless stage of sleep, not much is on your mind, says neuroscientist and psychiatrist Giulio Tononi of the University of Wisconsin in Madison. Somehow, consciousness has faded.

To investigate why, Tononi and colleagues used magnetic pulses to stimulate the brains of awake or dozing human volunteers, and then tracked the resulting electrical activity. During dreamless snoozing, neural signals didn't jump from one region to the next like they did during wakefulness. "The various brain areas can't really talk to each other effectively," says Tononi. But consciousness returns in the form of dreams, especially during REM sleep, he says, and preliminary data indicates that then the connectivity patterns are more similar to those of an awake mind.

The studies are helping Tononi fine-tune a theory that views consciousness as an integrated system of information, with parts of the cortex and underlying thalamus ideally suited for managing the integration. Although overall progress in the field is slow, he says, a growing number of scientists are now using the best neuroscientific tools to ask questions about consciousness. And that in itself, he says, is a big leap forward.



*Figure 5: When the Brain Takes a Break. Using transcranial magnetic stimulation, researchers can apply magnetic pulses to the brain (left panel) and then use EEG recordings to monitor electrical activity across the cerebral cortex). University of Wisconsin investigators observe neural signals jumping across the cortex during wakefulness (right panel, top). But that connectivity appears to break down with deepening sleep (right panel, middle and bottom), as consciousness fades. (Courtesy of Giulio Tononi)*

## About The Kavli Foundation

The Kavli Foundation, based in Oxnard, California, is dedicated to the goals of advancing science for the benefit of humanity and promoting increased public understanding and support for scientists and their work.

The Foundation's mission is implemented through an international program of research institutes, professorships, and symposia in the fields of astrophysics, nanoscience, neuroscience and theoretical physics as well as prizes in the fields of astrophysics, nanoscience and neuroscience.

The Kavli Foundation was established in December 2000 by its founder and benefactor, Fred Kavli, a prominent California business leader and noted philanthropist whose foundation is currently actively involved in establishing major research institutes at leading universities throughout the United States, in Europe and China, the Kavli Institutes.

To date, The Kavli Foundation has made grants to establish Kavli Institutes on the campuses of the University of California, Santa Barbara, Stanford University, the California Institute of Technology, the University of Chicago, Columbia University, Yale University, Cornell University, the University of California, San Diego, Delft University of Technology in the Netherlands, the Massachusetts Institute of Technology, Peking University, the Chinese Academy of Sciences, Harvard University, the University of Cambridge in England and the Norwegian University of Science and Technology.

In addition to the Kavli Institutes, six professorships have been established; two at the University of California, Santa Barbara, one at University of California, Irvine, one at Columbia University, and one at California Institute of Technology.

## About Fred Kavli

Fred Kavli is a Norwegian-born physicist, entrepreneur and business-leader, innovator and philanthropist who is dedicated to supporting research and education that has a positive long-term impact on the human condition.

Mr. Kavli received his education in physics at the Norwegian Institute of Technology. Immediately upon completing his studies in 1955, he left for Canada and after one year he came to the United States. After two years in California he founded the Kavlico Corporation in Los Angeles, later located in Moorpark, California. Under his leadership, the company became one of the world's largest suppliers of sensors for aeronautic, automotive and industrial applications. The company received many distinguished awards, and Mr. Kavli patented numerous technological breakthroughs. He remained CEO and sole shareholder of the company until he divested his interest in 2000.

He subsequently established The Kavli Foundation and The Kavli Operating Institute (now merged with The Kavli Foundation) to support scientific research aimed at improving the quality of life for people around the world. The Foundation has established research institutes at leading universities worldwide and will give prizes to promote and recognize excellence in research focusing on cosmology, neuroscience and nanoscience.

Mr. Kavli has endowed two chairs in engineering at the University of California, Santa Barbara - the Fred Kavli Chair in MEMS Technology and the Chair in Optoelectronics and Sensors. Through the Foundation, he has also endowed chairs in Earth Systems Sciences at the University of California, Irvine, in Nano-systems Sciences at University of California, Los Angeles, and Theoretical Physics at the California Institute of Technology.

Mr. Kavli and the Foundation are sponsoring research institutes at leading universities worldwide.

Mr. Kavli was elected a Fellow of the American Academy of Arts and Sciences, is a member of the U.S. President's Council of Advisors on Science and Technology, the Norwegian Academy of Technological Sciences, and the University of California President's Board on Science and Innovation, and is a Trustee of the University of California Santa Barbara Foundation. He is awarded the Royal Norwegian Order of Merit for Outstanding Service. In addition, he is a Distinguished Grand Patron of the Alliance for the Arts, which has named the Fred Kavli Theatre for the Performing Arts at Thousand Oaks Civic Arts Plaza in his honor.

## Nomination and Selection of the Kavli Laureates

The Norwegian Academy of Science and Letters appoints three Prize Committees consisting of leading international scientists. These distinguished panels of international scientists will review and recommend the prize winners on basis of a nomination process.

Nominations of candidates for The Kavli Prizes should be submitted to the Norwegian Academy of Science and Letters using a nomination form obtained from The Kavli Prize website (<http://www.kavliprize.no>). The nomination process is open to all potential candidates, with the exception that self-nominations are not allowed.

The Norwegian Academy of Science and Letters appoints the Prize Committees after receiving recommendations made by the following international academies and equivalent scientific organisations:

- *The Chinese Academy of Sciences*
- *The French Academy of Sciences*
- *The Max Planck Society (Germany)*
- *The National Academy of Sciences (US)*
- *The Norwegian Academy of Science and Letters*
- *The Royal Society (UK)*

The Norwegian Academy of Science and Letters will administer the selection process and announce the prize winners.

Additional information about The Kavli Prizes may be obtained from The Kavli Prize website (<http://www.kavliprize.no>).

## The Kavli Prize

Each Kavli Prize will consist of USD 1,000,000, a scroll and a medal for each scientific field.

The Prize was established to:

- Recognise outstanding scientific research
- Honour highly creative scientists
- Promote public understanding of scientists and their work
- Foster international cooperation among scientists

Through a joint venture, the Norwegian Academy of Science and Letters, the Norwegian Ministry of Education and Research, and The Kavli Foundation (based in California) have agreed to jointly sponsor and award The Kavli Prizes.

The Prizes will be awarded at a ceremony in Oslo, Norway, Fred Kavli's native country, every two years, beginning in 2008.

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