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Parallel Unstructured Mesh Infrastructure

Parallel Unstructured Mesh Infrastructure for Massively Parallel Adaptive Simulation

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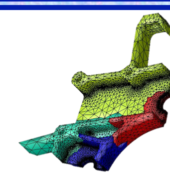
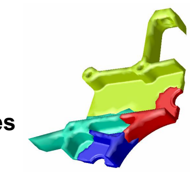
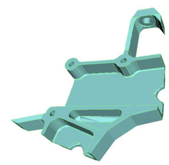




Mesh
0-3D topological entities and adjacencies



Geometric model
analysis domain

Fields
distribution of solution over mesh

Partition model
distribution of mesh across computing resources

Parallel Control
communication utilities

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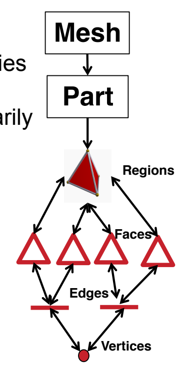
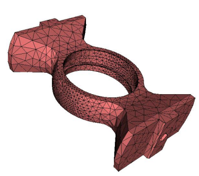
Background

Geometry-Based Analysis

- Geometry, Attribute: analysis domain
- Mesh: 0-3D topological entities and adjacencies
- Field: distribution of solution over mesh
- Common requirements: data traversal, arbitrarily attachable user data, data grouping, etc.
- Complete representation: store sufficient entities and adjacencies to get any adjacency in O(1) time



Geometric model



Mesh

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Notations

- P_i: distributed mesh part mapped to a process (1-to-N)
- V_i^d: entity of dimension *d*, where V is G (geometric model), M (mesh) or P (partition model)
  E.g. M_i^3: mesh regions, G_i^2: geometric face , P_i^0: partition vertex
- $\mathcal{P}[V_i^d]$: operator to return a set of part id's where V_i^d exists
  - *E.g.* $\mathcal{P}[M_1^0] = \{P_0, P_1, P_2\}$
- $V_i^d \sqsubset W_j^q$, $d \le q$: classification which represents a relation from V_i^d to W_j^q, *where* V_i^d *is partial representation of* W_j^q
  - $M_i^d \sqsubset G_j^q$, $d \le q$: geometric classification
  - $M_i^d \sqsubset P_j^q$, $d \le q$: partition classification
- S_i : a set of entities

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General Mesh Data Structure

Functional Requirements for Adaptive Simulations

- *Part*: A unit of mesh data decomposition for distribution on parallel computers.
- *Mesh entities*: a constituent of mesh distinguished by type
  - vertex (0D), edge (1D), face (2D), or region (3D)
- *Adjacencies*: how the mesh entities connect to each other.
- *Geometric classification*: a relation that each mesh entity maintains to a geometric model entity for partial representation
- *Entity set*: mechanism for grouping mesh entities
- *Tag*: mechanism to attach arbitrary user data (tag data) to a part, entity set or mesh entity
- *Iterator*: mechanism to traverse mesh entities in a specific range with various options (type, classification, etc.)

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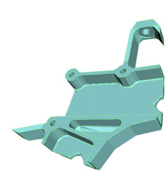
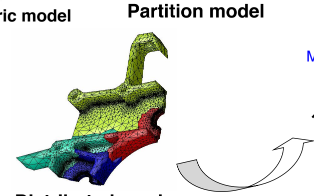
Distributed Mesh Data Structure

- Capability to partition mesh to multiple parts per process

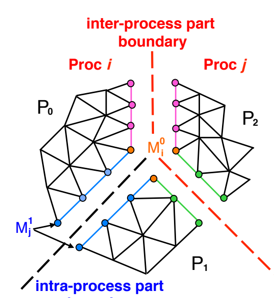


Geometric model

Partition model



Distributed mesh



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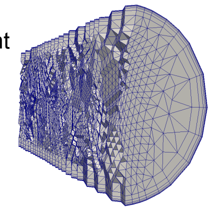
Distributed Mesh Requirement (1/2)

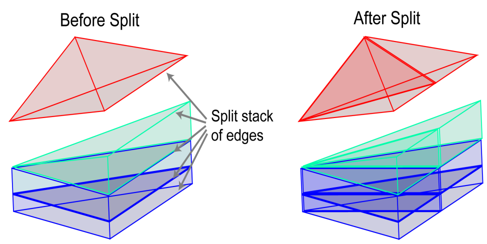
- File I/O – parallel mesh/set/tag loading, saving
- Part – create, delete, query (neighbor, id, etc), entity iterator
- Part boundary – query, entity iterator
- Entity – query (owner part, status, copies, etc.)
  - Entity ownership imbues the right to modify (in other words, only owning part can modify the entity and transfer the modification to its remote copies)
- Modification
  - Migrating entities and p-sets to destination part
  - Pulling part boundary entity's *remote* partition objects to the owner part
  - Pushing owner's vertex coordinates to remote copies
  - Ghosting – temporarily keeping remote adjacent entities on local part
  - Tag –automatic tag data migration during migration
- Mesh partitioning control
  - Static/dynamic, global/local
  - Weight control per individual entity/set or type/topology

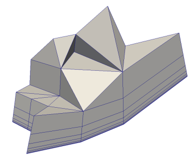
Distributed Mesh Requirement (2/2)

Boundary layer stacks

- NP-set: Entity set w/o single part constraint
- P-set: Entity set with single part constraint
  - Data structure for boundary layer stack
  - Entity is partition object entity
  - Entity can be contained in at most one p-set

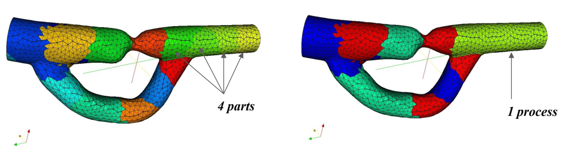






Distributed Mesh Representation (1/6)

- $Part_i$ consists of mesh entities assigned to i^{th} part
- Multiple-parts per process
  - Changing number of parts per process
  - Dealing with problems with current graph-based partitioners that tend to fail on really large numbers of processors (*See Slides 19-21*)
  - Architecture-aware two-level mesh partitioning (*See Slides 22-23*)
  - For effective manipulation, a mesh instance defined on each processor contains part handles assigned to the process



A 3D mesh in 4 parts per process (16 parts total)

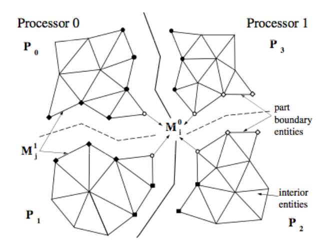
(LEFT) Different color represents different part

(RIGHT) Different color represents different process

Distributed Mesh Representation (2/6)

Each part P_i assigned to a processor

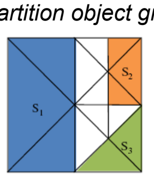
- Uniquely identified by handle or global ID
- Treated as a serial mesh with the addition of *part boundaries*
  - *Part boundary*: groups of mesh entities on shared links between parts
  - *Part boundary entity*: duplicated entities on all parts for which they bound with other higher order mesh entities
  - *Remote copy*: duplicated entity copy on non-local part
  - *Partition object* : basic unit to assign dest. part id in migration
  - *Residence parts and owing part* : list of parts where the entity exists and the part designated to be in charge of modification



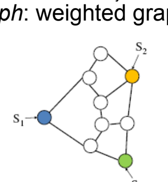
Distributed Mesh Representation (3/6)

Partition Object

- Basic unit to assign destination part id in mesh migration
  - p-set
  - mesh entity with no higher order adjacency *not contained in* p-set
- For partition object x, residence part operator $\mathcal{P}(x)$ returns a set of part id's where x exists based on adjacencies.
  E.g. $\mathcal{P}[M_i^0] = \{P_0, P_1, P_2, P_3\}$, $\mathcal{P}[M_j^1] = \{P_0, P_1\}$
- *Partition object graph*: weighted graph G(V, E)



A mesh part with 3 p-sets



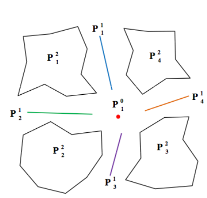
Partition object graph

- **Node *V*: partition object**
- **Edge *E*: dependencies between graph nodes identified by adjacencies**
- **Node and edge weights**

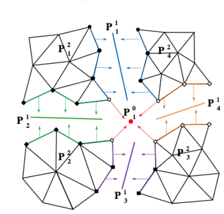
Distributed Mesh Representation (4/6)

Partition Model

- a conceptual model existing between a geometric model and distributed mesh representing mesh partitioning in topology
- Partition (model) entity: a topological entity in the partition model, P_i^d, representing a group of mesh entities of dimension *d with* the same *residence parts*.



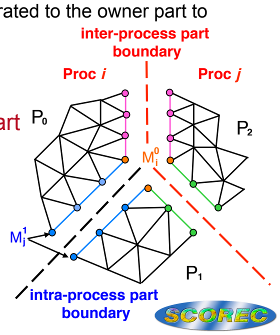
Partition model of mesh in Slide 14



Partition classification in arrows

Distributed Mesh Representation (5/6)

- For each partition model entity, owning part is *defined* by a *rule* which says the part with the *fewest* number of *partition object* entities is the owner.
  - Rationale: keeping load balance during adaptation - part boundary entity's *remote* partition objects are migrated to the owner part to obtain cavity
- Proper maintenance of partition classification is all about modifying entity's residence parts and owning part
  - $M^1_j@P_0$ and $M^1_j@P_1$ know they are duplicated in P_0 and P_1
  - M^1_j's owning part changes dynamically as mesh partitioning changes



Distributed Mesh Representation (6/6)

Other tools for efficient mesh modification

- No global ID synchronization
  - global part ID = process rank * local part ID
    local part ID = 0..n-1, where n is # parts per process
  - No global entity ID
- No mesh size operation
  - O(1) Entity search based on adjacencies
  - O(N) Mesh migration, N - # entities to migrate
- Parallel Control Utility
  - Provides parallel infrastructure to control communications
  - Being extended to deal with hybrid (message passing and threads)
  - More on this later

Mesh Migration (1/2)

Purpose: Moving mesh entities between parts

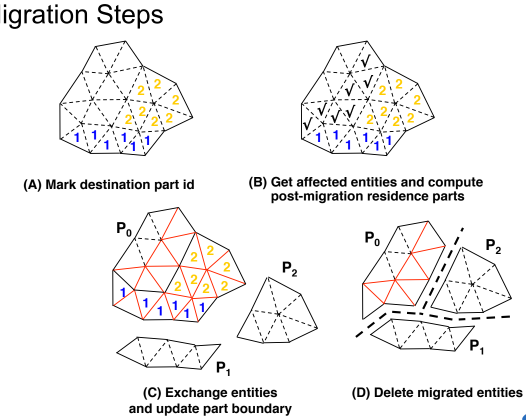
- Dictated by operation - in swap and collapse it's the mesh entities on other parts needed to complete the mesh modification cavity
- Entities to migrate are determined based on adjacencies

Major Complexities

- A function of mesh representation w.r.t. adjacencies, p- set and arbitrary user data attached to them
  - Complete mesh representation can provide any adjacency without mesh traversal - a requirement for satisfactory efficiency
- Performance factorized by
  - Synchronization, communications, load balance and scalability
  - How to benefit from on-node thread communication (all threads in a processor share the same memory address space)

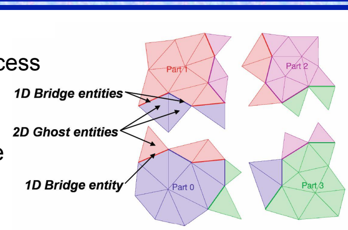
Mesh Migration (2/2)

Migration Steps



Ghosting (1/2)

- *Goals*: localizing off-part mesh data to avoid inter-process communications for computations
- *Ghost*: read-only, duplicate entity copies not on part boundary including tag data



- *Ghosting rule*: triplet (ghost dim, bridge dim, # layers)
  - Ghost dim: entity dimension to be ghosted
  - bridge dim: entity dimension used to obtain entities to be ghosted through adjacency
  - # layers: the number of ghost layers measured from the part boundary

E.g, to get two layers of region entities in the ghost layer, measured from faces on part boundary, use ghost_dim=3, bridge_dim=2, and # layers=2

(source: FASTMath iMeshP.h)

Ghosting (2/2)

Ghosting Steps