USC

USC Viterbi
School of Engineering

New Challenges In Dynamic Load Balancing

Karen D. Devine, et al.

Presentation by
Nam Ma & J. Anthony Toghia

What is load balancing?

- **Assignment of work to processors**
- **Goal: maximize parallel performance through minimal CPU idle time and interprocessor communication overhead**

Static vs. dynamic load balancing

- Static
  - Applications with constant workloads (i.e. predictable)
  - Pre-processor to the computation
- Dynamic
  - Unpredictable workloads (e.g. adaptive finite element methods)
  - On-the-fly adjustment of application decomposition

Current challenges

- Most load balancers are custom written for an application
  - Lack of code reuse
  - Inability to compare different load balancing algorithms
  - Limited range of applications (symmetric, sparsely connected relationships)
  - Architecture dependence

Zoltan Parallel Data Services Toolkit

USC Viterbi School of Engineering

- Library of expert implementations of related algorithms
  - General purpose application to a wide variety of algorithms
  - Code reuse / portability
  - More thorough testing
  - Comparison of various load balancers by changing a run-time parameter
  - Data structure neutral design (data structures represented as generic objects with weights representing their computational costs)

USC

Zoltan: additional tools

- Data migration tools to move data between old and new decompositions
- Callbacks to user defined constructors for data structures to support data-structure neutral migration
- Unstructured communication package (custom, complex migrations)
- All tools may be used independently (e.g. user can use Zoltan to compute decomposition but perform data migration manually or vice versa)

Tutorial: The Zoltan Toolkit

Karen Devine and Cedric Chevalier
Sandia National Laboratories, NM

Umit Çatalyürek
Ohio State University

CSCAPES Workshop, June 2008

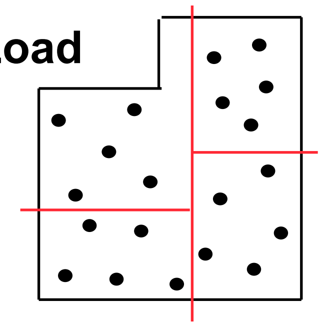
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Sandia National Laboratories

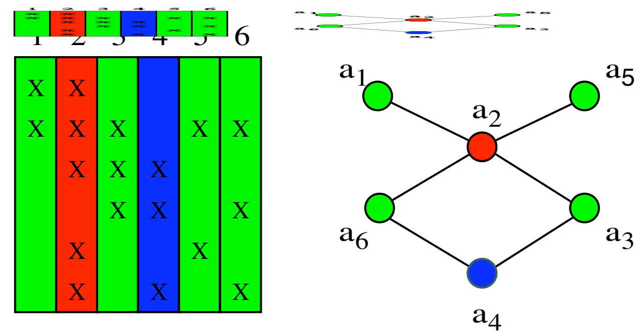
The Zoltan Toolkit

- Library of data management services for unstructured, dynamic and/or adaptive computations.

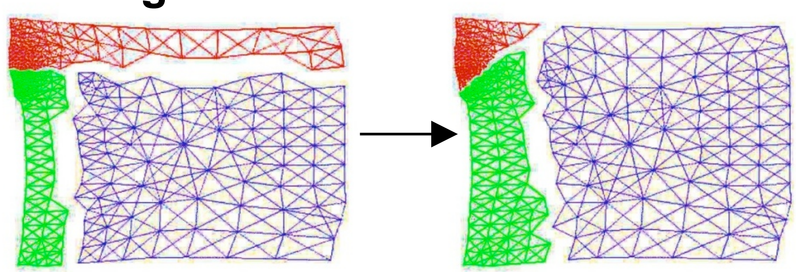
Dynamic Load Balancing



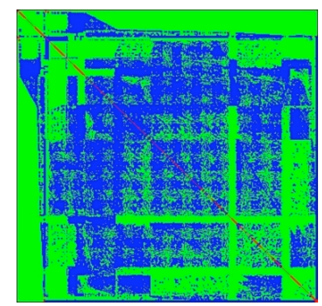
Graph Coloring



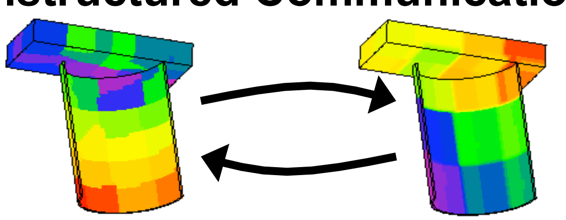
Data Migration



Matrix Ordering



Unstructured Communication



Distributed Data Directories

A	B	C	D	E	F	G	H	I
0	1	0	2	1	0	1	2	1

Zoltan Application Interface

APPLICATION

Initialize Zoltan
(Zoltan_Initialize, Zoltan_Create)

Select Method and Parameters
(Zoltan_Set_Params)

Register query functions
(Zoltan_Set_Fn)

COMPUTE

Re-partition
(Zoltan_LB_Partition)

Move data
(Zoltan_Migrate)

Clean up
(Zoltan_Destroy)

ZOLTAN

Zoltan_LB_Partition:

- **Call query functions.**
- **Build data structures.**
- **Compute new decomposition.**
- **Return import/export lists.**

Zoltan_Migrate:

- **Call packing query functions for exports.**
- **Send exports.**
- **Receive imports.**
- **Call unpacking query functions for imports.**

Sandia National Laboratories

Static Partitioning

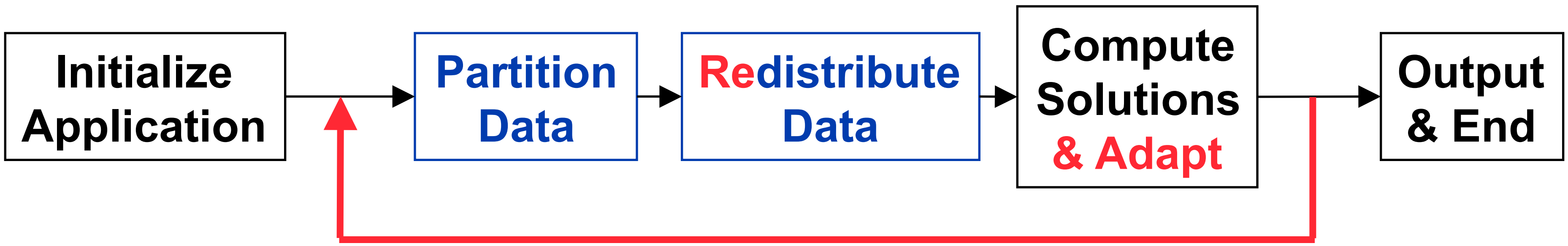
Initialize Application → Partition Data → Distribute Data → Compute Solutions → Output & End

- **Static partitioning in an application:**
  - **Data partition is computed.**
  - **Data are distributed according to partition map.**
  - **Application computes.**

- **Ideal partition:**
  - **Processor idle time is minimized.**
  - **Inter-processor communication costs are kept low.**

- **Zoltan_Set_Param(zz, "LB_APPROACH", "PARTITION");**

Dynamic Repartitioning (a.k.a. Dynamic Load Balancing)



- Dynamic repartitioning (load balancing) in an application:
  - Data partition is computed.
  - Data are distributed according to partition map.
  - Application computes and, perhaps, adapts.
  - Process repeats until the application is done.

- Ideal partition:
  - Processor idle time is minimized.
  - Inter-processor communication costs are kept low.
  - Cost to redistribute data is also kept low.

- Zoltan_Set_Param(zz, “LB_APPROACH”, “REPARTITION”);

Zoltan Toolkit: Suite of Partitioners

- No single partitioner works best for all applications.
  - Trade-offs:
    - Quality vs. speed.
    - Geometric locality vs. data dependencies.
    - High-data movement costs vs. tolerance for remapping.
- Application developers may not know which partitioner is best for application.

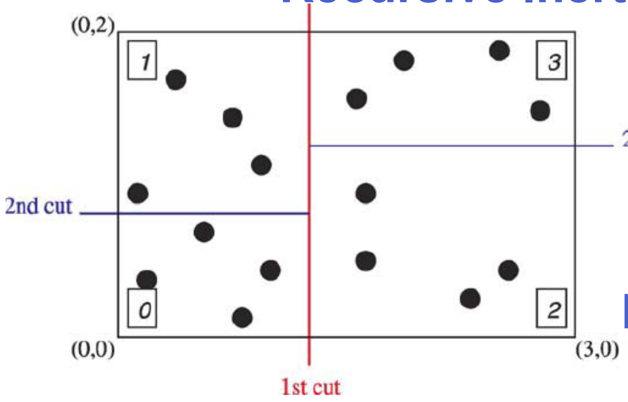
- Zoltan contains suite of partitioning methods.
  - Application changes only one parameter to switch methods.
    - Zoltan_Set_Param(zz, "LB_METHOD", "new_method_name");
  - Allows experimentation/comparisons to find most effective partitioner for application.

Partitioning methods

Geometric (coordinate-based) methods

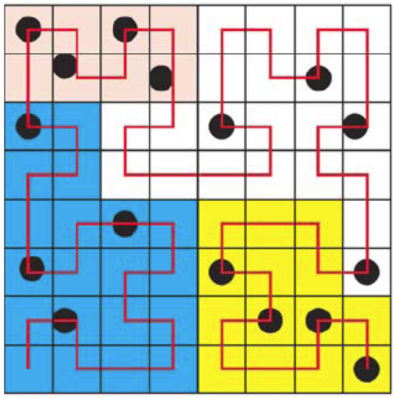
Recursive Coordinate Bisection (Berger, Bokhari)

Recursive Inertial Bisection (Taylor, Nour-Omid)

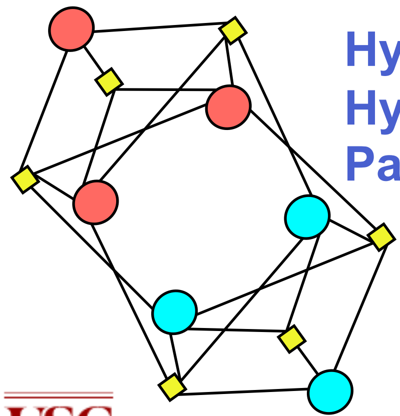


Space Filling Curve Partitioning (Warren&Salmon, et al.)

Refinement-tree Partitioning (Mitchell)



Combinatorial (topology-based) methods



Hypergraph Partitioning

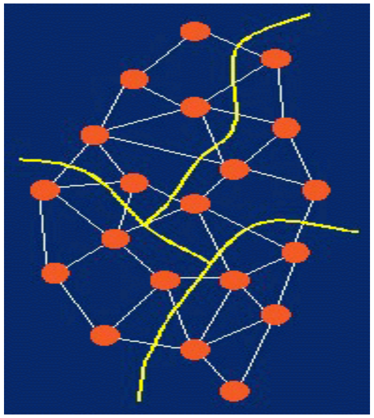
Hypergraph Repartitioning

PaToH (Catalyurek & Aykanat)

Zoltan Graph Partitioning

ParMETIS (U. Minnesota)

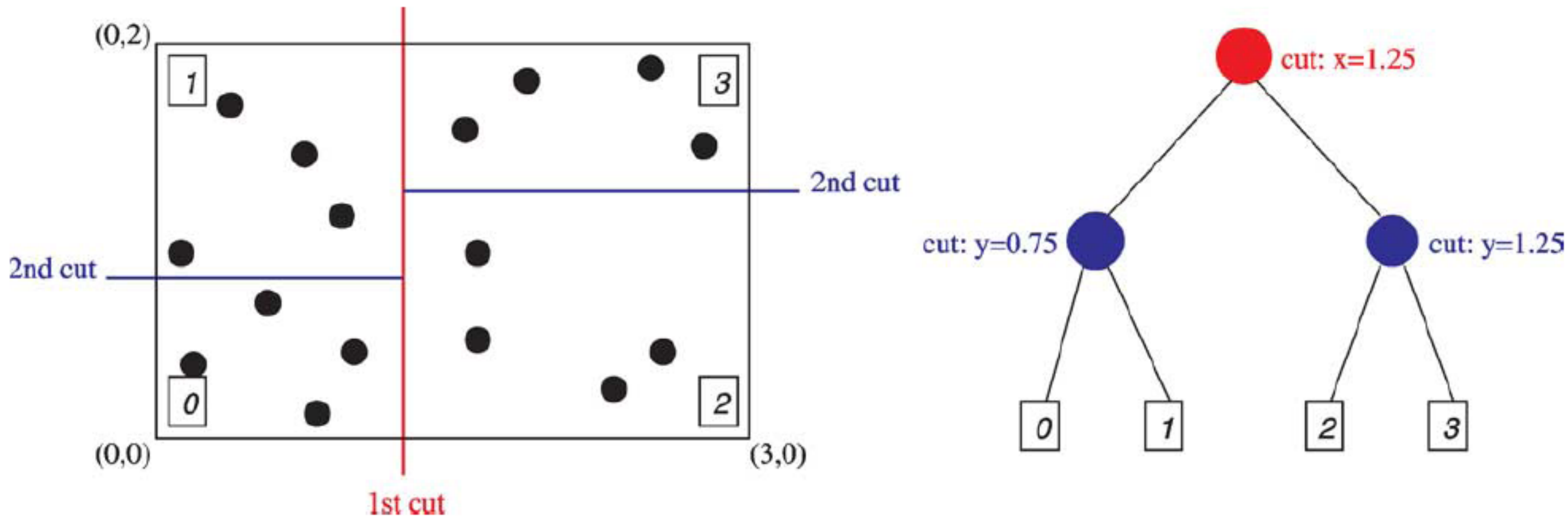
Jostle (U. Greenwich)



Geometric Partitioning

- Suitable for a class of applications, such as crash and particle simulations.
  - Geometric-coordinate based decomposition is a more natural and straightforward approach.
  - Graph partitioning is difficult or impossible.
  - Frequent changes in proximity require fast and dynamic repartitioning strategies.
- Based on two main algorithms
  - Recursive coordinate bisection
  - Space filling curve

Recursive Coordinate Bisection (RCB)

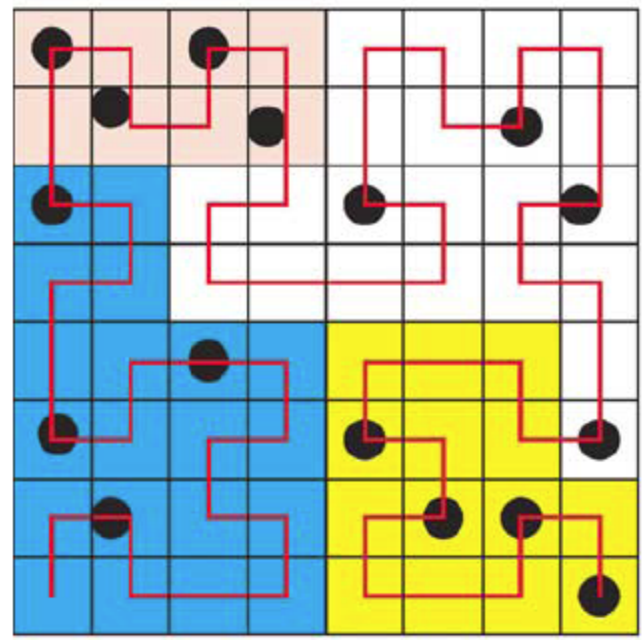


- **Divide the domain into two equal subdomains using a cutting plane orthogonal to a coordinate axis.**
- **Recursively cut the resulting subdomains.**

- **A variation of RCB: Recursive Inertial Bisection, which computes cuts orthogonal to principle inertial axes of the geometry**

Space Filling Curve (SFC)

- **SFC: Mapping between R^n to R^1 that completely fills a domain**
- **SFC Partitioning:**
  - **Run SFC through domain**
  - **Order objects according to position on curve**
  - **Perform 1-D partition of curve**



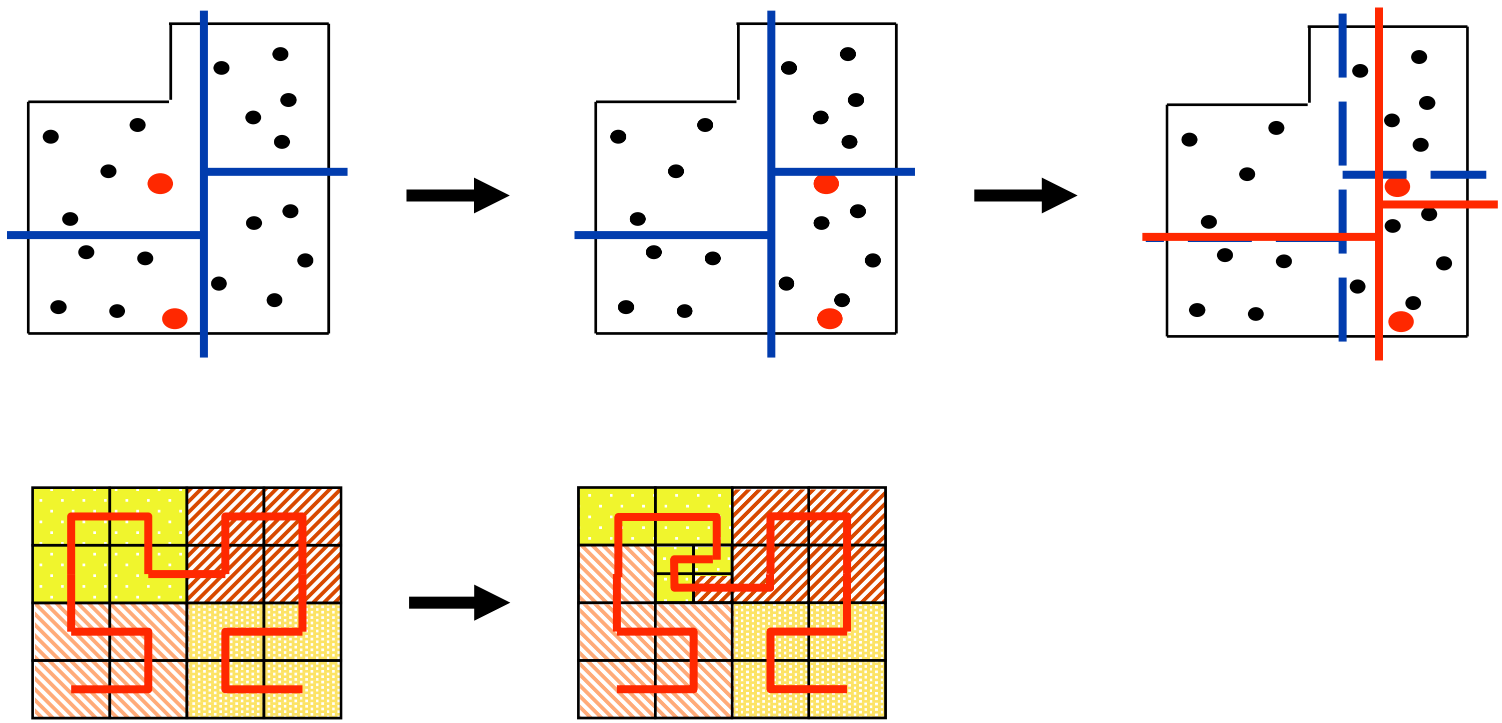
Geometric Partitioning - Advantages and Disadvantages

- **Advantages**
  - **Simple, fast, inexpensive**
  - **Effective when geometric locality is important**
  - **No connectivity needed**
  - **Implicitly incremental for repartitioning**
- **Disadvantages**
  - **No explicit control of communication costs**
  - **Need coordinate information**

Repartitioning

- **Implicitly incremental: small changes in workloads produce only small change in the decomposition**

→ **Reduce the cost of moving application data**



An Application: Contact Detection in Crash Simulation

- **Identify which partition's subdomains intersect a given point (point assignment) or region (box assignment)**
  - **Point assignment: given a point, it returns the partition owning the region of space containing that point**
  - **Box assignment: given an axis-aligned region of space, it returns a list of partitions whose assigned regions overlap the specified box**

Performance

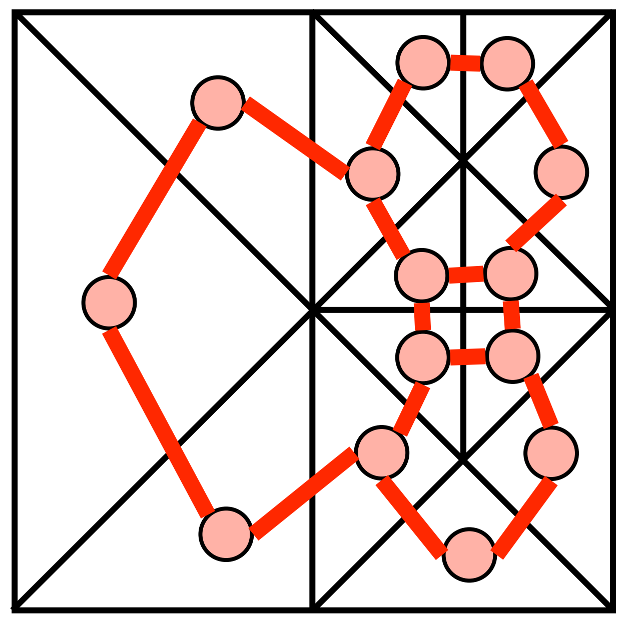
- **Experimental Setup:**
  - **Initialized 96 partitions on a 16-processor cluster**
  - **Performed 10,000 box-assignments**
- **Results comparing RCB and SFC**

Partitioner	# of Intersecting Parts for 10 000 box-assignments	Partitioning Time	Time for 10,000 box-assignments
RCB	10,931	0.71 secs	0.027 secs
HSFC	10,983	0.59 secs	0.176 secs

Graph Partitioning

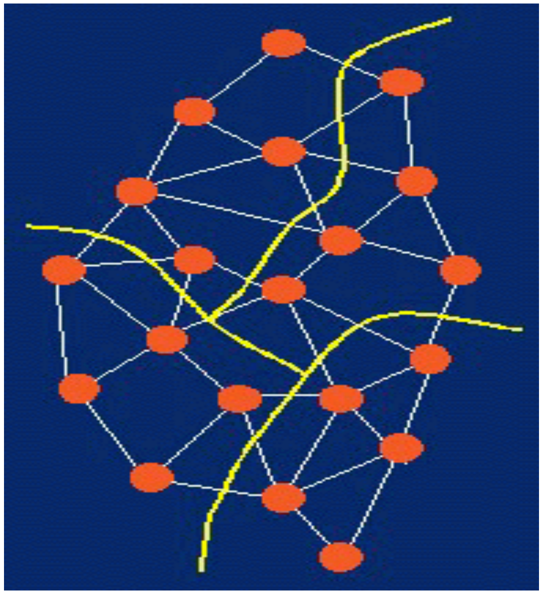
Best for mesh-based partial differential equation (PDE) simulations

- Represent problem as a weighted graph.
  - Vertices = objects to be partitioned.
  - Edges = dependencies between two objects.
  - Weights = work load or amount of dependency.
- Partition graph so that …
  - Parts have equal vertex weight.
  - Weight of edges cut by part boundaries is small.



Graph Partitioning: Advantages and Disadvantages

- **Advantages:**
  - **Highly successful model for mesh-based PDE problems.**
  - **Explicit control of communication volume gives higher partition quality than geometric methods.**
  - **Excellent software available.**
    - **Serial:** Chaco (SNL)
      Jostle (U. Greenwich)
      METIS (U. Minn.)
      Party (U. Paderborn)
      Scotch (U. Bordeaux)
    - **Parallel:** Zoltan (SNL)
      ParMETIS (U. Minn.)
      PJostle (U. Greenwich)

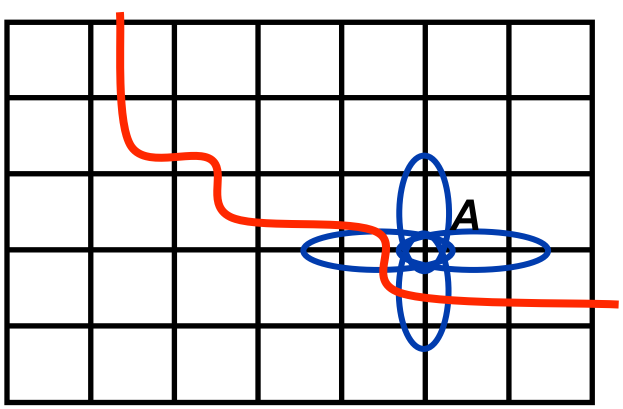


- **Disadvantages:**
  - **More expensive than geometric methods.**
  - **Edge-cut model only approximates communication volume.**

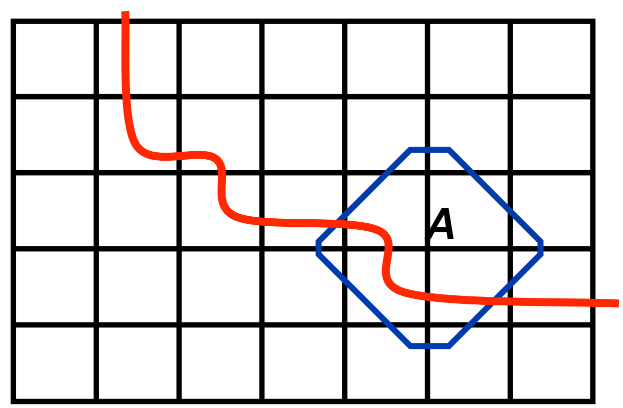
Hypergraph Partitioning

- Zoltan_Set_Param(zz, “LB_METHOD”, “HYPERGRAPH”);
- Zoltan_Set_Param(zz, “HYPERGRAPH_PACKAGE”, “ZOLTAN”); or Zoltan_Set_Param(zz, “HYPERGRAPH_PACKAGE”, “PATOH”);

- Alpert, Kahng, Hauck, Borriello, Çatalyürek, Aykanat, Karypis, et al.
- Hypergraph model:
  - Vertices = objects to be partitioned.
  - Hyperedges = dependencies between two or more objects.
- Partitioning goal: Assign equal vertex weight while minimizing hyperedge cut weight.



Graph Partitioning Model



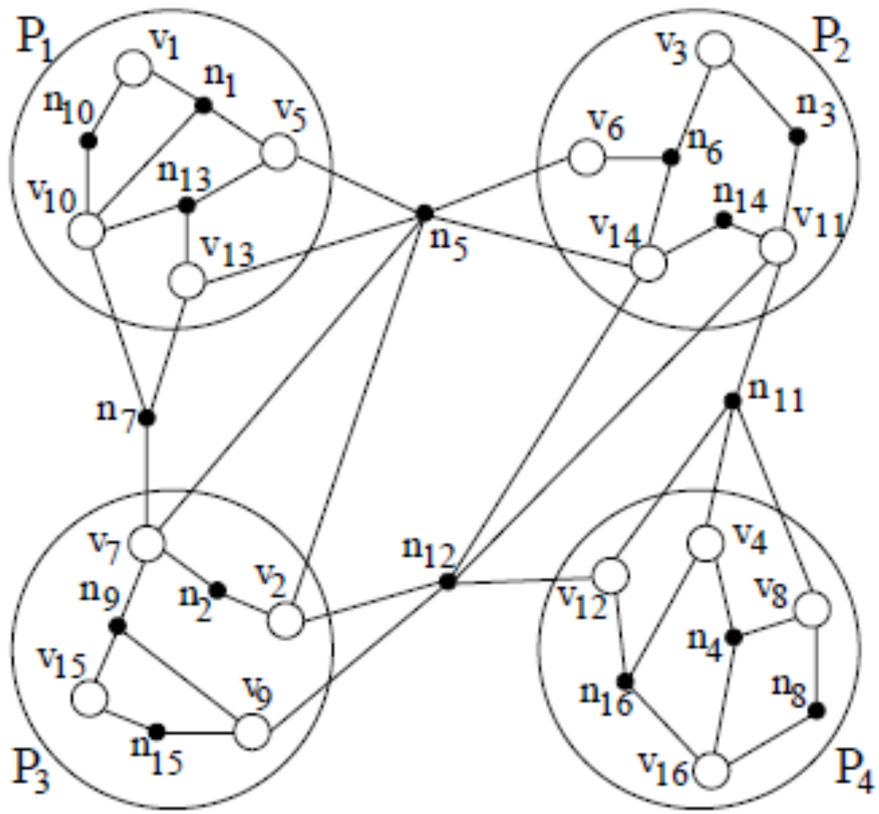
Hypergraph Partitioning Model

Hypergraph partitioning

USC Viterbi School of Engineering

- **Coarsening phase (Clustering)**
  - **Hierarchical (simultaneous clustering)**
    - 1. Pick an unreached vertex (random)
    - 2. Connect it to another vertex based on selection criteria (e.g. shortest edge)
  - **Agglomerative (build 1 cluster at a time)**
    - $N_{u,Cuv}$ Connectivity value of vertex N = # of edges connected to N
    - $W_{u,Cv}$, Weight = number of vertices in any cluster
    - 1. Choose cluster or singleton with highest $N_{u,Cuv}$ / $W_{u,Cv}$,
    - 2. Choose edge based on selection criteria
- **Partitioning phases (Bisecting hypergraph)**
- **Uncoarsening phase**
  - **Project coarsened, bisected graph back to previous level**
  - **Refine bisection by running boundary force method (BFM)**

Hypergraph Example



Kernighan/Lin Algorithm

- **E(a) = external cost of a in A = Σ {W(a,b) for b in B}**
- **I(a) = internal cost of a in A = Σ {W(a,a') for other a' in A}**
- **D(a) = total cost of a in A = E(a) – I(a)**
- **Consider swapping a in A and b in B**
  - **New Partition Cost = Old Partition Cost – D(a) – D(b) + 2*W(a,b)**
- **Compute D(n) for all nodes**
- **Repeat**
  - **Unmark all nodes**
  - **While there are unmarked pairs**
    - Find an unmarked pair (a,b)
    - Mark a and b (but do not swap)
    - Update D(n) for all unmarked nodes, as if a and b had been swapped
    - Pick maximizing gain
    - If Gain > 0 then swap
- **Until gain <= 0**
- **Worst case $O(N^2 \log N)$**

Sandia National Laboratories

Hypergraph Repartitioning

- Augment hypergraph with data redistribution costs.
  - Account for data's current processor assignments.
  - Weight dependencies by their size and frequency of use.
- Partitioning then tries to minimize total communication volume:

  Data redistribution volume

  <u>+ Application communication volume</u>

  Total communication volume
- Data redistribution volume: callback returns data sizes.
  - Zoltan_Set_Fn(zz, ZOLTAN_OBJ_SIZE_MULTI_FN_TYPE, myObjSizeFn, 0);
- Application communication volume = Hyperedge cuts * Number of times the communication is done between repartitionings.
  - Zoltan_Set_Param(zz, "PHG_REPART_MULTIPLIER", "100");

Best Algorithms Paper Award at IPDPS07
"Hypergraph-based Dynamic Load Balancing for Adaptive Scientific Computations"
Çatalyürek, Boman, Devine, Bozdag, Heaphy, & Riesen

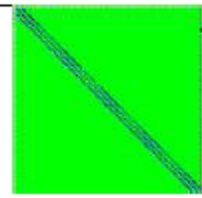
Hypergraph Partitioning: Advantages and Disadvantages

- **Advantages:**
  - Communication volume reduced 30-38% on average over graph partitioning (Catalyurek & Aykanat).
    - 5-15% reduction for mesh-based applications.
  - More accurate communication model than graph partitioning.
    - Better representation of highly connected and/or non-homogeneous systems.
  - Greater applicability than graph model.
    - Can represent rectangular systems and non-symmetric dependencies.
- **Disadvantages:**
  - Usually more expensive than graph partitioning.

Hypergraph – Hexagonal graph

Table 3
Comparison of graph and hypergraph partitioning for HexFEM matrix (Example 3).

HexFEM Matrix:
- Hexahedral 3D structured-mesh finite element method.
- 32,768 rows
- 830,584 non-zeros
- Five partitions

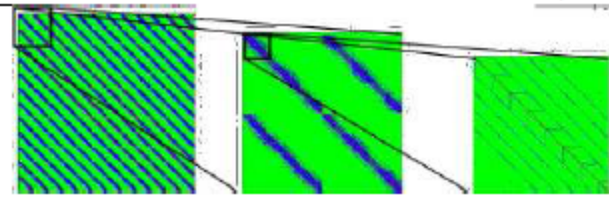


Partitioning Method	Imbalance (Max / Avg Work)	# of Neighbor Partitions per Partition		Communication Volume over all Partitions		Reduction of Total Communication Volume
		Max	Avg	Max	Total	
Graph method (METIS PartKWay)	1.03	4	3.6	1659	6790	
Best Zoltan hypergraph method (RRM)	1.013	4	3.6	1164	5270	22%
Worst Zoltan hypergraph method (RHP)	1.019	4	2.8	2209	6644	2%

Table 4

Comparison of graph and hypergraph partitioning for PolyDFT matrix (Example 3).

PolyDFT matrix
- Polymer self-assembly simulation
- Density functional theory code
- 46,176 rows
- 3,690,048 non-zeros
- Eight partitions



Partitioning Method	Imbalance (Max / Avg Work)	# of Neighbor Partitions per Partition		Communication Volume over all Partitions		Reduction of Total Communication Volume
		Max	Avg	Max	Total	
Graph method (METIS PartKWay)	1.03	7	6	7382	44,994	
Best Zoltan hypergraph method (MXG)	1.018	5	4	3493	19,427	56%
Worst Zoltan hypergraph method (GRP)	1.03	6	5.25	5193	28,067	37%

Resource-aware Load Balancing

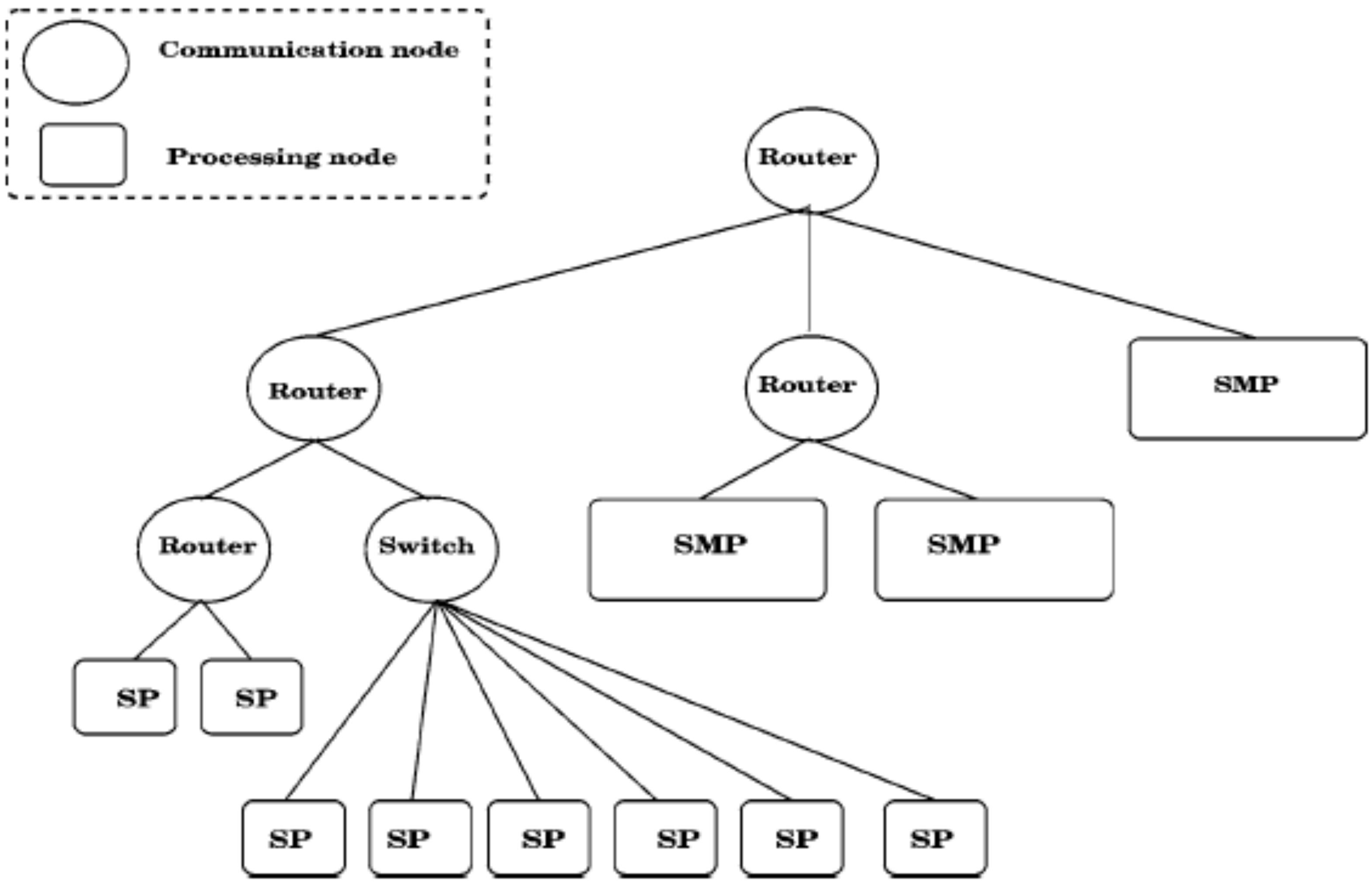
USC Viterbi School of Engineering

- Heterogeneous Architectures
  - Clusters may have different types of processors with various capacity
- Assign "capacity" weight to processors
- Balance with respect to processors capacity
- Hierarchical partitioning: Allows different partitioners at different architecture levels

Dynamic Resource Utilization Model (DRUM)

- **DRUM provides applications aggregated information about the computation and communication capabilities of an execution environment**
- **The tree constructed by DRUM represents a heterogeneous network.**
  - **Leaves represent individual computation nodes (i.e. single processors (SP) or SMPs)**
  - **Non-leaf nodes represent routers or switches, having an aggregate power**

Tree represents a heterogeneous network by DRUM



Power Representation

- **Power of a node is computed as weighted sum of a processing power p_n and a communication power c_n**

$$power_n = w_n^{\text{comm}} c_n + w_n^{\text{cpu}} p_n, \qquad w_n^{\text{comm}} + w_n^{\text{cpu}} = 1.$$

- **For each node *n* in L_i (the set of nodes at level *i*) in the network, the final power is computed by**

$$power_n = pp_n \left(w_n^{\text{comm}} \frac{c_n}{\sum_{j=1}^{|\mathcal{L}_i|} c_j} + w_n^{\text{cpu}} \frac{p_n}{\sum_{j=1}^{|\mathcal{L}_i|} p_j} \right),$$

where pp_n is the power of the parent of node *n*.

Sandia National Laboratories

For More Information...

- Zoltan Home Page
  - http://www.cs.sandia.gov/Zoltan
  - User's and Developer's Guides
  - Download Zoltan software under GNU LGPL.

- Email:
  - {kddevin,ccheval,egboman}@sandia.gov
  - umit@bmi.osu.edu

Questions and Comments