Tutorial: The Zoltan Toolkit

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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
The Zoltan Toolkit

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

Dynamic Load Balancing

Data Migration

Graph Coloring

Matrix Ordering

Unstructured Communication

Distributed Data Directories
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

- Different applications, requirements, data structures.

- Linear solvers & preconditioners

- Multiphysics simulations

- Adaptive mesh refinement

- Crash simulations

- Particle methods
## Zoltan’s use in large-scale experiments and simulations

<table>
<thead>
<tr>
<th>Partitioning Method</th>
<th>Application</th>
<th>Problem Size</th>
<th>Number of Processes</th>
<th>Number of Parts</th>
<th>Architecture</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graph</td>
<td>PHASTA CFD</td>
<td>34M elements</td>
<td>16K</td>
<td>16K</td>
<td>BG/P</td>
<td>Zhou, et al., RPI</td>
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<tr>
<td>Hypergraph</td>
<td>PHASTA CFD</td>
<td>1B elements</td>
<td>4096</td>
<td>160K</td>
<td>Cray XT/5</td>
<td>Zhou, et al., RPI</td>
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<tr>
<td>Hypergraph</td>
<td>Sparta LB algorithms</td>
<td>800M zones</td>
<td>8192</td>
<td>262K</td>
<td>Hera (AMD Quadcore)</td>
<td>Lewis, LLNL</td>
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<tr>
<td>Geometric</td>
<td>Pic3P particle-in-cell</td>
<td>5B particles</td>
<td>24K</td>
<td>24K</td>
<td>Cray XT/4</td>
<td>Candel, et al., SLAC</td>
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<tr>
<td>Geometric</td>
<td>MPSalsa CFD</td>
<td>208M nodes</td>
<td>12K</td>
<td>12K</td>
<td>RedStorm</td>
<td>Lin, SNL</td>
</tr>
<tr>
<td>Geometric</td>
<td>Trilinos/ML Multigrid in ALEGRA shock physics</td>
<td>24.6M rows 1.2B non-zeros</td>
<td>24K</td>
<td>24K</td>
<td>RedStorm</td>
<td>Hu, et al., SNL</td>
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</table>
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.
- Achieved strong scalability up to 128K cores (BG/P) for CFD code PHASTA.
- We continue work with ITAPS to improve robustness on >10K cores.

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

<table>
<thead>
<tr>
<th>Number of cores</th>
<th>Time (s)</th>
<th>Efficiency</th>
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<tbody>
<tr>
<td>16k</td>
<td>222.03</td>
<td>1</td>
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<tr>
<td>32k</td>
<td>112.43</td>
<td>0.987</td>
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<tr>
<td>64k</td>
<td>57.09</td>
<td>0.972</td>
</tr>
<tr>
<td>128k</td>
<td>31.35</td>
<td>0.885</td>
</tr>
</tbody>
</table>
SciDAC Collaborations: ComPASS (SLAC)

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)
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.
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)
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

**APPLICATION**

- Initialize Zoltan (Zoltan_Initialize, Zoltan_Create)
- Select Method and Parameters (Zoltan_Set_Params)
- Register query functions (Zoltan_Set_Fn)

**ZOLTAN**

- (Re)partition (Zoltan_LB_Partition)
  - Call query functions.
  - Build data structures.
  - Compute new decomposition.
  - Return import/export lists.

- Move data (Zoltan_Migrate)
  - Call packing query functions for exports.
  - Send exports.
  - Receive imports.
  - Call unpacking query functions for imports.

- Clean up (Zoltan_Destroy)
# Zoltan Query Functions

## General Query Functions

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<td>Coordinates of items.</td>
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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.
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

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

- 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 Algorithms in the Zoltan Toolkit

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

- 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

- Adaptive Mesh Refinement
- Parallel Volume Rendering
- Particle Simulations
- Crash Simulations and Contact Detection
Geometric Methods: Advantages and Disadvantages

• 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.

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

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

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Graph Partitioning

- 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.

- 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.
Applications using Graph Partitioning

Finite Element Analysis

Multiphysics and multiphase simulations

Linear solvers & preconditioners
(square, structurally symmetric systems)
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)
      PTScotch (U. Bordeaux)

• Disadvantages:
  – More expensive than geometric methods.
  – Edge-cut model only approximates communication volume.
### Graph Partitioning: Query Functions

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<tr>
<th>Category</th>
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Hypergraph Partitioning

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

- 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 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

Circuit Simulations

Linear programming for sensor placement

Multiphysics and multiphase simulations

Linear solvers & preconditioners (no restrictions on matrix structure)

Data Mining

Linear programming for sensor placement

Multiphysics and multiphase simulations

Data Mining

Linear solvers & preconditioners (no restrictions on matrix structure)
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 Partitioning with Hypergraph Query Functions

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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.

• \texttt{Zoltan\_Set\_Param(zz, \textit{"OBJ\_WEIGHT\_DIM"}, \textit{"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

• 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.
- 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
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
Zoltan Data Migration Tools

- 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

- 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.
• 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.
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

• 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
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

```cpp
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 Partitioning: Example 2

```cpp
using Isorropia::Epetra::Partitioner2D;

ParameterList params;
params.set("PARTITIONING_METHOD", "HGRAPH2D_FINEGRAIN");
params.set("IMBALANCE_TOL", "1.03");

// rowmatrix is an Epetra_RowMatrix
Partitioner2D partitioner(rowmatrix, params, false);
partitioner.partition();
```

- **2D partitioning of rowmatrix**
  - 2D fine-grain hypergraph partitioning
  - Balancing number of nonzeros (implicit)
  - Load imbalance tolerance of 1.03
Isorropia: Redistributing Matrix Data

```cpp
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

```cpp
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/redistribution of data
For More Information...

- Zoltan Home Page
  - User’s and Developer’s Guides
  - Tutorial: “Getting Started with Zoltan: A Short Tutorial”
  - Download Zoltan software under GNU LGPL

- Trilinos Home Page

- ITAPS Home Page
  - http://www.itaps.org

- CSCAPES Home Page
  - http://www.cscapes.org

- Email
  - zoltan-dev@software.sandia.gov
Partitioning Interface

Zoltan computes the difference ($\Delta$) 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
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.
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

**SLAC 6.0M LCLS**

**SLAC 2.9M Linear Accelerator**

**Xyce 680K circuit**

**Cage15 5.1M electrophoresis**

Number of parts = number of processors.
Partitioning Time:
Lower is better

SLAC 6.0M LCLS
1024 parts. Varying number of processors.

SLAC 2.9M Linear Accelerator

Xyce 680K circuit

Cage15 5.1M electrophoresis
Extra Slides

• Experimental results: Repartitioning
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

SLAC 6.0M LCLS

Xyce 680K circuit

Repartitioning Method

Data Redistribution Volume

Application Communication Volume

Repartitioning Time (secs)
Extra Slides

• Experimental results: Coloring
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
Experimental Results

Graphs showing speedup and normalized number of colors for different scenarios.
Extra Slides

• More details on callback/query functions.
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.

```c
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

```c
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

```c
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]);
    }
}
```
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
Example Graph Callbacks

```c
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

```c
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`

<table>
<thead>
<tr>
<th>Vertices</th>
<th>Proc 0</th>
<th>Proc 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
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<tr>
<td>D</td>
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<tr>
<td>a</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
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