An Overview of Resource-Aware Parallel Computing

(With an Emphasis on Hierarchical Partitioning and Load Balancing)

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Minisymposium MS60/MS78: *Resource-Aware Parallel Computation*

Co-organizers: Jim Teresco (Williams College), Jamal Faik (Rensselaer)

Yet another Powerpoint-free presentation!

Overview

- Minisymposium introduction
  - resource-aware computation: why? how? who?
  - minisymposium talks and topics
- Hierarchical partitioning and load balancing
  - motivation
  - target applications
  - a hierarchical cluster
  - parallel adaptive scientific computation
  - dynamic load balancing
  - DRUM
  - hierarchical balancing idea
  - hierarchical balancing implementation
  - early results

Resource-Aware Parallel Computing

- Optimize software for performance on a particular computer
- Everyone does some:
  - compilers: portable source code
  - optimizing compilers: architecture-specific optimizations
- Another example: special-purpose memory management
  - allocate contiguous memory for linked structures
  - try to improve cache utilization
- Parallel computing introduces more variety
  - more need and opportunity for architecture-specific optimizations
  - heterogeneity and hierarchy of resources
  - wider variety of programming paradigms and tools

Target Computational Environments

- FreeBSD Lab, Williams: 12 dual 2.4 GHz Intel Xeon processor systems
- *Momentum*, RPI: SGI Origin 2000, 12 400 MHz MIPS R10000 processors
- *Bullpen Cluster*, Williams: 13 node Sun cluster, total of 4 300 MHz and 21 450 MHz UltraSparc II processors
- *ASCI Red*, Sandia National Labs: 4600+ nodes, each with 2 Intel Pentium II Xeon processors, first TeraOp machine in 1997
- *ASCI White*, LLNL: 512 nodes, each with 16 Power3 Nighthawk-2 processors, 12 TeraOps total, was world's fastest until 2002
- *ASCI Q*, LANL: 8192 HP AlphaServer 1.25 GHz processors, 15 TeraOps
- *Big Mac*, Virginia Tech: 1100 dual 2.0 GHz Apple G5 nodes, 17.6 TeraOps
- *ASCI Purple*, First 100+ Teraflop system, coming soon
- *Squall*, Williams College: Macintosh PowerBook, 1.25 GHz Power PC G4

Less Traditional Environments

- Internet Computing: “actor/theater” model of computation allowing a large distributed computation using resources that may be shared or unreliable
- Cray (formerly Tera) MTA: “multithreaded architecture” has fully multi-threaded hardware and OS
- Earth Simulator, Yokohama Institute for Earth Sciences, Japan: 640-node NEC system, each node with 8 vector processors, total of 5,120 CPUs, peak performance 40 TeraOps
- Computational Grids, such as the NSF TeraGrid: nodes at NCSA, San Diego Supercomputing Center, Argonne National Laboratory, Caltech, and the Pittsburgh Supercomputer Center, peak projected performance 20 Tera-Ops
- Many other Grids deployed or planned

Motivations

- Heterogeneous processor speeds
  - seem straightforward to deal with
  - does it matter?
  - assumptions of homogeneous processor speeds may be well-hidden
- 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

Motivations

- Relative speeds of processors/memory/networks
  - important even when targeting different homogeneous clusters
- Heterogeneous processor architectures (*e.g.*, Sparc + x86)
- Operating system support for programming paradigms
  - multithreading
  - priority thread scheduling
  - distributed shared memory
- Availability of tools (*e.g.*, MPI, OpenMP, Java, *etc*.)
  - may choose something less than optimal to maximize portability
- Transient resource availability
- Reliability (or lack thereof) of processors, networks
  - last year at SIAM PP04, several sessions on fault tolerance
- Scalability concerns
  - what works well for 10’s of processors may not for 1000’s+

What Can Be Adjusted?

- Choice of programming language (*e.g.*, Java for smoother portability)
- Choice of solution methods and algorithms
  - some approaches are better for multithreading
  - some approaches are better for 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
- Replication of computation
- Optimal message sizes

What Can Be Adjusted?

- Communication patterns (*e.g.*, ordering of collective communication)
- Optimal number of processors, processes, or threads
  - not necessarily one process/thread per processor
- Process placement
  - resource-aware initial allocation of processes to nodes
  - dynamic process migration
- Partitioning and dynamic load balancing
  - tradeoffs for imbalance *vs*. communication volume
  - variable-sized partitions
  - avoid communication across slowest interfaces

Who Can Make Adjustments?

- Compiler developers
- Low-level tool developers
  - MPI implementations
- Other tool developers
  - partitioners and dynamic load balancers
  - optimized numerical libraries
- Middleware
  - monitoring tools
  - autonomous migration systems
  - automated selection from among a group of available algorithms
- Application programmers
  - parallel programming paradigm
  - distribution of work: strict balance *vs.* minimal communication
  - frequency of dynamic load balancing
  - memory management techniques

What Is Needed?

- Knowledge of computing environment
  - manual specification
  - benchmarking *a priori*
  - discover automatically at run time
  - monitor dynamically
- Knowledge of software performance characteristics
  - performance models
  - studies to compare performance
- Tools to use this knowledge
  - middleware or libraries to hide architecture-aware details
  - partitioners and dynamic load balancers

Minisymposium: *Resource-Aware Parallel Computation*

Today:

- Remainder of this talk: *Hierarchical Partitioning and Load Balancing*
- *Scientific Computation on Heterogeneous Clusters using DRUM*
  Jamal Faik, RPI
- *Architecture-Aware Autonomic Adaptations within the CCA*
  Manish Parashar, Rutgers, **Jaideep Ray**, Sandia National Laboratories

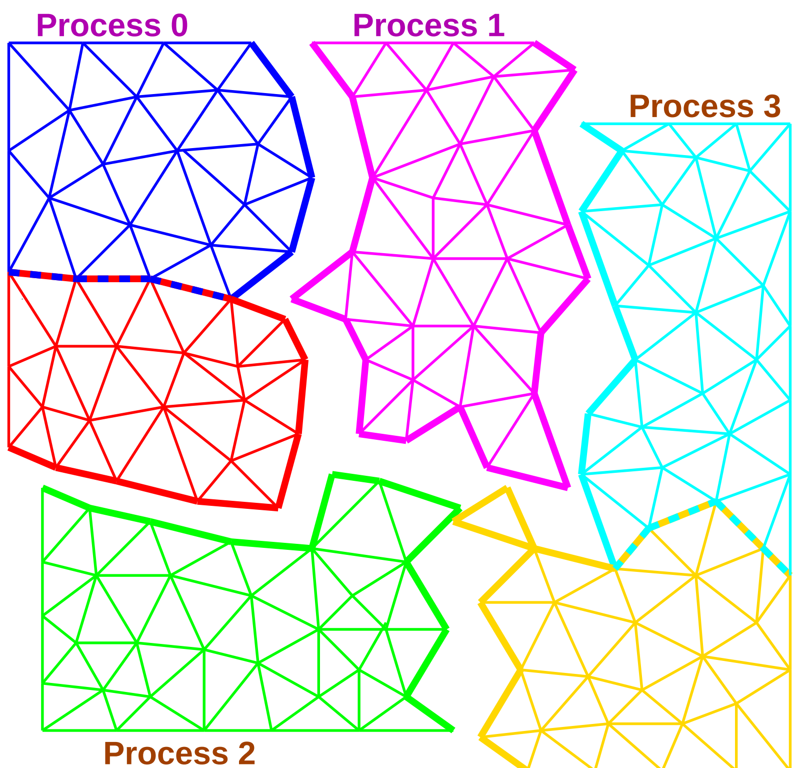
Tomorrow:

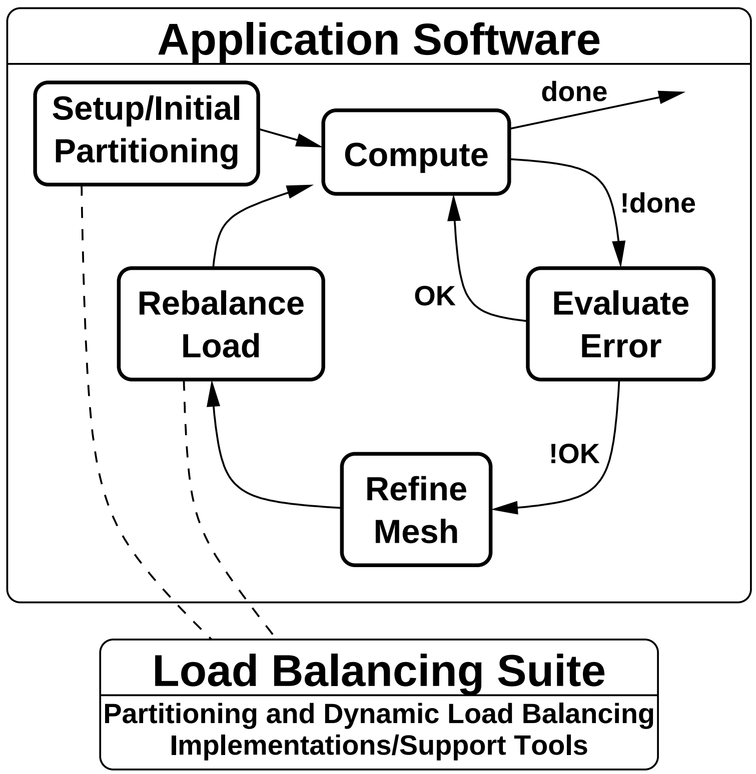
- *Automatic Deployment of MPI Applications on a Computational Grid*
  Sébastien Lacour, Argonne, and IRISA / INRIA Rennes, France and Argonne, Christian Pérez, IRISA / INRIA Rennes
- *Towards an Internet OS: Middleware for Adaptive Distributed Computing*
  Carlos Varela, RPI
- *Performance-Directed Resource Allocation*
  Seung-Hye Jang, Xingfu Wu, and Valerie Taylor, Texas A&M University

Resource-Aware Load Balancing for Scientific Computation on a Heterogeneous Cluster

Motivation: run large-scale parallel adaptive solution procedures in varying environments

- Finite element and related methods, parallelized by domain decomposition

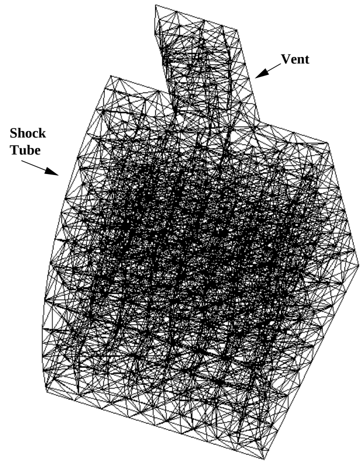


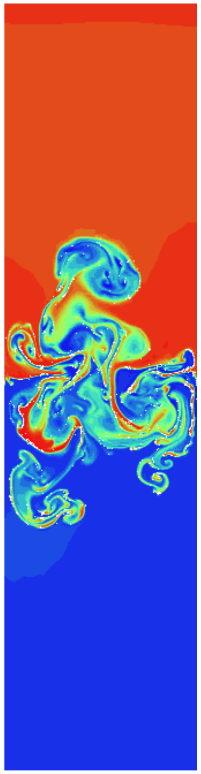


Example Parallel Adaptive Software

We wish to run several applications.

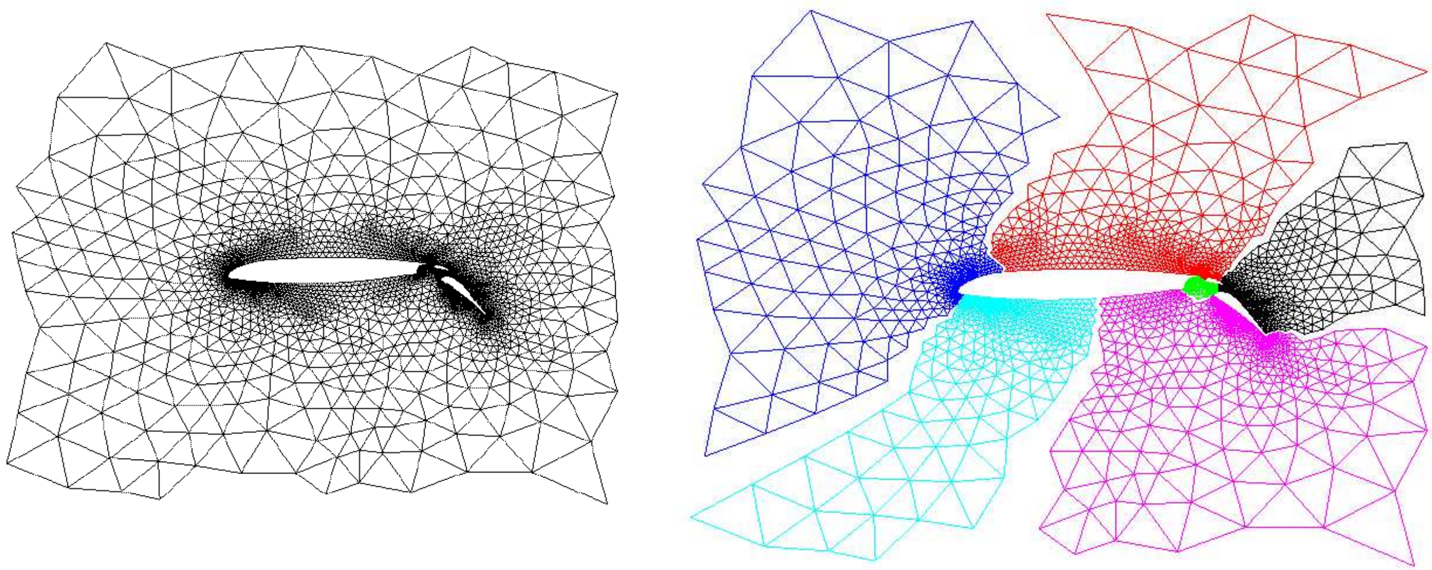
- Rensselaer's "LOCO"
  - parallel adaptive discontinuous Galerkin solution of compressible Euler equations in C.
  - "perforated shock tube" problem
- Rensselaer's "DG"
  - also discontinuous Galerkin methods, but in C++
  - using Algorithm-Oriented Mesh Database
  - Rayleigh-Taylor flow instabilities and others
- Mitchell's PHAML
  - Fortran 90, adaptive solutions of various PDEs
- Simmetrix, Inc. MeshSim-based applications
- Others





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!*

Example Parallel Adaptive Solution

Example adaptive computation: mesh-dens.mov

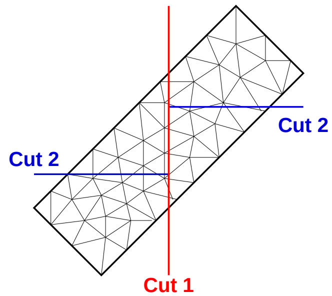
Real interest for parallel computing is in 3D transient problems.

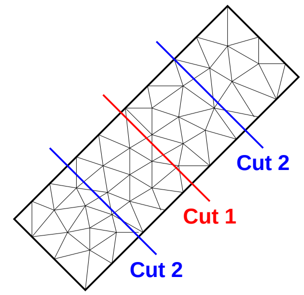
Mesh Partitioning/Load Balancing

Geometric methods, use only coordinate information

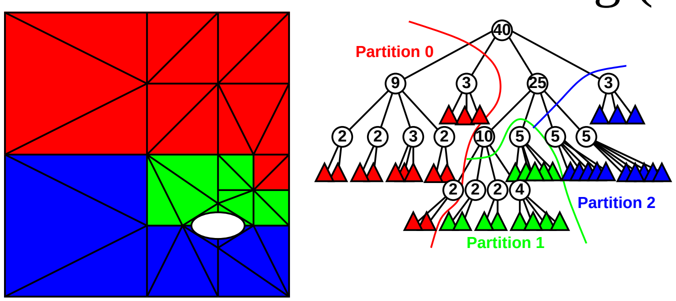
- Recursive methods, recursive cuts determined by

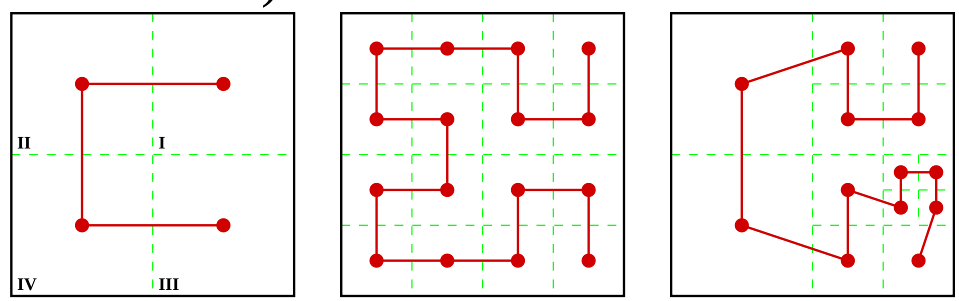
Coordinate Bisection (RCB) Inertial Bisection (RIB)





- Octree/SFC Partitioning (OCTPART/HSFC)



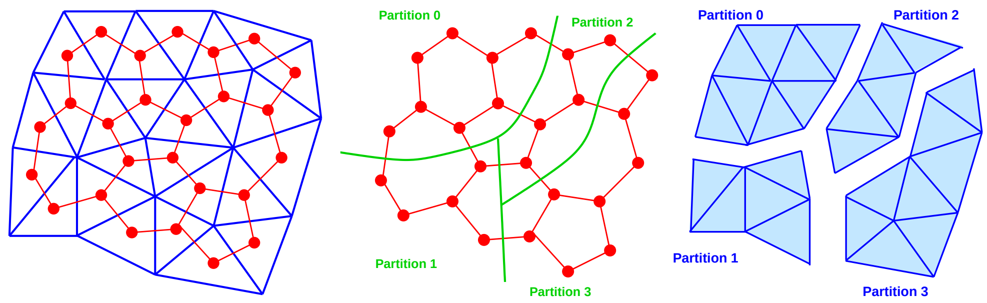


  - Morton, Grey Code, and Hilbert traversals available for OCTPART
  - Hilbert traversal for HSFC

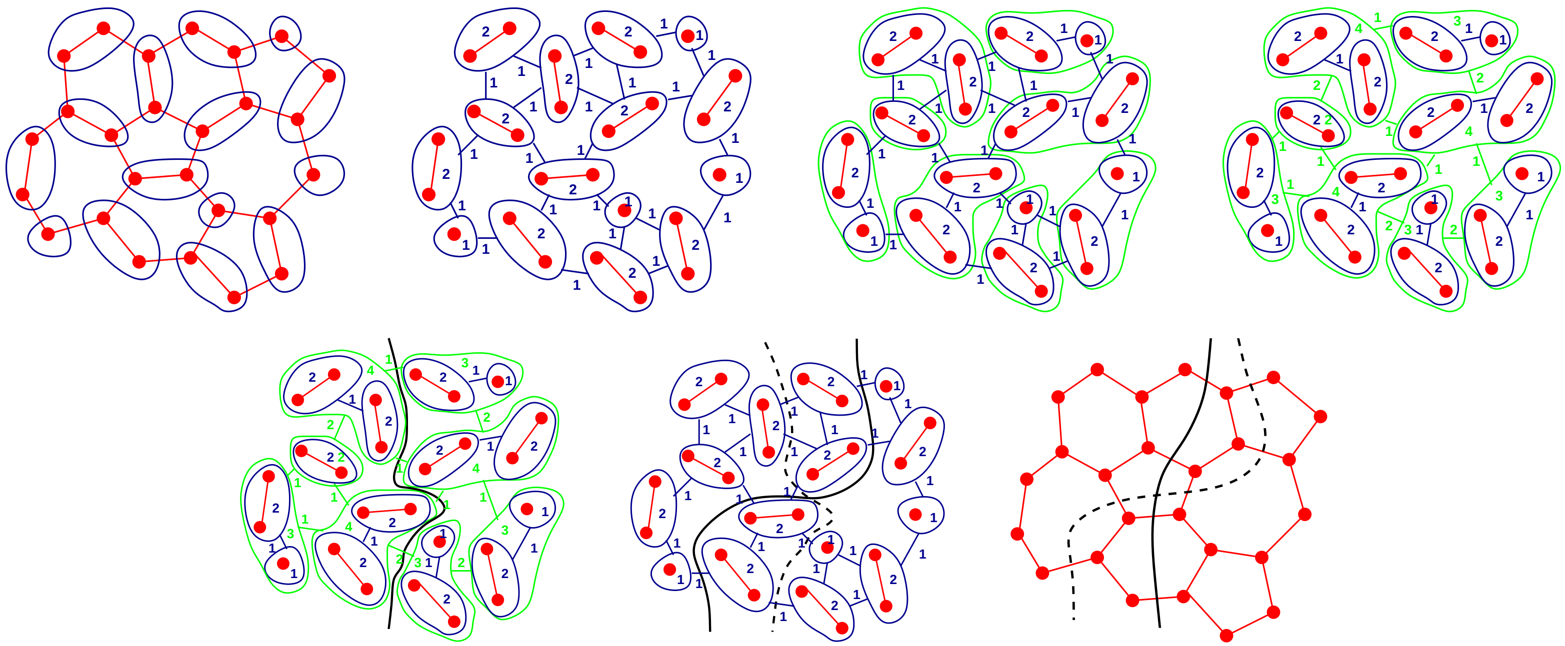
- Tend to be fast, and can achieve strict load balance
- “Unfortunate” cuts may lead to larger partition boundaries

Mesh Partitioning/Load Balancing

Graph-based methods use connectivity information



- Spectral methods (Chaco), Multilevel partitioning (ParMetis, Jostle)



- More expensive, but usually produce smallest partition boundaries
- May introduce some load imbalance to improve boundary sizes

Load Balancing Considerations

Many important factors must be considered

- Like a partitioner, a load balancer seeks
  - computational balance
  - minimization of communication
- 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
- No one approach will be best in all circumstances
  - depends on application
  - depends on parallel computing environment

Zoltan Toolkit

Includes suite of partitioning algorithms, developed at Sandia National Laboratories

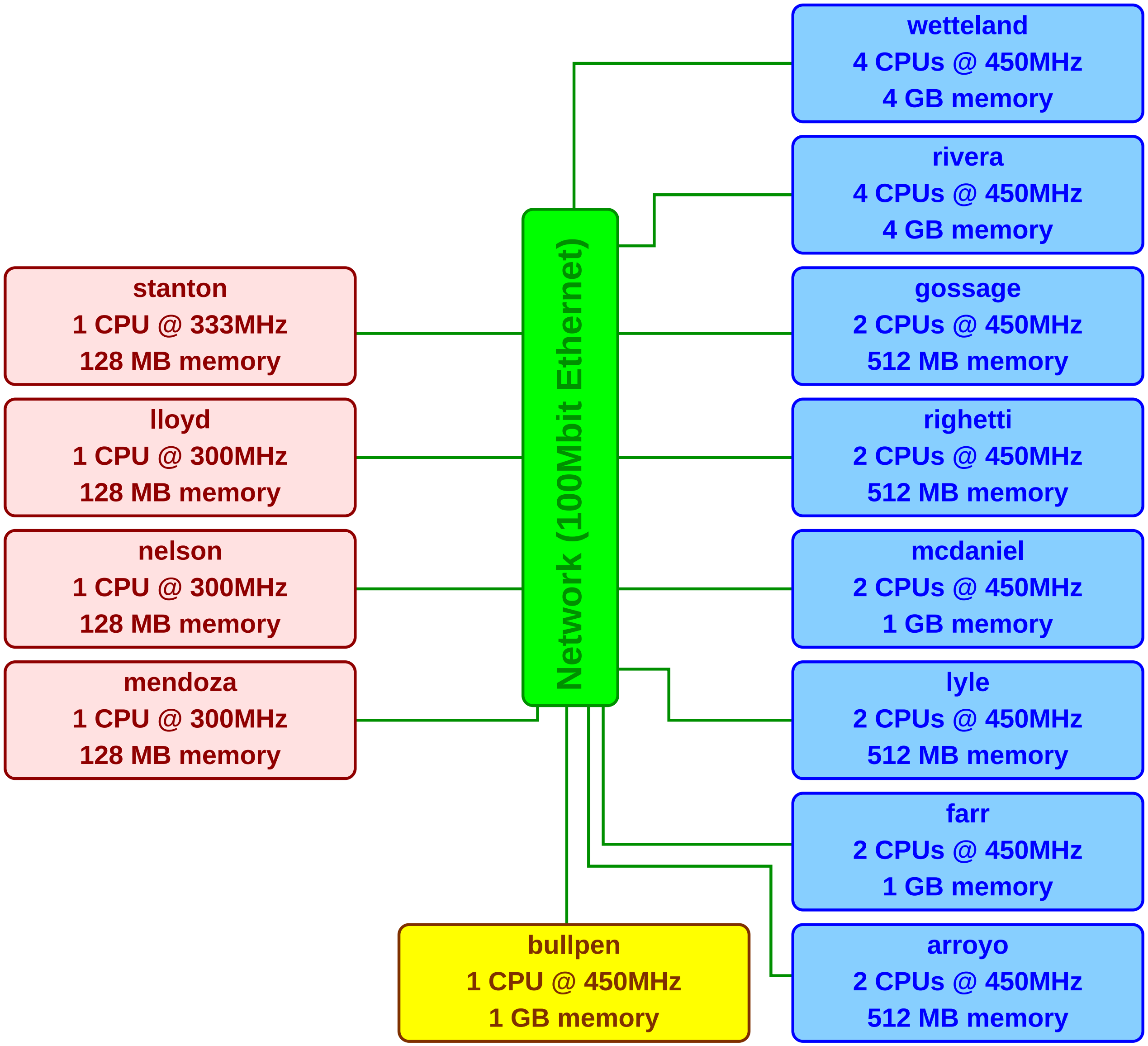
- General interface to a variety of partitioners and load balancers
- Application programmer can avoid the details of load balancing
- Interact with application through callback functions and migration arrays
  - "data structure neutral" design
- Switch among load balancers easily; experiment to find what works best
- Provides high quality implementations of:
  - Orthogonal bisection, Inertial bisection
  - Octree/SFC partitioning (with Loy, Gervasio, Campbell – RPI)
  - Hilbert SFC partitioning (Edwards, Heaphy – Sandia; Bauer – Buffalo)
  - Refinement tree balancing (Mitchell – NIST)
- Provides interfaces for:
  - Metis/Parmetis (Karypis, Kumar, Schloegel – Minnesota)
  - Jostle (Walshaw – Greenwich)
- Freely available: `http://www.cs.sandia.gov/Zoltan/`

Bullpen Cluster

View from the door of TCL 312d.

http://bullpen.cs.williams.edu/

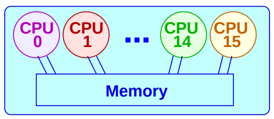
Bullpen Cluster



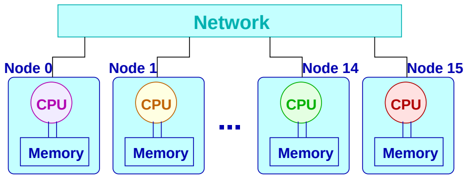
Hierarchical Partitioning Motivation

- We observe that
  - geometric partitioners are fast, give excellent balance
  - graph partitioners reduce boundary, may introduce load imbalence
  - in shared-memory environments, load balance is the key
  - in distributed environments with slow networks, reducing communication is the key
- May choose
  - a graph partitioner in the context of a slow network
  - geometric in SMPs
- What about clusters of SMPs or other hierarchical environments?
  - wish to reduce communication across slow networks
  - but maintain strict balance within a node

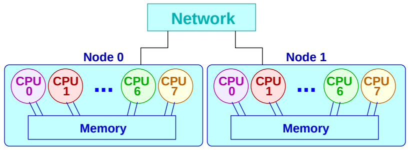
Hierarchical Load Balancing



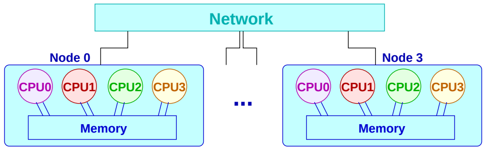
Fast Network



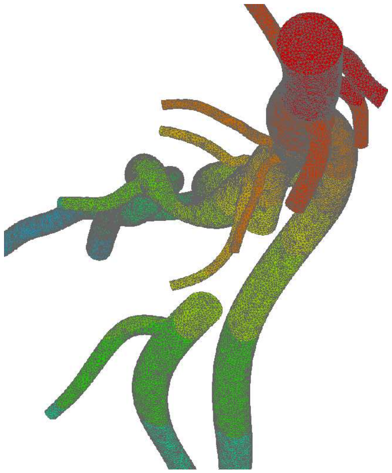
Slow Network



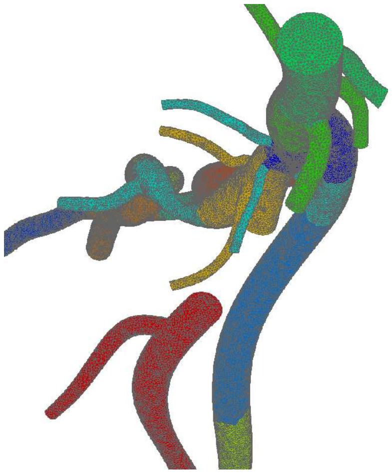
Combination



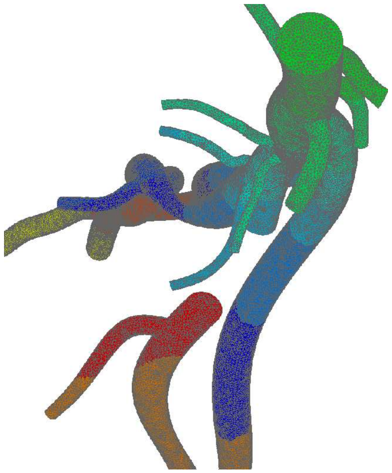
Combination



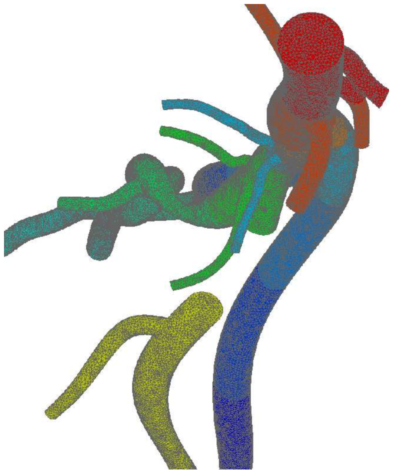
Strict Balance



Minimize Boundary



Mixed

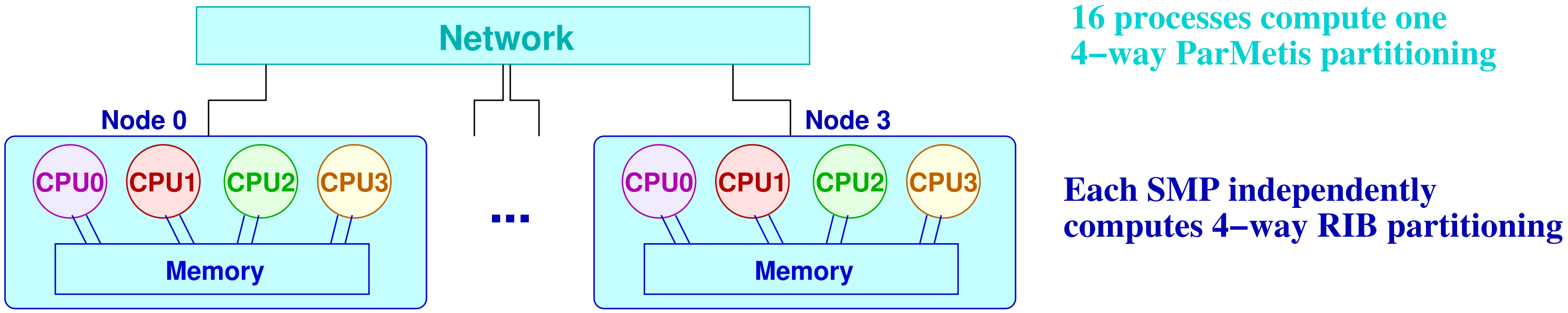


Mixed

- 1,103,018-element mesh of human arteries, partitioned using RIB and ParMetis
- Minimize communication across slow networks, balance strictly within SMPs
  - for the 2 8-way node case, only 0.3% of faces are on "slow" boundary

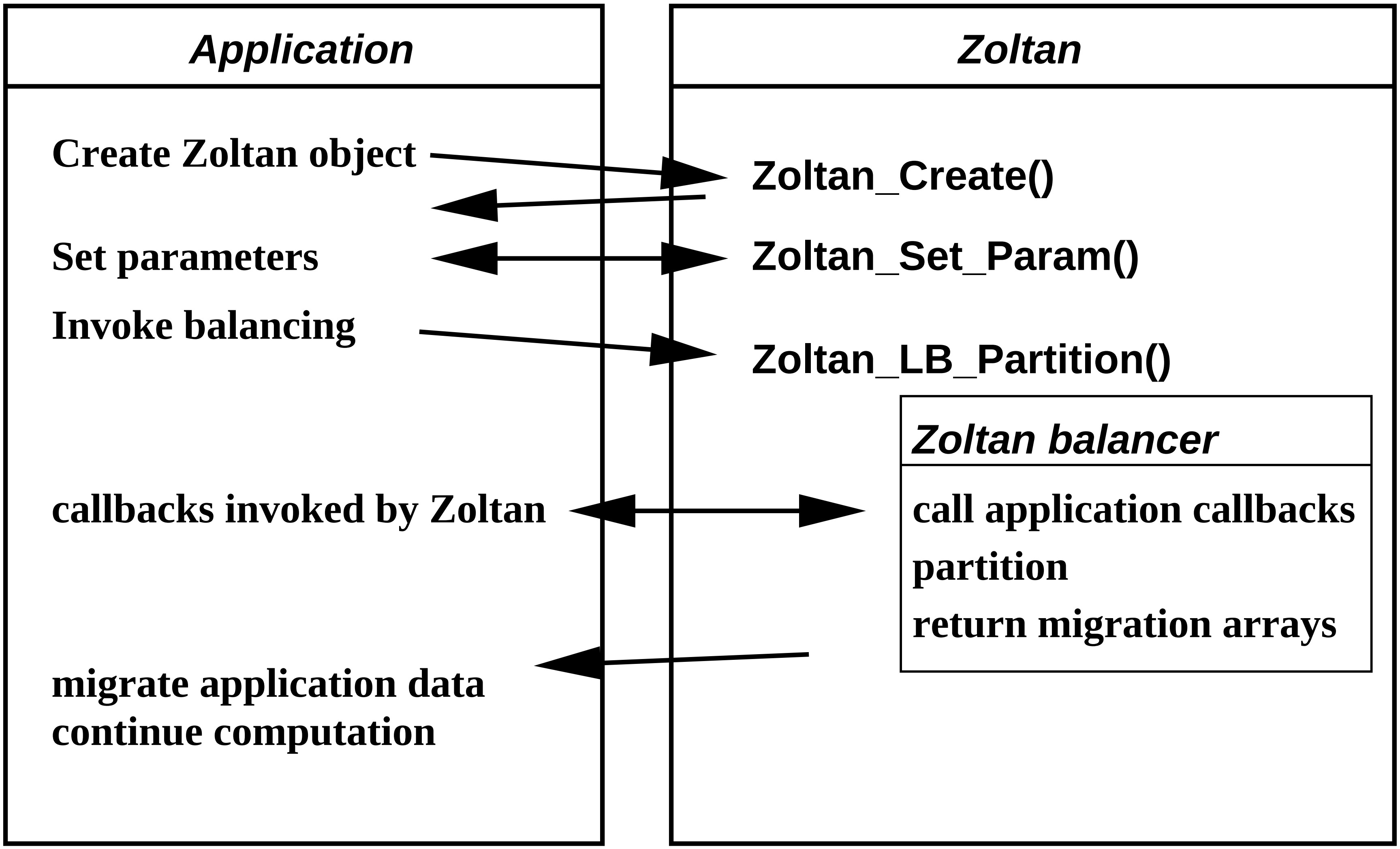
Hierarchical Partitioning and Load Balancing

- Automatic generation of hierarchical partitions using Zoltan method "HIER"

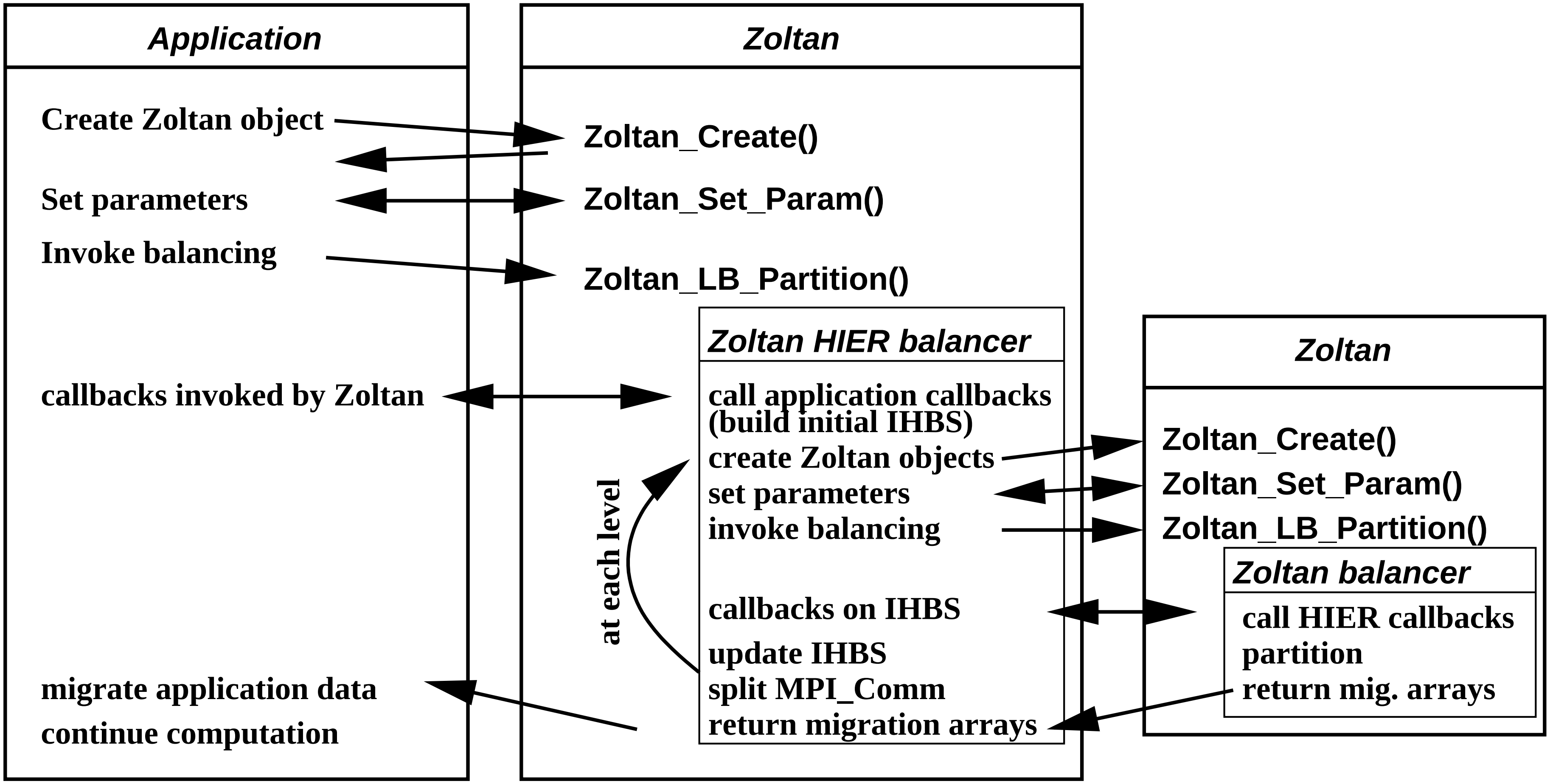


- Implemented during visit to Sandia's CSRI in 2003-04.
- Approach:
  - lightweight "intermediate structure" built from application callbacks
  - intermediate structure is augmented version of the structure built to feed to ParMetis
  - implement internal Zoltan callbacks to access intermediate structure
  - intermediate structure eliminates impact on Zoltan procedures
  - use Zoltan partitioners to partition at each of an arbitrary number of levels
  - object migration only at the end

Load Balancing with the Zoltan Toolkit



Hierarchical Load Balancing with the Zoltan Toolkit



- 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

Specification of Zoltan HIER partitionings

- Small set of new Zoltan callbacks
  - set number of levels of hierarchy
  - at each level, set which partitions to be computed by each process
  - at each level, set LB method and parameters
- zoltanParams library: simple file-based configuration for HIER
  - provides the HIER-related callbacks
  - example

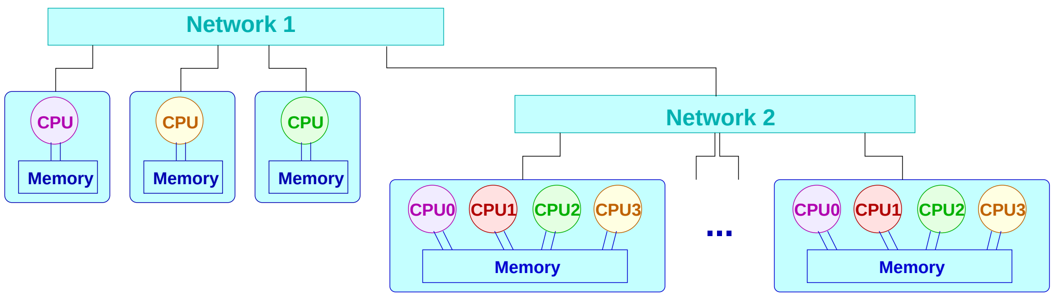
```
LB_METHOD HIER
2
0 0 1 1 2 2 3 3
LB_METHOD PARMETIS
PARMETIS_METHOD PARTKWAY
LEVEL END
0 1 0 1 0 1 0 1
LB_METHOD RCB
LEVEL END
```

  - can also be used for other Zoltan parameters
  - `http://www.cs.williams.edu/zoltanParams/`

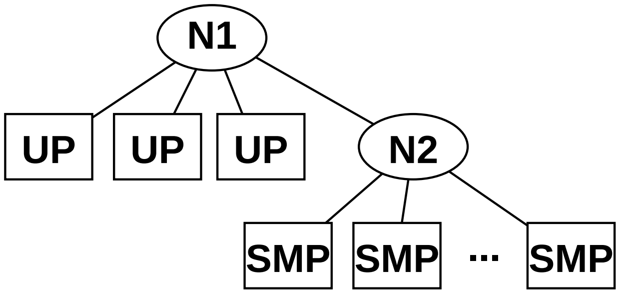
DRUM: Dynamic Resource Utilization Model

A run-time model of the parallel execution environment

(and topic of the next talk)



Computing Environment

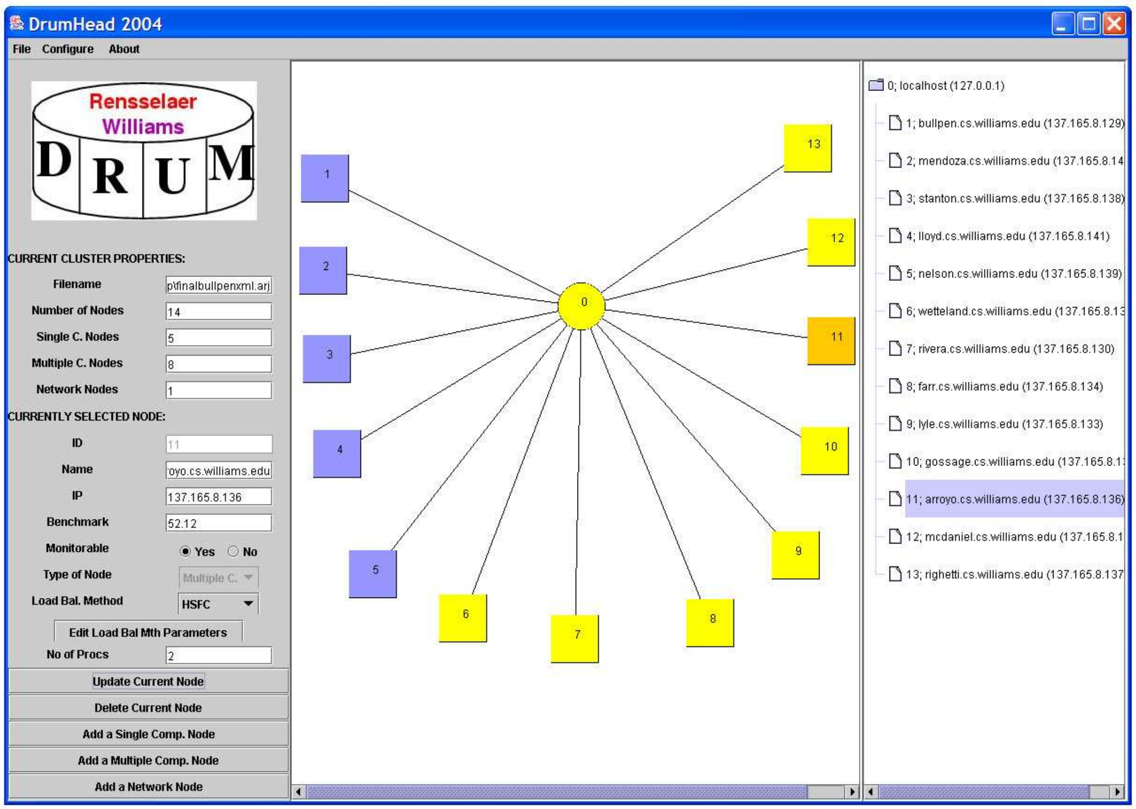


Machine Model

- Tree structure based on network hierarchy
- Computation nodes, assigned “computing power”
  - UP – uniprocessor node
  - SMP – symmetric multiprocessing node
- Communication nodes
  - network characteristics (bandwidth, latency)
  - assigned a computing power as a function of children
- Combine static capability information and dynamic monitoring feedback
- Powers guide creation of weighted partitions using existing procedures

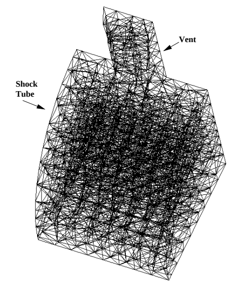
DRUM-guided Hierarchical Partitioning

- Coming soon: HIER partitions guided by DRUM machine model
  - network topology and load balancing parameters specified by DRUM's *DrumHead* configuration tool
  - stored in DRUM's XML-format configuration file
  - DRUM provides callbacks for Zoltan



Preliminary Hierarchical Balancing Results

- Run three-dimensional adaptive simulation



  - discontinuous Galerkin solution of a perforated shock tube
  - start with 69,572 tetrahedral elements, after 4 adaptive refinements, 254,510
  - cluster of multiprocessors: 4 2-way SMPs, 2 4-way SMPs
- measure time to solution for all traditional and hierarchical procedures
- Best hierarchical balancing combination:
  - ParMetis multilevel graph partitioning for inter-node partitioning
  - inertial recursive bisection within each node
- Results depend on how much imbalance is introduced by graph partitioning
  - when little imbalance occurs, graph partitioning produces the best results
  - otherwise, hierarchical partitions help

Hierarchical Partitioning and Load Balancing Current/Future

- Test on more applications, parallel environments (including Grids)
- More verification and testing to include in next Zoltan release
- Better integration with DRUM machine model
- Many efficiency improvements
  - avoid IHBS updates when not needed
  - maintain IHBS between successive rebalancings
  - avoid building redundant structures (*e.g.*, ParMetis applied first)
- Use IHBS to allow incremental enhancements through post-processing
- Use IHBS to compute multiple “candidate” partitionings
  - compute statistics about each
  - only accept and use the one deemed best
- Apply hierarchical structure to other parts of the computation

Other Current Approaches?

Minisymposium speakers today and tomorrow will tell us.

Acknowledgements

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- Sun multiprocessors at Sandia National Laboratories
- Workstations and multiprocessors in Computer Science and at SCOREC at RPI
- The PASTA Laboratory at Union College

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