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Tutorial: The Zoltan Toolkit

Siva Rajamanickam

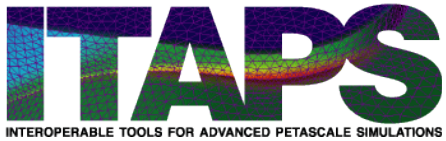
Erik Boman, Karen Devine, Vitus Leung, Lee Ann Riesen

Sandia National Laboratories, NM

Umit Çatalyürek, Doruk Bozdag: Ohio State University

Cedric Chevalier: CEA-DAM

Michael Wolf: MIT Lincoln Lab



ACTS Workshop: August 2010

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Outline

- High-level view of Zoltan
- Requirements, data models, and interface
- Load Balancing and Partitioning
- Matrix Ordering, Graph Coloring
- Utilities
- Isorropia
- Zoltan2

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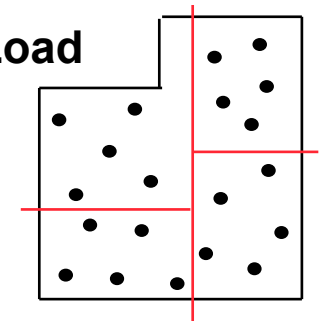
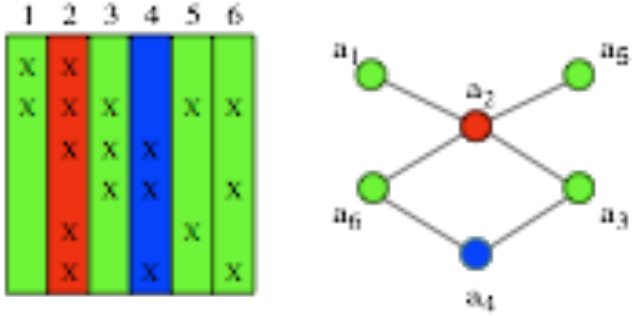
The Zoltan Toolkit

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

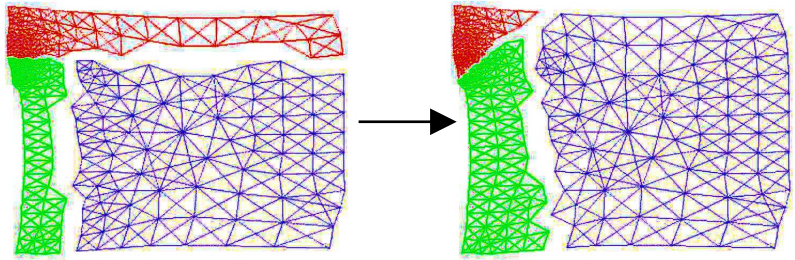
Dynamic Load Balancing



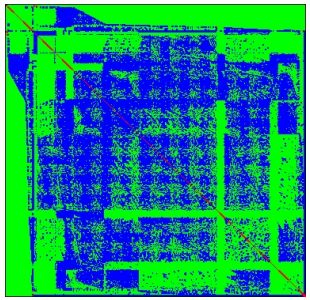
Graph Coloring



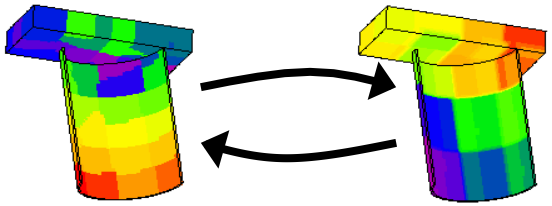
Data Migration



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

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Zoltan System Assumptions

- Assume distributed memory model.
- Data decomposition + “Owner computes”:
  - The data is distributed among the processors.
  - The owner performs all computation on its data.
  - Data distribution defines work assignment.
  - Data dependencies among data items owned by different processors incur communication.
- Zoltan is available in Trilinos since version 9.0
- Requirements:
  - MPI (when running in parallel)
  - C compiler
  - Autotools or CMake.

Zoltan Supports Many Applications

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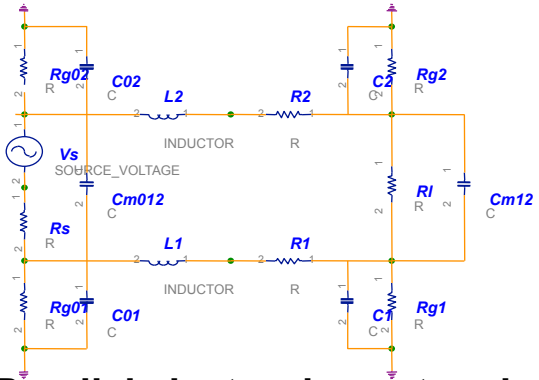
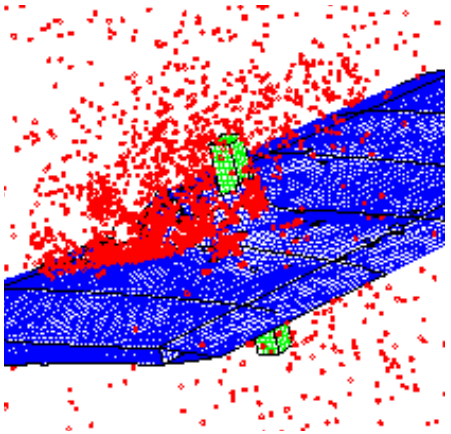
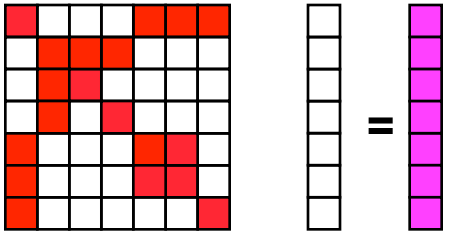
- **Different applications, requirements, data structures.**



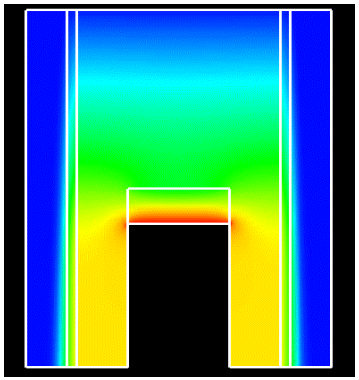
Parallel electronics networks



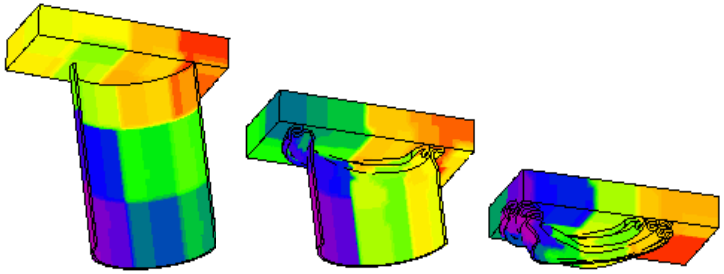
Particle methods



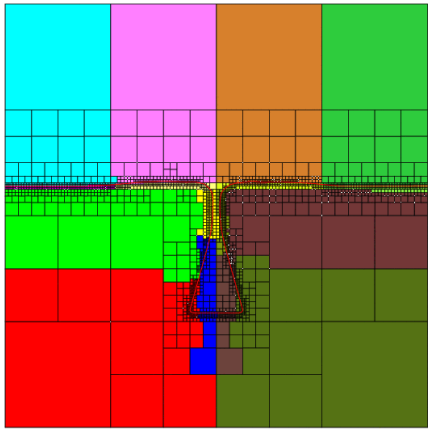
Linear solvers & preconditioners



Multiphysics simulations



Crash simulations



Adaptive mesh refinement

Zoltan's use in large-scale experiments and simulations

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Partitioning Method	Application	Problem Size	Number of Processes	Number of Parts	Architecture	Source
Graph	PHASTA CFD	34M elements	16K	16K	BG/P	Zhou, et al., RPI
Hypergraph	PHASTA CFD	1B elements	4096	160K	Cray XT/5	Zhou, et al., RPI
Hypergraph	Sparta LB algorithms	800M zones	8192	262K	Hera (AMD Quadcore)	Lewis, LLNL
Geometric	Pic3P particle-in-cell	5B particles	24K	24K	Cray XT/4	Candel, et al., SLAC
Geometric	MPSalsa CFD	208M nodes	12K	12K	RedStorm	Lin, SNL
Geometric	Trilinos/ML Multigrid in ALEGRA shock physics	24.6M rows 1.2B non-zeros	24K	24K	RedStorm	Hu, et al., SNL

SciDAC Collaboration: ITAPS

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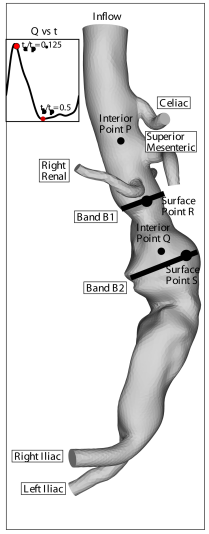
- **ITAPS developers at RPI use Zoltan for dynamic load balancing in their Flexible Mesh DataBase (FMDB) through iZoltan and iMeshP.**
  - **Initial partitioning of large meshes (1B elements) for up to 128K cores.**
  - **Dynamic repartitioning of adaptively refined meshes.**
- **FMDB is used by SLAC and PPPL for adaptive meshing.**

- **RPI also uses Zoltan for static parallel graph and hypergraph partitioning of non-adaptive simulations.**
  - **Achieved strong scalability up to 128K cores (BG/P) for CFD code PHASTA.**
  - **We continue work with ITAPS to improve robustness on >10K cores.**

ITAPS
INTEROPERABLE TOOLS FOR ADVANCED PETASCALE SIMULATIONS

Results courtesy of K. Jansen, M. Shephard, M. Zhou, T. Xie, O. Sahni; Rensselaer Polytechnic Institute.



Number of cores	Time (s)	Efficiency
16k	222.03	1
32k	112.43	0.987
64k	57.09	0.972
128k	31.35	0.885

SciDAC Collaborations: ComPASS (SLAC)

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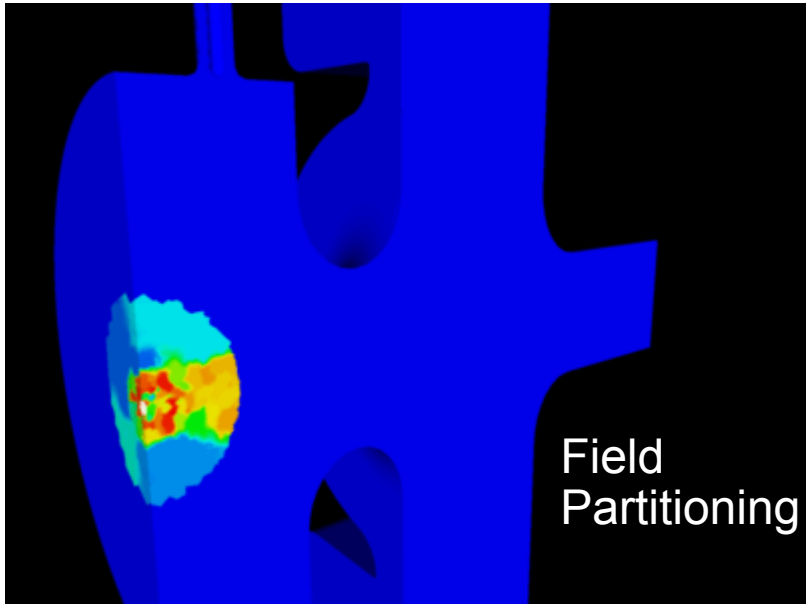
Enhanced Pic3P accelerator simulation capability with new partitioning scheme

- Pic3P solves Maxwell's equations with moving particles
- Our suggested load balance strategy: Use two different data decompositions
  - Fields partitioned with graph-based methods (ParMETIS)
  - Particles partitioned geometrically (Zoltan RCB 3D)
- Enables solution of larger problems: 24k CPUs, 750M DOFs, 5B particles



Example: LCLS RF gun, colors indicate distribution to different CPUs
(fields are computed only in causal region, using *p*-refinement)

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Zoltan Interface Design

- Common interface to each class of tools
- Tool/method specified with user parameters

- Data-structure neutral design
  - Supports wide range of applications and data structures
  - Imposes no restrictions on application's data structures
  - Application does not have to build Zoltan's data structures.

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Zoltan Interface

- **Simple, easy-to-use interface.**
  - **Small number of callable Zoltan functions.**
  - **Callable from C, C++, Fortran.**

- **Requirement: Unique global IDs for objects to be partitioned/ordered/colored. For example:**
  - **Global element number.**
  - **Global matrix row number.**
  - **(Processor number, local element number)**
  - **(Processor number, local particle number)**

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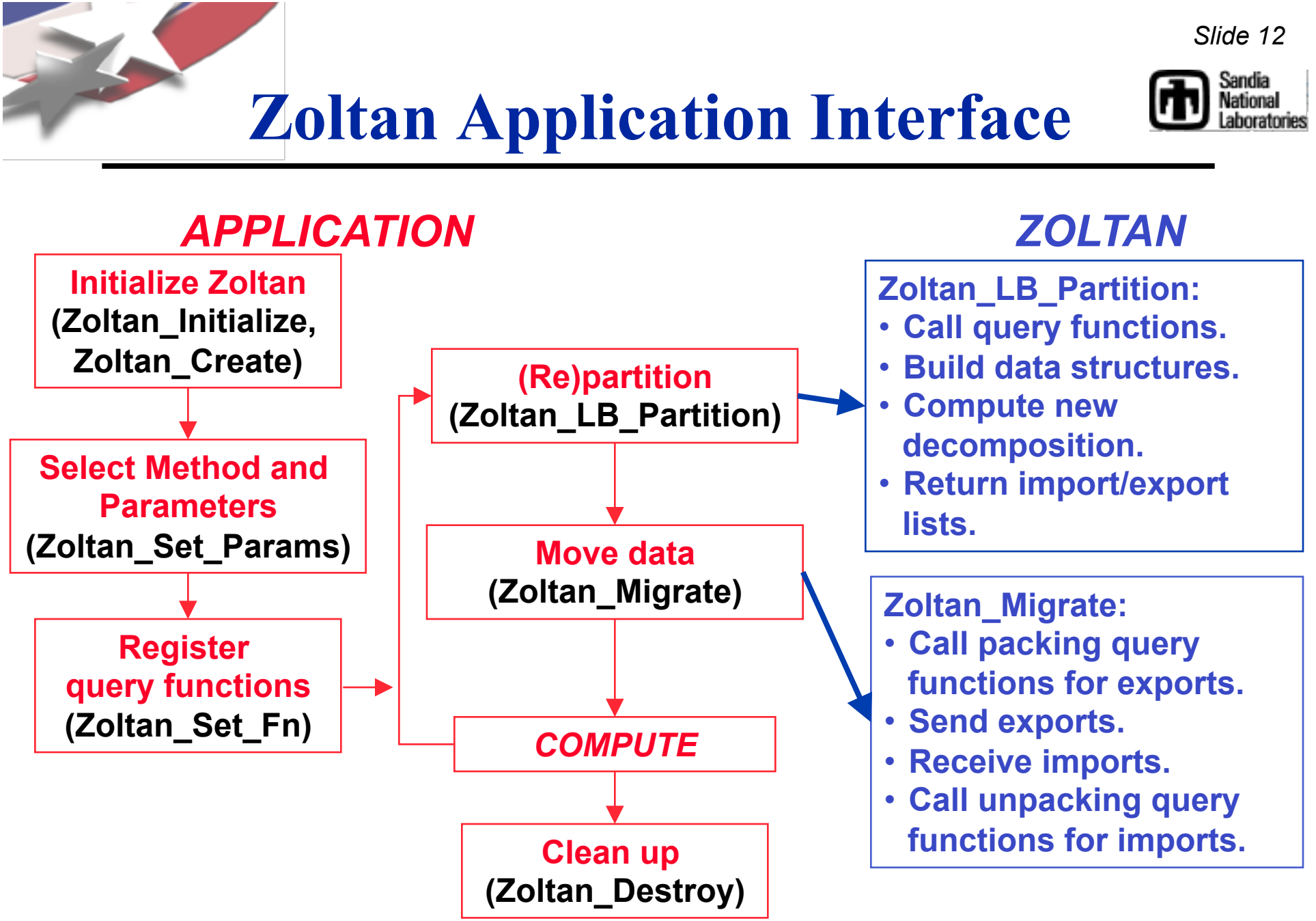
Zoltan Application Interface

- **Application interface:**
  - **Zoltan queries the application for needed info.**
    - **IDs of objects, coordinates, relationships to other objects.**
  - **Application provides simple functions to answer queries.**
  - **Small extra costs in memory and function-call overhead.**
- **Query mechanism supports…**
  - **Geometric algorithms**
    - **Queries for dimensions, coordinates, etc.**
  - **Hypergraph- and graph-based algorithms**
    - **Queries for edge lists, edge weights, etc.**
  - **Tree-based algorithms**
    - **Queries for parent/child relationships, etc.**
- **Once query functions are implemented, application can access all Zoltan functionality.**
  - **Can switch between algorithms by setting parameters.**

Zoltan Application Interface



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Zoltan Query Functions

General Query Functions	
`ZOLTAN_NUM_OBJ_FN`	Number of items on processor
`ZOLTAN_OBJ_LIST_FN`	List of item IDs and weights.
Geometric Query Functions	
`ZOLTAN_NUM_GEOM_FN`	Dimensionality of domain.
`ZOLTAN_GEOM_FN`	Coordinates of items.
Hypergraph Query Functions	
`ZOLTAN_HG_SIZE_CS_FN`	Number of hyperedge pins.
`ZOLTAN_HG_CS_FN`	List of hyperedge pins.
`ZOLTAN_HG_SIZE_EDGE_WTS_FN`	Number of hyperedge weights.
`ZOLTAN_HG_EDGE_WTS_FN`	List of hyperedge weights.
Graph Query Functions	
`ZOLTAN_NUM_EDGE_FN`	Number of graph edges.
`ZOLTAN_EDGE_LIST_FN`	List of graph edges and weights.

Using Zoltan in Your Application

1. Decide what your objects are.
   - Elements? Grid points? Matrix rows? Particles?
2. Decide which tools (partitioning/ordering/coloring/utilities) and class of method (geometric/graph/hypergraph) to use.
3. Download Zoltan.
   - http://www.cs.sandia.gov/Zoltan (or http://trilinos.sandia.gov)
4. Write required query functions for your application.
   - Required functions are listed with each method in Zoltan User's Guide.
5. Call Zoltan from your application.
6. #include "zoltan.h" in files calling Zoltan.
7. Configure and build Zoltan.
8. Compile application; link with libzoltan.a.
   - mpicc application.c -lzoltan

Partitioning and Load Balancing

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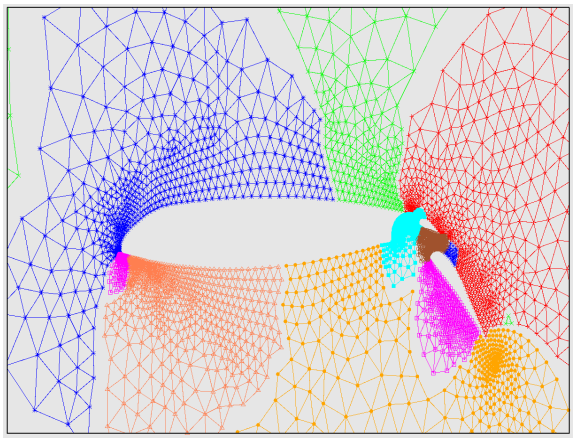
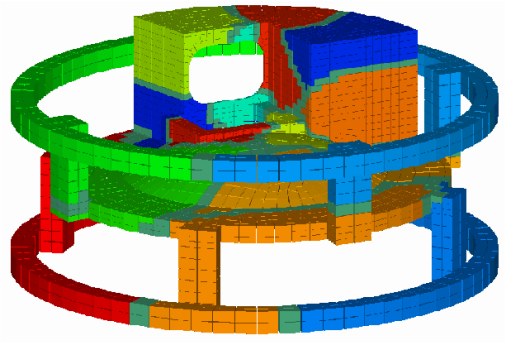
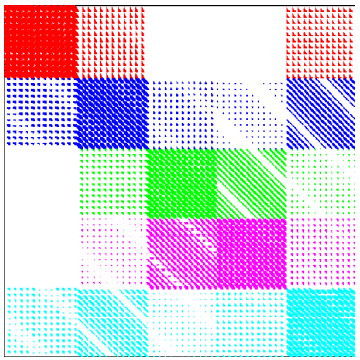
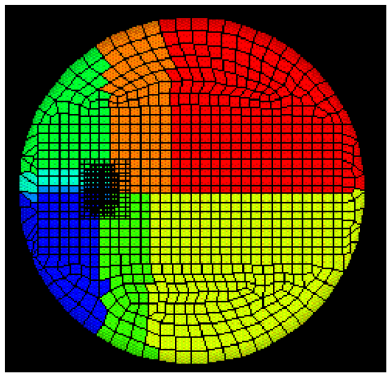
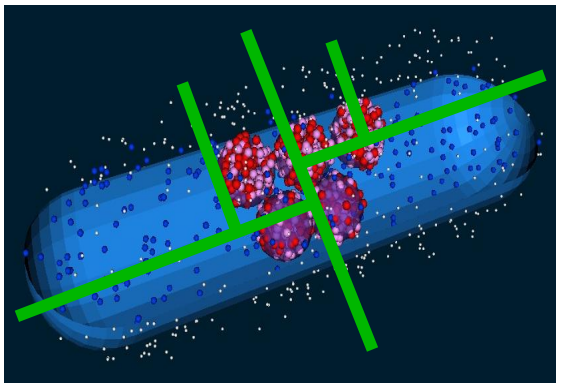
- Assignment of application data to processors for parallel computation.
- Applied to grid points, elements, matrix rows, particles, ….











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Static Partitioning

- **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)

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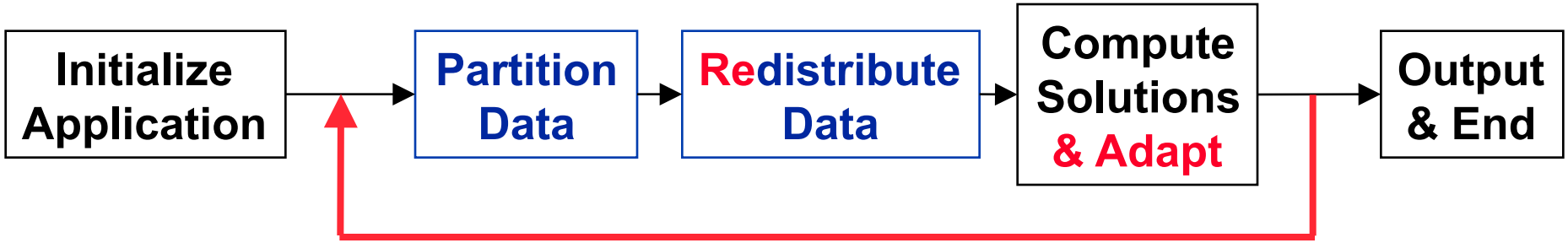

- Dynamic repartitioning (load balancing) in an application:
  - Data partition is computed.
  - Data are distributed according to partition map.
  - Application computes and, perhaps, adapts.
  - Process repeats until the application is done.

- 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

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- **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 Algorithms in the Zoltan Toolkit

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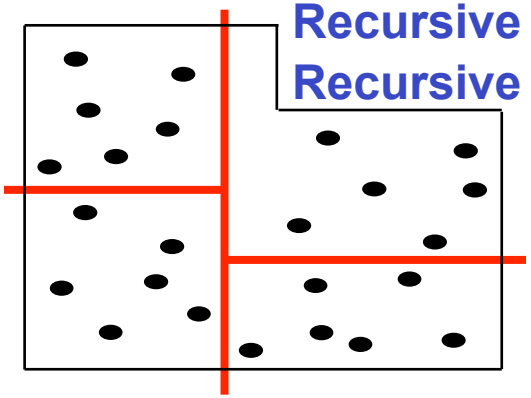
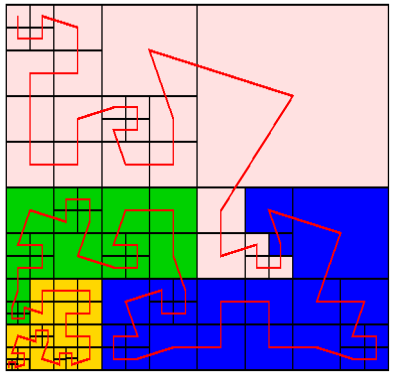
Geometric (coordinate-based) methods



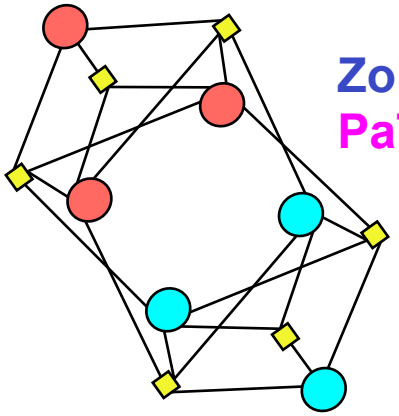
Recursive Coordinate Bisection (Berger, Bokhari)

Recursive Inertial Bisection (Taylor, Nour-Omid)

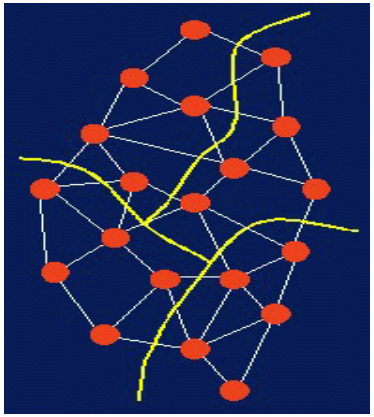


Space Filling Curve Partitioning
(Warren&Salmon, et al.)

Combinatorial (topology-based) methods



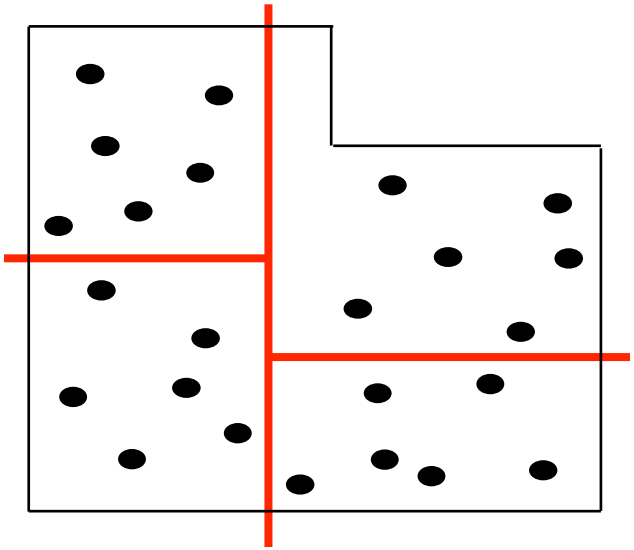
Zoltan Hypergraph Partitioning (PHG)
PaToH (Catalyurek & Aykanat)



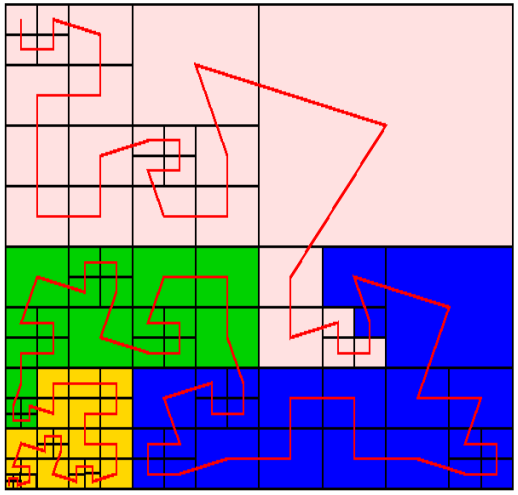
Zoltan Graph Partitioning (PHG)
ParMETIS (Karypis, et al.)
PT-Scotch (Pellegrini, et al.)

Geometric Partitioning

- **Zoltan_Set_Param(zz, "LB_METHOD", "RCB");**
  Zoltan_Set_Param(zz, "LB_METHOD", "RIB");
  Zoltan_Set_Param(zz, "LB_METHOD", "HSFC");
- **Partition based on geometric locality.**
  - **Assign physically close objects to the same processor.**



Recursive Coordinate Bisection (RCB)
Berger & Bokhari, 1987



Space Filling Curve Partitioning (HSFC)
Warren & Salmon, 1993;
Pilkington & Baden, 1994; Patra & Oden, 1995

Geometric Repartitioning

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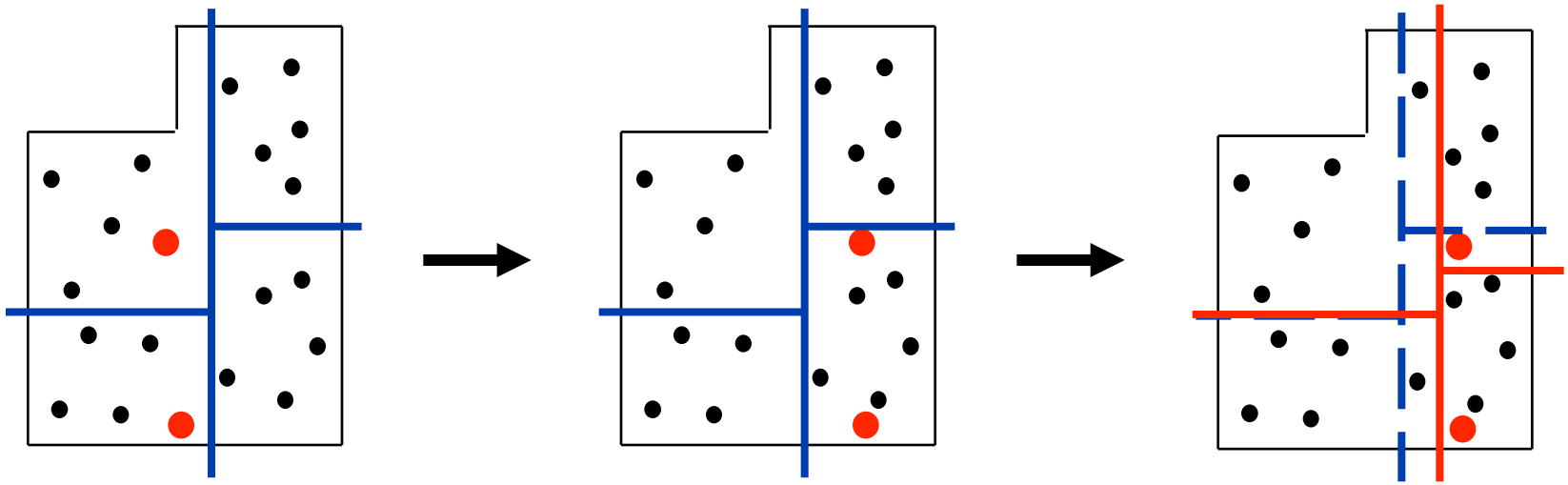
- No explicit control of migration costs, but…
- Implicitly achieves low data redistribution costs
- For small changes in data, cuts move only slightly, resulting in little data redistribution.



Recursive Coordinate Bisection (RCB)

Applications of Geometric Partitioners

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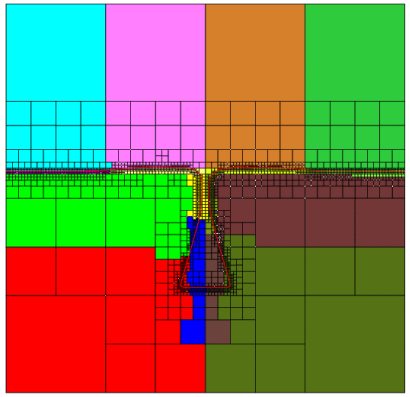
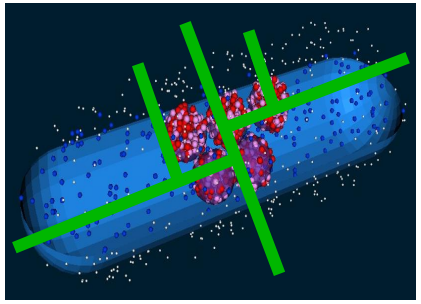
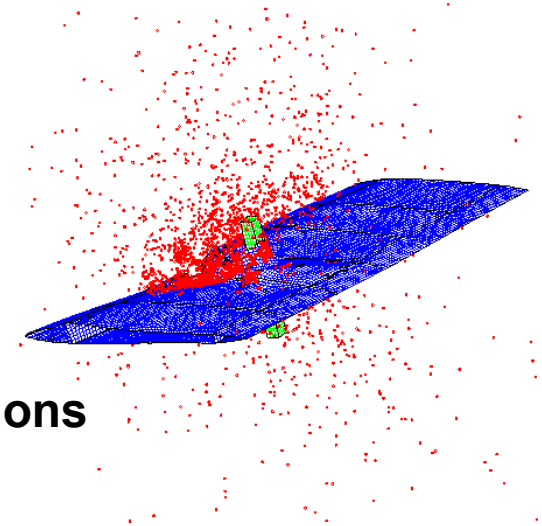
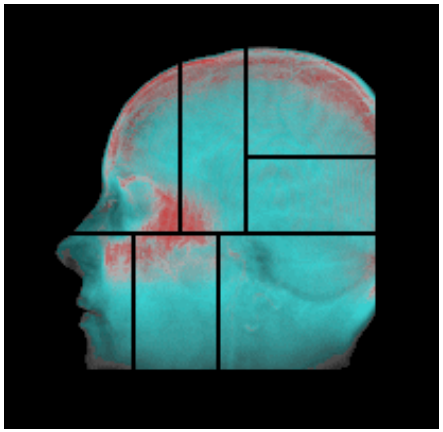


Adaptive Mesh Refinement

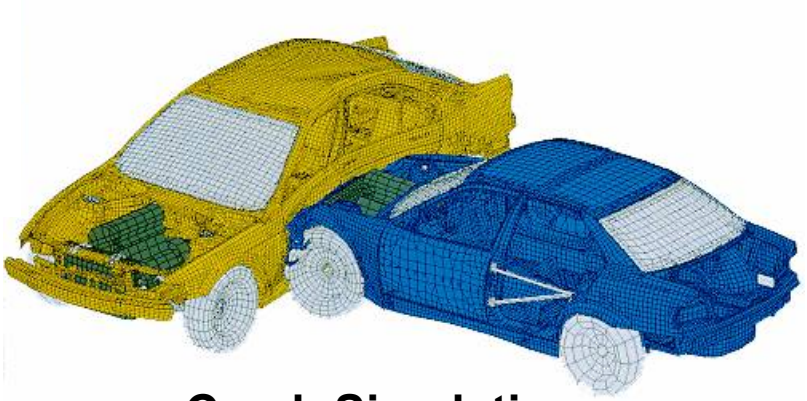




Particle Simulations



Parallel Volume Rendering



Crash Simulations
and Contact Detection

Geometric Methods: Advantages and Disadvantages

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- **Advantages:**
  - **Easiest partitioners to use.**
  - **Conceptually simple; fast and inexpensive.**
  - **All processors can inexpensively know entire partition (e.g., for global search in contact detection).**
  - **No connectivity info needed (e.g., particle methods).**
  - **Good on specialized geometries.**

SLAC'S 55-cell Linear Accelerator with couplers: One-dimensional RCB partition reduced runtime up to 68% on 512 processor IBM SP3. (Wolf, Ko)

- **Disadvantages:**
  - **No explicit control of communication volume.**
  - **Mediocre partition quality (in terms of volume).**
  - **Can generate disconnected subdomains for complex geometries.**
  - **Need coordinate information.**

Geometric Partitioning: Query Functions

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General Query Functions	
`ZOLTAN_NUM_OBJ_FN`	Number of items on processor
`ZOLTAN_OBJ_LIST_FN`	List of item IDs and weights.
Geometric Query Functions	
`ZOLTAN_NUM_GEOM_FN`	Dimensionality of domain.
`ZOLTAN_GEOM_FN`	Coordinates of items.
Hypergraph Query Functions	
`ZOLTAN_HG_SIZE_CS_FN`	Number of hyperedge pins.
`ZOLTAN_HG_CS_FN`	List of hyperedge pins.
`ZOLTAN_HG_SIZE_EDGE_WTS_FN`	Number of hyperedge weights.
`ZOLTAN_HG_EDGE_WTS_FN`	List of hyperedge weights.
Graph Query Functions	
`ZOLTAN_NUM_EDGE_FN`	Number of graph edges.
`ZOLTAN_EDGE_LIST_FN`	List of graph edges and weights.

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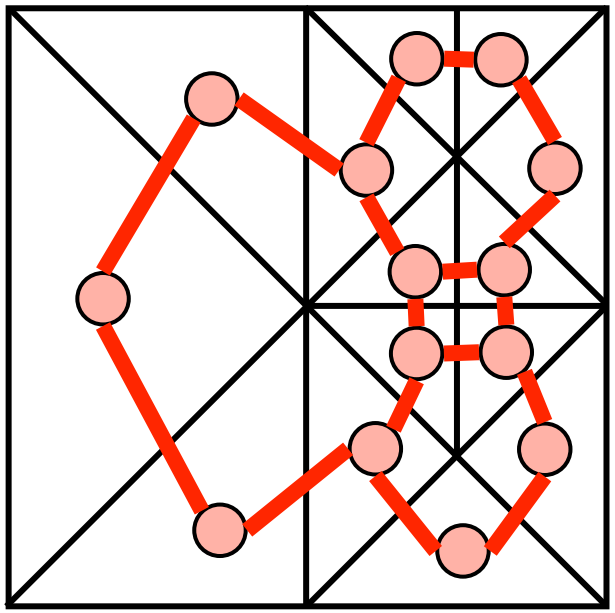
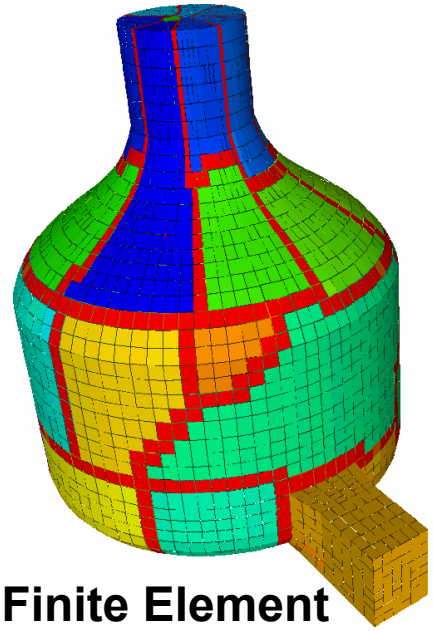
Graph Partitioning

- Zoltan_Set_Param(zz, "LB_METHOD", "GRAPH");
- Zoltan_Set_Param(zz, "GRAPH_PACKAGE", "PHG"); or
  Zoltan_Set_Param(zz, "GRAPH_PACKAGE", "PARMETIS"); or
  Zoltan_Set_Param(zz, "GRAPH_PACKAGE", "SCOTCH");

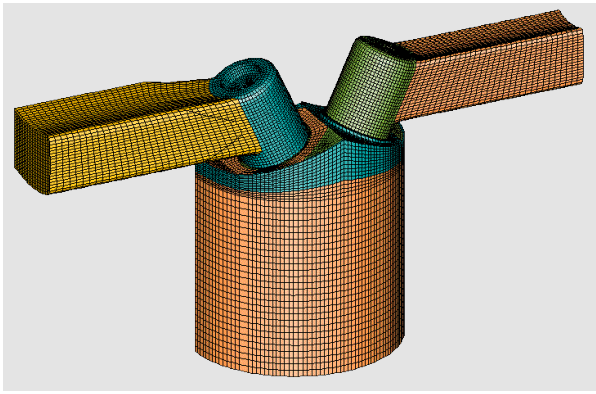
- Kernighan, Lin, Schweikert, Fiduccia, Mattheyes, Simon, Hendrickson, Leland, Kumar, Karypis, et al.
- Represent problem as a weighted graph.
  - Vertices = objects to be partitioned.
  - Edges = dependencies between two objects.
  - Weights = work load or amount of dependency.
- Partition graph so that …
  - Parts have equal vertex weight.
  - Weight of edges cut by part boundaries is small.



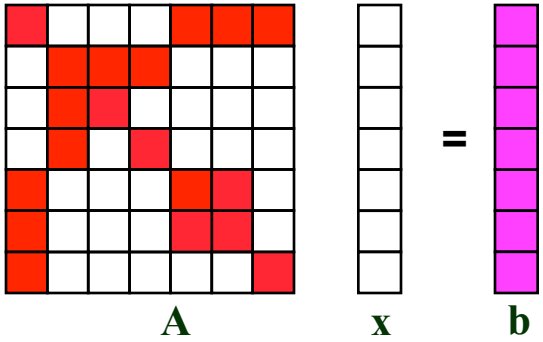
Applications using Graph Partitioning



Finite Element Analysis



Multiphysics and multiphase simulations



Linear solvers & preconditioners
(square, structurally symmetric systems)

Graph Partitioning: Advantages and Disadvantages

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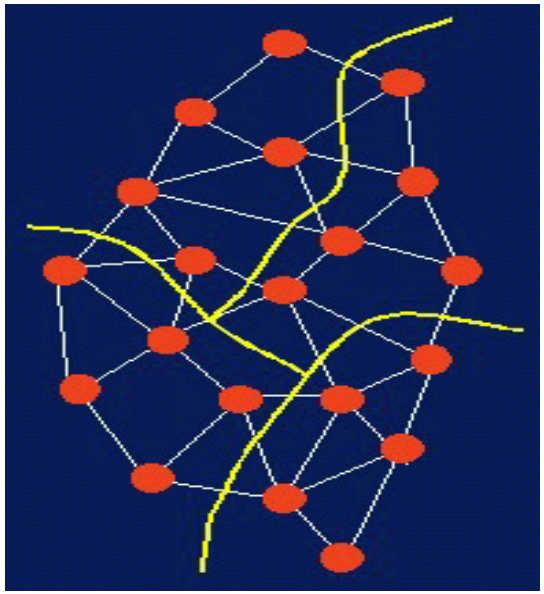
- **Advantages:**
  - **Highly successful model for mesh-based PDE problems.**
  - **Explicit control of communication volume gives higher partition quality than geometric methods.**
  - **Excellent software available.**
    - **Serial:** Chaco (SNL), Jostle (U. Greenwich), METIS (U. Minn.), Party (U.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



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

Graph Partitioning: Query Functions

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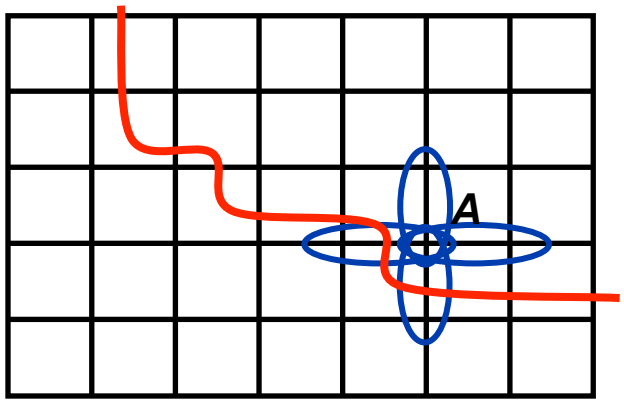
General Query Functions	
`ZOLTAN_NUM_OBJ_FN`	Number of items on processor
`ZOLTAN_OBJ_LIST_FN`	List of item IDs and weights.
Geometric Query Functions	
`ZOLTAN_NUM_GEOM_FN`	Dimensionality of domain.
`ZOLTAN_GEOM_FN`	Coordinates of items.
Hypergraph Query Functions	
`ZOLTAN_HG_SIZE_CS_FN`	Number of hyperedge pins.
`ZOLTAN_HG_CS_FN`	List of hyperedge pins.
`ZOLTAN_HG_SIZE_EDGE_WTS_FN`	Number of hyperedge weights.
`ZOLTAN_HG_EDGE_WTS_FN`	List of hyperedge weights.
Graph Query Functions	
`ZOLTAN_NUM_EDGE_FN`	Number of graph edges.
`ZOLTAN_EDGE_LIST_FN`	List of graph edges and weights.

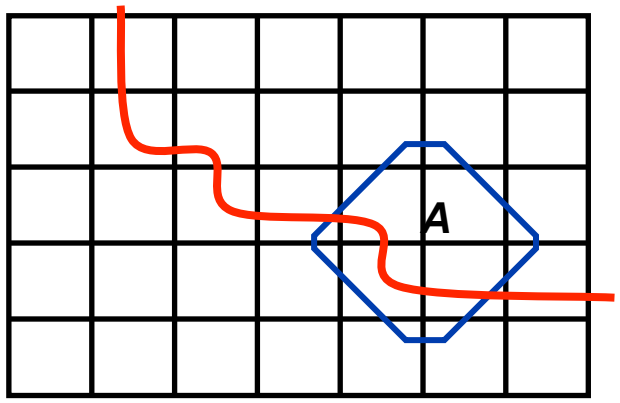
Hypergraph Partitioning

- 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

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Hypergraph Repartitioning

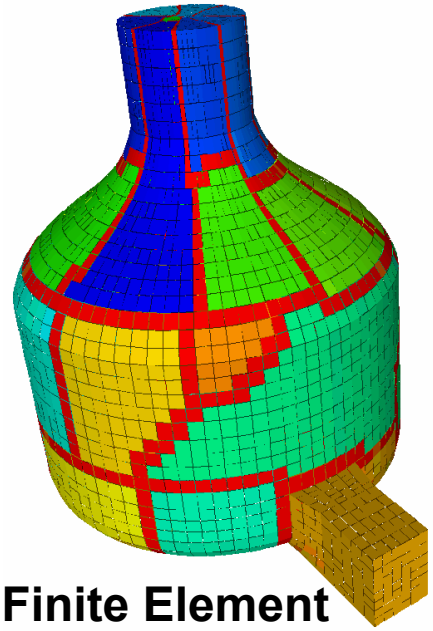
- Augment hypergraph with data redistribution costs
  - Account for data's current processor assignments
  - Weight dependencies by their size and frequency of use
- Partitioning then tries to minimize total communication volume:

  Data redistribution volume

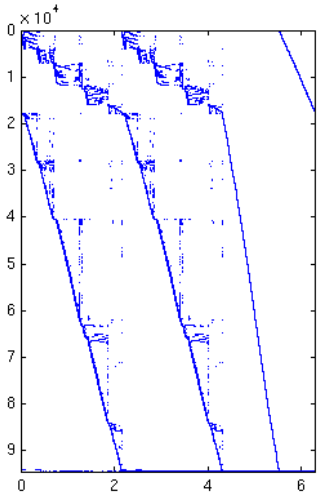
  + Application communication volume

  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");

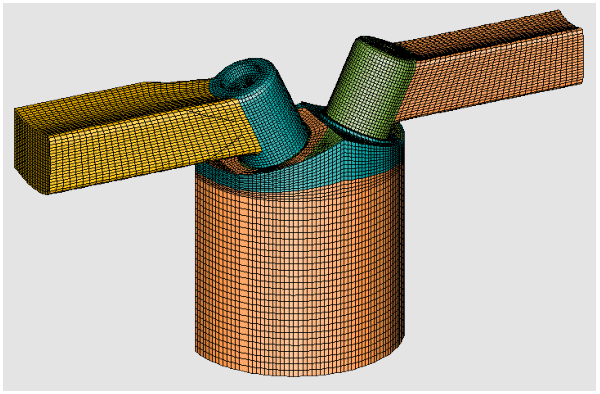
Hypergraph Applications



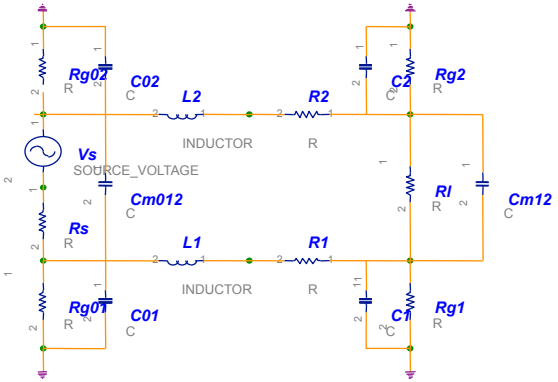
Finite Element Analysis



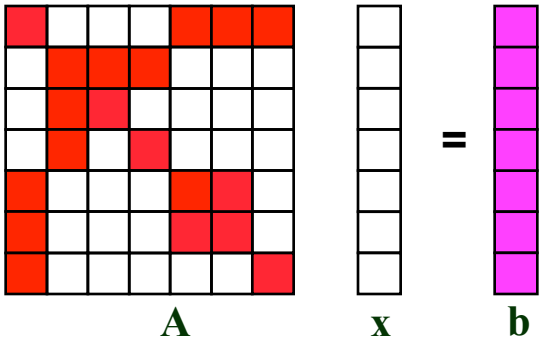
Linear programming for sensor placement



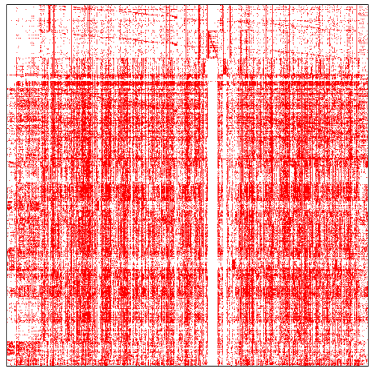
Multiphysics and multiphase simulations



Circuit Simulations



Linear solvers & preconditioners
(no restrictions on matrix structure)



Data Mining

Hypergraph Partitioning: Advantages and Disadvantages

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- **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 Partitioning with Hypergraph Query Functions

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General Query Functions	
`ZOLTAN_NUM_OBJ_FN`	Number of items on processor
`ZOLTAN_OBJ_LIST_FN`	List of item IDs and weights.
Geometric Query Functions	
`ZOLTAN_NUM_GEOM_FN`	Dimensionality of domain.
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`ZOLTAN_NUM_EDGE_FN`	Number of graph edges.
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Hypergraph Partitioning with Graph Query Functions

Sandia National Laboratories

General Query Functions	
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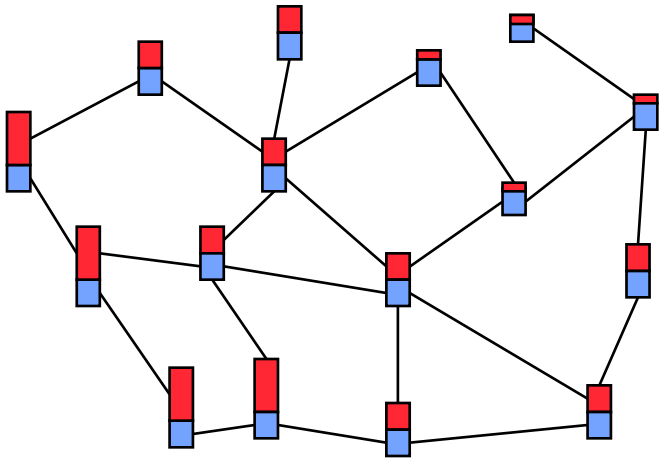
Graph Query Functions	
`ZOLTAN_NUM_EDGE_FN`	Number of graph edges.
`ZOLTAN_EDGE_LIST_FN`	List of graph edges and weights.

Multi-Criteria Load-Balancing

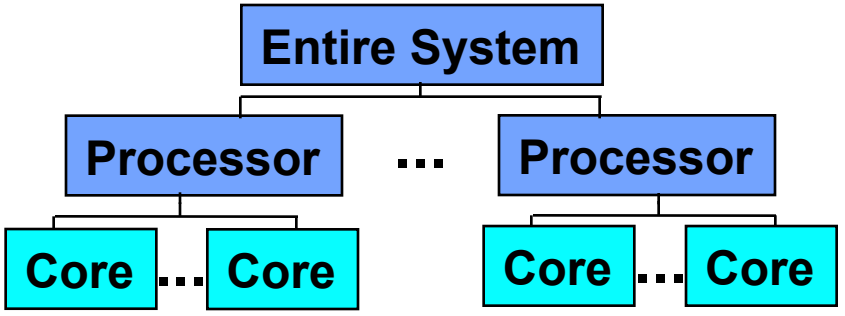
- Multiple constraints or objectives
  - Compute a single partition that is good with respect to multiple factors.
    - Balance both computation and memory
    - Balance multi-phase simulations
  - Extend algorithms to multiple weights
    - Difficult. No guarantee good solution exists.
- Zoltan_Set_Param(zz, "OBJ_WEIGHT_DIM", "2");
  - Available in RCB, RIB and ParMETIS graph partitioning



Heterogeneous Architectures

- Clusters may have different types of processors.
- Assign "capacity" weights to processors.
  - E.g., Compute power (speed).
  - Zoltan_LB_Set_Part_Sizes(…);
    - Note: Can use this function to specify part sizes for any purpose.
- Balance with respect to processor capacity.

- Hierarchical partitioning: Allows different partitioners at different architecture levels.
  - Zoltan_Set_Param(zz, "LB_METHOD", "HIER");
  - Requires three additional callbacks to describe architecture hierarchy.
    - ZOLTAN_HIER_NUM_LEVELS_FN
    - ZOLTAN_HIER_PARTITION_FN
    - ZOLTAN_HIER_METHOD_FN



Zoltan Ordering

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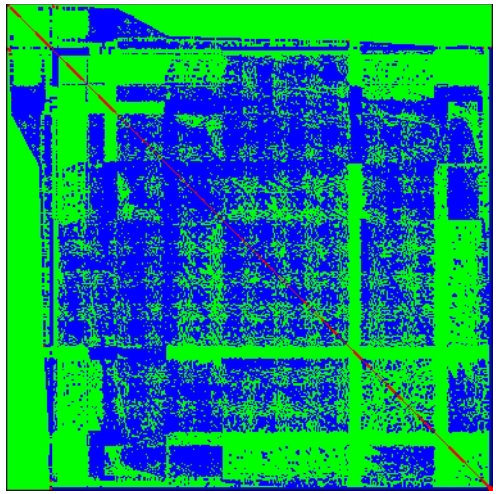
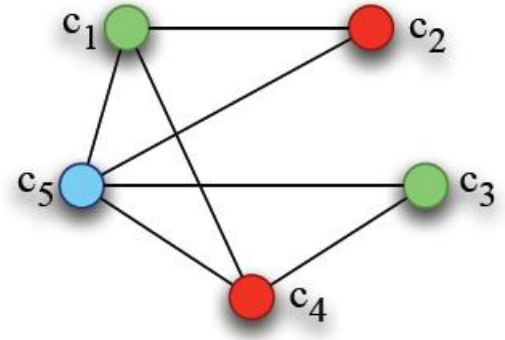
- **Global ordering produces fill-reducing permutations for sparse matrix factorization.**
  - **Interface to PT-Scotch (Pellegrini, Chevalier; INRIA-LaBRi)**
  - **Interface to ParMETIS (Karypis et al.; U. Minnesota)**
- **Local ordering improves cache utilization.**
  - **Space-filling curve ordering of in-processor data.**
- **Ordering algorithms use the same callback function interface as partitioning algorithms.**



Zoltan Graph Coloring



- Parallel distance-1 and distance-2 graph coloring.
- Graph built using same application interface and code as graph partitioners.
- Generic coloring interface; easy to add new coloring algorithms.
- Algorithms
  - Distance-1: Bozdag, Gebremedhin, Manne, Boman, Catalyurek
  - Distance-2: Bozdag, Catalyurek, Gebremedhin, Manne, Boman, Ozguner

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Other Zoltan Functionality

- Tools needed when doing dynamic load balancing:
  - Data Migration
  - Unstructured Communication Primitives
  - Distributed Data Directories
- Functionalities described in Zoltan User's Guide
  - http://www.cs.sandia.gov/Zoltan/ug_html/ug.html

Zoltan Data Migration Tools

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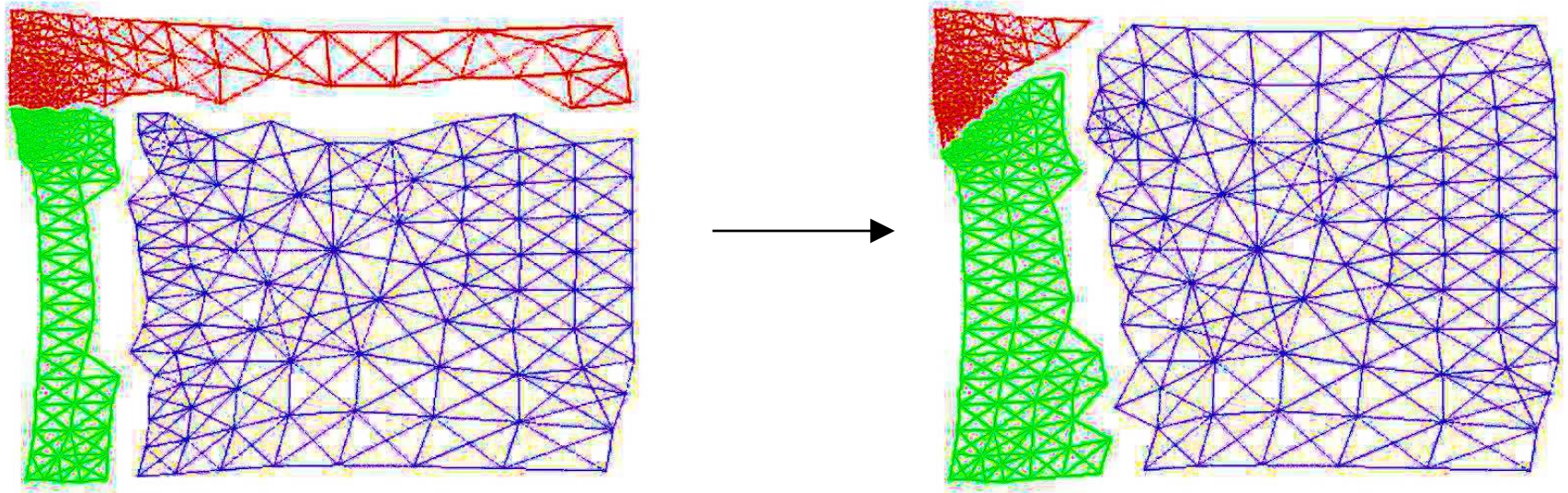
- **After partition is computed, data must be moved to new decomposition.**
  - **Depends strongly on application data structures**
  - **Complicated communication patterns**
- **Zoltan can help!**
  - **Application supplies query functions to pack/unpack data.**
  - **Zoltan does all communication to new processors.**



Zoltan Unstructured Communication Package

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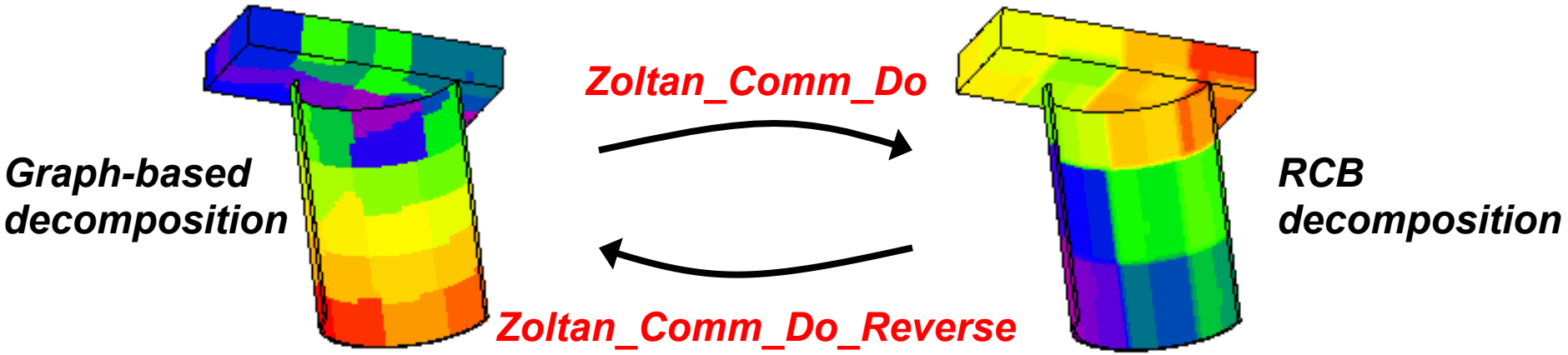
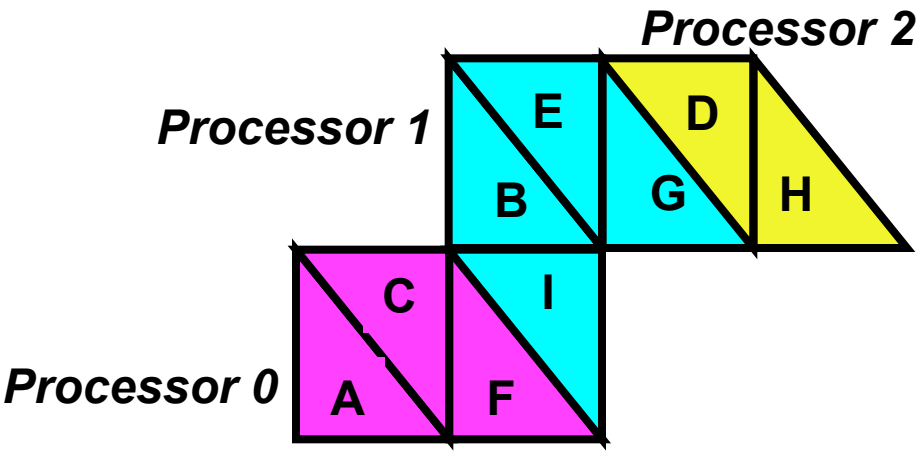
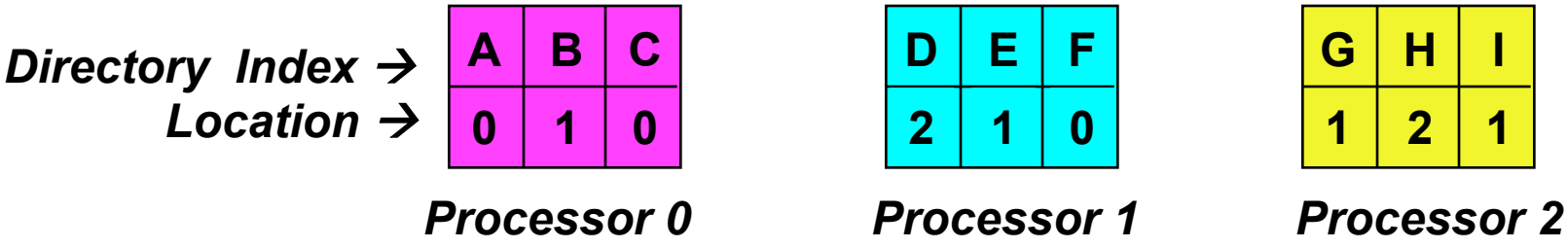
- **Simple primitives for efficient irregular communication.**
  - **Zoltan_Comm_Create: Generates communication plan.**
    - **Processors and amount of data to send and receive.**
  - **Zoltan_Comm_Do: Send data using plan.**
    - **Can reuse plan. (Same plan, different data.)**
  - **Zoltan_Comm_Do_Reverse: Inverse communication.**
- **Used for most communication in Zoltan.**



Zoltan Distributed Data Directory

- **Helps applications locate off-processor data.**
- **Rendezvous algorithm (Pinar, 2001).**
  - **Directory distributed in known way (hashing) across processors.**
  - **Requests for object location sent to processor storing the object's directory entry.**





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Interfaces to Zoltan

- C, C++ and F90 interfaces in Zoltan
- Mesh-based interface in ITAPS
- Isorropia: matrix-based interface in Trilinos

ITAPS Dynamic Services: Mesh-based Interface to Zoltan

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- **Interoperable Technologies for Advanced Petascale Simulations (L. Diachin, LLNL, PI)**
  - **SciDAC2 CET.**
- **ITAPS Goals:**
  - **Develop the next generation of meshing and geometry tools for petascale computing.**
    - **E.g., adaptive mesh refinement, shape optimization.**
  - **Improve applications' ability to use these tools.**
    - **"Standardization" of mesh interfaces.**
- **Dynamic Services toolkit:**
  - **ITAPS-compliant mesh interface to Zoltan tools.**
  - **Integration with ITAPS iMeshP parallel mesh interface to be released FY09.**

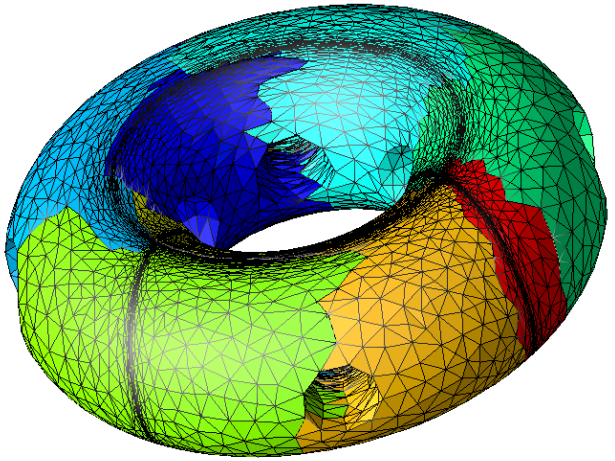

Image courtesy of M. Shephard, RPI

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Trilinos and Isorropia

- **Trilinos (M. Heroux, SNL, PI)**
  - **Framework for solving large-scale scientific problems**
  - **Focus on packages (independent pieces of software that are combined to solve these problems)**
  - **Epetra: parallel linear algebra package**

- **Isorropia**
  - **Trilinos package for combinatorial scientific computing**
  - **Partitioning, coloring, ordering algorithms applied to Epetra matrices**
  - **Utilizes many algorithms in Zoltan**
  - **“Zoltan for sparse matrices”**

- **Partitioning methods**
  - **1D linear/block, cyclic, random**
  - **1D hypergraph**
  - **1D graph**
  - **2D fine-grain hypergraph**

Isorropia Partitioning: Example 1

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```
using Isorropia::Epetra::Partitioner;

ParameterList params;
params.set("PARTITIONING_METHOD", "HYPERGRAPH");
params.set("BALANCE_OBJECTIVE","NONZEROS");
params.set("IMBALANCE_TOL","1.03");

// rowmatrix is an Epetra_RowMatrix
Partitioner partitioner(rowmatrix,params,false);
partitioner.partition();
```

- **Simple partitioning of rowmatrix**
  - **1D row hypergraph partitioning**
  - **Balancing number of nonzeros**
  - **Load imbalance tolerance of 1.03**

Isorropia: Redistributing Matrix Data

Sandia National Laboratories

```
partitioner->partition();

// Set up Redistributor based on partition
Isorropia::Epetra::Redistributor rd(partitioner);

// Redistribute data
newmatrix = rd.redistribute(*rowmatrix, true);
```

- **After partitioning matrix**
  - **Build Redistributor from new partition**
  - **Redistribute data based on new partition**
  - **Obtain new matrix**

Isorropia: Redistributing Matrix Data

Sandia National Laboratories

```
using Isorropia::Epetra::createBalancedCopy;

ParameterList params;
params.set("IMBALANCE_TOL","1.03");
params.set("BALANCE_OBJECTIVE","NONZEROS");
params.set("PARTITIONING_METHOD", "HYPERGRAPH");

// crsmatrix and newmatrix are Epetra_CrsMatrix
newmatrix = createBalancedCopy(*crsmatrix, params);
```

- **Shortcut**
  - **Combines partitioning/redistibution of data**

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Zoltan2

- Rewrite of Zoltan to focus on petascale and exascale computing.
- Can handle > 2 Billion elements without recompiling with the help of templates
- Templated interface to support different data structures – Trilinos and Application data structures.
- Architecture aware load balancing algorithms for modern manycore systems.
- Under development.

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For More Information...

- Zoltan Home Page
  - http://www.cs.sandia.gov/Zoltan
  - User's and Developer's Guides
  - Tutorial: "Getting Started with Zoltan: A Short Tutorial"
  - Download Zoltan software under GNU LGPL
- Trilinos Home Page
  - http://trilinos.sandia.gov
- ITAPS Home Page
  - http://www.itaps.org
- CSCAPES Home Page
  - http://www.cscapes.org
- Email
  - zoltan-dev@software.sandia.gov

The End

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Partitioning Interface

Zoltan computes the difference (Δ) from current distribution

Choose between:

a) Import lists (data to import from other procs)

b) Export lists (data to export to other procs)

c) Both (the default)

```
err = Zoltan_LB_Partition(zz,
    &changes, /* Flag indicating whether partition changed */
    &numGidEntries, &numLidEntries,
    &numImport, /* objects to be imported to new part */
    &importGlobalGids, &importLocalGids, &importProcs, &importToPart,
    &numExport, /* # objects to be exported from old part */
    &exportGlobalGids, &exportLocalGids, &exportProcs, &exportToPart);
```

Extra Slides

- **Experimental results: Partitioning**

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Performance Results

- Experiments on Sandia's Thunderbird cluster.
  - Dual 3.6 GHz Intel EM64T processors with 6 GB RAM.
  - Infiniband network.
- Compare RCB, HSFC, graph and hypergraph methods.
- Measure …
  - Amount of communication induced by the partition.
  - Partitioning time.

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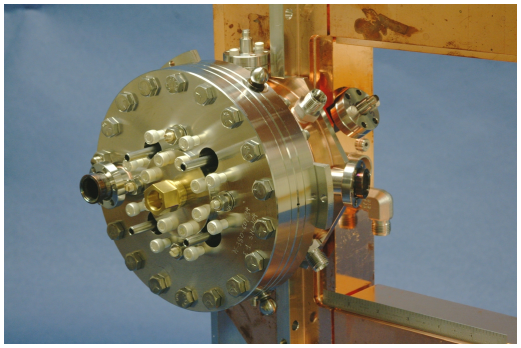
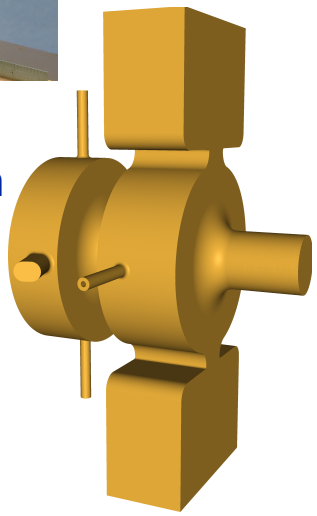
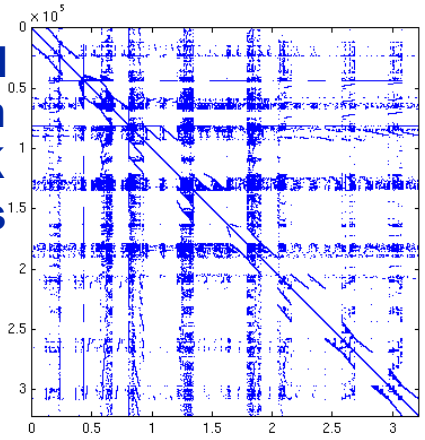
Test Data



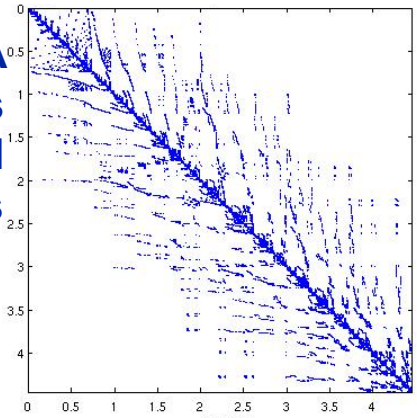
SLAC *LCLS
Radio Frequency Gun
6.0M x 6.0M
23.4M nonzeros



Xyce 680K ASIC Stripped
Circuit Simulation
680K x 680K
2.3M nonzeros



Cage15 DNA
Electrophoresis
5.1M x 5.1M
99M nonzeros



SLAC Linear Accelerator
2.9M x 2.9M
11.4M nonzeros

Communication Volume: Lower is Better

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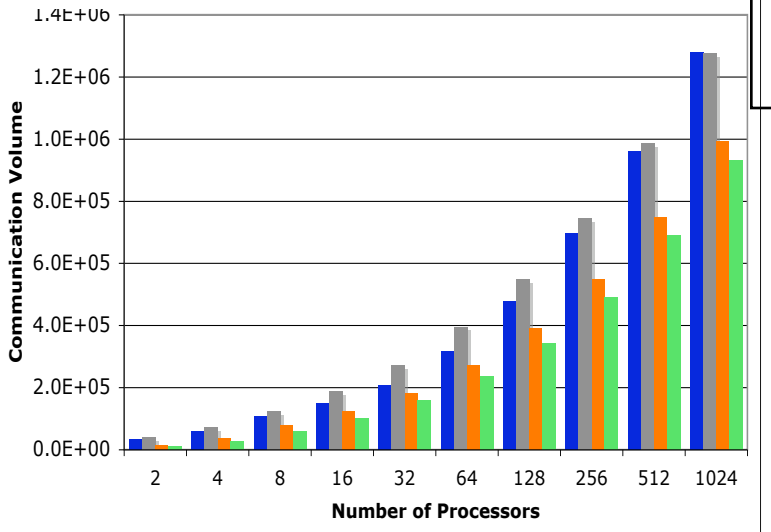
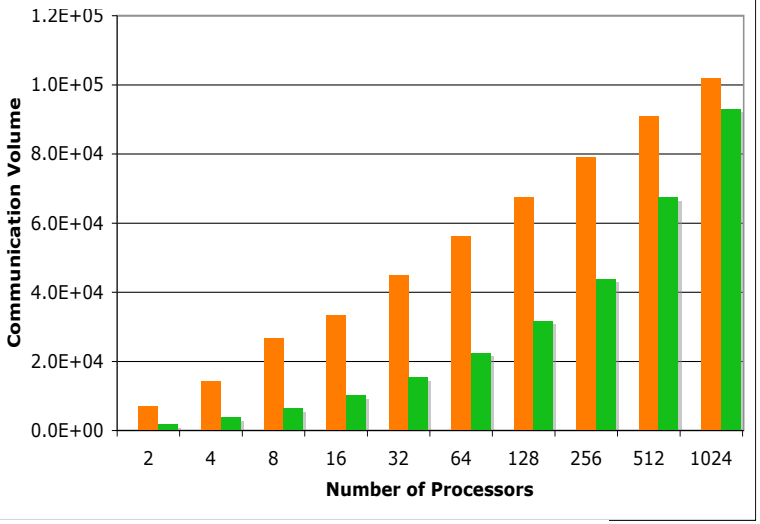
Number of parts = number of processors.

SLAC 6.0M LCLS

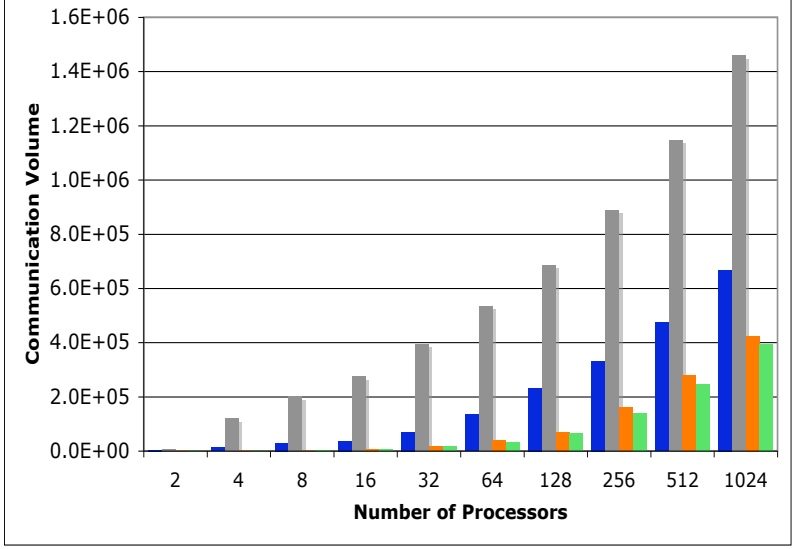


Xyce 680K circuit

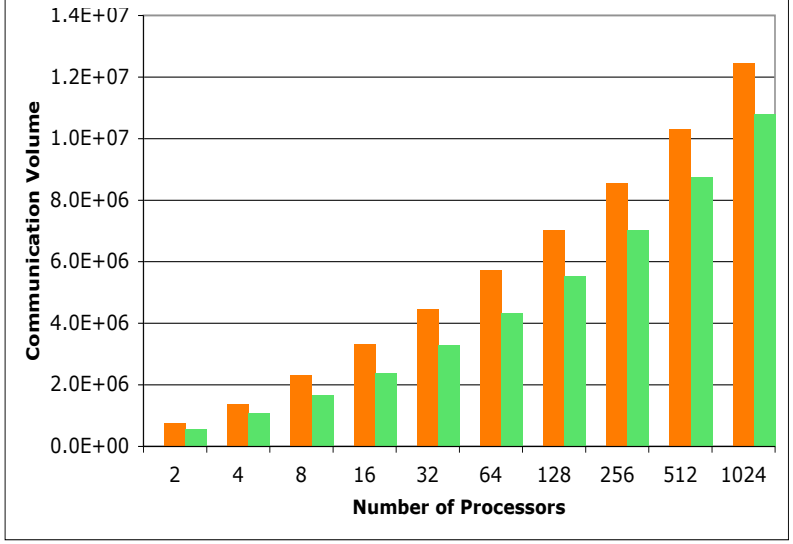


RCB
HSFC
Graph
Hypergraph

SLAC 2.9M Linear Accelerator



Cage15 5.1M electrophoresis



Partitioning Time: Lower is better

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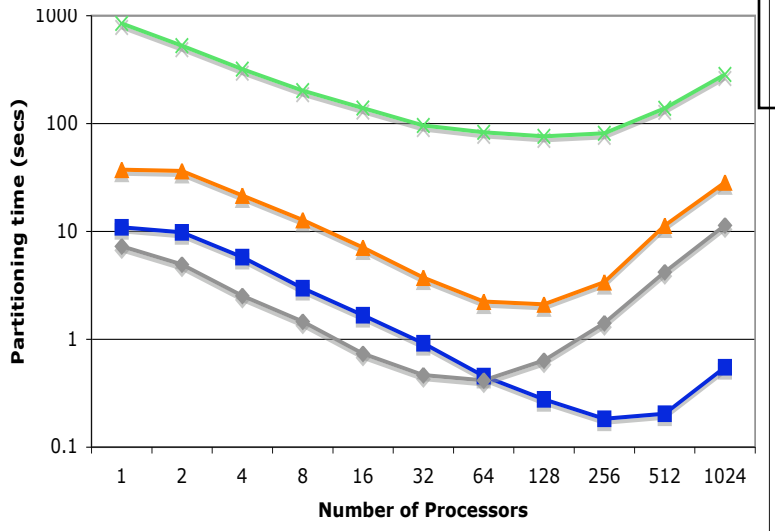
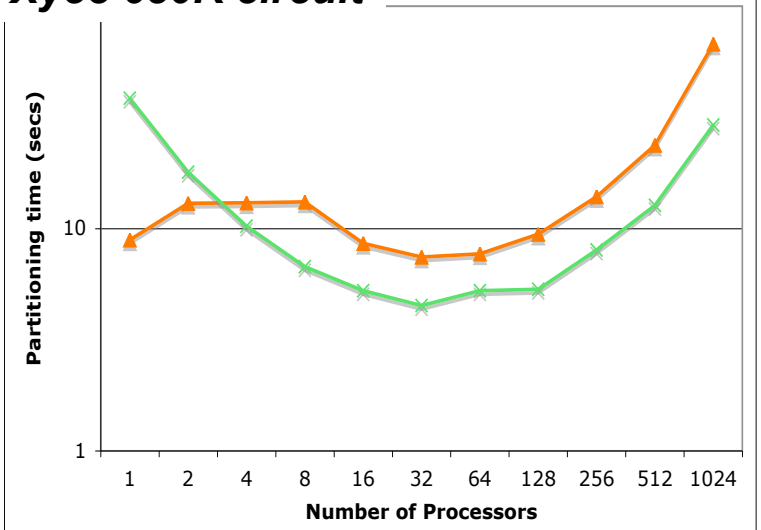
1024 parts. Varying number of processors.

SLAC 6.0M LCLS

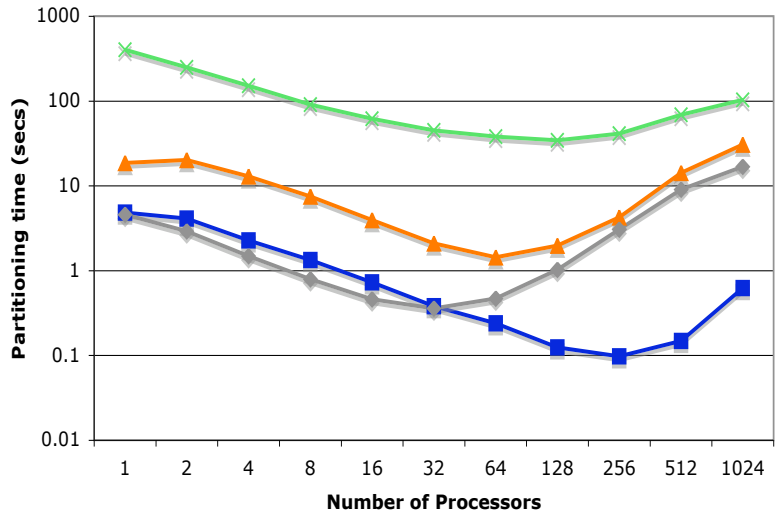


Xyce 680K circuit

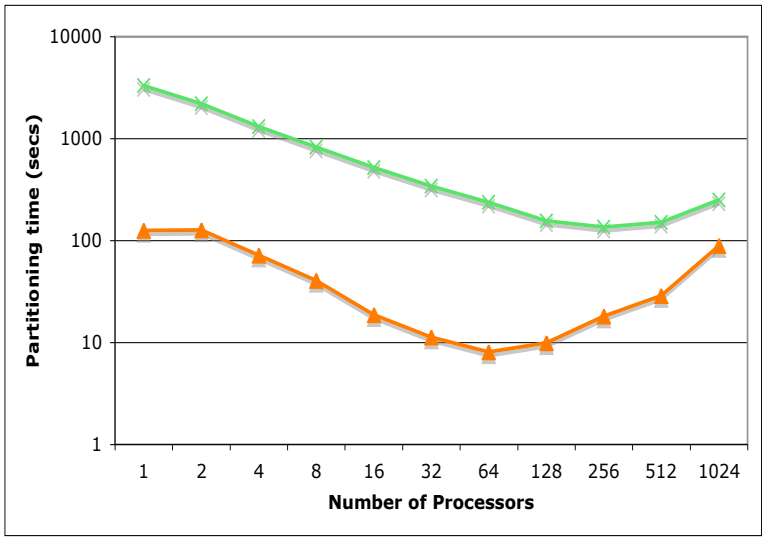


RCB
HSFC
Graph
Hypergraph

SLAC 2.9M Linear Accelerator



Cage15 5.1M electrophoresis



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Extra Slides

- **Experimental results: Repartitioning**

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Repartitioning Experiments

- Experiments with 64 parts on 64 processors.
- Dynamically adjust weights in data to simulate, say, adaptive mesh refinement.
- Repartition.
- Measure repartitioning time and total communication volume:

Data redistribution volume

+ Application communication volume

Total communication volume

Repartitioning Results: Lower is Better

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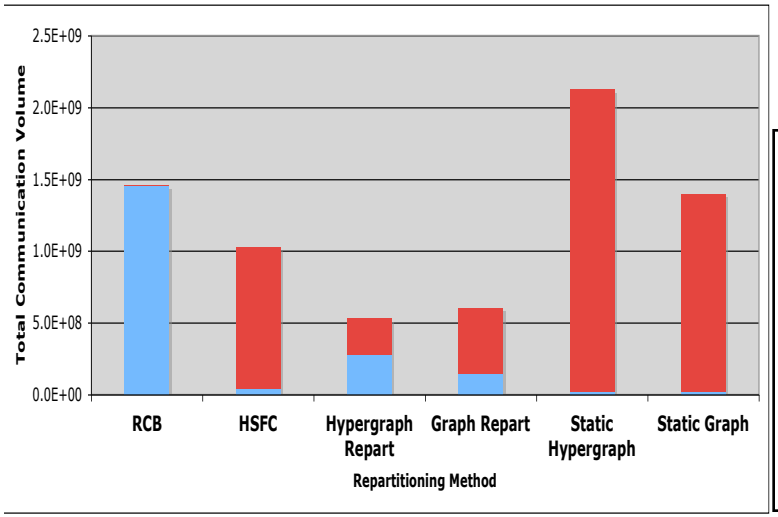
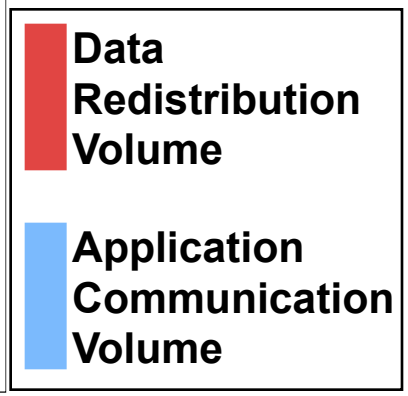
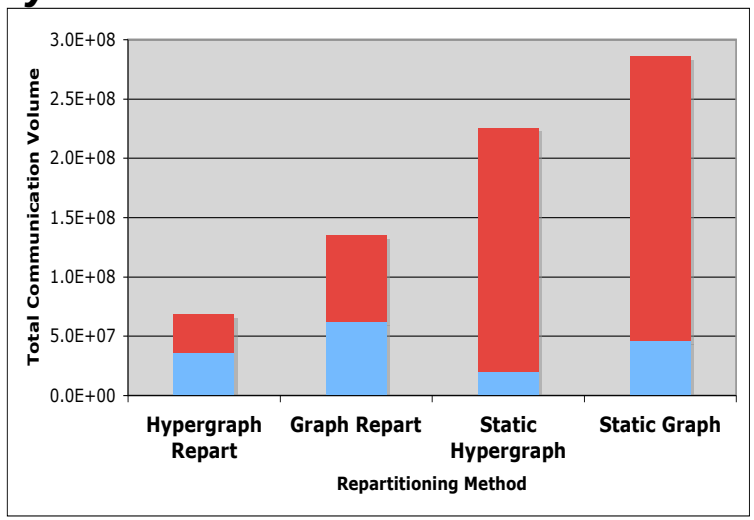
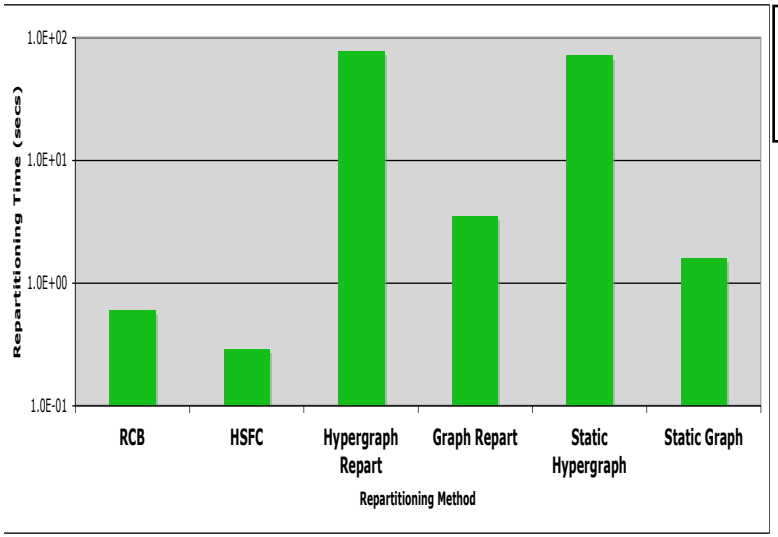
SLAC 6.0M LCLS

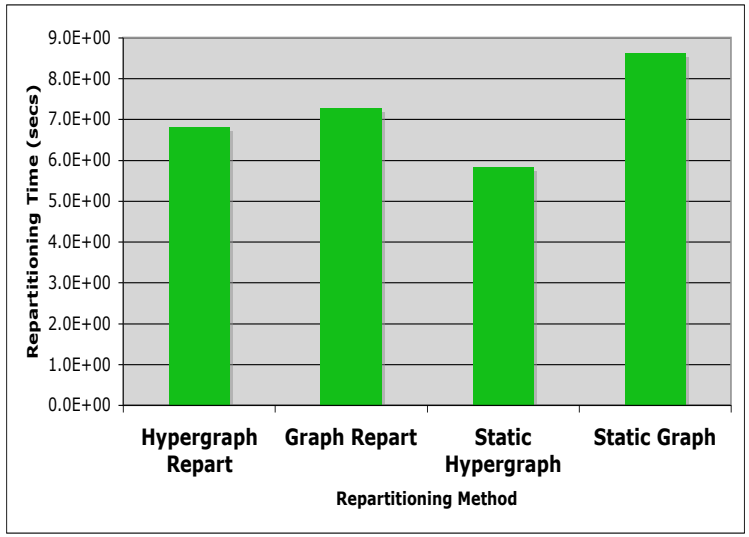




Xyce 680K circuit







Extra Slides

- **Experimental results: Coloring**

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A Parallel Coloring Framework

- Color vertices iteratively in rounds using a first fit strategy
- Each round is broken into supersteps
  - Color a certain number of vertices
  - Exchange recent color information
- Detect conflicts at the end of each round
- Repeat until all vertices receive consistent colors

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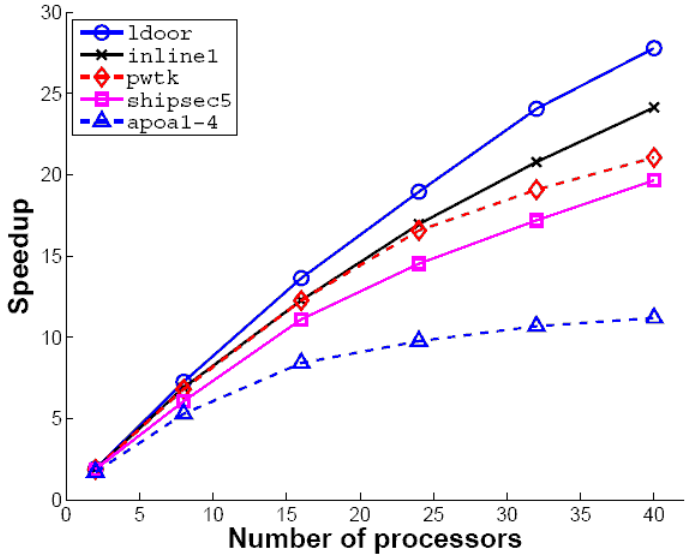
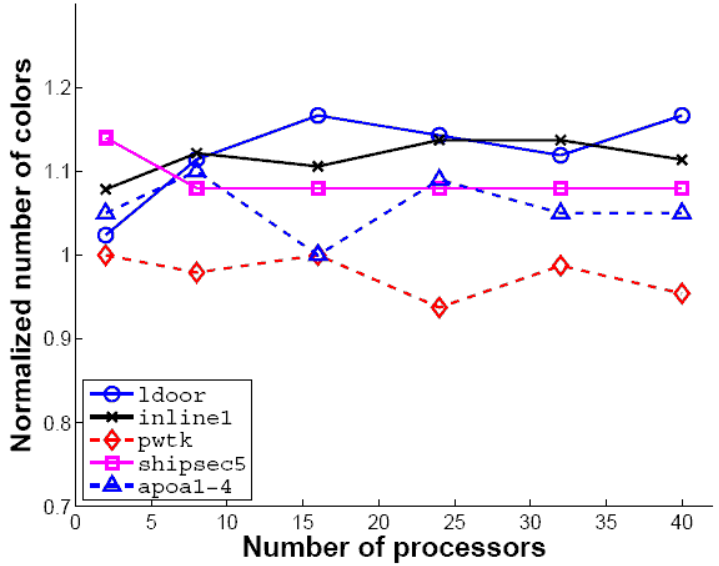
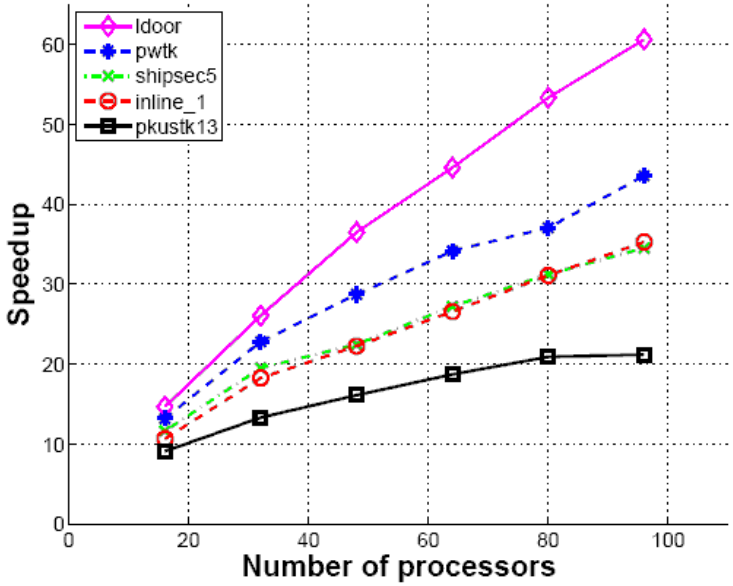
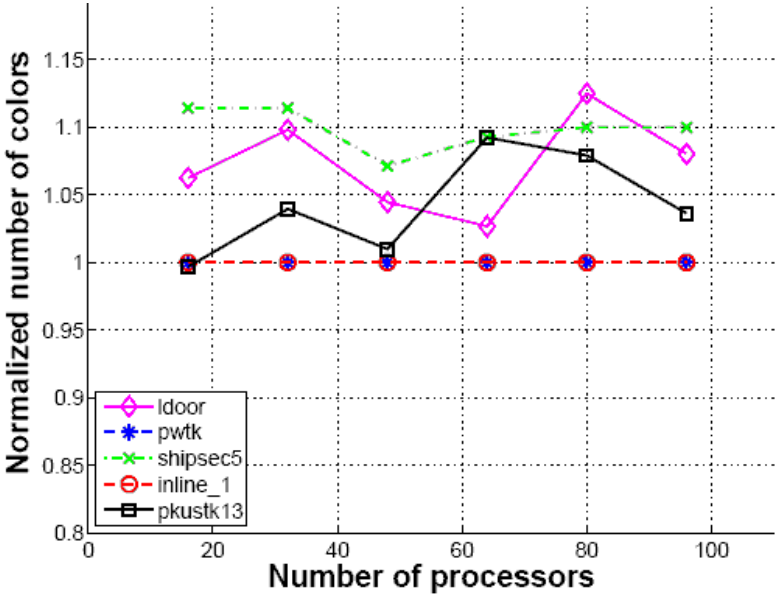
Experimental Results









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Extra Slides

- **More details on callback/query functions.**

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More Details on Query Functions

- **void* data pointer allows user data structures to be used in all query functions.**
  - **To use, cast the pointer to the application data type.**
- **Local IDs provided by application are returned by Zoltan to simplify access of application data.**
  - **E.g. Indices into local arrays of coordinates.**
- **ZOLTAN_ID_PTR is pointer to array of unsigned integers, allowing IDs to be more than one integer long.**
  - **E.g., (processor number, local element number) pair.**
  - **numGlobalIds and numLocalIds are lengths of each ID.**
- **All memory for query-function arguments is allocated in Zoltan.**

```
void ZOLTAN_GET_GEOM_MULTI_FN(void *userDefinedData,
                              int numGlobalIds, int numLocalIds, int numObjs,
                              ZOLTAN_ID_PTR gids, ZOLTAN_ID_PTR lids,
                              int numDim, double *pts, int *err)
```

Example zoltanSimple.c: ZOLTAN_OBJ_LIST_FN

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```
void exGetObjectList(void *userDefinedData,
                     int numGlobalIds, int numLocalIds,
                     ZOLTAN_ID_PTR gids, ZOLTAN_ID_PTR lids,
                     int wgt_dim, float *obj_wgts,
                     int *err)
{
/* ZOLTAN_OBJ_LIST_FN callback function.
** Returns list of objects owned by this processor.
** lids[i] = local index of object in array.
*/
  int i;

  for (i=0; i<NumPoints; i++)
  {
    gids[i] = GlobalIds[i];
    lids[i] = i;
  }

  *err = 0;

  return;
}
```

Example zoltanSimple.c: ZOLTAN_GEOM_MULTI_FN

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```
void exGetObjectCoords(void *userDefinedData,
                       int numGlobalIds, int numLocalIds, int numObjs,
                       ZOLTAN_ID_PTR gids, ZOLTAN_ID_PTR lids,
                       int numDim, double *pts, int *err)
{
/* ZOLTAN_GEOM_MULTI_FN callback.
** Returns coordinates of objects listed in gids and lids.
*/
  int i, id, id3, next = 0;
  if (numDim != 3) {
    *err = 1; return;
  }
  for (i=0; i<numObjs; i++){
    id = lids[i];
    if ((id < 0) || (id >= NumPoints)) {
      *err = 1; return;
    }
    id3 = lids[i] * 3;
    pts[next++] = (double)(Points[id3]);
    pts[next++] = (double)(Points[id3 + 1]);
    pts[next++] = (double)(Points[id3 + 2]);
  }
}
```

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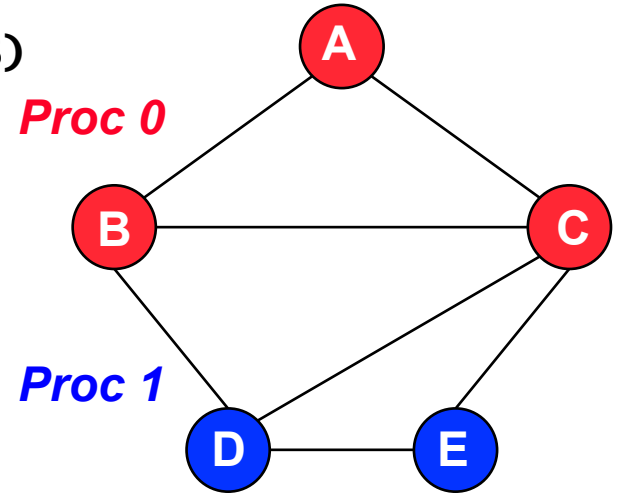
Example Graph Callbacks

```
void ZOLTAN_NUM_EDGES_MULTI_FN(void *data,
  int num_gid_entries, int num_lid_entries,
  int num_obj, ZOLTAN_ID_PTR global_id, ZOLTAN_ID_PTR local_id,
  int *num_edges, int *ierr);
```

Proc 0 Input from Zoltan:
num_obj = 3
global_id = {A,C,B}
local_id = {0,1,2}

Output from Application on Proc 0:
num_edges = {2,4,3}
(i.e., degrees of vertices A, C, B)
ierr = ZOLTAN_OK



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Example Graph Callbacks

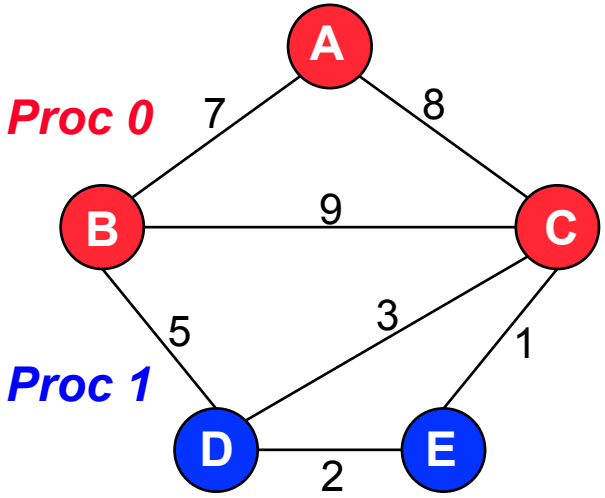
```
void ZOLTAN_EDGE_LIST_MULTI_FN(void *data,
  int num_gid_entries, int num_lid_entries,
  int num_obj, ZOLTAN_ID_PTR global_ids, ZOLTAN_ID_PTR local_ids,
  int *num_edges,
  ZOLTAN_ID_PTR nbor_global_id, int *nbor_procs,
  int wdim, float *nbor_ewgts,
  int *ierr);
```

Proc 0 Input from Zoltan:

```
num_obj = 3
global_ids = {A, C, B}
local_ids  = {0, 1, 2}
num_edges  = {2, 4, 3}
wdim = 0 or EDGE_WEIGHT_DIM parameter value
```

Output from Application on Proc 0:

```
nbor_global_id = {B, C, A, B, E, D, A, C, D}
nbor_procs     = {0, 0, 0, 0, 1, 1, 0, 0, 1}
nbor_ewgts     = if wdim then
                   {7, 8, 8, 9, 1, 3, 7, 9, 5}
ierr = ZOLTAN_OK
```



Example Hypergraph Callbacks

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```
void ZOLTAN_HG_SIZE_CS_FN(void *data, int *num_lists, int *num_pins,
  int *format, int *ierr);
```

```
Output from Application on Proc 0:
  num_lists = 2
  num_pins = 6
  format = ZOLTAN_COMPRESSED_VERTEX
           (owned non-zeros per vertex)
  ierr = ZOLTAN_OK

OR

Output from Application on Proc 0:
  num_lists = 5
  num_pins = 6
  format = ZOLTAN_COMPRESSED_EDGE
           (owned non-zeros per edge)
  ierr = ZOLTAN_OK
```

Vertices

Hyperedges	Proc 0 A	Proc 0 B	Proc 1 C	Proc 1 D
a	X			X
b		X		X
c			X	X
d		X		X
e	X		X	X
f	X	X	X	X

Example Hypergraph Callbacks

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```
void ZOLTAN_HG_CS_FN(void *data, int num_gid_entries,
  int nvtxedge, int npins, int format,
  ZOLTAN_ID_PTR vtxedge_GID, int *vtxedge_ptr, ZOLTAN_ID_PTR pin_GID,
  int *ierr);
```

Proc 0 Input from Zoltan:

- nvtxedge = 2 or 5
- npins = 6
- format = ZOLTAN_COMPRESSED_VERTEX or ZOLTAN_COMPRESSED_EDGE

Output from Application on Proc 0:

- if (format = ZOLTAN_COMPRESSED_VERTEX)
  - vtxedge_GID = {A, B}
  - vtxedge_ptr = {0, 3}
  - pin_GID = {a, e, f, b, d, f}
- if (format = ZOLTAN_COMPRESSED_EDGE)
  - vtxedge_GID = {a, b, d, e, f}
  - vtxedge_ptr = {0, 1, 2, 3, 4}
  - pin_GID = {A, B, B, A, A, B}
- ierr = ZOLTAN_OK

Vertices

Hyperedges	Proc 0 A	Proc 0 B	Proc 1 C	Proc 1 D
a	X			X
b		X		X
c			X	X
d		X		X
e	X		X	X
f	X	X	X	X