beam to the center of the linac structure to reduce divergence at the end of the beam's two-mile trip. The SLC designers calculated the required tolerance to be 0.1 mm, an alignment similar to that achieved in the CERN Super Proton Synchrotron. A rough analysis of the data shows the effect in agreement with the calculation within a factor of two.

The second part of the R&D program is to build a 1.2-GeV storage ring at the end of the linac's first sector (out of a total of 30 sectors). It will take a high-intensity bunch and shrink it by radiation damping or cooling. Then the radiation-damped bunch will be reinjected into the linac for continued studies of the beam–linac interaction. The storage ring is under construction: a 35-foot-deep hole has been dug, a vault and the magnets are being built. The entire ring is expected to be finished next summer.

The third part of the program is to design the tunnels and experimental halls. For this purpose DOE has given SLAC \$500 000 to hire an architectural and engineering firm.

The SLC has a design luminosity of 6×10^{30} $cm^{-2}sec^{-1}$ (including an enhancement factor of three from the pinch effect) at 100 GeV in the center of mass. At 90 GeV the luminosity would change slightly. As the energy is reduced to 60 GeV, the luminosity would be down by a factor of two, Richter said. However, he notes, SLC could easily have its center-of-mass energy raised to 140 GeV by adding more klystrons. At full luminosity and energy, Richter says the full width at half maximum energy spread would be 0.7 GeV, whereas the predicted total width of the Z^0 is even larger—2.6 GeV; the large width is expected because many decay modes are possible.

At Novosibirsk, Alexander Skrinsky and his collaborators are hoping to build a true linear collider. They are building a 30-cm-long accelerating section that is expected to produce 100 MV/meter (to be compared with the modified SLAC linac, which gets 17 MV/meter).

Meanwhile, Cornell University is also hoping to build an e^+e^- device with 100 GeV center of mass (PHYSICS TODAY, August 1981, page 20). The storage ring, CESR II, has a design luminosity of 3×10^{31} $cm^{-2}sec^{-1}$, a factor of five higher than that of SLC. Although CESR II is expected to cost more than twice as much as SLC, in addition to higher luminosity it would have four interaction regions operating simultaneously, whereas SLC could only operate one interaction region at a time.

Because the SLC is a single-pass device, the beams would not develop the depolarizing resonances that occur in a storage ring. The SLAC linac can already produce highly polarized electron beams; so SLC would be capable of doing polarized-electron experiments similar to that done in 1978 by Vernon Hughes, Charles Prescott, Charles Sinclair, Richard Taylor and their collaborators; they showed the existence of parity nonconservation in a neutral-current interaction. —GBL

Gambling with a theory of quarks

The aim of the game recently in quantum chromodynamics has been to find a single theory that describes both the short-range and the long-range interaction of quarks (PHYSICS TODAY, July 1976, page 17). The principal obstacle is that the coupling of quarks changes with the size scale: Gauge theories applied to the short range have predicted that the quark coupling there is weak, going to zero logarithmically with quark spacing. In this phenomenon of asymptotic freedom, the quarks behave as nearly free particles. By contrast, gauge theories applied to the long range have indicated that strong coupling would confine the quarks to bound states. The challenge is to bridge the gap between these two regions and to demonstrate that the long-range, strong-coupling property of confinement persists even when the short-range couplings are weak. The application of Monte Carlo techniques to a lattice gauge theory has moved the players ahead one step in this direction. The game will be advanced by several more steps if theorists have luck in extending the same procedure to calculate the masses of the lowest lying quark bound states such as the pi or rho mesons.

Even before the recent successes with Monte Carlo techniques, theorists had noted the analogy between the particle theory and statistical systems. In particular, the strong- and weak-coupling regions correspond, respectively, to the disordered and ordered phases of a statistical system, with confinement being a property of the strong-coupling disordered phase. If the two regions constitute distinct phases, one would expect a phase transition, that is the nonanalyticity of a physical parameter, between these two regions. In that case, the weak coupling might extend to longer ranges, and the weak-coupling phase could support free quarks and gluons. Indeed, the Abelian gauge group of electrodynamics manifests such a phase transition, and free electrons and photons do exist. On the other hand, if no phase transition occurs, confinement must continue to characterize the long-range behavior even when the short-distance coupling is weak. This second possibility seems to hold for the non-Abelian gauge fields of quantum chromodynamics, and agrees with the apparent absence in Nature of free quarks.

The first evidence for a smooth functional matching between the strong- and weak-coupling regions in non-Abelian gauge fields came[1] actually not from Monte Carlo techniques but from a Hamiltonian formulation of SU(3) gauge theory. This work was done by John Kogut (University of Illinois) and Robert Pearson and Junko Shigemitsu (Institute for Advanced Study), who applied a method outlined earlier by Kogut and Leonard Susskind (Stanford). Nearly simultaneously, Michael Creutz (Brookhaven) reported[2] the results of a Monte Carlo calculation applied to SU(2) gauge fields in four and five dimensions. Creutz found that only the former did not experience a first-order phase transition. The Monte Carlo procedure had earlier been applied to Abelian systems by Creutz, Claudio Rebbi (Brookhaven) and Lawrence Jacobs (now at the Institute for Theoretical Physics in Santa Barbara). Kogut commented that, although the Hamiltonian and Monte Carlo approaches are complementary, the Monte Carlo method permits a more complex form of quark interaction and allows better control over the intermediate coupling regime.

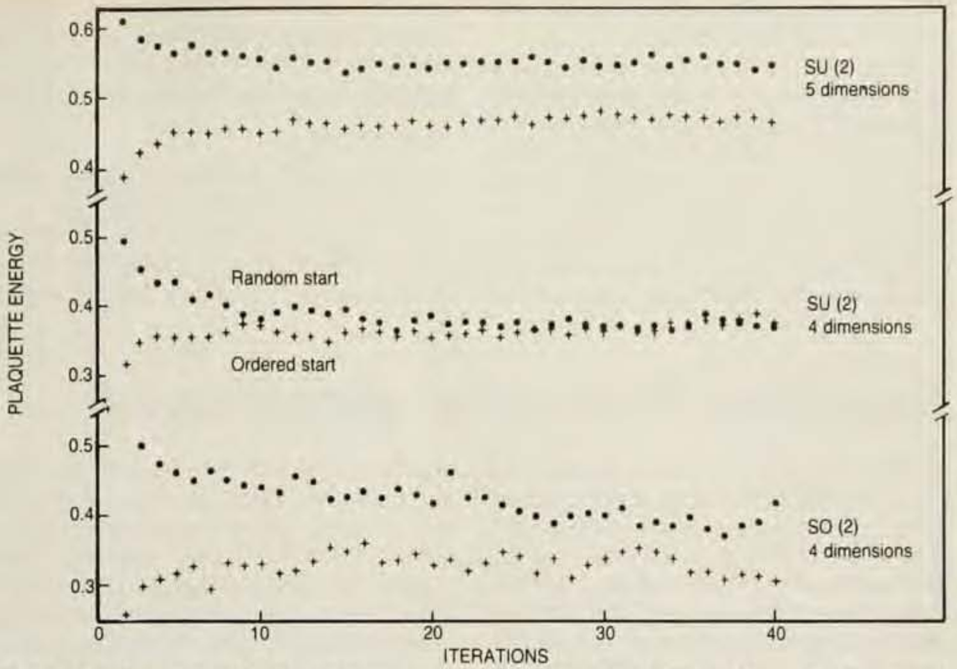
Lattice gauge theories. Both these approaches follow the pioneering work by Kenneth Wilson[3] (Cornell) and Alexander Polyakov[4] (Landau Institute in Moscow) in formulating gauge theories on a discrete, four-dimensional space-time lattice. Franz Wegner (Heidelberg), working on a problem in statistical mechanics, was the first to put a locally invariant field on a lattice. Wilson and Polyakov proposed such a lattice in particle physics to remove in a natural way the ultraviolet divergences that arise in quantum field theory: Wavelengths are essentially cut off at twice the lattice spacing because any shorter wavelengths would have no meaning. The more conventional schemes for removing the divergences are based on Feynman expansions and are thus perturbative calculations. Such expansions would break down for large quark separation, where the coupling constant becomes large. In calculating any physical number from a lattice gauge theory, of course, one must take the lattice spacing to zero at the end.

On the finite space–time lattice, the gluon gauge field is translated into variables associated with the links joining nearest-neighbor pairs. The world line of a particle interacting with the field is described by the product of the link variables encountered along its path.

Wilson feels that his strong-coupling expansion of the lattice gauge field provides the best framework for describing quark confinement: According to a previously existing continuum "string" model of confinement the quarks behave as though they are connected by strings with tension K such that the interaction energy between static sources is K times the separation distance. As Kogut put it, the string variables create electric flux tubes, which provide a linear confining potential. In Wilson's lattice theory, each pair of nearest-neighbor quarks is separated by a string that has a certain mass per unit length. To pull one quark away from another over many lattice spacings requires more string and hence more mass, or energy. Mathematically, each string is related to a link variable of the gauge field, and many strings correspond to the product of these links.

Wilson gives an equivalent argument for confinement in terms of the expectation value of the gauge field around a loop, where the loop product is averaged over all the configurations of link variables. Large loops can describe the behavior of a quark–antiquark pair (created at one end of the loop and annihilated at the other), separated by sufficient distance that they may be macroscopically observed. In the case of confinement, contributions from such large loops are vanishingly small, varying as the exponent of the loop area. Thus, free quarks should not be seen.

Linking the weak and strong coupling. The Monte Carlo procedure relies heavily on analogies between statistical mechanics and the gauge system. The Feynman path integral is mathematically akin to a partition function. Each configuration of link variables in the world line corresponds to one state in a statistical ensemble. The links can be represented by elements in the group representation of interest. The Monte Carlo procedure generates a sequence of field configurations by making random changes in the link elements, each weighted by a type of Boltzmann factor. The end result of Creutz's calculation is the expectation value of a "plaquette," that is, the path integral over an elementary square in the hypercube. This is a measure of the internal energy of a system. To demonstrate the absence or presence of a first-order phase transition, Creutz simulates "ordered" and "disordered" states by fixed or random initial values of the link elements in the field configuration. Independent of the initial ordering, he finds that the system converges to the same value of plaquette energy for both SU(2) and SU(3) in four dimensions. (See figure.)



The internal energy of a gauge field was calculated by Creutz[2] using Monte Carlo methods applied to a lattice gauge theory, and is plotted here against the number of iterations. In a four-dimensional SU(2) gauge field (middle plot) the results converge for both a disordered (dots) and ordered (crosses) start corresponding to strong-coupling and weak-coupling regions. The apparent absence of a phase transition in this theory implies the persistence of confinement into the weak-coupling region.

Creutz has used the same approach to extract a measure of the string tension K, and finds that it has the expected behavior as a function of the coupling constant at both high and low values. Many others have now adopted a Monte Carlo technique to investigate the phase diagrams of various gauge groups, the spatial characteristics of the heavy quark potential and additional topics. The one problem that all these efforts face is that of getting good enough statistics. Naturally, the larger the lattice, the more accurate are the results. Larger lattices demand either greater computational time, or more sophisticated algorithms to reduce that time. The largest calculation to date has involved a 16^4 lattice and was performed by Rebbi and Gyan Bhanot at Brookhaven to estimate the lowest bound state of the SU(2) gauge field.

Adding quarks to the theory. The Monte Carlo work so far has involved only pure gluon gauge fields without quarks (although theorists taking other approaches have tried to incorporate quarks). Addition of fermions to these theories constitutes a more stringent test because theorists can then compute the mass spectrum of quark bound states to compare with known hadron masses. Unfortunately, the inclusion of fermions is very difficult because of their anticommutation relations. Keeping track of the minus signs that arise from various permutations is a bookkeeping task that can require formidable computer time.

Basically two general approaches have been taken to treat fermions in Monte Carlo lattice gauge theories. In the first approach, one performs a formal integration over all the fermion degrees of freedom before applying the Monte Carlo techniques. Several variations on this theme exist for the different groups working in this field. They include Rebbi, Giorgio Parisi, Francesco Fucito and Enzo Marinari (University of Rome); Herbert Hamber (Brookhaven); Donald Weingarten and Donald Petcher (Indiana University), and Anthony Duncan and Ralph Roskies (University of Pittsburgh) with Hement Vaidya (Bell Labs). Hamber told us that he and Parisi are beginning to get numerical values for some hadron masses and other strong interaction parameters.

A second approach is to avoid any approximations and to perform the path integral for fermions as well as bosons using the Monte Carlo techniques. This tack has been taken at the Institute for Theoretical Physics in Santa Barbara by Richard Blankenbeckler (now at SLAC), Jorge Hirsch, Douglas Scalapino and Robert Sugar. So far they have applied their method to phenomena of condensed matter involving one space plus one time dimension, and they are gradually extending this work to particle theories and higher dimensions. H. DeRaedt and A. Lagendijk (University of Instelling, Antwerp) have also applied a related approach to statistical mechanical systems in two dimensions.

Even more than the pure gluon gauge theories, the recent theories that incorporate quarks are pushing the limits of computer technology. Wilson, who has been interested in the Monte Carlo techniques from the beginning, is actively promoting the development of very much more powerful computers for this and many other areas of scientific calculations. Ironically theorists may have to wait for machines of greater capabilities, just as experimenters have in the past. —BGL

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Sensitive fiber-optic gyroscopes

Special relativity teaches us that no contrivance, mechanical or electromagnetic, confined in a closed vehicle, can detect the uniform rectilinear motion of that vehicle. But anyone who suffers from motion sickness can attest to the fact that nonuniform motion (acceleration or rotation) is a different story. Thus it is possible to direct ships, aircraft or missiles by inertial navigation systems, once an initial direction is established, without reference to magnetic compasses or radio beams.

Although Georges Sagnac demonstrated in 1913 that the rotation of a closed optical path about an axis normal to its plane changes the interference pattern of two light beams traversing the loop in opposite directions, navigational rotation sensors have until now been exclusively mechanical—spinning gyroscopes. But optical rotation sensors making use of the "Sagnac effect" are about to encroach upon this monopoly. Ring-laser gyroscopes developed by Honeywell will soon make their commercial debut aboard the new Boeing 767 and 757 airliners.

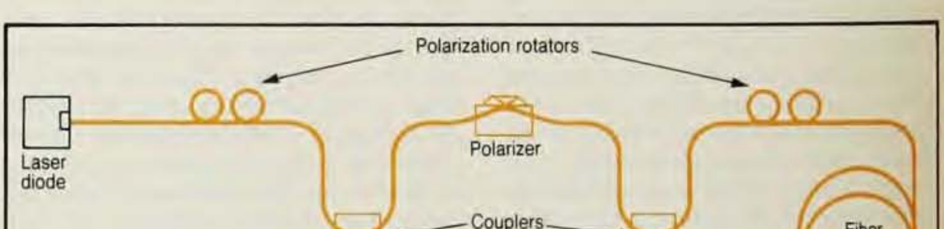
Two papers appearing in this month's *Optics Letters*[1,2] appear to promise that a second generation of optical rotation sensors—fiber-optics gyroscopes—is well on its way to achieving the sensitivity required for navigation. John Shaw and his colleagues at Stanford and an MIT group headed by Shaoul Ezekiel have constructed single-mode fiber-optic Sagnac gyroscopes with noise levels sufficiently low to permit detection of rotation rates about a hundredth of the Earth's rotation. Although this is still an order of magnitude less sensitive than what's needed for navigation (and what has already been achieved by ring-laser gyroscopes), both groups express confidence that no serious obstacles lie in the way of attaining a sensitivity of 0.01°/hour, a thousandth of "Earth rate." If this optimism is vindicated, fiber-optic gyroscopes would have a number of important practical advantages over ring-laser rotation sensors and mechanical gyros.

The Sagnac effect can be derived by a simple-minded argument that gives the Sagnac phase shift correctly to first order in v/c, the tangential velocity of the rotating optical loop divided by the speed of light. If two coherent light beams are made to travel in opposite directions around a stationary circular ring of radius R from a common source fixed on the ring, they will still be in phase when they return to the source. If we now rotate the ring and its light source with a tangential velocity v, the beam rotating with the ring will have an optical path longer than the counter-rotating beam by a distance $4\pi Rv/c$. For monochromatic light of wavelength λ, this would result in a Sagnac phase difference $\phi_s = 8\pi^2 Rv/\lambda c$ between the two beams after a single traversal of the loop, and hence an observable rotation-sensitive interference fringe pattern. For a single loop enclosing an area A and rotating with angular velocity Ω, the phase difference is given by $8\pi A\Omega/\lambda c$, independent of the shape of the loop.

The problem is that this Sagnac phase shift is exceedingly small for modest rotation rates. Shortly after Sagnac's original demonstration on a rapidly rotating table, Albert Michelson constructed a Sagnac interferometer, using about eight kilometers of evacuated sewer pipes, to detect the Earth's rotation. Even with an interferometer of such outlandish size, the Earth's rotation produces a phase shift at only about a tenth of a fringe, the smallest shift that could be detected with the instruments then available.

Ring-laser gyroscopes. With the development of the helium–neon laser (the first continuous-wave laser) in the early 1960's, a Sagnac rotation sensor became a practical possibility. W. M. Macek and D. T. M. Davis demonstrated the first such device at Sperry in 1963. In a ring-laser gyroscope, the He–Ne laser discharge tube is an integral part of the closed optical path of the interferometer. The usual end mirrors of the gas laser are replaced by the three or four mirrors that send laser light in opposite directions around the triangular or square optical path of the cavity. At rest, this laser system resonates in two degenerate modes—a clockwise and a counterclockwise traversal of the loop at a single frequency. When the system is rotated, the Sagnac effect breaks the degeneracy, producing a small frequency difference between the clockwise and counterclockwise modes.

This frequency difference is a direct measure of the rotation rate. The ring-laser gyroscope actually measures integrated rotation rather than rotation rate, by counting interference beats



Fully integrated fiber-optic gyroscope developed at Stanford is shown schematically. Infrared light from the GaAs laser diode is split by an integrated coupler into two components, which then traverse 580 meters of single-mode optical fiber (wound around a 14-inch-diameter spool) in opposite senses. Rotation of this fiber-optic loop causes a proportional "Sagnac" phase shift between the counter-rotating beams. The resulting rotation-sensitive interference pattern is sensed by the photodiode detector. With integrated polarizer, polarization rotators and piezoelectric phase modulator, the splice-free integrated fiber-optical path avoids the reflecting interfaces that contribute to noise, achieving a rotation sensitivity of 0.1°/hour.