

# Interoperable Tools for Advanced Petascale Simulations (ITAPS)

## TUTORIAL

November 2008



LLNL-PRES-407129

# Tutorial Overview

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## Morning

- Part 1: Introduction
- Part 2: Overview of ITAPS services
- Part 3: The ITAPS Data Model
- Part 4a: Basic ITAPS Interfaces
- *Hands on exercise:*
  - Hello iMeshP

## Afternoon

- Part 4b: Advanced ITAPS Interfaces
- Part 5: ITAPS Software
- Part 6: Experiences and use in applications
- Part 7: Conclusion
- *Hands on exercises:*
  - Accessing mesh information
  - Partitioning services through iMeshP

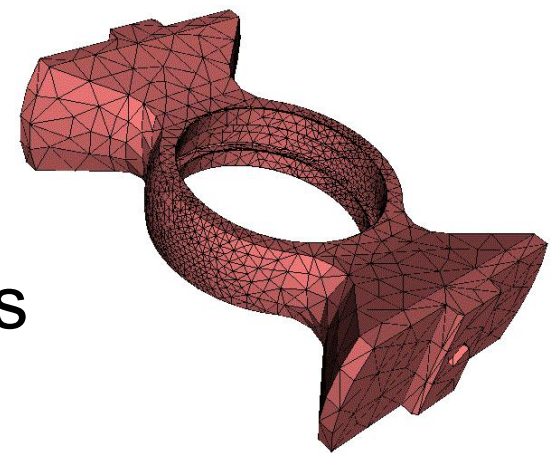
# PART 1: Introduction

# Unstructured meshes

- An unstructured mesh
  - A piece-wise space/time domain decomposition over which the simulation is to be run
  - General topology-based mesh representation consists of
    - 0-3 D topological entities (vertices, edges, faces and regions)
    - Connectivity between entities called *adjacencies*
  - Mesh data structure provide services to create and/or use the mesh data



**Geometric domain**

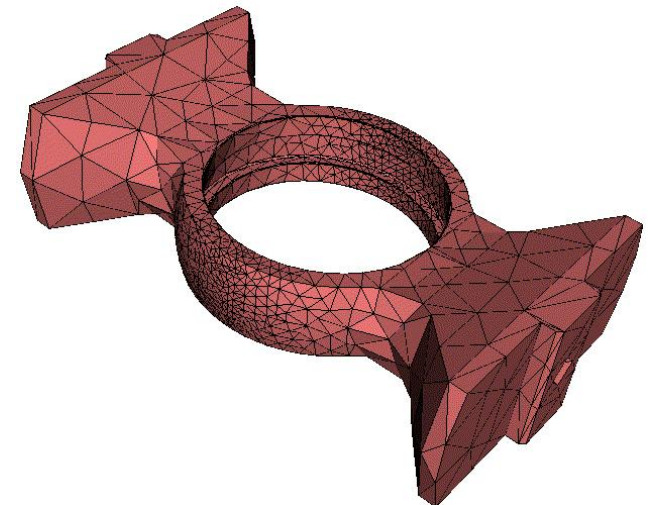
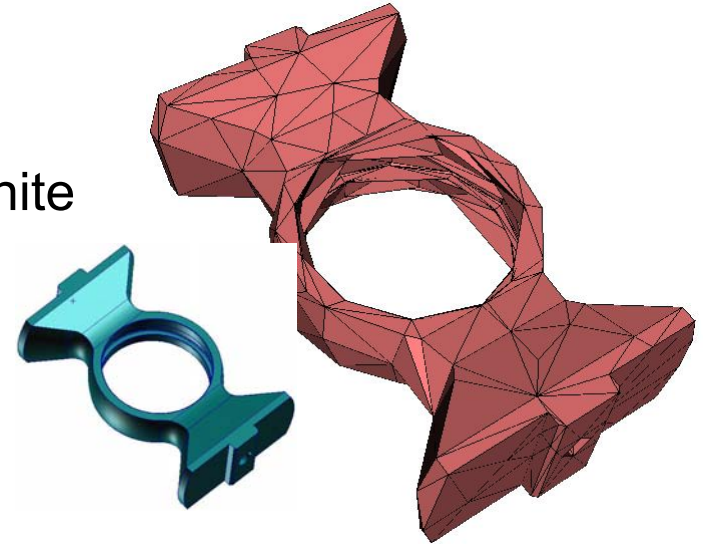


**Mesh** 4



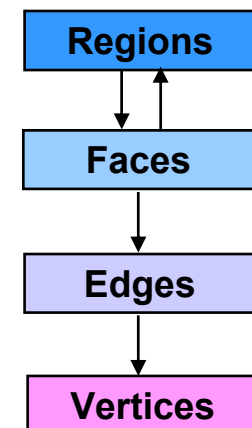
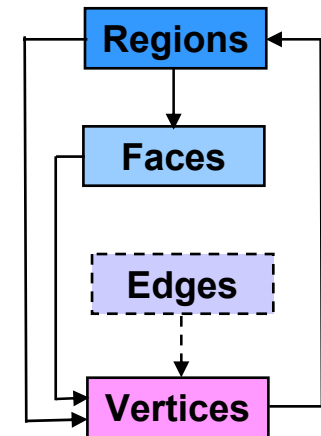
# Unstructured mesh methods offer key advantages for numerical simulation

- Some Basic Characteristics
  - Meshes of mixed topologies and order easy
  - Commonly used spatial decomposition for finite element discretizations
  - Data structures larger and more complex
  - Solution algorithms can be more complex
- Some Advantages
  - Mesh adaptation can account for curved domains
  - General mesh anisotropy can be obtained
  - Easy to create strong mesh gradations without special numerical techniques
  - Alignment with multiple curved geometric features



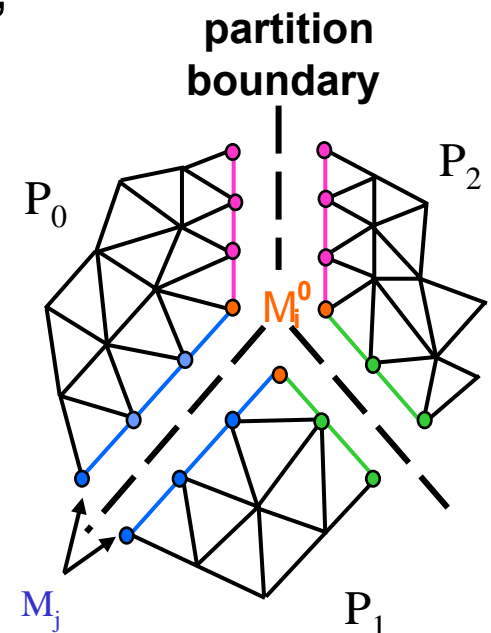
# Adjacency information is critical in managing unstructured meshes

- Each particular mesh application has its own needs of mesh representation in terms of levels of entities and adjacencies used
- Approaches mesh data structure design
  - Fixed, specific mesh representation
  - Fixed, general mesh representation
  - Flexible mesh representation
- Different unstructured mesh databases will provide different entities and adjacencies



# Unstructured Meshes on Parallel Computers

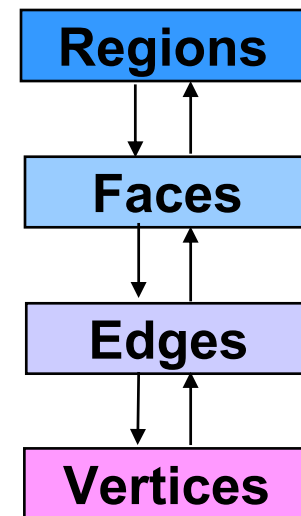
- Typically the mesh is distributed over independent memories
- A mesh partition groups mesh entities and places them into parts
- Applications using a partitioned mesh need
  - Communication links for between “shared” mesh entities on neighboring parts
  - Ability to move mesh entities between parts (while maintaining links)
  - Algorithms to maintain load balance of parts which minimizing communications



# Unstructured Meshes on Parallel Computers

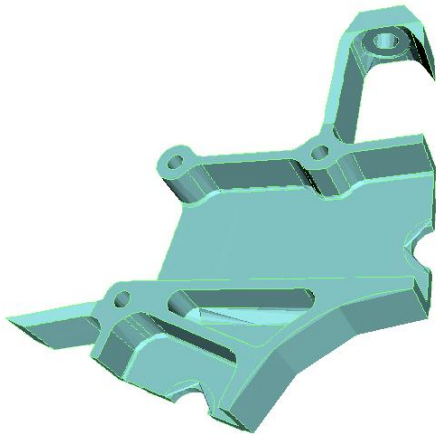
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- Communication links for distributed meshes need to provide information associated with mesh entities and adjacencies
- Extending concepts of mesh entity topology and entity adjacency to parallel can address these communication needs
- Will describe the basics through the conceptual construct of a partition model

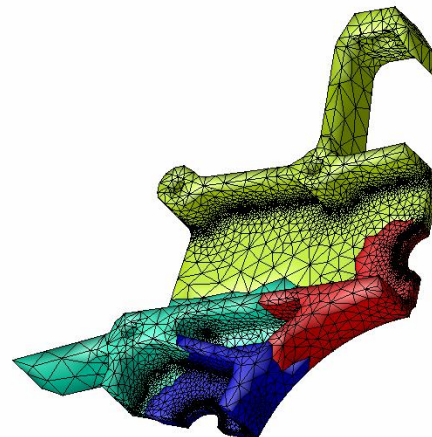




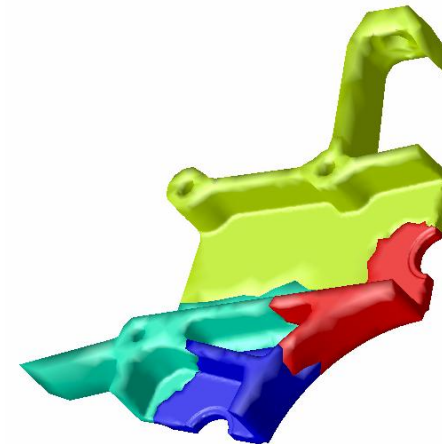
# Conceptual view of an unstructured mesh partition model



Domain of  
Interest



Mesh distributed  
over four parts



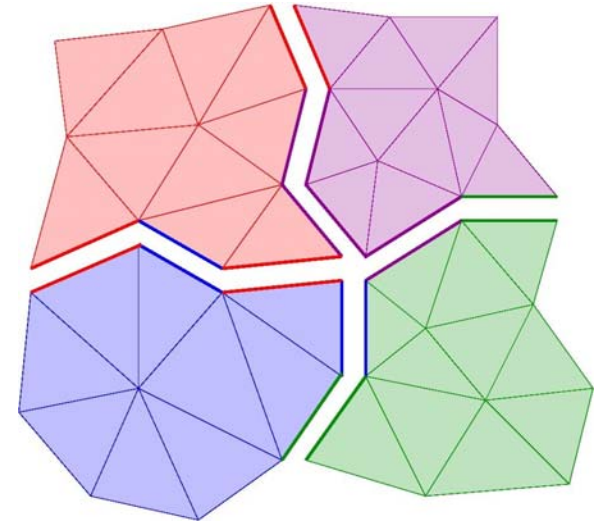
Partition model focuses on  
mesh entities between parts

- Mesh adjacency information can provide
  - Entities on part boundaries to define inter-part communications shared entities
  - Adjacencies to entities bounded by those entities (for ghosting, etc.)

# Distributed mesh representations have several functional requirements

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- Entity ownership
  - Each mesh entity is owned by exactly one part
  - Ownership imbues right to modify
  - Ownership is not static during the course of a simulation
    - Repartitioning
    - Local micro-migration
  - Some entities have read-only **copies** on other parts (e.g. along part boundaries and ghosts)
- Communication links
  - Efficient mechanisms to update mesh partitioning and keep the links between parts are mandatory



# Basic parallel solution on unstructured meshes has several key steps

**Construct** the initial mesh (serial or parallel)

Improve the mesh using **smoothing** and **swapping**

If necessary, **(re)partition** the mesh across processors

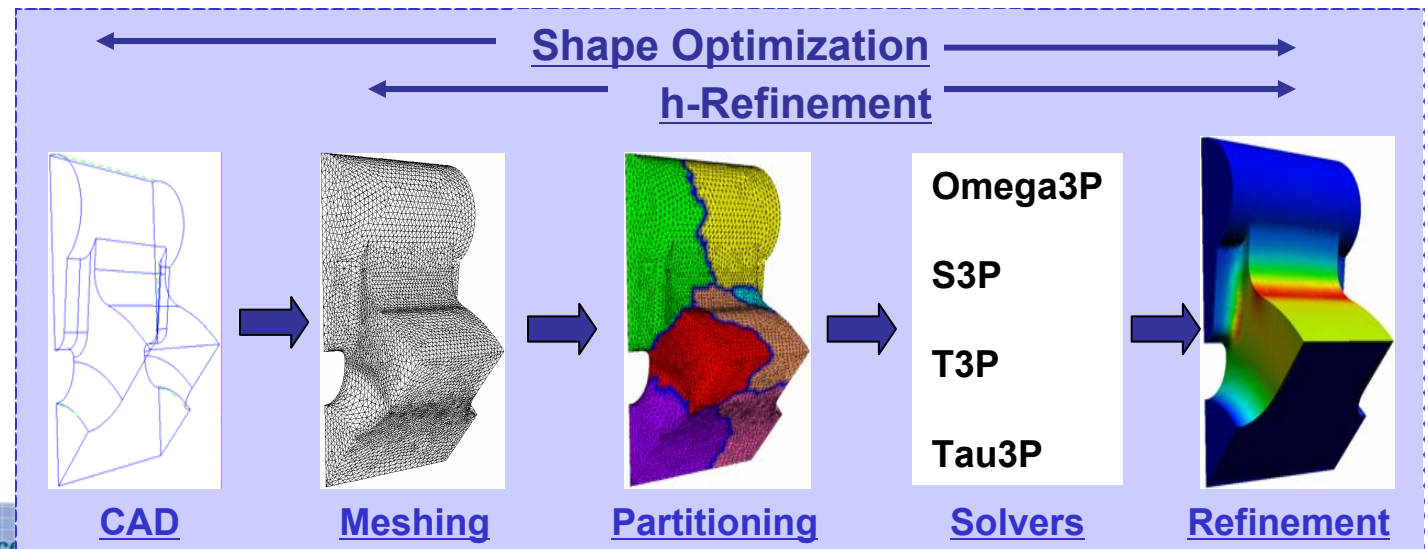
Solve the PDE on mesh and estimate the error

While error > tolerance

**Refine, coarsen, improve and repartition** the mesh

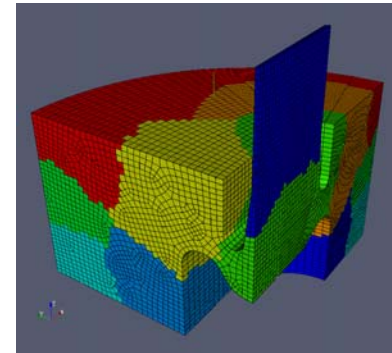
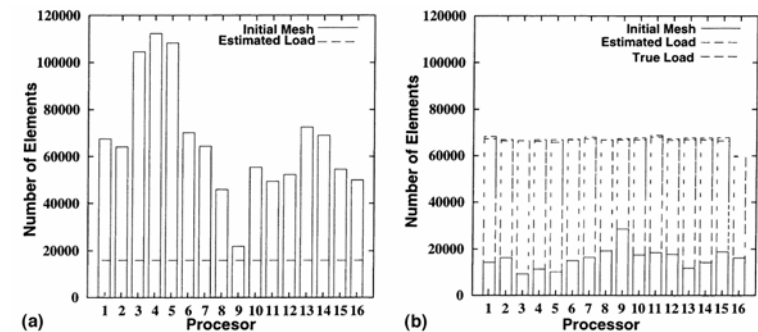
Solve the PDE on the mesh and estimate the error

End



# Key issues that must be addressed for parallel computation

- Scalability
  - Load balance as the mesh changes
  - Low communication overhead costs
  - Efficient use of distributed memory
- Function
  - Consistent, correct mesh operations
  - Management of complex communication schedules
- Performance
  - Near optimal serial efficiency on each processor
  - Minimal overhead when using general tools relative to native implementations

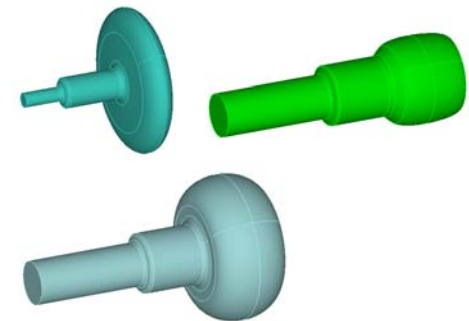
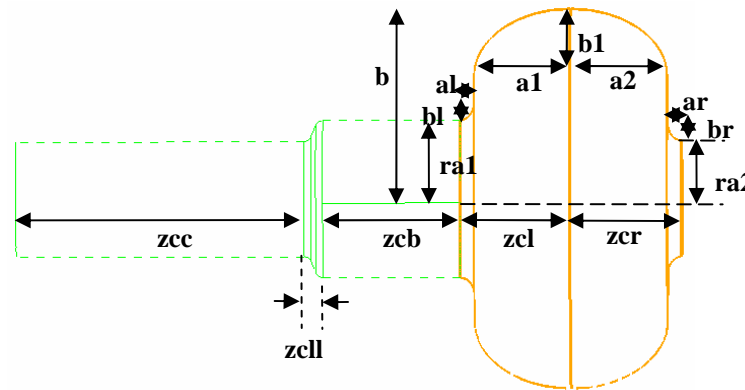
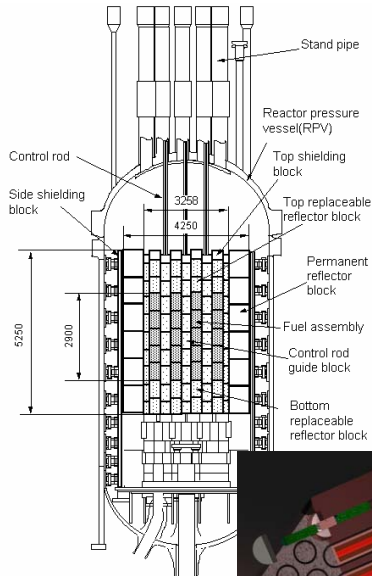




# Parallel solution is further complicated by the needs of advanced simulations

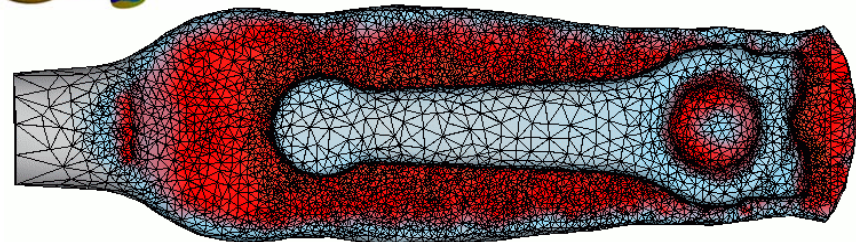
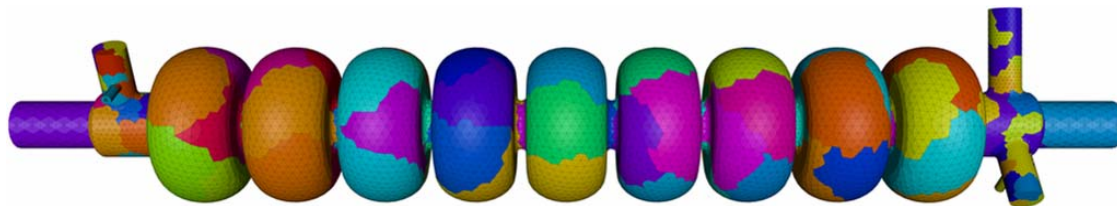
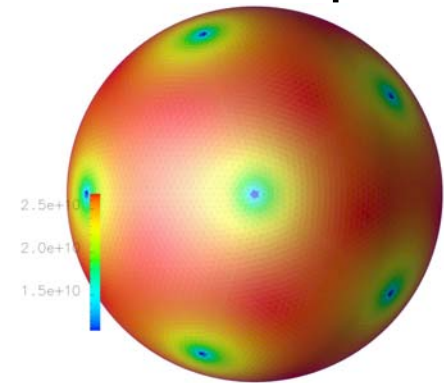
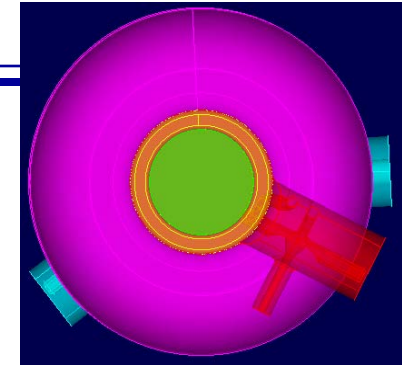
## Examples:

- Design optimization requires geometry modification, remeshing, derivative computations
- Multi-physics applications require mesh to mesh transfer, interpolation methods, sophisticated adaptive methods



# The ITAPS team has developed tools to address these needs

- CAD interaction: CGM
- Mesh generation: GRUMMP, NWGrid
- Mesh databases: FMDB, MOAB
- Mesh improvement: Mesquite, swapping tools
- Parallel Adaptive loops: FMDB, NWGrid, MeshAdapt
- Front tracking: Frontier
- Partitioning: Zoltan



## While these tools exist, significant challenges remain

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Developing and using these technologies requires significant software expertise from application scientists

- Difficult to improve existing codes
- Difficult to design and implement new codes

These tools all meet particular needs, but

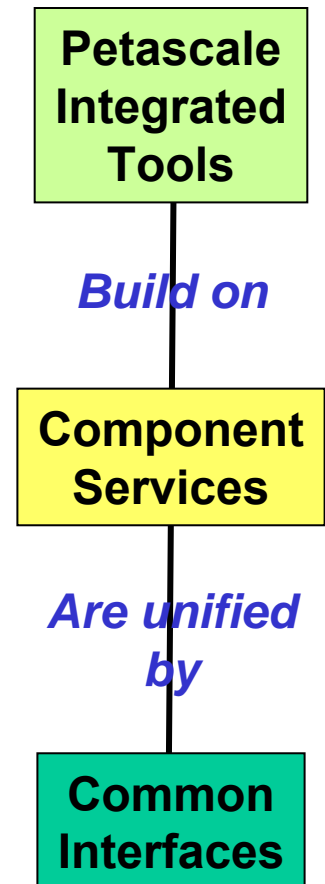
- They do not interoperate to form high level services
- They cannot be easily interchanged in an application

***The ITAPS center is developing key technologies to ease the use of advanced meshing tools on large scale parallel computers***

# ITAPS uses a component-based approach to address these challenges

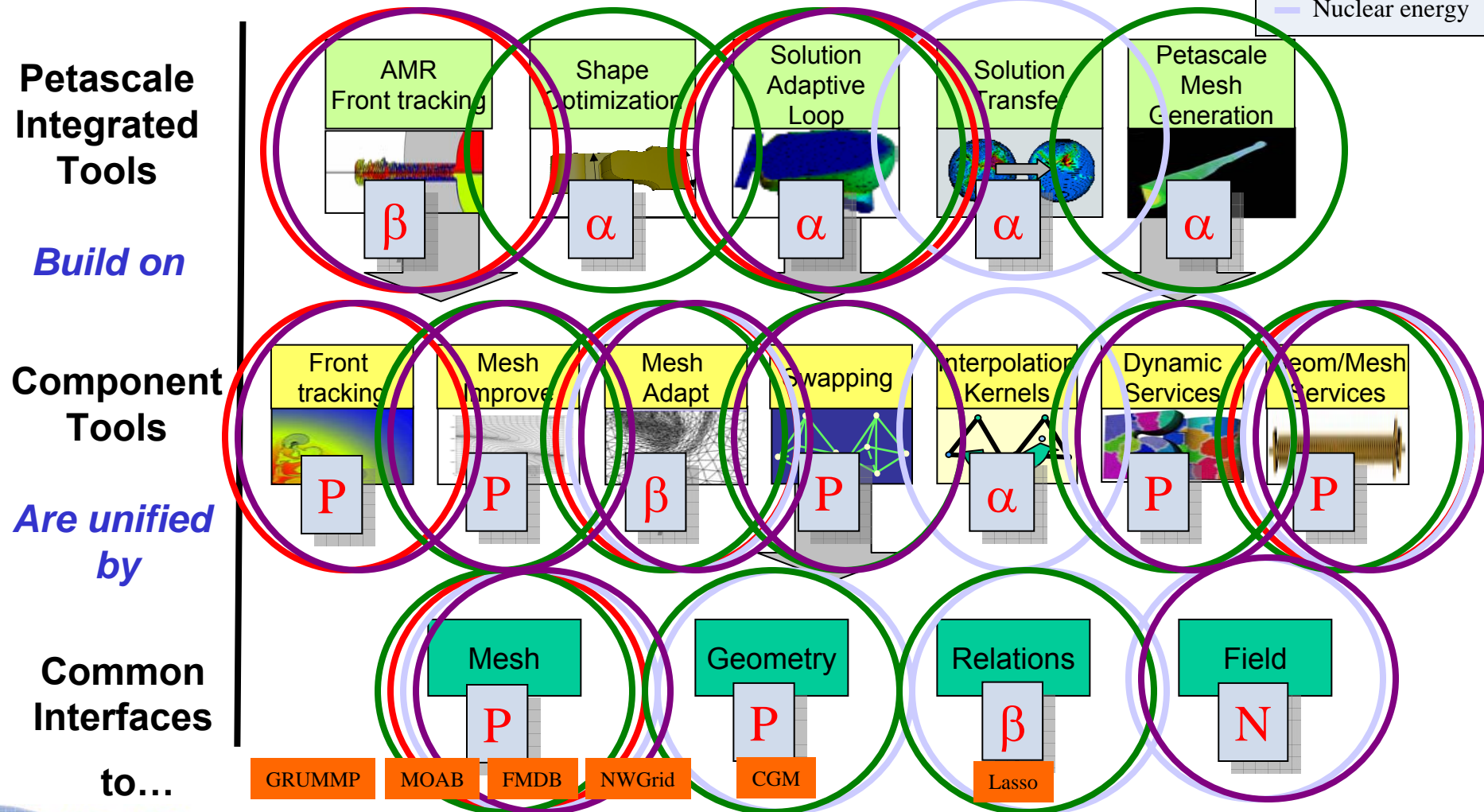
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- Develop and deploy key mesh, geometry and field manipulation *component services* needed for petascale computing applications
- Develop advanced functionality *integrated services* to support SciDAC application needs
  - Combine component services together
  - Unify tools with *common interfaces* and *data model* to enable interoperability
  - Interfaces are implemented on top of existing mesh databases
- Work with key application teams to insert ITAPS technologies into simulations

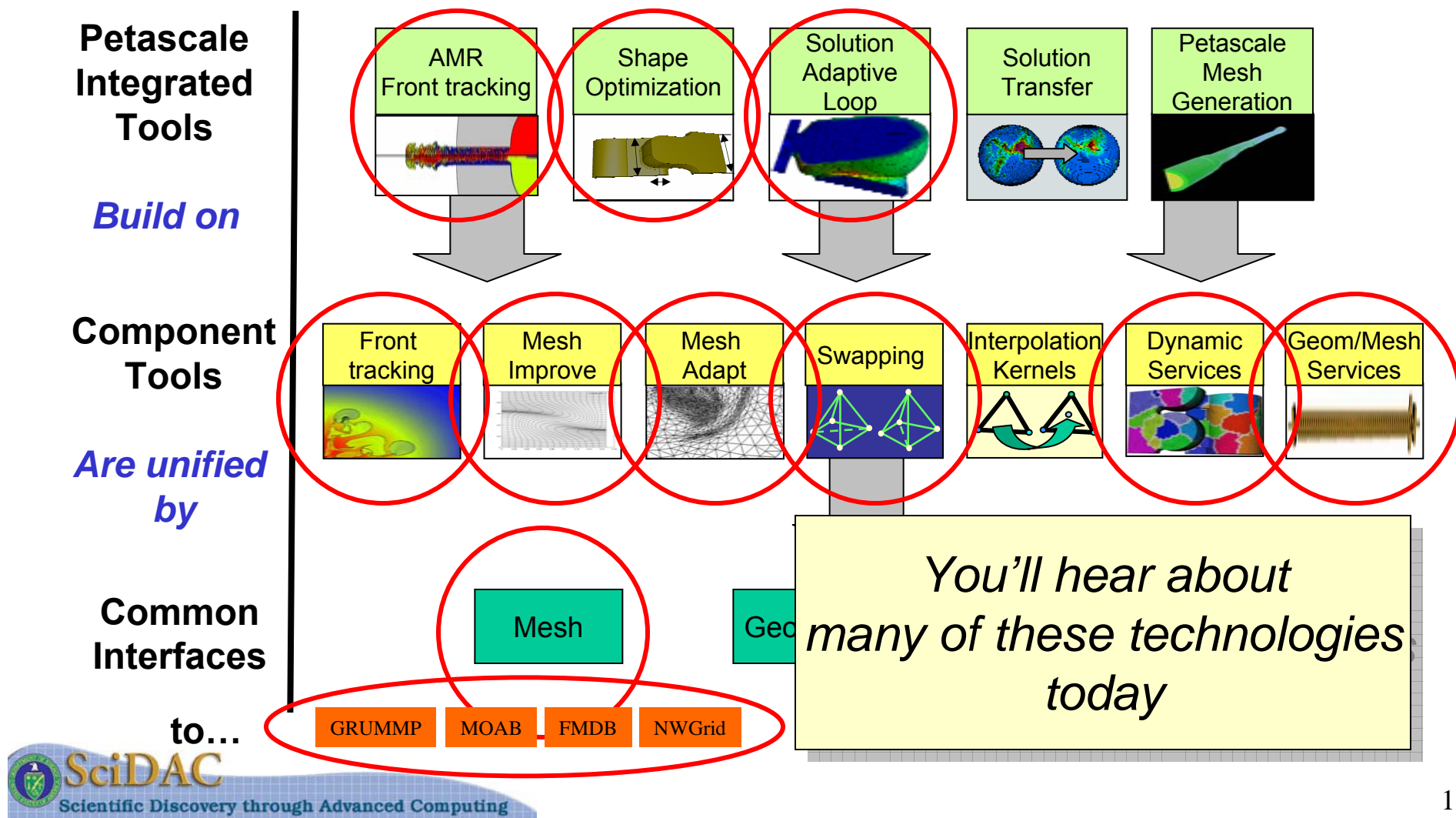




# ITAPS produces mesh services that meet application needs

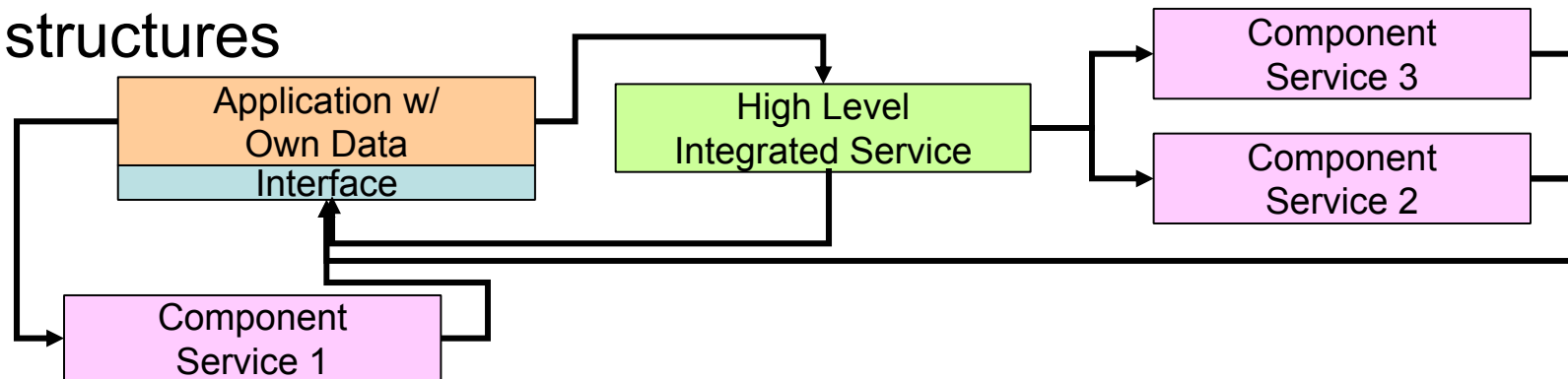


# ITAPS is developing meshing services available as stand-alone components

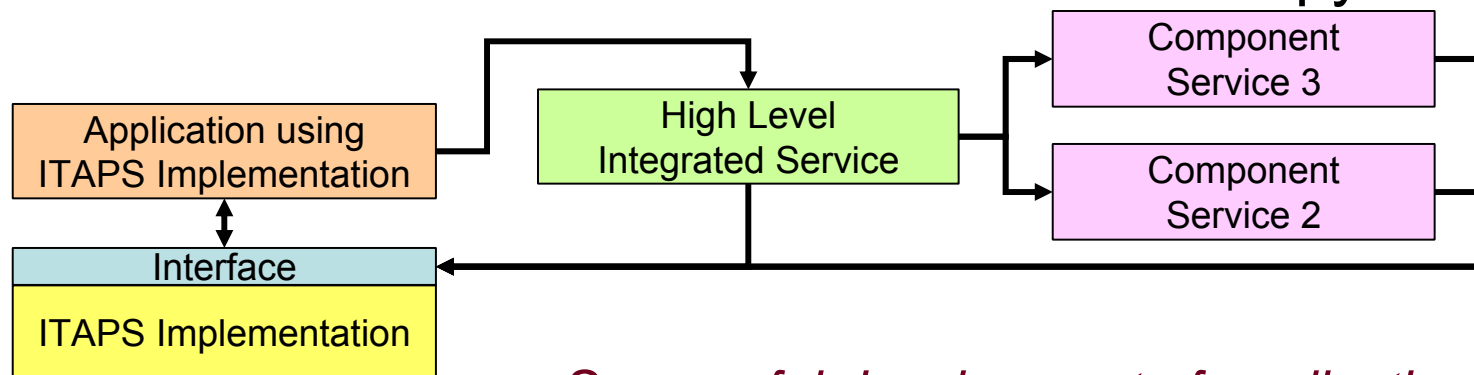


# Applications can access ITAPS services in two ways

1. Implement ITAPS interfaces on top of application data structures



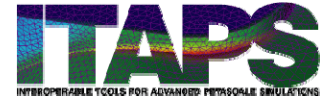
2. Use a reference implementation of the interfaces to provide access to ITAPS services at the cost of a data copy



*Successful development of applications has been accelerated by close collaboration.*

# There are several advantages of the component-based approach ITAPS uses

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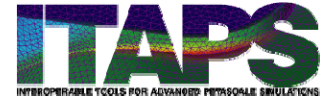
- Focus on interfaces not on data structures or file formats
- Use independent interfaces for distinct data model abstractions to make adoption easier
- Incremental adoption for applications; only service dependent interfaces need to be implemented
- Finer granularity of interoperable functionality reduces the need to mix huge libraries together



## PART 2: An Overview of ITAPS Services

# Interoperable services speed the development of simulation technologies

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- ITAPS provides stand-alone services as libraries
- Improve applications' ability to leverage advanced tools
  - Mesh quality improvement
  - Mesh adaptation loops
  - Front tracking
  - Mesh partitioning
  - Visualization

*We'll provide a brief overview of each of these tools; more information can be found on [www.itaps-scidac.org](http://www.itaps-scidac.org)*

# Mesh Quality Improvement

Lori Diachin (LLNL)  
Patrick Knupp (SNL)  
Carl Olivier-Gooch (UBC)

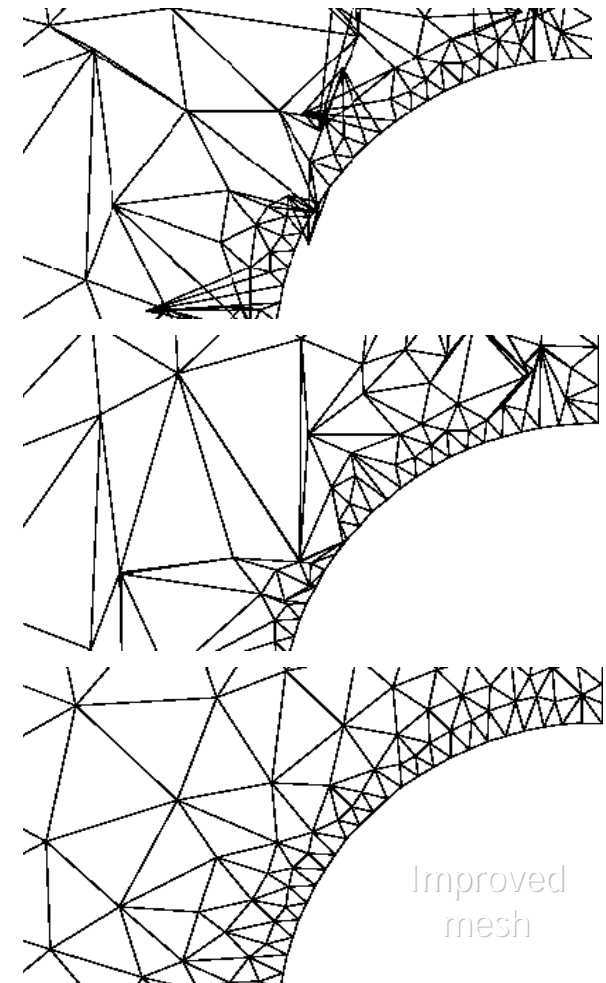


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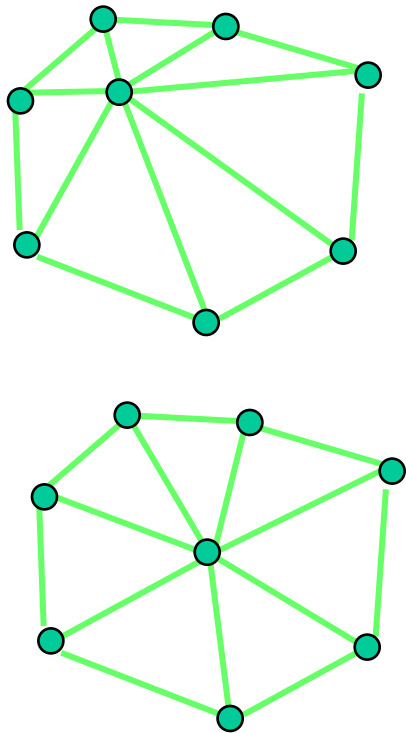
# Unstructured mesh quality is a critical factor in solution efficiency and accuracy

- In general, mesh size and quality affects
  - **Solution efficiency** (e.g. Axelsson, 1976; Fried 1972; Axelsson and Barker, 1984)
    - Iterations grow as a function of  $N$
    - Iterations grow as a function of minimum angle
  - **Solution accuracy**
    - Solution from iterative solver is less accurate
    - For isotropic fields, discretization error adversely affected by distorted elements (e.g. Babuska and Aziz, 1976)
- Understanding application solution characteristics is critical
  - stretched elements are more accurate than equilateral elements for boundary layer flow



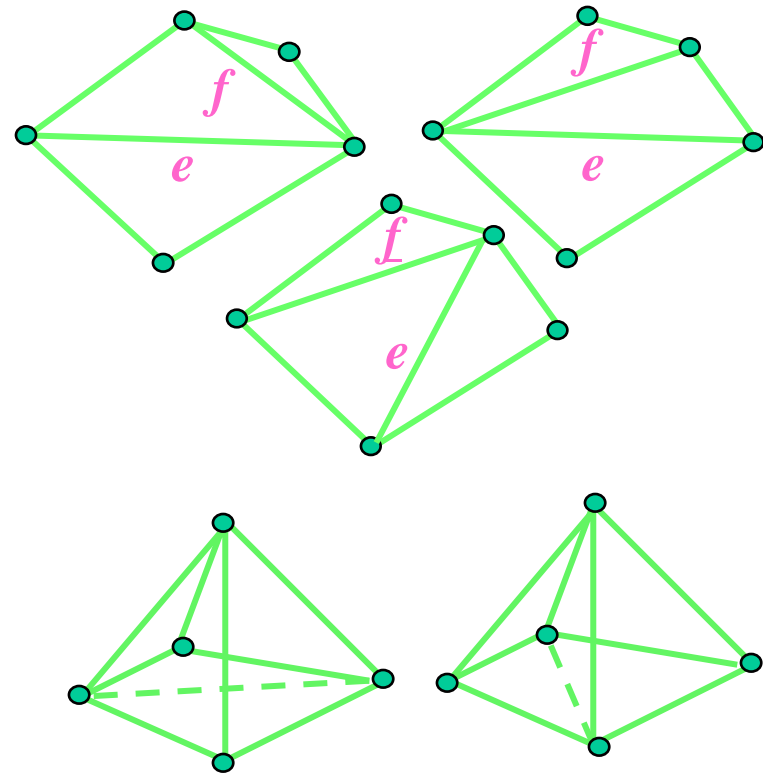
# Mesh quality can be improved using a variety of methods

## Node Movement



Moving grid points without changing mesh topology

## Edge or Face Flipping

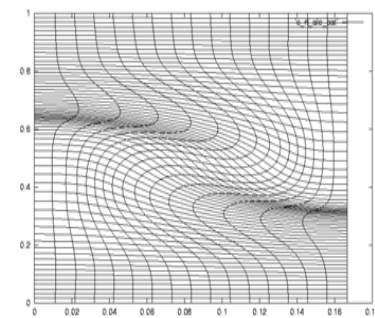
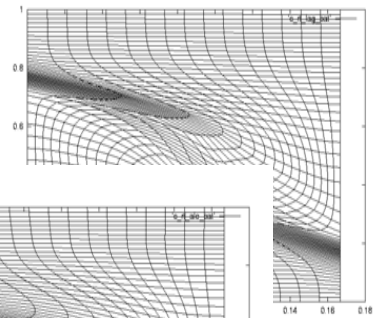
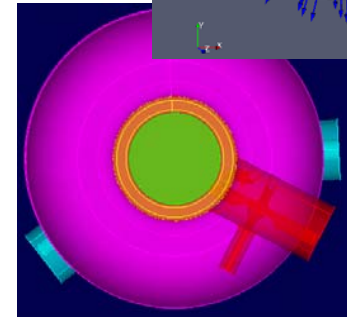
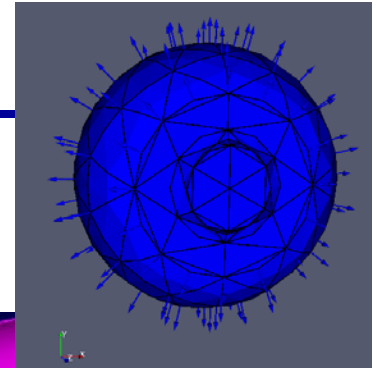


Modify topology without changing grid point location



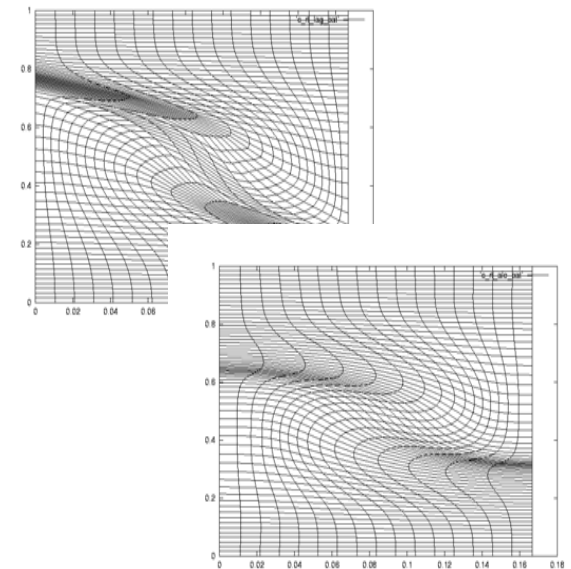
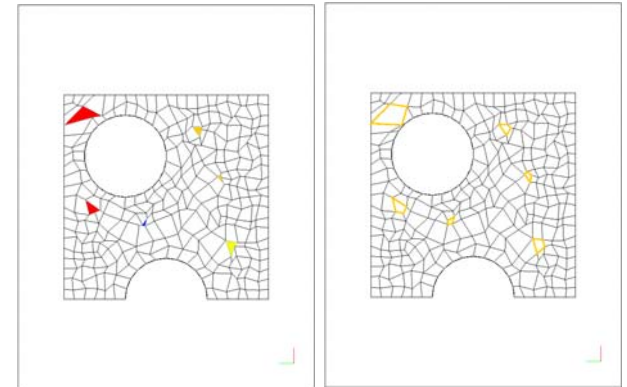
# Mesquite provides advanced mesh smoothing capabilities

- Mesquite is a comprehensive, stand-alone library for mesh quality improvement with the following capabilities
  - Shape Quality Improvement
  - Mesh Untangling
  - Alignment with Scalar or Vector Fields
  - R-type adaptivity to solution features or error estimates
    - Maintain quality of deforming meshes
    - Anisotropic smoothing
    - Control skew on mesh boundaries
- Uses node point repositioning schemes



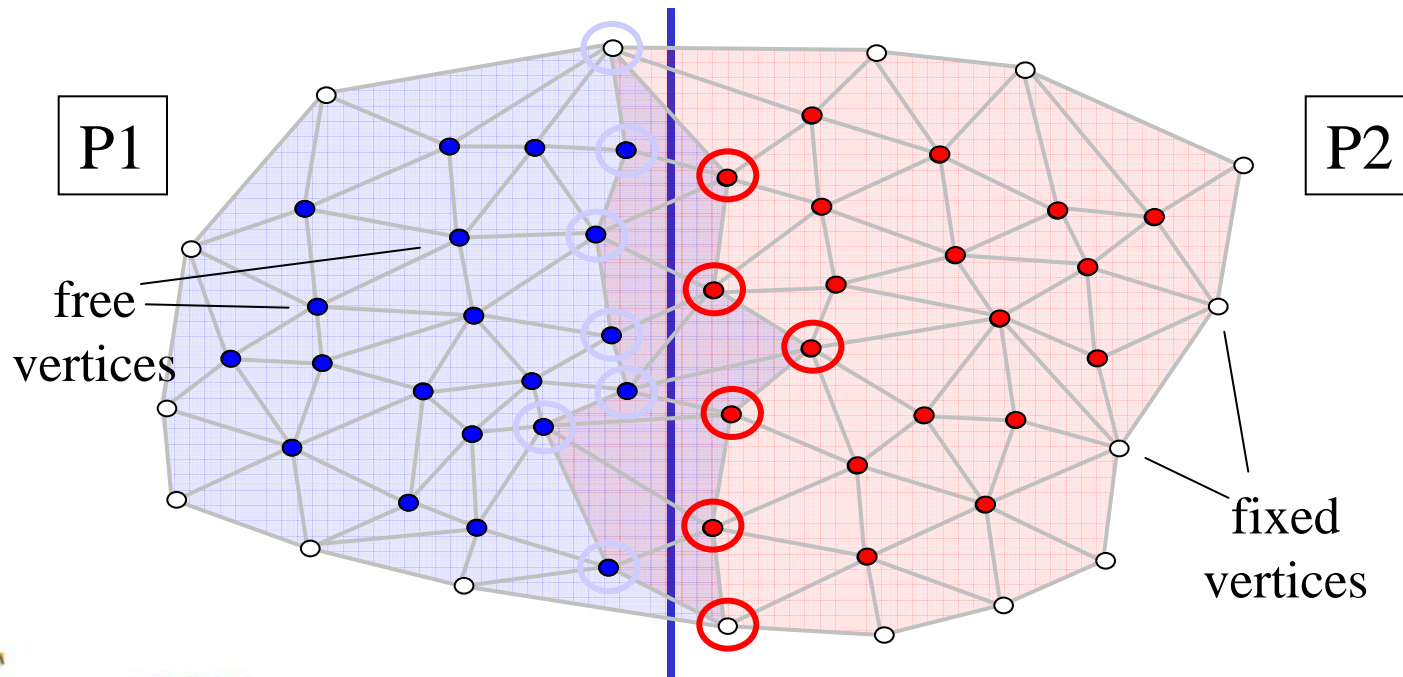
# Mesquite is versatile and comprehensive

- 2/3D Structured, Unstructured, Hybrid Meshes
- Many different element types
- State-of-the-art algorithms and metrics
- Efficient to run
- Customizable
  - User-defined metrics, objective functions, and algorithms



# Parallel smoothing requires special attention at partition boundaries

Incorrect execution of the smoothing algorithm can occur unless partition boundaries maintain consistent updates of vertex locations; requires synchronization with partition neighbors



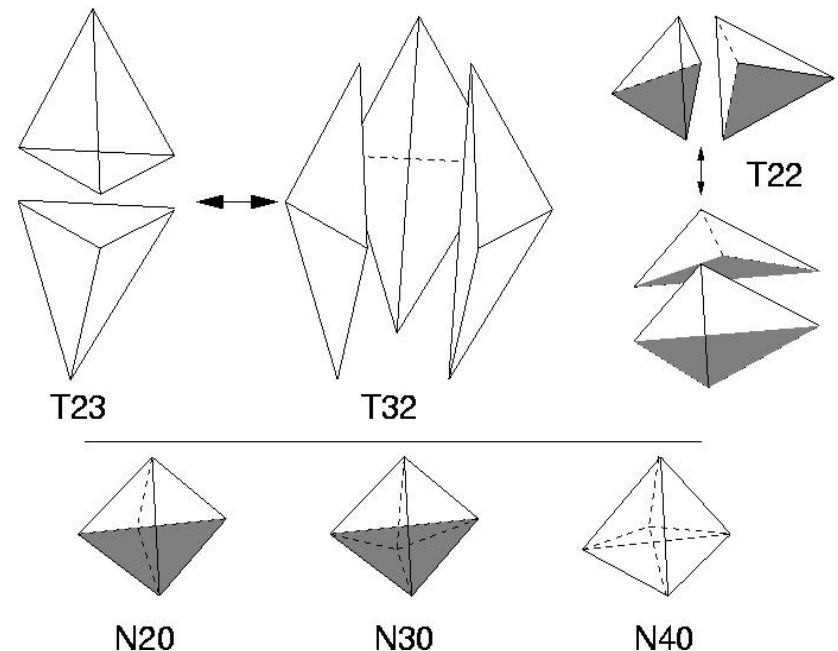
# Swapping complements node point movement in improving mesh quality

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- Changing topology can eliminate poorly-shaped mesh entities directly
- Particularly effective in combination with node point movement (Freitag and Ollivier-Gooch, IJNME, 1997)
- Swapping decisions and (especially) topology change challenging to implement correctly
- Service using standard interface can handle all the difficult, error-prone aspects

# Mesh swapping capabilities are available using ITAPS

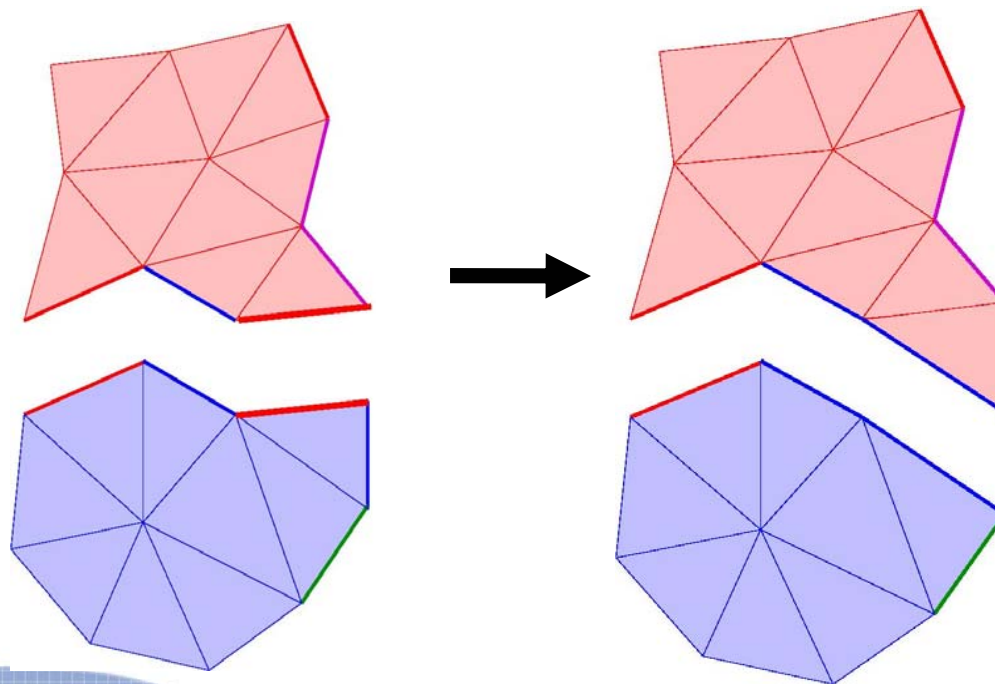
- Triangular/tetrahedral swapping with variety of criteria
- Single edge/face, mesh subset, or entire mesh
- Boundary modification optional in 3D
- Built in and user-defined swapping criteria provide both ease of use and flexibility



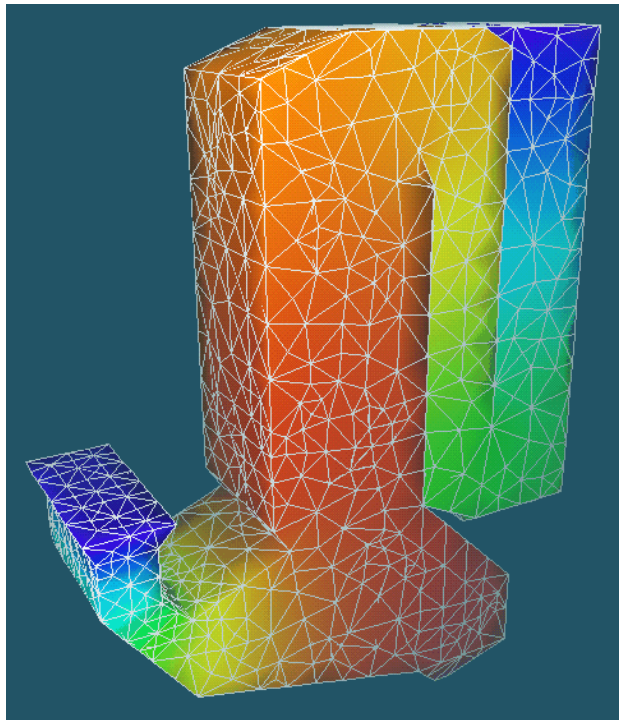


# Issues with swapping in parallel

- Must migrate data onto single processor to modify
- Load balance and communication overhead issues



# Smoothing and swapping improvement operations work well in concert

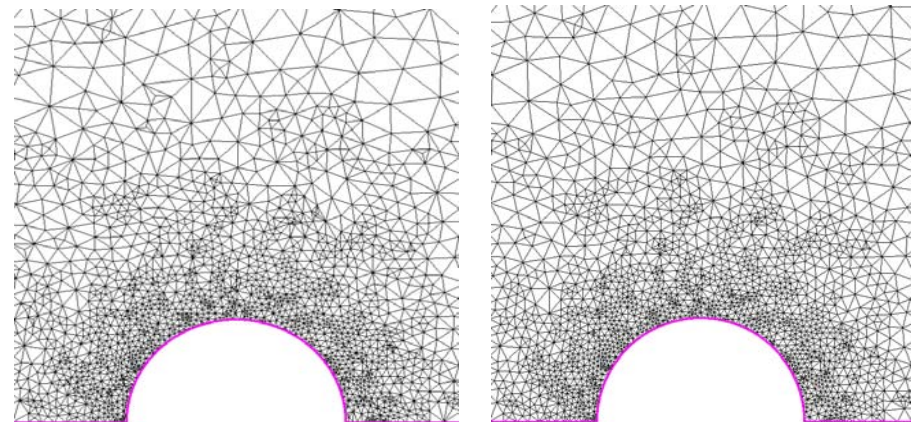


**Compressible Flow Over a Cylinder** Combining smoothing and swapping improved the convergence rate by 25% compared to smoothing alone

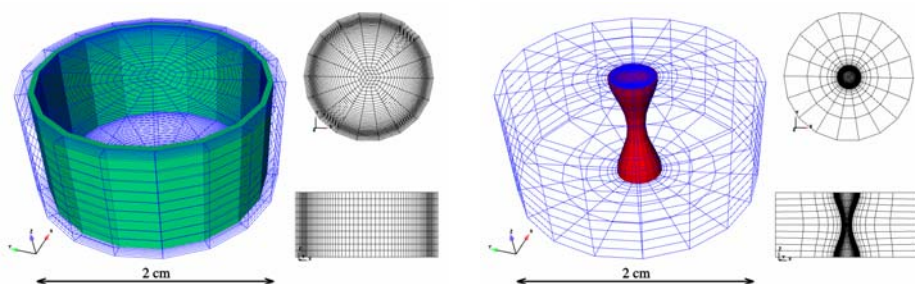
*Overall mesh improvement cost less than one multigrid iteration*

|                 |           |             |
|-----------------|-----------|-------------|
| Original mesh:  | Min: .56  | Max: 178.86 |
| Smoothing only: | Min: 12.3 | Max: 145.6  |
| Both:           | Min: 23.2 | Max: 131.9  |

|                |           |            |
|----------------|-----------|------------|
| Swapping only: | Min: .66  | Max: 178.9 |
| Both:          | Min: 4.34 | Max: 174.3 |



# Our mesh quality improvement work has impacted many DOE applications



*Application:* Plasma implosion using ALE methods

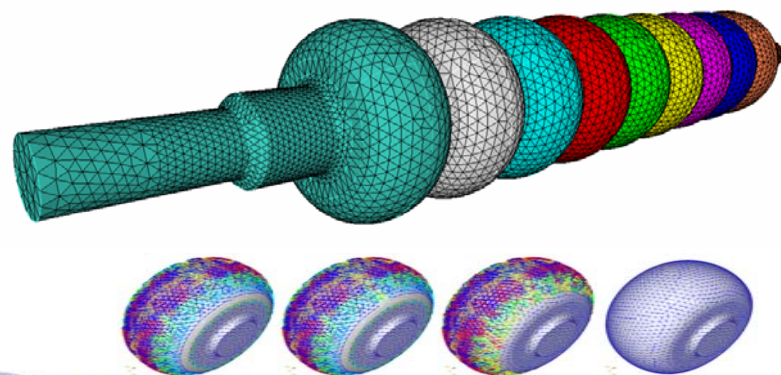
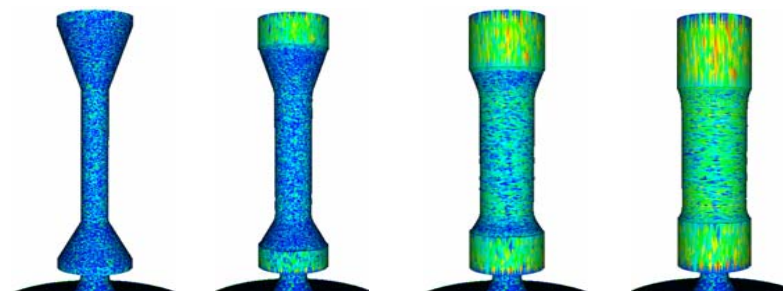
*Challenge:* Maintain good mesh quality and biasing during deformation of plasma.

*Impact:* Prior to use of Mesquite, this calculation could not be performed by Alegra due to ineffective mesh rezoning algorithm.

*Application:* Burn of rocket propellants in a time-deforming domain

*Challenge:* Maintain good tetrahedral element shape quality as domain deforms

*Impact:* Condition number smoother (through ShapeImprovementWrapper) enabled many burn simulations at CSAR/UIUC.



*Application:* Shape optimization for accelerator cavities to minimize losses

*Challenge:* Rapidly and smoothly update the mesh to conform to trial geometries

*Impact:* Used the deforming mesh metric to prototype geometry & mesh update model for potential use in SLAC accelerator design studies.



# ITAPS Adaptive Mesh Service

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Sandia  
National  
Laboratories



Rensselaer



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BROOK  
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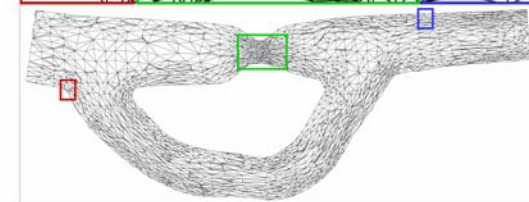
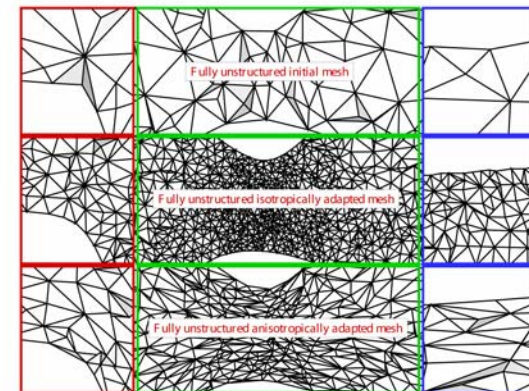
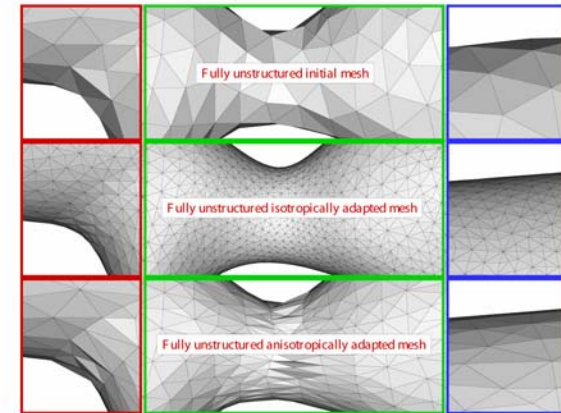
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# Motivation

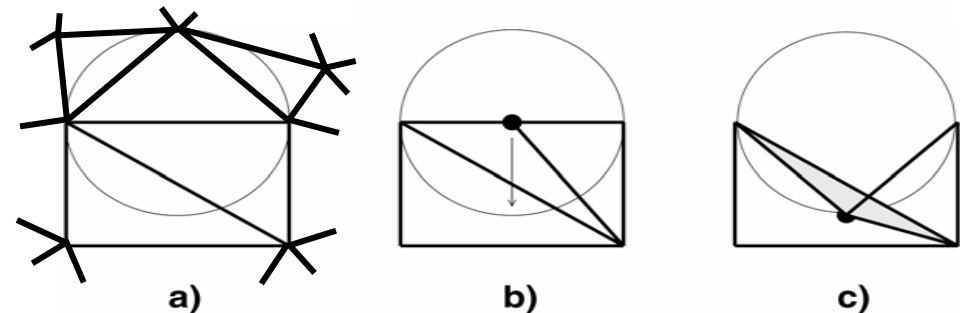
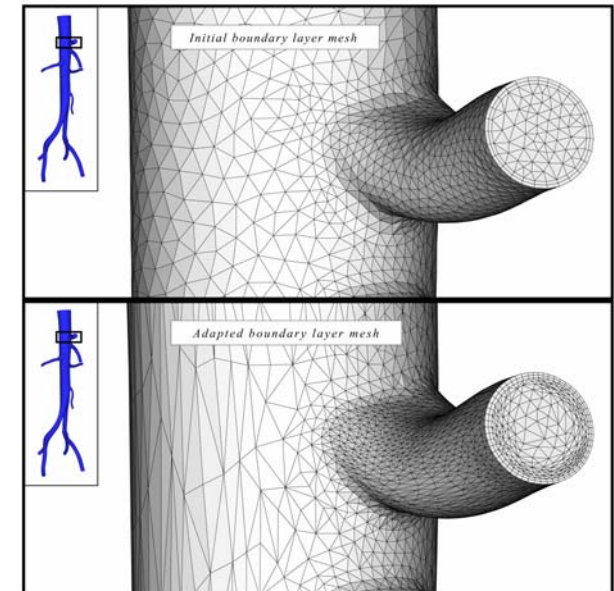
- Complex geometry and/or complex physics generate solutions with large variation in length scales
- Assigning near optimal mesh sizes for initial mesh generation in such cases is not possible
- ITAPS Mesh Adapt Service starts with an arbitrary initial mesh with a solution and alters the mesh via local mesh modifications (may be isotropic or anisotropic)
- CFD example:
  - Isotropic adaptivity yields same accuracy as uniform with one order of magnitude fewer elements
  - Anisotropic adaptivity yields same accuracy as uniform with two orders of magnitude less than uniform





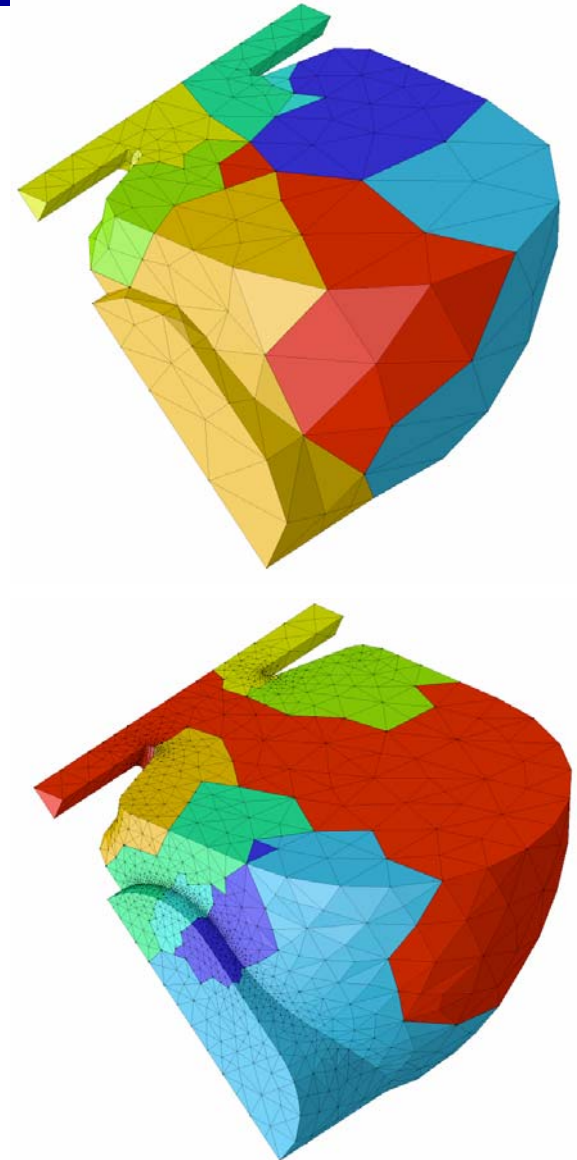
# ITAPS Mesh Adapt Service

- Components of an adaptive analysis loop
  - PDE solver
  - Error estimation procedure
  - Mesh adaptation - **ITAPS Mesh Adapt Service**
  - Field solution transfer - **ITAPS Mesh Adapt Service** can support
- ITAPS Mesh Adapt Service
  - Input is a mesh and new mesh size field definition: isotropic or anisotropic
  - Mesh adaptation uses local mesh modification to support:
    - Curved Boundaries
    - Anisotropy
    - Parallel mesh adaptation



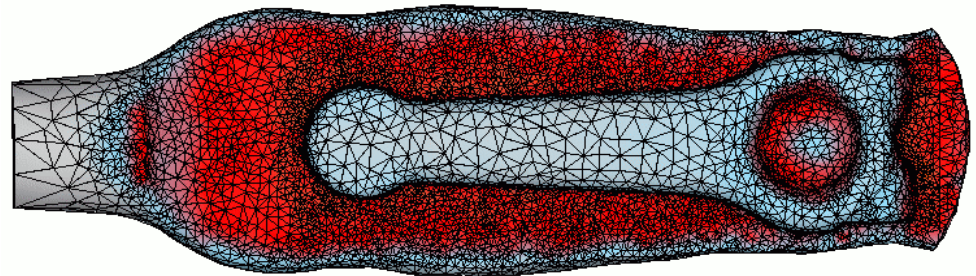
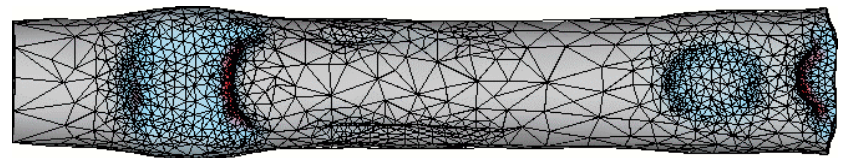
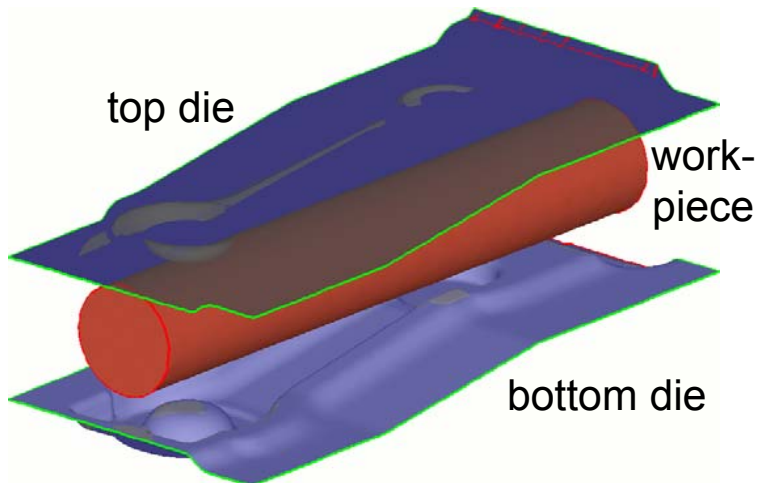
# Parallel Mesh Adaptation

- Operates with a partitioned mesh
- Control parallel communication and operations
- Part boundaries do not introduce artificial constraints on execution of mesh modification operations
- By including dynamic load balancing (**Zoltan**), can be easily integrated with parallel solvers that also operate with partitioned meshes

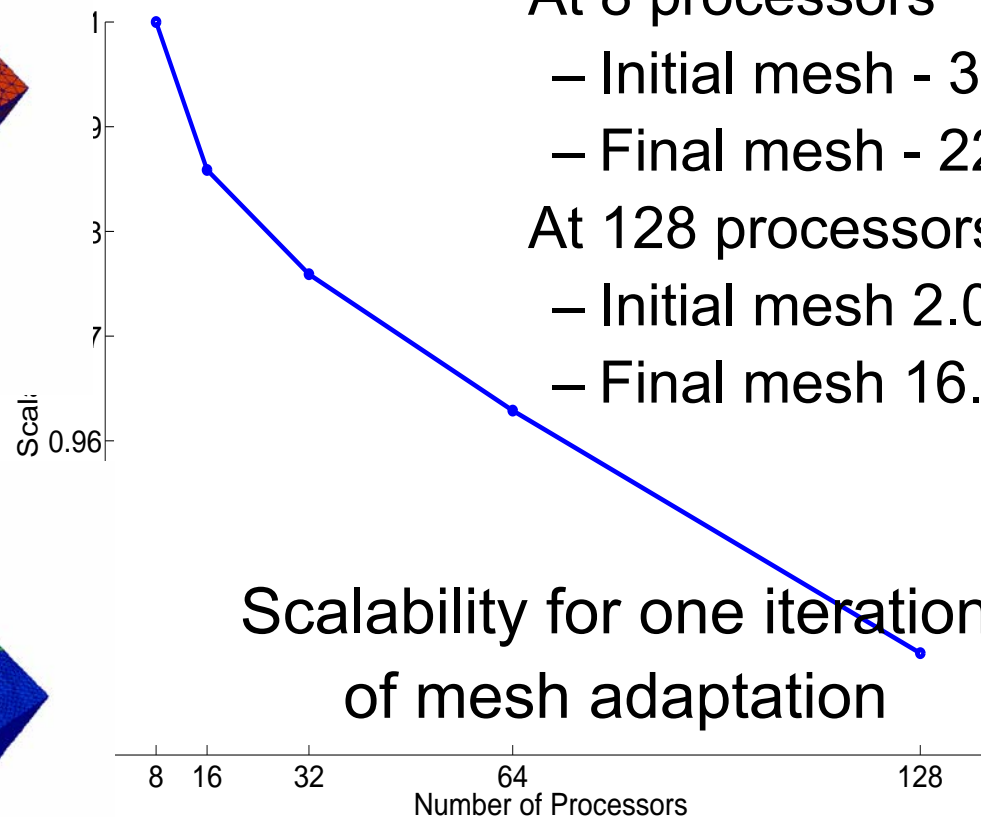
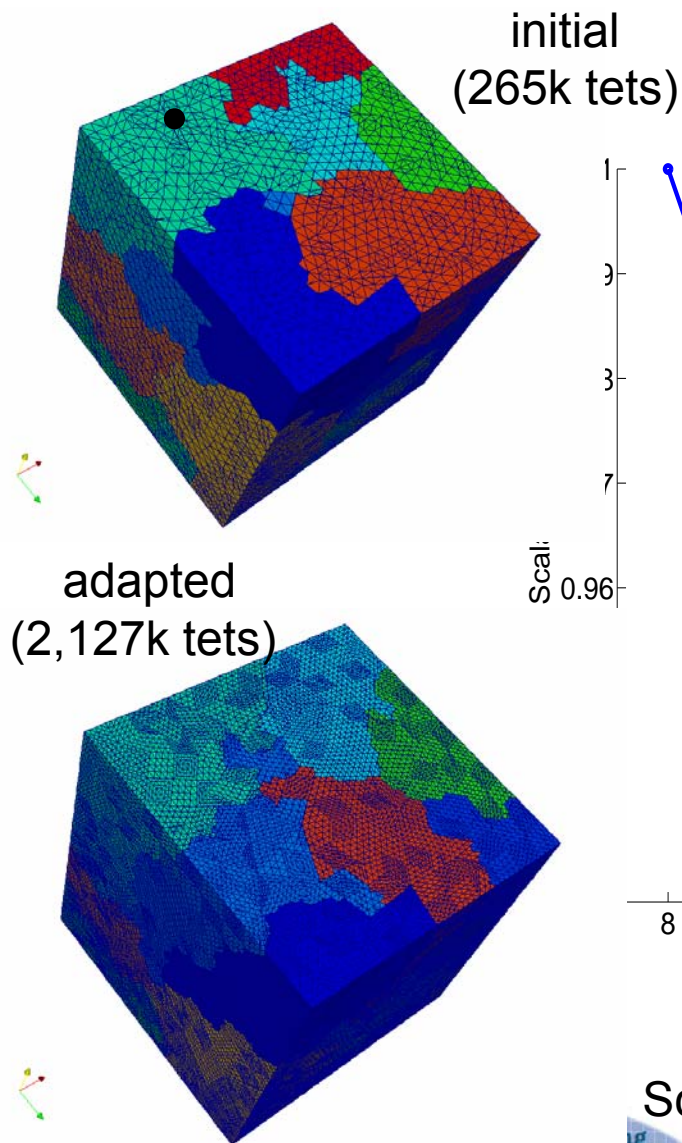


## Example Application: Forming Simulation

- Large plastic deformation - Meshes become invalid
- Components of automated adaptive simulation
  - Model topology update based on contact evolution
  - Mesh adapted using automation tools to account for
    - Discretization errors
    - Geometric approximation
    - Element shape control



# Parallel Refinement



Tests run on IBM Blue Gene/L

At 8 processors

- Initial mesh - 33K/processor
- Final mesh - 226K/processor

At 128 processors

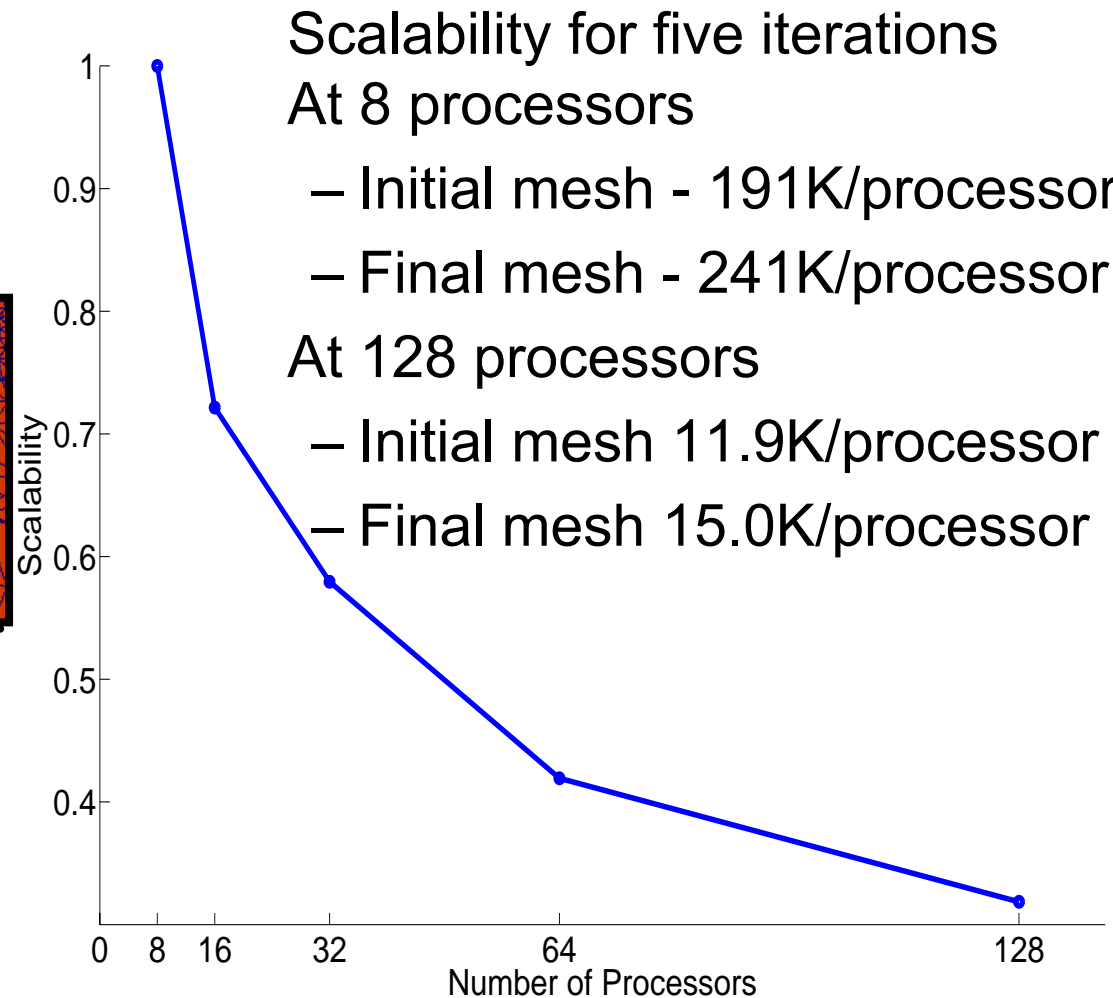
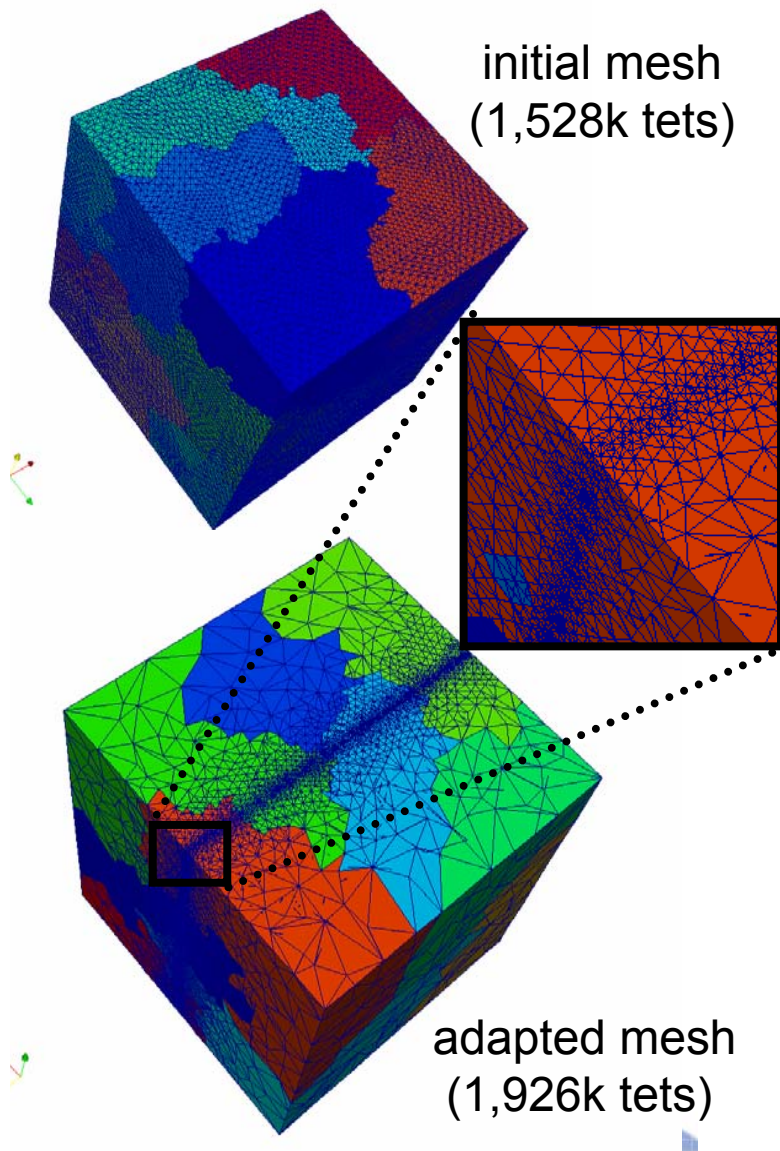
- Initial mesh 2.0K/processor
- Final mesh 16.7K/processor

Scalability for one iteration  
of mesh adaptation

$$\text{Scalability} = \frac{\text{run-time}_{\text{base}} \cdot n \text{ processors}_{\text{base}}}{\text{run-time} \cdot n \text{ processors}}$$



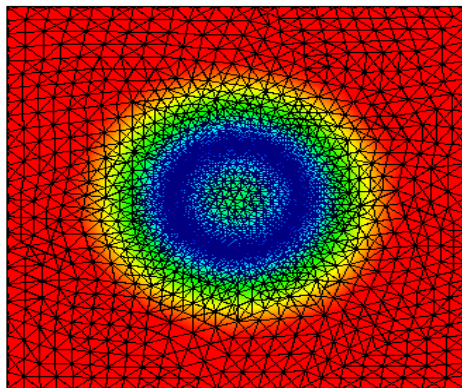
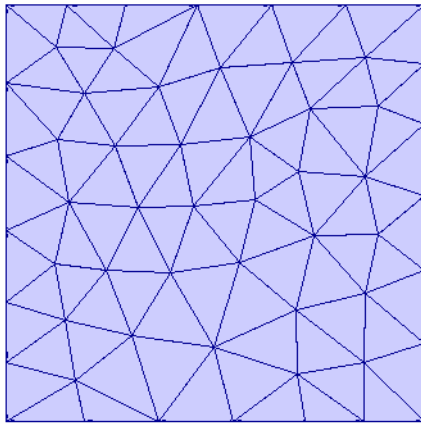
# Parallel Refinement and Coarsening



$$\text{Scalability} = \frac{\text{run-time}_{\text{base}} \cdot n \text{ processors}_{\text{base}}}{\text{run-time} \cdot n \text{ processors}}$$

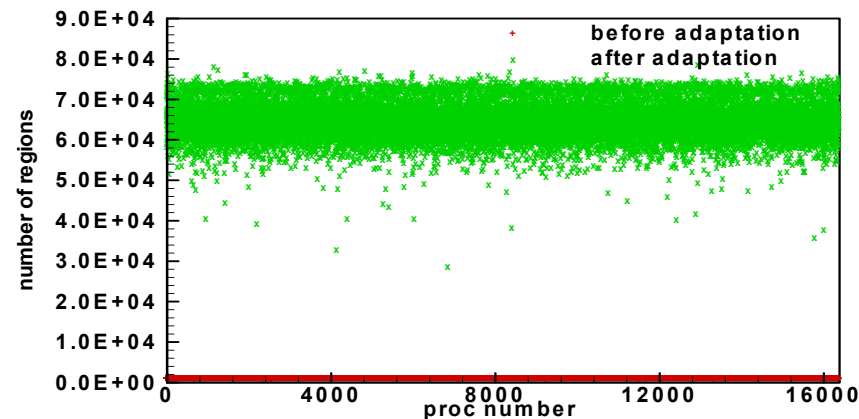


# Mesh Adaptation for 1 Billion Element Mesh



Initial and adapted mesh at one bubble - colored by magnitude of mesh size field

Mesh size field of air bubbles distributing in a tube (segment of the model)



Number of regions of adapted mesh among 16k parts

- Initial mesh: uniform, 17,179,836 mesh regions
- Adapted mesh: 160 air bubbles 1,064,284,042 mesh regions
- Multiple predictive load balance are used to make the adaptation possible
- Larger meshes possible (not out of memory) but this element count is appropriate for solver

# FronTier Lite

Brian Fix, Ryan Kaufman, Xiaolin Li, and James Glimm

Stony Brook University

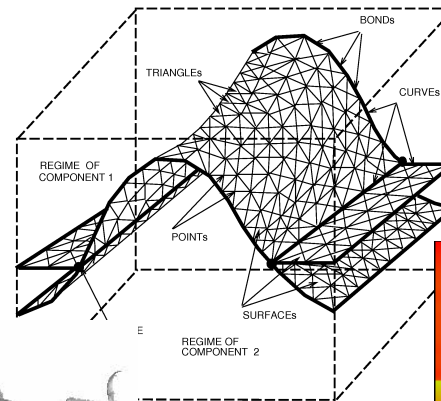
Zhiliang Xu and Roman Samulyak

Brookhaven National Laboratory

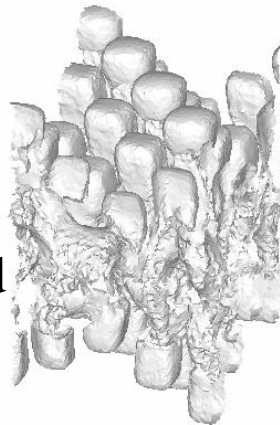


# FronTier

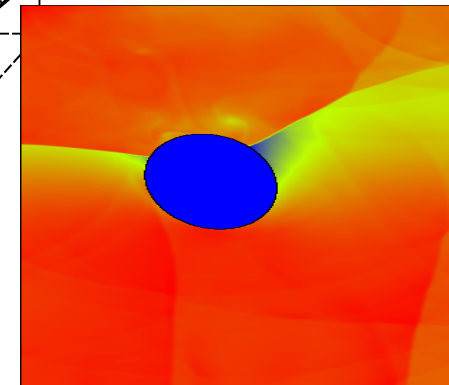
- Computational domains sharply different quantitatively or qualitatively, boundary dynamic
- Track the dynamic motion of distinct bodies, or interfaces between distinct physical regions
- Coupled with hyperbolic, parabolic, and elliptic PDE solvers
- Suitable for fluid-fluid, fluid-structure, crystal growth, phase transition, elastic-plastic, and other moving interfaces
- Track shock waves, contact discontinuities, and material interfaces in computational continuum mechanics.



FronTier meshed data structure



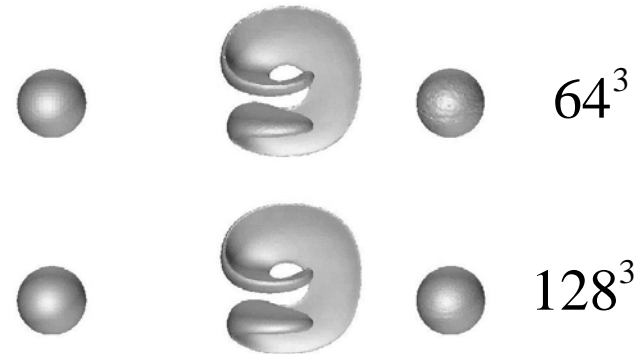
Study of fluid interface instabilities



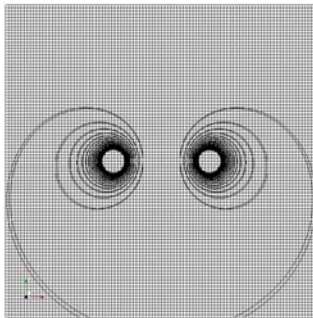
Simulation of moving rigid body

# *FronTier* is a library for meshed interfaces

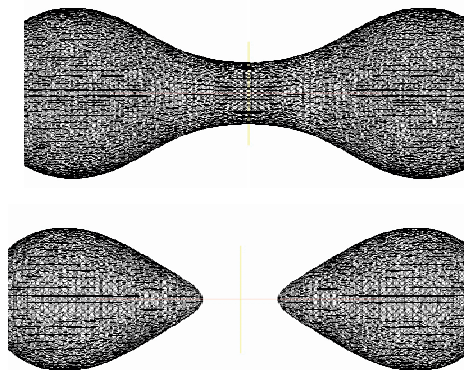
- Preservation of geometry for rigid body interface
- Accurate interface point propagation
- High resolution at subgrid level
- Robust surface topological change (mesh merge and bifurcation)



**Accuracy (reversal) tests**

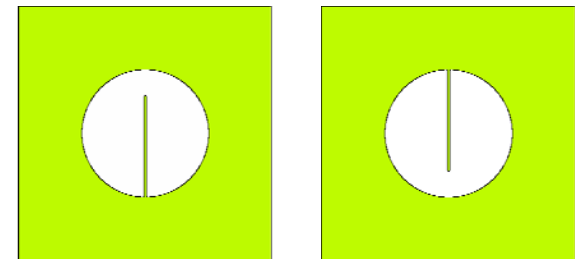


**Subgrid resolution**



**Robust topological bifurcation**

**Geometry preservation**





# FronTier Service Capabilities

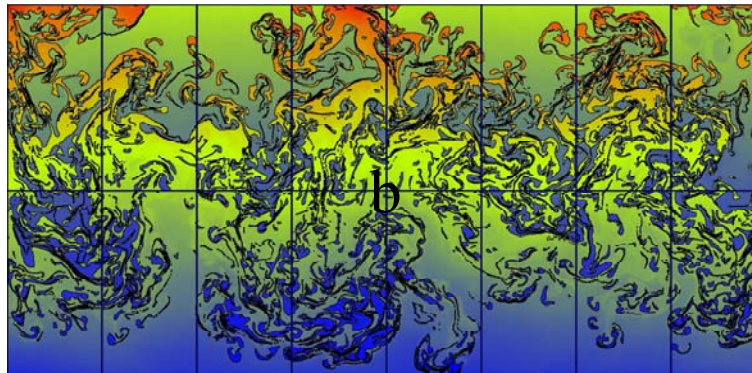
---

- FronTier can be coupled with Riemann solver to give exact solution of interface propagation in gas dynamics
- FronTier can be coupled with projection solver for incompressible fluid simulation
- FronTier can be coupled with elliptic solvers for steady state problems with unstructured interior boundary
- FronTier has been used for MHD simulation in fusion
- FronTier has implemented embedded boundary method
- FronTier has implemented iMesh interface
- FronTier can be inter-operated with PETSc, Hypre, AMR packages (Overture, Chombo, Samrai), and several graphics and movie libraries
- FronTier is fully parallelized under open-MPI.



# Parallel Model

- FronTier parallel model is the geometric rectangular partitioning domain.



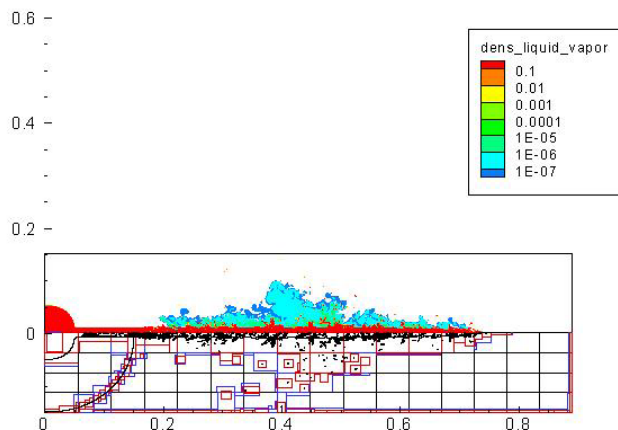
- Entities in some buffer region about the boundaries are ghosted.
- FronTier's bulk communication method is designed to operate well when communication is a bottleneck

## Parallel issues

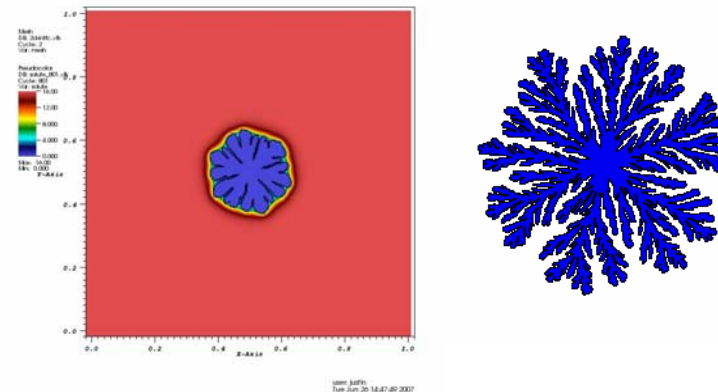
---

- FronTier native parallel model implements a shared ownership of boundary entities
- Ghost entities are modified locally, and then compared with parents each time step
- These are things to keep in mind when working with FronTier in parallel

# Application to DOE energy related research

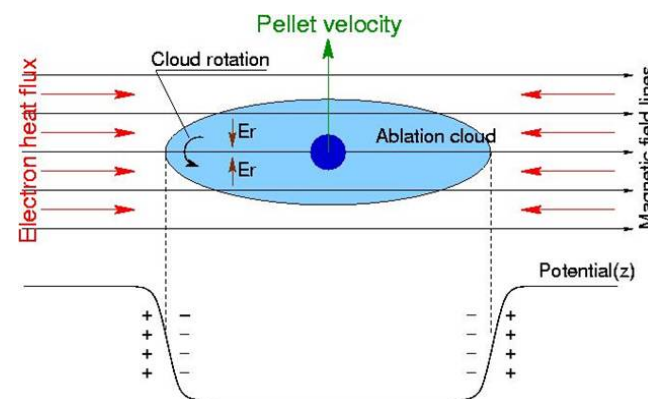


Simulation of bio-fuel jet for efficient and renewable energy  
Collaborated with ORNL etc



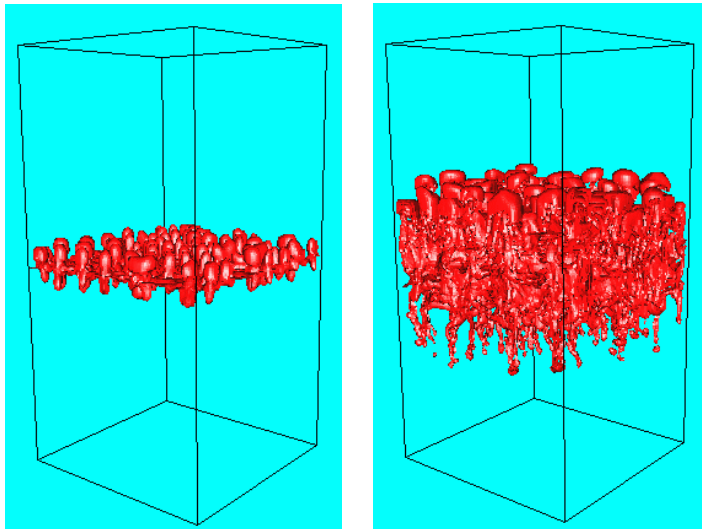
**Study of subsurface solute precipitation**  
**In collaboration with PNNL**

Front Tracking simulation of pellet Ablation, we focus on detailed ablation physics, ablation rates etc. By Roman Samulyak et al at BNL in collaboration with General Atomic

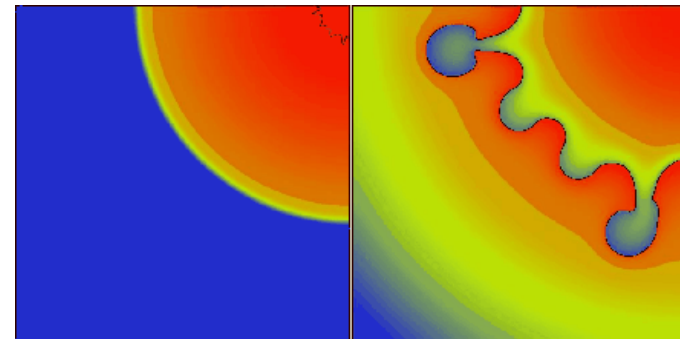


## Other *FronTier* applications

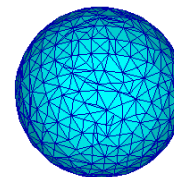
- Acceleration driven fluid interface instabilities
- Supernova explosion
- Shock-bubble interaction



**Rayleigh-Taylor Mixing**



**Simulation of supernova  
Explosion By Tulin Kaman**



**Simulation  
Of cell  
motion**

# Dynamic Services (Zoltan)

Vitus Leung and Karen Devine  
Sandia National Laboratories





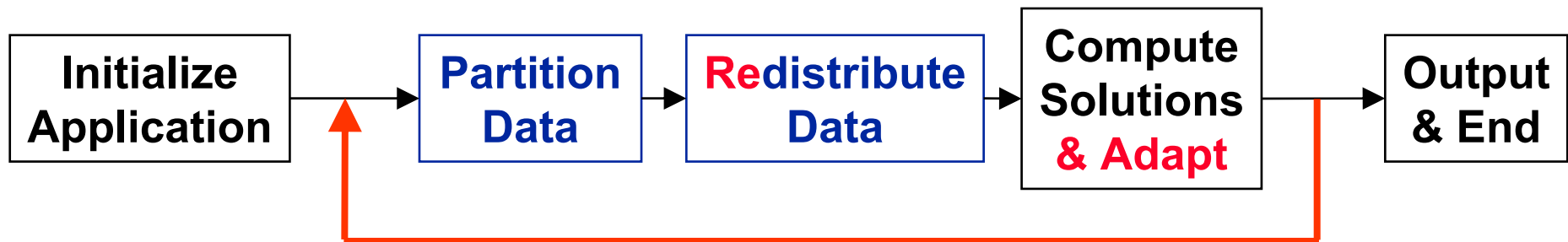
# Static Partitioning

---



- Assign mesh entities to processors for parallel computation.
  - Minimize processor idle time.
  - Maintain low inter-processor communication costs.
- Static partitioning in an application:
  - Data partition is computed.
  - Data are distributed according to partition map.
  - Application computes.

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



- Redistribute mesh entities among processor to adjust for changes in the computation.
  - Changing workloads in adaptive mesh refinement.
  - Changing geometric locality in crash simulations/contact detection.
- 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.**

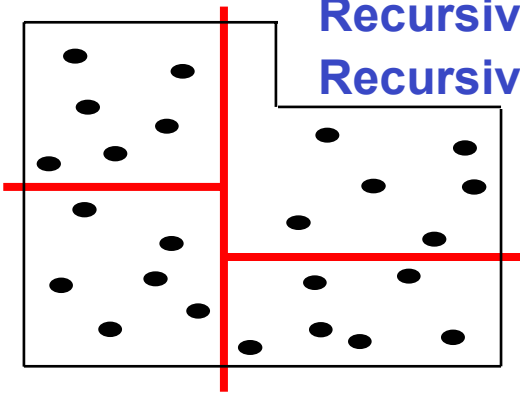
# Zoltan Suite of Parallel Partitioners and Repartitioners

**No single method is appropriate for all applications.**

## *Geometric (coordinate-based) methods*

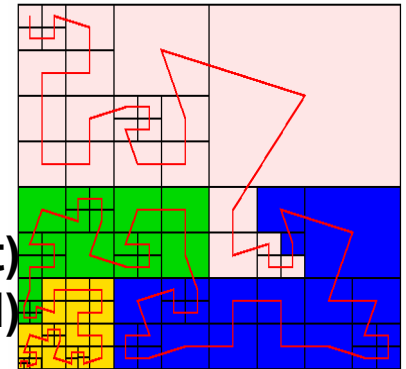
Recursive Coordinate Bisection (Berger, Bokhari)

Recursive Inertial Bisection (Taylor, Nour-Omid)



Space Filling Curves (Peano, Hilbert)

Refinement-tree Partitioning (Mitchell)

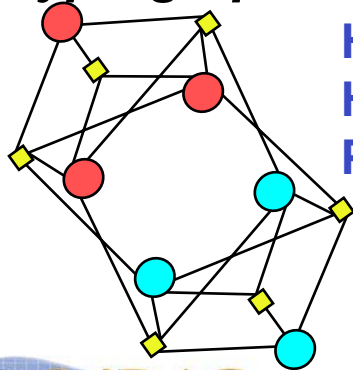


## *Hypergraph and graph (connectivity-based) methods*

Hypergraph Partitioning

Hypergraph Repartitioning

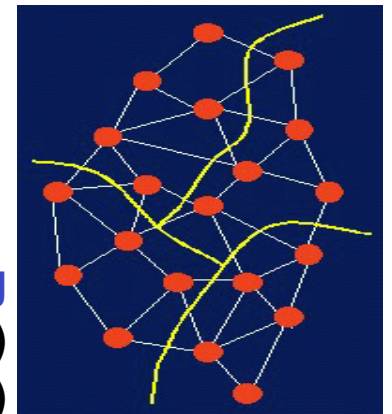
PaToH (Catalyurek)



Zoltan Graph Partitioning

ParMETIS (U. Minnesota)

PT-Scotch (U. Bordeaux)



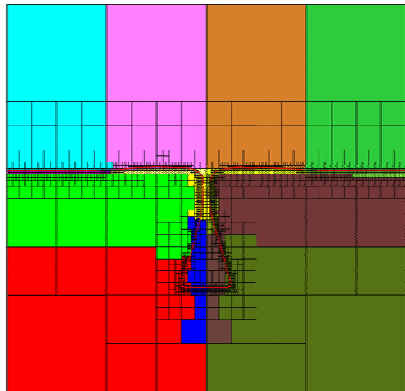
# Geometric Partitioning and Repartitioning in Zoltan

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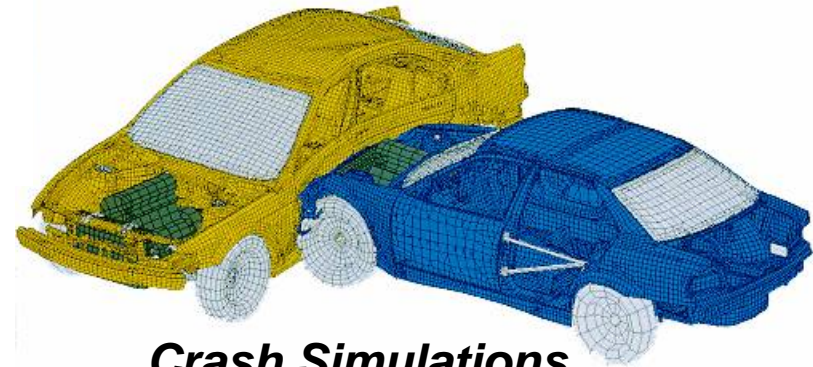
- Partition with respect to entities' geometric coordinates.
  - Assign physically close entities to the same processor.
- Advantages:
  - Easy to use; need only coordinate info.
  - Fast and inexpensive; suitable for adaptive mesh refinement with frequent repartitioning.
  - Grouping of physically close entities is essential for contact detection and particle simulations.
  - All processors can inexpensively know the entire partition; needed for global search in contact detection.
- Disadvantages:
  - Mediocre partition quality; no explicit control of communication costs.
  - Can generate disconnected subdomains for complex geometries.



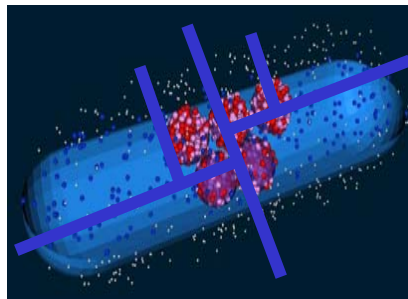
# Applications of Geometric Repartitioners



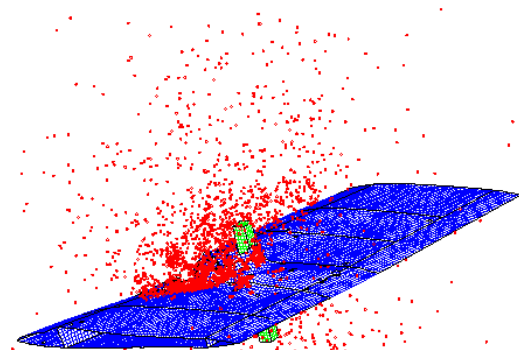
***Adaptive Mesh Refinement***  
*(Frequent adaptation  
requires fast repartitioning.)*



***Crash Simulations  
and Contact Detection***  
*(Geometric locality needed  
for global search.)*



***Particle Simulations***  
*(Geometric locality needed  
for particle interactions.)*

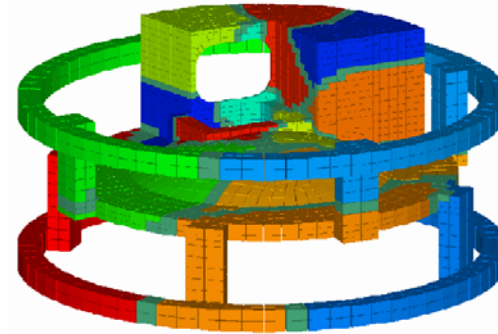
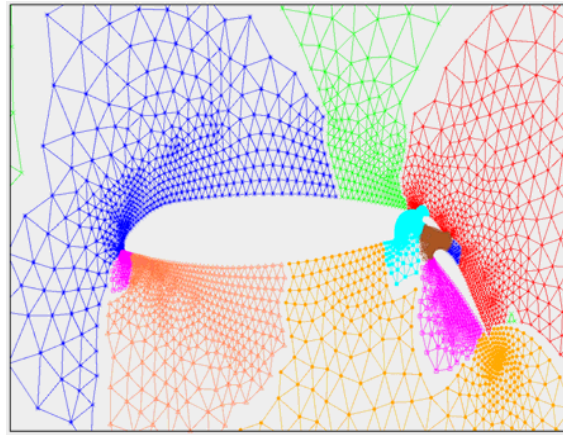


# Connectivity-based Partitioning and Repartitioning in Zoltan

---

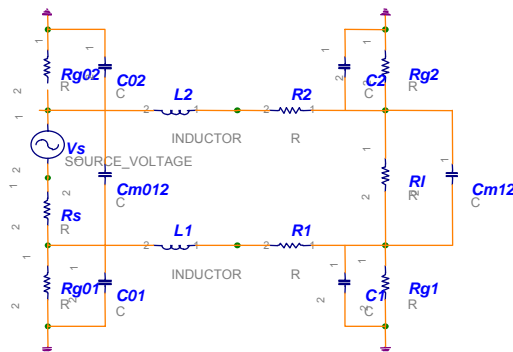
- Partition with respect to entities' data dependencies.
  - Assign entities that depend on each other to the same processor.
  - Graph/Hypergraph representation:
    - Entities are graph/hypergraph vertices.
    - Dependencies are edges/hyperedges.
- Advantages:
  - Proven highly successful for mesh-based PDE problems.
  - Explicit control of communication volume gives higher partition quality than geometric methods.
- Disadvantages:
  - More expensive than geometric methods.
  - More difficult to use than geometric methods.

# Applications of Connectivity-based Partitioners



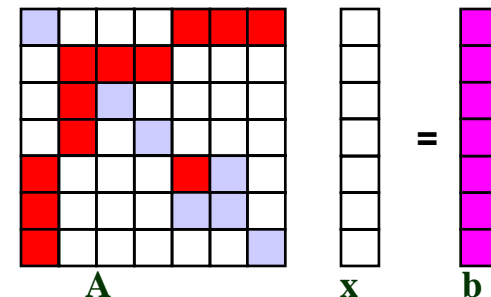
## Finite Element Simulations

*(Explicit control of communication costs enables efficient computation.)*



## Electronic Circuit Simulations

*(Network-based data does not have coordinate info.)*



**Linear Solvers & Preconditioners**  
*(Partitioners' communication metrics are designed for matrix operations<sub>57</sub>)*

# Visualization using VisIt

Mark Miller

Lawrence Livermore National  
Laboratories



**BROOKHAVEN**  
NATIONAL LABORATORY



**Rensselaer**

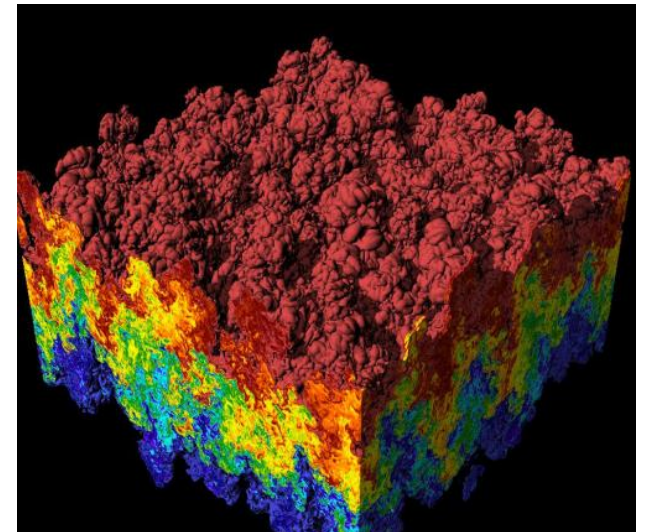
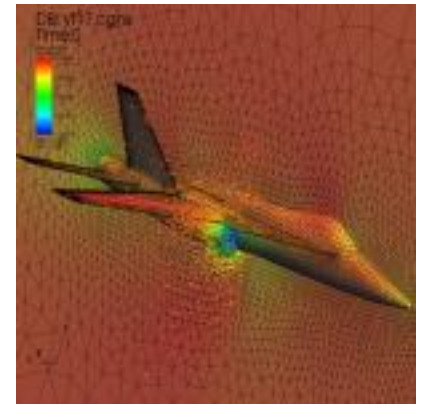




# VisIt provides many advanced capabilities

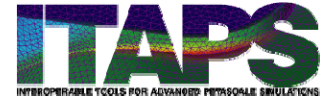
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- Free interactive parallel visualization and graphical analysis tool for scientific visualization
- Useful for scalar, vector, and tensor fields in multiple dimensions
- Can visualize data on point, rectilinear, curvilinear and unstructured grids
- Powerful, full featured graphical user interface
- Parallel architecture for visualizing terascale data sets
- Extensible with dynamically loadable plug-ins

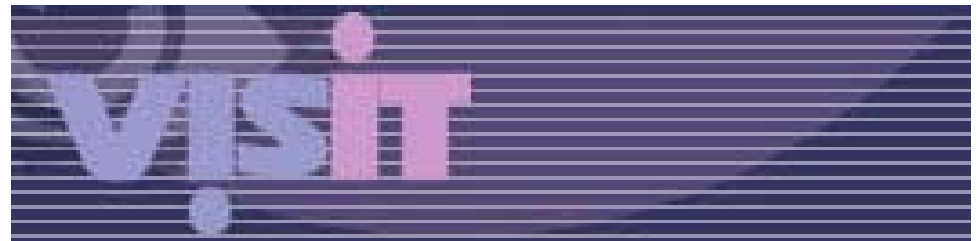


# ITAPS has been integrated with VisIt as a database plug-in

---

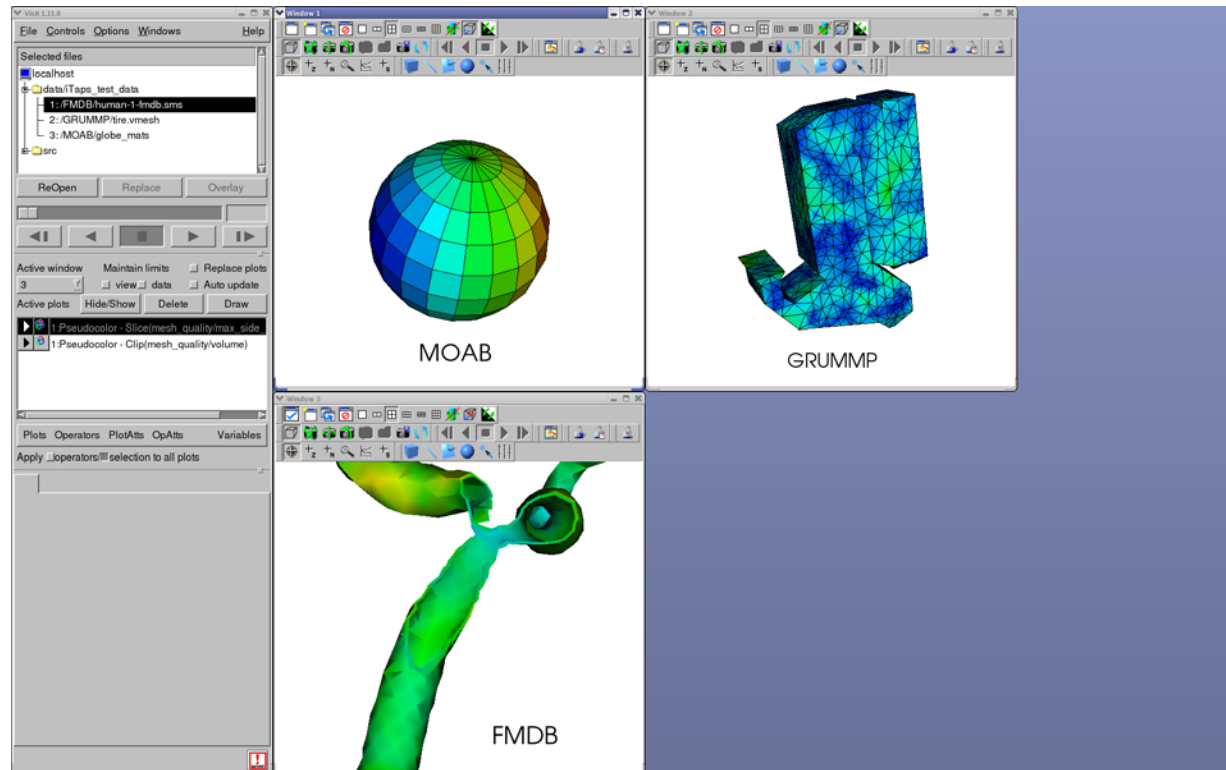


- A single plug-in supports multiple ITAPS implementations
- Supports all entity types
- Supports subset and tag data visualization
- Future integration will use VisIt's in-situ 'simulation' interface
  - Will enable any ITAPS-compliant software to integrate with VisIt at run-time



# VisIt can be used to display test data from multiple implementations

Example of VisIt displaying test data from multiple ITAPS implementations simultaneously

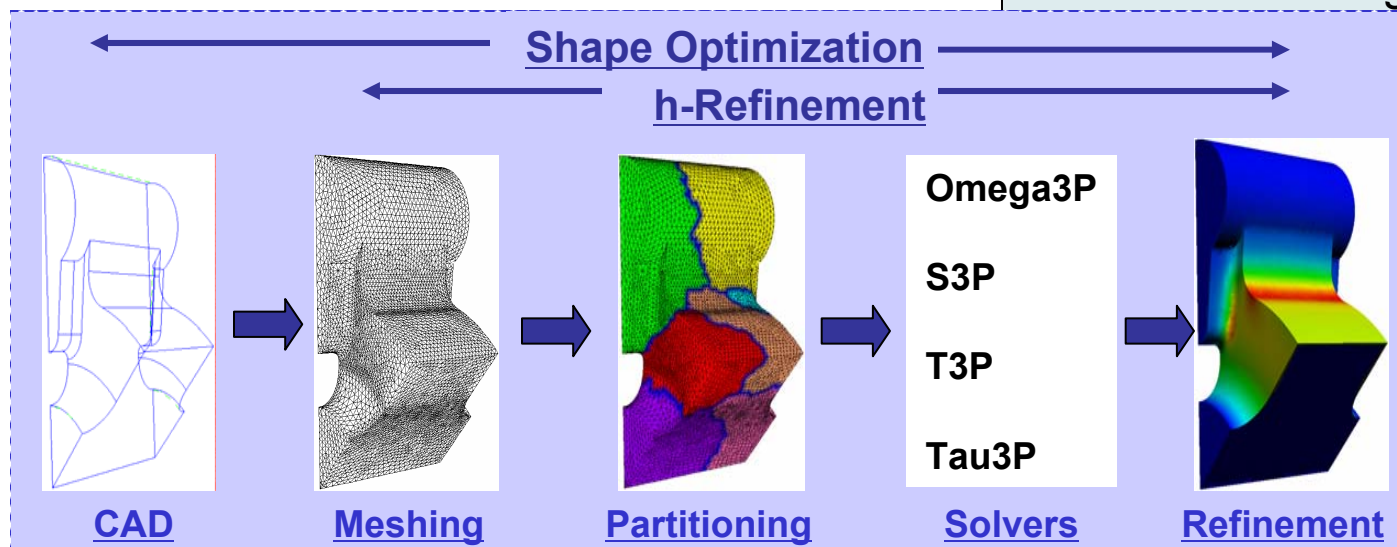


## PART 3: ITAPS Data Model

# The ITAPS interoperability goal requires abstracting the data model

- Information flows from geometrical representation of the domain to the mesh to the solvers and post-processing tools
- Adaptive loops and design optimization requires a loop

- The data model must encompass a broad spectrum of mesh types and usage scenarios
- A set of common interfaces
  - Implementation and data structure neutral
  - Small enough to encourage adoption
  - Flexible enough to support a broad range of functionality





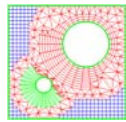
# The ITAPS data model abstracts PDE-simulation data hierarchy

---

- Core Data Types



- *Geometric Data*: provides a high level description of the boundaries of the computational domain; e.g., CAD, image, or mesh data ([iGeom](#))



- *Mesh Data*: provides the geometric and topological information associated with the discrete representation of the domain ([iMesh](#))



- *Field Data*: provides access to time dependent physics variables associated with application solution. These can be scalars, vectors, tensors, and associated with any mesh entity. ([iField](#))

- Data Relation Managers ([iRel](#))

- Provides control of the relationships among the core data types
- Resolves cross references between entities in different groups
- Provides functionality that depends on multiple core data types

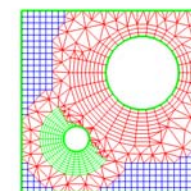
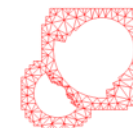
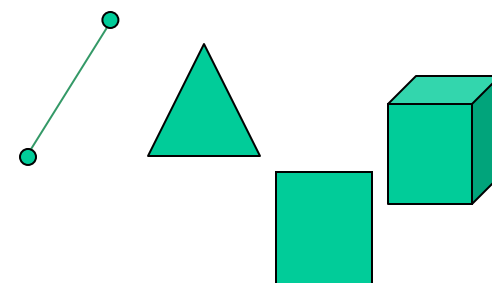
# The ITAPS data model has four fundamental “types”

---

- *Entity*: fine-grained entities in interface (e.g., vertex, face, region)
- *Entity Set*: arbitrary collection of entities & other sets
  - Parent/child relations, for embedded graphs between sets
- *Interface Instance*: object on which interface functions are called and through which other data are obtained
- *Tag*: named datum annotated to Entities and Entity Sets

# These core data types blend abstract and specific concepts

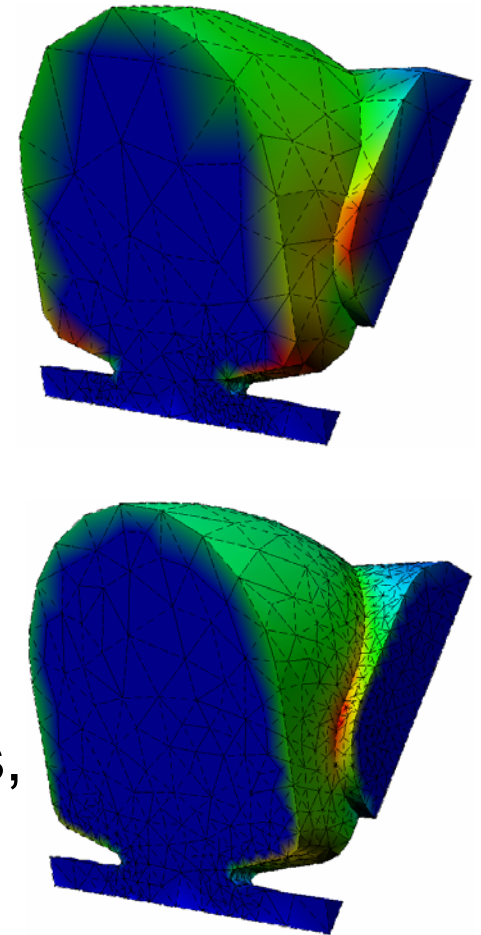
- Entity Definition
  - Unique type and topology
  - Canonical ordering defines adjacency relationships
- Entity Set Definition
  - Arbitrary grouping of ITAPS entities and other sets
  - There is a single “Root Set”
  - Relationships among entity sets
    - Contained-in
    - Hierarchical
- These objects are accessed using opaque (type-less) “handles”



# iMesh(P) provides access to the discrete representation of the domain

---

- iMesh supports local access to the mesh
- iMeshP complements iMesh with parallel support
- Must support
  - Access to mesh geometry and topology
  - User-defined mesh manipulation and adaptivity
  - Grouping of related mesh entities together (e.g. for boundary conditions)
- Builds on a general data model that is largely suited for unstructured grids
- Implemented using a variety of mesh types, software, and for a number of different usage scenarios



# The iMesh interface supports basic and advanced local operations

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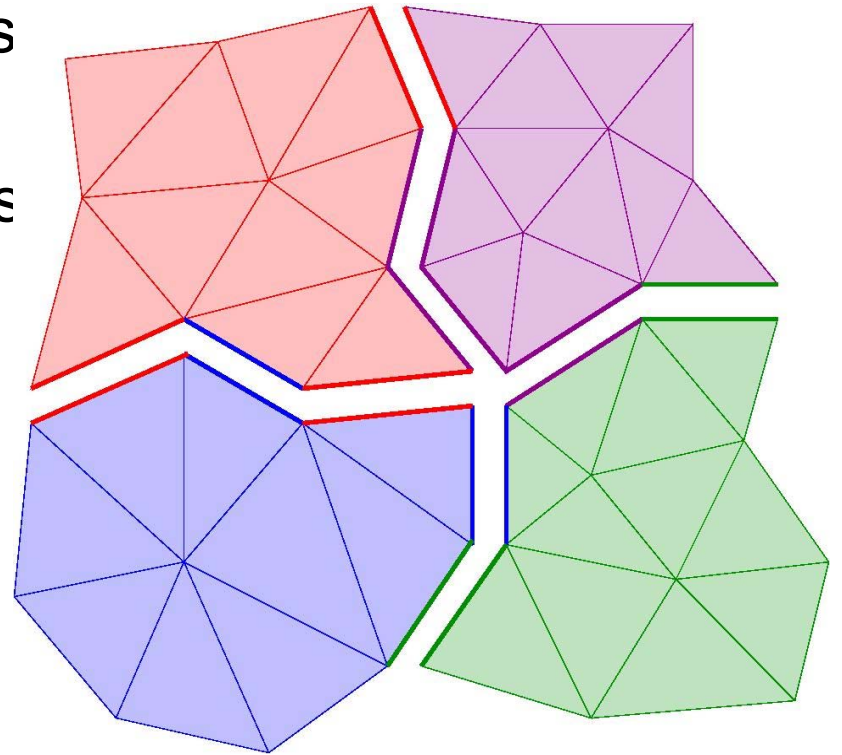
- Provides basic access to vertex coordinates and adjacency information
  - Mesh loading and saving
  - Global information such as the root set, geometric dimension, number of entities of a given type or topology
  - Access to all entities in a set as single entities, arrays of entities, or entire set
  - Set/remove/access tag data
- Set functionality
  - Boolean operations (union, subtract, intersect)
  - Hierarchical relationships
- Mesh modification
  - Adding / Deleting entities
  - Vertex relocation
  - No validity checks



# iMeshP extends iMesh to support parallel computations

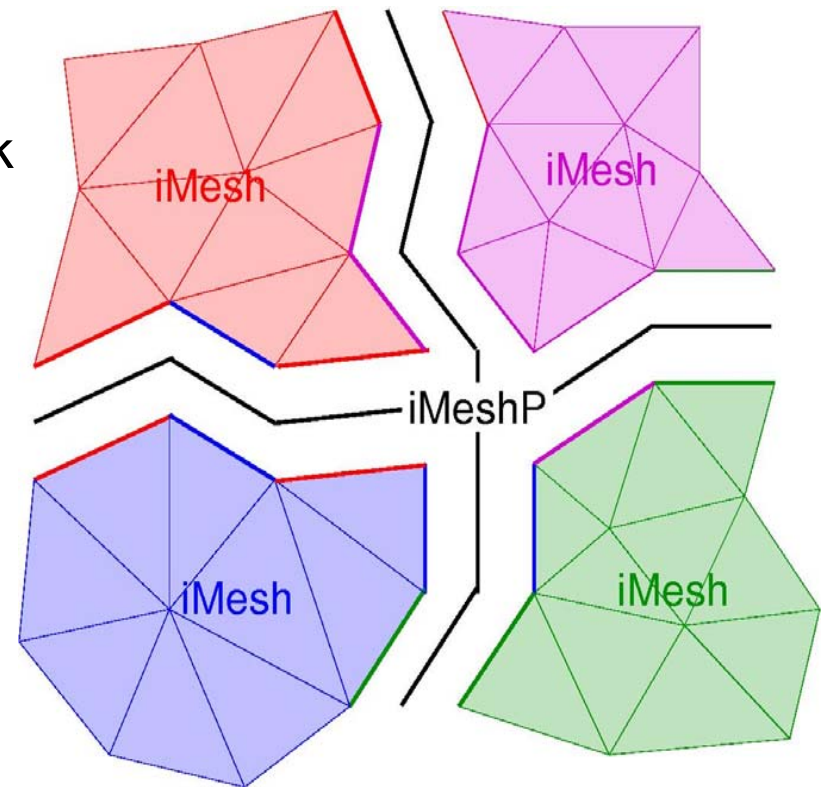
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- Focus on distributed memory
  - For example: use application's MPI communicators
  - But allow use of global address space and shared memory paradigms
- Leverage serial iMesh
  - Works as expected within a process
  - Works as expected for global address space and shared memory programs



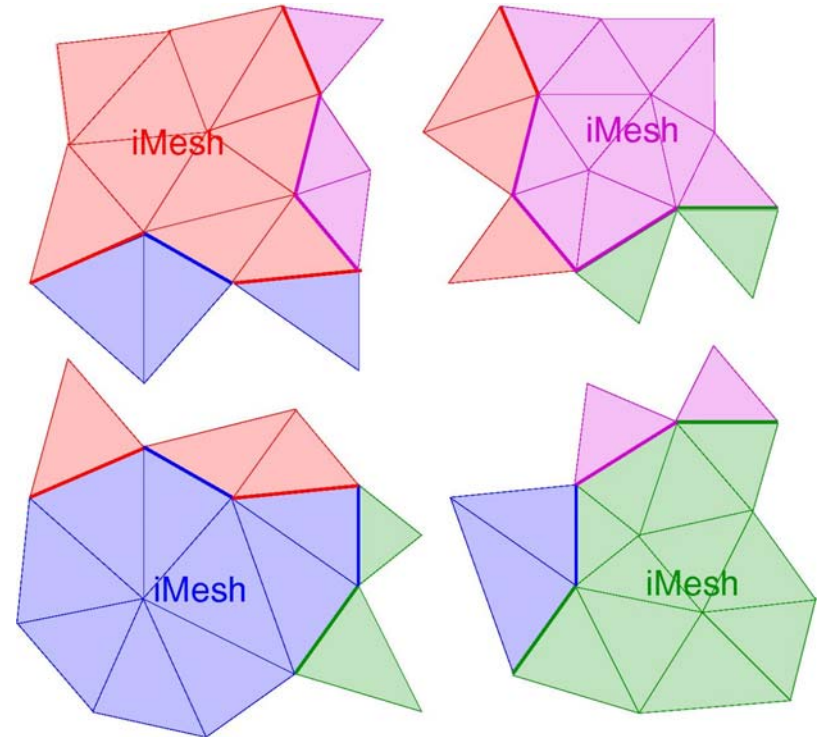
# The iMeshP parallel interface defines a partition model

- *Process*: a program executing;  
MPI process
  - # of processes == MPI\_Comm\_size
  - Process number == MPI\_Comm\_rank
- *iMesh instance*: mesh database provided by an implementation
  - One or more instances per process
- *Partition*: describes a parallel mesh
  - Maps entities to subsets called *parts*
  - Maps parts to processes
  - Has a communicator associated with it



# The Partition Model

- *Ownership*: right to modify an entity
- *Internal entity*: Owned entity not on an interpart boundary.
  - E.g., all triangles w/ same color as iMesh label for part
- *Part-Boundary entity*: Entity on an interpart boundary
  - E.g., bold edges
  - *Shared* between parts (owner indicated by color; other parts have copies).
- *Ghost entity*: Non-owned, non-part-boundary entity in a part
  - E.g., triangles whose color is different from iMesh label
  - Needed for adjacency and/or solution data
- *Copies*: ghost entities + non-owned part-boundary entities.



# Partition Characteristics

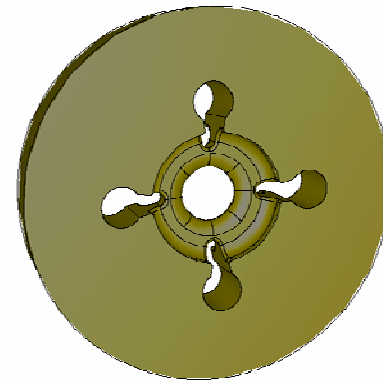
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- Maps entities to parts
  - Part assignments computed with respect to a set of entities
  - Computed assignments induce part assignments for adjacent entities
- Maps parts to processes
  - Each process may have one or more parts
  - Each part is wholly contained within a process
- Has a communicator associated with it
  - “Global” operations performed with respect to data in all parts in a partition’s communicator
  - “Local” operations performed with respect to either a part’s or process’ data

# The geometry interface provides access to the computational domain

---

- Must support
  - automatic mesh generation
  - mesh adaptation
  - tracking domain changes
  - relating information between alternative discretizations
- Builds on boundary representations of geometry
- Used to support various underlying representations
  - Commercial modelers (e.g., Parasolid, ACIS)
  - Modelers that operate from standard files (e.g. IGES, STEP)
  - Models constructed from an input mesh

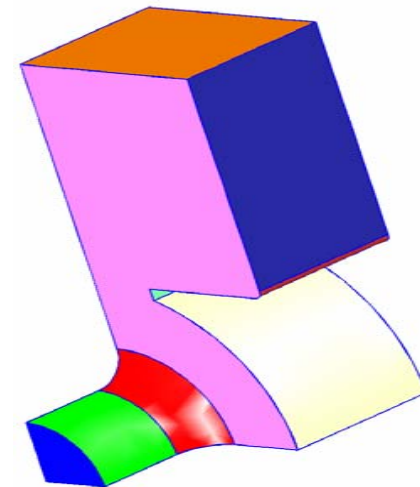
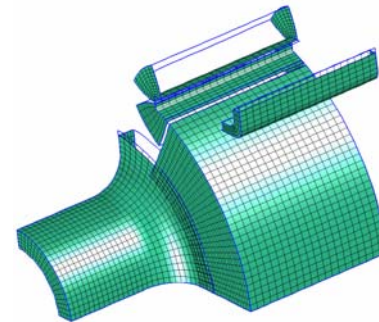




# Basic and advanced functionalities are supported in the geometry interface

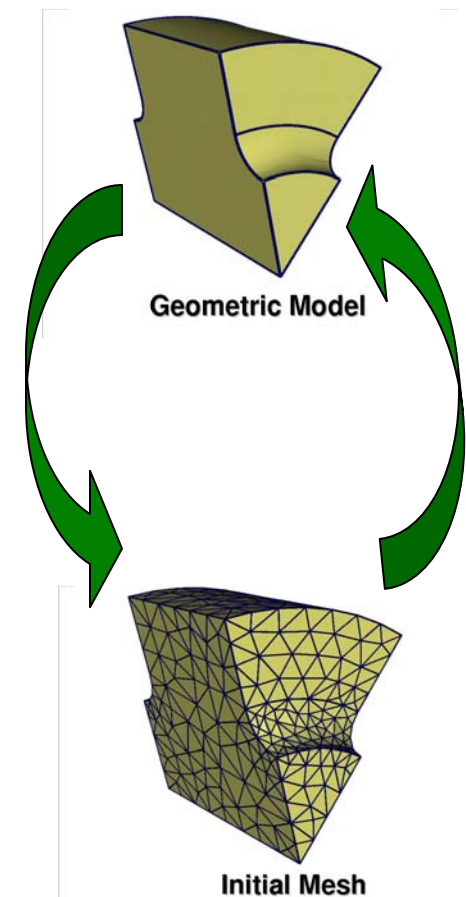
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- Model loading and initiation
- Topological queries of entities and adjacencies
- Pointwise geometric shape interrogation
- Parametric coordinate systems
- Model topology modification



# Relating mesh and geometry data is critical for advanced ITAPS services

- Required for e.g., adaptive loops, mesh quality improvement
- Mesh/Geometry Classification Interface
  - Manages the relationship between the high level geometric description and the mesh
  - Called by an application that knows about both
- Capabilities
  - For a given mesh entity, get the geometric entity against which it is classified
  - Establish a classification relationship between a mesh entity and a geometric entity



# Multiple approaches can be used to embed application specific data

---

- Boundary conditions
  - Approach 1:
    - Boundary conditions associated with geometric model
    - Mesh classified on geometric model connects boundary conditions to mesh entities
  - Approach 2:
    - Mesh entities grouped together into an entity set that is tagged to represent boundary conditions
- Solution data
  - Tags associated with the appropriate mesh entities

## Summary of the ITAPS data model

---

- The data model abstracts the information flow in PDE simulations: Geometry, Mesh, Fields and their Relations
- Each core abstraction has a separate interface definition: iMesh, iGeom, iField, iRel
- The core building blocks of the data models are entities, entity sets, interfaces and tags
- The parallel data model defines partitions, parts, and entity ownership concepts

# PART 4a: Basic ITAPS Interfaces



# Outline

---

- iMeshP ITAPS Interface (w/ examples)
- Best Practices (for Performance)
- Language Interoperability
  - C-binding interface
  - SIDL/Babel

# An overarching philosophy guides our interface definition efforts

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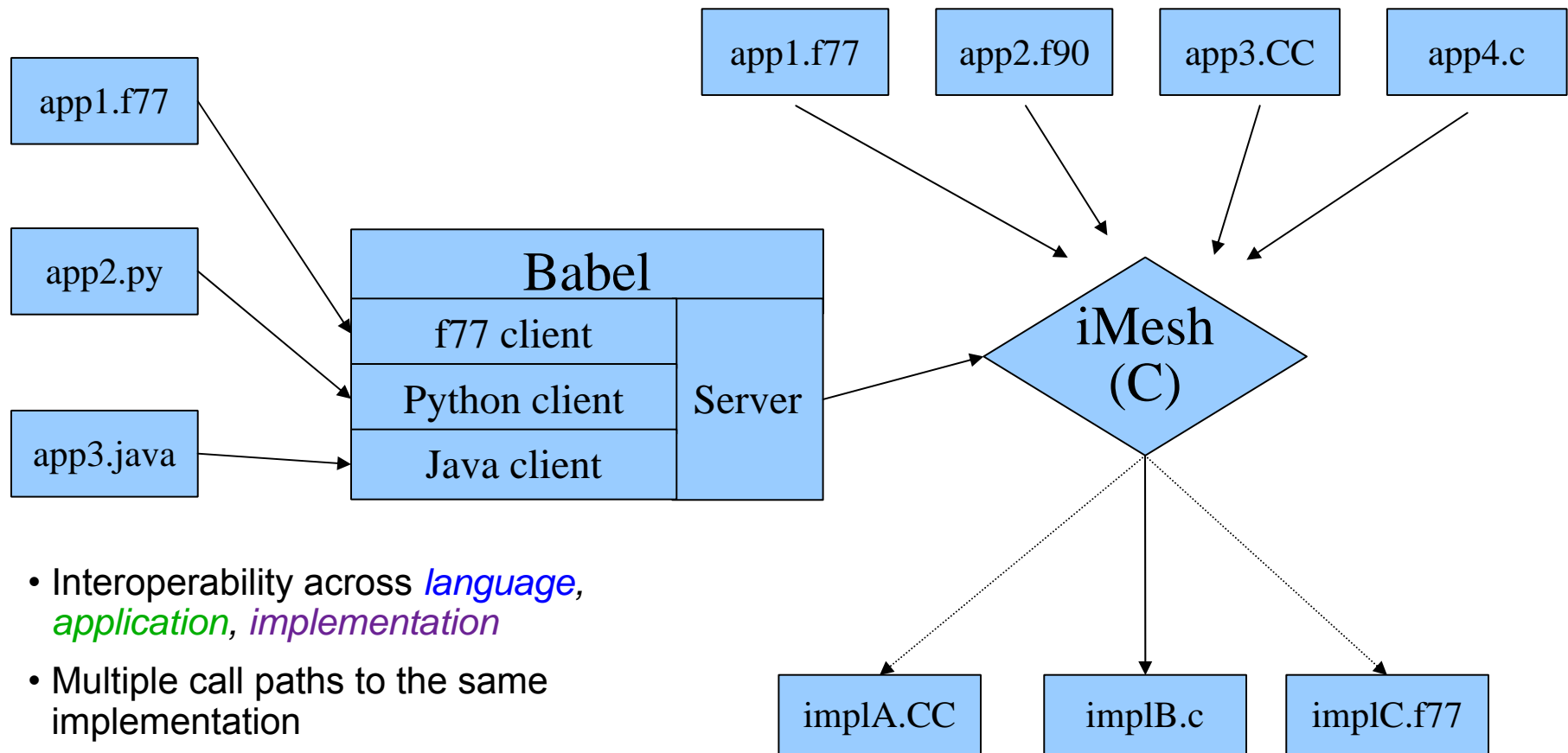
- Create a small set of interfaces that existing packages can support
  - Should be able to implement the interfaces based on your representation of data structures
  - Allows incremental adoption
- Keep interfaces for the different core data model abstractions separate
- Balance performance and flexibility
- Work with a large tool provider and application community to ensure applicability
- Language Interoperability
  - C interface callable from C, C++ and Fortran
  - Use SIDL/Babel for Java and python support

Lowers the burden for adoption of the interface

Performance is critical for kernel computations involving mesh access; flexibility is critical for covering a broad usage spectrum

CCA provides infrastructure and guidance for domain-specific interface definition efforts

# ITAPS Interfaces Designed for Interoperability



- Interoperability across *language*, *application*, *implementation*
- Multiple call paths to the same implementation
- Efficiency preserved using direct, C-based interface

# Enumerated types used in the ITAPS interface

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- Important enumerated types:
  - EntityType (iBase\_VERTEX, EDGE, FACE, REGION)
  - EntityTopology (iMesh\_POINT, LINE, TRI, QUAD, ...)
  - StorageOrder (iBase\_BLOCKED, INTERLEAVED)
  - TagDataType (iBase\_INTEGER, DOUBLE, ENTITY\_HANDLE)
  - ErrorType (iBase\_SUCCESS, FAILURE, ...)
- Enumerated type & function names both have iBase, iMesh, iGeom, other names prepended

# Simple Example: HELLO iMesh

```
#include "iMesh.h"
int main(int argc, char *argv[]){
    char *options = NULL;
    int ierr, dim, num, options_len = 0;
    iMesh_Instance mesh;
    iBase_EntitySetHandle root;

    /* create the Mesh instance */
    1 iMesh_newMesh(options, &mesh, &ierr, options_len);
    iMesh_getRootSet(mesh, &root, &ierr);

    /* load the mesh */
    2 iMesh_load(mesh, root, argv[1], options, &ierr,
               strlen(argv[1]), options_len);

    /* report the number of elements of each dimension */
    3 for (dim = iBase_VERTEX; dim <= iBase_REGION; dim++) {
        iMesh_getNumOfType(mesh, root, dim, &num, &ierr);
        printf("Number of %d-D elements = %d\n", dim, num);
    }
    iMesh_dtor(mesh, &ierr);
    return 1;
}
```

**Simple application that**

- 1) Instantiates iMesh interface**
- 2) Reads mesh from disk**
- 3) Reports # entities of each dimension**

*Note: for brevity, there's no error checking here, but there should be in your code!!!*



# HELLO iMesh Makefile

---

```
CC = cc -g
CXX = c++ -g

FMDB_TOP = /usr/local/itaps/visit/fmdb
LIBDIR += -L$(FMDB_TOP)/lib
LIBS += -lFMDB -lSCORECModel -lSCORECUtil
INCPATH += -I$(FMDB_TOP)/include

hello: hello.c
    $(CC) $(INCPATH) -c hello.c
    $(CXX) $(LD_FLAGS) -o $@ hello.o $(LIBDIR) $(LIBS)
```

# Simple Example: HELLO iMeshP

```
#include "iMesh.h"
#include "iMeshP.h"
#include <mpi.h>
int main(int argc, char *argv[]) {
    char *options = NULL;
    iMesh_Instance mesh;
    iMeshP_PartitionHandle partition;
    int me, dim, num, ierr, options_len=0;
    iBase_EntitySetHandle root;
    /* create the Mesh instance */
    iMesh_newMesh(options, &mesh, &ierr, options_len);
    iMesh_getRootSet(mesh, &root, &ierr);

    MPI_Init(&argc, &argv);
    MPI_Comm_rank(MPI_COMM_WORLD, &me);
    /* Create the partition. */
    iMeshP_createPartitionAll(mesh, MPI_COMM_WORLD, &partition, &ierr);

    /* load the mesh */
    iMeshP_load(mesh, partition, root, argv[1], options, &ierr,
                strlen(argv[1]), options_len);

    /* Report number of Parts in Partition */
    iMeshP_getNumParts(mesh, partition, &num, &ierr);
    printf("%d Number of Parts = %d\n", me, num);
    . . .
}
```

## ***Parallel Version: HELLO iMeshP***

- 1) Instantiates Partition***
- 2) Reads mesh into mesh instance and Partition***
- 3) Reports # parts in Partition***



# HELLO iMeshP Makefile

---

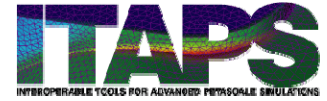
```
CC = mpicc -g
CXX = mpicxx -g

FMDB_TOP = /mnt/disk2a/txie/tmp
LIBDIR += -L$(FMDB_TOP)/lib \
          -L../Zoltan/Obj_linux64 \
          -L../ParMETIS3_1 -L../FMDB_iMeshP/lib/linux64
LIBS += -lFMDB -lSCORECModel -lSCORECUtil \
        -lzoltan -lparmetis -lmetis -lautopack
INCPATH += -I$(FMDB_TOP)/include/FMDB
CC += -DIMESHP -DPARALLEL

helloP: helloP.c
        $(CC) $(INCPATH) -c helloP.c
        $(CXX) $(LD_FLAGS) -o $@ helloP.o $(LIBDIR) $(LIBS)
```

# ITAPS API's: Argument Handling Conventions

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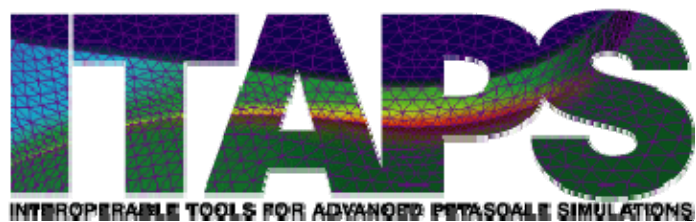


- ITAPS API's are C-like and can be called directly from C, Fortran, C++
- Arguments pass by value (in) or reference (inout, out)
  - Fortran: use %VAL extension
- Memory allocation for lists done in application *or* implementation
  - If inout list comes in allocated, length must be long enough to store results of call
  - By definition, allocation/deallocation done using C malloc/free; application required to free memory returned by implementation
  - Fortran: Use “cray pointer” extension (equivalences to normal f77 array)
- Handle types typedef'd to size\_t (iBase\_EntityHandle, iBase\_EntitySetHandle, iBase\_TagHandle, iMesh\_Instance)
- Strings: char\*, with length passed by value after all other args
- Enum's: *values (iBase\_SUCCESS, etc.) available for comparison operations, but passed as integer arguments*
  - *Fortran: named parameters*

# Argument Handling Conventions

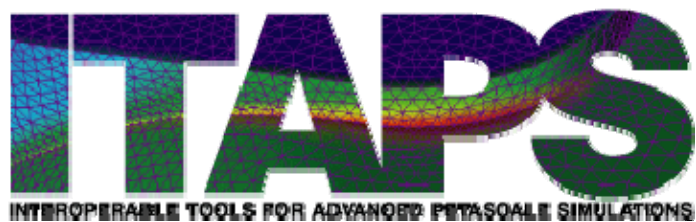
| Issue                    | C   | FORTRAN   | SIDL   |
|--------------------------|---|---|--|
| Function Names           | iXxxx_ prefix   | Same as C   | Removed iXxxx_ prefix; SIDL interface organization   |
| Interface Handle         | Typedef'd to size_t, as type iXxxx_Instance; instance handle is 1 <sup>st</sup> argument to all functions   | #define'd as type Integer; handle instance is 1 <sup>st</sup> argument to all functions           | Interface type derived from sidl.BaseInterface   |
| Enumerated Variables     | All arguments integer-type instead of enum-type; values from enumerated types   | Same, with enum values defined as FORTRAN parameters  | Int-type arguments; enumerated types defined in iXxxx:: namespace, and values appear as iXxxx::enumName_enumValue  |
| Entity, Set, Tag Handles | Typedef'd as size_t; typedef types iBase_EntityHandle, iBase_EntitySetHandle, iBase_TagHandle   | #define'd as type Integer   | Handles declared as SIDL opaque type (mapped to void* in C/C++ server)   |
| Lists                    | <ul style="list-style-type: none"> <li>In: X *list, int occupied_size</li> <li>Inout: X **list, int *allocated_size, int **occupied_size</li> <li>malloc/free-based memory allocation/deallocation</li> </ul> | Same, with Cray pointers used to reference arrays (see FindConnectF example)                      | <ul style="list-style-type: none"> <li>In: sidl::array&lt;X&gt; list, int occupied_size</li> <li>Inout: sidl::array&lt;X&gt; &amp;list, int &amp;occupied_size</li> <li>sidl::array class memory allocation</li> </ul> |
| String                   | char*-type, with string length(s) at end of argument list   | char[]-type without extra length argument (this length gets added implicitly by FORTRAN compiler) | sidl::string type without extra length argument  |





# MORNING SESSION HANDS ON





# ITAPS Tutorial: Afternoon Session



# Tutorial Overview

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## Morning

- Part 1: Introduction
- Part 2: Overview of ITAPS services
- Part 3: The ITAPS Data Model
- Part 4a: Basic ITAPS Interfaces
- *Hands on exercise:*
  - Hello iMeshP

## Afternoon

- Part 4b: Advanced ITAPS Interfaces
- Part 5: ITAPS Software
- Part 6: Experiences and use in applications
- Part 7: Conclusion
- *Hands on exercises:*
  - Accessing mesh information
  - Partitioning services through iMeshP

# PART 4b: Advanced ITAPS Interfaces



# iMesh API Summary

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- Logically arranged into interfaces, but not explicitly arranged as such in C
  - See iMesh.h or iMesh.sidl
- Basic (Mesh): load, save, getEntities, getNumOfType/Topo, getAllVtxCoordinates, getAdjacencies
- Entity: init/get/reset/endEntIter (iterators), getEntType/Topo, getEntAdj, getVtxCoord
- Arr (Entity arrays): like Entity, but for arrays of entities
- Modify: createVtx/Ent, setVtxCoord, deleteEnt



# iMesh API Summary (cont.)

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- From iBase:
  - Tag: create/destroyTag, getTagName/SizeBytes/SizeValues/Handle/Type
  - EntTag: get/setData, get/setInt/Dbl/EHData, getAllTags, rmvTag
  - ArrTag: like EntTag, but for arrays of entities
  - SetTag: like EntTag, but for entity sets
  - EntSet: create/destroyEntSet, add/remove entity/entities/set, isEnt/EntSetContained
  - SetRelation: add/rmvPrntChld, isChildOf, getNumChld/Prnt, getChldn/Prnts
  - SetBoolOps: subtract, intersect, unite
- iBase-inherited function names still start with 'iMesh\_' to avoid name collision with other iBase-inherited interfaces (iGeom, iRel, etc.)

# Slightly More Complicated Example: FindAdjacency (C)

```
#include <iostream>
#include "iMesh.h"

typedef void* EntityHandle;

int main( int argc, char *argv[] )
{
    // create the Mesh instance
    iMesh_Instance mesh;
    int ierr;
    iMesh_newMesh("", &mesh, &ierr, 0);

    // load the mesh
    iMesh_load(mesh, 0, "125hex.vtk", "",
        &ierr, 10, 0);

    // get all 3d elements
    iMesh_EntityHandle *ents;
    int ents_alloc = 0, ents_size;
    iMesh_getEntities(mesh, 0, iBase_REGION,
        iMesh_ALL_TOPOLOGIES,
        &ents, &ents_alloc,
        &ents_size, &ierr);

    int vert_uses = 0;
```

```
// iterate through them
for (int i = 0; i < ents_size; i++) {
    // get connectivity
    iBase_EntityHandle *verts;
    int verts_alloc = 0, verts_size;

    iMesh_getEntAdj(mesh, ents[i], iBase_VERTEX,
        &verts, &verts_alloc, &verts_size,
        &ierr);

    // sum number of vertex uses
    vert_uses += verts_size;
    free(verts);

    // now get adjacencies in one big block
    iBase_EntityHandle *allv;
    int *offsets;
    int allv_alloc = 0, allv_size,
        offsets_alloc = 0, offsets_size;
    iMesh_getEntArrAdj(mesh, ents, ents_size,
        iBase_VERTEX,
        &allv, &allv_alloc, &allv_size,
        &offsets, &offsets_alloc, &offsets_size,
        &ierr);

    // compare results of two calling methods
    if (allv_size != vert_uses)
        std::cout << "Sizes didn't agree" <<
            std::endl;
    else
        std::cout << "Sizes did agree" << std::endl;

    return true;
}
```

## FindAdjacency(C) Notes

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- Typical inout list usage
    - `X *list, int list_alloc = 0, int list_size`
    - Setting `list_alloc` to zero *OR* `list = NULL` indicates *list is unallocated, so it will be allocated inside iMesh\_getEntities*
    - Addresses of these parameters passed into `iMesh_getEntities`
1. Inout list declared inside 'for' loop
  2. Memory de-allocated inside loop

# Slightly More Complicated Example: FindAdjacency (Fortran)

```

program findconnect

#include "iMesh_f.h"

c declarations
  iMesh_Instance mesh
  integer ierr, ents
  pointer (rpents, ents(0:*))
  ① integer rpverts, rpallverts, ipoffsets
  pointer (rpverts, verts(0:*))
  pointer (rpallverts, allverts(0:*))
  pointer (ipoffsets, ioffsets(0,*))
  integer ents_alloc, ents_size
  integer verts_alloc, verts_size
  integer allverts_alloc, allverts_size
  integer offsets_alloc, offsets_size

c create the Mesh instance
  call iMesh_newMesh("MOAB", mesh, ierr)

c load the mesh
  call iMesh_load(%VAL(mesh), %VAL(0),
  1 "125hex.vtk", "", ierr)

c get all 3d elements
  ents_alloc = 0
  call iMesh_getEntities(%VAL(mesh),
  ② 1 %VAL(0), %VAL(iBase_REGION),
  1 %VAL(iMesh_ALL_TOPOLOGIES),
  1 rpents, ents_alloc, ents_size,
  1 ierr)

```

```

  ivert_uses = 0

c iterate through them;
  do i = 0, ents_size-1
c get connectivity
  ③ verts_alloc = 0
  call iMesh_getEntAdj(%VAL(mesh),
  1 %VAL(ents(i)), %VAL(iBase_VERTEX),
  1 rpverts, verts_alloc, verts_size, ierr)
c sum number of vertex uses
  vert_uses = vert_uses + verts_size
  call free(rpverts)
  ④ end do

c now get adjacencies in one big block
  allverts_alloc = 0
  offsets_alloc = 0
  call iMesh_getEntArrAdj(%VAL(mesh),
  1 %VAL(rpents), %VAL(ents_size),
  1 %VAL(iBase_VERTEX), allverts,
  1 allverts_alloc, allverts_size, offsets,
  1 offsets_alloc, offsets_size, ierr)

c compare results of two calling methods
  if (allverts_size .ne. vert_uses) then
    write(*, '("Sizes didn't agree!")')
  else
    write(*, '("Sizes did agree!")')
  endif
end

```

# FindAdjacency (Fortran) Notes

---

## 1. Cray pointer usage

- “pointer” (rpverts, rpoffsets, etc.) declared as type integer
- “pointee” (verts, ioffsets, etc.) implicitly typed or declared explicitly
- pointer statement equivalences pointer to start of pointee array
- pointee un-allocated until explicitly allocated

## 2. Set allocated size (ents\_alloc) to zero to force allocation in iMesh\_getEntities; arguments passed by reference by default, use %VAL extension to pass by value; pointers passed by reference by default, like arrays

## 3. Allocated size set to zero to force re-allocation in every iteration of do loop

## 4. Use C-based free function to de-allocate memory



# Slightly More Complicated Example: FindAdjacency (SIDL/C++)

```
#include <iostream>
#include "iMesh.hh"
using std;

typedef void* EntityHandle;

int main( int argc, char *argv[] )
{
    // create the Mesh instance
    iMesh::Mesh mesh = iMesh::newMesh("");

    // load the mesh
    mesh.load(0, "125hex.g", "");

    // get all 3d elements
    sidl::array<EntityHandle> ents;
    int ents_size;
    mesh.getEntities(0,
        iBase::EntityType_REGION,

        iMesh::EntityTopology_ALL_TOPOLOGIES,
        ents, ents_size);

    int vert_uses = 0;

    // iterate through them; first have to get an
    // Entity interface instance
    iMesh::Entity mesh_ent = mesh;
    for (int i = 0; i < ents_size; i++) {
        // get connectivity
        sidl::array<EntityHandle> verts;
        int verts_size;
        mesh_ent.getEntAdj(ents[i],
            iBase::EntityType_VERTEX,
            verts, verts_size);
        // sum number of vertex uses
        vert_uses += verts_size;
    }

    // now get adjacencies in one big block
    sidl::array<EntityHandle> allverts;
    sidl::array<int> offsets;
    int allverts_size, offsets_size;
    iMesh::Arr mesh_arr = mesh;
    mesh_arr.getEntArrAdj(ents, ents_size,
        iBase::EntityType_VERTEX,
        allverts, allverts_size,
        offsets, offsets_size);

    // compare results of two calling methods
    if (allverts_size.ne. vert_uses) then
        cout << "Sizes didn't agree!" << endl;
    else cout << "Sizes did agree!" << endl;

    return true;
}
```

## FindAdjacency (SIDL/C++) Notes

---

1. Static function on iMesh class used to instantiate interface
2. List declaration using SIDL templated array
3. getEntities member function called on iMesh instance
4. Assignment operator-based cast to iMesh::Entity interface
5. Declaration of list inside for loop; re-constructed on every iteration, and de-constructed using use counts

# FindAdjacency Makefile

```
include /home/tautges/MOAB_gcc4.2/lib/iMesh-Defs.inc

FC = gfortran-4.2
CXX = g++-4.2
CC = gcc-4.2

CXXFLAGS = -g
CFLAGS = -g
FFLAGS = -g -fcray-pointer
FLFLAGS = -g -L/home/tautges/gcc-4.2/lib -L/usr/lib/gcc/i486-linux-gnu/4.2.1 -
lgfortranbegin -lgfortran -lm

FindAdjacencyS: FindAdjacencyS.o
$(CXX) $(CXXFLAGS) -o $@ FindAdjacency.o ${IMESH_SIDL_LIBS_LINK}

FindAdjacencyC: FindAdjacencyC.o
$(CC) $(CFLAGS) -o $@ FindAdjacencyConnectC.o ${IMESH_LIBS_LINK}

FindAdjacencyF: FindAdjacencyF.o
$(CXX) -o $@ FindAdjacencyF.o $(FLFLAGS) ${IMESH_LIBS_LINK}

.cpp.o:
    $(CXX) -c $(CXXFLAGS) ${IMESH_INCLUDES} $<
.cc.o:
    $(CC) -c $(CFLAGS) ${IMESH_INCLUDES} $<
.F.o:
    $(FC) -c $(FFLAGS) ${IMESH_INCLUDES} $<
```

# ListSetsNTags Example

---

- Read in a mesh
- Get all sets
- For each set:
  - Get tags on the set and names of those tags
  - If tag is integer or double type, also get value
  - Print tag names & values for each set
- Various uses for sets & tags, most interesting ones involve both together
  - Geometric topology
  - Boundary conditions
  - Processor decomposition

# ListSetsNTags Example (C)

```
#include "iMesh.h"

int main( int argc, char *argv[] )
{
    char *filename = argv[1];

    // create the Mesh instance
    iMesh_Instance mesh;
    int err;
    iMesh_newMesh(NULL, &mesh, &err, 0);

    iBase_EntitySetHandle root_set;
    iMesh_getRootSet(mesh, &root_set, &err);

    // load the mesh
    iMesh_load(mesh, root_set, filename, NULL,
        &err, strlen(filename), 0);

    // get all sets
    iBase_EntitySetHandle *sets = NULL;
    int sets_alloc = 0, sets_size;
    iMesh_getEntSets(mesh, root_set, 1, &sets,
        &sets_alloc, &sets_size, &err);

    // iterate through them
    iBase_TagHandle *tags = NULL;
    int tags_alloc = 0, tags_size;
    int i, j;
    for (i = 0; i < sets_size; i++) {
        // get connectivity
        iMesh_getAllEntSetTags(mesh, sets[i],
            &tags, &tags_alloc, &tags_size, &err);

        if (0 != tags_size) {
            printf("Set %ld: Tags:", sets[i]);

            // list tag names on this set
            for (j = 0; j < tags_size; j++) {
                char tname[128];
                int int_val, tname_size, tag_type;
                double dbl_val;
                iMesh_getTagName(mesh, tags[j], tname,
                    &err, tname_size);
                printf("%s", tname);
                iMesh_getTagType(mesh, tags[j],
                    &tag_type, &err);
                if (iBase_INTEGER == tag_type) {
                    iMesh_getEntSetIntData(mesh, sets[i],
                        tags[j], &int_val, &err);
                    printf("(val = %d);", int_val);
                }
                else if (iBase_DOUBLE == tag_type) {
                    iMesh_getEntSetDblData(mesh, sets[i],
                        tags[j], &dbl_val, &err);
                    printf("(val = %f);", dbl_val);
                }
                else printf("; ");
            }
            printf("\n");
            free(tags); tags = NULL; tags_alloc = 0;
        }
    }

    return 0;
}
```



## ListSetsNTags Example Notes

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- Enumerated variables passed as int, compared to enum types (e.g. iBase\_SUCCESS, iBase\_INTEGER)

# iMesh Interface Review

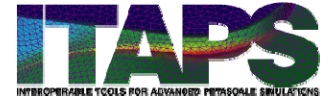
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- Data model consists of 4 basic types: Interface, Entity, Entity Set, Tag
- Applications reference instances of these using opaque handles
- ITAPS interfaces use C-based APIs, for efficiency and interoperability
  - SIDL-based implementation also available, which works through C-based API
- Not covered here:
  - Iterators (intermediate-level, “chunked” access to mesh)
  - Modify (relatively coarse-grained, basically create and delete whole entities)
  - Set parent-child links

# Parallel Mesh Interfaces

# iMeshP extends iMesh to support parallel computations

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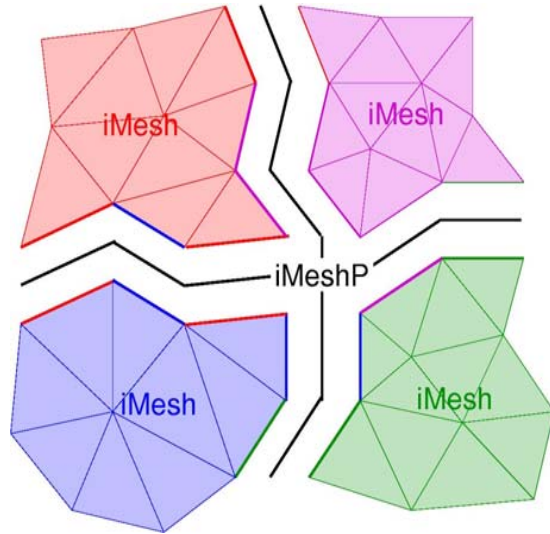
Example functionalities directly supported by iMeshP:

- Loading meshes onto parallel computers
- Maintaining relationships between mesh entities on different parts including boundary and ghost data
- Communicating tag data between parts
- Moving mesh entities between parts and re-establish communication links

Sufficient for building services such as:

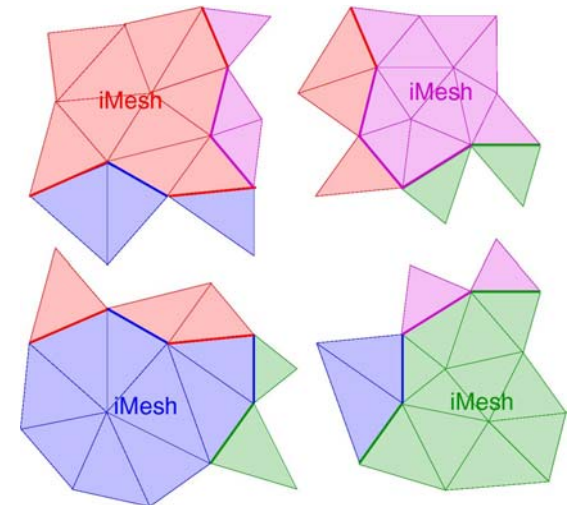
- Parallel mesh generation/improvement/modification
- Partitioning and repartitioning

# Recall the partition model defined by the iMeshP parallel interface



- *Process*: a program executing; MPI process
  - # of processes == MPI\_Comm\_size
  - Process number == MPI\_Comm\_rank
- *iMesh instance*: mesh database provided by an implementation
  - One or more instances per process
- *Partition*: describes a parallel mesh
  - Maps entities to subsets called *parts*
  - Maps parts to processes
  - Has a communicator associated with it

- *Ownership*: right to modify an entity
- *Internal entity*: Owned entity not on an interpart boundary
- *Part-Boundary entity*: Entity on an interpart boundary
- *Ghost entity*: Non-owned, non-part-boundary entity in a part
- *Copies*: ghost entities + non-owned part-boundary entities





# iMeshP Partition API Functions

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- Create partition
  - Accepts pointer to MPI Communicator or NULL
  - `iMeshP_createPartitionAll`
- Destroy partition
  - `iMeshP_destroyPartitionAll`
- Sync partition
  - After parts are added/updated, compute and store global information about the partition
  - `iMeshP_syncPartitionAll`
- Return number of parts in partition
  - `iMeshP_getNumParts`
- Return global number of entities of given type/topology in partition
  - May require collective communication

## Part characteristics

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- Think in terms of parts, not processes
  - Number of parts may be less than, equal to, or greater than number of processes
- Part contains entities it owns + copies of entities needed for computation within the part
- Wholly stored in a single process
- Accessed and identified via part IDs
  - Unique global identifiers for parts
- Local (on-process) parts also can be accessed through part handles

# iMeshP Part API Functions

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- Create part and add to partition.
  - iMeshP\_createPart
- Remove part and destroy it.
  - iMeshP\_destroyPart
- Return part neighbors.
  - Parts A and B are neighbors if Part A has copies of entities owned by Part B or vice versa.
  - iMeshP\_getNumPartNbors, iMeshP\_getPartNbors
- Iterate over part-boundary entities.
  - iMeshP\_initPartBdryEntIter

## iMeshP Part API Functions

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- Part handles can be used as set handles.
  - iMesh functions overloaded to take part handles.
- Examples:
  - Add and remove entities from part with `iMesh_addEntToSet` and `iMesh_rmvEntFromSet`.
  - Get number of entities in part with `iMesh_getNumOfType`, `iMesh_getNumOfTopo`.
  - Get info for entities in part with `iMesh_getEntities`, `iMesh_getVtxArrCoords`, `iMesh_getAdjEntities`, etc.

# Entity Characteristics

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- No globally unique entity IDs are required or supplied.
  - Can be constructed by user as pair: [part ID, entity handle].
- Each entity is owned by only one part per partition.
  - Ownership grants right to modify.
- Entities may be copied on other parts.
- Duplicated information for copies:
  - Owner of an entity knows remote part and remote entity handle of all its copies.
  - All boundary entities know all remote parts and remote entity handles of all copies.
  - All ghost copies of entity know the entity owner's part and the entity handle on the owner.
- Remote parts and entities are computed by a collective function called after mesh modification.
  - Queries for remote data do not require communication.



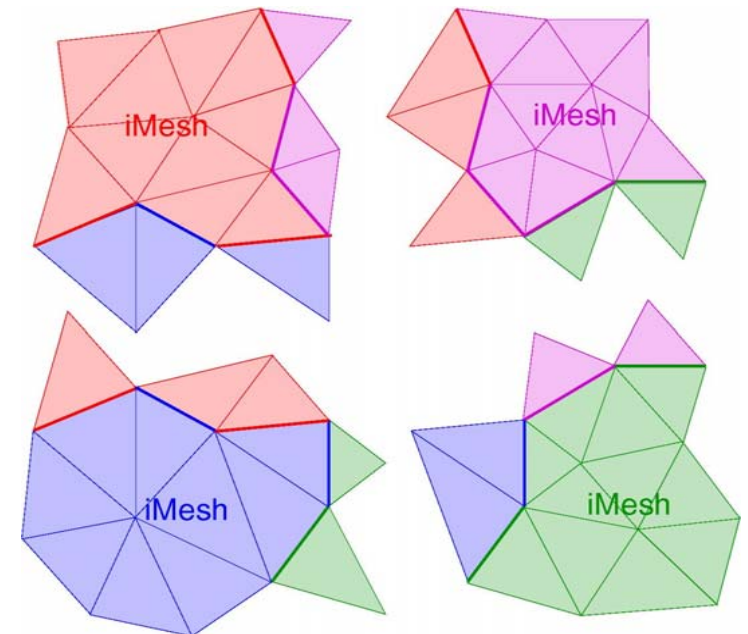
# iMeshP Entity API Functions

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- Determine ownership of entity.
  - iMeshP\_getEntOwnerPart, iMeshP\_isEntOwner
- Determine whether entity is internal, boundary, ghost.
  - iMeshP\_getEntStatus
- Return remote part and remote entity handles for copies of entity.
  - iMeshP\_getNumCopies, iMeshP\_getCopyParts, iMeshP\_getCopies, iMeshP\_getCopyOnPart
- Return owner part and owner entity handle for an entity.
  - iMeshP\_getEntOwnerPart, iMeshP\_getOwnerCopy

# Ghost Entities

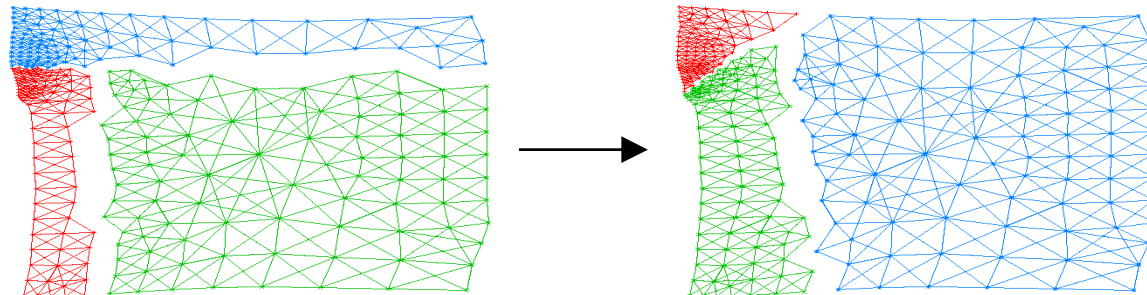
- Create ghost entities for each part.
  - `iMeshP_createGhostEnts`
  - Specify ghost-entity dimension, bridge dimension, and number of layers.
    - E.g., one layer of ghost triangles for all boundary triangles sharing edges:
      - Ghost-entity dimension = 2
      - Bridge-entity dimension = 1
      - Number of layers = 1
    - Cumulative over multiple calls.
- Delete all ghost entities.
  - `iMeshP_deleteGhostEnts`



# Inter-part Mesh Operations

---

- iMeshP provides functions for inter-part operations on mesh entities.
  - Exchange tag values.
  - Migrate large numbers of entities for, say, load balancing.
  - Migrate small numbers of entities for, say, mesh modification.
  - Update mesh database during mesh modification.



# Inter-part Mesh Operation Requests

---

- Inter-part mesh operations are coordinated via iMeshP\_Requests.
  - More than an MPI\_Request!
  - Indicate status of a given iMeshP mesh operation.
    - Migrate entity.
    - Update vertex coordinates.
    - Update part-boundary entities.
    - Exchange tag data.
  - iMeshP encodes type of request and operations to be performed in iMeshP\_Request.
  - iMeshP\_Request completes when entire mesh operation is completed.

# Inter-part Mesh Operations can be blocking or non-blocking.

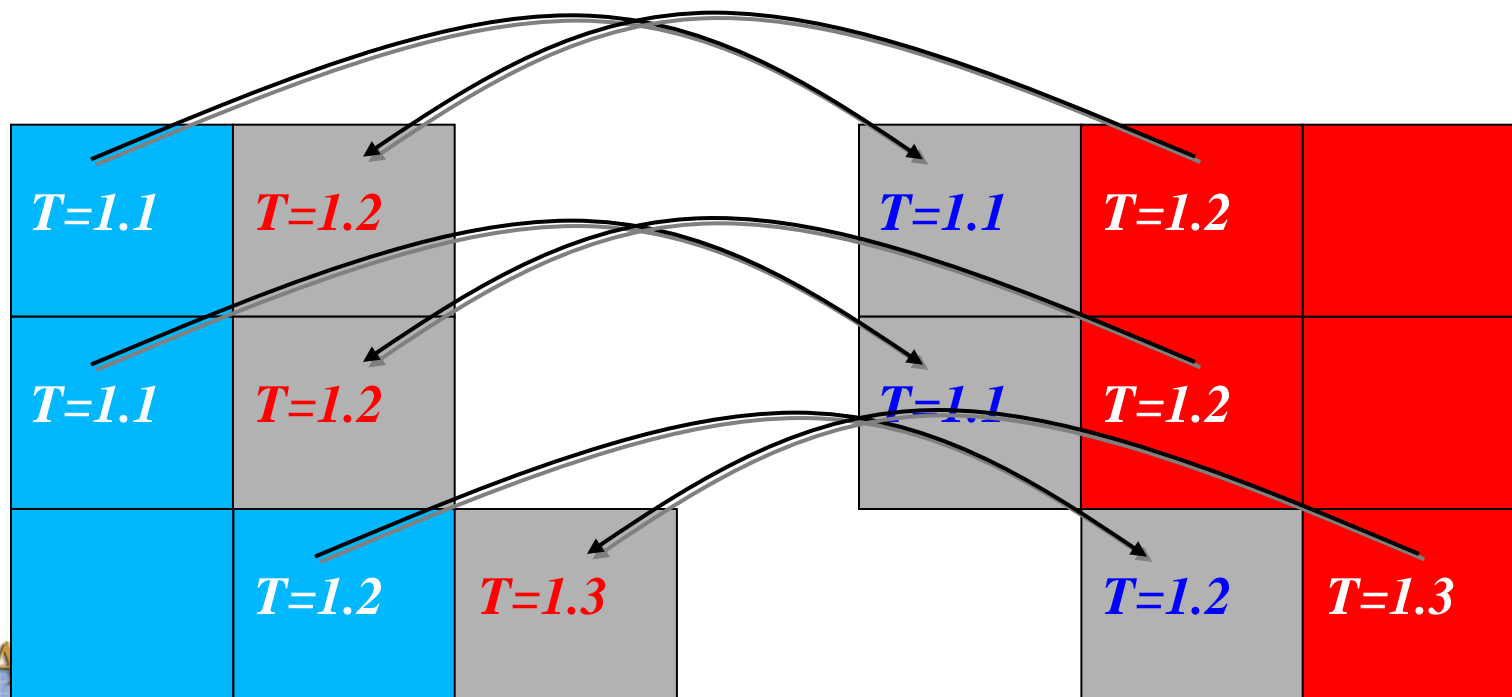
---

- Blocking operations do not return from iMeshP until request is complete.
- Non-blocking operations return from iMeshP after request is made. Application later waits until request is fulfilled.
  - iMeshP API contains functions to ...
    - Wait for request completion,
    - Test for request completion, and
    - Poll for and carry out requests received.
  - Allows overlapping communication/computation.
  - Allows asynchronous communication.



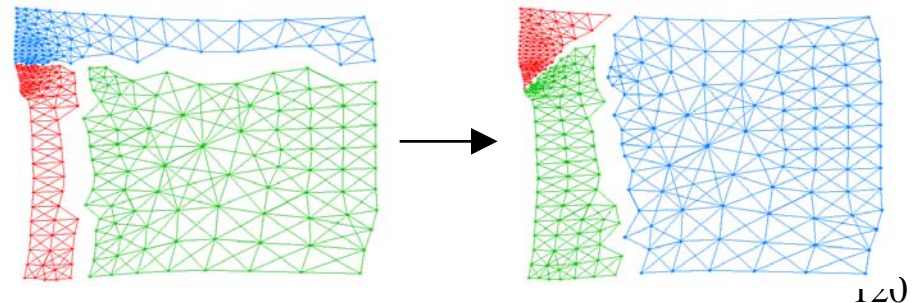
# Communicate Entity Tag Data

- Entity owners send tag data to copies.
- iMeshP API provides both blocking and non-blocking versions of tag-data exchange.
  - iMeshP\_pushTagData, iMeshP\_iPushTagData



# Large-Scale Migration

- In application, each part calls iMeshP to migrate (push) array of entities to new parts. (iMeshP\_sendEntArr)
  - iMeshP computes and posts appropriate receives.
  - iMeshP sends entities to new parts.
  - iMeshP deletes entities from old parts.
  - iMeshP returns an iMeshP\_Request.
- Application does something else for awhile.
- In application, each part calls iMeshP\_Wait function with the iMeshP\_Request returned by send.
  - iMeshP waits to receive messages.
  - iMeshP adds entities to new parts and updates mesh.



# Updating Mesh Consistency

---

- After all mesh modification is done, application calls **iMeshP\_syncMeshAll**.
  - A collective, blocking call that signals mesh modification operations are completed.
  - Polls for and processes outstanding requests.
  - Updates ghost entities for modified mesh.
  - Performs operations needed for parallel mesh consistency.

# Parallel I/O

---

- Load a mesh from files.
  - Populate a mesh instance and a partition handle.
  - iMeshP\_Load
- Write a mesh to files.
  - Store mesh data and partition data in files.
  - iMeshP\_Save
- Options specified through parameter strings.
  - File names, file format, number of files, initial partitioning.
  - Analogous to iMesh load and save functions.

# PART 5: ITAPS Software

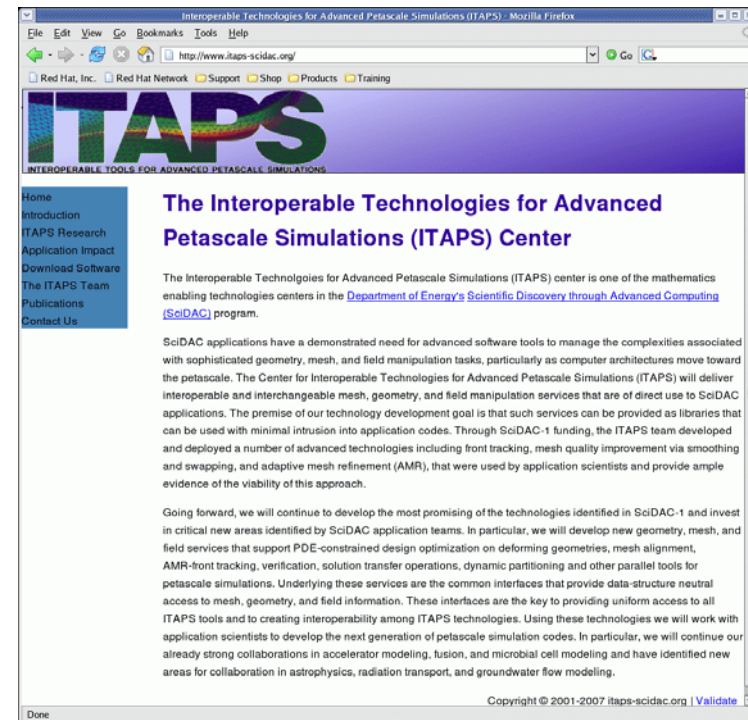




# ITAPS Web Pages

*<http://www.itaps-scidac.org>*

- Provides help getting started
- Usage strategies
- Data model description
- Access to interface specifications, documentation, implementations
- Access to compatible services software



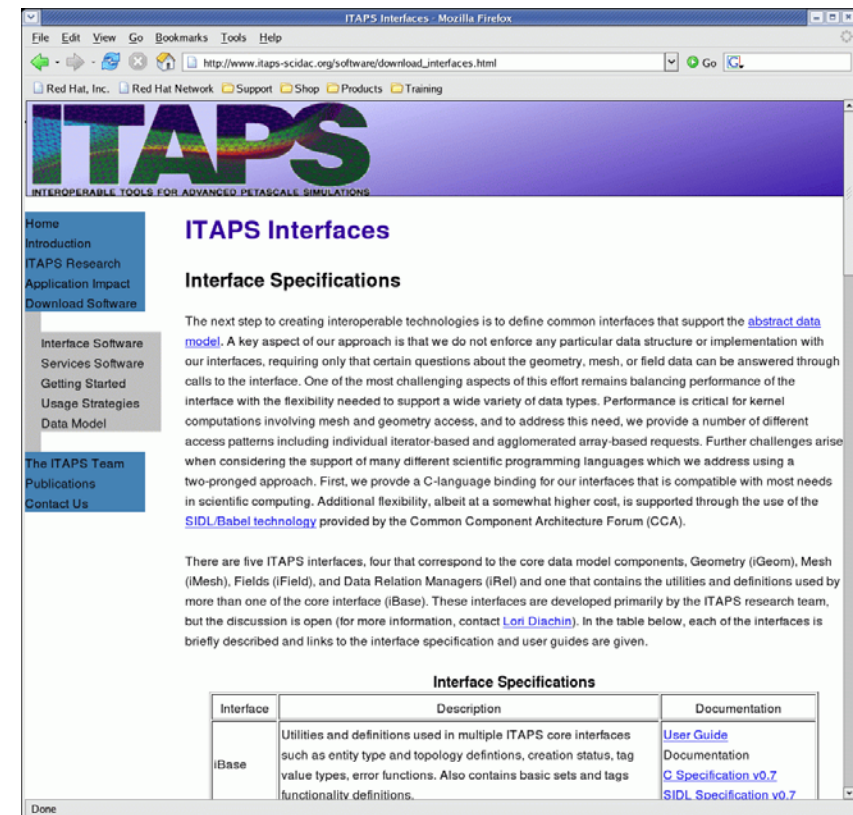
# Interface implementations are well underway

---

- iMesh 0.7 Interface complete
- iMeshP 0.5 specified and alpha implementations underway
- iGeom and iRel 0.7 interfaces complete
- Implementations
  - iMesh: FMDB, GRUMMP, NWGrid, MOAB
  - iMeshP: FMDB, MOAB
  - iGeom: CGM (Acis, OpenCasCade)
  - iRel: Lasso
- Interfaces have been used to build services and test interoperability
- Analyzing performance when using interface

# Interface Software Access

- Links to the interface user guides and man pages where available
- Links to implementations for iMesh, iGeom, iRel
  - Version 0.7 compatible software
  - Links to the home pages for more information
- Simple examples, compliance testing tools and build skeletons



**ITAPS Interfaces**

**Interface Specifications**

The next step in creating interoperable technologies is to define common interfaces that support the [abstract data model](#). A key aspect of our approach is that we do not enforce any particular data structure or implementation with our interfaces, requiring only that certain questions about the geometry, mesh, or field data can be answered through calls to the interface. One of the most challenging aspects of this effort remains balancing performance of the interface with the flexibility needed to support a wide variety of data types. Performance is critical for kernel computations involving mesh and geometry access, and to address this need, we provide a number of different access patterns including individual iterator-based and agglomerated array-based requests. Further challenges arise when considering the support of many different scientific programming languages which we address using a two-pronged approach. First, we provide a C-language binding for our interfaces that is compatible with most needs in scientific computing. Additional flexibility, albeit at a somewhat higher cost, is supported through the use of the [SIDL Babel technology](#) provided by the Common Component Architecture Forum (CCA).

There are five ITAPS interfaces, four that correspond to the core data model components, Geometry (iGeom), Mesh (iMesh), Fields (iField), and Data Relation Managers (iRel) and one that contains the utilities and definitions used by more than one of the core interface (iBase). These interfaces are developed primarily by the ITAPS research team, but the discussion is open (for more information, contact [Lori Diachin](#)). In the table below, each of the interfaces is briefly described and links to the interface specification and user guides are given.

| Interface Specifications |  |  |
|--------------------------|--|--|
| Interface                | Description  | Documentation  |
| iBase                    | Utilities and definitions used in multiple ITAPS core interfaces such as entity type and topology definitions, creation status, tag value types, error functions. Also contains basic sets and tags functionality definitions. | <a href="#">User Guide</a><br><a href="#">Documentation</a><br><a href="#">C Specification v0.7</a><br><a href="#">SIDL Specification v0.7</a> |

# FMDB Implementation

---

- Supports general set of mesh topologies
- Strengths are: adaptively changing meshes, flexible adjacency information
- Formal partition model supports parallel operations
- **iMesh** implementation is complete
- **iMeshP** implementation is alpha; current successful tests include functions required for some mesh adapt functions, partitioning, and migration
- Application use includes Fusion, Accelerators, and CFD

# MOAB Implementation

---

- Supports hex, tet, prism, pyramid, tri, quad
  - Reads meshes generated by CUBIT, including geometric topology and a few other common formats
- Strengths are efficient memory management
- Includes tools for
  - OBB and kd tree construction and query
  - Read CGM/iGeom model & save as mesh-based model
  - Solution coupling
- Complete implementation of iMesh, iMeshP
- Application use includes nuclear reactor modeling, neutron transport, accelerator design optimization



# GRUMMP Implementation

---

- Supports tri, quad, tet
- Strengths are: tri/tet meshing, mesh improvement and adaptation
- iMesh implementation is complete
- iMeshP implementation is planned
- Application use includes CFD, especially aerodynamics and non-Newtonian fluids

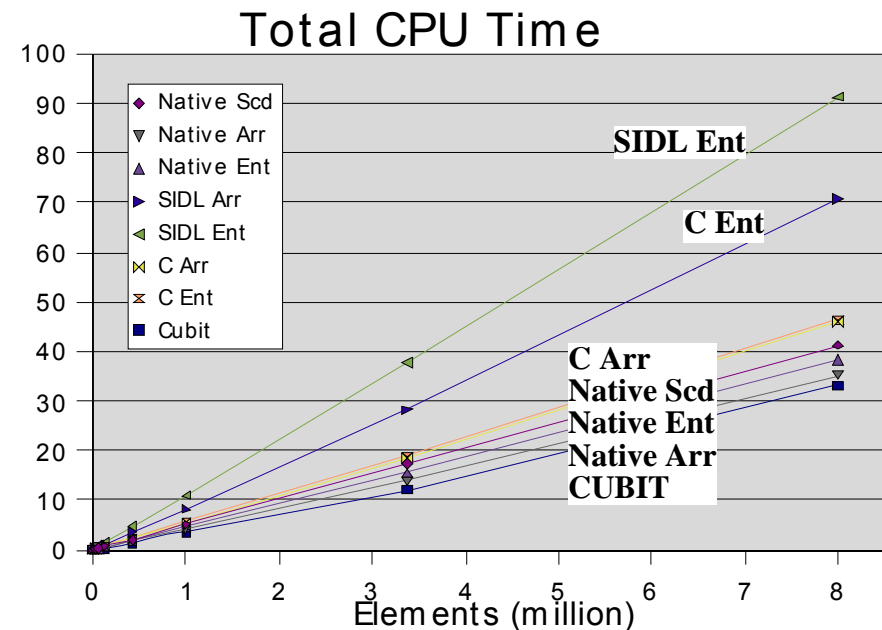
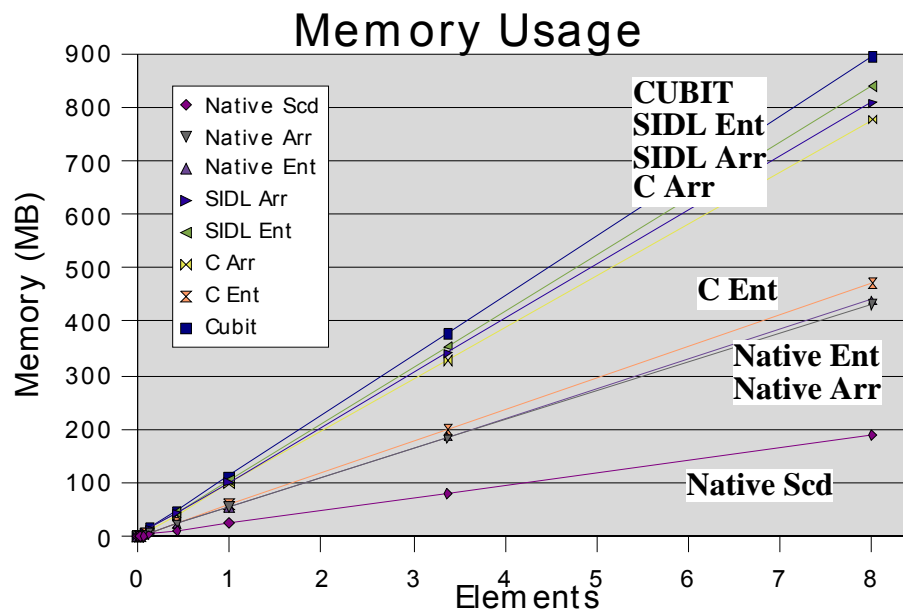
# NWGRID Implementation

---

- Supports hex, tet, pyramid, tri, quad and hybrid meshes
- Strengths are: adaptive mesh refinement and dynamic mesh reconnections for simplex meshes
- Supports shared memory parallelism using Global Arrays
- iMesh implementation is complete
- iMeshP implementation is in process
- Application use includes biology, CFD/CMM/CEM, subsurface transport

# Performance

- Large applications balance memory and cpu time performance
- Implementations of iMesh vary on speed vs. memory performance
  - Create, v-E, E-v query, square all-hex mesh
  - Entity- vs. Array-based access
- Compare iMesh (C, SIDL), Native (MOAB), Native Scd (MOAB), CUBIT
  - Ent-, Arr-based access
  - All-hexahedral square structured mesh



# Performance in building a finite element stiffness matrix

- Set up a simple stiffness matrix for a 2D diffusion equation
- Examine costs of entity access via native data structures, arrays, entity iterators and workset iterators
- Arrays minimize time overhead but require a data copy
- Entity iterators are straightforward to program, minimize memory overhead, but maximize time cost
- Entity array iterators balance time/memory tradeoffs but are the most difficult to program

$$\nabla^2 u = f$$

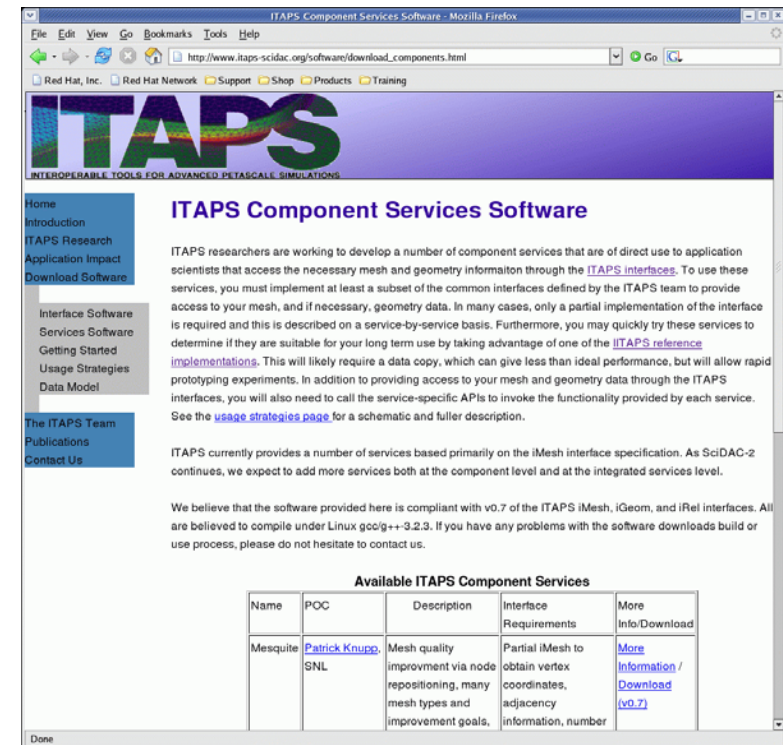
$$u(x=0)=1 \quad u(x=1) = 1$$

$$u_y(x=0, x=1) = 0$$

|                       | Time (ms) | iMesh Overhead |
|-----------------------|-----------|----------------|
| Native                | 10479     |                |
| Array-based           | 10774     | 2.8%           |
| Entity Iterator       | 11642     | 11.1%          |
| Workset Iterator (1)  | 11351     | 8.3%           |
| Workset Iterator (3)  | 11183     | 6.7%           |
| Workset Iterator (5)  | 11119     | 6.1%           |
| Workset Iterator (10) | 11095     | 5.8%           |
| Workset Iterator (20) | 11094     | 5.8%           |

# Services Software Access

- Links to the services built on the ITAPS interfaces
- Currently or very soon to be available
  - Mesquite (C, SIDL)
  - Zoltan (C, SIDL)
  - Swapping (SIDL)
  - Frontier (SIDL)
  - VisIt Plug In (C, SIDL)
- Links to home pages for more information
- Instructions for build and links to supporting software



**ITAPS Component Services Software**

ITAPS researchers are working to develop a number of component services that are of direct use to application scientists that access the necessary mesh and geometry information through the [ITAPS interfaces](#). To use these services, you must implement at least a subset of the common interfaces defined by the ITAPS team to provide access to your mesh, and if necessary, geometry data. In many cases, only a partial implementation of the interface is required and this is described on a service-by-service basis. Furthermore, you may quickly try these services to determine if they are suitable for your long term use by taking advantage of one of the [ITAPS reference implementations](#). This will likely require a data copy, which can give less than ideal performance, but will allow rapid prototyping experiments. In addition to providing access to your mesh and geometry data through the ITAPS interfaces, you will also need to call the service-specific APIs to invoke the functionality provided by each service. See the [usage strategies page](#) for a schematic and fuller description.

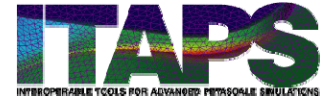
ITAPS currently provides a number of services based primarily on the iMesh interface specification. As SciDAC-2 continues, we expect to add more services both at the component level and at the integrated services level.

We believe that the software provided here is compliant with v0.7 of the ITAPS iMesh, iGeom, and iRel interfaces. All are believed to compile under Linux gcc/g++-3.2.3. If you have any problems with the software downloads build or use process, please do not hesitate to contact us.

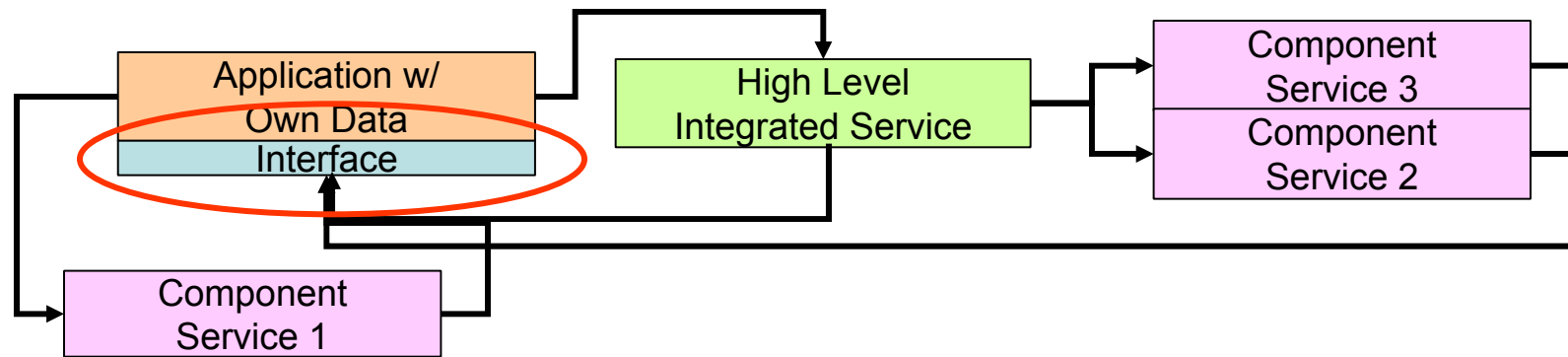
| Available ITAPS Component Services |                                    |   |   |  |
|------------------------------------|------------------------------------|---|---|--|
| Name                               | POC                                | Description   | Interface Requirements  | More Info/Download                                 |
| Mesquite                           | <a href="#">Patrick Knupp, SNL</a> | Mesh quality improvement via node repositioning, many mesh types and improvement goals. | Partial iMesh to obtain vertex coordinates, adjacency information, number | <a href="#">More Information / Download (v0.7)</a> |



# Implementing ITAPS interfaces allows use of services on your data structures



- Need to implement some ITAPS interface functions using your data structures – BUT NOT ALL
- Most ITAPS functions reflect things you already do with your databases; most implementation tasks are a thin wrapper
- Compliance testing tools ensure correctness
- Can use a reference implementation at the cost of a data copy to experiment with services



# Interface functions needed by the various services

---

|               | Coordinates | Adjacency | Other queries | Iterators | Modification | Basic Sets | Tags | Parallel | iGeom/iRel | Total |
|---------------|-------------|-----------|---------------|-----------|--------------|------------|------|----------|------------|-------|
| Mesquite      | 1           | 1         | 4             | 4         | 1            | 2          | 13   |          | 6          | 32    |
| Swapping      | 1           | 1         | 4             | 4         | 2            |            |      |          |            | 12    |
| Mesh Adapt    | 1           | 2         | 5             | 3         | 3            |            | 7    | 13       |            | 34    |
| FronTier Lite | 3           | 1         | 5             | 3         | 3            |            | 3    |          |            | 18    |
| Zoltan        | 1           | 2         | 5             |           |              |            |      | 14       |            | 22    |
| VisIt         | 1           | 1         | 9             | 3         |              | 1          | 16   |          |            | 31    |

# Notes regarding the interfaces needed by services

---

- Basic functionality such as vertex query, adjacency information, get type/topo are widely used
- Swapping needs efficient, correct iterators under modification
- Mesquite relies on tags and set boolean operations that may impact performance
- VisIt visualization routines require tag implementations to retrieve data to be analyzed
- MeshAdapt and Zoltan both use parallel interface functions for setting and getting partition data as well as exchanging data among processors.

# Performance of iMesh Swap for 3D Meshes

- Comparing GRUMMP native implementation to service with GRUMMP iMesh implementation
- Most remaining overhead is in transcribing data to return format expected by iMesh

| Case     | # of Tets | Native |            | iMesh |            |
|----------|-----------|--------|------------|-------|------------|
|          |           | Swaps  | Rate (1/s) | Swaps | Rate (1/s) |
| Rand1    | 5104      | 10632  | 29500      | 10838 | 21300      |
| Rand2    | 25704     | 65886  | 27700      | 67483 | 22100      |
| Airplane | 251140    | 25448  | 3380       | 28629 | 2800       |
| Rocket   | 464080    | 53331  | 3540       | 59330 | 2790       |

# Performance of Zoltan Partitioning for 3D Meshes

- Comparing MOAB native implementation linking to Zoltan partitioning service with the MOAB iMesh implementation
- Using a coordinate bisection geometric partitioner on tetrahedral meshes and array-based access to the data

| Number of Tets | Native (sec) | iMesh (sec) | iMesh Overhead |
|----------------|--------------|-------------|----------------|
| 15591          | 0.866        | 0.869       | 0.35%          |
| 20347          | 0.971        | 0.976       | 0.51%          |
| 34750          | 1.28         | 1.31        | 2.34%          |
| 54383          | 1.72         | 1.75        | 1.74%          |
| 100630         | 2.76         | 2.82        | 2.17%          |



# Compliance testing is your friend

---

- Why bother?
  - Confirm an implementation complies with iMesh spec --- enhances interoperability
  - Confirm that a partial implementation supports a service --- ensures plug-and-play with services
- About the compliance test suite
  - Covers all functions
  - Supplements documentation with unambiguous software interpretation of interface
  - Coordinate and adjacency checks rely on consistency between different retrieval strategies
  - Set and tag functionality testable directly
  - Builds just like any other iMesh application
- Work in progress on testing partial implementations effectively

# ITAPS Interfaces: Best Practices

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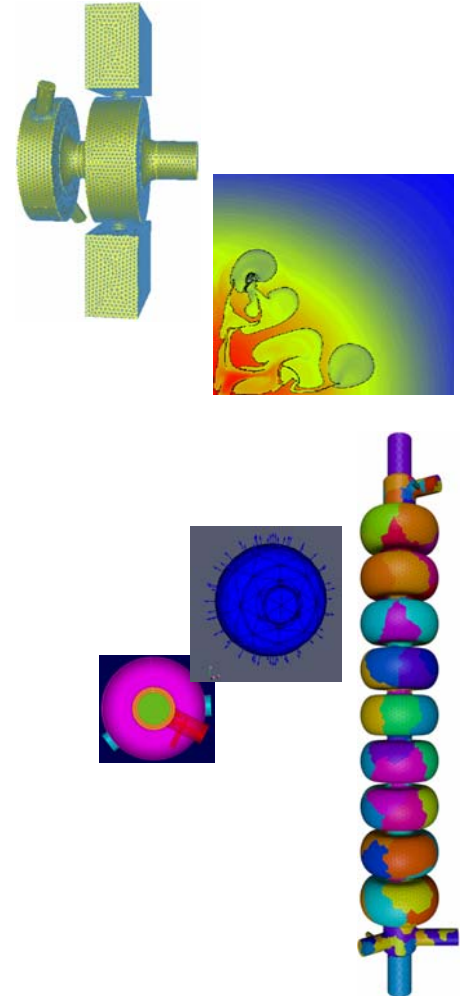
- Use C-based interface where possible, for efficiency
- Pre-allocate memory in application or re-use memory allocated by implementation
  - E.g. getting vertices adjacent to element – can use static array, or application-native storage
- Take advantage of implementation-provided capabilities and iMesh compliant services
  - Partitioning, IO, parallel communication, (parallel) file readers
- Try different implementations: they are tuned for different application uses – Experiment!
- Implement iMesh on top of your data structure
  - Take advantage of tools that work on iMesh API
- Let us help you
  - Not all best practices are easily described or self-evident

# PART 6: Using ITAPS: Approaches and Experiences

# ITAPS impact SciDAC applications in three ways

---

- Direct use of ITAPS technology in applications
  - Geometry tools, mesh generation and optimization for accelerators and fusion
  - Mesh adaptivity for accelerators and fusion
  - Front tracking for astrophysics and groundwater
  - Partitioning techniques for accelerators and fusion
- Technology advancement through demonstration and insertion of key new technology areas
  - Design optimization loop for accelerators (w/ TOPS)
  - Petascale mesh generation for accelerators
- Enabling future applications with ITAPS services and interfaces
  - Parallel mesh-to-mesh transfer for multi-scale, multi-physics applications
  - Dynamic mesh services for adaptive computations





# Case Study 1: Incorporating Parallel Adaptive Applications

# Parallel adaptive loops

— Accelerator

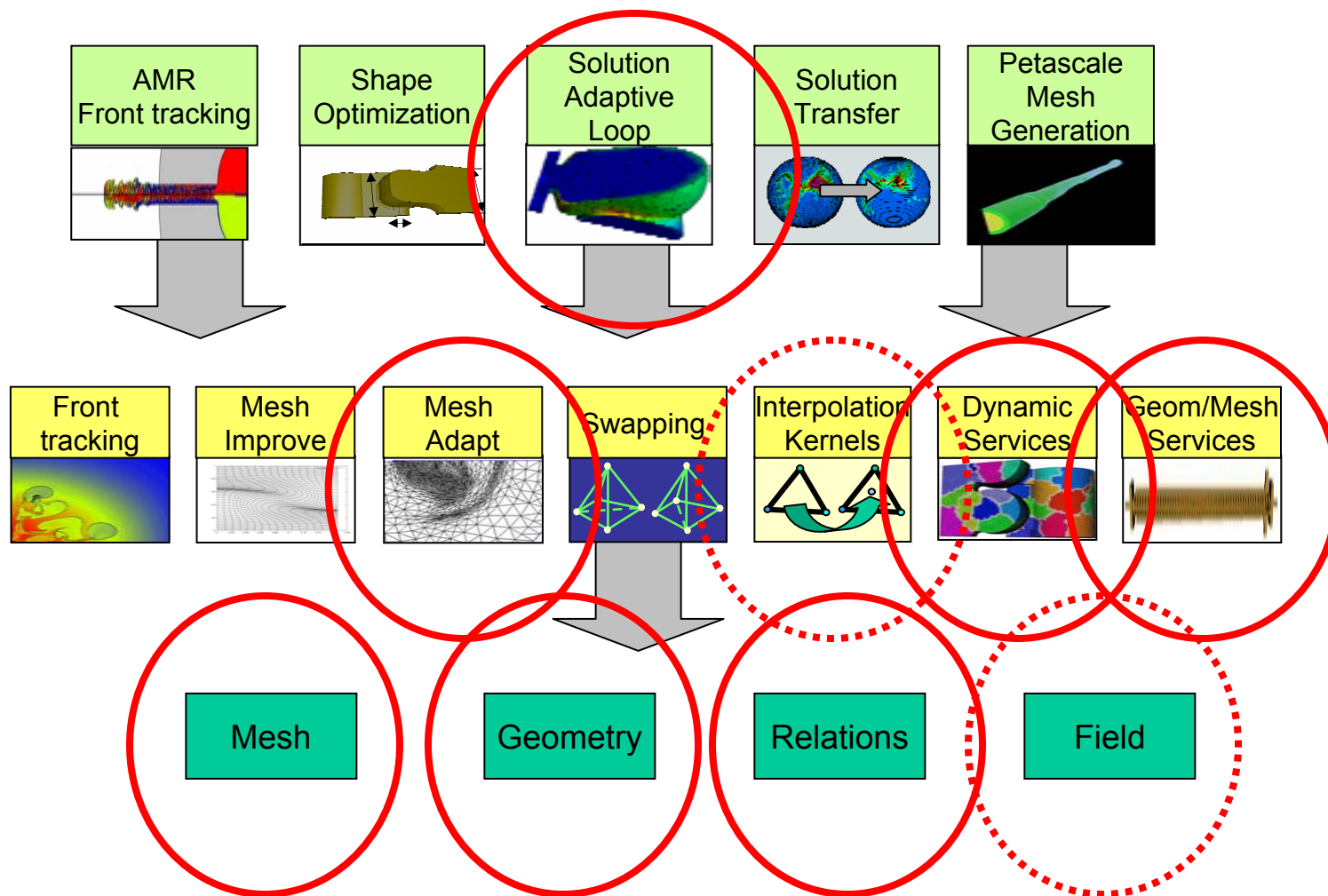
**Petascale  
Integrated  
Tools**

*Build on*

**Component  
Tools**

*Are unified  
by*

**Common  
Interfaces**





# Parallel Adaptive Applications

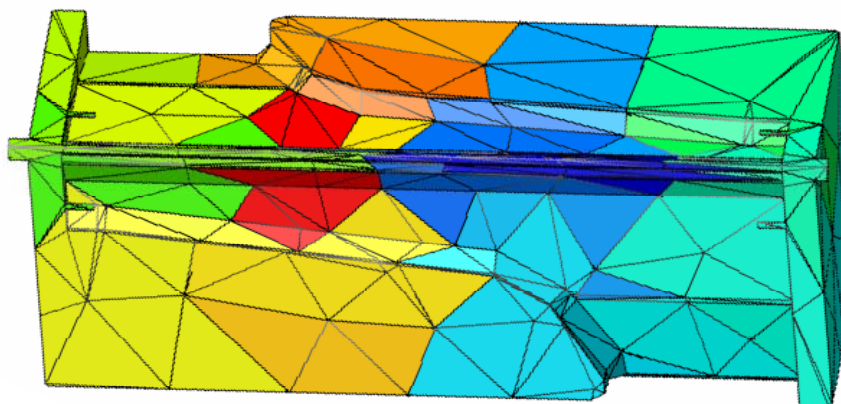
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- Parallel adaptive application requires integration of parallel components for
  - Unstructured grid solver
  - Error estimation and mesh size field construction
  - Mesh adaptation
  - Dynamic load balancing with repartitioning
- With these components ITAPS has constructed parallel adaptive applications

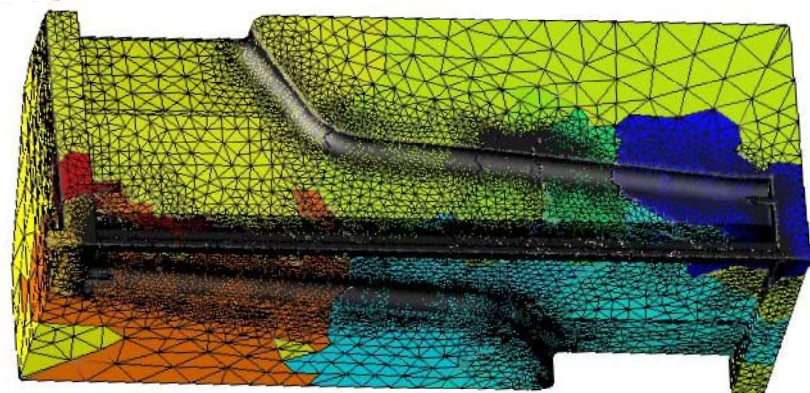
# Adaptive Loop for SLAC Accelerator Design

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- Components:
  - ACIS CAD modeler, Omega3P
  - ITAPS/SCOREC mesh adaptation
  - Error estimations
- Parallel adaptive loop control



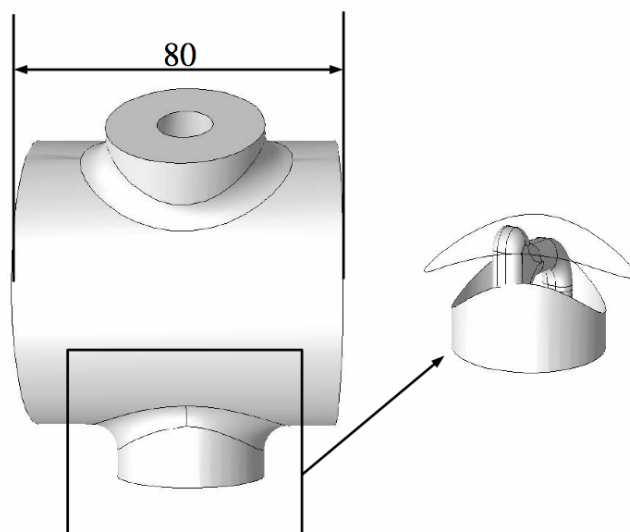
Initial mesh (1,595 tets)



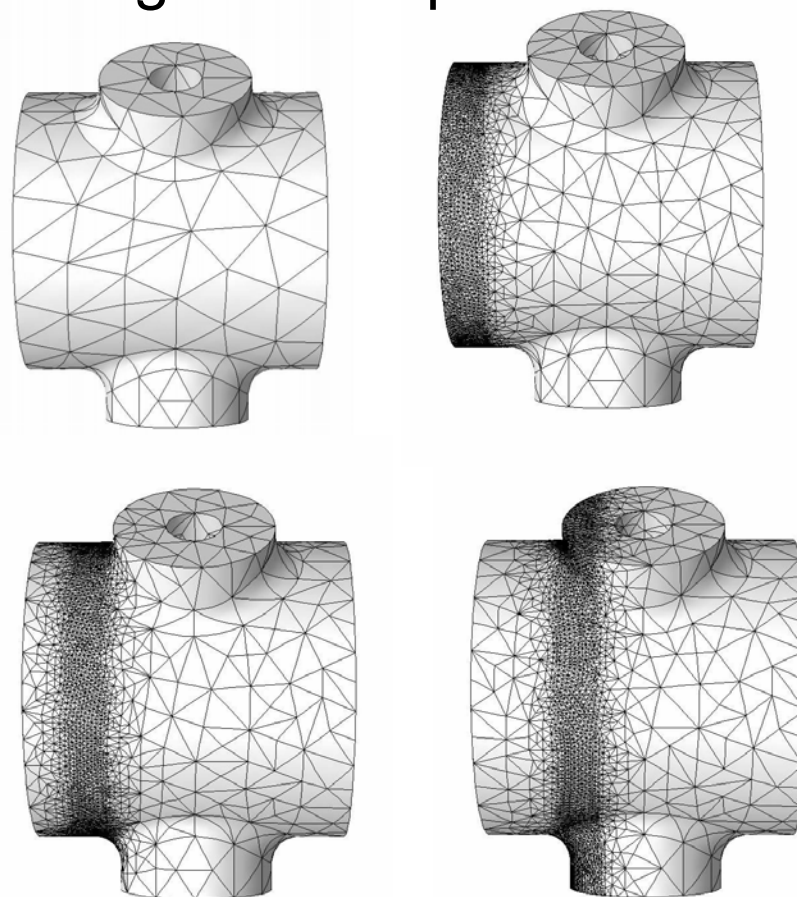
Adapted mesh (23,082,517 tets)

# Adaptive Mesh Refinement for SLAC Accelerator Design

- Higher order finite element time domain analysis in SLAC
- Require local mesh refinement around the particle domain
- The mesh refinement moves along with the particle



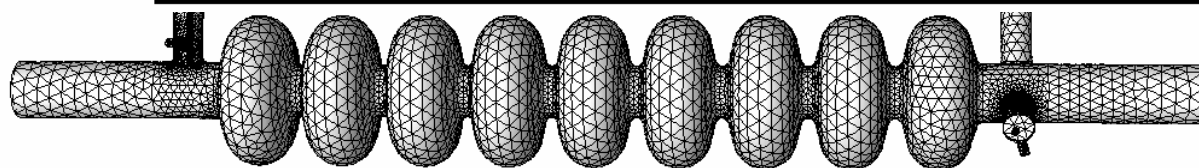
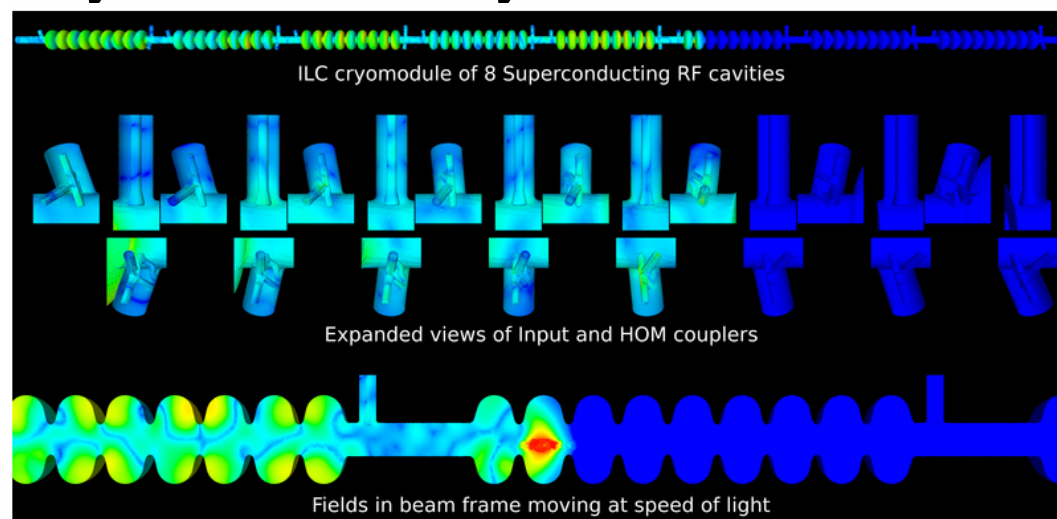
- Controlled refined meshes 1-1.5M
- Uniformly refined meshes 6 M



# Adaptive Mesh Curving for SLAC Accelerator Design

- Higher order finite element analysis engine - Omega3P from SLAC
- Valid higher order curvilinear mesh - adaptive mesh curving correction tools from ITAPS/SCOREC
- Improved solution accuracy and efficiency

- 2.97 million curved regions
- 1,583 invalid elements corrected
- lead to stable simulation and execute 30% faster



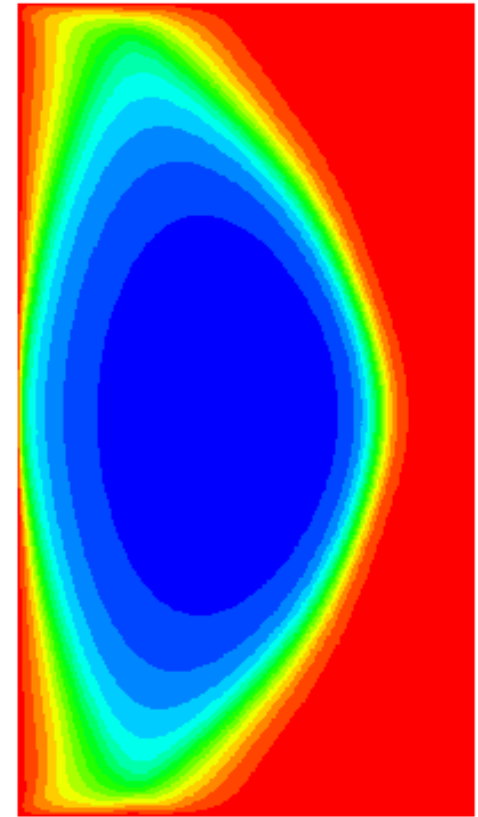
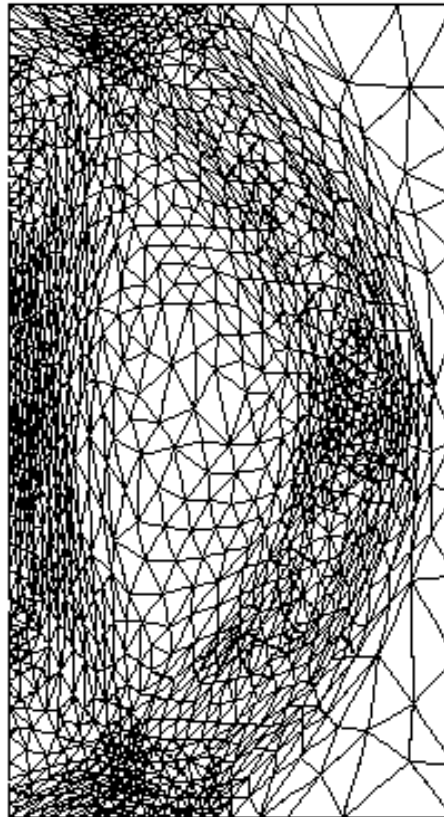
8-cavity cryomodule simulation



# Adaptive Loop for PPPL

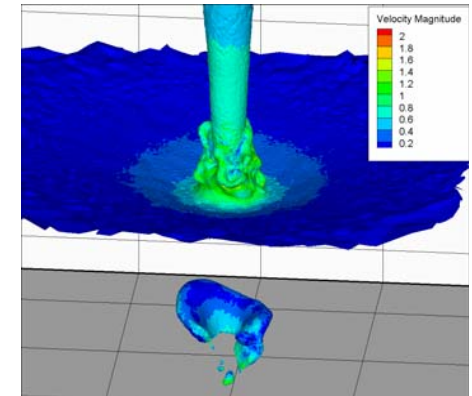
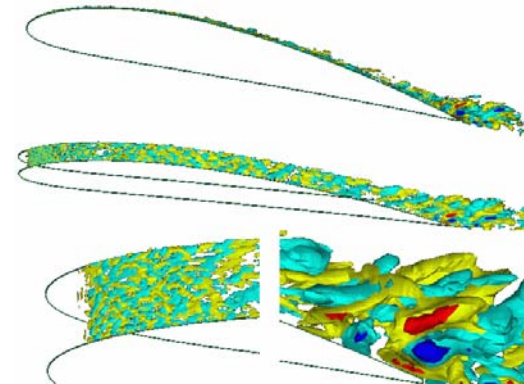
## CEMM M3D-C1 MHD Simulations

- Restructured M3D-C1 to support general unstructured meshes
- Provided API level for interacting with mesh and solvers (three-way interactions between CEMM, ITAPS and TOPS)
- Developed initial anisotropic mesh adaptation procedure
- Extending code to deal with complex boundary conditions on curved domains using the high order M3D-C1 elements



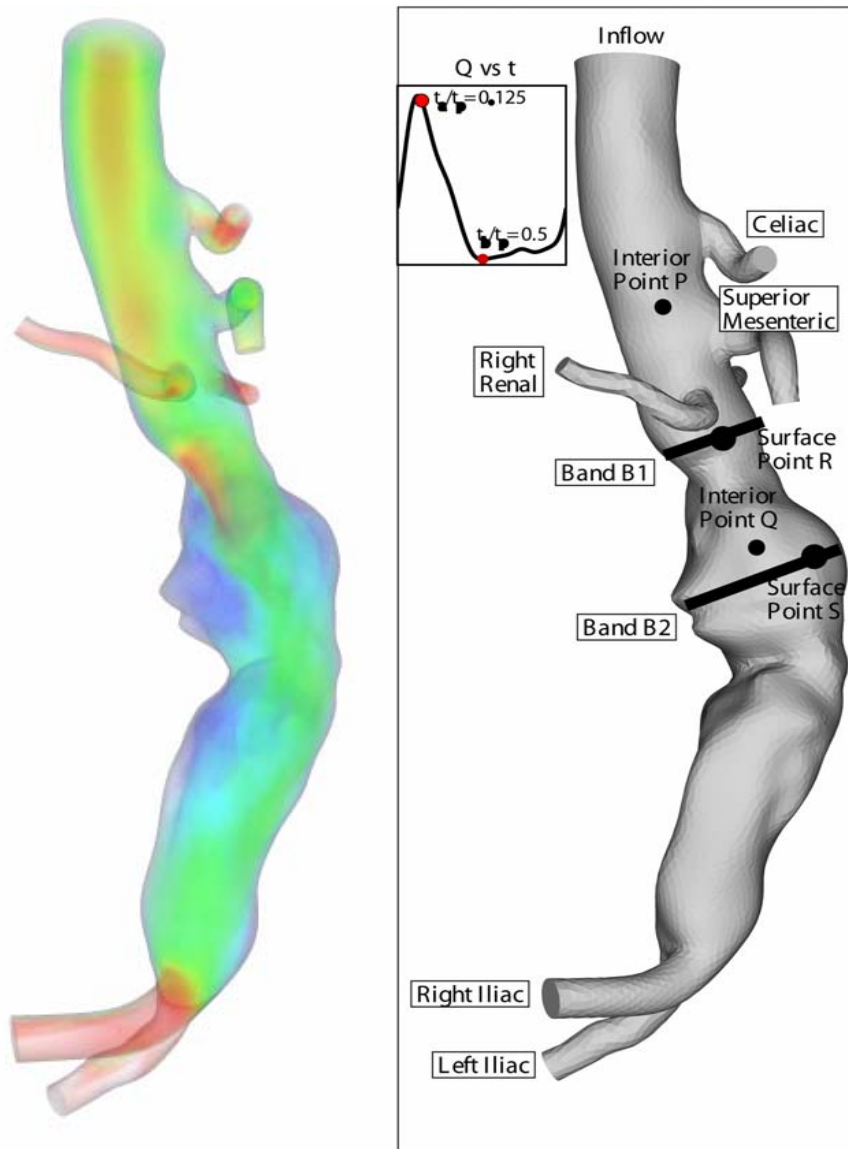
# PHASTA Flow Simulation Code

- Parallel finite element flow solver
  - compressible and incompressible flows
  - Turbulence DNS, LES, RANSS/DES
  - Two-phase (immiscible) fluids
- Implicit time integration -
  - solution of linear algebra at each time step using iterative solvers
- Breaks the total domain into parts with roughly the same number of elements on each processor.
- Work can be characterized as requiring:
  - Substantial floating point operations to form equations
  - Organized, substantial, and regular communication between partitions that touch each other
  - For each iteration ( $O(10)$  iterations per solve), there is a required ALL-REDUCE communication





# Scalability of the Solver

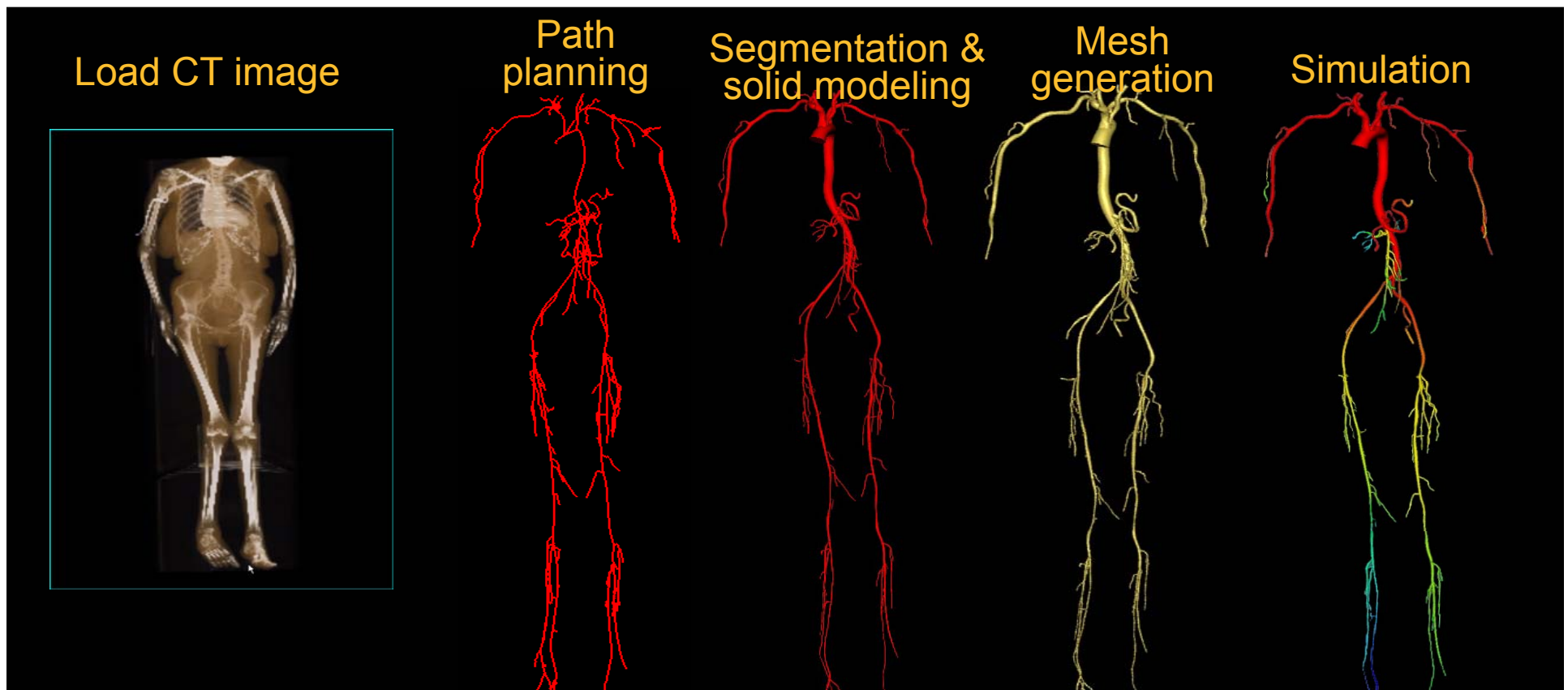


- Adapted mesh had  $> 50\text{M}$  dof
- Must be solve in 10 min.
  - Implicit FE flow solve scales

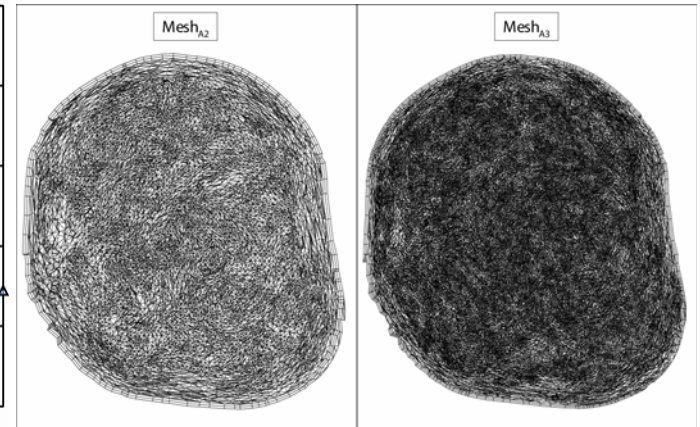
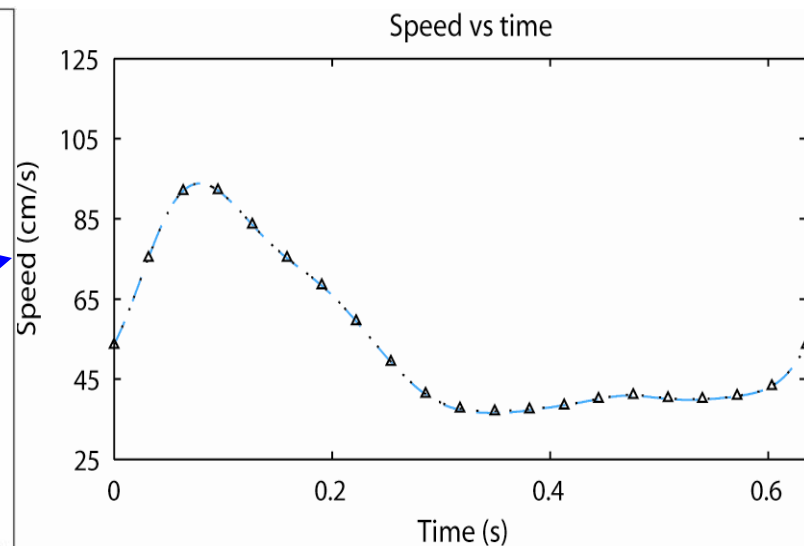
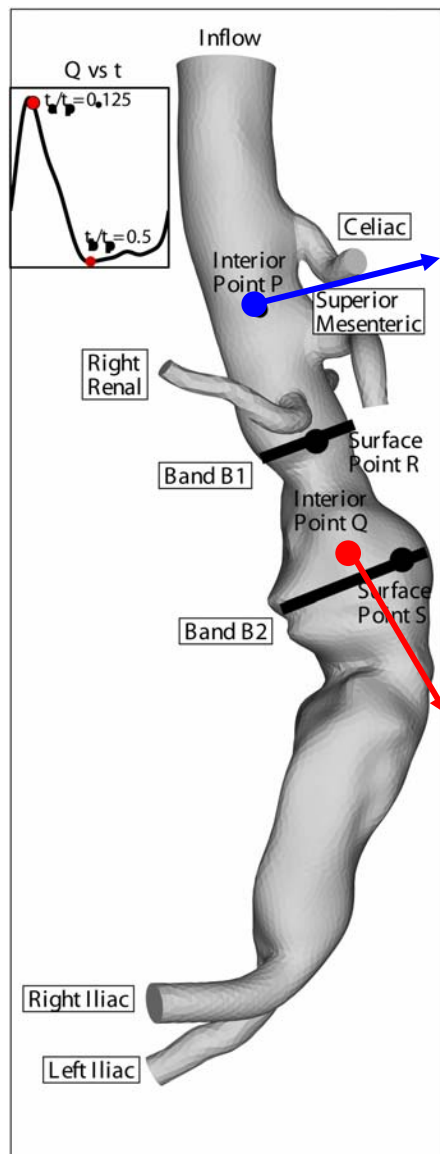
| # Proc. | t (sec) | scale |
|---------|---------|-------|
| 16384   | 60.6    | 1.04  |
| 8192    | 131.7   | 0.957 |
| 4096    | 241.6   | 1.04  |
| 2048    | 502.3   | 1.00  |
| 1024    | 1008.7  | 1.00  |

# Patient Specific Vascular Surgical Planning (Stanford, RPI)

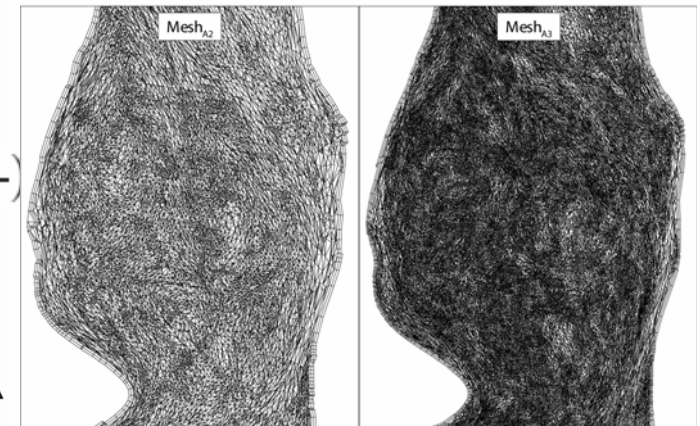
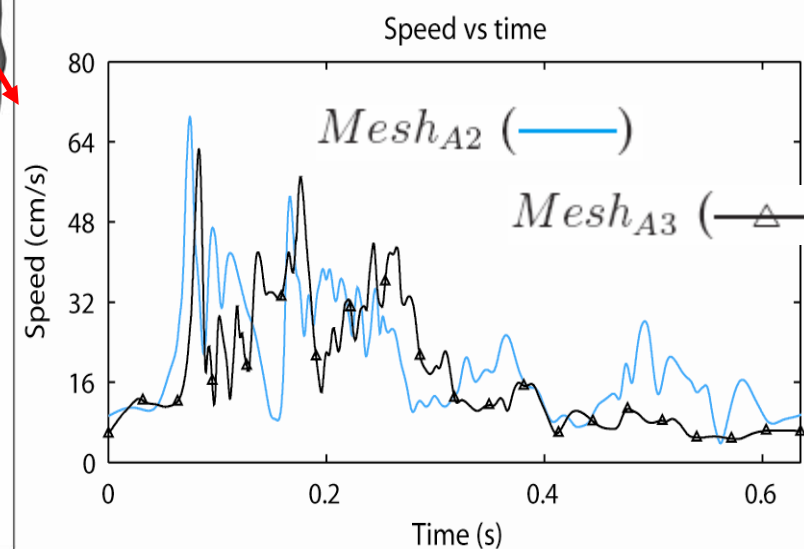
- Virtual flow facility for patient specific surgical planning
- High quality patient specific flow simulations needed quickly
- Image patent, create model, apply adaptive flow simulation



# Abdominal Aortic Aneurysm

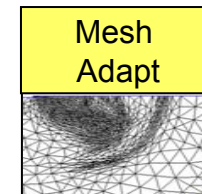
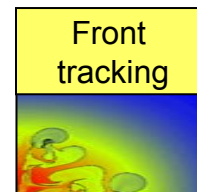
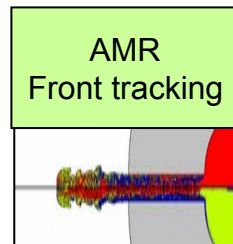


*Mesh<sub>A2</sub>* (—) *Mesh<sub>A3</sub>* (—△)



# Pellet Ablation for Tokamak Fuelling

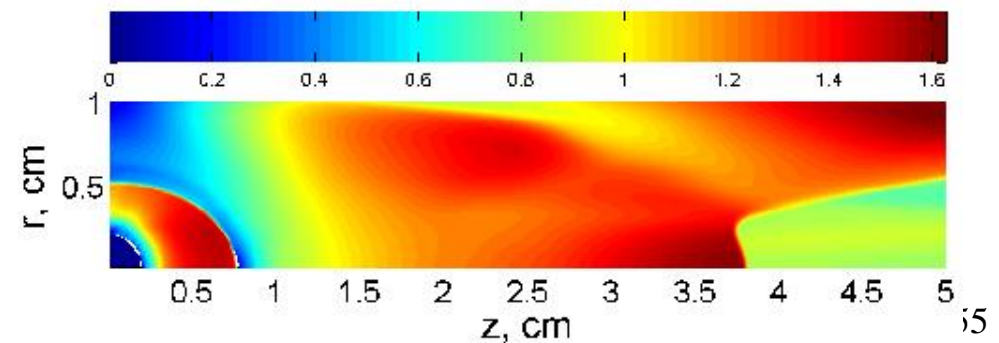
- Goals: Adaptive Meshing and Front Tracking for “microscale” studies of pellet ablation in tokamaks with subgrid models for with macroscale pellet simulation
- People involved: R. Samulyak, T. Lu, BNL P. Parks, General Atomics (Application)
- Based on Front Tracking. Code Includes:
  - Kinetic model for interaction with hot electrons
  - Surface ablation model
  - Equation of state with atomic processes
  - Cloud charging and rotation models
  - New conductivity model (ionization by electron impact)
- ITAPS Services Used



# Pellet Ablation for Tokamak Fuelling

- Code validation and benchmarks with other hydro studies
- First systematic “microscale” MHD studies of pellet ablation physics
- **Revealed new properties** of the ablation flow (supersonic rotation of the ablation channel)
- Explained the **factor of 2.2 reduction** of the ablation rate in hydrodynamic models with directional heating
  - In the literature, it was **incorrectly** attributed to the directional heating; we showed it was caused by Maxwellian electron heat flux vs. monoenergetic

Distributions of the Mach number of the ablation flow near the pellet





# Adaptive Loop Construction Experiences

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- ITAPS interfaces provide needed functionality to support adaptive mesh modifications
  - iMeshP supports mesh interactions
  - Zoltan supports needed dynamic load balancing
  - Interacting with solver for error estimation requires fields
- Reasonable straight forward to construct adaptive loops is solver used mesh partitions
- Approaches taken to date
  - Leave solver unaltered and communicate with files - easy implementation, not optimal efficiency
  - Tight integration into solver - improved efficiency, more learning and development needed to optimize

# Case Study 2: Mesh Generation for Nuclear Reactor Simulations

## Goals and people involved

---

- Technical goals – Utilize and integrate the ITAPS Geometry, Meshing, and various mesh services for Nuclear Reactor Simulations
- People involved – Tim Tautges and Valmor de Almeida—ITAPS, Andrew Siegel, Glen Hansen and Kevin Clarno---Nuclear Energy)

# ITAPS tools used in nuclear energy

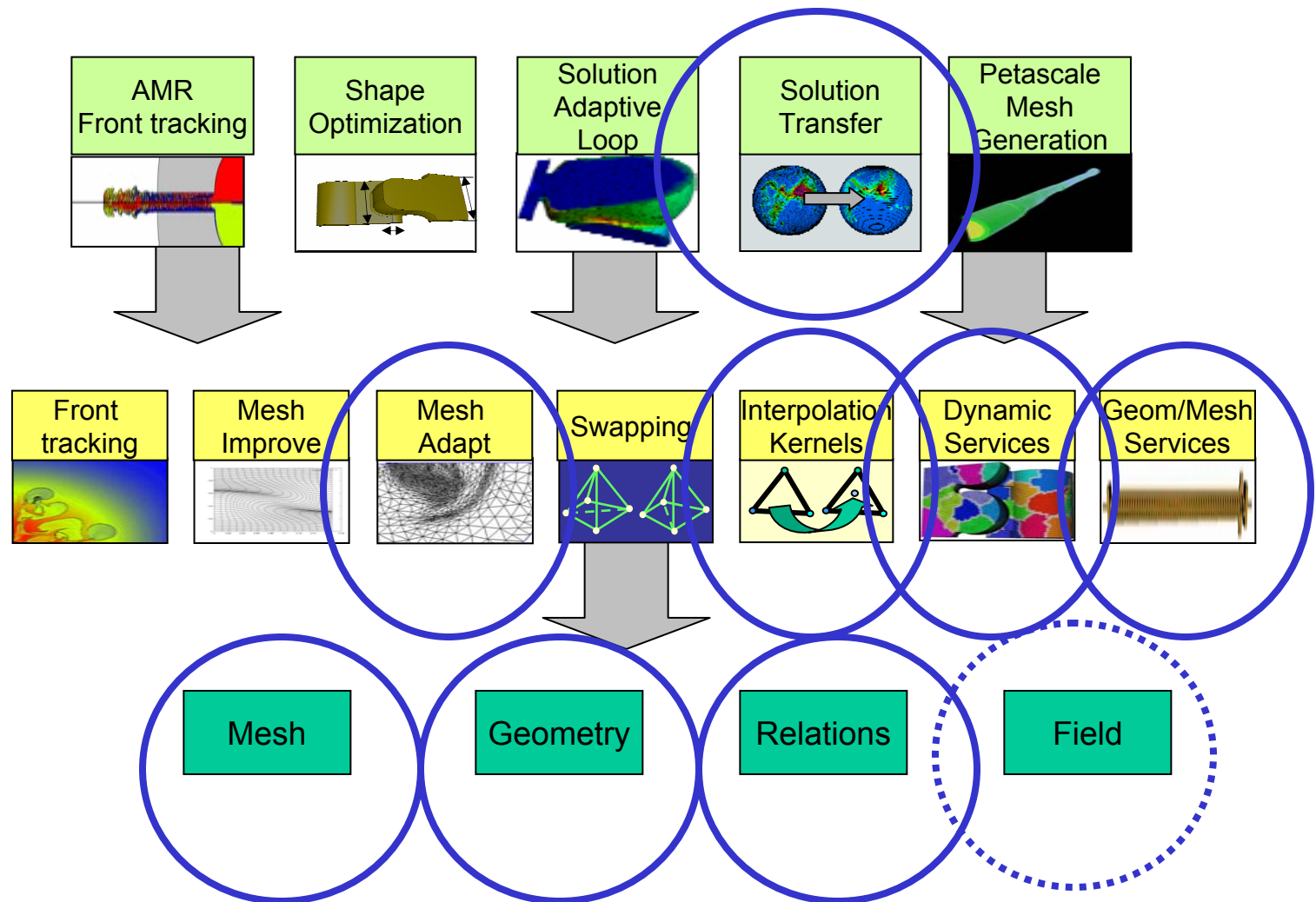
**Petascale  
Integrated  
Tools**

*Build on*

**Component  
Tools**

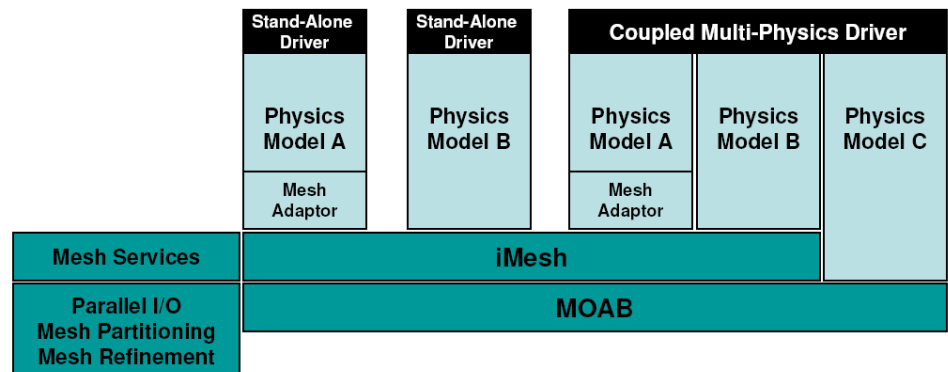
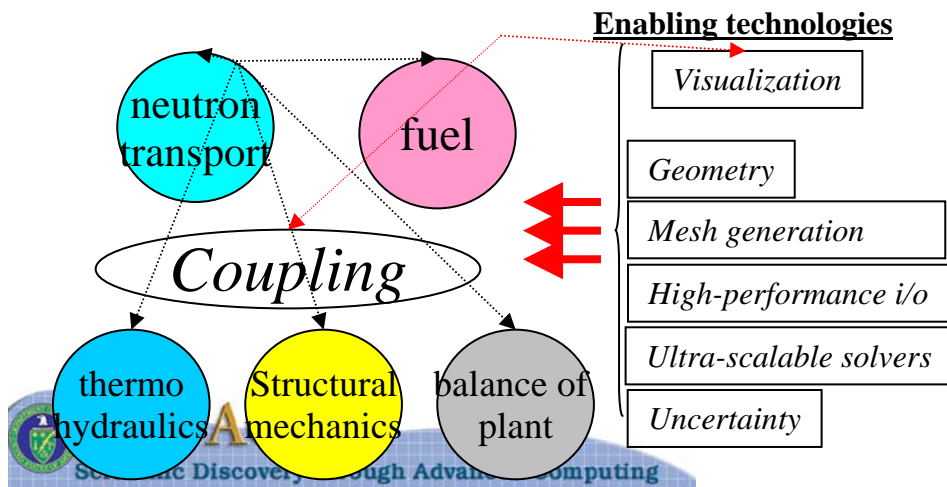
*Are unified  
by*

**Common  
Interfaces**



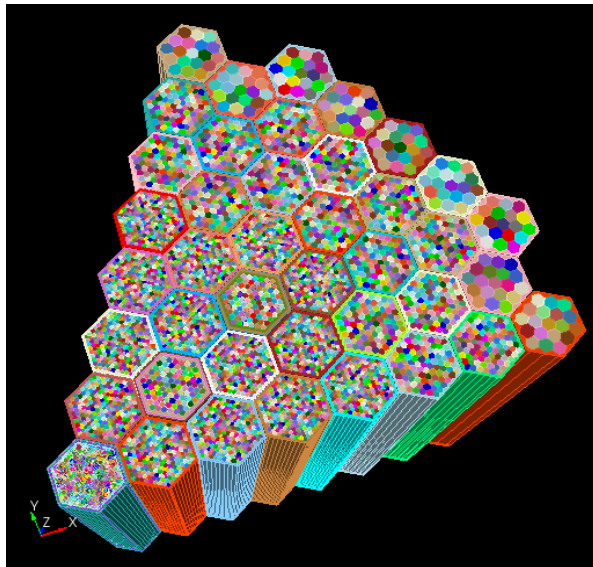
# SHARP framework: Multi-Physics Reactor Simulation

- Reactor safety depends on thermal/hydraulics-structural mechanics-neutronics feedback
- Interoperability crucial
  - Interacting with multiple modules
  - Need variety of tools to operate on mesh & field data
- Coupling requires meshes & results in the same place
- Centralized parallel mesh infrastructure needed, to support coupling while allowing modules freedom
- Metadata needed to coordinate coupling (normalization/conservation)





# Advanced Burner Test Reactor Mesh Generation

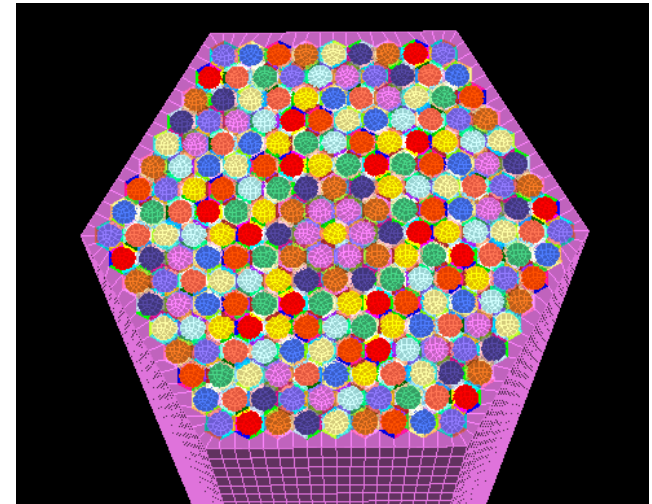


## ← 1/6 ABTR core

- 7k volumes (core, ctrl, reflect, shield)
- 43k-5m hex elements
- ~6 GB to generate using CUBIT

## 217-pin fuel ass'y →

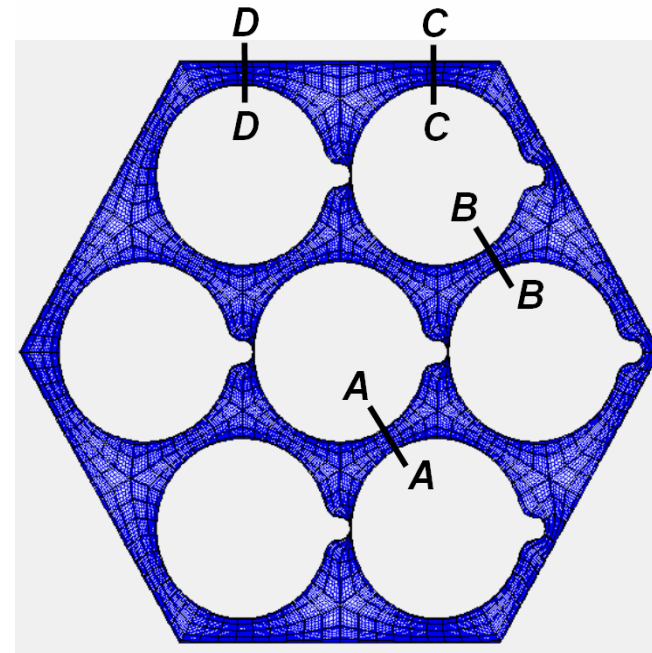
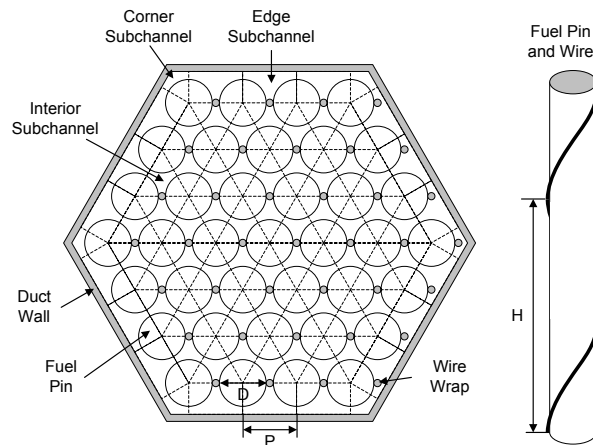
- Conformal hex mesh
- 1520 vols
- Multiple homogenization options, e.g. pins resolved



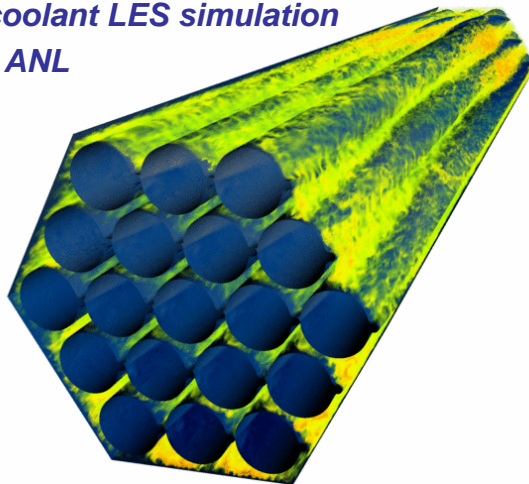
- Varying fidelity geometry, mesh
- Need scalable geometry & mesh generation
- Parallel mesh IO, representation to support ANL UNIC neutron transport code
- Need for mixed quad/tri extrusion, unavailable in CUBIT
- Customized mesh generation would make this easy (simple swept model)

# ABTR Mesh Generation

## Wire-Wrapped Fuel Pin Assembly



*Sodium coolant LES simulation*  
*Nek5000, ANL*

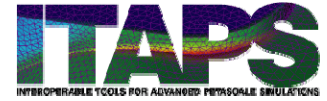


- Currently using MATLAB for meshing
- Wire-pin junction smoothed using fillets
- Mesh “slides” over wires through sweep

# Reactor Simulation

## Required Mesh Services

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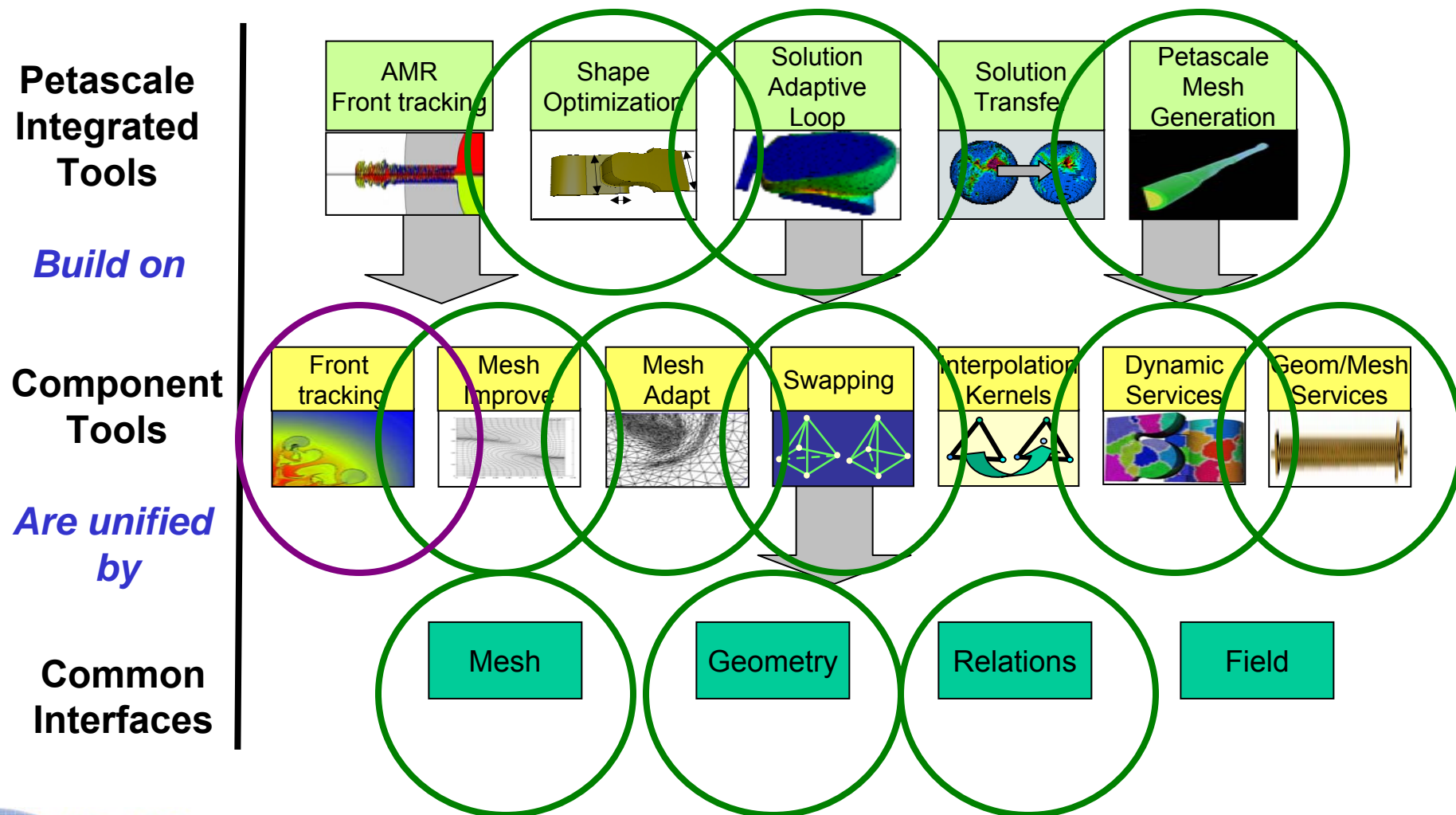


- Robust mesh generation for complex & large geometric models
  - Developing MeshKit, based on iGeom, iMesh, iRel
- Assembly of SHARP framework, by connecting physics modules to iMesh “backbone”
- Coupling of solution results through iMesh
  - Implemented using MOAB data searching functions
  - Will provide data searching as iMesh service eventually
- Partitioning, visualization, other iMesh-based services

# Case Study 3: Geometry & Mesh Services for Shape Optimization



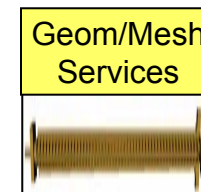
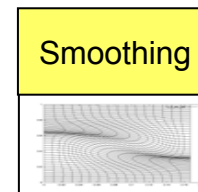
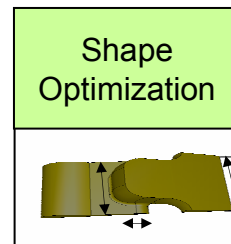
# Design optimization for accelerators





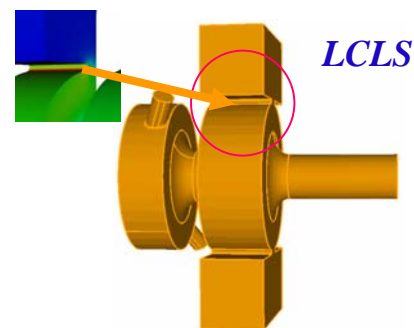
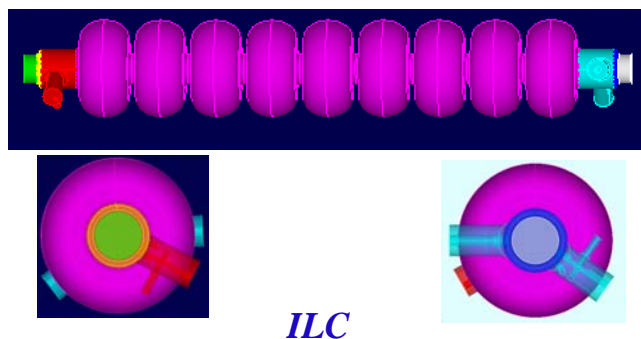
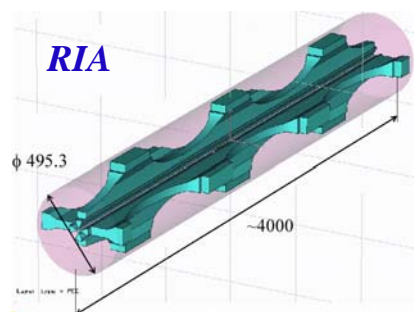
# Goals and People Involved

- Technical goals:
  - Develop shape optimization for accelerator cavity tuning and de-tuning, and for reverse engineering as-assembled cavity shape
  - ITAPS provides the geometry control and meshing components
- People involved:
  - SLAC: Rich Lee, Cho Ng, Volkan Ancelik
  - ITAPS: Tim Tautges and Pat Knupp
  - TOPS: Volkan Ancelik and Omar Ghattas
- ITAPS Services Used:

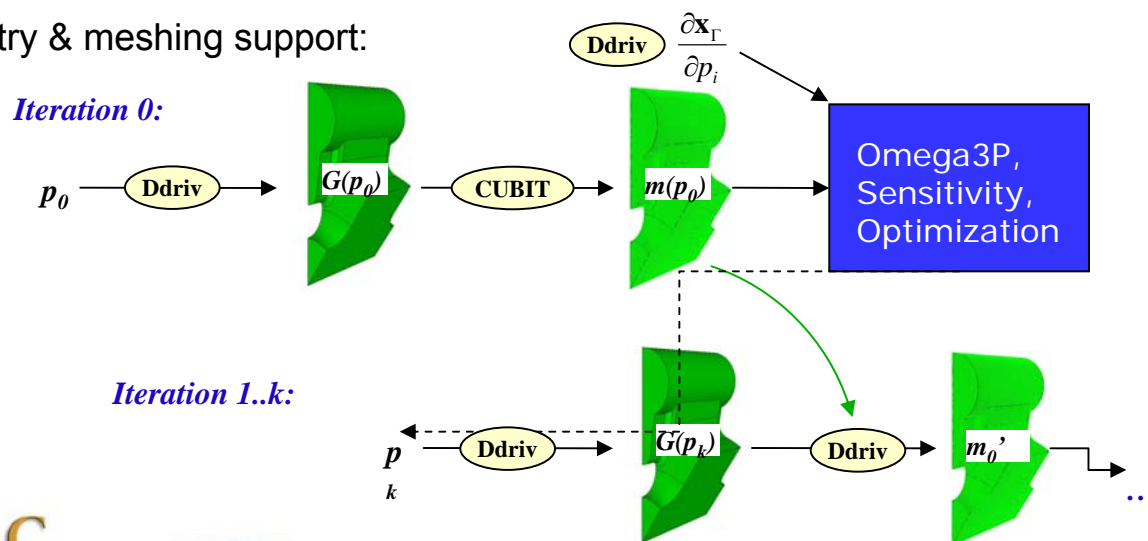


# Shape Optimization for Accelerator Cavity Design

- Optimizing a cavity design is still mostly a manual process
- Future accelerators employ complex cavity shapes that require optimization to improve performance



- Geometry & meshing support:

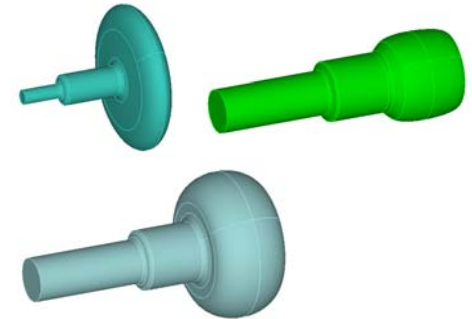
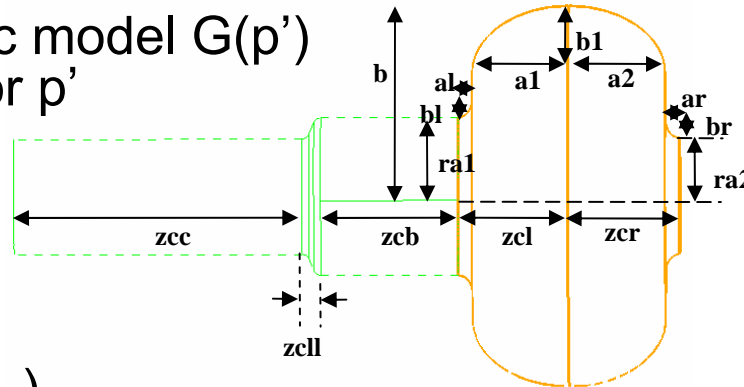


*Fixed mesh topology:  
Convergence  
No re-meshing  
Re-use factorization*

# Shape Optimization for Accelerator Cavity Design

- Generate new geometric model  $G(p')$  given a parameter vector  $p'$

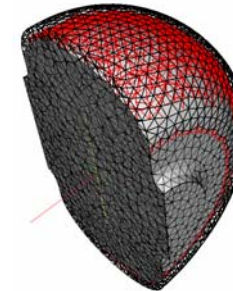
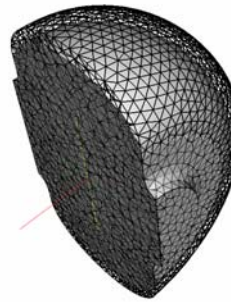
- *MkILCCell* function
- DDRIV
- CGM (iGeom)



- Associate old mesh  $m(p_o)$  to new geometry  $G(p')$ , project to CAD

- DDRIV
- CGM (iGeom)
- MOAB (iMesh)
- LASSO (iRel)

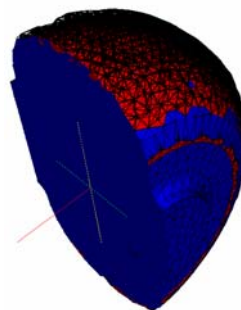
*New geom,  
old mesh*



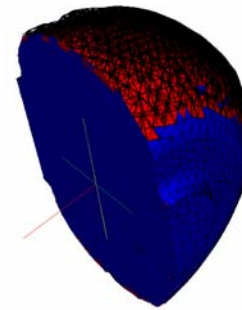
*Project to CAD,  
inverted elements*

- Smooth mesh

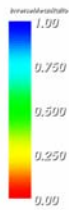
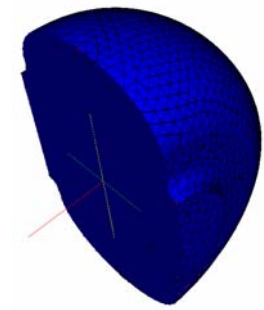
- ...
- Mesquite



*Smooth Curves*



*Smooth Surfaces*



*Smooth Volume*

## Services Provided by DDRIV

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- Parameterized geometric model construction
  - You write function which constructs model using iGeom
  - DDRIV acts as driver and handles IO
- Coordination of mesh smoothing on geometric model
- Re-classification of “old” mesh on “new” model
- Target matrix-based smoothing of re-classified mesh
- Computation of design velocities & embedding on mesh using iMesh Tags

## PART 7: Conclusions



## What you learned today

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- A component-based approach to mesh services and tools is both flexible and effective
- The ITAPS interfaces provide an avenue to leverage many existing technologies and a path to incremental adoption

# None of this would be possible without a strong team of contributors

---

*We thank all those who have contributed to the  
ITAPS interface definition effort and software!*

- **ANL: Tim Tautges**
- **LLNL: Lori Diachin, Mark Miller, Kyle Chand, Martin Isenburg**
- **PNNL: Harold Trease**
- **RPI: Mark Shephard, Ken Jansen, Eunyoung Seol, Xiaojnan Luo, Ting Xie, Onkar Sahni**
- **SNL: Vitus Leung, Karen Devine**
- **SUNY SB: Xiaolin Li, Brian Fix, Ryan Kaufman**
- **UBC: Carl Ollivier-Gooch**
- **U Wisconsin: Jason Kraftcheck, Jane Hu**

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<http://www.itaps-scidac.org/software>
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Mark Shephard, RPI  
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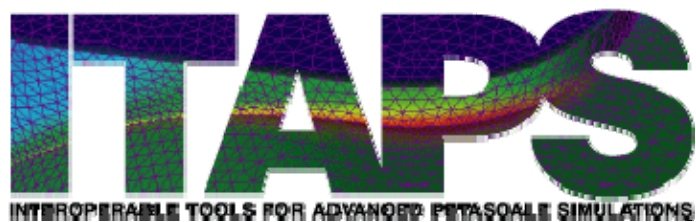
Tim Tautges, ANL  
[tautges@mcs.anl.gov](mailto:tautges@mcs.anl.gov)

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