Lattice QCD Initiative

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Nuclear Physics Long Range Plan Meeting
March 27, 2001

Outline

Motivation

Physics goals: Physics of hadrons and hadronic matter

Lattice Hadron Physics Collaboration

Cost-optimized custom machines for lattice QCD

Clusters

Prototype clusters

Physics results

Phase I clusters

Phase II clusters

QCDDOC

Considerations for the long-range plan

Lattice resources available nationally and internationally

Coherent national plan for lattice QCD

Nuclear physics budget

Meeting the needs of hadron physics
Motivation

• Lattice field theory is only known way to solve nonperturbative QCD

• Lattice calculations essential to extract physics from major experimental studies of hadrons and hadronic matter
  
  Bates, CEBAF, HERMES, EMC, SMC, NMC, Fermilab, RHIC

• Fundamental problems can be solved now with adequate human and computer resources

• Algorithm development is creating new opportunities

• Prior to this initiative:
  
  No large-scale computer resources available to national hadronic physics community

  No collaboration established to carry out calculations on appropriate scale

Goal

To build the physics collaboration and computer resources to understand the structure and interactions of hadrons and properties of hadronic matter from first principles
Nonperturbative QCD

- Fundamental differences relative to QED
  - Self-interacting – highly nonlinear
  - Interaction increases at large distance – confinement
  - Strong coupling $\alpha_s \gg \alpha_{em}$
  - Rich topological structure

- Solution of QCD
  - Present analytical techniques inadequate
  - Numerical evaluation of path integral on space-time lattice
Lattice QCD

Euclidean:
\[ e^{i \int dt \, d^3 x \, L} \rightarrow e^{-\int d\tau \, d^3 x \, \mathcal{H}} \]

\[ \langle T e^{-\beta H} \psi \psi \psi \cdots \bar{\psi} \bar{\psi} \bar{\psi} \rangle \]
\[ = \frac{1}{Z} \int \mathcal{D}[\psi] \mathcal{D}[\bar{\psi}] \mathcal{D}[A] e^{-\int d^4 x \left[ \bar{\psi} (\partial^\mu + i g A^\mu) \psi + \frac{1}{4} F_{\mu\nu}^2 \right] \psi \psi \psi \cdots \bar{\psi} \bar{\psi} \bar{\psi}} \]
\[ \rightarrow \prod_n \frac{1}{Z} \int d\psi_n \, d\bar{\psi}_n \, dU_n e^{-\sum_n \left[ \bar{\psi} M(U) \psi + S(U) \right] \psi \psi \psi \cdots \bar{\psi} \bar{\psi} \bar{\psi}} \]
\[ = \prod_n \int dU_n \frac{1}{Z} \det M(U) e^{-S(U)} \sum M^{-1}(U) M^{-1}(U) \cdots M^{-1}(U) \]
Sample with M.C.
\[ \rightarrow \frac{1}{N} \sum_{i=1}^{N} \sum_{U_i \in \det M(U)} e^{-S(U)} \frac{1}{Z} \det M(U) M^{-1}(U_i) M^{-1}(U_i) M^{-1}(U_i) \]

\[ S(U) = \sum_{\Box} \frac{2N}{g^2} (1 - N^{-1} \text{ReTr} U_{\Box}) \rightarrow \frac{1}{4} F_{\mu\nu}^2 \quad U_{\Box} = U_1 U_2 U_3 U_4^\dagger \]
\[ \bar{\psi} M(U) \psi = \sum_n \left[ \bar{\psi}_n \psi_n + \kappa (\bar{\psi}_n (1 - \gamma_\mu) U_{n,\mu} \psi_{n+\mu} + \bar{\psi}_{n+\mu} (1 + \gamma_\mu) U_{n,\mu}^\dagger \psi_n \right] \]
Observables

\[ \langle T e^{-\beta H} \hat{\psi} \hat{\bar{\psi}} \psi \cdots \hat{\psi} \hat{\bar{\psi}} \rangle \]

\[ = Z^{-1} \int \mathcal{D}(U) \mathcal{D}(\bar{\psi} \psi) e^{-\bar{\psi} M(U) \psi - S(U) \bar{\psi} \psi \psi \cdots \psi \psi \psi} \]

\[ = Z^{-1} \int \mathcal{D}(U) e^{\text{ln det } M(U) - S(U)} \sum M^{-1}(U) M^{-1}(U) \cdots M^{-1}(U) \]

1. \( M^{-1} = (1 + \kappa U)^{-1} \) connects \( \bar{\psi} \) and \( \psi \) with line of \( U \)'s
   → Sum over all valence quark paths.

2. \( \text{ln det } M \) generates closed loops of \( U \)'s
   → Sum over all \( \bar{q}q \) excitations from sea
   omit in quenched approximation

3. \( S(U) \) tiles with plaquettes
   → sum all gluons

\[ 32^3 \times 64 \text{ lattice} \implies 10^8 \text{ gluon variables} \]
Quantitative Calculation of Observables

- **Full QCD**  
  sea quark contributions

- **Chiral fermions**  
  exact chiral symmetry

- **Continuum limit**  
  $a$ small

- **Large volume limit**  
  $V$ large

- **Chiral limit**  
  $m_q$ small

- **Requires 10’s of Teraflops**

Insight

- Use numerical evaluation of path integrals to identify paths that dominate action

- Calculate overlap with trial wave function

$$\left| \langle \psi_{\text{trial}} | \psi_{\text{exact}} \rangle \right|^2$$

- Explore dependence on:

  $$m_q, \ N_f, \ N_c$$
Physics Goals

Nucleon structure

- Form factors
  
  Electromagnetic  \( G_E(q^2) \)  \( G_M(q^2) \)

  Pion cloud essential – demanding lattice calculation
  
  large volume \( L^3 \)
  
  small \( m_q \)

- Axial  \( G_A \)

Strange form factor

Parity-violating electron scattering at Bates and JLab measures strange quark content of nucleon

\[ \langle r^2 \rangle^{1/2}_{\text{strange}}, \quad \langle \mu \rangle_{\text{strange}} \]

Sea quark physics – disconnected diagrams
Nucleon structure (cont.)

Parton distributions at $Q = 5$ GeV

- Moments of quark and gluon distributions

**Leading twist**

\[
\langle p | \bar{\psi} \gamma_{\mu} D \cdots D \psi | p \rangle \rightarrow \int dx \ x^n (q_\uparrow(x) + q_\downarrow(x))
\]

\[
\langle p | \bar{\psi} \gamma_5 \gamma_{\mu} D \cdots D \psi | p \rangle \rightarrow \int dx \ x^n (q_\uparrow(x) - q_\downarrow(x))
\]

\[
\langle p | \bar{\psi} \gamma_5 \sigma_{\mu\nu} D \cdots D \psi | p \rangle \rightarrow \int dx \ x^n (q_\uparrow(x) - q_\downarrow(x))
\]

**Higher twist**

\[
\langle p | \bar{\psi} \tilde{F}^{\mu\nu} \gamma_5 \gamma_{\mu} \psi | p \rangle, \ldots
\]

**Off forward**

\[
\langle p' | \bar{\psi} \mathcal{O} D \cdots D | p \rangle
\]
Physics Goals (cont.)

Spectroscopy

- $N^*$ spectrum
  - Number and structure of states
  - Flux tube confinement
  - Fine and hyperfine structure
  - Transition form factors
  - Experimental focus at JLab – CLAS spectrometer

- Glueballs

- Exotics, $H$
Physics Goals (cont.)

Hadron-hadron interactions

- Heavy-light mesons and baryon interactions
  - Light quark exchange
  - Gluon contributions

Fundamental aspects of QCD

- Chiral symmetry breaking
  - Role of instantons, zero modes
- Confinement
  - Role of center vortices, monopoles
- Dense hadronic matter
  - Phases and equation of state
- Effective Chiral Lagrangian

Adiabatic potential for $I = S = 0$ heavy-light mesons
Physics Goals (cont.)

The Quark Gluon Plasma

- Map phase diagram as function of $m_{u,d}, m_s$
  - order of transition $T_c$
- Equation of state $E(T), P(T)$
- Predicting real-time excitations of the plasma
- Understanding the role of instantons in the phase transition
- Study axial U(1) anomaly
Physics Goals (cont.)

Lattice field theory

- Improved actions
- Chiral fermions
  - Overlap
  - Domain walls
- Low-eigenmode expansion
  - Zero-mode dominance
  - Tool for disconnected diagrams
- D-theory approach to lattice field theory
  - Discrete spin formulation of lattice QCD
  - Meron cluster algorithm

\[ \text{Sign}[n] = 1 \]

\[ \text{Sign}[n] = -1 \]

Two configurations of fermion occupation numbers
Jefferson Lab-MIT-Wuppertal
Lattice Hadron Physics Collaboration

Founded 8/98, collaboration meetings 1/99, 4/99, 7/99, 1/00, 6/00
Collaborate on physics and cluster development

• Initial physics focus
  Full QCD calculation of moments of structure functions
  Calculate strange quark content of nucleon

• Cluster development
  Performance analysis for initial clusters
  Performance optimization
  Network analysis and optimization

MIT
• Started initiative 8/98
• Purchased Alpha164 and ES-40 clusters with startup funds
• Sharing support of Pochinsky and Capitani

Jefferson Lab
• Strong support by H. Grunder, C. Leemann, and N. Isgur
• Purchased XP1000 and UP2000 clusters with startup funds
• Hired D. Richards and R. Edwards
• Sharing support of Pochinsky and Capitani

University of Wuppertal
• K. Schilling, T. Lippert, postdocs, and students
• ALiCE: 128-node, 158 Gflops cluster of DS10’s
• NICse: 6-node, 16 Gflops cluster of dual UP2000’s
• Sharing full QCD configurations for structure functions
• Collaborating on network and performance optimization
The Lattice Hadron Physics Collaboration

Richard Brower* Boston University
Matthias Burkardt New Mexico State University
Shailesh Chandrasekharan Duke University
Shao-Jing Dong University of Kentucky
Terrence Draper University of Kentucky
Patrick Dreher Massachusetts Institute of Technology
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David Richards Jefferson Laboratory
Eric Swanson University of Pittsburgh
Chung-I Tan Brown University
Harry B. Thacker University of Virginia
Steve Wallace University of Maryland
Chip Watson** Jefferson Laboratory
Uwe-Jens Wiese Massachusetts Institute of Technology

† Principal Investigator
* Application Software Coordinator
** Cluster Coordinator
Cost-Optimized Custom Machines for Lattice QCD

- Highly parallel custom machines much cheaper than general purpose supercomputers
  - regular grid structure
  - local communications
  - overlapping computation and communications

- Dual approach
  - optimization of commodity clusters
  - fully custom parallel machine

- Robust strategy for national resources
Motivation for Alpha Cluster

- General-purpose architecture and software environment
  
  Linux operating system, standard compilers
  
  Source code compatibility with workstations
  
  Flexibility, ability to implement innovative new approaches
  
  Efficient use by everyone in community
  
  Ideal for local development by dispersed collaborators

- Double-precision needed for many applications

- Commodity processors and networks offer maximal flexibility
  
  Follow best technology in each generation
  
  Purchase state-of-art technology any year
  physics or funding motivate it

- Cost-effective:
  
  Market forces on processors and communications
  
  Processor chip price/performance improving
  like Moore’s Law
  
  System integration costs falling
  
  Large cluster improvement better than Moore’s Law

- For present generation, high-performance Alpha processor
  optimal for scaling to largest possible systems

- Next generation: EV7 computer on a chip
Prototype Clusters

- Evaluated XP1000, DS10, DS20, ES40, UP2000 nodes
- Incorporated Wuppertal DS10 and UP2000 cluster experience
- Joint research agreement with Compaq

MIT Cluster

Optimize network and memory costs using 4-processor nodes connected by Myrinet

- $12 \times 4$-processor ES40’s – 64 Gflops
  
  - EV67 667 MHz processors
  - 8 MB cache/processor
  - 1 GB memory/SMP
  - 9 GB disk

- 500 GB file server
- 4 Alpha 164 workstations
- Myrinet (Lanai 7)
- Installed 12/99–8/00
Prototype Clusters (cont.)

Jefferson Lab Clusters

- 16 × 1-processor XP1000’s – 16 Gflops
  - 500 MHz
  - 4 MB cache
  - 256–512 MB memory

- 12 × 2-processor UP2000’s – 32 Gflops
  - 667 MHz
  - 4 MB cache
  - 512 MB memory / SMP
  - Expand to 12 or 16 SMP’s

- 400 GB filed server

- Myrinet
  - Currently Lanai 7,
  - Ordered Lanai 9
Optimization at Three Levels

- Single-processor performance on 667 MHz ES40
  Conjugate gradient inverter
  58% of peak for lattice in cache

- Multiprocessor performance across SMP
  Nearly linear scaling from 1 to 4 processors
  Conjugate gradient on ES40

- Cluster

  Need 128-processor cluster to study and optimize scaling of QCD across network

  Myrinet has sufficient bandwidth and latency to allow overlap of computation and communication
Physics on Prototype Clusters

- Hadron spectroscopy: $N^*$ spectrum and exotics
- Hadron-hadron interactions
- Domain wall and overlap fermions
- Meron cluster algorithm for nonzero chemical potential
- Production of dynamical configurations
- Moments of structure functions
Hadron Spectroscopy

Nucleon Parity Partner

D. Richards, LHPC, UKQCD hep-lat/0011025

Quark mass extrapolation of nucleon and its parity partner
Moments of Proton Quark Distributions

Local operators measure moments of quark distributions

\[
\langle p | \bar{\psi} \gamma_\mu (D)^n | p \rangle \rightarrow \langle x^n q \rangle \equiv \int_0^1 dx \ x^n \left( q(x, Q^2) - (-1)^n \bar{q}(x, Q^2) \right)
\]

\[
\langle p | \bar{\psi} \gamma_5 \gamma_\mu (D)^n | p \rangle \rightarrow \langle x^n \Delta q \rangle \equiv \int_0^1 dx \ x^n \left( \Delta q(x, Q^2) + (-1)^n \Delta \bar{q}(x, Q^2) \right)
\]

On lattice:

\[
\langle xq \rangle \ 3^+_1 \quad \bar{q} \gamma_4 \tilde{D}_4 q - \frac{1}{3} \sum_{i=1}^3 \bar{q} \gamma_i \tilde{D}_i q \quad p = 0
\]

\[
\langle x^2q \rangle \ 8^-_1 \quad \bar{q} \gamma_{\{1D_1D_4\}} q - \frac{1}{2} \sum_{i=2}^3 \gamma_{\{2D_iD_4\}} q \quad p \neq 0
\]

\[
\langle x^3q \rangle \ 2^+_1 \quad \bar{q} \gamma_{\{1D_1D_4D_4\}} q + \bar{q} \gamma_{\{2D_2D_3D_3\}} q - \{3 \leftrightarrow 4\} \quad p \neq 0
\]

\[
\langle \Delta q \rangle \ 4^+_4 \quad \bar{q} \gamma_5 \gamma_3 q \quad p = 0
\]

\[
\langle x\Delta q \rangle \ 6^-_3 \quad \bar{q} \gamma_5 \gamma_{\{3D_4\}} q \quad p = 0
\]

\[
\langle x^2\Delta q \rangle \ 4^+_2 \quad \bar{q} \gamma_5 \gamma_{\{1D_3D_4\}} q \quad p \neq 0
\]
Hadron Matrix Elements on Lattice

- Calculate plateau: measure $\langle O \rangle$, for $m_q$, $a$, $L$
- Connected diagrams
  $$p = 0$$
  $$p \neq 0$$
- Disconnected diagrams
- Extrapolate
  $$m_q : m_\pi \to 140 \text{ MeV}$$
  $$a \to \sim 0.05 \text{ fm}$$
  $$L \to \sim 5.0 \text{ fm}$$
- Note: For $\langle O \rangle_u - \langle O \rangle_d$, disconnected diagrams cancel
Results for Full QCD

- Used SESAM lattices (Insufficient resources to generate)
  200 configurations on $16^3 \times 32$ lattices, $a \sim 0.1\, fm$.
  $3 \, m_q$ with $m_\pi \geq 0.7\, GeV$
- Plateaus for connected diagrams
  \[ p = 0 \quad p \neq 0 \]

- Close agreement between full and quenched QCD

- Qualitative agreement between full QCD and only instantons.
Moments of Proton Quark Distributions (cont.)

- Linear extrapolation in $m_q$ yields serious discrepancies
  \[
  \langle xu \rangle - \langle xd \rangle \sim 0.24 - 0.28 \quad (0.16)
  \]
  \[
  \langle \Delta u \rangle - \langle \Delta d \rangle \sim 1.0 - 1.1 \quad (1.26)
  \]

- Chiral extrapolation
  \[
  \text{Pion cloud is essential}
  \]
  \[
  \langle x^n u \rangle - \langle x^n d \rangle \sim a_n \left[ 1 - \frac{4g_A^2}{(4\pi f_\pi)^2} \ln \left( \frac{m_\pi^2}{m_\pi^2 + \mu^2} \right) \right] + b_n m_\pi^2
  \]

  Consistent results for $\mu \sim 500MeV$
  \[
  \langle xu \rangle - \langle xd \rangle, \quad \langle x^2 u \rangle - \langle x^2 d \rangle, \quad \langle x^3 u \rangle - \langle x^3 d \rangle
  \]
  Nucleon magnetic moment
  Chiral bag models

- Definitive calculation
  5% measurement at $m_\pi^2 = 0.05GeV^2$
  \[
  N \sim 0.38 \left[ \frac{L}{4} \right]^{4.55} \left[ \frac{0.8}{a} \right]^{7.25} \left[ \frac{0.3}{m_\pi/m_\rho} \right]^{2.7}
  \]
  $\Rightarrow$ 8 Teraflops-years
Chiral Extrapolation of Moments of Quark Distributions

\[ \langle x \rangle_{u-d} \]

\[ \langle x^2 \rangle_{u-d} \]

\[ \langle x^3 \rangle_{u-d} \]

\[ m_{\pi}^2 \text{ [GeV}^2\text{]} \]

- QCDSF Ref. [7]
- QCDSF Ref. [8]
- QCDSF Ref. [9]
- MIT-DD6Q
- MIT-SESAM (Full)

Experiment
CBM
Phase I Clusters

- One component of coherent national plan by Lattice QCD Executive Committee for 2001–2002
- NP proposal submitted to DOE, March 1999
  ftp://www-ctp.mit.edu/pub/negele/LatProp/

Hardware (*current market estimate*)

- FY 01
  64 2-way SMP nodes
  \[ \geq \] 833 MHz Alpha 21264
  4 MB cache
  512 MB memory/SMP
  Myrinet 2000 switch and PCI cards

- FY 02
  128 2-way SMP nodes
  \[ \geq \] 1.25 GHz
  Myrinet interconnect
  \[ \geq \] 425 Tflops sustained
Phase I Clusters (cont.)

Lattice QCD Metacenter

Major clusters at JLab and MIT

Highly integrated environment for ongoing joint leadership of scientific and computational effort

Follows successful Brookhaven/Columbia model

Facilitates strong coupling with vendors

Lattice QCD Metacenter

[Diagram of Lattice QCD Metacenter with detailed specifications of hardware and network connections]
Phase I Clusters (cont.)

Project Administration

- Jefferson Lab and MIT
  
  Develop, procure, construct, and operate clusters
  
  Host regular collaboration meetings

- Lattice Hadron Physics Collaboration
  
  Open to individual theorists who are:
  
  Interested in solving lattice QCD to understand hadron structure
  
  Willing to collaborate in coherently sharing computational resources

  Collaborators commit to one or more core projects
  
  Hadron structure
  
  Hadron-hadron interactions
  
  Spectroscopy
  
  Lattice field theory

  Collaborators determine major research projects
Phase II Clusters

- Coherent national plan by Lattice QCD Executive Committee for 2003–2005 calls for multi-Teraflops resources from a combination of QCDOC and Clusters.
- MIT/Jlab are using collaboration with Compaq to explore the commodity cluster opportunities in this timeframe.

**Alpha 21364 (EV7)**

- Computer on a chip well suited to QCD
- Alpha 21264 core at 1250 MHz
- Integrated 1.75 MB L2 cache
- Integrated memory controller – RAMbus at 6 GB/s
- Integrated network interface
  
  NEWS $4 \times 2 \times 3.2$ GB/s
  
  I/O interface 3 GB/s

**Alpha 21464 (EV8)**

- 8-wide superscalar – 4 floats/clock
Phase II Clusters (cont.)

Rough cost, performance estimates

Assume $\sim$ $2K$/processor

50% peak performance

18 300 MB/s links/box

<table>
<thead>
<tr>
<th>Processor</th>
<th>EV7</th>
<th>EV7</th>
<th>EV7</th>
<th>EV8</th>
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</thead>
<tbody>
<tr>
<td>Speed (GHz)</td>
<td>1.25</td>
<td>1.25</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td># Processors</td>
<td>1024</td>
<td>4096</td>
<td>4096</td>
<td>4096</td>
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<tr>
<td>Lattice</td>
<td>$16^3 \times 24$</td>
<td>$24^3 \times 32$</td>
<td>$32^3 \times 48$</td>
<td>$32^3 \times 48$</td>
</tr>
<tr>
<td>Cost, $M$</td>
<td>2.5</td>
<td>9.9</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td>Tflops sustained</td>
<td>1.2</td>
<td>4.5</td>
<td>6.2</td>
<td>12.4</td>
</tr>
<tr>
<td>$/$ MF</td>
<td>2.1</td>
<td>2.2</td>
<td>1.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>
QCDOC (QCD On a Chip)

- Natural extension of custom QCDSP machines at Columbia and RIKEN

- Partnership with IBM since December 1999 to design and manufacture ASIC
  
  Processor: 1 Gflops peak 440 Power PC
  4 MB on-chip memory
  8 Gbits/sec interprocessor communication

- Schedule

  ASIC December 2001
  Prototype March 2002
  10 Tflops sustained QCDOC at BNL October 2003
  Hardware cost: $10 M

- Collaboration

  Columbia University
  RIKEN
  IBM
  Edinburgh
  Fermilab
QCDOC ASIC DESIGN

- 4 MBytes of Embedded DRAM
- 8 Gbyte/sec Memory/Processor Bandwidth
- 1 Gflops Double Precision RISC Processor
- 2.6 GByte/sec Interface to External Memory
- 2.6 GByte/sec EDRAM/SDRAM DMA
- 24 Link DMA Communication Control
- 24 Off-Node Links 12 Gbit/sec Bandwidth
- Complete Processor Node for QCD Supercomputer on a Single Chip Fabricated by IBM

Mission-critical, custom logic (hatched) for high-performance memory access and fast, low-latency off-node communications is combined with standards-based, highly integrated commercial library components.
Considerations for Long Range Plan

Lattice resources available nationally and internationally


- State-of-art quenched calculation: 50 Gflops-ys
- Largest NERSC FY00 QCD allocation: 2 Gflops-ys
- Largest NSF FY00 QCD allocation: 10 Gflops-ys

<table>
<thead>
<tr>
<th>Country</th>
<th>FY00 Sustained Gflops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>264</td>
</tr>
<tr>
<td>Italy</td>
<td>554</td>
</tr>
<tr>
<td>Japan</td>
<td>980</td>
</tr>
<tr>
<td>U.K.</td>
<td>41</td>
</tr>
<tr>
<td>U.S. (Columbia)</td>
<td>120</td>
</tr>
<tr>
<td>U.S. (RIKEN)</td>
<td>180</td>
</tr>
<tr>
<td>U.S. (open)</td>
<td>20</td>
</tr>
</tbody>
</table>

European Committee for Future Accelerators (ECFA) report

- Several 10 Tflops computers in FY03
- UKQCD committed to buy QCDOC
Coherent National Plan

Lattice QCD Executive Committee

M. Creutz  BNL
N. Christ  Columbia
P. MacKenzie Fermilab
J. Negele  MIT
C. Rebbi  BU
S. Sharpe  U Washington
R. Sugar  UCSB, chair
W. Watson  JLab

Coherent national high energy and nuclear physics effort in lattice QCD

• Broad range of fundamental physics
  Electroweak matrix elements
  QCD thermodynamics
  Hadron structure and interactions

• Unified conceptual and algorithmic foundations

• Common needs for computational resources

• Potential synergy between high energy and nuclear physics
Coherent National Plan (cont.)

National Facility Plan

- FY 01–02
  2 1/2 TFlops sustained clusters at
  JLab/MIT and Fermilab

- FY 03–05
  3 10 TFlops sustained national facilities at
  BNL, JLab/MIT, and FNAL

Schedule and estimated hardware cost

<table>
<thead>
<tr>
<th>FY</th>
<th>$M</th>
<th>Primary hardware items</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>4</td>
<td>JLab/MIT and Fermilab 0.5 Tfnops clusters</td>
</tr>
<tr>
<td>02</td>
<td>7</td>
<td>JLab/MIT and Fermilab 0.5 Tfnops clusters</td>
</tr>
<tr>
<td>03</td>
<td>12</td>
<td>BNL QCDOC</td>
</tr>
<tr>
<td>04</td>
<td>10</td>
<td>JLab/MIT and Fermilab 10 Tfnops clusters</td>
</tr>
<tr>
<td>05</td>
<td>10</td>
<td>JLab/MIT and Fermilab 10 Tfnops clusters</td>
</tr>
</tbody>
</table>

National lattice QCD proposals to DOE SciDAC program
(Scientific Discovery through Advanced Computation)

- March 2001: National Computational Infrastructure Proposal
  $4.8 M Software development
  $2.0 M Cluster hardware

- 2002: Plan topical center proposal for completion of 1/2 Tfnops clusters plus 10 Tfnops facilities
Nuclear Physics Budget

• Natural to split lattice effort 50-50 between nuclear physics and high energy physics.

• Natural institutionally
  Jlab 100 % nuclear physics
  Fermilab 100 % high energy physics
  BNL shares both missions
    50-50 agreeable to T. Kirk, L. McLerran

• Nuclear physics would support full range of lattice calculations relevant to understanding hadron structure, hadronic interactions, and the quark-gluon plasma

• 5-yr budget projections by Jlab and BNL for hardware, construction, and operations for Jlab and half of BNL:

<table>
<thead>
<tr>
<th>FY</th>
<th>$M</th>
<th>Major construction items</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1.2</td>
<td>Begin JLab .5 Tflops cluster</td>
</tr>
<tr>
<td>02</td>
<td>4.1</td>
<td>Complete Jlab cluster + BNL site prep</td>
</tr>
<tr>
<td>03</td>
<td>7.0</td>
<td>Half of 10 Tflops QCDOC at BNL</td>
</tr>
<tr>
<td>04</td>
<td>8.2</td>
<td>Build half of 10Tflops machine at Jlab</td>
</tr>
<tr>
<td>05</td>
<td>7.7</td>
<td>Complete 10Tflops machine at Jlab</td>
</tr>
<tr>
<td></td>
<td>28.2</td>
<td>Total</td>
</tr>
</tbody>
</table>

• Out-year expenses

$4.75 M Jlab/MIT: operations plus replacing 1/3 of hardware

$1.25 M BNL : half of operations and support equipment

$6 M/year in FY01 $'s
Meeting the Needs of Hadronic Physics

- Advances in lattice field theory and computer technology now make lattice QCD a crucial tool for hadronic physics.

- Lattice QCD essential to obtain full physics potential of investment in accelerators and detectors.

- Already aggressively pursued in Europe and Japan:
  0.5 - 1 Tflops (00) → 10’s of Tflops (03)

- To exploit physics opportunities and compete with Europe and Japan, U.S. nuclear physics community needs:
  0.5 Tflops sustained cluster in 01-02
  Use of 10 Tflops sustained facilities in 03-05

- Nuclear physics community needs to begin thinking about lattice facilities the way it thinks about experimental facilities, with manpower and budgets to match.

- As with other new initiatives, support of manpower and bridge positions is important.

- We hope SciDAC will provide major support, but nuclear physics will need to be prepared to be a major partner. FY01-02 is crucial.

- Coupled with frontier experimental facilities, lattice QCD provides unprecedented opportunity for fundamental understanding of hadronic physics.
Recommendation for Lattice QCD

Advances in lattice field theory and computer technology now make lattice QCD a crucial tool in hadronic physics. Lattice calculations are essential to obtain the full physics potential of investments that are being made in accelerators and detectors.

To exploit these physics opportunities, and to compete effectively with efforts in Europe and Japan, we strongly recommend building dedicated cost-optimized QCD facilities sustaining 0.5 Teraflops in FY 01–02 and increasing to 15 Teraflops in FY 02–05 for hadronic physics research.