Using Transactions in Delaunay Mesh Generation

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Workshop on Transactional Memory Workloads, 2006

Introduction

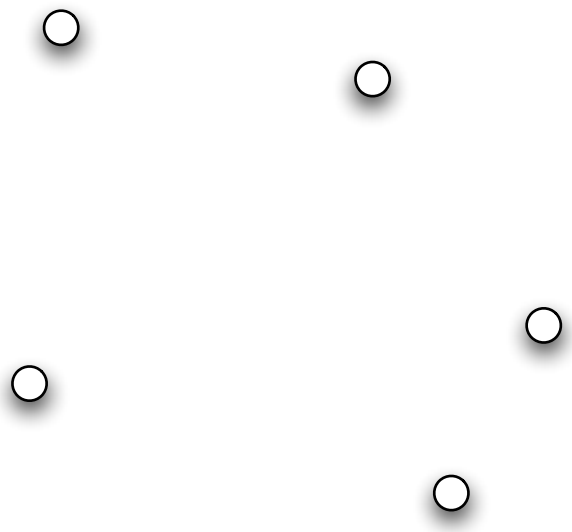
- New benchmark: Delaunay mesh generation
  - Algorithm well suited for optimistic parallelization/transactions
  - Useful for evaluating transactional memory
- Problems with naïve TM implementations
  - How to mitigate while using standard TM

Mesh Generation

- Mesh generation useful for
  - Finite element method for solving PDEs
  - Graphics
    - Tessellation of surface into polygons for rendering
- Delaunay mesh generation
  - Mesh generation algorithm which provides guaranteed quality meshes

Delaunay Mesh Generation

- What is a Delaunay mesh?
  - Tessellation of a surface given vertices



Delaunay Mesh Generation

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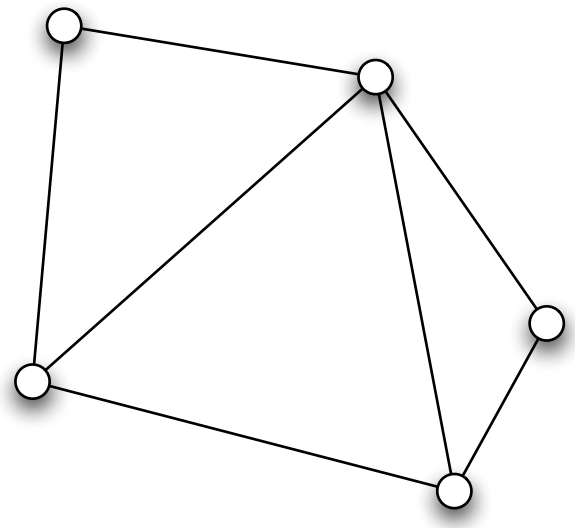
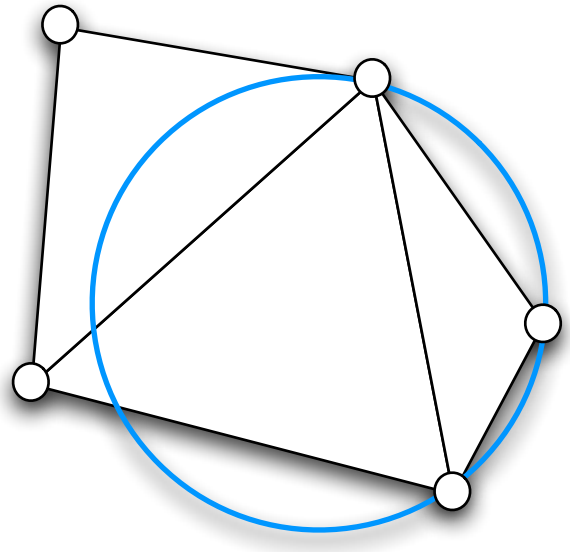


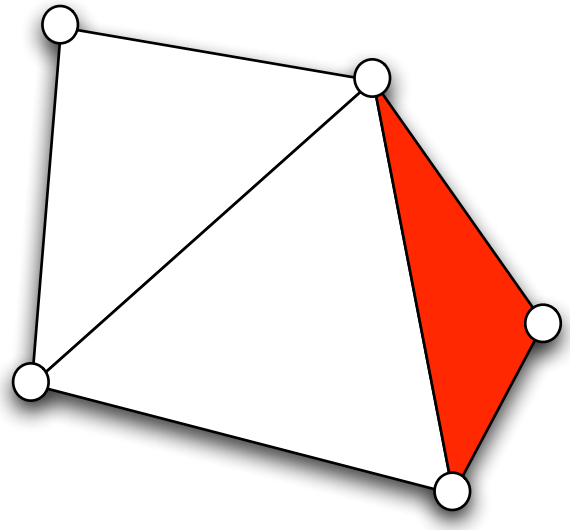
Delaunay Mesh Generation

- What is a Delaunay mesh?
  - Tessellation of a surface given vertices
  - Satisfies the Delaunay property
    - Circumcircle of any triangle does not contain another point in the mesh



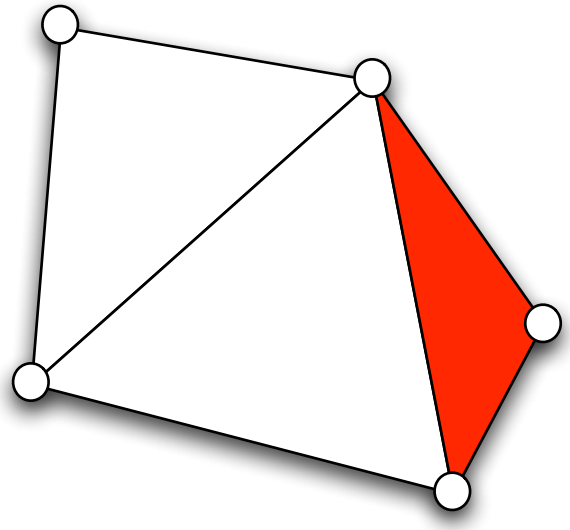
Delaunay Mesh Generation

- Want all triangles in mesh to meet quality constraints
  - No angle < 30°
- Fix bad triangles through iterative refinement
  - Add new vertices to mesh and retriangulate



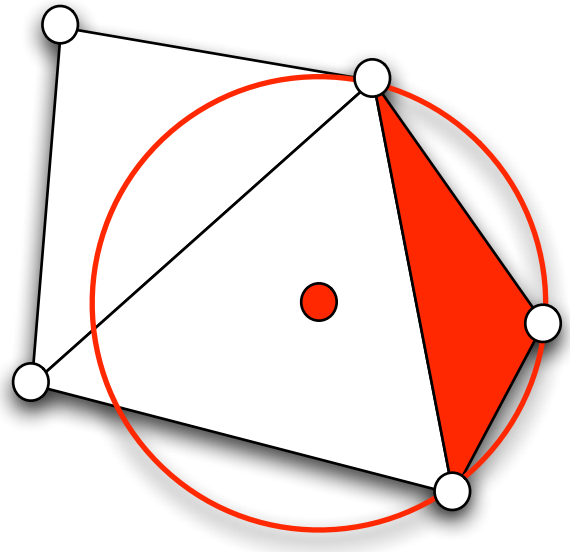
Mesh Refinement

- Choose "bad" triangle



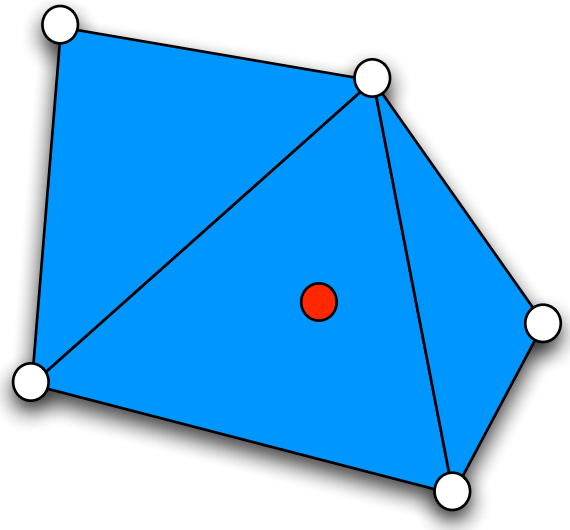
Mesh Refinement

- Choose "bad" triangle
- Add new vertex at center of circumcircle



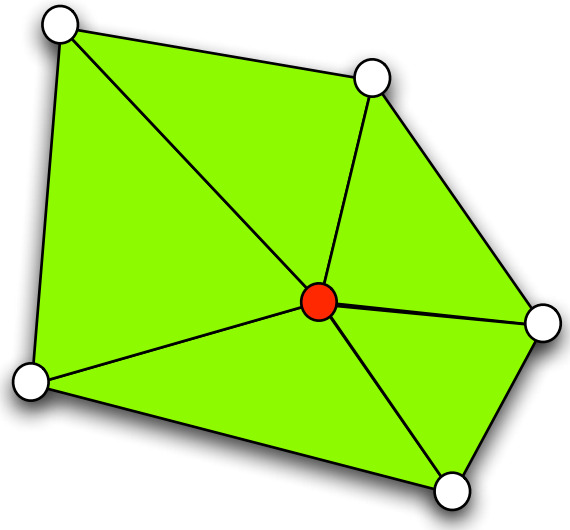
Mesh Refinement

- Choose "bad" triangle
- Add new vertex at center of circumcircle
- Gather all triangles that no longer satisfy Delaunay property into cavity



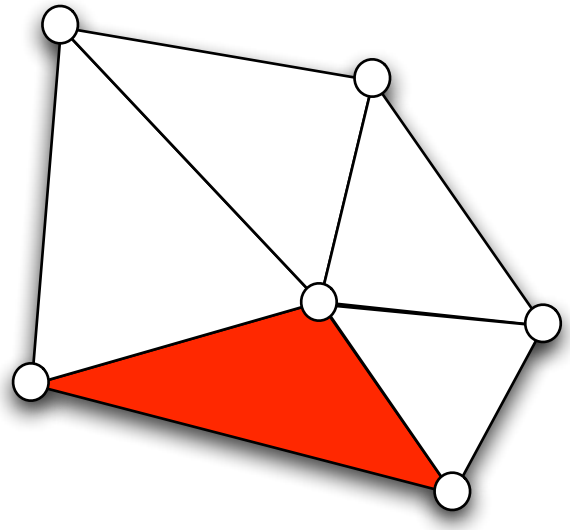
Mesh Refinement

- Choose "bad" triangle
- Add new vertex at center of circumcircle
- Gather all triangles that no longer satisfy Delaunay property into cavity
- Re-triangulate affected region, including new point

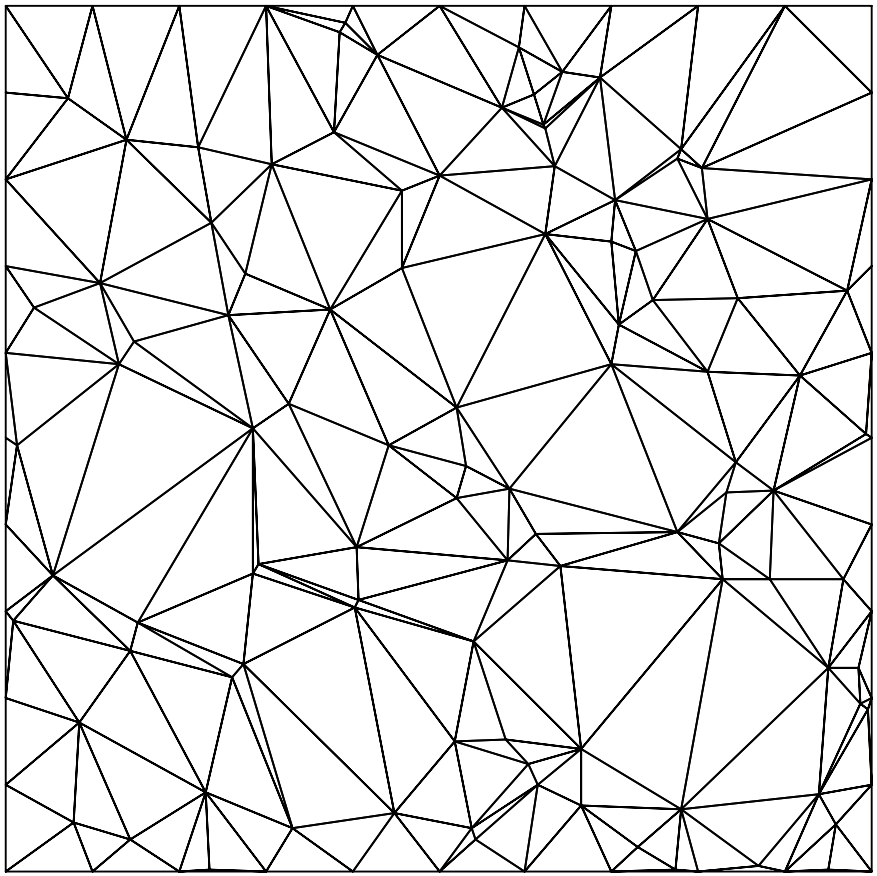


Mesh Refinement

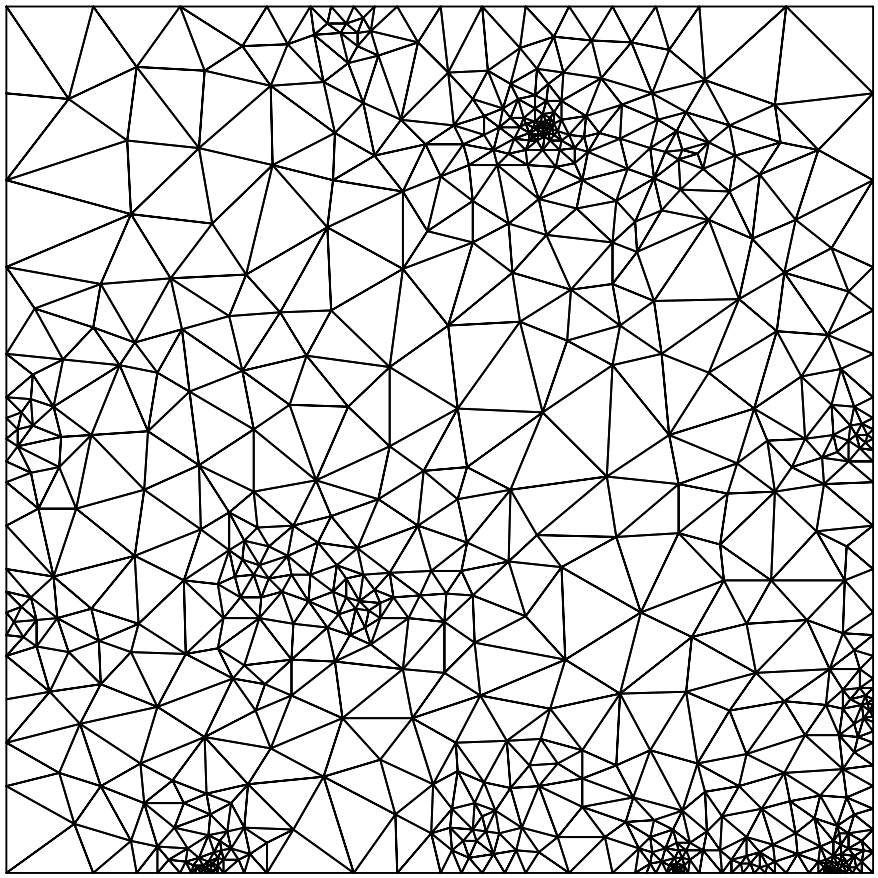
- Choose "bad" triangle
- Add new vertex at center of circumcircle
- Gather all triangles that no longer satisfy Delaunay property into cavity
- Re-triangulate affected region, including new point
- Continue until all bad triangles processed



Refinement Example



Original Mesh



Refined Mesh

Sequential Algorithm

```
Mesh m = /* read in mesh */
WorkList wl;
wl.insert(mesh.badTriangles());

while (!wl.empty()) {
    Element e = wl.removeAny();    //non-deterministic choice

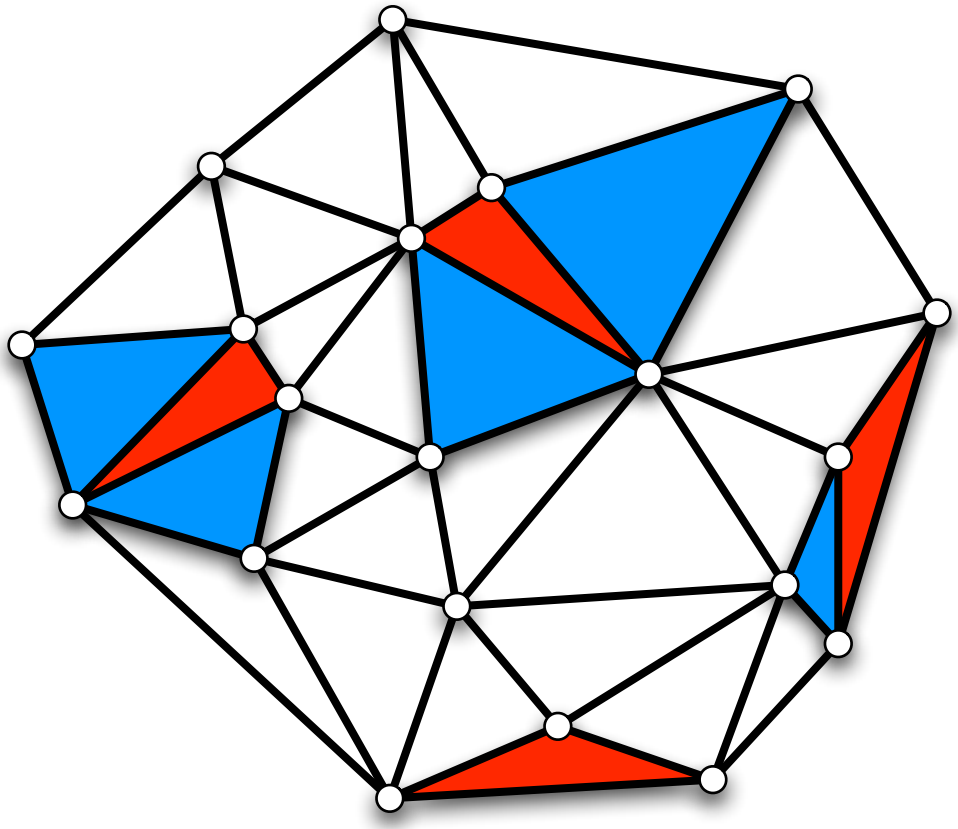
    if (e no longer in mesh) continue;

    Cavity c = new Cavity(e);      //determine new vertex
    c.expand();                    //determine affected triangles
    c.retriangulate();             //re-triangulate region

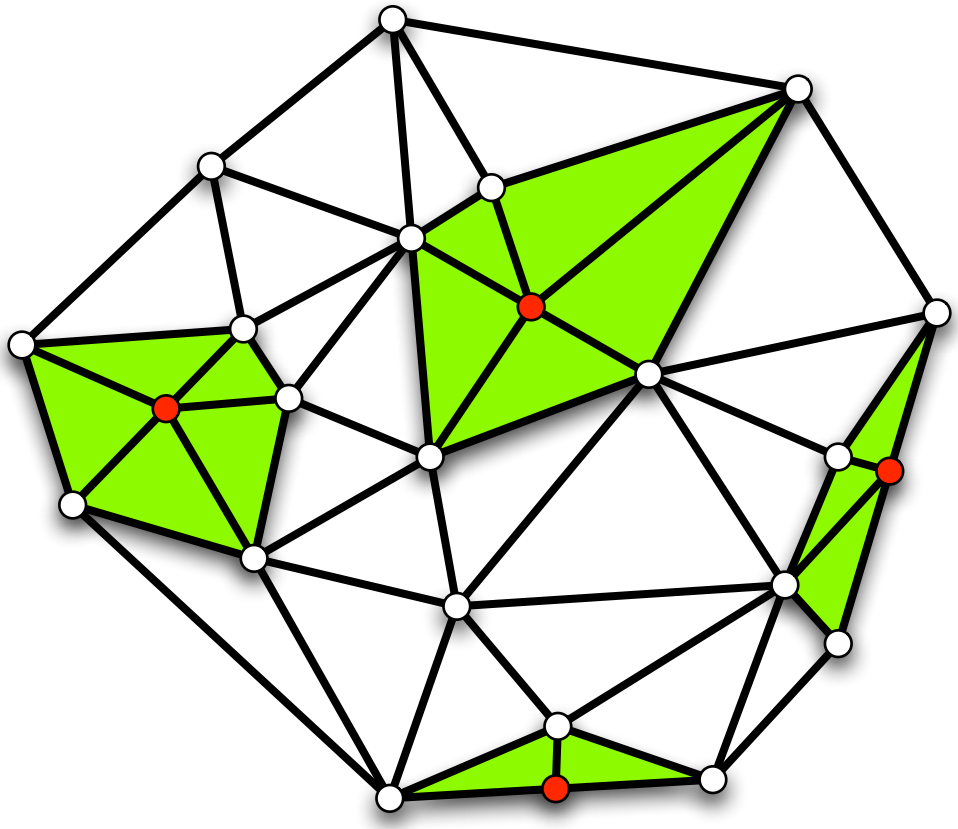
    m.update(c);                   //update mesh

    wl.insert(c.badTriangles());   //add new bad triangles to queue
}
```

Parallelization Opportunities



Before



After

Parallelization Strategy

- Process bad triangles in parallel
  - One bad triangle per iteration
- Only safe if iterations are independent
  - Cavities must not overlap

- "Pessimistic" solutions infeasible
  - Static Analysis
    - Dependences are highly data dependent
  - Inspector-Executor
    - Inspector stage must perform entire computation

Optimistic Parallelism

- Only feasible solution
  - Process bad triangles in parallel regardless of dependences
  - Detect cavity overlap at run time
  - If interference detected, roll back execution
- How do we ensure no conflicts?

```
void main() {
   /* initialization */
   for (/*number of threads*/)
      spawn_thread(process)
}

void process() {
   while (!wl.empty()) {
      Element e = wl.removeAny();

      if (e no longer in mesh) continue;

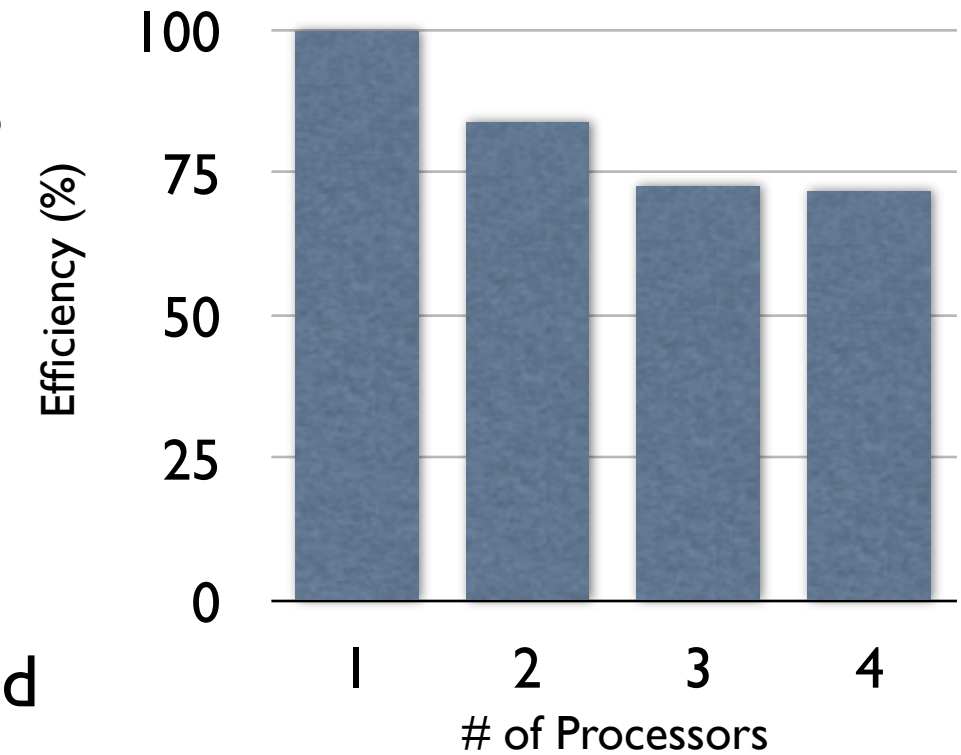
      Cavity c = new Cavity(e);
      c.expand();
      c.retriangulate();

      m.update(c);

      wl.insert(c.badTriangles());
   }
}
```

Lock-based Implementation

- Uses two-phase locking protocol (with rollback) to provide optimistic parallelism
- 40K triangles in mesh
  - 19K initial bad triangles
  - 58K triangles processed
  - 32% of iterations aborted



- Implementation is very complex

System details:
- 4 processors
- Itanium 2 @ 1.6GHz
- pthreads

Transactional Approach

- Processing each bad triangle is a transaction
- Transactional memory detects conflicts between transactions
  - Safety: conflicts must occur if cavities overlap
  - Optimality: conflicts *if and only if* cavities overlap
- Transactional memory automatically performs rollbacks when conflicts detected

Transactional Approach

- Naïve use of transactional memory
- Satisfies safety conditions, but does not exhibit parallelism

```
startTransaction();

Element e = wl.removeAny();
if (e no longer in mesh)
    endTransaction();
    continue;

Cavity c = new Cavity(e);
c.expand();
c.retriangulate();
m.update(c);

wl.insert(c.badTriangles());

endTransaction();
```

TM Limitations

- Problem: Worklist manipulations must be visible to other transactions before commit
- Solutions
  - Move worklist operations outside transaction
  - Use open nesting
    - Must specify undo action for nested operations

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```
startTransaction();

beginOpen();
Element e = wl.removeAny();
endOpen();

if (e no longer in mesh)
    endTransaction();
    continue;

Cavity c = new Cavity(e);
c.expand();
c.retriangulate();
m.update(c);

beginOpen();
wl.insert(c.badTriangles());
endOpen();

endTransaction();
```

TM Limitations

- Mesh data structure
  - Basic implementation: adjacency list using STL map
    - Rebalancing red-black trees causes conflicts
- Solution
  - Carefully choose data structures to avoid unwanted conflicts
    - e.g. Use hash tables

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endOpen();

if (e no longer in mesh)
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Cavity c = new Cavity(e);
c.expand();
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m.update(c);

beginOpen();
wl.insert(c.badTriangles());
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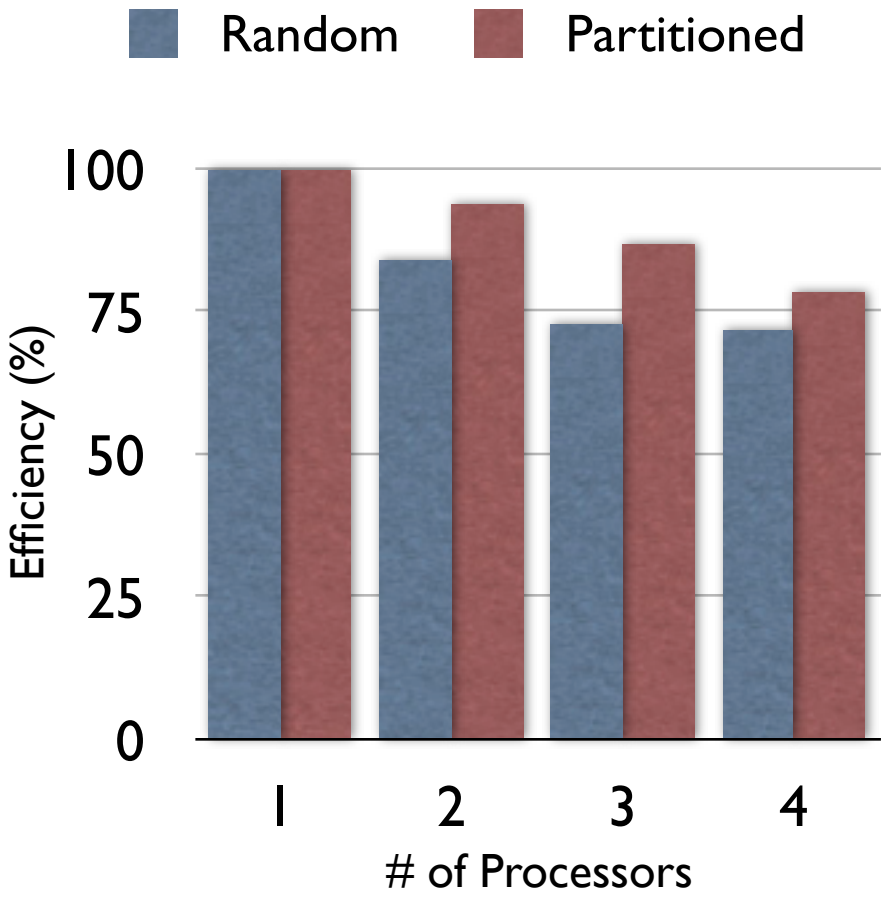
endTransaction();
```

Scheduling issues

- Transactions are long running, so rollbacks expensive
- Empirical results: 30% of transactions abort with random scheduling
  - Can partition mesh and worklist to eliminate virtually all rollbacks
- Transaction scheduling important



Related work

- Original Delaunay refinement algorithm by Chew and Ruppert
  - L. Paul Chew, *Guaranteed Quality Mesh Generation for Curved Surfaces*
  - Jim Ruppert, *A New and Simple Algorithm for Quality 2-dimensional Mesh Generation*
- Previous implementations
  - Sequential implemenation
    - J. Shewchuck, *Triangle: Engineering a 2D Quality Mesh Generator and Delaunay Triangulator*
  - Parallel, distributed memory implementation
    - Antonopoulos et al, *Multigrain Parallel Delaunay Mesh Generation: Challenges and Opportunities for Multithreaded Architectures*
  - Scale to real world problems

Conclusions

- Delaunay mesh generation is ideal transactional memory benchmark
  - Real-world application
  - Optimistic parallelization only approach
    - Well suited for TM
- Platform to explore several TM issues
  - Careful demarcation of transactions and use of open nesting
  - Choosing data structures with understanding of TM limitations
  - Managing scheduling policy to reduce rollbacks
- New style of TM to encompass all these issues?

Questions/Comments?