Optimistic Parallelism Requires Abstractions

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Motivation

- Parallel programming very important
  - Multicore processors
- Parallel programming is hard!
  - Limited success in domains which deal with structured data
    - Array programs
    - Database applications
- What about irregular applications which deal with unstructured data?
  - Compile time techniques have failed

Galois System: Core Beliefs

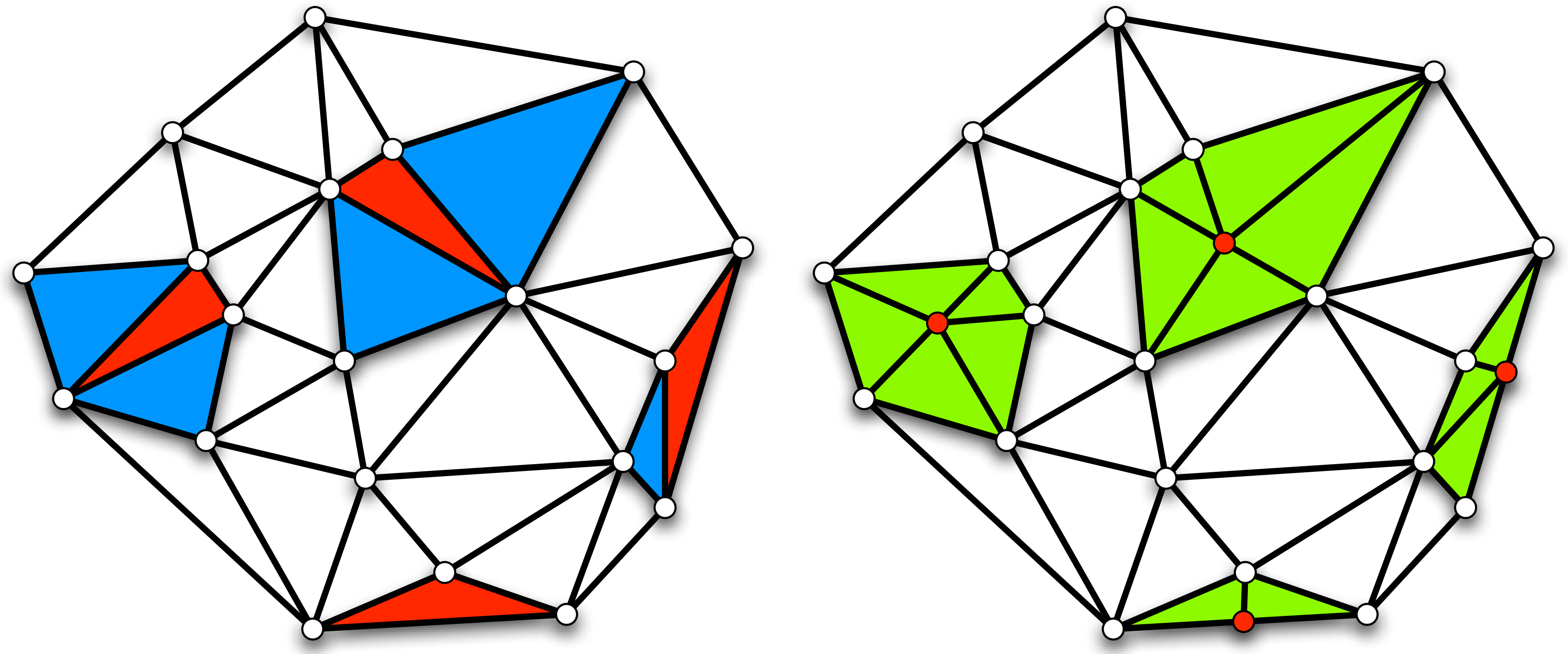
- Irregular applications have worklist-style data parallelism
- Optimistic parallelization is crucial
- Parallelism should be hidden within natural syntactic constructs
- High level application semantics are critical for parallelization

Outline

- Two challenge problems
- Galois programming model and implementation
- Evaluation
- Related Work
- Conclusions

Delaunay Mesh Refinement

- Iterative refinement procedure to produce guaranteed quality meshes



Delaunay Pseudo-code

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

while (wl.size() != 0) {
   Element e = wl.get();
   if (e no longer in mesh)
      continue;
   Cavity c = new Cavity(e);
   c.expand();
   c.retriangulate();
   mesh.update(c);
   wl.add(c.badTriangles());
}
```

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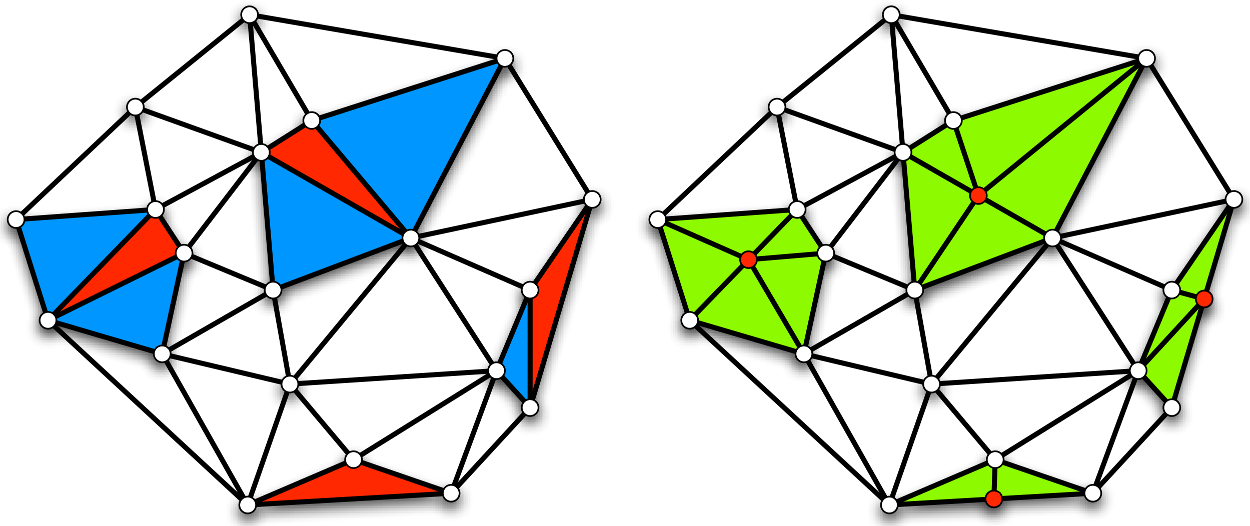
Worklist idiom

Finding Parallelism

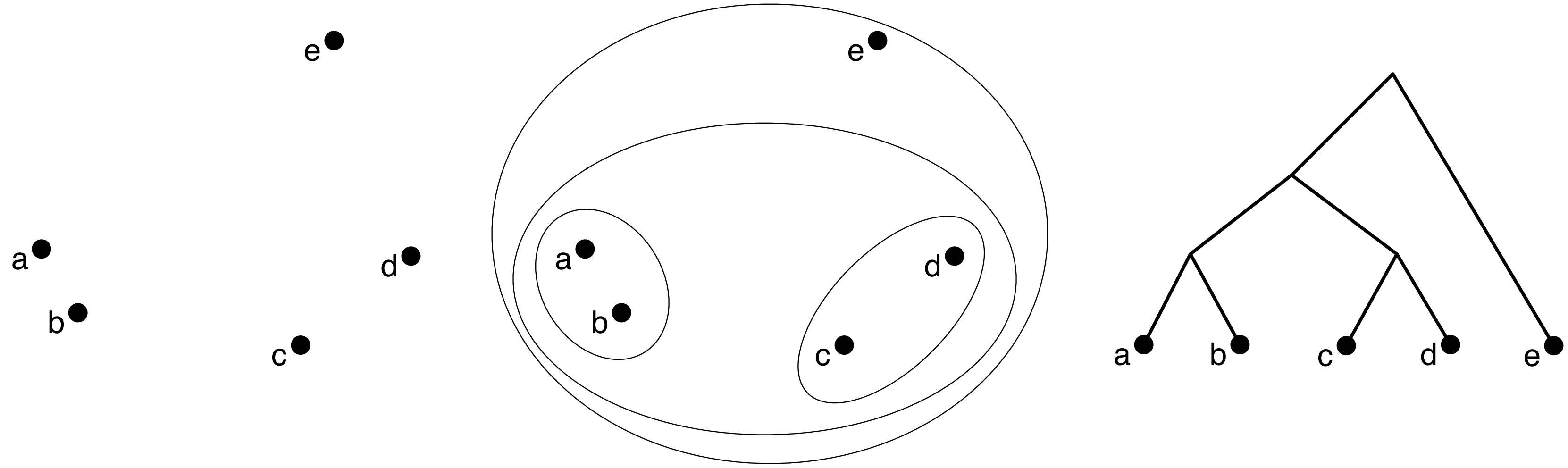
- Can expand multiple cavities in parallel
  - Provided cavities do not overlap



- Determining this statically is impossible
  - Solution: Optimistic parallel execution

Agglomerative Clustering

- Create binary tree of points in a space in bottom-up fashion
- Always choose two closest points to cluster



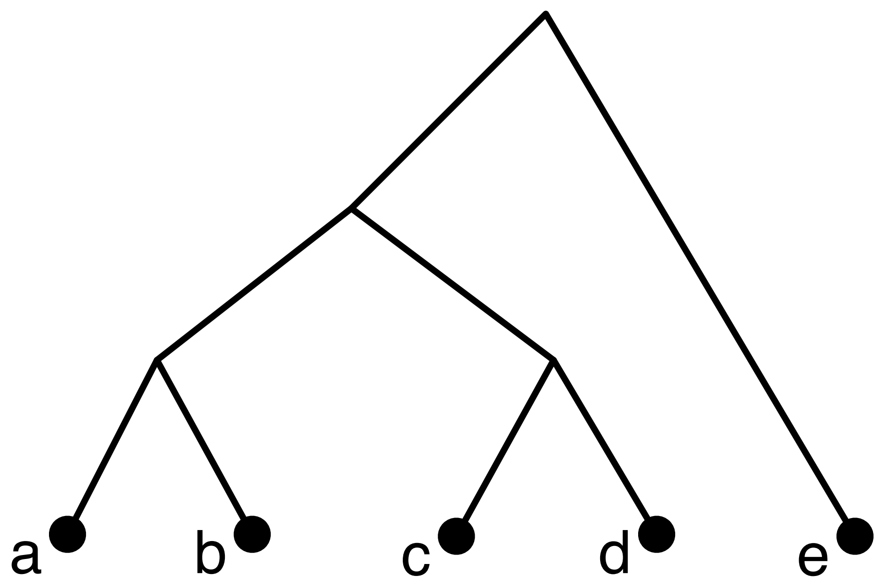
(a) Data points (b) Hierarchical clusters (c) Dendrogram

Agglomerative Clustering

- Two key data structures
  - Priority Queue – Keeps pairs of points <*p*,*n*> where *n* is the nearest neighbor of *p*
    - Ordered by distance
  - KD-tree – Spatial structure to find nearest neighbors

Finding Parallelism

- Priority queue functions as a worklist
  - Seems to be completely sequential
- If clusters are independent, can be done in parallel



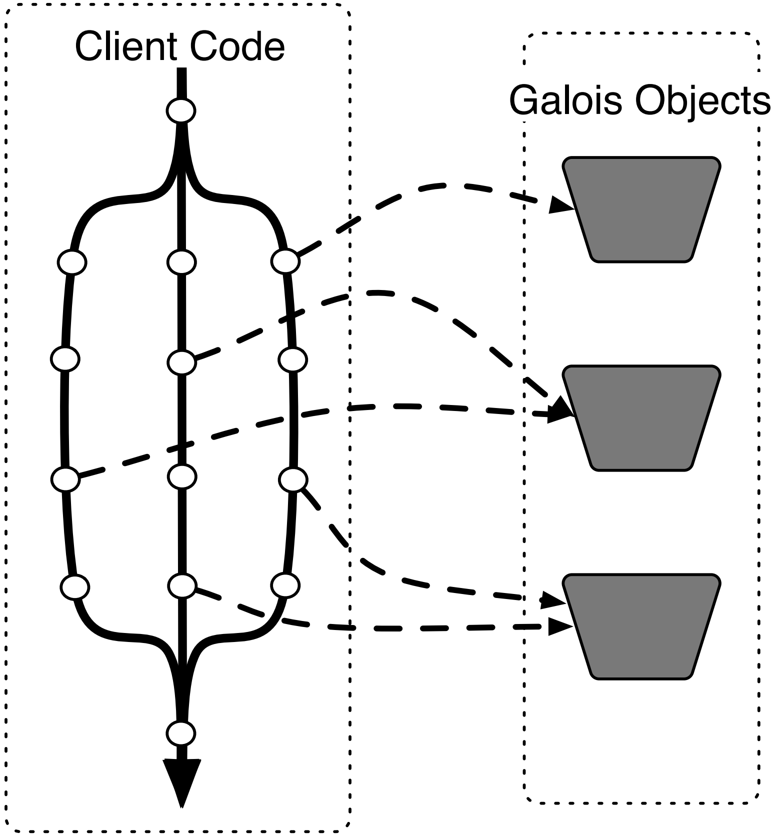
Lessons Learned

- Worklist-style data parallelism
  - May be dependences between iterations
- However, worklist abstractions are missing from the code
- Concurrent access to shared objects a must
  - worklist, priority queue, kd-tree

Galois Programming Model and Implementation

Programming Model

- Object-based shared memory model
  - Client code must invoke methods to access object state
- Client code has sequential semantics
  - But runtime system may execute code in parallel



Worklist Abstractions

- Iterators over collections
  - `foreach e in set S do B(e)`
    - Iterations can execute in any order
      - As in Delaunay mesh refinement
  - `foreach e in poSet S do B(e)`
    - Iterations must respect ordering of `S`
      - As in agglomerative clustering
- May be dependences between iterations
- Sets can change during execution

Delaunay Example

```
Mesh m = /* read in mesh */
WorkList wl;
wl.add(mesh.badTriangles());
while (wl.size() != 0) {
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Delaunay Example

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Mesh m = /* read in mesh */
WorkList wl;
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   mesh.update(c);
   wl.add(c.badTriangles());
}
```

rest of code unchanged

Delaunay Example

```
Mesh m = /* read in mesh */
WorkList wl;
wl.add(mesh.badTriangles());
foreach Element e in wl {
```

Iterators expose worklist abstraction to runtime system

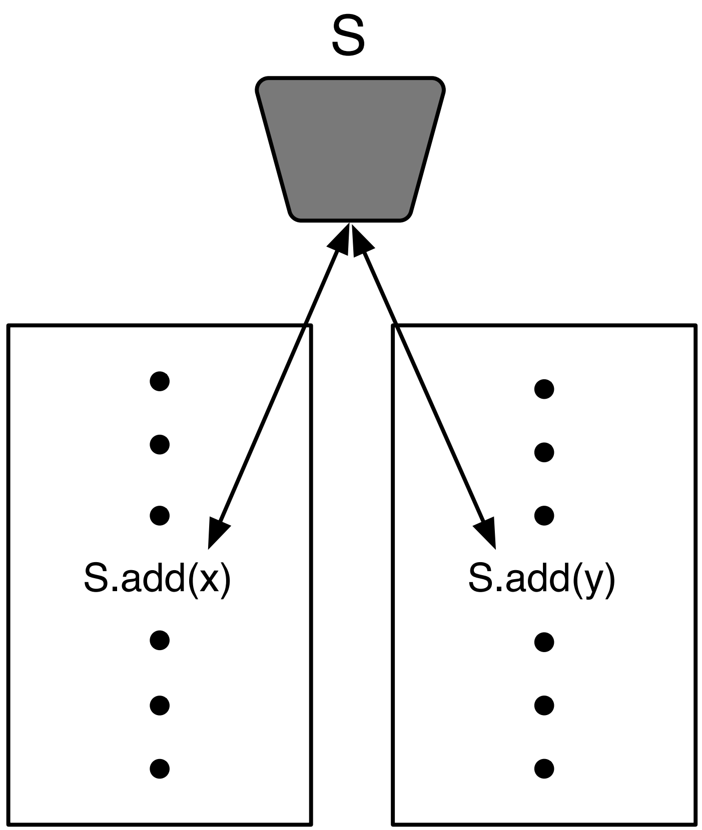
```
    c.expand();
    c.retriangulate();
    mesh.update(c);
    wl.add(c.badTriangles());
}
```

Execution Model

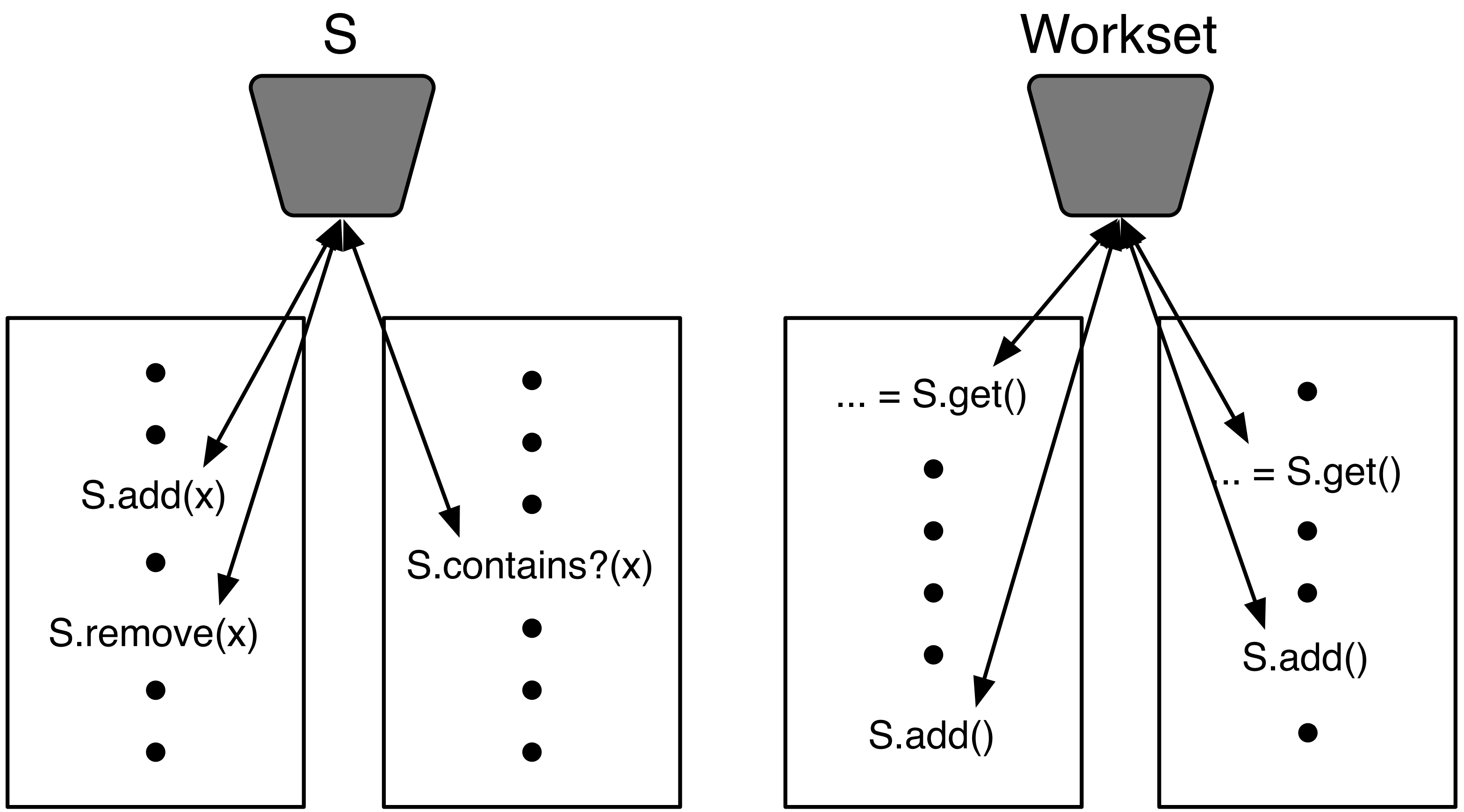
- Master thread begins execution
- When it encounters an iterator, it uses helper threads to aid in execution of iterations
  - Iterations assigned to thread according to scheduling policy (for now, dynamic to ensure load balance)
- Parallel execution of iterator must respect sequential semantics of iterator
  - Concurrent access control
  - Serializability of iterations

Concurrent Access

- Concurrent invocations to a shared object must not interfere
  - Our current implementation uses locks
  - Can use other techniques such as TM



Serializability



(a) Interleaving is illegal

(b) Interleaving is legal (and necessary)

Semantic Commutativity

- Method calls which commute can be interleaved
  - Else, commutativity violation
- Property of abstract data type
  - Implementation independent

Galois Classes

- Inverse methods
  - Allow for rollback when commutativity violated
- Commutativity and inverse specified through interface annotation

```
class SetInterface {
  void add(T x);
    [commutes]
      add(y) {y != x}
      remove(y) {y != x}
      contains(y) {y != x}
    [inverse]
      remove(x)

  bool contains(T x);
    [commutes]
      add(y) {y != x}
      remove(y) {y != x}

  ...
}
```

Galois Classes

- Inverse methods
  - Allow for rollback when commutativity
    v

- Commutativity and inverse specified through interface annotation

```
class SetInterface {
  void add(T x);
    [commutes]
      add(y) {y != x}
      remove(y) {y != x}
      contains(y) {y != x}

                        x);
    [commutes]
      add(y) {y != x}
      remove(y) {y != x}

  ...
}
```

Galois Classes expose abstractions to the runtime system

Runtime System

- Two main components:
  - Global commit pool
    - Manages iterations
    - Similar to reorder buffer in OOE processors
  - Per object conflict logs
    - Detects commutativity violations
    - Triggers aborts if commutativity violated

Evaluation

- Evaluation platform:
  - Implementation in C++
  - gcc compiler on Red Hat Linux
  - 4 processor, shared memory system
  - Itanium 2 @ 1.5 GHz

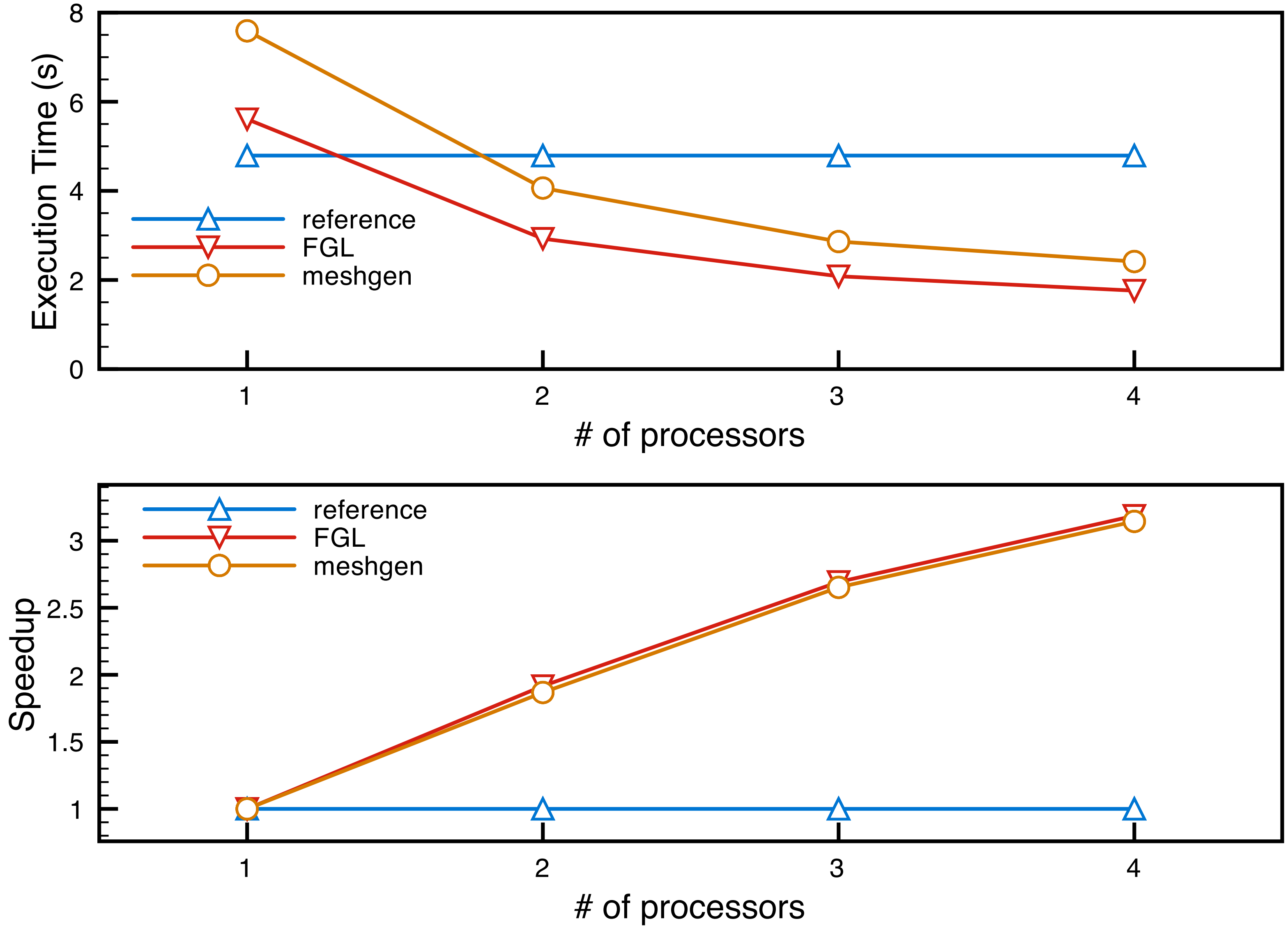
Evaluation – Delaunay

- Three different versions of benchmark
  - reference – purely sequential code
  - FGL – hand-written, optimistic parallel code using fine-grained locking
  - meshgen – Galois version of code
- Input mesh generated using Triangle
  - ~10K triangles
  - ~4K bad triangles

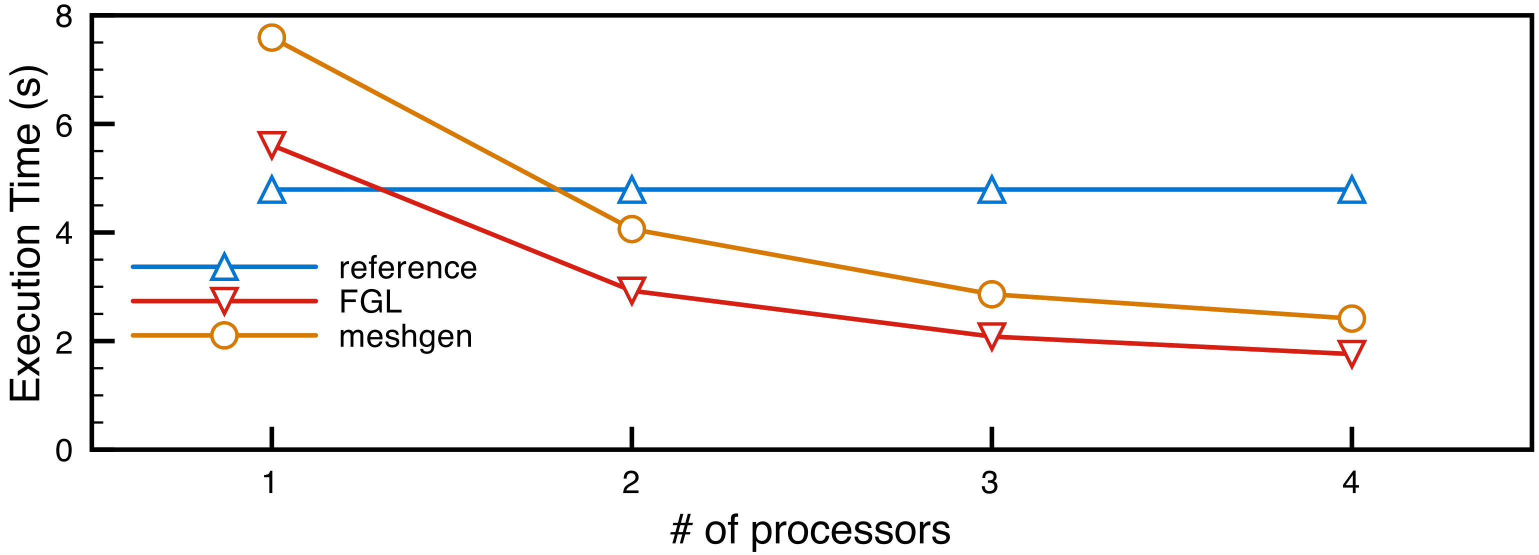
Abort Ratios

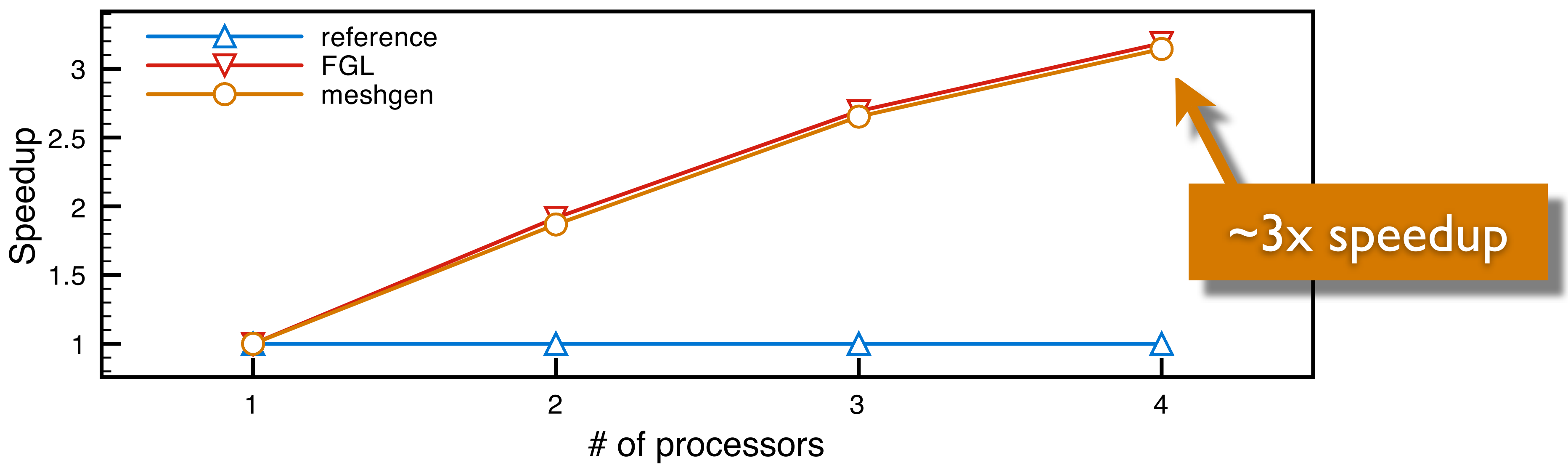
- Optimism must be warranted
  - Conflicts lead to rollbacks, which waste work
- FGL and meshgen have abort ratios <1% on 4 processors
- Closely tied to scheduling policy
  - Choice of proper scheduling policy is crucial for good performance

Evaluation – Delaunay

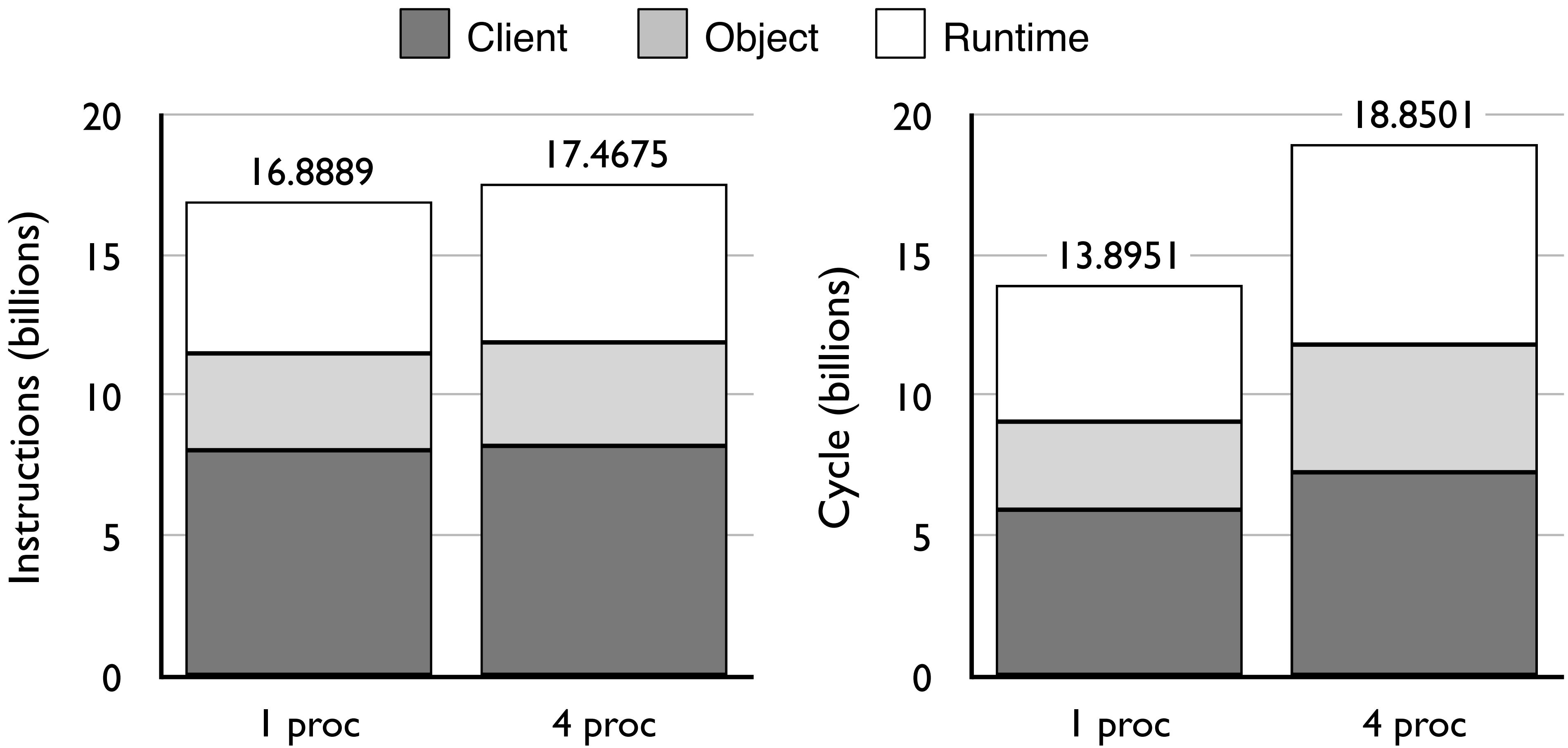


Evaluation – Delaunay





Performance Breakdown



Related Work

- Weihl, 1988 – Concurrency control using commutativity properties of ADTs
- Rinard & Diniz, 1996 – Static commutativity analysis for parallelization
- Wu & Padua, 1998 – Exploiting semantic properties of containers in compilation
- Ni *et al*, 2007 – Open nesting using abstract locks

Conclusions

- Optimistic parallelism necessary to parallelize irregular, worklist-based applications
- Need to exploit high-level semantics
  - Iterators to expose parallelism
  - Galois classes to expose semantics of objects

Thank You!

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