Dynamic Load Balancing and Partitioning using the Zoltan Toolkit

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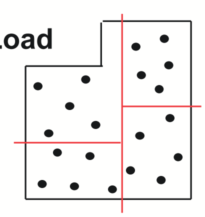
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

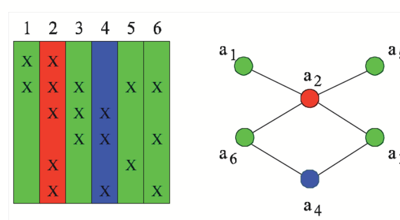
The Zoltan Toolkit

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

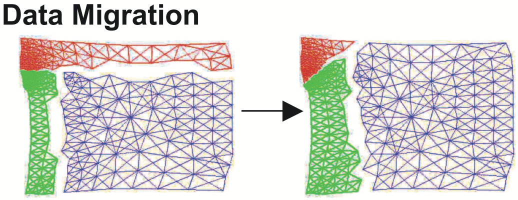
Dynamic Load Balancing



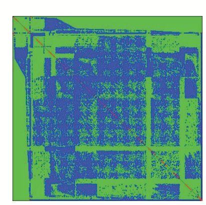
Graph Coloring



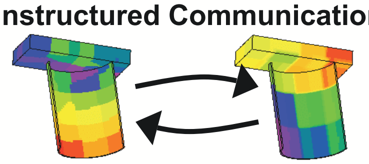
Data Migration



Matrix Ordering



Unstructured Communication



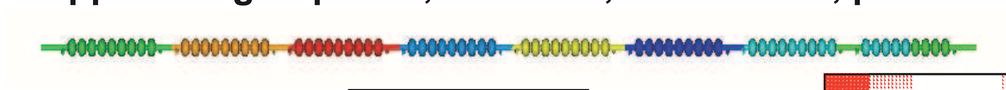
Distributed Data Directories

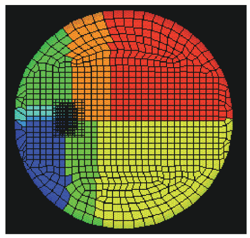
A	B	C	D	E	F	G	H	I
0	1	0	2	1	0	1	2	1

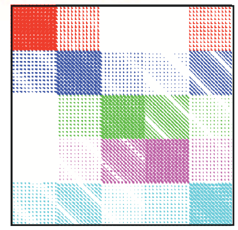
Dynamic Memory Debugging

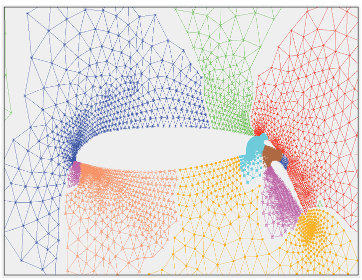
Partitioning and Load Balancing

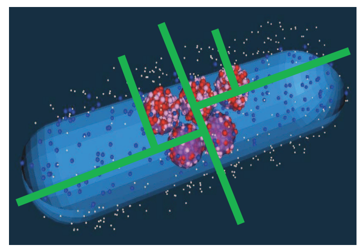
- Assignment of application data to processors for parallel computation.
- Applied to grid points, elements, matrix rows, particles, ….









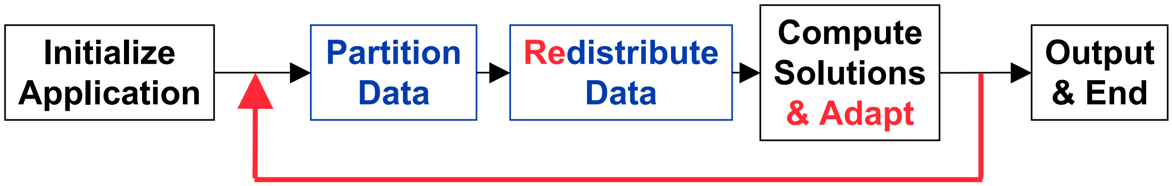


Static Partitioning

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.

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.

What makes a partition "good," especially at petascale?

- Balanced work loads.
  - Even small imbalances result in many wasted processors!
    - 50,000 processors with one processor 5% over average workload is equivalent to *2380 idle processors* and 47,620 perfectly balanced processors.

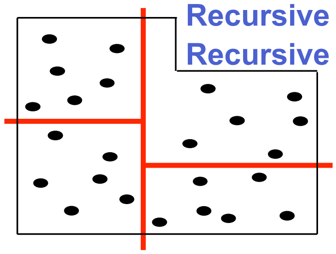
- Low interprocessor communication costs.
  - Processor speeds increasing faster than network speeds.
  - Partitions with minimal communication costs are critical.

- Scalable partitioning time and memory use.
  - Scalability is especially important for dynamic partitioning.

- Low data redistribution costs (for dynamic partitioning).
  - Redistribution costs must be recouped through reduced total execution time.

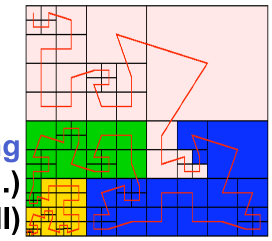
Partitioning Algorithms in the Zoltan Toolkit

Geometric (coordinate-based) methods

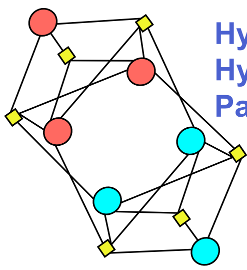


Recursive Coordinate Bisection (Berger, Bokhari)
Recursive Inertial Bisection (Taylor, Nour-Omid)

Space Filling Curve Partitioning (Warren&Salmon, et al.)
Refinement-tree Partitioning (Mitchell)

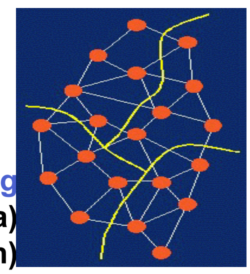


Hypergraph and graph (connectivity-based) methods



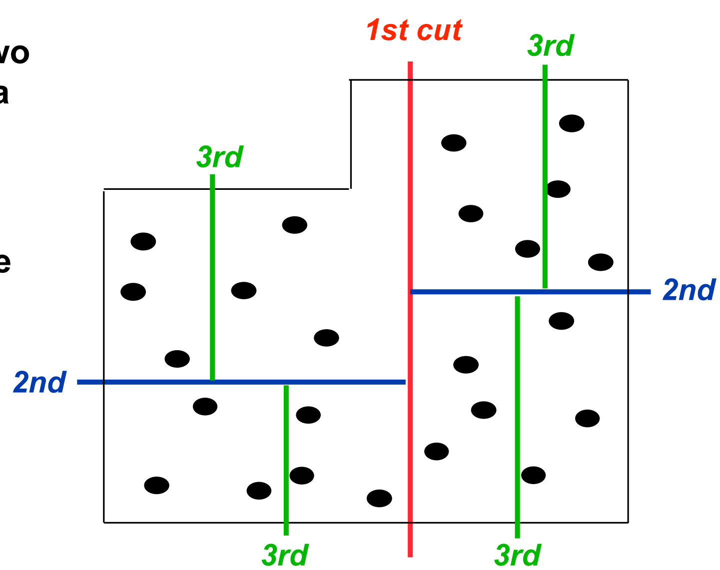
Hypergraph Partitioning
Hypergraph Repartitioning
PaToH (Catalyurek & Aykanat)

Zoltan Graph Partitioning
ParMETIS (U. Minnesota)
Jostle (U. Greenwich)



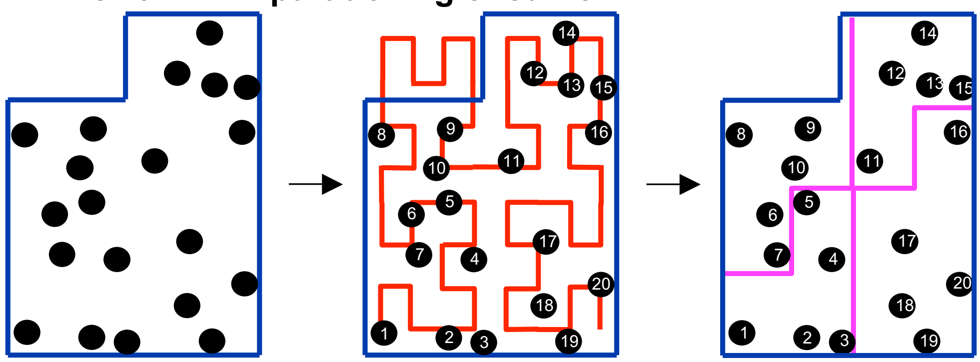
Geometric Partitioning: RCB

- Recursive Coordinate Bisection: Developed by Berger & Bokhari (1987) for Adaptive Mesh Refinement.
- Idea:
  - Divide work into two equal parts using a cutting plane orthogonal to a coordinate axis.
  - Recursively cut the resulting subdomains.

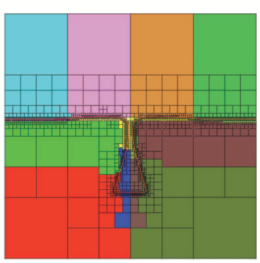


Geometric Partitioning: SFC

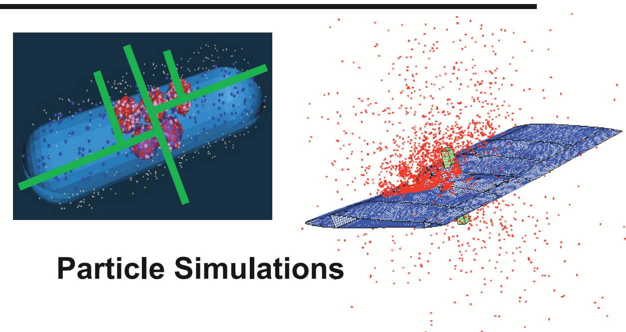
- Space-Filling Curve Partitioning
  - Gravitational simulations (Warren & Salmon, 1993)
  - Smoothed particle hydrodynamics (Pilkington & Baden, 1994)
  - Adaptive mesh refinement (Patra & Oden, 1995).
- SFC Partitioning Algorithm:
  - Run SFC through domain (mapping from R^3 to R^1).
  - Order objects according to position on curve.
  - Perform 1-D partitioning of curve.



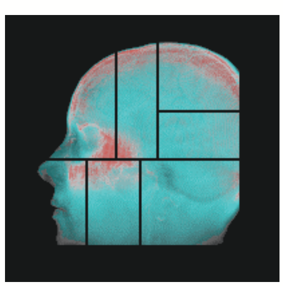
Applications of Geometric Methods



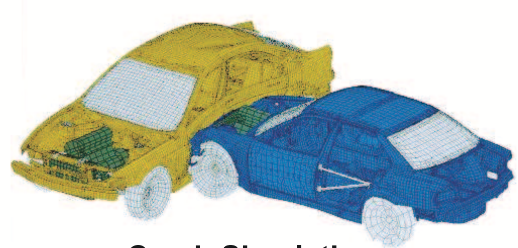
Adaptive Mesh Refinement



Particle Simulations



Parallel Volume Rendering



Crash Simulations
and Contact Detection

Geometric Methods Advantages and Disadvantages

- Advantages:
  - 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.

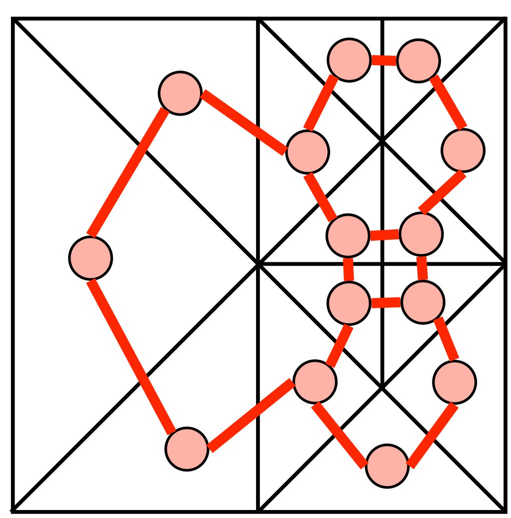
SLAC'S 55-cell Linear Accelerator with couplers: One-dimensional RCB partition reduced runtime up to 68% on 512 processor IBM SP3. (Wolf, Ko)

- Disadvantages:
  - No explicit control of communication costs.
  - Mediocre partition quality.
  - Need coordinate information.

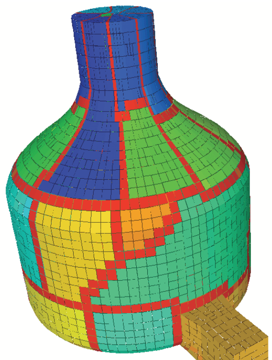
Graph Partitioning

- Kernighan, Lin, Schweikert, Fiduccia, Mattheyes, Simon, Hendrickson, Leland, Kumar, Karypis, et al.

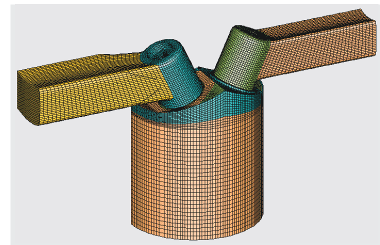
- Represent problem as a weighted graph.
  - Vertices = objects to be partitioned.
  - Edges = dependencies between two objects.
  - Weights = work load or amount of dependency.
- Partition graph so that …
  - Parts have equal vertex weight.
  - Weight of edges cut by part boundaries is small.



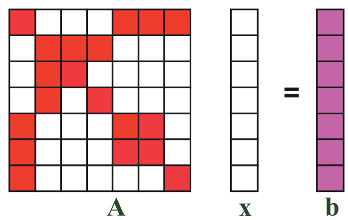
Applications using Graph Partitioning



Finite Element Analysis



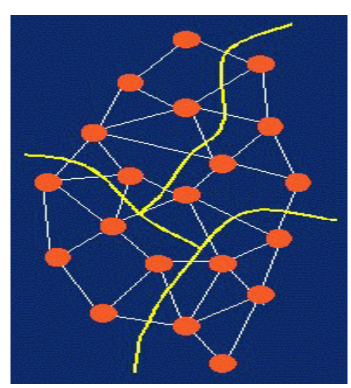
Multiphysics and multiphase simulations



Linear solvers & preconditioners
(square, structurally symmetric systems)

Graph Partitioning: Advantages and Disadvantages

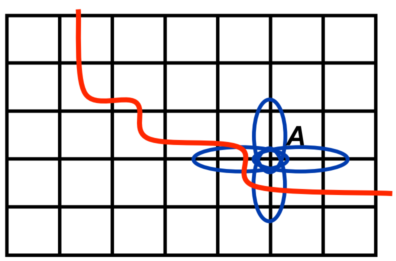
- Advantages:
  - Highly successful model for mesh-based PDE problems.
  - Explicit control of communication volume gives higher partition quality than geometric methods.
  - Excellent software available.
    - Serial: Chaco (SNL)
      Jostle (U. Greenwich)
      METIS (U. Minn.)
      Party (U. Paderborn)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



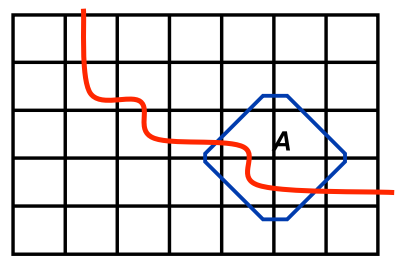
- Disadvantages:
  - More expensive than geometric methods.
  - Edge-cut model only approximates communication volume.

Hypergraph Partitioning

- 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.

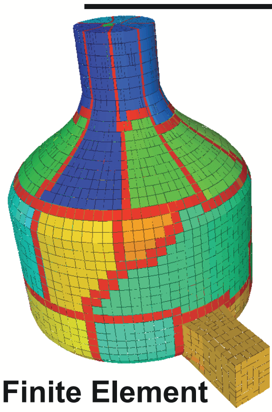


Graph Partitioning Model

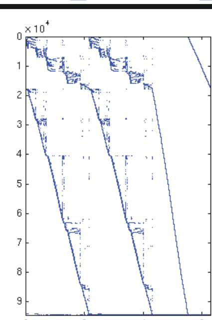


Hypergraph Partitioning Model

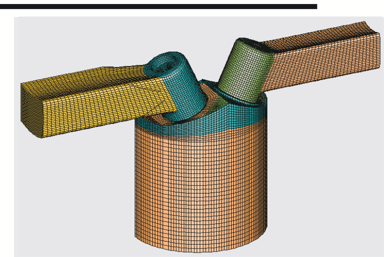
Hypergraph Applications



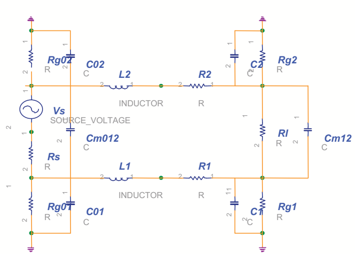
Finite Element Analysis



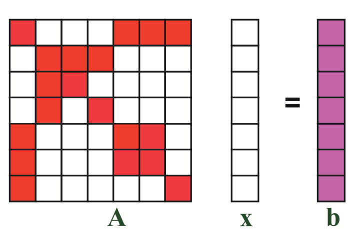
Linear programming for sensor placement



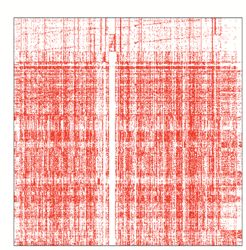
Multiphysics and multiphase simulations



Circuit Simulations



Linear solvers & preconditioners
(no restrictions on matrix structure)



Data Mining

Hypergraph Partitioning: Advantages and Disadvantages

- 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:
  - More expensive than graph partitioning.

Performance Results

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

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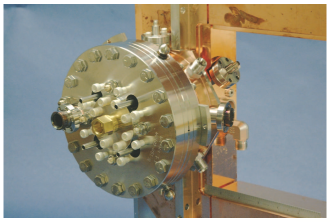
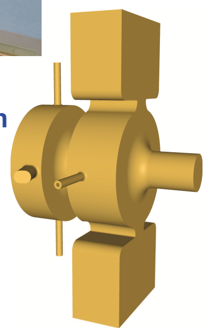
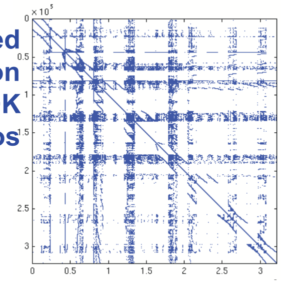
Test Data



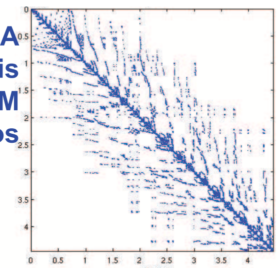
SLAC *LCLS
Radio Frequency Gun
6.0M x 6.0M
23.4M nonzeros



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

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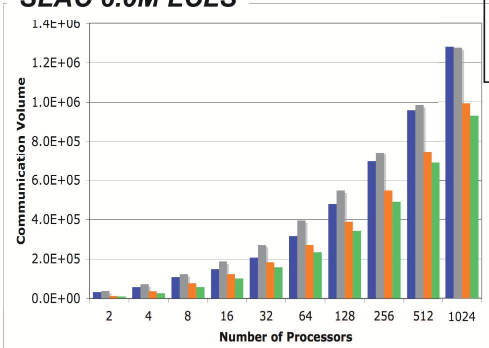
Communication Volume: Lower is Better

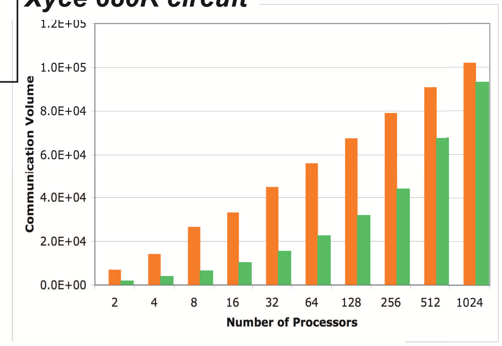
Number of parts = number of processors.

RCB
SFC
Graph
Hypergraph

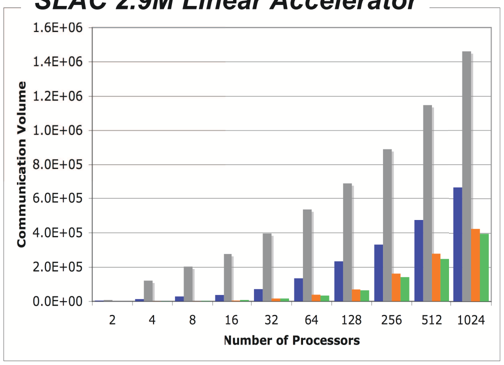
SLAC 6.0M LCLS



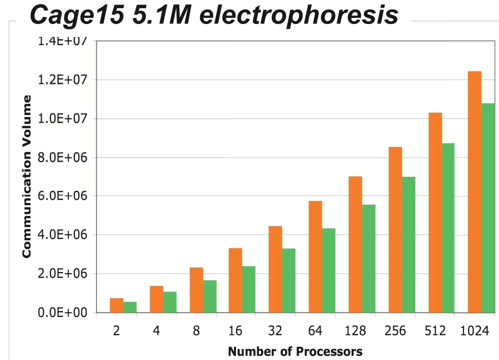
Xyce 680K circuit



SLAC 2.9M Linear Accelerator



Cage15 5.1M electrophoresis



Partitioning Time: Lower is better

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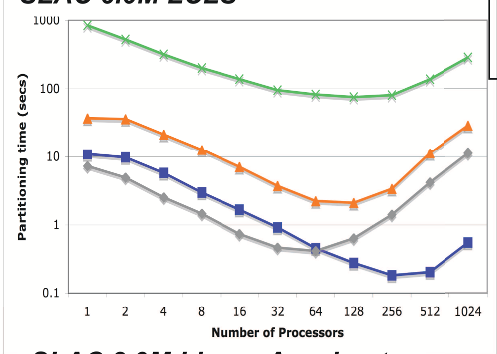
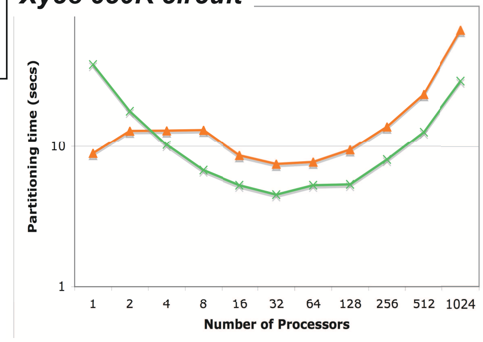
1024 parts. Varying number of processors.

RCB · **SFC** · **Graph** · **Hypergraph**

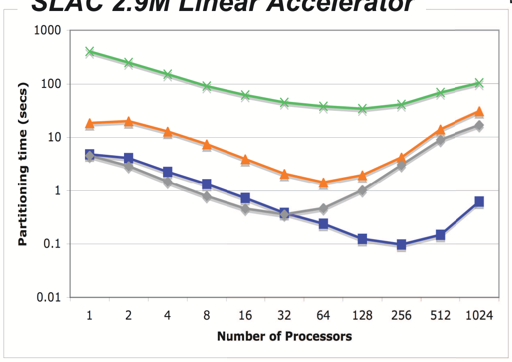
SLAC 6.0M LCLS



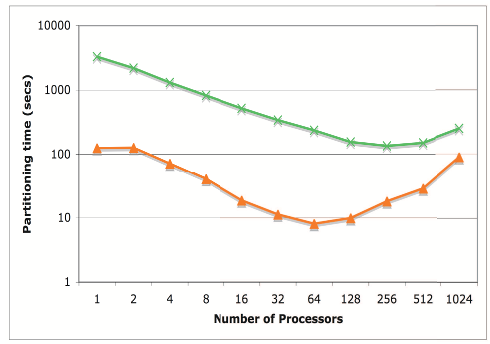
Xyce 680K circuit



SLAC 2.9M Linear Accelerator



Cage15 5.1M electrophoresis



Repartitioning Experiments

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- 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

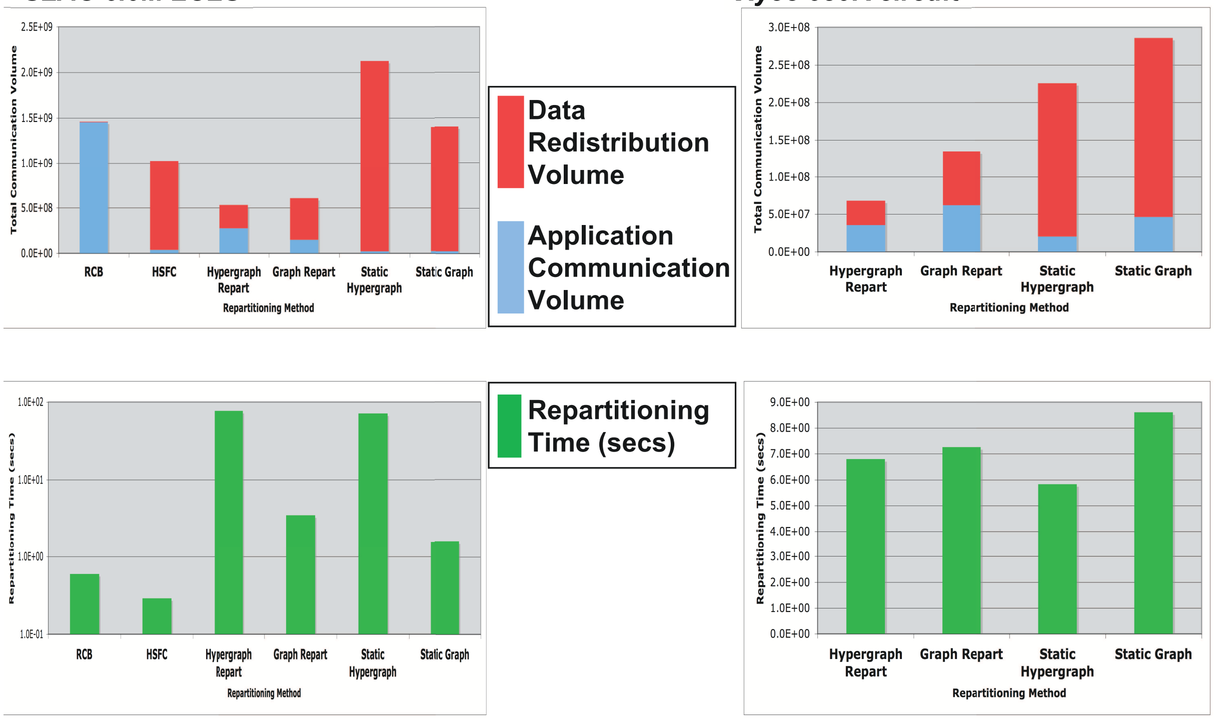
  <u>+ Application communication volume</u>

  Total communication volume

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

Repartitioning Results: Lower is Better

SLAC 6.0M LCLS *Xyce 680K circuit*

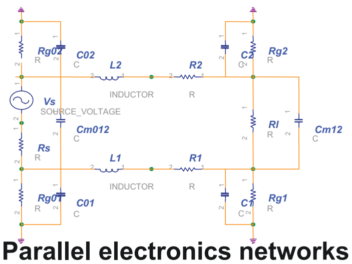


Zoltan Toolkit: Suite of Partitioners

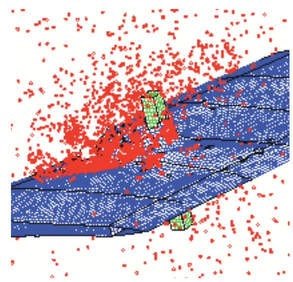
- No single partitioner works best for all applications.
  - Trade-offs:
    - Quality vs. speed.
    - Geometric locality vs. data dependencies.
    - High-data movement costs vs. tolerance for remapping.
- Application developers may not know which partitioner is best for application.
  - Suite of partitioners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

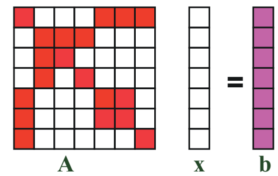
Zoltan Interface Supports Many Applications

- *Different applications, requirements, data structures.*

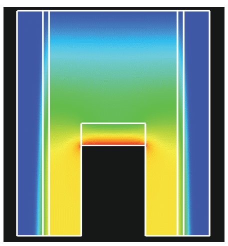


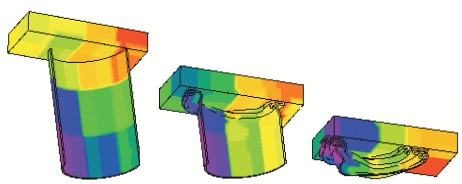
Parallel electronics networks

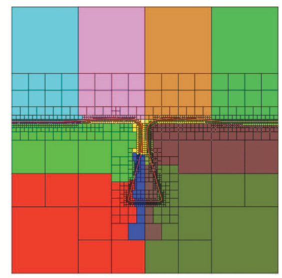

Particle methods



Linear solvers & preconditioners


Multiphysics simulations


Crash simulations


Adaptive mesh refinement

Zoltan Interface

- Simple, easy-to-use interface.
  - Small number of callable Zoltan functions.
  - Callable from C, C++, Fortran90.
- Two ways to access Zoltan:
  - Through ITAPS mesh implementation.
  - Directly from application through native Zoltan interface.
- Coming in FY08:
  - Matrix-based interface through Trilinos/Isorropia.

Zoltan ITAPS Interface

- Interoperable Tools for Advanced Petascale Simulations
- ITAPS iMesh implementation provides information to Zoltan for partitioning.
  - Number of mesh entities, connectivity, coordinates.
- Given a loaded iMesh_Instance, the application …
  - Constructs an ITAPSZoltan object;
  - Specifies number of parts, partitioning method, etc.; and
  - Invokes partitioning.
- Parts returned as tagged entity sets.
- Initial ITAPS-compliant implementation available.
  - https://svn.scorec.rpi.edu/wsvn/TSTT/Distributions/

Zoltan Native Interface Design

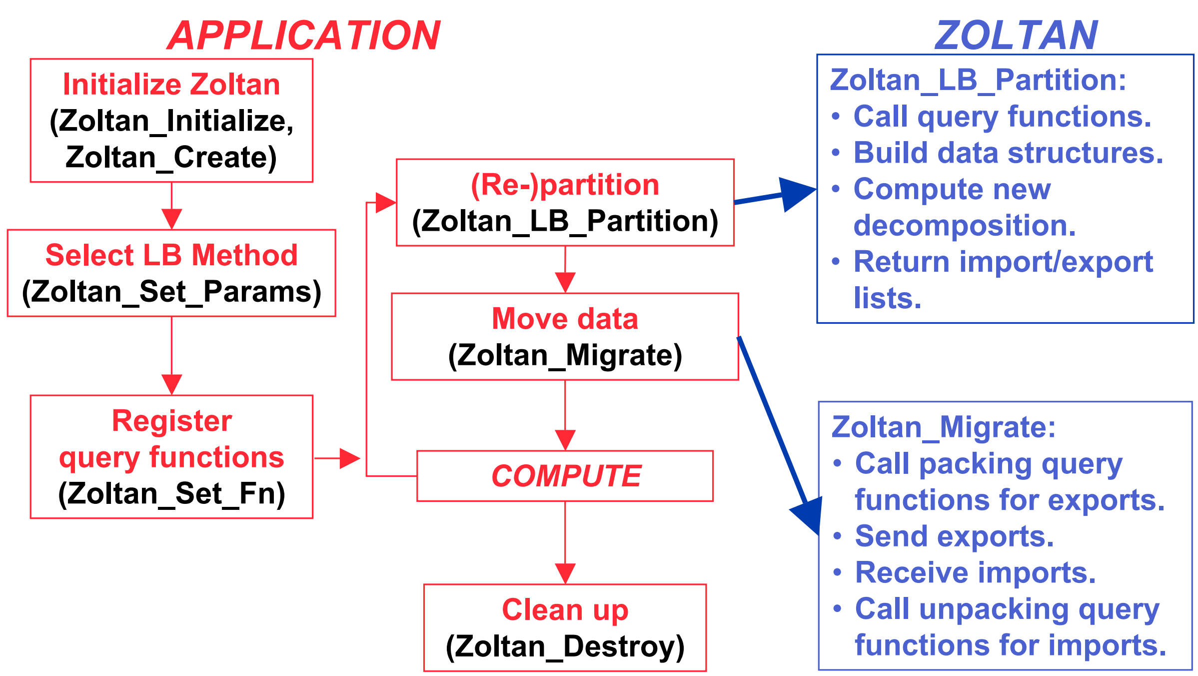
- Data-structure neutral design.
  - Supports wide range of applications and data structures.
  - Imposes no restrictions on application's data structures.
  - Application does not have to build Zoltan's data structures.
- Requirement: Unique global IDs for objects to be partitioned. For example:
  - Global element number.
  - Global matrix row number.
  - (Processor number, local element number)
  - (Processor number, local particle number)

Zoltan Native Interface

- Application interface:
  - Zoltan queries the application for needed info.
    - IDs of objects, object weights, part assignments.
    - Geometric algorithms: dimensions, coordinates.
    - Connectivity-based algorithms: edge lists, edge weights.
  - Application provides simple functions to answer queries.

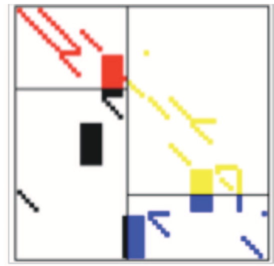
- Once query functions are implemented, application can access all Zoltan functionality.
  - Can switch between algorithms by setting parameters.

Zoltan Application Interface



Aiming for Petascale

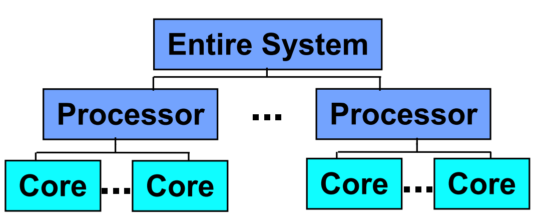
- Reducing communication costs for applications.
  - Reducing communication volume.
    - Two-dimensional sparse matrix partitioning (Catalyurek, Aykanat, Bisseling).
    - Partitioning non-zeros of matrix rather than rows/columns.
  - Reducing message latency.
    - Minimize maximum number of neighboring parts (with Kumfert, LLNL).
    - Balancing *both* computation and communication (Pinar & Hendrickson); balance criterion is complex function of the partition instead of simple sum of object weights.
  - Reducing communication overhead.
    - Map parts onto processors to take advantage of network topology.
    - Minimize distance messages travel in network.

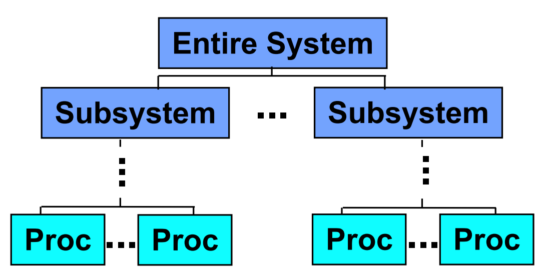


Mondriaan Partitioning
Courtesy of Rob Bisseling

Aiming for Petascale

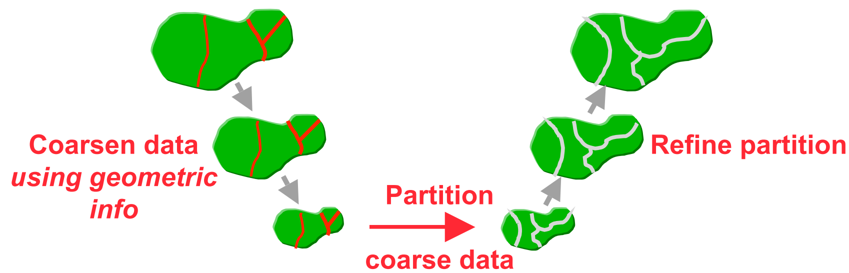
- Hierarchical partitioning in Zoltan v3.
  - Partition for multicore/manycore architectures.
    - Partition hierarchically with respect to chips and then cores.
    - Similar to strategies for clusters of SMPs (Teresco, Faik).
    - Treat core-level parts as separate threads or MPI processes.
  - Support 100Ks processors.
    - Reduce collective communication operations during partitioning.
    - Allow more localized partitioning on subsets of processors.





Aiming for Petascale

- Improving scalability of partitioning algorithms.
  - Hybrid partitioners (particularly for mesh-based apps.)
    - Use inexpensive geometric methods for initial partitioning; refine with high quality hypergraph/graph-based algorithms.
    - Use geometric information to accelerate multilevel hypergraph/graph-based partitioners.



  - Refactored partitioners for bigger data sets and processor arrays.

Aiming for Petascale

- Developing specialized partitioning strategies.
  - E.g., for particle-in-cell applications, multiscale.
- Data ordering within a processor.
  - Better memory performance.
  - Multicore support.
- Testing and performance evaluation.
  - Examine effectiveness of partitions in applications.

- *Wanted: Collaborations with application developers!*

For More Information…

- Zoltan web page: http://www.cs.sandia.gov/Zoltan
  - Download Zoltan v3 (open-source software).
  - Tutorial and User's Guide.

- ITAPS Interface to Zoltan:
  https://svn.scorec.rpi.edu/wsvn/TSTT/Distributions/

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http://www.cs.sandia.gov/Zoltan