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Scientific and Computational Foci: We will focus on developing the capability to carry out large scale simulations of complex, multiple, interacting fault systems using a software environment adapted for rapid prototyping of new phenomenological models. The software environment will require: 1) Developing algorithms for solving computationally difficult nonlinear problems involving ("discontinuous") thresholds and nucleation events in a networked parallel (super) computing environment; 2) Adapting new "fast multipole" methods previously developed for general N-body problems; 3) Adapting existing modern Web and other commodity technologies to allow researchers to rapidly integrate simulation data with field and laboratory data (visually and quantitatively).

Significance of Anticipated Results: The GEM approach will allow the physics of large networks of earthquake faults to be analyzed within a general computational and theoretical framework for the first time. Using recent advances in space-time Pattern Dynamics analysis methods for complex nonlinear threshold systems, GEM may lead to several forecast methodologies similar to those now used for El Niño forecasts. The computational techniques developed by the project will find significant applications in many other computationally hard problems of great technological importance, for example, 1) simulating nonlinear threshold systems such as large neural networks with learning and cognition; 2) magnetic depinning transitions in superconductors and charge density wave systems; 3) growth of magentized domains in ferromagnets; and 4) statistical physics approaches to random field spin systems.

Investigator Team: Our team is internationally recognized in the three areas of 1) Earth science 2) statistical mechanics and complex systems and 3) computational science. The latter include world experts in the critical algorithms, software and both HPCC and commodity systems required. We plan a vigorous education and outreach program, so technology transfer to related projects, as well as educational benefits, will follow easily. Rundle will serve as Principal Investigator. The Investigators will participate in periodic workshops at which 1) results will discussed; and 2) specific research avenues will be formulated on a regular and timely basis. We will partner actively with scientists from the existing Southern California earthquake Center and the proposed California earthquake Research Center.

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☐ Please check if Results from Prior NSF Support already have been reported to NSF via the NSF FastLane System, and list the Award Number for that Project

NSF Award No.: ____________

Appendix Items:

*Proposers may select any numbering mechanism for the proposal, however, the entire proposal must be paginated. Complete both columns only if the proposal is numbered consecutively.

NSF Form 1359 (10/97)

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C. Project Description

C.1 Web References and Resources:

GEM Web Site: http://www.npac.syr.edu/projects/gem
(This site has information on the GEM team, scientific results, codes and plans)

ftp site: ftp://fractal.colorado.edu/pub/Viscocodes/Virtual_California

on host: fractal.colorado.edu
(This site has current versions of the basic numerical codes from *Rundle* [1988] upon which many of the initial GEM methods will be based, together with results from recent small scale model runs possible on current workstations)

C.2 Earthquake Science: Issues and Opportunities

Rationale for Earthquake Research: Earthquakes, even those significantly smaller than the largest magnitude events of about magnitude 9.5 (e.g., Chile, 1960), are capable of producing enormous damage today and in the future. The recent January 16, 1995 Kobe, Japan earthquake (magnitude ~ 7) was responsible for an estimated $200 billion in damages, accounting for lost economic income as well as direct structural damage. This event was a complete surprise, inasmuch as the immediate region had been relatively inactive in historic time (see, e.g., *Trans. AGU*, **76** Supp., 1995). It has also been estimated that a repeat of the 1933 Long Beach California earthquake, which had a maximum Modified Mercalli Intensity of IX, would today cause in excess of $500 billion in damages, rather than the $41 million loss that occurred in 1933 . These figures can be compared to the total assets of the US Property Insurance Industry, which is at present about $200 billion (*Insurance Institute for Property Loss Reduction*, pers. comm., 1997). Losses in a repetition of the 1906 San Francisco earthquake would be far larger. The magnitude of these potential losses, even in an economy the size of the United States in 1998, $1.7 trillion, clearly indicate the need to evolve approaches to understand, forecast, and mitigate the risk. The importance of developing techniques to eventually predict or forecast earthquakes has been underscored by the fact that an increasing proportion of the global population lives along active fault zones (*Bilham*, 1996).

Status of Earthquake Science: Although a great deal of data has accumulated about the phenomenology of earthquakes in recent years, these events remain one of the most destructive and poorly understood of the forces of nature (see e.g., *Reid*, 1908; *Richter*, 1958; *Scholz*, 1990; and the review by *Rundle and Klein*, 1995). In the last decade, a series of national policy decisions and programs have culminated in the establishment of the Southern California earthquake Center (SCEC) (http://www.scec.org/); and parallel efforts in other countries, e.g., (http://shake2.Earthsciences.uq.edu.au/ACES/). An even larger group of Universities have come together to propose the new California Earthquake Research Center, under the NSF Science and Technology Centers program, to succeed SCEC in the year 2001. Together with efforts initiated several decades ago by the United States Geological Survey (http://www.usgs.gov/themes/Earthqk.html), the accuracy, reliability, and availability of observational data for earthquakes, particularly in southern California, have increased enormously.

Despite this, the scientific community is unable to even approximately forecast the time, date, and magnitude of earthquakes. At the moment, the best that can be done is embodied in the Phase II report of earthquake probabilities published by the SCEC (*SCEC*, 1995; (http://www.scec.org/). These probabilities are based on "scenario earthquakes" and probabilistic assumptions about whether, for example, contiguous segments of faults ("characteristic earthquakes") do or do not tend to rupture together to produce much larger events. Attempts to forecast large events based on recurrence intervals or physical precursory phenomena have been pursued since the 1970s without notable success.

Recent research indicates that earthquakes exhibit a wealth of complex phenomena over a very large range of spatial and temporal scales, including space-time clustering of events, self-organization and scaling (e.g., *Scholz*, 1990; *Turcotte*, 1992). It is has often been suggested that the most promising strategy for forecasting large earthquakes would be to learn how to recognize the space-time patterns of the smaller earthquakes that precede them. Several strategies have emerged ranging from pure pattern recognition techniques (*Keilis-Borok et al,* 1996; *Minster and Williams,* 1996; *Pepke et al*, 1994; *Ben Zion and Eneva*, 1996) to methods based on analogies with the statistical mechanics of critical phenomena (e.g. *Sornette, et al.,* 1996) to new Pattern Dynamics approaches (*Rundle et al*., 1998).

Why GEM, and Why Now? There is a growing consensus in the scientific community that the time has come to establish a feedback loop between observations, theory and computer simulations within the field of earthquake science similar to that which currently exists in the study of climate and atmospheric science. The goals of the General earthquake Model (GEM) project are similar to those of the GCM community: 1) to develop sophisticated computer simulations based upon the best available physics, with the goal of understanding the physical processes that determine the spatial and temporal distribution of earthquakes on active fault networks, and 2) to develop a model of the earthquake process that will allow current data to be projected forward in time, so that model predictions can be tested against future observations.

A “Pattern Dynamics” pattern recognition methodology has recently been developed for earthquakes (*Rundle and Klein*, 1988a). It is similar to the approach used in climate studies for El Niño predictions, which have made it possible to forecast these events 6 months to 1 year before onset, with an approximately ~ 70% success rate (e.g. *Barnston et al.*, 1994; *Chen et al.*, 1995; *Penland and Magorian*, 1993). The success of such El Niño investigations bodes well for earthquake studies since both problems involve nonlinear systems with structure developed on a wide range of scales.

The GEM project is a large, complicated, and expensive undertaking (by academic standards). It involves more than 40 scientists at about 20 institutions. Since the difficulty of the problem is comparable to numerical climate/weather forecasting, which today involves thousands of scientists at many institutions as well as entire federal agencies, the scale of the GEM project should not be surprising. Moreover, the functions described below, 1) modeling and analysis, 2) computations, 3) calibration / validation / assimilation, are the same as those for the climate/weather problem. Although earthquake modeling and simulation techniques have been the focus of small research projects for the past two decades, the various groups have not tended to work in the kind of large, collaborative modes that have become the norm in the climate/weather community. Rather, these activities have tended to remain small, disconnected, and relatively isolated from each other and from observational and laboratory seismologists.

However, there is growing suspicion that much larger numerical models of multiscale fault networks are required to simulate spatio-temporal patterns of seismicity, with sufficient veracity to be used in concert with real-time seismicity and geodetic data in a predictive mode. Specifically, such models must ultimately incorporate the physics of rupture on individual faults and the time dependent rheology of the crust between faults. Of greatest interest is the capability to study the space-time characteristics of large populations of earthquakes, rather than focusing on individual events. Other factors motivating the initiation of a large scale numerical simulation program at this time include the extremely rapid increase of computational capability within the last five years, the recent availability of extensive new data sources such as InSAR and GPS, and the even more rapid increase in the economic cost of earthquake disasters.

C.3 Computational Science: Issues and Opportunities

Computational Significance of GEM: While there are similarities to the weather/climate problem, the earthquake problem presents unique computational aspects implying that entirely new and novel algorithms will be needed. Specifically, the observational Gutenberg-Richter magnitude-frequency relation and the Omori aftershock law, both of which are scaling relations, indicate that the earthquake system is always operating in close proximity to a critical point (*e.g., Carlson et al.*, 1991; *Rundle and Klein*, 1994; *Sornette and Sammis*, 1995). Consequently, correlation lengths and correlation times will always be large. This is in contrast to large scale weather forecasting, which tends to focus on "forecastable" synoptic-scale problems and to neglect sub-grid scale turbulent processes. Earthquake simulations cannot afford this luxury. Scaling laws in fluid dynamics calculations such as the Kolmagorov five-thirds law (e.g., Frisch, 1995) are observed only intermittently in space and time, in strongly turbulent flows. This difference in "persistence" of the dynamics is the reason why weather and climate are clearly "forecastable" to some extent at present, and why earthquakes are not. For these reasons, the computational aspects of GEM will have important implications for simulation techniques used to model similar nonlinear threshold systems, including large neural networks (*Hertz et al.*, 1991; *Herz and Hopfield*, 1995), depinning transitions in driven superconductors and charge density wave materials (*Fisher*, 1985), driven foams (*Gopal and Durian*, 1995), magnetized domains in ferromagnets (*Urbach et al.*, 1995), sandpiles (*Bak et al.*, 1987) and so forth. Many of these systems have considerable technological significance.

Why GEM is an HPC-class Problem: Current evidence indicates that forecasting the damaging earthquakes of magnitude ~ 6 and greater almost certainly depends upon understanding the space-time patterns displayed by smaller events, e.g., the magnitude 3's, 4's and 5's (*Sornette et al.*, 1996; *Keilis-Borok et al*, 1996; *Minster and Williams*, 1996). With at least 40,000 km^2 of fault area in southern California capable of participating in magnitude 6 and greater events, and needing a spatial resolution of about 100 m to eliminate grid-scale effects and to capture the physical processes of the magnitude 3 events, we arrive at the conclusion that as much as 10^6 grid sites will be necessary for a maximally realistic simulation. If grid sizes at the 10 m scale are used to capture the failure physics of the magnitude 3 events, then ~ 10^8 grid sites will be needed. Below we give run time estimates of several months for such a problem based upon current technology. This clearly puts the GEM problem into the HPC range.

The scientific establishment in Japan clearly recognizes these facts. Officials at the Japanese RIST funding agency recently announced (*H. Nakamura, Personal communication*, 1997) a funded program of some $400 million over the period 1996-2001 to construct a 32 TERAFLOP computer to be dedicated to weather and earthquake forecasting. At the present time, no such computer, and no such GEM-type program is even contemplated in the United States.

A significant feature of the GEM HPC challenge is the lack of major large “legacy” codes. This deficiency turns out to be an advantage, because we can immediately adopt modern distributed object-oriented technology from the outset. We have used initial computations to estimate that the simulation of a fault network containing 107 elements requires machines of 1 to 100 TERAFLOPs, in the same range as the machine announced by the Japanese. The uncertainty in our estimate reflects the currently unknown requirements stemming from needed accuracy in earthquake simulation. The development of a forecast/predictive capability will thus require enormous computational resources, which are comparable to those needed for the large-scale simulations of DOE's ASCI program. We expect such capabilities to be available from general facilities such as the Los Alamos Advanced Computing Laboratory (ACL), NPACI - San Diego, NCSA - Illinois, and the Boston University MARINER project. Eventually one might expect to set up dedicated resources for earthquake forecasting as planned in the major Japanese program in this area. Although these high-end machines may well have distributed shared memory architecture, our software should also support the increasingly popular clusters of PC hardware, which provide a cost-effective development environment. The many levels of complexity present in the current and future generations of New Computational Challenge simulations will call for an interactive team of Earth scientists, physicists and computational scientists working together.

GEM Computational Infrastructure: The GEMCI will involve the following elements:

User Interface
Non-local Equation Solver (Green’s functions)
Modules specifying local Physics and friction
Evaluation, Data analysis and Visualization
Data storage, indexing and access for experimental and computational information
Complex Systems and Pattern Dynamics Interactive Rapid Prototyping environment for developing new phenomenological models with their analysis and visualization.
Overall Integration of GEMCI into a problem solving environment

We will describe the details in sections C.7, C.8 and C.9 but here we summarize our overall approach. One important feature of GEM is that there are no major large “legacy” codes. This can be turned into an advantage, because we can adopt modern distributed object-oriented technology from the outset. There are ambitious high performance computing projects in this area: ***POOMA*** (http://www.acl.lanl.gov/PoomaFramework/; ***Nile*** (http://www.nile.utexas.edu/) and ***Legion*** (http://www.cs.virginia.edu/~legion/). We intend to adopt a simpler approach where we do not initially link distributed object and parallel computing concepts. We will use traditional Message Passing Interface (MPI) based parallel systems with extensive use of libraries so that for instance the fast multipole algorithm can be used by application programs from a high level interface that hides the details of its MPI implementation. Sequential or parallel programs will then be encapsulated as Common Object Broker Architecture (CORBA) objects which will allow us to link them together and with databases, visualization and collaboration tools with invocations that do not depend on the computing platform and module implementation. Early on, we intend to establish an overall ***Computational Seismic Framework***, which will allow the team to develop different modules separately, in such a way as to enable this integration. This involves effectively defining a "CORBA vertical facility" with the properties and methods of the GEM modules defined in terms of a specific IDL (Interface Definition Language) syntax. NPAC has substantial experience in this area with projects for the NCSA Alliance, DoD Modernization and ASCI. A new book *'Building Distributed Systems for the Pragmatic Object Web'* (http://www.npac.syr.edu/users/shrideep/book/) co-authored by Fox and his colleagues describes how other commodity technologies including Microsoft's COM and Java can be integrated with CORBA in the emerging object web.

As most of our software will be built from scratch, we expect that we can establish and enforce the uniform practices of a ***Computational Seismic Framework*** which will lead to a GEMCI consisting at a high level of a set of coarse grain “Distributed Scientific Objects.” These can be in any language (such as parallel C, C++ Java or Fortran) but with a uniform Javabean applet front end. Note, for instance, that cellular automata models are natural applications for Fortran or HPF, but the complex hierarchical data structures of the fast multipole method are much more naturally handled in C or C++. One can also anticipate using Java to directly develop some application modules as this is rapidly emerging as an attractive modeling language (http://www.npac.syr.edu/projects/javaforcse). The support of multiple paradigms will not lead to a chaotic environment because we will enforce uniformity at the module interfaces. Integration of these multi-paradigm coarse grain objects will rely either on commercial CORBA or COM object brokers or on custom technology such as NPAC's WebFlow/JWORB (which integrates Web CORBA and COM in a single Java Server.) NPAC has also already demonstrated (http://www.npac.syr.edu/users/gcf/alliance98/index.html) how one can use a multi-tier architecture to link Globus (http://www.globus.org) with CORBA and Web modules to achieve high-performance when necessary. This complication is only needed to enhance inter-module performance; we use conventional parallel computing approaches internally to each module.

We do not propose to assign significant resources to develop an overall computer science infrastructure: we will be using well established parallel computing techniques and impose a uniform overall design framework to allow commodity distributed object systems such as CORBA to manage the coarse grain structure of GEMCI. It is clear that a rich set of tools is quickly becoming available to support this approach. Our clear separation of parallel and object technologies is not the most ambitious approach possible but ensures an excellent system, which can adapt to inevitable change with a modest level of effort.

C.4 GEM Scientific Objectives

In previous sections we discussed the philosophy of the GEM simulations by drawing analogies with the GCM climate simulation project. There are scientific similarities as well. Both are extended non-linear systems which develop structures cascading over a wide range of scales and both require that as wide a range of scales as possible be included in the model. However there are significant differences. The physics of climate is governed by continuum mechanics and thermodynamics, for which appropriate partial differential equations (e.g. Navier-Stokes) have been identified and validated. In contrast, earthquakes are probably best described as threshold phenomena involving nucleation and rupture processes which are, themselves, not well understood. For seismicity simulations we must in principle deal with both the complexity of the individual events (rupture phenomenon) and the complexity of a population of events on a multi-scale network (patterns of events). A well constructed simulation technology should hold the promise of an iterative solution to both problems through a direct comparison of simulations with seismicity and geodetic data. In this context, specific **scientific objectives** of our research include :

Objective 1. Cataloguing and understanding the nature and configurations of space-time patterns of earthquakes and examining whether these are scale-dependent or scale-invariant in space and time (e.g., *Scholz*, 1990; *Ben-Zion & Rice*, 1993; 1995; 1996, 1997; *Ben-Zion*, 1996; *Eneva and Ben-Zion*, 1997a,b; *Lyakovsky et al.*, 1997; *Rundle et al.*, 1998). Correlated patterns may indicate whether a given event is a candidate foreshock. We want to study how patterns form and persist. One application will be to assess the validity of the "gap" and "antigap" models for earthquake forecasting (e.g., *Kagan and Jackson*, 1991; *Nishenko et al.*, 1993). Another will be to understand the physics of "correlation at a distance," and "time delayed triggering," which result in seismicity that seems correlated over larger distances and time intervals than previously thought (e.g. *Hill et al.*, 1993).

Objective 2. Identifying the key parameters that control the physical processes and space-time patterns. We want to understand how fault geometry, friction laws, and Earth rheology enter the physics of the process, and which of these are the controlling parameters.

Objective 3. Understanding the importance of inertia and seismic waves in determining details of space time patterns and slip evolution.

Objective 4. Understanding the role of sub-grid scale processes, and whether these might be parameterized in terms of uncorrelated or correlated noise.

Objective 5. Ascertaining the possible effects of unmodeled processes, including neglected, hidden or blind faults, lateral heterogeneity, variability in friction laws, nature of the tectonic forcing and Earth rheology.

Objective 6. Developing and testing potential earthquake forecast algorithms, based upon the use of space-time pattern dynamics (*Rundle et al.*, 1998) or other methods, such as log-periodic (*Sornette et al.*, 1996) and other algorithms (e.g. *Keilis-Borok et al*, 1996; *Minster and Williams*, 1996)**.**

C.5 Complexity, Nonlinearity, Space-Time Patterns and Scales

Approach: Credible, realistic earthquake simulations must be expected to display space-time complexity comparable to the real world. Simulations allow experiments to understand better the origin and stability of such complexity. For example: 1) Calculations can be repeated with different random initial conditions to study the influence of fluctuations and annealed noise; 2) Slightly different geometries and parameter families, with different grid scales can be adopted to determine the effects of quenched noise; 3) Parameters can be tuned to optimize or isolate selected effects, and so forth. While these and other numerical experiments can be carried out, there is also a need to use these simulations in order to develop analysis techniques that can be applied to natural seismic data and earthquake fault systems. We highlight below a sampling of current ideas and approaches.

Hierarchy of Spatial and Temporal Scales: The presence of hierarchies of spatial and temporal scales is a recurring theme in modern ideas about earthquakes. It is known, for example, that fault and crack systems within the Earth are distributed in a scale invariant manner over a wide range of scales (*Brown and Scholz*, 1985; *Power et al.*, 1988; *Scholz*, 1990; *Turcotte*, 1992). Moreover, the time intervals between characteristic earthquakes on this fractal system is known to form a scale invariant set (*Allègre et al.*, 1982, 1994 1996; *Smalley et al.*, 1985; 1987). Changes in scaling behavior have been observed at length scales corresponding to the thickness of the Earth's lithosphere, but the basic physics remains nevertheless similar over many length scales (e.g., *Rundle and Klein*, 1995). It is also known that nucleation and critical phenomena—which are now suspected to govern many earthquake-related phenomena—are associated with divergent length and time scales and long range correlations and coherence intervals (see, e.g., *Rundle and Klein*, 1995 for a literature review and discussion). Our philosophical approach to simulations will begin by focusing on the largest scales first, working down toward shorter scales as algorithms and techniques improve. Moreover, our practical interest is limited primarily to the largest faults in a region, and to the largest earthquakes that may occur. Therefore, focussing on quasistatic interactions and long wavelength interactions is the most logical initial strategy.

We plan to model smaller faults and events as a background “noise” in the simulations, as discussed in the proposed work. In this respect, we will have to address the issue of “cascades,” —similar to cascades encountered in turbulence models—, and determine whether such cascades cause difficulties near the “Nyquist” wavelength of the grid.

Dynamics of Space-Time Patterns: Anecdotal evidence accumulated over many years indicates the existence of space-time patterns in seismicity data (*Scholz*, 1990; *Das et al.,* 1986; *Simpson and Richards,* 1981; *Rundle et al.,* 1996). The exact nature of these patterns, however, has so far eluded identification. Recent attempts to forecast seismic activity have been based upon several approaches. One of the oldest ones is exemplified by the M8 algorithm of *Keilis-Borok* and coworkers (*SCEC*, 1997): several seismic activity functions are tracked as functions of time. When these attain preset values, a “Time of Increased Probability” (TIP) is triggered, and remains in effect for several years. Another method relies on identification of a precursory “Active Zone” before the largest events that seems to be evident in a variety of numerical simulations (*Shaw et al.* 1992; *Pepke et al.,* 1994). Still another promising approach is the log-periodic time-to-failure method (e.g. *Sammis et al*., 1996) that relies on a characteristic signature arising from an earthquake failure process involving a discrete scale invariant hierarchy of smaller events. Finally, *Eneva and Ben-Zion* (1997a,b) have applied standard pattern recognition techniques to simulations in an effort to categorize the kinds of space-time patterns that may exist in real data. It should be noted that all of these approaches implicitly assume that space-time patterns do exist in the data and can be discovered through analytical techniques.

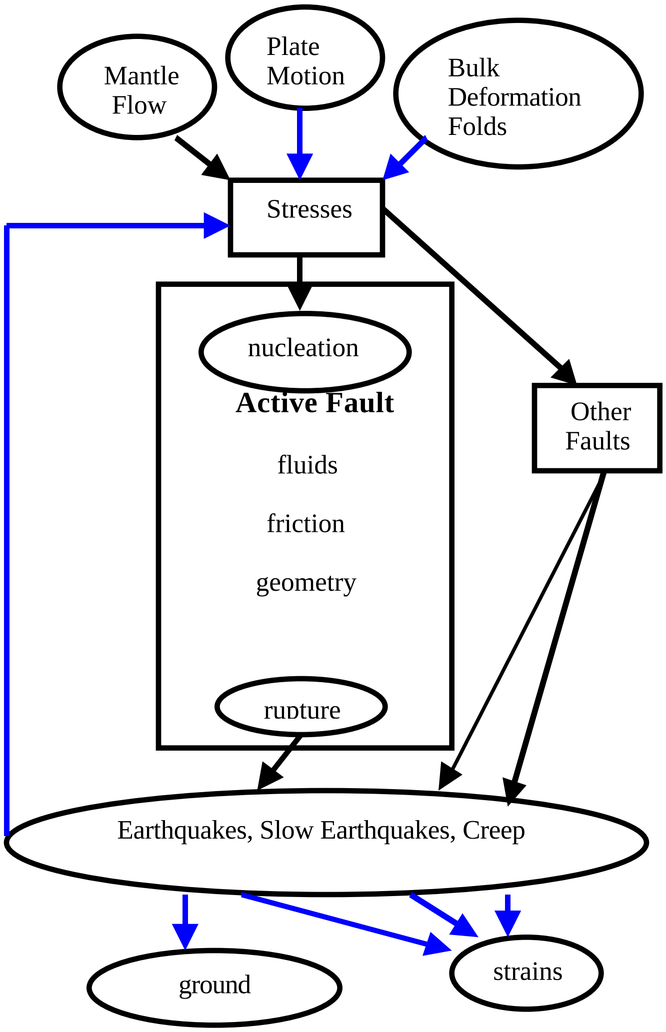
Quite recently, a new Pattern Dynamics approach has been devised, that holds the promise of identifying and classifying all possible space-time patterns that may exist for a given set of faults, together with the probabilistic master equation that governs their evolution (*Rundle and Klein,* 1998a).The patterns are represented by a complete set of orthonormal eigenfunctions (eigen-patterns) of an appropriately defined matrix operator that embodies the dynamics of the various fault segments. A pattern state evolution operator can be then constructed and used to propagate the pattern states probabilistically in time. Similar pattern state operators can be retrieved from real earthquake datasets, if one has a long enough time series of observations. Numerical simulations can be used to construct the pattern state evolution operators as long as the simulation captures the statistical characteristics of actual seismicity. These operators can then be used on real datasets 1) to identify in which eigen-pattern the real fault system currently resides, and 2) to forecast into which space-time pattern the real fault system is likely to evolve. A similar approach is currently used in El Niño forecasting with an approximately ~ 70% success rate (e.g. *Barnston et al.,* 1994; *Chen et al.,* 1995; *Penland and Magorian,* 1993).

C.6 Proposed Scientific Approach

Fundamental Equations: The basic problem to be solved in GEM is the following (e.g., *Rundle* 1988a): Given a network of faults embedded in an Earth with a given rheology, subject to loading by distant stresses, and neglecting elastic waves (see discussion below), evolution of the state of slip $\mathbf{s}(\mathbf{x},t)$ on a fault at $(\mathbf{x},t)$ is determined from the equilibrium of stresses according to Newton's Laws:

$$\frac{\partial \mathbf{s}(\mathbf{x},t)}{\partial t} = \Phi \left\{ \Sigma_i \ (\sigma_i) \right\} \tag{1}$$

where $\Phi\{\}$ is a nonlinear functional, and $\Sigma_i \ (\sigma_i)$ represents the sum of all stresses acting within the system. These stresses include 1) the interaction stress $\sigma_{int}[\mathbf{x},t;\ \mathbf{s}(\mathbf{x}',t');\ \mathbf{p}]$ provided by transmission of stress through the Earth's crust arising from background tractions $\mathbf{p}$, as well as stresses due to slip on other faults at other sites $\mathbf{x}'$ at times t'; 2) the cohesive fault frictional stress $\sigma_f[\mathbf{x},t;\ \mathbf{s}(\mathbf{x},t)]$ at the site $(\mathbf{x},t)$ associated with the state of slip $\mathbf{s}(\mathbf{x},t)$; and 3) other stresses such as those due to dynamic stress transmission and inertia. The transmission of stress through the Earth's crust involves both dynamic effects arising from the transient propagation of seismic waves, and from static effects that persist after wave motion has ceased. Rheologic models typically used for the Earth's crust between faults are all linear (e.g., *Rundle and Turcotte,* 1993) and include 1) a purely elastic material on both long and short



time scales; 2) a material whose instantaneous response is elastic but whose long term deformation involves bulk flow (viscoelastic); and 3) a material that is again elastic over short times, but whose long term response involves stress changes due to the flow of pore fluids through the rock matrix (poroelastic). In the adjacent figure, we show the basic conceptual "wiring diagram" for the model, which indicates the interplay between loading stresses, rupture, interactions with other faults, and relaxation processes following a major earthquake.

Green's Functions: Focusing on GEM models that assume a linear interaction rheology between the faults implies that the interaction stress can be expressed as a spatial and temporal convolution of a stress Green's function $\mathbf{T}_{ij}^{kl}(\mathbf{x}-\mathbf{x}',t - t')$ with the slip deficit variable $\varphi(\mathbf{x},t) = \mathbf{s}(\mathbf{x},t) - \mathbf{V}t$, where $\mathbf{V}$ is the long term rate of offset on the fault. Once the slip deficit is known, the displacement Green's function $\mathbf{G}_{ij}^{k}(\mathbf{x}-\mathbf{x}',t-t')$ can be used to compute, again by convolution, the deformation anywhere in the surrounding medium exterior to the fault surfaces (e.g. *Rundle* 1988a). We know of no approach other than a Green's function method that can be used in the context of specified fault geometries, realistic earth models and linear rheologies, and specified friction and failure laws, to quantitatively and numerically compute synthetic earthquake sequences, space-time stress and seismicity patterns, and surface deformation for direct comparison to observations (see for example *Scholz*, 1990; *Kostrov and Das*, 1988).

Seismic Waves: In the first implementation of GEM models, we will further specialize to the case of quasistatic interactions, even during the slip events. Although we plan to include elastic waves and inertia for synthetic earthquakes in the future (e.g., *Aki and Richards*, 1980; *Zheng et al.*, 1995; *Kanamori*, 1993; *Beroza*, 1995; *Jordan*, 1991; *Imhlé et al.*, 1993). Recent work (*Perrin and Rice*, 1995; *Shaw*, 1995), has shown that many important features of earthquakes and slip evolution on faults can be reproduced without including waves (*Rundle*, 1988; *Rundle and Klein*, 1995a; *Ben-Zion and Rice*, 1993; 1995; 1997). Examples of these features include statistics (*Rundle and Jackson*, 1977; *Rundle and Klein*, 1993; 1995a,b; 1996; 1997; *Carlson and Langer*, 1989; 1991a,b; *Shaw*, 1992; 1995; *Fisher, et al.*, 1997), characteristics of source-time functions (*Rundle and Klein*, 1995a), and space-time slip patterns (*Rundle* 1988; *Rundle et al.*, 1998b). Observational evidence supports the hypothesis that simulations carried out without including inertia and waves will have substantial physical meaning. *Kanamori and Anderson* (1975) and *Kanamori et al.* (1998) estimated that the seismic efficiency η, which measures the fraction of energy in the earthquake lost to seismic radiation, is less than 5%-10%, implying that inertial effects in the dynamical evolution of slip in studying large populations of earthquakes will be of lesser importance for initial calculations. Elastic waves will be included in later simulations when errors arising from other effects are reduced to the 5%-10% level. At present, inclusion of these effects is severely limited by available computational capability, so we anticipate that it may be only practical to include only the longest wavelengths or largest spatial scales. This computational plan is consistent with our philosophical approach.

Inelastic Rheologies: In quasistatic interactions, the time dependence of the Green's function typically enters only implicitly through time dependence of the elastic moduli (e.g., *Lee*, 1955). Because of linearity, the fundamental problem is reduced to that of calculating the stress and deformation Green's function for the rheology of interest. For materials that are homogenous within horizontal layers, numerical methods to compute these Green's functions are well known (e.g., *Okada*, 1985, 1992; *Rundle*, 1982a,b, 1988*; Rice and Cleary*, 1976; *Cleary*, 1977*; Burridge and Varga,* 1979; *Maruyama*, 1994). Problems in heterogeneous media, especially media with a distribution of cracks too small and too numerous to model individually, are often solved by using effective medium approaches, self-consistency assumptions (*Hill*, 1965; *Berryman and Milton*, 1985; *Ivins*, 1995a,b), or damage models *Lyakovsky et al.* (1997). Suffice to say that a considerable amount of effort has gone into constructing quasistatic Green's functions for these types of media, and while the computational problems present certain challenges, the methods are straightforward as long as the problems are linear. In the proposed work, we will focus on elastic (with possible incorporation of damage parameters) and layered viscoelastic models only.

Friction Models: At the present time, six basic classes of friction laws have been incorporated into computational models.

1. Two basic classes of friction models arise from **laboratory experiments:**

Slip Weakening **-** This friction law (*Rabinowicz*, 1965; *Bowdon and Tabor*, 1950; *Beeler et al.*, 1996; *Stuart*, 1988; *Li*, 1987; *Rice*, 1993; *Stuart and Tullis*, 1995) assumes that the frictional stress at a site on the fault $\sigma_f = \sigma_f[\mathbf{s}(\mathbf{x},t)]$ is a functional of the state of slip. In general, $\sigma_f[\mathbf{s}(\mathbf{x},t)]$ is peaked at regular intervals. The current state of the system is found from enforcing the equality $\sigma_f[\mathbf{s}(\mathbf{x},t)] = \sigma_{int}[\mathbf{x},t;\ \mathbf{s}(\mathbf{x}',t');\ \mathbf{p}]$ prior to, and just after, a sliding event.

Rate and State **-** These friction laws are based on laboratory sliding experiments in which two frictional surfaces are slid over each other at varying velocities, usually without experiencing arrest (*Dieterich*, 1972; 1978; 1981; *Ruina*, 1983; *Rice and Ruina*, 1983; *Ben Zion and Rice*, 1993; 1995; 1997; *Rice*, 1993; *Rice and Ben Zion*, 1996). In these experiments, the laboratory apparatus is arranged so as to be much "stiffer" than the experimental "fault" surfaces. The rate dependence of these friction laws refers to a dependence on logarithm of sliding velocity, and the state dependence to one or more state variables $\theta_i(t)$, each of which follows an independent relaxation equation.

2. Two classes of models have been developed and used that are based on laboratory observations, but are **computationally simpler.**

Coulomb-Amontons **-** These are widely used because they are so simple (e.g., *Rundle and Jackson*, 1977; *Nakanishi*, 1991; *Brown et al.*, 1991; *Rundle and Brown*, 1991; *Rundle and Klein*, 1992; *Ben Zion and Rice*, 1993, 1995, 1997). A static failure threshold, or equivalently a coefficient of static friction μ^S is prescribed, along with a residual strength, or equivalently a dynamic coefficient of friction μ^D. When the stress at a site increases, either gradually or suddenly, to equal or exceed the static value, a sudden jump in slip (change of state) occurs, that takes the local stress down to the residual value. These models naturally lend themselves to a Cellular Automaton (CA) method of implementation.

Velocity Weakening **-** This model (*Burridge and Knopoff*, 1967; *Carlson and Langer*, 1989) is based on the observation that frictional strength diminishes as sliding proceeds. A constant static strength $\sigma_f = \sigma^F$ is used as above, after which the assumption is made that during sliding, frictional resistance must be inversely proportional to sliding velocity.

3. Two classes of models are based on the use of **statistical mechanics** involving the physical variables that characterize stress accumulation and failure. Their basic goal is to construct a series of nonlinear stochastic equations whose solutions can be approached by numerical means:

Traveling Density Wave **-** These models (*Rundle et al.*, 1996; *Gross et al.*, 1996) are based on the slip weakening model. The principle of evolution towards maximum stability is used to obtain a kinetic equation in which the rate of change of slip depends on the functional derivative of a Lyapunov functional potential. This model can be expected only to apply in the mean field regime of long range interactions, which is the regime of interest for elasticity in the Earth. Other models in this class include those of *Fisher et al* (1997) and *Dahmen et al* (1997).

Hierarchical Statistical Models **-** Examples include the models by *Allègre et al*. (1982, 1996); *Smalley et al.* (1985); *Blanter et al.* (1996); *Allègre and Le Mouel* (1994); *Heimpel* (1996); *Newman et al.* (1996); and *Gross* (1996). These are probabilistic models in which hierarchies of blocks or asperity sites are assigned probabilities of failure. As the level of external stress rises, probabilities of failure increase, and as a site fails, it influences the probability of failure of nearby sites.

C.7 Proposed Computational Approach

The GEM Computational Infrastructure (GEMCI) described in section C.3 requires several technological components. A major one is the detailed simulation modules for the variety of physics and numerical approaches discussed above. This includes the non-local equation solver and physics/friction modules (GEMCI.2,3). The fast multipole, statistical mechanics and cellular automata subsystems will need state of the art algorithms and parallel implementations. These will be built as straightforward MPI-based parallel systems, within the overall modular structure implied by our proposed *Seismic Framewor*k.

Estimate of Computational Resources Needed: A careful analysis reveals that the algorithms needed for large scale simulations are rather different from those used up to now. We base our analysis on simulations performed so far, which use 80 to 64,000 sites and various interaction laws. We also use the known results from the fast multipole approach to astrophysics simulations with 100 million particles. We estimate an execution time between 4 and 40 milliseconds for each segment and each GEM calculation step on a 300 MHz Pentium II processor. Thus, on a 128 node Origin2000, a large GEM simulation with 100 million segments (corresponding to 10 meter segment sizes) would take between 3 and 36 months. There are many natural ideas to alleviate the computational complexity, but, conversely, many physical effects that could increase needed computing resources. Our estimates suggest that TERAFLOP-class machines will be effective for the very large simulations envisioned for the future, even though we are still able to perform meaningful simulations on the machines available to us today.

Caltech, Colorado and Syracuse have already begun building the necessary high performance non-local equation solver modules. A starting point is the simulation technology developed by *Rundle* (1988), the source code for which is publicly available (anonymous ftp) on host: fractal.colorado.edu at: /pub/Viscocodes/Virtual_California. The Green’s function approach in present and future computations will be formulated numerically as a long-range all-pairs interaction problem. We are parallelizing this aspect using well-known algorithms. However one cannot reach the required level of resolution without switching from an order N^2 ($O(N^2)$) to one of the $O(N)$ or $O(N \log N)$ approaches. As in other fields, this can be achieved by dropping or approximating the long-range components and implementing a neighbor-list based algorithm. However it is more attractive to formulate the problem as interacting dipoles and adapt existing fast-multipole technology developed for particle dynamics problems. We have already produced a prototype general purpose “fast multipole template code” by adapting the very successful work of *Salmon and Warren* (1994). These codes have already simulated over 300 million gravitating bodies on a large distributed memory system (a 4500-processor subset of the ASCI “Red” machine), so we expect these parallel algorithms to scale efficiently up to the problem sizes needed by GEM. If we make the conservative assumption that the GEM dipole-dipole Green's function evaluations are ten times as computationally expensive as the Newtonian Green's functions evaluated in Salmon and Warren's code, then a machine comparable to 1000 300Mhz Pentium II systems should be able to compute between 10 and 100 events per day. Notice that the target level of performance can be achieved through a combination of effective use of parallelism and evolution in the microprocessor market.

Multipolar Representation of Fault Systems: A primary key to a successful implementation of GEM models of faults systems will be to utilize computationally efficient algorithms for updating the interactions between fault segments. Converting the Green's function integrals to sums, without truncation or approximation, would require $O(N^2)$ operations between earthquakes, and possibly more for segments of faults experiencing an earthquake. For quasistatic interactions, the Green's functions $\mathbf{T}_{ij}^{kl}$ and $\mathbf{G}_{ij}^{k}$ for linear elasticity have a simple time dependence. Moreover, the Green's functions for linear viscoelasticity and for linear poroelasticity can be obtained from the elastic Green's functions using the correspondence principle (e.g., *Lee*, 1955; *Rundle* 1982a,b). These simplifications strongly suggest that multipole expansions (*Goil*, 1994; *Goil and Ranka*, 1995) will be computationally efficient algorithms.

The stress and displacement Green's functions $\mathbf{T}_{ij}^{kl}$ and $\mathbf{G}_{ij}^{k}$ represent the tensor stress and vector displacement at $\mathbf{x}$ due to a point double couple located at $\mathbf{x}'$ (*Steketee*, 1958). The orientation at $\mathbf{x}'$ of the equivalent fault surface normal vector, and of the vector displacement on that fault surface, are described by the indices i and j. Displacement and stress indices at the field point $\mathbf{x}$ are described by indices k and l. Integration of $\mathbf{T}_{ij}^{kl}$ and $\mathbf{G}_{ij}^{k}$ over the fault surface then corresponds to a distribution of double couples. For that reason, representation of the stress over segments of fault in terms of a multipole expansion is the natural basis to use for the GEM computational problem. In fact, the use of multipolar expansions to represent source fields in earthquake and explosion seismology was introduced by Archambeau (1968) and Archambeau and Minster (1978), and later revisited from a different perspective by Backus and Mulcahy (1976). Minster (1985) gives a review of these early representations.

Application of Fast Multipole Methods to GEM: In the gravitational N-body problem, each body interacts with every other one in the system according to the familiar law of gravitational attraction. Simply computing all pairs of interactions requires N(N-1)/2 separate evaluations of the interaction law. This formulation of the problem has some important advantages: it is easy to code, it is easy to vectorize and parallelize, it is readily expressible in HPF, and it is even amenable to special-purpose hardware [e.g. GRAPE]. Nevertheless, even today's fastest special-purpose systems, running in a dedicated mode for extended times at rates of nearly 1 TERAFLOP, cannot simulate systems larger than about 100,000 bodies.

Tremendous computational savings may be realized by combining bodies into “cells” and approximating their external field with a truncated multipole expansion. When this idea is applied systematically, the number of interactions may be reduced to O(N logN) (*Appel*, 1985; *Barnes and Hut,* 1986) or O(N) (*Greengard and Rokhlin*, 1987; *Anderson*, 1992). The cells are generally arranged in a tree, with the root of the tree representing the entire system, and descendants representing successively smaller regions of space. *Salmon and Warren* (1997) have demonstrated that such codes can run in parallel on thousands of processors and have simulated highly irregular cosmological systems of over 300 million bodies using ASCI facilities.

There is a direct analogy between the bodies in an astrophysical N-body system and the fault segments in a GEM. In both cases, there exists a pair-wise interaction that seems to require $O(N^2)$ interactions. But if we represent the distribution of sources in a region by a multipole expansion, the external field generated by a large number of bodies can be computed to any desired degree of accuracy in constant time. Thus, the GEM problem can also be reduced to O(NlogN) or O(N) total interactions, so that large calculations are tractable. On the other hand, although multipole methods can deliver large performance gains, they also require a considerable infrastructure. This is especially true of efficient parallel implementations. We will develop the multipole version of GEM using a library that has been abstracted from Salmon and Warren's successful astrophysical N-body codes. The continued development of this library, and in particular any new features needed to support GEM will be supported by the project. This new library is:

Modular - The “physics” is cleanly separated from the “computer science”, so that in principle, alternative physics modules such as the evaluation of the GEM Green's functions, can simply be "plugged in". The first non-gravitational demonstration was a vortex dynamics code written by *Winckelmans et al.* (1995). The interface to the physics modules is extremely flexible. A general decision-making function tells the treecode whether or not a multipole, or any other approximation, is adequate for a given field evaluation. Short-range interactions, which vanish outside a given radius, can be handled as well.

Tunable **-** Careful attention to analytical error bounds has led to significant speed-ups of the astrophysical codes, while retaining the same level of accuracy. Analytic error bounds may be characterized as quantifying the fact that the multipole formalism is more accurate when the interaction is weak: when the analytic form of the fundamental interaction is well-approximated by its lower derivatives; when the sources are distributed over a small region; when the field is evaluated near the center of a "local expansion"; when more terms in the multipole expansion are used, and when the truncated multipole moments are small. These issues are primarily the concern of the "physics" modules, but the library provides a sufficiently powerful interface to make these parameters adjustable. The formulation is general enough that the same library can be used to support evaluation of O(N), O(NlogN) and O(N^2) approximation strategies, simply by changing the decision criteria and interaction functions.

Adaptive **-** The tree automatically adapts to local variations in the density of sources. This can be important for GEM as it is expected that large earthquakes are the result of phenomena occurring over a wide range of length and time scales.

Scalable **-** The library has been successfully used on thousands of processors, and has sustained 170 Gflops aggregate performance on a distributed system of 4096 200Mhz PentiumPro processors.

Out of core **-** The library can construct trees, and facilitates use of data sets that do not fit in primary storage. This can allow one to invest hardware resources into processing rather than memory, resulting in more computations at constant resources.

Dynamically load balanced **-** The tree data structure can be dynamically load-balanced extremely rapidly by sorting bodies and cells according to an easily computed key.

Portable **-** The library uses a minimal set of MPI primitives and is written entirely in ANSI C. It has been ported to a wide variety of distributed memory systems - both 32-bit and 64-bit. Shared memory systems are, of course, also supported simply by use of an MPI library tuned to the shared memory environment.

Versatile **-** Early versions of the library have already been applied outside the astrophysics and molecular dynamics area. In particular the Caltech and Los Alamos groups have successfully used it for the vortex method in Computational Fluid Dynamics.

In the full GEM implementation, we have a situation similar to the conventional O(N^2) N-body problem but there are many important differences. For instance, the critical dynamics -- namely earthquakes -- are found by examining the stresses at each time step to see if the friction law implies that a slip event will occur. As discussed above, many different versions of the friction law have been proposed, and the computational system needs be flexible so we can compare results from different laws. Analogies with statistical physics are seen by noting that earthquakes correspond to large-scale space-time correlations including up to perhaps a million 10-to-100 meter segments slipping together. As in critical phenomena, clustering occurs at all length scales and we need to examine this effect computationally. However, we find differences with the classical molecular dynamics N-body problems not only in the dynamical criteria of importance but also in the dependence of the Green's function (i.e. "force" potential) on the independent variables. Another area of importance, which is still not well understood in current applications, will include use of spatially dependent time steps (with smaller values needed in active earthquake regions). An important difference between true particles and GEM is that in the latter case, fault positions are essentially fixed in space. Thus the N-body gravitational problem involves particles whose properties are time-invariant but whose positions change with time, while GEM involves "particles" whose positions are fixed in time, but whose properties change with the surrounding environment. Of course a major challenge in both cases is the issue of time-dependent "clustering" of "particles." It may be possible to exploit this in the case of GEM - for example by incrementally improving parallel load-balancing.

We believe a major contribution of this project will be an examination of the software and algorithmic issues in this area with the integration of data and computational modules. We will demonstrate that the use of fine grain algorithmic templates combined with a coarse-grained distributed object framework can allow a common framework across many disciplines.

C.8 GEM Computational Interface Software Environment

As a complement to our general approach described in Section C.3, we sketch here key features of the various components.

GEMCI.1: User Interface

This will include a Javabean applet to control execution of the computational modules. It will support the *Seismic Framework* by allowing the user to get values, set parameters, and invoke the distributed executable objects. NPACI has substantial experience with this technology, which provides a well-defined way of building seamless interoperable interfaces. The "front-end" will support an interactive 2D or 3D map on which one can specify individual faults. The system will support access to computational objects, data and visualization resources.

GEMCI.3: Local Physics

We propose to represent local physics modules in an object-oriented framework. This is possible if we adopt approaches such as Legion or POOMA but we believe a simpler approach may suffice. We will build equation solvers through templates where physics modules are interfaced through defined subroutine interfaces; this will allow us to use modules interchangeably. The *Seismic Framework* will specify interfaces that specify not only the modules to use but also the necessary parameters. These modules will be local and hence sequential and must achieve high performance. We expect therefore to use mature language (Fortran or C) to code them.

GEMCI.4: Evaluation, Data analysis and Visualization

As our simulations grow in fidelity, we expect to need increasingly sophisticated visualization capabilities and we will base these on the experience of other grand challenge projects. We must support both distributed low-level and high-performance workstation visualization as well as high-end capabilities at major sites such as Boston and NPACI (http://www.npaci.edu). Boston University has substantial expertise in simulation physics, acceleration algorithms, and visualization and display. Earth System Science (ESS) is one of four thrust areas within NPACI where major efforts are now underway in Multi-Scale, Multi-Resolution (MSMR) modeling (using climate change as the initial area of study.) The infrastructure developing under the MSMR activities will apply directly to GEM. In addition, the Data Intensive Computing Environments, and Interaction Environments technology thrusts of NPACI are working to expand data management and archival systems capabilities, as well as visualization support. Existing collaborations between the ESS and Technology thrusts of NPACI, in the areas of ecological and environmental modeling and remote sensing, will be brought to bear on the GEM project. This approach will naturally link the visualization and data storage/access components of GEMCI

Syracuse has developed a sophisticated collaborative environment dubbed ***TangoInteractive*** (http://trurl.npac.syr.edu/tango/). It will be available to support remote interactions among the GEM community. *TangoInteractive* can be considered as technology to share distributed objects within a rich interactive environment allowing shared text, white-boards and audio-video interactions. The *Seismic Framework* will of course draw on *TangoInteractive*. Furthermore, NCSA has developed a prototype collaborative visualization system using *TangoInteractive* and this will be available in production mode for the purposes of this proposal. Thus, one group using a high-end *ImmersaDesk* could share visualizations with a remote site running systems like *SciVis* (http://kopernik.npac.syr.edu:8888/scivis/index.html) on a PC. This will facilitate collaboration with GEM simulations.

GEMCI.5: Data storage, indexing and Access:

Growing repositories of geophysical data will be assimilated within the simulations to evaluate and calibrate them. Our approach will exploit the expertise of both NPACI and Syracuse who both are using *Persistent Distributed Objec*t models for such problems. This would be illustrated in the *Seismic Framework* through the use of standard relational databases together with JDBC (Java Database Connectivity) and CORBA (Enterprise Javabean) middleware. Such approaches will allow elegant user interfaces and data access using standard commercial technology. This part of GEMCI will need the development of specialized assimilation modules to support overlaying experimental and computational data. These will be the responsibility of the Colorado team.

GEMCI.6: Complex Systems (Pattern Dynamics) Environment

An important feature of GEM is that it will produce *ab initio* simulations and numerical systems with predictive characteristics, which link data and patterns abstracted from the simulations. An interactive Rapid Prototyping environment for developing new phenomenological models will help with their analysis and visualization. This aspect entails somewhat different trade-offs than the core simulations, in that interactivity is perhaps more critical than performance. We can then view the pattern dynamics module as another execution integrated into the same user interface, data access and visualization subsystems.

C.9 Calibration and Validation of Simulations: We plan to build on the data collection and archive activities of the Southern California Earthquake Center (SCEC) and the planned California Earthquake Research Center (CERC). From our perspective, data are viewed as a means of validating simulations. The GEM team expects, however, that recommendations for new data collection activities might emerge as a natural outgrowth of the simulations, and that an interesting new feedback loop will be initiated between observation seismologists and modelers as a result of the project.

Management of earthquake Data: Primary responsibility for earthquake data collection and archiving lies with the SCEC and CERC, as well as the Seismological Laboratory of the California Institute of Technology, and the Pasadena field office of the United States Geological Survey. Data in these archives include, 1) Broadband seismic data from the TERRASCOPE array; 2) Continuous (SCIGN) and "campaign style" geodetic data; 3) Paleoseismic data collected on the major faults of southern California; 4) Near field strong motion accelerograms of recent earthquakes; 5) Field structural geology of major active faults, 6) Other data including pore fluid pressure, *in situ* stress, and heat flow. These will be used, for example, to update the fault geometry models used by GEM, and to update fault slip histories used to validate earthquake models. Primary responsibility for interacting with elements of this database will be given to a committee chaired by Kanamori and Jordan.

A new and extremely promising type of geodetic data *is Synthetic Aperture Radar Interferometry* (InSAR), which permits "stress analysis of the Earth." A number of SAR missions are currently acquiring data over southern California, including the C-band (5.8 cm) European ERS 1/2 satellites and the L-band Japanese JERS satellite. These missions have already produced revolutionary images of the complete deformation fields associated with earthquakes in the United States and Japan (e.g., *Massonnet et al.*, 1993). These techniques rely on radar interferograms that represent the deformation field at a resolution of a few tens of meters over areas of tens of thousands of square kilometers, and over time intervals of weeks to years. We are now able to see essentially the complete surface deformation field due to an earthquake, and eventually, due to the interseismic strain accumulation processes.

Model Calibration/Validation/Data Assimilation: GPS, InSAR and broadband seismic (TERRASCOPE) data, together with archived and newly developed paleoseismic information in the SCEC database must be used in conjunction with our proposed simulation capabilities to establish the relevant model parameters. These parameters include the current geometry of faults; slip rates on any given segment; recurrence intervals and historic variations in slip during earthquakes—leading to estimates of frictional parameters; deformation data leading to estimates of elastic plate thickness and sub-crustal stress; relaxation times; poroelastic stress relaxation in the crust following earthquakes, leading to estimates of drained and undrained elastic moduli; and variations in seismicity, leading to estimates of the variable properties of friction and fault geometry at depth. Fits of models to data will be accomplished by standard techniques (e.g., *Menke*, 1989), including least squares, evolutionary programming, and simulated annealing (*Michalewicz*, 1996; *Holland*, 1975; *Rawlins*, 1991), among others. In addition, our purpose is to develop new methods so as to adapt models to assimilate new data as that becomes available, a concept that has served meteorological and climate studies extremely well. Self-adaptation techniques can be based on the same kinds of back-propagation methods that have been useful in analysis of neural network models (*Hertz et al.*, 1991). All of these methods pose unique problems, but all of them depend heavily on the use of data visualization methodologies of the type that have been discussed in C.9.

C.10 Role of Senior Investigators: (See also Organization/Management Plan)

Project Leadership:

Rundle	Colorado	Lead Earth Science -- Develop earthquake models, stat. mech approaches, validation of simulations (AL, PSE, AN, VA, SCEC)
Fox	Syracuse	Lead Computer Science -- Develop multipole algorithms and integrate projects internally and with external projects including HPCC and WWW communities (AL, PSE, AN))

Major Senior Investigators:

Andrews	USC/SCEC	Outreach organization, liaison with SCEC (O)
Ben-Zion	USC	Cellular Automata, space-time patterns, rate and state models, dynamic Green's functions (AL, AN)
Giles	Boston	Object oriented friction model algorithms, Cellular Automata computations (AL, AN, PSE)
Henyey	USC/SCEC	Outreach organization, liaison with SCEC (O)
Helly	UCSD/SDSC	Visualization methodologies (AL)
Jordan	MIT	Validating models with "slow earthquake" data (VA, SCEC)
Marone	MIT	Validating models with friction laboratory data (VA)
Kanamori	Caltech	Validating models with broadband earthquake source mechanism data (VA, SCEC)
Kellogg	UC Davis	Nature of driving stresses from mantle processes (AN)
Klein	Boston	Statistical mechanics analogies and methods: Langevin equations for fault systems dynamics, meanfield models (AL, AN)
Minster	UCSD	Validation with GPS & InSAR data (VA, SCEC))
Salmon	Caltech	Parallel multipole algorithms, linkage of model validation with simulation (AL, VA, PSE)
Sammis	USC	Pattern analysis, validation with seismicity (AN)
Shaw	Lamont	Inertial models, stat mech., stress transfer (AL)
Teng	USC	Stress transfer/wave modeling (AL)
Turcotte	Cornell	Nature of driving stresses from mantle processes (AN)
York	Northeastern	Cellular Automata, implementing computational approaches (AL, PSE)
Ward	UC Santa Cruz	Earthquake models, Green's functions, validation (AL, VA)

*Roles: AL) Algorithms; PSE) Problem Solving Environment; AN) Analysis by statistical mechanics/statistical mechanics; VA) Validation; SCEC) Interaction with SCEC/CalTech and other earthquake data bases; O) Outreach

Results from Prior NSF Funding for PI (J.B. Rundle):

John Rundle has been eligible for NSF funding only since he arrived at the University of Colorado at the end of 1993. Over the years, the overwhelming majority of his funding has originated from the Office of Basic Energy Sciences at the US Department of Energy, and from the Geodynamics/Natural Hazard Office of the National Aeronautics and Space Administration. The other investigators on this proposal however, have a much longer and very distinguished record of research supported by NSF. This is NOT summarized here. Nevertheless, we provide below a summary of results from NSF proposals upon which Rundle was Principal Investigator.

EAR-9318648, $11,305 to the Santa Fe Institute for the Study of Complexity for the period 1/1/94-6/30/95, WORKSHOP ON REDUCTION AND PREDICTABILITY OF NATURAL DISASTERS, J.B. Rundle (University of Colorado), W. Klein (Boston University), and D.L. Turcotte (Cornell University)

A workshop on Reduction and Predictability of Natural Disasters was held at the Santa Fe Institute on January 5-9, 1994, with funding generously provided by NASA, DOE, and NSF. The general theme of the meeting was the application of the techniques of statistical mechanics to problems in the earth sciences, and their use in forecasting and understanding natural disasters.

Publications resulting from grant:

1) Rundle, J.B., W. Klein, and D.L. Turcotte, Meeting report, workshop on reduction and predictability of natural disasters, *Trans. Am. Geophys. Un. EOS*, in press, 1994.

2) A book in the Santa Fe Institute series on the sciences of complexity, to be edited by Rundle, Turcotte and Klein, is being prepared for publication to appear in early spring, 1996. It will include the following papers by Rundle, Klein and Turcotte:

a) J.B. Rundle, W. Klein, D.L. Turcotte, and S. Gross, Observation of Boltzmann fluctuations in stochastic massless slider-block simulations.

b) J.B. Rundle and W. Klein, Rupture characteristics, recurrence, and predictability in a slider-block model for earthquakes.

c) W. Klein, C. Ferguson and J.B. Rundle, Spinodals and scaling in slider block models.

EAR-9526814, $110,000 to the University of Colorado at Boulder, "Clustering and Correlations in Seismicity", JB Rundle, S. Gross, V.K. Gupta (University of Colorado).

Work completed to date on this proposal is summarized below:

Rundle, J.B., W. Klein, S. Gross and C.D. Ferguson, The traveling density wave model for earthquakes and driven threshold systems, *Phys. Rev. E*, **56**, 293-302, 1997.

We discuss and interpret new simulation results from a recently proposed, physically-based earthquake model (``traveling density wave" model). This model produces a mixture of scaling and characteristic event ruptures. Stresses are transferred well beyond nearest neighbors in the two-dimensional lattice which represents the fault in the model. Cohesive forces due to small scale fault topography produce large scale friction, showing how friction is a function of length scale and why it is proportional to normal stress. Healing during rupture creates strongly irregular stress distributions, and displacement fields that have the statistical characteristics of a random walk. Strong cohesive forces introduce characteristic length scales into the size distributions. Event frequency statistics are in the range of those observed for natural seismicity.

Gross, S. and J.B. Rundle, A systematic test of time-to-failure analysis, *Geophys. J. Int.*, **133**, 57-64, 1997.

Time-to-Failure analysis is a technique for predicting earthquakes in which a failure function is fit to a time series of accumulated Benioff strain. Benioff strain is computed from regional seismicity in areas that may produce a large earthquake. We have tested the technique by fitting two functions, a power-law proposed by Bufe & Varnes (1993) and a log-periodic function proposed by Sornette & Sammis (1995). We compared predictions from the two time-to-failure models to observed activity and to predicted levels of activity based upon the Poisson model. Likelihood ratios show that the most successful model is Poisson, with the simple Poisson model four times as likely to be correct as the best time-to-failure model. The best time-failure model is a blend of 90% Poisson and 10% log-periodic predictions.

Gross, S.J., Repeating earthquakes on heterogeneous faults, *Bull. Seism. Soc. Am.*, in review, 1998.

Repeating earthquakes are defined to be events with hypocenters within one kilometer of one another having magnitudes within two tenths of a unit. A comparison of the observed number of repeated earthquakes with the number expected based upon the distribution of hypocenters has shown more repeating events than expected by chance in and near the creeping section of the San Andreas Fault. Areas with slower stress accumulation, such as the Landers and Northridge source regions, show no surplus of repeating earthquakes and little difference between the inter-event times of repeated earthquakes as compared to inter-event times of repeated events with dissimilar magnitudes. Studies of slider block models with and without structural heterogeneity support the interpretation that fault structure or strength heterogeneity plays an important role in determining rupture area and consequently the magnitudes of earthquakes.

Other papers in preparation:

Rundle, J.B.E. Preston, S. McGinnis, W. Klein, Why earthquakes stop: Growth and arrest in stochastic fields, to be submitted to *Phys. Rev. Lett.*, 1997.

According to classical Griffith theory, earthquakes nucleating in a homogeneous stress field will not stop until the boundaries of the fault are encountered. We show in this paper that when the stress field is heterogeneous, however, the roughness of the stress field determines whether the rupture will self arrest or spread over the entire fault. An associated stress difference field can be defined whose spectral characteristics determine whether the rupture arrests. If the stress field is characterized by red noise, the rupture will eventually arrest; if blue noise, the rupture cannot self arrest.

Rundle, J.B., W. Klein and K. Tiampo, Linear pattern dynamics in nonlinear threshold systems, to be submitted to *Phys. Rev. Lett.*, 1998.

Anecdotel evidence over many years indicates the existence of space time patterns in seismicity data. Complex nonlinear threshold systems such as earthquakes frequently show space-time behavior that is difficult to interpret. We describe a new technique that allows patterns to be understood as eigenstates of a suitably constructed Impulse Correlation Function (ICF). The dynamics can then be viewed as a progression through the pattern state space of the system. Temporal evolution of the normalized pattern vectors is governed by a Schroedinger equation. The ICF is the generator of motion of patterns states through state space.

Education, Outreach And Institutional Resource Commitments

1. Outreach: Results of our work will of course be published in the most prestigious scientific journals, as has our research on similar topics in the past. *However, even the possibility of forecasting earthquakes would have a considerable impact on society. Therefore, the investigators feel that the GEM project should have a major component of education and outreach to the government agencies and the public at large.* Through the outreach staff of USC and the Southern California Earthquake Center, we will have access to a highly professional, dedicated, and effective outreach and education program that has a proven record of success over the last eight years. Tom Henyey, Director of SCEC, and the Director of Education and Outreach for USC/SCEC, Jill Andrews, will therefore play critical role in disseminating the results of our research to the public. We have therefore included funds in our budget for Tom and Jill to design and conduct an effective public education and outreach program. Following is a brief description of these plans.

An Earth Science Module -- World Wide Web Based Teaching and Learning Tools to Enhance Nationwide Middle School Earth Science Curricula:

Jill Andrews heads a results-oriented team that manages an array of activities consisting of workshops, publications, WWW sites, education modules, partnerships in industry and education, and database development and management, currently for USC and the Southern California Earthquake Center (SCEC). This group will be an effective broker of information between the academic community and practitioners, between earth scientists and engineers, between technical professionals and public officials, and between scientists and educators. The Center is already known for its effective partnerships with local, state, and national government entities, academic institutions, industry, and the media. The Southern California Earthquake Center Education program, a component of Center Outreach, focuses on earthquake-related education in the K-14 environments. We emphasize the importance of adhering to National Science Education Standards as we create educational materials and tools for use in the nation's classrooms. The General Earthquake Models (GEM) project provides a platform we can build on to characterize, through creation of a WWW-based education module, the use of high performance computing methods to reliably forecast earthquakes.

Because the education standards of today strongly encourage an inquiry-based, accessible approach to learning science, the SCEC-funded Web-based modules now under construction (see http://www.scecdc.scec.org/Module/module.html), "Investigating Earthquakes through Regional Seismicity", have met with enthusiastic acceptance among reviewers from the California Science Implementation Network. Partnership with the GEM principal investigators will enhance the material presented in the existing modules. The central themes in the first modules are earth sciences and the study of earthquake phenomena, and fit into middle school curricula. We propose creation of a mathematically-oriented Web-based module, using GEM as the illustrative example, to acquaint high school instructors and students with the concept of an integrated approach to solving computational challenges, and to lead them through an exercise to produce their own earthquake forecast (probability) models. Students using the first two science modules will have already become familiar with new technologies such as broad-band, high dynamic range digital seismometers, continuously recording GPS systems, and Interferometric Synthetic Aperture Radar (InSAR). The GEM module would build on the foundation and framework set by the first two modules. As in the first modules, animated graphics and links to other Web sites, a glossary of terms, and hands-on activities will be included. We will employ a Web author who will work under the supervision of Jill Andrews, SCEC Outreach Director. Andrews will assemble a special team of scientists and educators (representatives of the California Science Implementation Network) who will review the work in progress for scientific accuracy and who will align the product to the State and National Education Standards.

Institutional Resource Commitments:

GEM investigators all have access to state of the art computer workstation environments. A brief summary of these are given below. As Lead Investigator, and as Director of the Colorado Center for Chaos and Complexity, Rundle will make available all of the facilities of the Center, which has 2 full time staff assistants, over 2000 square feet of meeting space and offices, a network of 10 SUN, WINTEL, and other machines, and reading room/libraries. The Center also has access to all of the facilities of the Cooperative Institute for Research in Environmental Sciences, in which the C4 Center is housed. These include SUN multiprocessor computers, researchers, faculty and staff that number over 500 persons, and access to NOAA facilities and personnel. Since the GEM problem is so similar to El Nino forecasting, we are establishing collaborations with the Climate Diagnostic Center, a part of CIRES, to leverage their expertise.

A letter from Dr. Claudio Rebbi, Director of the MARINER node at Boston University, in which Giles and Klein have leading roles, authorizes 25,000 hours of supercomputer time on the SGI Power Challenge array during the first funded year of the proposal, and will consider an application for similar allotments in succeeding years. The San Diego Supercomputer Center will make available considerable expertise and machine resources to support the visualization requirements in the proposed work. The attached letter from Dr. Sid Karin also describes the previously established procedures that we shall follow for allocation of supercomputer resources at NPACI. The National Parallel Architectures Center at Syracuse University is directed by Geoffrey Fox. NPAC's infrastructure consists of clusters of PC's and many Sun and SGI servers with from 1 to 8 processors. They are interconnected by modern ATM and other networks. These systems will be sufficient for testing the computational software on significant problems but not very relevant as a production simulation resource. NPAC has excellent support for commercial databases and object brokers which will be used in initial implementations of the GEMCI environment. These servers will run on our Sun 4 processor systems and be transferred to larger facilities at Boston or SDSC when necessary. NPAC's system staff will provide professional support to these resources.

Jordan and Marone at the Massachusetts Institute of Technology will make available their network of SUN workstations for computation and data analysis. Together with graduate students they will use SparcUltra machines for calibration and testing of the GEM simulations. In addition, Marone's laboratory is available, which houses a biaxial loading frame for friction and fracture experiments and a triaxial apparatus for work involving fluid flow at higher temperatures. Each of these are servo-controlled and are capable of complex loading histories and a wide range of strain rates.

The Seismological Laboratory of the California Institute of Technology will contribute resources arising from its computer facilities, which include a SUN ULTRA-2 based workstation system, as well as data and processing facilities from its extensive network of 250 short-period seismic stations and 80 broadband TriNet stations operating throughout southern California.

Personnel from the Jet Propulsion Laboratory, although not funded by this proposal, are interested in working with us on various aspects of the proposed work, particularly on calibration and validation of codes using GPS/SCIGN and InSAR data. The attached letter from Diane Evans expresses their primary interest in developing techniques to process InSAR interferograms to develop large crustal deformation data sets for southern California. GEM models will also be a necessary prerequisite for both the LightSAR and ECHO satellite missions that are under development by JPL and NASA, as described in the letter.

The remaining investigators all are well equipped with a variety of UNIX workstations, and intend to use these extensively in support of the proposed work.

April 29, 1998

Dr. John B. Rundle
Department of Physics & CIRES
Colorado Center for Chaos & Complexity
University of Colorado, Boulder, CO

Dear Dr. Rundle,

I am writing in support of your proposal "General Earthquake Models: A New Computational Challenge." The Center for Computational Science at Boston will support the work in this proposal by providing the researchers access to advanced computer facilities described below together with support and applications consulting. In addition, we are at the center of an active community of users and developers of high performance parallel computing technology. As partners in the NCSA Alliance (a recent Partnerships for Advanced Computational Infrastructure Awardee), we are able to link this research effort with a large national community of applications scientists, developers, and resources.

Boston University has a long tradition of support for high performance computational research and has provided leading edge computational resources to its researchers on a university wide basis since the installation of its first massively parallel supercomputer in 1988. The recent installation of the SGI/Cray Origin2000 with 192 processors represents the fourth generation parallel supercomputing technology at the University. The high-end resources also include a 38 processor SGI POWER CHALLENGEarray, high performance graphics workstations, graphics and computational workstation laboratories, a virtual reality laboratory with RealityEngine II graphics and two ImmersaDesks, and high performance ATM and HIPPI based networking with a connection to the vBNS.

We will support the activities of GEM proposal at the level of 25,000 processor hours in the first year, based on your proposal to us for computer resources. We would normally expect that your future use at a comparable level would be approved.

Sincerely,

Claudio Rebbi
Director, Center for Computational Science
Boston University
3 Cummington Street
Boston, MA 02215

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April 24, 1998

Dr. John Rundle
Professor of Physics and Geophysics
Director, Colorado Center for Chaos & Complexity (C4)/CIRES
Campus Box 216
Boulder, CO 80309

Dear John:

We are pleased to team with you in pursuit of the National Science Foundation's Knowledge and Distributed Intelligence (KDI) funding opportunity (NSF9855). Our proposal, General Earthquake Models, is a clear example of the computationally challenging research envisioned by the Earth System Sciences thrust area of our National Partnership for Advanced Computing Infrastructure (NPACI). I will look to Dr. Helly, who is on your proposal team, to provide the liaison between the GEM effort and the NPACI community.

The computational, data, and visualization resource requirements described in this proposal are well within the scope of the NPACI and SDSC capabilities. Geologically realistic simulations will represent a true computational challenge, which our team shall endeavor to meet.

Although time on the HPCC resources within NPACI must be allocated through our competitive resource allocation process, I am confident that this project will fit well in the context of our Earth System Science objectives, and will amply justify the required computational resources.

We will be happy to support the additional efforts in visualization and data management within the scope of the KDI grant itself in conjunction with Dr. Helly and his research team.

Sincerely,

Sid Karin

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, California 91109-8099

(818) 354-4321

JPL

March 24, 1998

Dr. John Rundle,
Director
Center for Chaos & Complexity
University of Colorado at Boulder
Campus Box 216
Boulder, CO 80309-0216

Dear Dr. ~~Rundle~~ John:

As you know, both NASA and JPL are extremely interested in the proposed, "General Earthquake Models: A New Computational Challenge" activity. Efforts such as these are required to maximize the value of space based observations from the Global Positioning Satellites (GPS) and Synthetic Aperture Radar (SAR) interferometry. We currently have several internally funded activities that we believe we can contribute to your effort through the participation of Andrea Donnellan, Jay Parker, Ron Blom, Gilles Peltzer, Greg Lyzenga and Paul Rosen. Our particular interests are related to high performance processing of SAR interferograms and analysis of data from the South California Integrated GPS Network (SCIGN) Array. We plan to propose several additional complimentary activities to NASA over the course of the next year culminating with a proposal for a dedicated SAR Interferometry Mission in 2001, for which your model will be invaluable.

Please let me know if any of us can provide you further assistance with this effort.

Sincerely,

Diane L. Evans
Program Scientist for Earth Science
Space and Earth Science Programs Directorate

DLE/jrh
Ref. No. 730-98-014.DLE

Performance Goals

Year 1 Major Activities:

Earthquake Physics:

1. Level 0 simulations based on existing codes of Rundle (1988), with 3D geometry, viscoelastic rheology, algorithms for CA TDW, Rate & State friction interfaces
2. Establishment of basic specifications for GIS-type overlays of simulation outputs upon data
3. Use of existing data bases to establish the basic model parameters, including major fault geometries.
4. Analyzing fault interactions to understand effects of screening and frustration

Computational Science, Software Support & System Integration:

1. Quasistatic Green's functions for other kinds of faults, and establishment of their basic multipolar representations
2. Prototype the fast multipole method with changes needed for GEM
3. Prototype optimal approaches for CA - type, TDW and Rate & State computations
4. Develop Seismic Framework with initial user interface and visualization subsystems.

Year 2 Major Activities:

Earthquake Physics:

1. Level I simulations with evolving fault geometries, shear & tensional fractures
2. First calculations with inertia and waves
3. Pattern evaluation and analysis techniques using phase space reconstruction, and machine reconstruction, and other techniques
4. Systems analysis of faults, and analysis of nonplanar geometries

Computational Science, Software Support & System Integration:

1. Develop and use a simple brute force $O(N^2)$ TDW and Rate & State solution system with fixed time and variable spatial resolution, based on adaptive methods
2. Test initial parallel multipole schemes with machine benchmarking
3. Incorporate multipole solver on an ongoing basis with friction laws, multiresolution time steps.
4. Integrate simpler simulations and data access into operational Problem Solving Environment (GEMCI) supporting distributed simulations, data analysis & collaborative visualization
5. Design and prototype initial Pattern Dynamics interactive environment

Year 3 Major Activities:

Earthquake Physics:

1. Protocols for calibration and validation of full-up simulation capability, numerical benchmarking, scaling properties of models (with SCEC, PEER, CERC)
2. Protocols for assimilation of new data types into models (SCEC, PEER, CERC)
3. Further analysis and cataloguing of patterns, evaluation of limits on forecasting and predictability of simulations
4. Define requirements for future simulations, transfer technology to third parties, outreach to local, state, government agencies as appropriate

Computational Science, Software Support & System Integration:

1. Develop/implement operational Fast Multipole system in terms of full GEMCI
2. Investigate and prototype full time dependent multipole method
3. Fully integrated GEMCI supporting large scale simulations, data access and Pattern Dynamics analysis.

Organization/Management Plan

As described, the GEM undertaking is complex and expensive. We provide a guide to the personnel involved in the various activities, together with names of those responsible for leadership. We felt that in order to ensure success, the broadest participation possible is mandatory. Note that the persons listed below include all collaborators, funded and unfunded, not just major senior personnel.

GEM Team -- Investigator Roles:

Planning and Coordination: The Principal Investigator, Rundle, will be responsible for overall planning, coordination, and integration of the project. Henyey and McRaney will also assist in planning relating to logistics, with liaison to the Southern California Earthquake Center, and with other activities associated with outreach modules.

Modeling and Analysis: Includes Ben-Zion, Gross, Ivins, Kellogg, Klein, Lyzenga, Rundle, Sammis, Shaw, Teng, Turcotte, Ward. Leadership will be provided by Klein and Sammis.

Computations: Includes Bosl, Bradley, Fox, Giles, Helly, Salmon, York. Leadership will be provided by Fox.

Validation/Data Assimilation: Includes Blom, Donnellan, Kanamori, Jordan, Marone, Minster, Peltzer, Rosen. Leadership will be provided by Jordan and Kanomori.

Outreach/Information Dissemination: Although all scientists will participate in this activity, we will focus our efforts around Jill Andrews and John McRaney. Andrews will plan and lead several yearly workshops dedicated to disseminating our results to the public.

Project Management: Rundle, the PI, will have full authority and responsibility for making decisions as to appropriate directions for the GEM KDI project. In particular he will approve budgets and work plans by each contractor and subcontractor. These must be aligned with the general and specific team goals. The PI will be advised by an executive committee made up of a subset of the PI's representing the key subareas and institutions. This committee will meet approximately every 4 months in person and use the best available collaboration technologies for other discussions. The expectation is that the executive committee will operate on a consensus basis. Note that the goals of the KDI project are both Scientific (simulation of Earth Science phenomena) and Computational (development of an object based Problem Solving Environment). The needs of both goals will be respected in all planning processes and contributions in both areas will be respected and viewed as key parts for the mission of the project.

The executive committee will be expanded to a full technical committee comprising at least all the funded and unfunded investigators. The technical committee will be responsible for developing the GEM plan which will be discussed in detail at least every 12 months at the major annual meeting, probably coordinated with the SCEC annual meeting, that we intend to hold for scientists inside and outside this project. As well as this internal organization, we expect NSF may wish to set up an external review mechanism. However we suggest that a GEM external advisory committee consisting of leading Earth and Computer Scientists might be set up and that it will attend GEM briefings and advise the PI as to changes of direction and emphasis. At the present, no budget line is included for this activity.

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