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New Directions in Physics

Man's understanding of his universe and his technological abilities to satisfy his needs are undergoing major change because of new discoveries in all branches of physics

The universal and lasting things that man knows about inanimate nature are the body of physics. While much of nature is neither universal nor permanent, generations of physicists have shown that the underlying forces which shape it obey universal laws. Because of such discoveries, what would have appeared complicated or capricious can be seen as essentially simple and, in a deep sense, orderly. This economy of thought, this return always to first causes, is what characterizes physics.

It is worth noting at the outset that physics spans an enormous range in space, in time, and in many of the other dimensions we choose to describe nature. The radius of the universe is close to 10^{40} times the natural unit length, the radius of an elementary particle; the age of the universe is close to 10^{40} times the natural unit of time, the time taken for light to pass over an elementary particle; the mass of the visible universe is close to $(10^{40})^2$ times the mass of one of the simplest elementary particles; and, as we shall note below, the strongest natural force is close to 10^{40} times stronger than the weakest.

A first suspicion that physics is anything but a closed book emerges when we recognize that we have not the slightest idea as yet concerning the origin of this very large number, 10^{40}, which appears again and again; there is a clear implication, however, that nature is trying to tell us something if we can but understand. This is only the first of a very great many such puzzles which remain.

The structure of physics

There is a natural hierarchy within physics. Fundamental to all else is the underlying stratum of space-time; its study is cosmology or relativistic astrophysics. Matter is essential to all our phenomena; elementary particle physics focuses on the most basic aspects of matter and the underlying forces and symmetries of nature. Nuclear physics is the study of atomic nuclei, the complex entities formed by aggregation of elementary particles. At high temperatures, characteristic of much of our universe, assemblages of nuclei can only achieve electrical neutrality through matching of their positive charges with the negative charges of an interacting electron cloud. This by definition is a plasma, and its study, plasma physics. At much lower temperatures, characteristic of the earth, the electrons are captured by individual nuclei to form atoms; these in turn interact with one another to give the rich variety of molecular species on which all chemistry, all biology—and life itself—are based. Atomic and molecular physics addresses the challenging problems posed by this wide spectrum of phenomena. With lowering temperatures the atoms and molecules combine to form first liquids and then solids, the province of condensed matter physics. And having liquids and solids we have all the phenomena of fluid physics, optics, acoustics, and all the classical fields of physics.

Such a listing does not include the vitally important interfaces between physics and other sciences—biophysics, geophysics, astrophysics, chemical physics, and the like. Frequently these interfaces contain the areas of greatest excitement in either of their parent sciences; however, they lie outside the scope of the present paper. In considering the different subfields of physics, we note areas of greatest current interest and activity—those where the future may hold surprises. For reasons that will become obvious, we shall defer consideration of relativistic astrophysics until the end of the paper.

Elementary particle physics

Until the late 1940s life was simple in elementary particle physics. Nuclei were composed of neutrons and protons; to these were added electrons to construct atoms, and it was early learned that isolated neutrons decayed into a proton and an electron (and an antineutrino) with a half-life of about 12 minutes. This left the proton and the electron as the fundamental particles (with the massless photon and neutrino, which were considered somewhat separately). No one had any idea why the proton and electron charges, although opposite in sign, were

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the same in magnitude (now known to be true to 1 part in 10^{20}); nor did anyone know why the proton was roughly 2,000 times more massive than the electron. Nor do we yet! Indeed we have no idea why the electronic charge e has the value it does; conceivably some distant descendant will look back on this ignorance with the same tolerant amusement we now devote to our forebears who deduced the value of π by wrapping string around cylinders.

Already at this stage, however, we were fully familiar with the idea of particles and antiparticles in the case of the positron (antielectron) and the antineutrino. The concept of antiparticles was fully understood within the Dirac theory; perhaps the most important prediction of the theory was that an energy equal to twice the rest mass of the particle in question was required to produce its antiparticle. While this amounted to only about one MeV in the case of the positron and was thus readily available, physics had to wait until 1954 when the Bevatron accelerator was able to provide the 2,000 MeV required to make an antiproton. Since then we have produced not only antiparticles in profusion but also antiatoms of hydrogen and helium, for example. This entire subject of antimatter, while fundamentally very simple, has been vastly confused outside of physics.

The elementary particles. As ever larger accelerators became available during the 1950s and 1960s, ever more "elementary particles" were discovered. Together with their antiparticles, each of which was also produced, they totaled well over a hundred. There were two classes, the leptons and the hadrons. The leptons (*weak* interaction) were the photon, the electron, and the neutrino; to these were added the muon and a new kind of neutrino which bore the same relation to the muon as did the original neutrino to the electron. The muon is roughly 200 times as massive as the electron; otherwise it appears to be precisely identical to the electron. Again no one has the slightest idea why nature needs a heavy electron—or why it needs its own neutrino. New experiments soon to be undertaken at the Los Alamos Meson Physics Facility and at the National Accelerator Laboratory should answer the question of whether there are even heavier electrons. This is a fundamental question for our deeper understanding of the weak nuclear force inasmuch as these leptons interact only through it.

In contrast, the hadrons (*strong* interaction) interact via the strong

Table 1. "Stable" hadrons

Name	*Symbol*	*Electric charge*	*Mag. of Mc* (MeV)	*Spin*	*Parity*	*Isotopic spin*	*Strangeness*
pion	$\pi^\pm$ π^0	$\pm e$ 0	140 135	0	neg.	1	0
K-meson	K^+ K^0	$+e$ 0	494 498	0	neg.	1/2	+1
$\bar{\mathrm{K}}$-meson	K^- $\bar{\mathrm{K}}^0$	$-e$ 0	[a]	[a]	[a]	[a]	−1
nucleon	p n	$+e$ 0	938.3 939.6	1/2	pos.	1/2	0
antinucleon	$\bar{\mathrm{p}}$ $\bar{\mathrm{n}}$	$-e$ 0	[a]	[a]	[a]	[a]	0
lambda	Λ	0	1116	1/2	pos.	0	−1
antilambda	$\bar{\Lambda}$	0	[a]	[a]	[a]	[a]	+1
sigma	$\Sigma^\pm$ Σ^0	$\pm e$ 0	1197 1192	1/2	pos.	1	−1
antisigma	$\bar{\Sigma}^\pm$ $\bar{\Sigma}^0$	$\pm e$ 0	[a]	[a]	[a]	[a]	+1
cascade	Ξ Ξ^0	$-e$ 0	1321 1314	1/2	pos.	1/2	−2
anticascade	$\bar{\Xi}^+$ $\bar{\Xi}^0$	$+e$ 0	[a]	[a]	[a]	[a]	+2
omega minus	Ω^-	$-e$	1672	1/2	pos.	0	−3
antiomega minus	$\bar{\Omega}^+$	$+e$	[a]	[a]	[a]	[a]	+3

[a] Masses and indicated quantum numbers are the same for particle and antiparticle of opposite charge.

nuclear force. Here again there are two subclasses. There are 25 so-called stable hadrons, and a great many more unstable ones which can break up into various combinations of the stable ones. These hadrons, with some of their properties, are listed in Table 1. *Stable* here is a relative word, since the most stable hadron, the pion, lives only about a microsecond. The 25 hadrons range from the neutral pion, with a mass equivalent of 135 MeV, to the omega minus, with a mass equivalent of 1,672 MeV.

The quark hypothesis. This apparent proliferation of "elementary" particles spurred a dedicated search for underlying simplicity—a retreat to a more fundamental understanding. This has culminated in the quark hypothesis. With guidance from group theory it was found possible to group the hadrons into families or multiplets; the mesons (light hadrons) fell into one family, while the baryons (heavy hadrons) fell into another. This classification gained great credibility when its prediction of the characteristics of the Ω^- hadron, the last of the stable hadrons to be discovered, was in spectacular accord with the measured values when it was subsequently found. It was recognized that *all* the hadron characteristics could be reproduced *if* there existed in nature three rather remarkable entities, three types of quarks, which together with their antiparticles, antiquarks, would combine to give the hadrons. Each of the mesons would represent a quark-antiquark complex; each of the baryons would represent a triplet of quarks; and each of the antibaryons, a triplet of antiquarks. The quarks are now labeled as proton, neutron, and lambda quarks and have electrical charges $+\frac{2}{3}\,e$, $-\frac{1}{3}\,e$, and $-{}^{1}{}_{3}\,e$, respectively; the first two have zero strangeness (a new quantum number required to specify the hadron family relationships), while the last has strangeness -1.

Whether the substantial successes of the simple quark model mean that the quarks are real remains to be seen. If they do exist, our concept of the nature of matter will be fundamentally altered. The quarks would become the basic building blocks of nature, and the force between quarks would be the fundamental force of nature. Although as yet we know nothing about it, this force (the superstrong force?) will presumably be much stronger than our present strong nuclear force.

Despite vigorous and imaginative searches throughout the world, the quark remains elusive. The fact that quarks would be the only entities in nature having fractional electric charge implies that once produced they could *not* readily disappear before finding other free quarks. With this, and the possibility of primary production by cosmic radiation in mind, vast quantities of oysters (maybe they concentrate quarks from sea water?), dust from air-conditioning filters (maybe airborne quarks would stick to dust?), and similar materials have undergone extensive mass spectrometric searches for quarks. Large electrified fences have been mounted to sweep quarks, if present, from passing breezes. All these searches thus far have failed.

So also have the more orthodox searches using our largest accelerators. It may well be that quarks are simply so massive that we lack adequate energy to produce a quark or a quark-antiquark pair. At first sight this may seem to contradict the three quarks postulated as being inside a proton. But if the forces that bind them are superstrong, it is quite possible for three massive entities to be bound together to form a much less massive product; the apparently missing mass simply has been converted into a very large amount of binding energy.

The search goes on. Measurements on the deep inelastic scattering of very high energy electrons from the Stanford Linear Accelerator (SLAC) from protons have produced data which can be interpreted as scattering from three heavy-point charges within the proton. This is very reminiscent of the original Rutherford alpha-particle scattering measurements, which located the heavy point-like nucleus in the atom. Because of the extremely fundamental nature of the questions asked, this search will be pushed in future. New studies, scattering polarized electrons off polarized protons, are underway at SLAC; newer higher energy studies are in progress at the National Accelerator Laboratory.

The coalescence of natural forces. One of the most exciting recent areas of theoretical work in particle physics has been on the relationship between the weak nuclear and the electromagnetic forces. There are strong suggestions that these may, in fact, be only two aspects of a more fundamental underlying natural force. Such a coalescence of two of our four existing forces (gravitational, electromagnetic, weak nuclear, strong nuclear) would again represent a major triumph and a vast simplification of our understanding of nature. These new insights are being pushed vigorously in centers around the world in the hope of uncovering this more fundamental "parent" force; there is even a suggestion that a third of our four forces, the strong nuclear force, may be included as yet another facet of this "parent."

The symmetries of nature. Basic to our understanding of the nature of our universe are the concepts of symmetry. In physics these are embodied in such concepts as parity P, charge conjugation C, and time reversal T. Until 1956, generations of physicists had accepted the belief that if laws of nature were obtained by refining hypotheses deduced from direct observations on an experimental system, then the *same* laws would emerge if one observed the system via a mirror. In short, at a fundamental level, we believed that nature had no handedness—there was no preference in any elementary process for a left- or right-handed system. Formally this was embodied in the conservation of parity. From a puzzle originating in elementary particle physics experiments, a brilliant suggestion from elementary particle theorists, and an elegant nuclear physics experiment, it emerged, in 1956, that the weak nuclear interaction did *not* conserve parity. Under the appropriate conditions it readily distinguished between right- and left-handed systems. This downfall of a cherished conservation law shook physics and forced a healthy reexamination of other fundamentals.

It was quickly established that if,

at the same time, one switched from direct to mirror observation, one changed each particle in the system to its antiparticle (charge conjugation C). It appeared that physical laws *were* invariant under the combined change—CP invariance. This was gratifying inasmuch as the requirements of special relativistic invariance, combined with what we know of quantum theory, guarantee that *all* physical phenomena must remain invariant under simultaneous parity, charge conjugation, and time reversal. This is the CPT theorem, one of the most fundamental in physics. And physicists have always believed that elementary processes were invariant under time reversal; that is, in elementary processes, as in the collision of two isolated billiard balls, it would be *impossible* to tell whether a movie film of the event were being run forward or backward.

It was thus with some consternation that measurements on the decay of neutral kaons were found to show incontrovertible evidence for violation of CP invariance. Taken together with the CPT theorem, this would require that T invariance also is violated. Direct search for T invariance violation in weak nuclear interactions has thus far failed. This remains an extremely important open question on which much effort will be expended in the next few years. It could well signal a breakdown of our concepts of space-time at very small distances *or* the existence of yet another force of nature—a superweak force—that is much weaker than the normal weak nuclear force but which clearly distinguishes between the directions of time flow.

Applications. It might appear that these interests are very far removed indeed from the concerns of the average citizen. Somewhat paradoxically, however, as we probe ever smaller dimensions we require larger and more sophisticated instruments. The two-mile length of the Stanford Linear Accelerator and the four-mile circumference of the National Accelerator are clear examples. More important, however, is the fact that, in developing each new instrument of this class, technology is pushed to its limits. The consequences for applications are frequent, and we choose a single example from a wide variety of possibilities. In order to produce very thin-walled targets and detectors, it has been necessary to develop new super-tough plastic films which can be used in a very small, inexpensive ($15) artificial kidney. This is in striking contrast to the cumbersome, scarce, and very expensive (hundreds of thousands of dollars) earlier artificial kidneys which could be made available to save the lives of only a relative few of the thousands of kidney disease victims each year.

Nuclear physics

New precision. In recent years, with new detectors, new accelerators, and new data-handling techniques, nuclear measurements are between ten and one hundred times more precise than was ever possible previously. At the same time there has been a great increase in our understanding of nuclear structure and dynamics, and in consequence it has become possible to frame much more significant questions with a reasonable hope of quantitative answer.

The nuclear domain. In all of nature there are only 300 stable isotopes; in the past two decades some 1,300 additional species have been produced artificially, making a total of 1,600. But this is only a very small fraction of those which we know to be stable against immediate decay. In the cases of calcium, tin, and uranium, we can predict that there are 39, 84, and 107 of these isotopes; thus far we know only 12, 25, and 14 of them, respectively. We know, too, that in collisions between a uranium target and a 2,000 MeV uranium beam, some 6,000 different nuclear species will be produced. We shall return to these below.

With increasing knowledge of nuclear phenomena, we can now predict, too, the existence of entirely new elements of very high nuclear charge. With the recent demonstration that plutonium occurs in nature, the natural elements run from a proton number of 1 to 94; during the past two decades work in the United States and in the USSR has led to identification of elements having proton numbers up to 105, with the possibility of 107. In going from 94 to 105 or 107, the production difficulty increases enormously, and the lifetime decreases markedly to values of microseconds and less. But detailed studies on nuclei in the lead region have allowed extrapolation to predict that proton numbers 114 and 126—perhaps 164—could have lifetimes, once produced, measured in tens if not thousands of years. These would be truly man-made elements inasmuch as there are no known natural processes which could produce them. The same calculations which predict that these new species could be stable also predict that when fissioned they will yield three times as many neutrons as uranium or plutonium and thus have very much smaller critical masses. This has focused considerable attention on these new species as possible energy sources. Even if they are found to exist, however, the cost of production in any way now envisaged would appear to be totally prohibitive for this purpose. On the other hand, these supertransuranic species represent a treasure trove of new physics and chemistry, and it is not surprising that they are the focus of a brisk international race.

Shell model phenomena. The recent high-precision studies in the lead region have also demonstrated that the long-held shell-model ideas, in which neutrons and protons move in well-defined orbits relative to the nuclear centroid, have remarkable validity. Whole new classes of nuclear excitation have been discovered in which these simple particle orbits are coupled not to an inert nuclear core but rather to a core excited into quadrupole or octupole—or higher—vibrations. In many instances, paired neutrons or protons, entirely analogous to the paired electrons in superconducting metals, lead to "superconducting" nuclear systems. The pairs also move in independent orbits relative to nuclear cores, just as do the individual particles; most recently, new classes of nuclear states have been found in which four nucleons move together in orbits relative to the core. From detailed high-precision studies, in which neutrons, protons, or groups of nucleons are added to or subtracted from target nuclei in nuclear reactions, it has been possible to develop a quantitative understanding of the structure of at least the low energy quantum states of a large fraction of the known nuclei.

Considerable progress has been made toward putting this understanding on a more fundamental basis, toward reproducing these observed phenomena in calculations assuming only an appropriately measured basic nucleon-nucleon force. Impressive results have already been obtained in isolated cases for nuclei as heavy as osmium, but this study can only be considered as in its infancy. This calculation of finite nuclei is of formidable difficulty, reflecting the fact that the nucleus bridges the gap between the few-body problems of particle physics and the extreme, many-body problems of plasma physics and theory of metals. This, however, holds the promise of important new insights into the many-body problem central to much of contemporary physics.

Fission. Much new insight has been gained into the mechanisms of fission, one of the oldest and most important nuclear phenomena but also one of the most poorly understood. Whereas it had been thought that once a nucleus had been induced to fission (by neutron capture, for example) it proceeded very rapidly to complete the fission process, recent measurements showed the very surprising result that delays of up to seconds occurred. As a consequence of a concerted international attack on this problem, it is now almost entirely understood within the framework of shell-model phenomena. The application of fission phenomena as a burgeoning source of energy—and one on which the continuance of our civilization will rest at least for decades—is too well known to require discussion here.

The inverse of fission represents one of the two newest frontiers of nuclear physics, the area of heavy-ion physics. With new accelerators it has become possible to use all nuclear species up to and including uranium as projectiles in nuclear studies. This has opened a door to entirely new classes of nuclear dynamics in the collision of massive nuclei and to the study of new structures of the cluster and molecular type noted above. Heavy-ion collisions are the only method whereby the supertransuranic species can be made. Reactions induced by light and heavy nuclear projectiles are very highly complementary in that they probe quite different parts of the wave function of the final states involved. For a given amount of energy, heavy ions bring very large angular momenta, and it is now possible to spin nuclei more than ten times faster than ever before and so study their behavior under large centrifugal and Coriolis forces. Striking phenomena have been observed, as when the Coriolis forces break nucleon pairs and lead to dramatic and abrupt changes in the nuclear moments of inertia: the nucleus abruptly changes from a superfluid to a normal state. Very recently it has been recognized, too, that study of heavy-ion collisions can provide totally new tests of the most fundamental aspects of quantum electrodynamics.

High energy nuclear physics. A second frontier of nuclear physics is that of high energy beams and mesonic probes typified by the Los Alamos Meson Physics Facility. In the past, attention in nuclear physics has largely centered on the outer nuclear regions—on the valence nucleons. With high energy proton beams it will be possible, for the first time, to probe deep in the nuclear interior to study the behavior of the deep-core nucleons. Use of pion and kaon beams in nuclear physics is still in its infancy, but already very interesting results have been obtained which support the idea that a high degree of subclustering exists in nuclei.

By utilizing the fact that the heavier baryons available from the higher energy accelerator are not forbidden by the Exclusion Principle from occupying otherwise full nuclear shell-model orbits, it is possible to create hypernuclei. Study of these is also in its infancy but promises to provide a whole new dimension in the exploration of nuclear systems. In going to ever higher energy, the spallation processes become of greater importance. Here the incident projectile fragments the target to yield a wide range of new isotopes; if the projectile is a very high energy heavy ion, there also exists the possibility of developing a shock wave in a heavy target nucleus, with consequences as yet unforeseen, although "doughnut" and "bubble" nuclei are among the available predictions.

Tailored isotopes. The combination of nuclear reactors, high energy, and heavy-ion accelerators has revolutionized the production of radioactive nuclear species. In a real sense the day of the tailored radioisotope has arrived, with profound consequences in biological and technological applications. To give a single example, the clinician's choice of element is dictated by the organ in question: for thyroid treatment the choice is iodine, and in the past the best available isotope, in terms of lifetime and radiations involved, was iodine-131. But this isotope lives for eight days and has many unwanted radiations. Recently iodine-123, which lives only 13 hours and has very few unwanted radiations, was developed as a tailored replacement. Whereas iodine-131 is produced cheaply and in quantity in reactors, iodine-123 must be produced by an accelerator. The human advantages, however, are so striking that the changeover will proceed rapidly. This is only one example of the usual situation where the radioisotope user made do with what he had or could find; in future it should be possible to specify much more precisely what is required.

Atomic, molecular, and electron physics

During the first three decades of this century, atomic physics was clearly a frontier field, with strong experimental emphasis on optical spectroscopy and equally strong theoretical emphasis on the development of quantum mechanics as a working tool. Apart from a brief flurry of activity reflecting the transfer of microwave techniques from wartime crash programs to atomic and molecular studies, it then suffered at least two decades of relative neglect as the fashionable frontiers moved forward first to nuclear and then to subnuclear studies.

With the advent of the laser, the

development of practical atomic and molecular beam accelerators, and the use of nuclear accelerators in new probing of atomic structure, the entire field has undergone a renaissance in recent years and can be expected to continue as a vital part of the overall physics enterprise. Coupled with these experimental advances has been a major improvement in calculational techniques that take advantage of the rapidly increasing power of large-scale computers.

Atomic and molecular collisions. Just as in nuclear and particle physics, some of the most important new information comes from collision studies. These span all possible combinations of electrons, ions, atoms, and molecules. The energy ranges involved are as high as hundreds of keV and as low as fractions of an electron volt. Among the more dramatic phenomena thus far obtained have been sharp resonances attributable to compound structure effects in the electron-atom and electron-molecule scatterings; inelastic electron scattering experiments have located totally new quantum states in complex atomic systems. Indeed, we are witnessing a transfer back to atomic physics of many of the techniques that nuclear physics borrowed from atomic physics years ago and refined and extended in the intervening period.

In a very real sense such work is revolutionizing physical chemistry. Rather than observe chemical reactions following bulk admixture of chemical reactants, it is now possible to prepare beams of the reactants and follow the fundamental processes at an elementary level on a molecule-by-molecule basis. Coupling of this new insight with the number crunching capability of large computers is only beginning. But already it is possible to solve an approximate Schrödinger equation for an elementary atom-atom collision and display the collision on a computer screen on a slow time scale, permitting observation of the evolution of the electronic orbitals in the scattering or resultant molecular binding. Such information is also of vital importance in low-density gas-dynamic studies and in plasma physics. It is clear that this will continue to be a major and growing area of atomic physics.

Beam foil spectroscopy. Beam foil spectroscopy, in which a rapidly moving ion is stripped of most or all of its electrons in passage through a thin film and the subsequent electronic transitions studied spectroscopically, is rapidly taking over small nuclear-accelerator installations throughout the country. This process gives access to the very highly ionized atomic configurations that are not reached in either arc or spark spectral studies but which are extremely important in plasma physics and in processes involved in re-entry into planetary atmospheres.

Ultraprecision studies. Atomic physics has provided the most precise measurements in all of science. The hyperfine interaction of hydrogen, for example, with the present definition of the second, is 1,420,405,751.77 Hz and is the most accurately known physical quantity. Atomic clocks have an intrinsic accuracy better than one part in 10^{12}—or, equivalently, of one second in 30,000 years. For the first time it becomes feasible to consider the possibility of defining the absolute standards of both length and time with the same molecular transition; this has not yet been done but should be within a matter of a few years.

Atomic physics has also generated a wealth of essential instruments all based on precisely defined and controlled electron and ion beams. The new scanning electron microscopes have revolutionized many areas of biology and of metallurgy and are used throughout science. New ultramicroscopes capable of one angstrom resolution are now on the horizon; these should answer man's historic dream of seeing individual atoms.

The laser. Beyond question, however, the most dramatic and far-reaching development in atomic physics has been the laser. The tunable laser has closed the last gap in the electromagnetic radiation spectrum between the near infrared and the microwave regions, and from the infrared through the far ultraviolet, it now provides a probe of unprecedented power. And an X-ray laser is already on the horizon.

Nonlinear laser techniques have led to laser pulses that last only picoseconds (10^{-12} sec). Because a typical such pulse contains a joule of light energy, the corresponding power flux is 10^{12} W. This enormous power, roughly equal to the generating capacity of all the electrical generating plants on the earth, is packed into a pancake-shaped pulse of photons about 0.3 mm in thickness and at most a few millimeters in diameter. The electrical field amplitude in such a pulse can be as high as one hundred million volts per centimeter—beyond anything man has ever known before. Using these same laser techniques it has been possible to develop optical shutters which operate in the picosecond range and allow these individual light pulses to be photographed in flight. Any material exposed to these super-energy pulses for as much as 10^{-10} sec will be vaporized to form a very dense plasma at thermonuclear temperatures. We shall return to this in the following section. At lower energies it becomes possible to follow the time development of atomic and chemical processes by observing behavior as a function of time after very short pulse excitation.

The other dominant character of the laser output is, of course, its coherence: all the emitted photons are effectively in step. With this the holograph has come of age with a myriad of applications from information storage, through dimensional gauging, to potential home entertainment. So also has Raman and other forms of spectroscopy, now opening up entirely new areas of atomic-structure study and chemical microanalysis. Light radar ranging to Apollo-located reflectors on the lunar surface permits earth-moon distance measurements to within 6 inches; accuracies of less than an inch are in sight. Laser ranging from satellites has made feasible direct measurements of continental drifts as well as dynamic profiling of the temperature, pressure, and content of the earth's atmosphere—a crucial first step in any envisaged global or long-range understanding—and hopefully prediction—of weather patterns.

Perhaps no other development in physics has so quickly been transformed into a powerful tool throughout science and technology; nor is there any end in sight either to the laser developments themselves or to their applications.

Plasma physics

Plasma physics is the study of ionized yet electrically neutral gas systems. Almost all matter in the universe is in an ionized state except for the relatively small but important fraction in planets and gas clouds. Plasma, the so-called fourth state of matter, exists with a very large range of physical parameters; particle densities range from 1–100 cm^{-3} in interstellar gas, through 10^8–10^{20} cm^{-3} in laboratory plasmas, to 10^{22}–10^{25} cm^{-3} in stellar interiors and in nuclear explosions. Plasma temperatures range from fractions of electron volts in low-current arc discharges, through 10^5 eV in fusion plasmas, to extreme relativistic energies in cosmological plasmas such as that of the Crab Nebula, to which we return below.

The fusion reactor. The major goal driving plasma physics for the past two decades has been the attainment of economical nuclear fusion power with its inexhaustible low-cost fuel from the sea and its hoped-for much-reduced environmental side issues. The goal in this field is the Lawson number of 10^{14}—the product of the density of the reacting nuclear species with the time during which they are contained within immediate contact. At the Lawson number it is calculated that the plasma will be self-sustaining, generating sufficient energy through nuclear fusion to maintain itself and all its associated facilities.

There are two major thrusts at present toward this goal. In the first, attention is focused on confining a low-density plasma for a relatively long time—magnetic confinement; in the second, the converse holds—a very dense plasma is brought to thermonuclear temperatures in a very short time. In either case, temperatures range from 40 to 100 million °K, and pressures from 10 to 100 million lb/psi.

The magnetic confinement approach dates from the early 1950s and has been plagued from the outset by inadequate knowledge of fundamental plasma physics and inadequate plasma diagnostic techniques. Major progress, both experimental and theoretical, has been made in the past few years. The inertial confinement approach is only a few years old and depends on the availability of superpower lasers (and, more recently, superpower electron beams). An array of such lasers is focused on a frozen pellet of solid heavy-hydrogen fuel, and the temperature is raised to thermonuclear values in so short a time that simple inertia prevents the dispersal of the reactants before thermonuclear fusion occurs. The design of the array makes possible optimum coupling of the laser energy to the pellet and effective implosion of the pellet itself.

Both approaches show high promise at present and should come to fruition, as laboratory demonstrations, in the next five to ten years at most. In the magnetic confinement case, remaining plasma instabilities continue to limit the containment lifetime, although the number of such instabilities already identified and vanquished is legion; in the inertial confinement systems, the apparent present limitation is one of available laser or electron-beam power. In both cases, the density-time product is between 10 and 100 removed from the Lawson number, but order-of-magnitude improvements have recently been attained.

Condensed matter physics

Condensed matter (solids, liquids, and amorphous materials) make up most of the earth; condensed matter physics considers all the properties of this matter, including mechanical, electrical, magnetic, optical, and thermal, together with its interaction with all forms of radiation. This matter ranges from states of exquisite order and essentially infinite range order—as in perfect crystals—to very imperfect and transitory short-range orders—as in liquids. Extremes of temperature and pressure, moreover, have revealed astonishing variants of these normal states of matter.

Superconductivity. One of the most striking variants, that of superconductivity at very low temperatures, was initially discovered as something of an isolated laboratory curiosity in 1911, understood first in 1957, and only now is evolving as a potential technological giant in power transmission, transportation, and many other industrial as well as scientific areas. Superfluidity is the analogous phenomenon in liquids cooled to very low temperatures, at which their viscosity drops to zero.

Because of the enormous potential of superconducting devices, one of the major searches in condensed-matter physics is for substances which remain superconducting to ever higher temperatures, thus minimizing the necessary refrigeration costs. Starting at a few degrees absolute, the maximum temperature has been raised to some 20°K; room temperature superconductivity is the Holy Grail in this field.

One of the most fascinating byproducts of superconductivity is the Josephson junction obtained when two superconducting metals are separated by a thin insulator. Paired electrons (paired to zero total angular momentum), which are now known to be responsible for the superconductivity phenomenon, can tunnel through the insulator in standard quantum mechanical fashion. The corresponding current through the junction is very sensitive to magnetic fields, and if a constant voltage is applied across the junction, a high-frequency oscillating current flows in the circuit with a frequency f directly proportional to the applied voltage V ($f = h/2e \cdot V$). These junctions have already been developed into ultrasensitive magnetometers and voltage measuring instruments. Inverting the process, it has been possible to measure h/e, the ratio of Planck's constant to the electronic charge (and a fundamental physical constant), to a precision much greater than was possible previously. The junctions also show high promise as bases for ultrahigh efficiency, high capacity, compact, and fast computer memories for data storage.

Solid-state devices. In this the twenty-fifth anniversary year of the discovery of the transistor, it would be difficult indeed to overemphasize the impact which reliable, efficient, compact, and inexpensive solid-state devices have already had on our civilization. Little need be said on the subject except to note that, with large-scale integration now commonplace, a further quantum jump in performance per unit cost is at hand. The utilization of the data-handling capacity of these units in the next few years will be limited primarily by the imagination of the user. The home market —appliances, entertainment devices, and the like—may well undergo the greatest change.

Material sciences. Mechanical properties of solids, such as strength, hardness, plasticity, and brittleness, all depend upon cohesive qualities related to the interatomic binding forces. In the past few years entirely new methods have been developed for probing these forces. It has been found, for example, that ion beams from nuclear accelerators, if properly aimed at a crystalline target, can be channeled through the crystal lattice; from detailed studies on the channeled and unchanneled ions traversing the sample, it has been possible to obtain extensive and precise new data on the interatomic forces in the lattice.

With intense neutron beams from large reactors, researchers can probe the vibrational and other characteristics of the crystalline lattice—and even in liquids—through observation of the scattered neutrons that have lost energy to vibrational modes (phonons, etc.) in the crystal. This technique has also been used to discover and study spin waves in solids—long-range correlations among individual nuclear spins over distances much greater than the characteristic unit cell dimensions involved.

Tailored materials. It should be emphasized that in condensed matter physics, as in nuclear physics discussed above, we are entering the age of tailored materials. Enough is now known about the basic physics and chemistry involved to enable materials—alloys, compounds, and the like—to be designed *ab initio* to give the desired physical characteristics. Moreover, with techniques exemplified by the ion beams just mentioned, we can now fabricate entirely new alloys and materials by physically implanting the alloying atoms in situations where chemical incompatibility previously made it impossible. The next few years will see extensive effort in this area of tailored materials.

Such ion beams also permit the fabrication of much more complex integrated circuit structures within crystal substrates than was ever possible when the impurity atoms were painted in carefully programmed patterns on the crystal surface and subsequently diffused, at elevated temperatures, into the lattice. With high-quality beams, the desired impurity atoms (no longer limited by diffusion characteristics) can be implanted in geometrically precise locations in cold crystals, thus making complex three-dimensional crystal circuit architecture possible. This approach to the fabrication of integrated circuit components is only now becoming economically competitive; it can have dramatic consequences in the years ahead.

Information storage and processing. The demands of information processing for ever more efficient, more compact information storage media have been a major impetus for new approaches in condensed matter physics. Magnetic "bubble" memories are an excellent illustration of the response. The magnetic bubbles are tiny regions of reversed magnetization, as small as 2/10,000 inch in diameter, that can be formed in thin crystals of a magnetic iron oxide and a rare earth metal such as yttrium. A typical memory element may consist of a 1 inch square crystalline film, 5/10,000 inch thick, containing 10^4 bubbles; memories storing 10^6 bubbles in a similar film now seem feasible. The bubbles are moved in the film through application of control voltages to a precise metal grid evaporated on the crystal face. The bubbles can be generated, replicated, or erased at will, and their presence or absence sensed electrically. In this technology the storage and logic functions are combined at great savings in cost, and the energy required to move a bubble is very much less than that required to switch other memory elements. Under design are bubble memories which will hold 15 million bits of information in between one and two cubic inches and require only about 10 W of power.

One of the ultimate limitations on the speed of any of the information handling devices is the time required for the electrical signals to move through the circuitry. It has long been recognized that substitution of optical light paths for the circuit interconnections could make a significant improvement; this has provided an important impetus for the development of integrated optics devices in which the light sources, solid-state lasers, optical interconnection paths, and optical wave guides and the information-processing systems, optical switches, scanners, and memories are all fabricated as integral parts of a single crystalline unit. The component parts of such devices have all been developed, and the next few years should witness this entirely new generation of devices spawned from a marriage of solid state and optics.

Optics

Classical optics emphasized instruments such as the microscope and telescope, visual phenomena such as color, and physical phenomena such as interference, diffraction, spectroscopy, polarization, and crystal optics. Modern optics has added the intricate new phenomena arising from the interaction of light with matter, such as holography, direct photon counting, the biophysics of vision, photoconduction, photoemission, and laser phenomena. These new topics have forced a marked renaissance in what had often seemed a few decades ago to be a closed subject.

The extent to which progress in many branches of science and technology has been optics-limited has only recently been adequately appreciated. The traditional wisdom was that no improvement was possible; therefore no improvement was made! Abbé theory had established a clear-cut limit to the possible resolution of a microscope, and it was implicitly assumed that microscopes could only be used on small opaque or self-luminous objects; the more powerful phase-contrast microscope arose from the realization that the Abbé limits simply did not apply when viewing small transparent objects.

Using large-scale computer power it has not only been possible to design optical lens systems of much superior quality, but also, using computer techniques on-line, it has become possible to employ ion beams to reshape lens surfaces during actual observation of the image in order to yield a more perfect image quality. The quality of very high-altitude surveillance camera lenses, which can resolve the white lines in a parking lot at distances of well over ten miles, would have been entirely impossible even a few years ago.

Spectrographic instruments provide a further interesting example. Elementary optics deals with the wavelength resolving power of a spectrograph and how this power depends upon the properties of the dispersing element; however, no mention is usually made of the observation time needed to attain given accuracy or of the signal-to-noise problems involved. Using Fourier transform methods, as first evolved in France, to improve the effective signal-to-noise ratio, it has been possible to obtain planetary spectra with 100 times greater resolving power and 10 times better signal-to-noise than can be obtained with the best prism spectrometers.

The entire field of holography has already been mentioned in connection with lasers. The availability of coherent laser light has revolutionized many areas of optics and, in particular, has had enormous impact on metrology—the science of precise measurements—which is in many ways a branch of optics. We can be confident that the next few years will see a stream of new instruments and continuing improvement in the precision with which physical parameters can be measured.

Thin-film optics is a field of very rapidly growing importance. It is now possible to design and fabricate multilayer thin films that will reflect chosen wavelengths and transmit others. High-pass, low-pass, band-pass, or low-band filters can now be built economically and reliably. Such films are routine as antireflection coatings on high-quality camera lenses. One of the most interesting current research areas is that of producing thin-film filters for use in solar energy installations. Very large area filters are required which will transmit a substantial fraction of the sea-level solar spectrum but block the reemission of radiation from the energy reservoir operating in the system at perhaps 1,000°F. Such film filters have been produced on a prototype basis, but the problems of reliability, long lifetime, stability, etc. are not yet solved for the very large areas (tens of square miles) that will be involved in any practical commercial solar-energy system.

Acoustics

Acoustics is another of the areas of classical physics which have undergone striking changes in recent years. Table 2 lists the now-fashionable divisions of acoustics in terms of frequencies.

Table 2. Frequency ranges in acoustics

Division of acoustics	*Frequency range*
Infrasonic	10^{-4}–20 Hz
Audio	20–2×10^4 Hz
Ultrasonic	2×10^4–5×10^8 Hz
Hypersonic	5×10^8–10^{12} Hz
Thermal vibrations	10^{12}–10^{14} Hz

One of the most active new areas involves study and use of surface waves. Major interest has centered on acoustic waves in the microwave frequency range. Through electroacoustic transducers, bulk acoustic waves have long been used to provide delays for electronic signals, reflecting the fact that the speed of sound is so much less than that of electromagnetic propagation. By turning to surface instead of bulk waves, it becomes trivial to tap off information from transducers located at will along the signal paths or to inject new information along the path. Much effort has been devoted to the search for low-loss materials; lithium niobate is currently the material of choice. Electron lithography is just now being explored as a means of constructing microacoustic devices. At present the practical upper limit of frequency for generation of acoustic surface waves is about 10^9 Hz; however, the electron lithography techniques show promise of at least 10^{10} Hz.

These surface waves have two obvious uses: information storage and signal filtering. Currently an acoustic surface wave memory 1 inch in diameter can store several thousand bits of information. In filtering, acoustic filters have the unique advantage of allowing the designer to prescribe the phase characteristics *independent* of the amplitude characteristic. This approach to ever sharper filter edges will become of greatly increased importance as the crowding of our electromagnetic spectrum continues. Acoustic filters are already widely used in very high-quality communications receivers.

Acoustic holography is a very rapidly developing field, building on the laser-induced work in optics. In geoscience and bioscience particularly, it can have profound effects. In geoscience, because such holography takes advantage of the fact that acoustic waves readily penetrate the earth's interior, it holds high promise of providing, with a precision hitherto impossible, not only new fundamental information about the structure of the interior but also the locations of oil and mineral deposits. In bioscience, acoustic holography offers hope of eliminating the major dangers inherent in X-ray examination of the human body and, at the same time, provides a greater depth of image than is possible with X-rays.

Nonlinear acoustics, characteristic of shock wave and correlation phenomena, or of streaming in liquids in high acoustic fields, has been an active area of study during the past five years, but, reflecting the extreme complexity of the problems involved, much work remains to be done before these phenomena are fully understood. The technological impact of such understanding would be enormous.

With the development of bolometric and other infrasound detectors it has become clear that infrasound provides a powerful tool for the study of large-scale motions of the earth's oceans and atmospheres and of readjustments in the earth itself. The extremely low attenuation of infrasonic waves, which results from their low frequencies and the wave-guide effect of the atmosphere, makes possible the detection of infrasonic signals of only a few microbars amplitude from sources thousands of miles away. Apollo launches, for example, are readily "heard" in New York on infrasound detectors.

Physics of fluids

The flow of fluids separates into two broad classes: laminar and turbulent. By and large laminar flow—a flow that is smooth and steady—is now understood. Turbulent flow, however, remains one of the major unsolved, challenging problems in physics. When the flow stream lines become distorted, convoluted, and mixed in turbulent flow, our fundamental knowledge of fluids breaks down almost completely. Turbulence falls in the very difficult region between ordered motion, which we can hope to understand through standard theoretical techniques, and completely chaotic motion, where we can apply statistical techniques to obtain average behavior. Turbulence is too complex for the first and too ordered for the second.

Understanding of turbulence has vital importance in such diverse areas as the flow of blood through the valves of the heart, the generation of noise by jet aircraft engines, and the flow patterns of the earth's atmosphere. By extension, turbulence studies have implications for weather, clear-air turbulence as a threat to aircraft, the drag phenomena on craft moving through both air and water, and the cosmological processes whereby galaxies and galactic clusters come into being.

Relativistic astrophysics

Pulsars. From the viewpoint of physics, one of the most exciting discoveries in decades—both because it requires *all* of physics for its understanding and because it may well present us with our greatest challenge since the failure of classical mechanics—is that of the pulsar and, by inference, the neutron star and black hole. Much has been written about them, and we need only a brief outline to illustrate the vital role of physics in responding to this challenge.

In the life cycle of a star, after all its hydrogen and, then, helium fuel has been burned, the twilight phases develop rapidly as the delicate balance between outflowing nuclear radiation pressure and gravitation becomes disturbed. Starting with normal stellar matter at a density of perhaps 0.001 tons per cubic inch, slow contraction begins. As the compression increases, at a density of perhaps 1 ton per cubic inch, the atomic electrons are effectively "popped off" their parent atoms to save space, and a very dense plasma forms. At a density just under 1,000 tons per cubic inch this compression reaches its maximum value without a change in the number of particles present. If the initial star had a mass less than about 1.4 solar masses, the process ceases, and the star is a white dwarf. It slowly radiates its energy until it ends its life as a dead cold mass of ultradense matter—a "clinker" in space.

If the star initially was more massive, however, the white dwarf plasma cannot resist the gravitational pressures, and the entire star begins to act as a giant quantum system: characteristic of such a system is the fact that the electrons, obeying the exclusion principle, must occupy ever higher energy states as the lower ones fill. In such a situation the most energetic electrons have adequate energy to reverse the normal neutron decay process; electrons and protons recombine to form neutrons and, in a rapid collapse, all nuclei of the star are converted to a gas of free neutrons. At this stage the density is about 10^5 tons per cubic inch. Gravitational attraction compresses this neutron gas rapidly until a density of 10^9 tons per cubic inch is reached; at this point the strong nuclear force resists further contraction. If the initial mass of the star was less than a few solar masses, the process stops here, and we have a neutron star such as we believe remains from the July 4, 1054, collapse of the parent of the Crab Nebula.

It is worth considering briefly the structure of such a star. The outer layer, less than a meter thick, is a hot gaseous liquid; below it is a thin crystalline crust of super-pure iron. Because of the enormous pressures on the iron, its melting temperature is raised to perhaps $(10^{10})°K$, and consequently, relative to its melting temperature, the iron is supercooled. It is 10^{18} times more rigid than terrestrial iron and 10^{20} times more incompressible. It is both the purest and the strongest material known in the universe. Underneath it a thin shell of superconducting protons maintains surface magnetic fields of 10^{12} gauss. These protons, in turn, coupling with the rapid rotation of the star (30 revolutions per sec for the Crab), generate electric fields as strong as 10^{12} V/cm between the poles and the equator. These enormous fields couple the atmosphere, crust, and superconducting shell so that they rotate together. The interior neutrons, however, are in a superfluid state, and since such a superfluid cannot rotate like a normal one, it must set up an array of tiny vortices whose axes tend to be parallel to the rotation axis of the fluid as a whole; as many as 10^5 such vortices per square centimeter may be involved. Clearly all of physics is required to understand so wonderful an object!

Gravitational collapse. But what if the initial star were more massive than a few solar masses? Then even the strong nuclear forces cannot resist the gravitational crunch. The neutrons are forced into one another to form heavier hadrons—and these in turn are coalesced to form even heavier entities of which we as yet know nothing. The density per cubic inch rises from 10^9 tons to about 10^{12} tons, at which a completely relativistic collapse occurs; existing theories predict a collapse to infinite density and infinitely small dimensions. Well before this, however, the surface gravitational fields would become so strong that no signal could ever leave the star—any photon emitted would fall back under gravitational attraction—and thus the star would become a black hole in space. There is recent evidence that such entities, in fact, exist; the best evidence comes from study of X rays from binary star systems in which it appears that one of the members has collapsed to a black hole and is drawing matter from its partner star into itself in visible and X-ray emitting streamers across the intervening gap.

This gravitational collapse poses a fundamental challenge to physics. When the best available theories predict such things as infinite density and infinitely small dimensions, it simply means that we are missing some vital insight. This last happened in physics about four decades ago, when it was recognized that electrons moved in stable orbits about nuclei in atoms. At the time, however, it was among the most established facts of physics that if a charge is accelerated, as it must be to remain in an orbit, it radiates energy. In doing so it would spiral into the nucleus and the atom would be destroyed. To remove this paradox it was necessary to develop quantum mechanics. It may well be that an equivalent advance awaits us in gravitational collapse.

Whatever the details involved, so cataclysmic an event as a stellar collapse would be expected to emit gravitational radiation—gravitons. Because the gravitational force is so weak, physicists had always assumed that the detection of gravitons would be impossible even if present at the earth. Recently this situation has changed, and a number of graviton antennae have been set up. In effect these are very large masses that are isolated to the greatest extent possible from the earth and have either strain-gauge or capacitive means for detecting very small dimensional changes. When a gravity wave passes over such a detector, it would be expected to elongate slightly in the direction of the wave and shrink slightly transverse to it.

This paper is written at a time of major controversy in the field. The original detection system has apparently located gravitational emission from our galactic center; detected events occur at least as often as once in two days, posing a major paradox. Based on all reasonable estimates, these measurements imply the liberation at the galactic center of gravitational energy equivalent to the mass of 1,000 suns each year. This is impossible; if the mass of the galactic center were changing at such a rate, the entire galaxy would have long since been loosed from its gravitational bonds and dispersed into space.

More recent preliminary measurements on newer graviton antennae do not appear to duplicate these early data. Great interest will center in this area of gravitational radiation in the near future. If this energy loss paradox cannot be removed by more and better measurements, then it too will force major revision of much of what we think we know about gravitation and space-time phenomena.

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In conclusion, this paper has been concerned with the individual subfields of physics, partly for convenience, partly to bring out the internal logic in each. To stop here, however, would be to neglect perhaps the most important aspect of physics—and one all too frequently forgotten: the study of natural phenomena proceeds simultaneously on many frontiers, each of which supports and nourishes the other. There is a very broad spectrum of research activities in physics ranging from the most basic to the most applied—from almost exclusively intrinsic to equally exclusively extrinsic activities with all intervening gradations.

"... and that goes for your damn moths, too."