Parallel, Adaptive Scientific Computation in Heterogeneous, Hierarchical, and Non-Dedicated Computing Environments

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Yet another Powerpoint-free presentation!
Overview

• Why parallel computing?
  – solve larger problems in less time: clusters, supercomputers
  – recent trends: clock speed increases slowing, more processors per node

• Target computational paradigm: parallel adaptive methods
  – distributed data structures and partitioning
  – dynamic load balancing algorithms
  – load balancing software: Zoltan Toolkit

• Heterogeneous, hierarchical and non-dedicated computing environments
  – target environments, including Bullpen cluster
  – what can be adjusted? who can make the adjustments?
  – what can we do at just the load balancing step?

• Resource-aware parallel computation
  – Dynamic Resource Utilization Model (DRUM)
  – other approaches: hierarchical partitions, process migration, operating system migration
Participants

- Rensselaer Polytechnic Institute
  - Ph.D. students: Jamal Faik (now at Oracle), Luis Gervasio
  - Faculty: Joseph Flaherty
  - Undergraduates: Jin Chang
  - Various SCOREC students/postdocs/staff

- Sandia National Laboratories
  - Karen Devine and the Zoltan group

- Williams College undergraduates
  - Most recent summers: Laura Effinger-Dean ’06, Arjun Sharma ’07, Bartley Tablante ’07
  - Previous: Kai Chen ’04, Lida Ungar ’02, Diane Bennett ’03
  - 2006 honors thesis student: Travis Vachon ’06
Why Parallel Computation?

Parallelism adds complexity, so why bother?

Traditionally, there are two major motivations.

**Computational speedup**
- Solve the same problem but in less time than on a single processor.

**Computational scaling**
- Solve larger problems than could be solved at all on a single processor within time or space constraints.
Recent Trends

• Until recently, computational scientists could assume that faster processors were always on the way

• Manufacturers are hitting the limits of current technology

• Focus now: multiple processors, hyperthreading, multi-core processors

• Today: dual core is common – Soon: 4, 8 or more cores per chip

• Parallel computing is needed to use such systems effectively!

Target Applications: Finite Element and Related Methods

- More elements $\implies$ better accuracy, but higher cost
- Adaptivity concentrates computational effort where it is needed
- Guided by error estimates or error indicators
- $h$-adaptivity: mesh enrichment

![Uniform mesh](image1.png) ![Adapted mesh](image2.png)
- $p$-adaptivity: method order variation; $r$-adaptivity: mesh motion
- Local refinement method: time step adaptivity
- Adaptivity is essential
A Simple Adaptive Computation

Refine the underlying mesh to achieve desired accuracy
Parallel Strategy

• Dominant paradigm: Single Program Multiple Data (SPMD)
  – distributed memory; communication via message passing (usually MPI)
• Can run the same software on shared and distributed memory systems
• Adaptive methods lend themselves to linked structures
  – automatic parallelization is difficult
• Must explicitly distribute the computation via a domain decomposition

• Distributed structures complicate matters
  – interprocess links, boundary structures, migration support
  – very interesting issues, but not today’s focus
Mesh Partitioning

- Determine and achieve the domain decomposition

- “Partition quality” is important to solution efficiency
  - evenly distribute mesh elements (computational work)
  - minimize elements on partition boundaries (communication volume)
  - minimize number of “adjacent” processes (number of messages)

- But.. this is essentially graph partitioning: “Optimal” solution intractable!
Why dynamic load balancing?

Need a rebalancing capability in the presence of:

- Unpredictable computational costs
  - Multiphysics
  - Adaptive methods
- Non-dedicated computational resources
- Heterogeneous computational resources of unknown relative powers
Load Balancing Considerations

- Like a partitioner, a load balancer seeks
  - computational balance
  - minimization of communication and number of messages
- But also must consider
  - cost of computing the new partition
    * may tolerate imbalance to avoid a repartition step
  - cost of moving the data to realize it
    * may prefer incrementality over resulting quality
- Must be able to operate in parallel on distributed input
  - scalability
- It is *not* just graph partitioning – no single algorithm is best for all situations
- Several approaches have been used successfully
Geometric Mesh Partitioning/Load Balancing
Use only coordinate information

• Most commonly use “cutting planes” to divide the mesh

- Tend to be fast, and can achieve strict load balance
- “Unfortunate” cuts may lead to larger partition boundaries
  - cut through a highly refined region

• May be the only option when only coordinates are available
• May be especially beneficial when spatial searches are needed
  - contact problems in crash simulations
Recursive Bisection Mesh Partitioning/Load Balancing
Simple geometric methods

- Recursive methods, recursive cuts determined by
  
  Coordinate Bisection (RCB)  Inertial Bisection (RIB)

- Simple and fast
- RCB is incremental
- Partition quality may be poor
- Boundary size may be reduced by a post-processing “smoothing” step
SFC Mesh Partitioning/Load Balancing

Another geometric method

- Use the locality-preserving properties of space-filling curves (SFCs)
- Each element is assigned a coordinate along an SFC
  - a linearization of the objects in two- or three-dimensional space

- Hilbert SFC is most effective

- Related methods: octree partitioning, refinement tree partitioning
Graph-Based Mesh Partitioning/Load Balancing
Use connectivity information

- Spectral methods (Chaco)
  - prohibitively expensive and difficult to parallelize
  - produces excellent partitions

- Multilevel partitioning (Parmetis, Jostle)
  - much faster than spectral, but still more expensive than geometric
  - quality of partitions approaches that of spectral methods

- May introduce some load imbalance to improve boundary sizes
Load Balancing Algorithm Implementations

• Again, no single algorithm is best in all situations
• Some are difficult to implement
• Bad: implementation within an application or framework
  – likely usable only by a single application
  – at best, usable by a few applications that share common data structures
  – unlikely that an expert in load balancing is the developer
• Better: implementation within reusable libraries
  – load balancing experts can develop and optimize implementations
  – application programmers can make use without worrying about details
  – but...how to deal with the variety of applications and data structures?
    * require specific input and output structures
      – applications must construct them
    * data-structure neutral design
      – applications only need to provide a small set of callback functions
Zoltan Toolkit

Includes suite of partitioning algorithms, developed at Sandia National Laboratories

- General interface to a variety of partitioners and load balancers
- Application programmer can avoid the details of load balancing
- Interact with application through callback functions and migration arrays
  - “data structure neutral” design
- Switch among load balancers easily; experiment to find what works best
- Provides high quality implementations of:
  - Coordinate bisection, Inertial bisection
  - Octree/SFC partitioning (with Loy, Gervasio, Campbell – RPI)
  - Hilbert SFC partitioning
  - Refinement tree balancing (Mitchell – NIST)
  - Hypergraph partitioning
- Provides easier-to-use interfaces for:
  - Metis/ParMetis (Karypis, Kumar, Schloegel – Minnesota)
  - Jostle (Walshaw – Greenwich)

Zoltan Toolkit Interaction with Applications

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<tr>
<td>migrate application data continue computation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zoltan balancer</td>
</tr>
<tr>
<td></td>
<td>call application callbacks partition return migration arrays</td>
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</tbody>
</table>
Typical Computation Flow

Application Software

- Setup/Initial Partitioning
- Compute
- Rebalance Load
- Evaluate Error
- Adaptive Step

Load Balancing Suite
Partitioning and Dynamic Load Balancing Implementations/Support Tools
Example Parallel Adaptive Software

We wish to run several applications.

• Rensselaer’s “LOCO”
  – parallel adaptive discontinuous Galerkin solution of compressible Euler equations in C.
  – using Parallel Mesh Database
  – “perforated shock tube” problem

• Rensselaer’s “DG”
  – also discontinuous Galerkin methods, but in C++
  – using Algorithm-Oriented Mesh Database
  – Rayleigh-Taylor flow instabilities and others

• Mitchell’s PHAML
  – Fortran 90, adaptive solutions of various PDEs

• Simmetrix, Inc. MeshSim-based applications

• Real interest for parallel computing is in 3D transient problems

Shock Tube Vent

Image of a shock tube experiment.
Target Computational Environments

• FreeBSD Lab, Williams CS: 12 dual hyperthreaded 2.4 GHz Intel Xeon processor systems

• *Bullpen Cluster*, Williams CS: 13 node Sun cluster, total of 4 300 MHz and 21 450 MHz UltraSparc II processors

• *Dhanni Cluster*, Williams CS: 14 nodes, 8 with 2 hyperthreaded 2.8 GHz Intel Xeon processors, 2 with 2 dual-core hyperthreaded 2.8 GHz Intel Xeon processors, 1 with dual hyperthreaded 2.4 GHz Intel Xeon processor (compile node), and 3 with 1 1GHz Intel Pentium III

• *Medusa Cluster*, RPI: 32 dual 2.0GHz Intel Xeon processor systems

• ASCI-class supercomputers: large clusters of SMPs

• Grid computers – “clusters of clusters” or “clusters of supercomputers”

This is just a small sample of the wide variety of systems in use.

• long-term “resource-aware computation” goal: software that can run efficiently on any of them

• work described here is one step toward this goal, current focus on systems found at places like Williams
Resource-Aware Computing Motivations

- Heterogeneous processor speeds
  - seem straightforward to deal with
  - does it matter? computation proceeds only as fast as the *slowest* process
- Distributed *vs.* shared memory
  - some algorithms may be a more appropriate choice than others
- Non-dedicated computational resources
  - can be highly dynamic, transient
  - will the situation change by the time we can react?
- Heterogeneous or non-dedicated networks
- Hierarchical network structures
  - message cost depends on the path it must take
- Relative speeds of processors/memory/networks
  - important even when targeting different homogeneous clusters
What Can Be Adjusted?

- Choice of solution methods and algorithms
  - different approaches for multithreading vs. distributed memory
- Parallelization paradigm
  - threads vs. message passing vs. actor/theater model vs. hybrid approaches
  - “bag-of-tasks” master/slave vs. domain decomposition
- Ordering of computation and/or communication
- Replication of data or computation
- Communication patterns (e.g., message packing)
- Optimal number of processors, processes, or threads
  - not necessarily one process/thread per processor
- Our focus: partitioning and dynamic load balancing
  - tradeoffs for imbalance vs. communication volume
  - variable-sized partitions
  - avoid communication across slowest interfaces
Bullpen Cluster at Williams College

All nodes contain (aging) Sun UltraSparc II processors

http://bullpen.cs.williams.edu/
Resource-Aware Load Balancing

- Goal: account for environment characteristics in load balancing
- Idea: build a model of the computing environment and use it to guide load balancing
  - represent heterogeneity and hierarchy
    * processor heterogeneity, SMP
    * network capabilities, load, hierarchy
  - static capability and dynamic monitoring feedback
- Use existing load balancing procedures to produce, as appropriate
  - variable size partitions
  - “hierarchical” partitions
- Longer-term: tailor other parts of the computation to the environment
- Alternate approach: process-level or system-level load balancing
DRUM: Dynamic Resource Utilization Model

- Run-time model encapsulates the details of the execution environment
- Supports dynamic load balancing for environments with
  - heterogeneous processing capabilities
  - heterogeneous network speeds
  - hierarchical network topology
  - non-dedicated resources
- Not dependent on any specific application, data structure, or partitioner

http://www.cs.williams.edu/drum/
Computation Flow with DRUM monitoring

Application Software

Setup/Initial Partitioning → Compute → Evaluate Error → Adaptive Step → Rebalance Load → Compute

Load Balancing Suite

Partitioning and Dynamic Load Balancing Implementations/Support Tools

Resource Monitoring System

Static Capabilities

Dynamic Monitoring

Performance Analysis
DRUM: Dynamic Resource Utilization Model

Computing Environment

- Tree structure based on network hierarchy
- Computation nodes, assigned “processing power”
  - UP – uniprocessor node
  - SMP – symmetric multiprocessing node
- Communication nodes
  - network characteristics (bandwidth, latency)
  - assigned a processing power as a function of children
DRUM: Dynamic Resource Utilization Model

- Static capabilities
  - gathered by benchmarks or specified manually once per system
  - processor speeds, network capabilities and topology

- Dynamic performance monitoring
  - gathered by “agent” threads managed through a simple API
  - communication interface (NIC) monitors
    * monitor incoming and outgoing packets and/or available bandwidth
  - CPU/Memory monitors
    * monitors CPU and memory usage and availability

- Combine static capability information and dynamic monitoring feedback
- Straightforward to use powers to create weighted partitions with existing procedures
- Optional Zoltan interface allows use by applications with no modifications
- More details and computational results in recent papers:
  * Applied Numerical Mathematics, 52(2-3), pp. 133-152, 2005
  * Computing in Science & Engineering, 7(2), pp. 40-50, 2005
DRUM Setup and Configuration

- DRUM needs some information about the environment to construct its model
- Some may be detected at run time, some must be specified
- DRUM reads a “cluster description file” in XML format

```xml
<machinemodel>
  <node type="NETWORK" nodenum="0" name="" IP="" isMonitorable="false"
    parent="-1" imgx="361.0" imgy="52.0">
    <lbmethod lbm="HSFC" KEEP_CUTS="1"></lbmethod>
  </node>
  <node type="SINGLE_COMPUTING" nodenum="2" name="mendoza.cs.williams.edu"
    IP="137.165.8.140" isMonitorable="true" parent="0"
    benchmark="52.43" imgx="50.0" imgy="138.0">
    <lbmethod lbm="HSFC" KEEP_CUTS="1"></lbmethod>
  </node>
  <node type="MULTIPLE_COMPUTING" nodenum="3" name="rivera.cs.williams.edu"
    IP="137.165.8.130" isMonitorable="false" parent="0"
    imgx="74.64" imgy="263.0" benchmark="82.55" numprocs="4">
    <lbmethod lbm="HSFC" KEEP_CUTS="1"></lbmethod>
  </node>
  ...  
</machinemodel>
```

- XML file needs only be updated if the cluster changes
- Arjun Sharma project Summer ’04: improve generation of these files
• Build topology description
• Run benchmark suite to determine static capabilities
• Specify hierarchical balancing parameters
• Write XML file description
DRUM Monitoring Capabilities

• DRUM needs to gather performance statistics at run time

• Some available through kernel statistics
  – specific to Solaris and Linux

• Some available through Simple Network Management Protocol (SNMP)
  – not all environments make SNMP information available

• Similar information is available through the Network Weather Service (NWS)
  – DRUM can use NWS information (Laura Effinger-Dean, Summer ’04)

• DRUM’s modular design allows other monitoring tools to be used in the future
DRUM: Dynamic Resource Utilization Model

- Straightforward to give less work to slower or busy processors
- Idea: also give less work to processes that communicate over slow or busy network interfaces

Compute the “power” for a process as the weighted sum

\[ \text{power} = w^{\text{comm}} c + w^{\text{cpu}} p, \quad w^{\text{comm}} + w^{\text{cpu}} = 1 \]

of processing power \( p \) and communication power \( c \)

- how to choose \( p \) and \( c \)?
- how to choose weights?
- can we do something better than a weighted sum?

- Processing power based on static benchmark plus monitored CPU usage and idle times
- Communication power based on interface packet counts or available bandwidth measures
- Communication and processing weights currently set manually
DRUM: Dynamic Resource Utilization Model

• Processing power, \( p_{n,j} \), for process \( j \) on node \( n \) based on:
  
  – the node’s “MFLOPS” rating obtained from benchmarking, \( b_n \)
  
  – per-process CPU utilizations, \( u_{n,j} \)
  
  – usable idle time

  * monitor fraction of idle time of CPU \( t \) (of \( m \) CPUs in node), \( i_t \)
  
  * compute the overall idle time in node \( n \), \( \sum_{t=1}^{m} i_t \)
  
  * compute total usable idle time on node \( n \), \( \min(k_n - \sum_{j=1}^{k_n} u_{n,j}, \sum_{t=1}^{m} i_t) \)
  
  – Compute average CPU usage and idle times per process:

\[
\bar{u}_n = \frac{1}{k_n} \sum_{j=1}^{k_n} u_{n,j}, \quad \bar{i}_n = \frac{1}{k_n} \min(k_n - \sum_{j=1}^{k_n} u_{n,j}, \sum_{t=1}^{m} i_t)
\]

  
  – processing power estimated as:

\[
p_{n,j} = b_n(\bar{u}_n + \bar{i}_n), \quad j = 1, 2, \ldots, k_n
\]
DRUM: Dynamic Resource Utilization Model

- Communication power, $c_n$, for interface $i$ (of $s$ interfaces) based on:
  - communication activity factor, $CAF_{n,i}$
  - software loopback interfaces and interfaces with $CAF = 0$ are ignored
    \[ c_n = \frac{1}{s \sum_{i=1}^{s} CAF_{n,i}} \]
- or, NWS-measured “available bandwidth” (Effinger-Dean, Summer ’04)
- Effectively just need a way to specify relative communication powers
- Considering other ways to determine a communication power and weight
DRUM: Early Computational Example

• Execution environment
  – eight processors of Williams College “Bullpen” cluster
  – five “fast” (450MHz), three “slow” (300MHz) processors

• Computation
  – 2D discontinuous Galerkin solution of R-T instability
  – 200 adaptive mesh refinement/rebalancing steps
  – maximum of 6320 elements

• DRUM resource-aware load balancing results
  – assigning 50% more work to fast nodes: theoretical 24% improvement
  – straightforward Octree/SFC partitioning: 9507 seconds
  – dynamic monitoring and partition-weighted Octree/SFC: 7351 seconds
  – 22.6% improvement, 94.1% of theoretical
DRUM: Dynamic Resource Utilization Model

Example results on a heterogeneous cluster

• Using Mitchell’s PHAML software to solve 2D Laplace equation

• Combination of “fast” (450 MHz) and “slow” (300 or 333 MHz) processors
  – 2, 4, 6, 8 fast processors
  – 0, 2, 4 slow processors

• Adaptive simulation for 17 refinement steps, resulting in 524,500 nodes

• Straightforward DRUM-aware HSFC partitioning used, vary $w^{comm}$
DRUM on a Heterogeneous Cluster

- Runs on a homogeneous subset of nodes indicate low overhead
- Adding 2 or 4 “slow” nodes to a run on “fast” nodes slows the computation without DRUM, but with DRUM these processors can be used effectively
- Here, accounting for communication \( w^{comm} > 0 \) is usually not helpful
  - the computation is latency-dominated
DRUM on a Heterogeneous Cluster

- Grey bars: “ideal” relative change – speedup we could get under perfect conditions by accounting only for processor speeds
- Red bars show best achieved on each combination of nodes across all attempted $w^{comm}$ values
- A significant part of the ideal change is achieved
DRUM: Dynamic Resource Utilization Model

Example computation in a dynamic system

- Same cluster and application parameters, but
  - external computational load on nodes running two of the processes

- Demonstrates DRUM’s dynamic capabilities

- DRUM dynamically adjusts the powers appropriately

![Graph showing PHAML Execution Time in seconds for different processor combinations: 8[2 fast (4)], 10[2 fast (4) + 2 slow], 12[2fast(4) + 2fast(2)], 14[2fast(4) + 2fast(2) + 2slow]. The graph compares Uniform and DRUM=0 and DRUM=0.1 scenarios.]
Modified Bullpen Cluster

When is a non-zero communication weight beneficial?

Four nodes removed from the main network and connected to the rest of the cluster through a slower 10Mbit Ethernet hub
Communication Weight Study

- Three-dimensional perforated shock tube problem on modified cluster
  - 4 processes on nodes connected to main switch
  - 4 processes on nodes connected to slower switch
- Vary communication weight $w^{comm}$
Communication Weight Study

- Best $w^{comm}$ values in the 0.30-0.33 range
- More examples with finer adjustments to $w^{comm}$
- With $w^{comm} = 0.315$, processes on nodes connected to slow switch assigned power 0.09, others assigned 0.15
Hierarchical Partitioning and Load Balancing

• Goal:
  – use different algorithms in different parts of the execution environment
  – tailor mesh (or other) partitions for network hierarchy, SMP nodes

• Takes advantage of characteristics of available procedures
  – graph partitioners such as those in ParMetis
    * minimize inter-partition boundaries, but may introduce imbalance
  – geometric methods such as inertial recursive bisection
    * achieve strict balance, but may have large boundaries
  – studies with Ungar and Bennett at Williams

• Need ability to produce: variable-sized partitions, $k \neq p$ partitions
Hierarchical Load Balancing with the Zoltan Toolkit

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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>callbacks invoked by Zoltan</td>
<td>Zoltan HIER balancer</td>
</tr>
<tr>
<td></td>
<td>call application callbacks (build initial IHBS)</td>
</tr>
<tr>
<td></td>
<td>create Zoltan objects</td>
</tr>
<tr>
<td></td>
<td>set parameters</td>
</tr>
<tr>
<td></td>
<td>invoke balancing</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>migrate application data</td>
<td>update IHBS</td>
</tr>
<tr>
<td>continue computation</td>
<td>split MPI_Comm</td>
</tr>
<tr>
<td></td>
<td>return migration arrays</td>
</tr>
</tbody>
</table>

- IHBS = internal hierarchical balancing structure
  - Parmetis-style arrays, augmented to maintain internal migration
- Can do any number of levels and use any combination of procedures
- Application is not modified; existing Zoltan procedures are not modified
- In Zoltan development version, expected to include in next release
Hierarchical Load Balancing

- 1,103,018-element mesh of human arteries, partitioned using RIB and Parmetis
- Minimize communication across slow networks, balance strictly within SMPs
  - for the 28-way node case, only 0.3% of faces are on “slow” boundary
Dhanni Cluster at Williams College

Legend: DC=dual core, HTT=hyperthreaded
Blue nodes have 4 logical processors, red nodes have 8 logical processors
Processor Heterogeneity on Dhanni

- “Slow” vs. “Fast” nodes – same issues as Bullpen
- But... hyperthreaded and multi-core nodes
  - A hyperthreaded processor appears to the OS as 2 “logical” processors

Hyperthreading enabled

Hyperthreading disabled

Hyperthreading must be enabled/disabled in system BIOS before bootup
Processor Heterogeneity on Dhanni

- How does hyperthreading come into play?
  - Benefit of better hardware utilization must outweigh costs of cache misses
  - Initial tests with DRUM’s 3D Cellular Automata example program
  - With hyperthreading disabled (in system BIOS):
    - 4 nodes, 1 processes per node: 182.1 seconds
    - 4 nodes, 2 processes per node: 91.9 seconds
  - With hyperthreading enabled:
    - 4 nodes, 1 processes per node: 182.4 seconds
    - 4 nodes, 2 processes per node: 142.5 seconds
    - 4 nodes, 3 processes per node: 110.1 seconds
    - 4 nodes, 4 processes per node: 82.1 seconds

- Expectation: effect of hyperthreading can be difficult to predict
- Expectation: DRUM’s dynamic monitors will “do the right thing”
Ongoing and Future Work in DRUM

• Apply DRUM to other applications (volunteers? terescoj@cs.williams.edu)
• Further DRUM management of the computation – triggering load balancing
• Prepare a public release of DRUM (currently available by request)
• Apply to Grid environments
  – more heterogeneity: more need for and more benefit from DRUM
  – more hierarchy: hierarchical balancing
  – take advantage of other Grid-aware discovery and monitoring tools
• Hyperthreaded and dual-core nodes
  – test current DRUM version in these environments
  – enhance DRUM for such environments – discovery, benchmarks
  – hierarchical partitions?
Balancing at Other Levels

- Process-level load balancing
  - migrate MPI processes among computing nodes
  - developing middleware MPI/IOS system with Varela and ElMaghraoui (RPI)
    * uses MPI-2 functionality to migrate MPI processes
    * migrate processes only at “convenient” times for the application using Process Checkpoint and Migration (PCM) library
  - migration is expensive
  - support for transient environments

- System-level load balancing
  - migrate entire virtual operating systems, enabled by Xen project
  - migration is expensive, but migrating systems can continue operating until the final step
  - just-completed senior honors thesis by Travis Vachon
  - initial focus on data center environments, but is this appropriate for HPC applications?
Closing Remarks

• Accounting for heterogeneity and hierarchy can improve efficiency

• DRUM and hierarchical balancing software are not dependent on specific application software or mesh structures
  – DRUM is a standalone library (but works well with Zoltan)
  – HIER is part of the Zoltan Toolkit

• DRUM and hierarchical balancing can be transparent to applications

• Tools like DRUM more important in more heterogeneous environments

• Heterogeneity was intentional here but will arise over time as nodes are added to clusters
  – “one man’s trash is another man’s new cluster node”
  – multi-core and hyperthreaded processors
  – also think of networks of workstations, grid environments

• Focus to date on application-level load balancing, but process- and system-level balancing may be appropriate in some circumstances
Acknowledgements

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- The “Dhanni Cluster” of Linux servers at Williams College
- Workstations and multiprocessors at Sandia National Laboratories and Rensselaer Polytechnic Institute
- The PASTA Laboratory at Union College (long, long ago)