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TECHNICAL PROGRESS REPORT

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Under this contract, research has been performed on both theoretical and experimental properties of elementary particles. A brief description of the work which is either in progress or has been completed is given below.

EXPERIMENT

Brandeis officially joined the CDF collaboration in May, 1982. Prior to that we had worked informally with the CDF group at Harvard on the design of CDF detectors. Areas of CDF in which Brandeis played a key role are:

- Design and construction of the Forward Electromagnetic Shower Counters.
- The development of the front end electronics for the data acquisition system.
- The creation of a database management system used throughout all of CDF.
- Test beam studies of the behavior of gas calorimeters.
- The design and construction of gain monitoring for the gas calorimeters.
- Leadership of the collaboration effort to develop electron identification algorithms.
- Simulation of the Forward Electromagnetic Shower Counters.

In addition we have fully participated in all of the activities of CDF including internal reviews, workshops, code development and evaluation, and assisted other members of the collaboration whenever local expertise or resources made that appropriate.

The CDF detector has run continuously for the last year accumulating 4.5 pb^{-1} of luminosity. The Brandeis group contributed to shift responsibilities during this period, as well as the specific tasks and data analysis detailed below.

Electroweak Decays

In 1987 CDF collected about 25 nb^{-1} of $\overline{p}p$ collision data at a center-of-mass energy of 1.8 TeV. In this data, 23 W $\rightarrow e\nu$ and 7 Z $\rightarrow e^+e^-$ events were identified. The analysis of these events was a cooperative effort of several CDF institutions, including Brandeis. The principle result of the W analysis was a measurement of the cross section times branching ratio of $2.6 \pm 0.6 \pm 0.5$ nb (the first error is statistical, the second is systematic), which was published in "Measurement of W-Boson Production in 1.8-TeV $\overline{p}p$ Collisions", F. Abe *et al.*, PRL **62**, p. 1005 (1988). Properties of the Z events were reported at conferences but not published. Properties of the W and Z measured with these events are consistent with those expected from theory and those measured at CERN, but the errors are large due to the limited statistics.

During the 1988-1989 run CDF collected 4.5 pb^{-1} of $\bar{p}p$ collision data at 1.8 TeV, a 200-fold increase in data from the 1987 CDF run. We expect to find roughly 5000 W $\rightarrow e\nu$ and 500 Z $\rightarrow e^+e^-$ events in this data. In addition, the CDF detector has proven to be very good at identifying and measuring electrons. This, combined with the sizable data sample, will allow CDF to begin to make precise tests of the standard electroweak theory at the energy scale of the W/Z mass.

The weak mixing angle, usually denoted $\sin^2(\theta_W)$, is one of the fundamental parameters of electroweak theory. Until now, this parameter was accurately determined only in low energy experiments, such as neutrino scattering. CDF will now be able to make accurate measurements of $\sin^2(\theta_W)$. Due to higher order electroweak corrections, the value of $\sin^2(\theta_W)$ is a function of the energy scale and reaction used to measure it. Comparison of $\sin^2(\theta_W)$ at the W,Z mass with that measured in low energy experiments allows a test of these higher order corrections, and hence, a test of electroweak theory at the quantum level. Discrepancies in these comparisons could also be a signal of new physics.

One measurement of $\sin^2(\theta_W)$ is the ratio of the W and Z masses. Experimentally, many systematic errors cancel in this ratio (such as the energy scale), allowing a precise measurement. One of us (Professor Blocker) has been working with two Harvard students on measuring the Z and W masses accurately. In addition to the masses, other parameters of the W and Z, such as width and cross section times branching ratio, will also be measured.

A second way of determining $\sin^2(\theta_W)$ in $\bar{p}p$ data is from the angular asymmetry in Z $\rightarrow e^+e^-$. We have begun a study of this angular distribution. It appears that during the coming year we will be able to make a determination of $\sin^2(\theta_W)$ that has a statistical error of about 5% and a systematic error that is much smaller.

In addition to some of the standard electroweak measurements, we are working on a unique search for supersymmetric electrons (selectrons) from Z decays. These selectrons should decay to an electron plus a photino. The photino is expected to be weakly interacting with matter, like a neutrino, and leave the detector without producing a signal. Thus the signature for selectron pair production from Z decay is an event with an e^+e^- pair that is not back-to-back and has an invariant mass less than the Z, along with large missing Et (from the photinos). If we are able to sufficiently separate these events from the Z $\rightarrow e^+e^-$, Drell-Yan pair production, and photon conversion backgrounds, we should be able to explore a mass range for selectrons that has not yet been studied.

Search for Top Decay into Leptons

The observation of the top quark is one of the main physics goals of CDF. Its existence would provide a key confirmation of the Standard Model, and the knowledge of its mass, and production and decay properties will improve our understanding of this model and have implications for new physics.

Top quark production at the Tevatron is dominated by the direct production of $t\bar{t}$ pairs. The most copious reaction is one in which both the t and the $\bar{t}$ decay into hadrons, producing a multi-jet final state This process is difficult to observe in the presence of a QCD background which is orders of magnitude larger.

An improvement in the signal to noise ratio can be made by requiring the semileptonic decay of one of the t-quarks ($t \rightarrow b\ell\nu$), which proceeds via either a real or virtual W depending upon whether the top mass is above or below the W threshold. For this mode (jets + lepton + neutrino) there is a substantial background from the production of W+jet(s). A further reduction in background is obtained by requiring the semileptonic decay of both the t and $\bar{t}$. This diminishes the QCD backgrounds but retains undesirable events from such sources as (Drell-Yan + jets) and (mismeasured Z)+jets. These can be eliminated if one considers only events in which the leptons belong to different families, e.g. one electron and one muon. The remaining sources of background in the $e-\mu$ channel are the semileptonic decays of the lighter b-quarks and the decays $Z \rightarrow \tau\tau \rightarrow e\mu$. These events are characterized by the soft P_t distribution of the leptons and their collinear topology.

The basic top signature is an opposite-sign electron-muon pair, with a sufficiently high P_t (non-collinear) to remove background from $b\bar{b}$ or τ pairs. In our current analysis, simple selections on the P_t and the charge of the leptons suffice to eliminate nearly all background. Additional requirements such as acollinearity, missing transverse energy, lepton isolation, and jet activity could be employed to further separate backgrounds from any potential signal. The $e-\mu$ channel thus provides a relatively clean top quark signal, with measurable cross-section for a range of top mass.

The following is a list with some of the studies we have carried out since the analysis started in October 1988.

- Triggering:

  CDF has three triggers capable of detecting electron-muon events:

  1. An electron trigger with a nominal threshold of $E_t(e) > 12$ GeV. The electron trigger is nearly 100% efficient for isolated electrons with $E_t > 15$ GeV. This has been determined by looking at data coming from lower (7 GeV) threshold runs.
  2. A muon trigger with a nominal threshold of $P_t(\mu) > 9$ GeV. The muon trigger has been measured to be about 50-60% efficient near threshold. Events where the inclusive electron trigger was satisfied were used for this study. There are indications that there is full efficiency for $P_t > 12$ GeV, but further studies are required.
  3. An electron and muon trigger with nominal thresholds of $E_t(e) > 5$ GeV and $P_t(\mu) > 5$ GeV. The threshold efficiency of this trigger has been studied using $e-\mu$ events in which either the inclusive muon or electron triggers were satisfied. The combined trigger efficiency is estimated to be better than 70% in the range 5-12 GeV.

  In this analysis we have defined our signal region to be $E_t(e) > 15$ GeV and $P_t(\mu) > 12$ GeV so that all three triggers are fully efficient.

- Data Reduction and Samples :

  To date we have used 3.6 pb^{-1} of data coming from an express filter and 1.0 pb^{-1} from the standard reconstructed data streams. The larger amount of data available from the former sample makes it ideal for searching for a signal, or in its absence, for setting mass limits. On the other hand, there are lower P_t thresholds in the standard stream which makes it useful for comparing with expected $b\bar{b}$ background as well as providing a check that no high-P_t events are lost by the express filters.

- Monte Carlo Event Samples :

  We have used ISAJET Monte Carlo and the CDF simulation program to generate and analyze several large event samples on the Brandeis computer cluster. Each sample contains several thousand events of $t\bar{t}$ having top masses between 20 and 100 GeV/c^2, as well as $b\bar{b}$ and $Z \rightarrow \tau\tau$ background events. A Monte Carlo study of $b\bar{b}$ backgrounds which include the processes of gluon splitting and flavor excitation is also under way.

- Reconstruction Efficiencies :

  From the data, we have extracted samples of Z $\rightarrow ee$ and Z $\rightarrow \mu\mu$ by requiring that one lepton passes our selections and the pair satisfies a mass constraint. Then we looked at the second lepton to study the effect of our cuts.

- Top Quark Mass Limits :

  A top signal has not yet been observed. For a preliminary limit on the top mass, we have utilized very conservative estimates of the production cross section, luminosity, event selection and acceptance. Our analysis so far excludes masses between 30 and 60 GeV/c^2.

These results were presented at a Fermilab seminar by the Brandeis student (Milciades Contreras) who is doing the analysis.

Search for Top Decay into Jets

At Brandeis, we have also investigated methods which would observe top decays which proceed via a purely hadronic mode, that is, in which the W from $t \rightarrow Wb$, decays to two quarks as opposed to a lepton and a neutrino. We refer to the first as the hadronic mode, and the second as the semileptonic mode.

Hadronic decays of the top offer different challenges than the semileptonic modes, since the electron is more easily identified. An alternate signature is therefore necessary in order to separate a top quark-enriched multijet sample from other events. We have investigated the use of global event shape measures for this purpose, based on the assumption that the decay of massive quarks such as top will produce events more spherical and less flat in η-ϕ space than QCD background. The separating power of various event shape measures, such as sphericity, circularity, and a sphericity-like measure based on transverse energy flow were compared using the ISAJET Monte Carlo. Our initial results indicated that this last measure, which we refer to as "E_t-weighted sphericity", combined with other event selection criteria, improve the signal (top) to noise (other QCD multijet events) by somewhat over an order of magnitude. However, such criteria also result in an 85 percent loss in signal, which is unacceptable at the low cross-section for top production. We concluded that an E_t-weighted sphericity cut is too stringent, and therefore not an efficient cut on which to select a top enriched sample.

One result of the Monte Carlo study was the confirmation that the principle axis determined from an E_t-weighted sphericity computation is well aligned with the axis along which the original t and $\bar{t}$ were produced. We used this axis to develop an algorithm for finding top by dividing each event into hemispheres according to the principle axis and then applying invariant mass combination rules appropriate for the specific event topology. This algorithm successfully identifies the top mass in Monte Carlo events. Application of the algorithm to a 1.5 pb^{-1} subset of the current CDF data run yielded no events, due to the width of the signal as compared to the background.

Electron Photon Algorithm Group

The CDF Electron/Photon Group has responsibility for the software that identifies electrons and photons in the CDF data. This includes code that identifies electron candidates, selects events for the inclusive electron output stream of the standard CDF production job for use in subsequent physics analysis of events with electrons, calculates quantities for electrons and photons to be used in subsequent analysis, and does corrections to the data (such as energy and position). Professor Blocker, who is the chairman of the Electron/Photon Group, has written much of the code used to select electron events for the 1988-89 CDF data and is responsible for managing the electron/photon code.

The electron/photon identification algorithm works by first finding clusters of energy in the CDF electromagnetic (EM) calorimeters. Next, tracks that extrapolate to the EM cluster are associated with that EM cluster. Finally, information from the strip chambers in the central and plug EM calorimeters is associated with the EM cluster. The electron/photon candidate selection is then based the requirement that the longitudinal and transverse development of the shower be consistent with an electron or photon shower and, for electrons, that the extrapolated position and momentum (when available) of the track match with the EM cluster's position and energy.

The Electron/Photon Group's code was used in the production analysis of the 1987 CDF data. The primary physics involving electrons from this data was the observation of the W and Z intermediate vector bosons via their decays $W \rightarrow e\nu$ and $Z \rightarrow e^+e^-$. The measurement of the cross section times branching ratio for the W was reported in "Measurement of W-Boson Production in 1.8-TeV $\bar{p}p$ Collisions", F. Abe *et al.*, PRL **62**, p. 1005 (1988). The primary photon related physics to come from the 1987 data was a measurement of direct photon production in jet events.

From what was learned in analyzing the 1987 data, many improvements were made to the electron/photon code. For one thing, the thresholds for electrons and photons were lowered in the trigger for the 1988-1989 data. This resulted in a large increase in the rate for electron/photon candidates, both from real electrons and from background. The electron/photon code had to be changed so that it accepted fewer background events while maintaining high efficiency for real electron and photons. In addition, and equally important, some representative sample of the background needed to be retained so its contribution to electron/photon signals can be determined.

Many analyses of events with electrons and photons from the 1988-1989 data are underway within the CDF collaboration. These include: (1) measurement of properties of W's and Z's, (2) study of Drell-Yan production of e^+e^- pairs, (3) measurment of direct photons from QCD events, (4) search for the top quark via the semileptonic decay of one of the top quarks in $t\bar{t}$ events (electron + jet events), (5) search for the top quark in $t\bar{t}$ events where both the t and the $\bar{t}$ decay in the semileptonic mode – one with an electron and one with a muon (electron-muon events), and (6) studies of bottom quark jets via semileptonic decay of the bottom quark.

Jet Momenta Corrections

The energy measured in the CDF calorimeter in response to hadrons is not linear with the energy of the incoming hadron. The energy measured by the calorimeters in response to charged hadrons with momentum of a few GeV is substantially lower than one would expect from calibration using hadrons with momenta of 50 GeV or more, which was used to calibrate the CDF central calorimeters. Thus when measuring jet energies the result depends on the momentum spectrum of the charged hadrons in the jet. We find that on average the uncorrected jet energy in the CDF central calorimeter is about $\frac{2}{3}$ of the sum of the particle energies, with almost all of the loss coming from an underestimate of the low momentum charged hadrons. The jet energy resolution is worse than it would be for a single particle of the same energy because the measured jet energy is a combination of responses to a mixture of particle momenta. We have developed an algorithm to make use of the tracking information to correct jet energies and improve the jet energy resolution.

The algorithm works as follows: We start with the standard CDF jet finding algorithm which combines the energy inside of a fixed cone in eta-phi space into a jet. Tracks are associated with jets if at the vertex they are within the same cone in eta-phi space that defines the jet. Each track is also projected to where it would strike the calorimeter and is associated with a jet cluster based on either the eta-phi distance from the jet axis or whether or not the calorimeter tower struck by the track is part of the cluster. For a track associated with a jet at the vertex we add the momentum vector of the track to the jet momentum. If the track is associated with the jet, we subtract from the jet momentum the average energy for a charged hadron of that momentum at the point where the hadron struck the calorimeter. Options allow the user to choose whether to add the momentum in the track direction or to only add the momentum projected along the jet axis and also to select the method used to associate tracks with jet clusters. The fact that the momentum and energy are added and subtracted in the appropriate direction for each also corrects for the error caused by the bending of charged hadrons in the magnetic field before they hit the calorimeter. This correction can only be done for jets in the central region where there is a tracking measurement. This algorithm does not allow changing the direction of the jet in eta since the tracking efficiency (and accuracy of the dip angle) might not be uniform in the edge of the central detector and in the plug and we want to avoid incorrectly biasing the jet direction toward the center of the detector.

Database

During the last year we concluded our responsibility for maintaining the CDF Database (CDFDB). We finished a major upgrade to the CDFDB in the fall of 1988, the purpose of which was to incorporate newly-available memory and data management software which facilitates direct disk access for data reads and writes. By implementing modifications necessary to take advantage of these new routines, contention between user processes for CDFDB resources has been considerably reduced. In addition, virtual space requirements for the database, and therefore for most CDF software, was greatly reduced in the new version. Finally, database access time was improved by one to two orders of magnitude using the direct disk access scheme.

The CDFDB, which was designed and constructed almost entirely by Brandeis, has performed well during data taking and data analysis. We have met the original requirement of such a system, to provide a simple, standard, and fast interface between CDF users and the vast amount of calibration and other run-related data collected by the detector.

Although our responsibility to maintain the software has ended, we continue to oversee code modifications to the CDFDB.

Gas Gain System

Before and during the 1988-89 CDF run considerable effort has been devoted toward improving the Gas Gain System at CDF. The gain, and hence the energy scale, of the Forward and Plug calorimeters depends primarily on three things, the voltage on the chambers, the exact composition of the gas, and its density. Most of our work on this system during the past year has dealt with accurately determining or controlling these factors.

In order to measure the gain of the detector, there is an elaborate system of monitoring tubes that are exposed to the same voltage and gas but also to a source of known energy. The current gain of the monitoring tubes gives the current gain of the detector. Before the present experimental run we calibrated the monitoring tubes with their electronics. We also calibrated the system that monitored the high voltages on the calorimeter chambers and monitor tubes to ensure calibration across the entire detector.

It was found during the last collider run that the mixture ratio of Ar/Ethane was not held to as close a tolerance as was required. Variations in the gas mixture are a problem because different mixtures have different gains and the low flow rate through the system makes it possible for different regions of the calorimeters to have different gains due solely to different length of time that the gas took to reach that region. The only way to adequately deal with this problem was to control very accurately the gas mixture flowing through the detector. With the aid of Fermilab technicians we designed and built a system to measure and correct the gas composition so that the gas gain variation due to gas composition was less than $\pm 0.5\%$ (from the gain variation $\pm 5.0\%$ in the delivered gas). This is done before the gas is introduced into the detector.

The other major change in the gas calorimetry system was a redesign of the plumbing used to deliver gas to the forward region. During the previous run the control solenoids in the gas system frequently failed and required excessive maintenance. In addition, the cycling of solenoids increased the aging of the cathode wires in our monitoring tubes decreasing their effective lifetime. A new pressure feedback system eliminates the need for solenoid cycling.

Superconducting Supercollider Program

One of us (Professor Bensinger) has been on leave from Brandeis to work with the conventional facilities section of the central design group (this has now become part of the physics division of the SSC laboratory). This decision was made because it is important that physicists, especially those with experience with $\bar{p}p$ colliders, lend their expertise at this critical phase of turning a conceptual design into a real accelerator. Another important reason for the decision is to insure that the Brandeis HEP group will have a significant role in one of the initial experiments at the SSC.

Many of the technical decisions and engineering solutions made early in the design of this facility will have a significant effect on the physics experiments that will be possible when the machine is complete. For many years the Brandeis group has been actively involved in experiments of the type (but not the scale) of those that will be done at the SSC. By becoming involved early in the design process we can help assure the quality of the experiments that will eventually be performed. It is also very important to the Brandeis high energy physics group that a proper decision be made about which of the SSC experiments to join. This decision should be based on both the quality of the physics goals of the experiment and the quality of the physicists that we will be working with. Being at the SSC at this time provides the information that would allow the best decision.

Our primary involvement with the SSC laboratory has been to develop test and calibration facilities for potential SSC experiments, both now and at the future SSC laboratory. At the present time we do not expect to have extracted beams at the SSC laboratory before 1996 when they will be used primarily for calibration of detectors and must be of high quality. For current and near future needs we have to develop facilities at existing laboratories. We are heavily involved in both of these projects.

Each experiment at the SSC is expected to cost several hundred million dollars, and in many cases, major components will be inaccessible for years after installation. These experiments will require a much higher level of understanding, simulation, and quality control than has ever been necessary before. Traditionally, when equipment is used in experiments and problems occur, access is either immediate or at most within a few hours or days so that a certain level of failure can be tolerated. The next generation of detectors will require a very different approach. We are working with people developing equipment for the SSC, trying to determine the full scope and phasing of the particle beams needed to test and calibrate equipment. We are also working with Brookhaven and Fermi National Laboratories and the SSC Division of the Department of Energy to determine what facilities will be available to fill these needs, when they will be available, what properties they will have (particle type, energy, flux density, etc.), how they will be instrumented, and how they will be paid for.

Beyond the needs for facilities at existing laboratories, we have to plan for the needs at the SSC laboratory itself. Here we are participating in the design of the beam transfer lines from the High Energy Booster (the 2 TeV injector for the SSC) to the collider, the extraction lines (which tap into these transfer lines to create external beams), and the surface facilities to receive the beams. The surface facilities include beam lines, beam splitters, target stations with radiation shields, secondary beams, experimental halls with facilities for handling multi-ton modules for experiments, and all the "civilization" such as power, water, and roads that will be needed to actually make it possible to operate at the SSC.

We have also been working on the design of a specific experiment for the SSC. George Trilling has been assembling a group of physicists, mostly from LBL, to be the nucleus of a proposal for one of the initial experiments at the SSC. Because Trilling has been able to put together a very strong group and has an early start, this proposal is expected to be a strong contender for one of the major "4π" detectors. We feel that at this point it is too early to join specific collaborations, but it is necessary to work seriously on SSC detector design in order to fully understand the issues involved in doing SSC experiments and to make an informed decision. As part of our participation in this effort, we have been working with a group on warm liquid calorimetry design.

Publications from June 1, 1988 to May 31, 1989

"Transverse Momentum Distribution of Charged Particles Produced in $\bar{p}p$ Interactions at $\sqrt{s} = 630$ and 1800 GeV" (with The CDF Collaboration), Phys. Rev. Lett. **61**, 16, 1819 (1988).

"Measurement of the Inclusive Jet Cross Section at Tevatron $\bar{p}p$ Collider" (with The CDF Collaboration), Phys. Rev. Lett. **62**, 6, 613 (1988).

"A Measurement of W Boson Production in 1.8 TeV $\bar{p}p$ Collisions" (with The CDF Collaboration), Phys. Rev. Lett. **62**, 9, 1005 (1988).

"Upper Limit for the $\Xi^{\circ} \rightarrow \Sigma^{\circ}\gamma$ Radiative Decay" (with Duke University, Notre Dame University, Southeastern Massachusetts University), Phys. Lett. **215**B, 195 (1988).

"Hadroproduction of the Iota Meson Observed in the $K_s K_s \pi^0$ Final State" (with University of Notre Dame, Brookhaven National Laboratory, City College of New York, and Duke University), Proc. of the BNL Workshop on Glueballs, Hybrids, and Exotic Mesons, Brookhaven National Laboratory, Aug. 29–Sept. 1, 1988. American Institute of Physics Conference Proceedings 185, Particles and Fields Series 36, 334 (1989), S. U. Chang, editor.

"Limits on the Masses of Supersymmetric Particles from 1.8-TeV $p\bar{p}$ Collisions" (with The CDF Collaboration), Phys. Rev. Lett. **62**, 16, 1825 (1989).

"A Study of Inclusive Hyperon Production using a Lead Glass Hodoscope" (Fortner), Brandeis University PhD Thesis (advisor: Kirsch).

"Measurement of the $\Xi^0 \rightarrow \Sigma^0\gamma$ Branching Ratio" (Zografou), Brandeis University PhD Thesis (advisor: Kirsch).

THEORY

During the past contract year the theoretical physics group pursued research in string theory, conformal field theory, cosmic strings, cosmology, and neural networks. A summary of this research follows.

The program was strengthened by the presence of Professor Edward Farhi of MIT, who spent a portion of his sabbatical year at Brandeis.

Strings and Conformal Field Theories

The study of conformal field theories is important since they form the basic building blocks of string theories, and describe two-dimensional statistical systems near second-order phase transitions. One of the main directions of the Brandeis group during the last year was the development of a Lagrangian description of conformal field theories in the very broad class of G/H coset theories. The motivation of such a program is the desirability of finding constructive methods, using conventional field theoretic techniques, for the construction of partition functions, correlation functions, etc. In this regard we were successful in replacing the Goddard, Kent, and Olive (GKO) *algebraic* construction of G/H conformal field theories with a Lagrangian formulation.

Karabali, Park, Schnitzer, and Yang presented a path integral formulation for G/H conformal theories, based on gauged Wess-Zumino-Witten (WZW) models, so as to provide a field theoretic formulation of such theories. The conformal charge of the model is $c = c_G - c_H$ exactly as in the GKO construction. Ghost modes appear in the formalism as a result of gauge fixing. As a consequence, the holomorphic stress-tensor T(z) obtained in the construction has ghost contributions. However, the GKO version of the stress-tensor is obtained if one restricts one's attention to matrix elements between physical states which are also ghost-free. It was shown that these physical states are specified in terms of first-class, weak operator constraints.

Schnitzer extended this work to superconformal G/H theories by means of a path integral construction based on a gauged supersymmetric WZW action. The conformal charge of the model coincides with that of the supersymmetric GKO construction. As a consequence of gauge fixing, the holomorphic stress-tensor $T(z)$ and superconformal generator G(z) obtained in the construction again has ghost contributions. Weak operator first-class constraints restrict the theory to physical states which satisfy the constraints. The superconformal algebra closes when evaluated between ghost-free physical states.

Karabali and Schnitzer provided a BRST reformulation of the weak first-class constraints appearing in the gauged WZW models describing G/H conformal field theories. A nilpotent operator Q was constructed, and the physical spectrum and unitarity of the theory was analyzed. When H coincides with the Cartan subalgebra of G, the BRST invariant current operators (the physical currents) were shown to be the parafermion operators. It was shown that when H is abelian, the physical states of the theory are unitary, and therefore *strong* operator equivalence with the GKO construction was established. It was conjectured, but not shown, that the same property holds for H non-abelian. These results also extend to the superconformal G/H theory discussed by Schnitzer.

Karabali, Park, and Schnitzer discussed a variety of issues interrelating non-abelian bosonization, generalized Thirring interactions, background Kaluza-Klein scalar fields and conformal invariance of two-dimensional field theories. It was found, through bosonization techniques, that the non-abelian Thirring model has a nontrivial conformal coupling which is related to the trivial one by an interchange of holomorphic and antiholomorphic components. In the abelian limit Coleman's constraint for the Thirring coupling constant is reproduced.

Naculich studied differential equations for rational conformal characters. The characters of a rational conformal field theory are the solutions of a modular invariant differential equation. By formulating this equation in terms of j, the universal modular invariant, one can determine the modular transformations of the characters from the monodromy of the solution of the equation. The requirement that the characters form a unitary representation of the modular group results in restrictions on the conformal weight h and conformal charge c. Knowledge of the modular transformations also allows one to find the relative normalization of the characters in the one-loop partition function, which specifies the absolute multiplicities of states in the conformal field theory. Naculich carried this out explicitly for a certain class of second-order equations in which the characters can be written in terms of hypergeometric functions.

Cosmic Strings

Harvey and Naculich discussed the properties of cosmic strings based on a spontaneously broken anomalous U(1) when the anomalies are cancelled via the Green-Schwarz mechanism. Such strings arise in a large class of superstring compactifications, and act as a source for an axion-like field which has model dependent couplings to QCD and QED. If this field couples to QED, but not QCD, these strings could exist today, and would exhibit novel optical properties. Such strings could be distinguished from other types of cosmic strings by studying the relative polarization of the images they produce when acting as gravitational lenses. If the axion-like field produced by these strings does couple to QCD, then these strings, as well as macroscopic heterotic superstrings, would become the boundaries of domain walls and would rapidly disappear. However there would be found configurations of the two types of strings which do not couple to QCD, and which could exist in the present universe.

Quantum Gravity and Wormholes

It is possible (although far from clear) that fluctuations which change the topology of spacetime have a significant impact on physics near the Planck scale. What is much more interesting is that they may also affect physics at lower, experimentally accessible energies. Since the discovery of wormhole solutions which seem to correspond to quantum-mechanical mixing of spaces with different topologies, numerous investigations have suggested that topology changing wormhole configurations may violate spontaneously broken (i.e. nonlinearly realized) global symmetries, that they may be important for understanding the vanishing of the cosmological constant and that they may even determine the values of other parameters as well.

Abbott and Wise have significantly extended work in this area by considering general scalar field theories and discovering new classes of wormhole solutions. The original wormhole solutions which were constructed were found in a scalar field theory with U(1) symmetry coupled to gravity, in the case when the mass term was negative so that the U(1) symmetry was spontaneously broken. In the original work of Giddings and Strominger the resulting Goldstone boson field was represented as a three-index antisymmetric tensor. Later Lee constructed solutions directly from the scalar theory itself. However, in this early work a simplifying assumption was made which is not always justified. Therefore we reconsidered this case by allowing for spatial variation in the scalar field and in particular we found that the behavior for small values of the U(1) breaking vacuum expectation value is different than in previous treatments.. However, our more interesting and novel results arose when we considered a U(1) invariant scalar theory where the mass term is positive and thus without spontaneous symmetry breaking. We constructed new wormhole configurations and found that they have infinite Euclidean action. This might suggest that such configurations have no physical relevance, but we showed that despite their infinite action, wormholes in the unbroken theory produce effects which can be reproduced in a low-energy effective field theory by including local U(1) non-invariant terms with non-zero coefficients in the effective Lagrangian and we showed how these coefficients could be calculated. Even in the spontaneously broken case we proved that when the mass, m, is much less than the Planck mass, the full wormhole action is not what controls the strength of the explicit U(1) violating terms in the low-energy effective theory. Our work led to a detailed proof that the effect of wormholes in the full theory with quantum gravity is reproduced at low energies by including local operators which violate the U(1) symmetry in the low-energy effective field theory.

We constructed the new wormhole solutions by solving the relevant Euclidean field equations. In the case where the U(1) symmetry of the underlying field theory is not spontaneously broken, as stated above, the action of the wormhole solutions is infinite. Physically this 'infrared divergence' arises because charge must flow in from $r = \infty$ if a wormhole located at $r = 0$ carries charge. The infinite action arises because in the unbroken theory all the charge carrying particles are massive. However, in the effective field theory (below the wormhole scale) the operator Φ^n acts as a point source of charge n and because the infrared divergence is reproduced exactly in the appropriate matrix element of Φ^n it does not enter into the coupling constant g_n. To compute g_n we regulated the infrared divergence by introducing a long-distance cutoff $r_{\max}$ and compared the transition amplitude between states of definite charge in the effective theory with the one-wormhole amplitude in the full theory. By doing this comparison we determined the coefficient of the local U(1) breaking term in the low-energy effective field theory and thus showed that the effect of a single wormhole carrying charge n is equivalent in a low-energy effective field theory to an insertion of the operator

$$g_n \int d^4y \Phi^n(y). \tag{1}$$

Integrating out multiple wormholes introduces into the low-energy effective field theory below the wormhole scale the interactions

$$L_I = \sum_{n=1}^{\infty} \alpha_n g_n \Phi^n \; + \; h.c. \tag{2}$$

which explicitly violate the global U(1) symmetry. Here the α_n are complex parameters which characterize the vacuum state of the theory as introduced by Coleman. The coupling constants g_n, for large $n\lambda$ are of order

$$g_n \approx \left(\frac{r_n}{\beta}\right)^n \frac{e^{-S_*^{(n)}}}{r_n^8 m_p^4} \tag{3}$$

where r_n is approximately the wormhole size

$$r_n \;\approx\; \frac{\lambda^{1/6} n^{2/3}}{m_p} \tag{4}$$

$$\beta \approx \frac{n^{1/3}}{\lambda^{1/6}} \tag{5}$$

and

$$S_w^{(n)} \approx m_p^2 r_n^2. \tag{6}$$

All work done on wormhole solutions including that described above is done in a Euclidean space formulation of gravity. In work now being completed, Abbott and E. Farhi (who has been a visitor at Brandeis for the spring semester) have constructed a Minkowski signature interpretation for the Euclidean wormhole solution. At the same time this work led to a construction of similar interpretations for Euclidean solutions corresponding to vacuum decay in spaces with a positive cosmological constant (de Sitter space). Although as physicists we frequently compute in Euclidean space, we live in Minkowski space. Thus, the results of Euclidean path integral calculations must be analytically continued back to Minkowski space before they can be physically interpreted. Solutions of the classical Euclidean field equations are often assumed to represent quantum tunnelling processes, but *it is* essential to find Minkowski *continuations* which can be correctly connected to the Euclidean solution before the physical meaning of the tunnelling process can be uncovered. Our purpose was to investigate what quantum-mechanical process in Minkowski space is being approximated by Euclidean wormhole solutions to the classical equations of gravity coupled to a U(1) invariant scalar field theory.

The topology changing interpretation of the flat space wormhole is suggested by the fact that this solution can be cut on three approximately maximal surfaces. Two of these can be taken to be the past and future of our own universe while the third connects to a baby universe at either its birth or death. For the flat-space wormhole the baby universe is just a closed Robertson-Walker universe while the large spacetime is flat Minkowski space. However, the introduction of even the smallest positive cosmological constant leads to a wormhole solution with a totally different structure.

The de Sitter wormhole solution looks like an infinite chain of spheres coupled in a chain through narrow necks (the wormholes). When cut this solution presents only two surfaces. One of these attaches naturally on to a closed Robertson-Walker spacetime as before, the baby universe. However, there is only one remaining surface to couple on to the large Minkowski signature de Sitter space. Thus, the question arises how can past and future de Sitter surfaces be connected to a Euclidean wormhole solution with only one free surface? If the entire de Sitter space is connected to this single wormhole cut then one gets a completely different interpretation of the wormhole, namely that it corresponds to quantum tunnelling between a de Sitter space and a Robertson-Walker universe as discussed by Strominger and Meyer. This is an interesting process but it does not involve any change of topology.

We have resolved this difficulty by reconsidering vacuum decay in de Sitter space where a very similar problem arises. Here the Euclidean bounce solution lives on a sphere which when cut in half likewise presents a single surface to be attached to both the past and future of the Minkowski signature de Sitter space. The resolution in both cases is a result of the unique double causal structure of de Sitter space. We use half of the cut sphere to provide final value data on the past side of a discontinuity in the classical evolution of the relevant field extending half way across the Minkowski de Sitter space. The other half of the sphere corresponds to an initial value surface for the future on the other side of this discontinuity. Thus, the Euclidean solution interpolates across a quantum-mechanical discontinuity in the classical evolution in just one-half of Minkowski signature de Sitter space. The other half of de Sitter space which is causally isolated from the half where the discontinuity is experiences completely unperturbed classical evolution. When applied to the wormhole this gives a consistent picture where the wormhole describes a violation of charge conservation in one-half of de Sitter space while charge is conserved normally in the other half. Work on this project is now being completed.

Neural Networks

A neural network memory uses fixed points of the map

$$S_i(t+1) = sign\left(\sum_{j=1}^{N} J_{ij} S_j(t)\right) \tag{7}$$

(where $S_i = \pm 1$ and $J_{ii} = 0$) as memory patterns which attract nearby input patterns providing associative recall. The dynamics (??) takes an initial input $S_i(0)$ and after a sufficient number of iterations maps it to an associated memory pattern ξ_i provided that ξ_i is a fixed point of (??) and that $S_i(0)$ lies within the domain of attraction of this fixed point. Learning in such a network is a process by which a matrix J_{ij} is constructed with the appropriate fixed points and required basins of attraction. Suppose we wish to 'learn' a set of memory patterns ξ_i^μ with $\mu = 1, 2, ..., \alpha N$. Important variables for characterizing a fixed point are

$$\gamma_i^\mu = \frac{1}{||J_i||} \sum_{j=1}^{N} J_{ij} \xi_i^\mu \xi_j^\mu \tag{8}$$

where the normalization factor $||J_i||$ is

$$||J_i|| = \sqrt{\sum_{j=1}^{N} J_{ij}^2} \quad . \tag{9}$$

In order for ξ_i^μ to be a stable memory pattern of the network, γ_i^μ must be positive for all i. In addition the distribution of γ_i^μ values has a great impact on the size of the basin of attraction associated with ξ_i^μ as shown by Abbott and Kepler.

A typical learning problem is to find a matrix J_{ij} satisfying

$$\gamma_i^\mu > \kappa \tag{10}$$

for all i and all μ with some specified value of κ. The standard method for finding a matrix satisfying (??) is to start with a random matrix and repeatedly apply the learning rule

$$J_{ij} \rightarrow J_{ij} + \frac{1}{N} \xi_i^\mu \xi_j^\mu (1 - \delta_{ij}) \theta(\kappa - \gamma_i^\mu) \tag{11}$$

at each site i and for each memory pattern μ until (??) is satisfied. It has been proven that this algorithm will converge in a finite number of steps if the desired matrix exists. However, in actual practice the standard algorithm is extremely slow.

Abbott and Kepler have constructed algorithms which are capable of finding a desired coupling matrix many times faster than this standard procedure. We considered learning algorithms of the form

$$J_{ij} \rightarrow J_{ij} + \frac{1}{N}\xi_i^\mu \xi_j^\mu (1-\delta_{ij}) f(\gamma_i^\mu) ||J_i|| \theta(\kappa - \gamma_i^\mu) \tag{12}$$

where once again the learning process consists of applying this algorithm at every site and for every memory pattern until (??) is satisfied. To study the convergence properties of the algorithm (??) we followed general methods from perception proofs. We were able to obtain analytically the form of the function $f(\gamma)$ which optimizes this learning process,

$$f(\gamma) = \kappa + \delta - \gamma + \sqrt{(\kappa + \delta - \gamma)^2 - \delta^2} \ , \tag{13}$$

where δ is a small parameter which may be taken to zero. In computer simulations this algorithm was dramatically faster than any other previously proposed.

In addition to considering the learning process Abbott and Kepler investigated both the number of coupling matrices available for a given task and the distribution of local field values γ corresponding to these matrices. The fractional interaction-space volume, storage capacity and local-field distribution of a wide variety of neural network associative memory models were computed using the interaction-space techniques of Gardner. Modifying the measure used to sum over coupling matrices allowed us to consider networks with a wide variety of behaviors away from saturation. However, near saturation network behavior was shown to be universal depending only on singular features of the measure but otherwise independent of its form. This means that the performance of a saturated network memory is relatively insensitive to the details of its construction and that network models fall into universality classes. Several universality classes were constructed, including those containing Hebb matrices, pseudo-inverse matrices and the original Gardner results, by considering a variety of singular measures.

The most commonly studied behavior in neural networks is simple fixed point behavior. However, asymmetrically coupled networks are capable of chaotic behavior as well and such behavior may have important practical applications. To study chaos in networks Abbott, Kepler and R. Meyer have constructed an electronic circuit analog. The circuit consists of four 'neurons' (this is the smallest network capable of exhibiting chaos without time-delay) which are clipped, high-gain integrating operational amplifiers. These are fully feedback coupled to each other through an array of digitally programmable resister ladders (Multiplying Digital to Analog Converters). The use of an MDAC array (which to our knowledge is unique among analog electronic networks which have been constructed) allows us to control and modify the connection matrix for the network using a digital computer interface.

For certain choices of the coupling matrix this circuit exhibits remarkable chaotic behavior. Furthermore, as the matrix of couplings is slowly adjusted we see all of the traditional approaches to chaotic behavior which have been described in the literature on chaos; period doubling, intermittency and quasi-periodic behavior. In fact, we have even seen strange attractors which exhibit all three approaches to chaos depending on how the chaotic strange attractor is reached. We have simulated idealized equations governing the network circuit and the excellent agreement between these computer simulations and actual circuit behavior convinces us that we have a good basic understanding of the behavior of the circuit. However, there is presently no theoretical understanding of its chaotic behavior other than the usual universal results applicable to all chaotic systems. A

preliminary study of coupling matrices which lead to chaotic behavior has indicated some statistical trends which might help us to predict and control the presence of chaotic behavior in networks, and to begin work on a more thorough theoretical understanding of chaos in networks.

Publications from June 1, 1988 to May 31, 1989

Strings and Conformal Field Theory

1. "A GKO Construction Based on a Path Integral Formulation of Gauged Wess-Zumino-Witten Actions" (Karabali, Park, Schnitzer, and Yang), Phys. Lett. **216B**, 307 (1989).
2. "A Path Integral Construction of Superconformal Field Theories from a Gauged Supersymmetric Wess-Zumino-Witten Action" (Schnitzer), Brandeis preprint BRX TH-254, published in Nuclear Physics B.
3. "Thirring Interactions, Non-Abelian Bose-Fermi Equivalences and Conformal Invariance" (Karabali, Park, and Schnitzer), Brandeis preprint BRX TH-262, to be published in Nuclear Physics B.
4. "BRST Quantization of the Gauged WZW Action and Coset Conformal Field Theories" (Karabali and Schnitzer), Brandeis preprint BRX TH-267.
5. "Differential Equations for Rational Conformal Characters" (Naculich), Brandeis preprint BRX TH-257, to be published in Nuclear Physics B.

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6. "Cosmic Strings from Pseudo-Anomalous U(1)'s" (Harvey and Naculich), Phys. Lett. **217B**, 231 (1989).

Quantum Gravity and Wormholes

7. "The Mystery of the Cosmological Constant" (Abbott), Sci. Am., May 1988.
8. "Baby Universes and Making the Cosmological Constant Zero" (Abbott), Nature **336**, 711 (1988).
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10. "Wormholes with a Past" (Abbott and E. Farhi) (in preparation).
11. "Quantum Gravity and Strings: Applications in Cosmology and the Quantization of the Superstring" (Xu), Brandeis University PhD Thesis (advisors: Abbott and Grisaru).

Neural Networks

12. "Model Neural Networks" (Kepler), Brandeis University PhD Thesis (advisor: Abbott).
13. "Domains of Attraction in Neural Networks" (Abbott and Kepler), J. de Phys. (France) **49**, 1657 (1988).
14. "Universality in the Space of Interactions for Network Models" (Abbott and Kepler), J. Phys. (to be published).

15. "Optimal Learning in Neural Network Memories" (Abbott and Kepler), J. Phys. (to be published).

16. "A Neural Network Circuit for Exploring Chaotic Behavior" (Abbott, Kepler and R. Meyer), (in preparation).