A Parallel Union-Find Library in Charm++

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Problem Statement

Definition:
A union-find algorithm is an algorithm that performs two operations on a disjoint-set data structure

- **Find** : Determine which subset a particular element is in
- **Union** : Join two subsets into a single subset

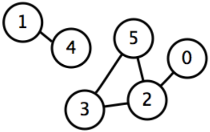


Figure 1: Connected Components in a graph

Other applications : Kruskal's minimum spanning tree algorithm

Outline

Outline

1. Related Work
2. A Charm++ Approach to Union-Find
3. Challenges
4. Optimizations
5. Current Status
6. What's In Store

Related Work

Connectivity in a graph is a very well explored problem

- Shiloach, Yossi, and Uzi Vishkin. "An O (logn) parallel connectivity algorithm." Journal of Algorithms 3.1 (1982): 57-67.
- Nassimi, David, and Sartaj Sahni. "Finding connected components and connected ones on a mesh-connected parallel computer." SIAM Journal on computing 9.4 (1980): 744-757.
- Krishnamurthy, A., Lumetta, S., Culler, D. E., & Yelick, K. (1997). "Connected components on distributed memory machines". Third DIMACS Implementation Challenge, 30, 1-21.
- Manne, Fredrik, and Md Patwary. "A scalable parallel union-find algorithm for distributed memory computers." Parallel Processing and Applied Mathematics (2010): 186-195.

Our motivation : A scalable union-find algorithm in a distributed asynchronous environment

Outline

Our algorithm

- Given a graph $G = (V, E)$, with $n = |V|$ and $m = |E|$
- An edge $e = (v_1, v_2)$ represents a union operation

Our algorithm:

1. Message v_1 for the operation $find(v_1)$
2. v_1 messages parents till $boss_1 = find(v_1)$
3. $boss_1$ messages v_2 for operation $find(v_2)$ and carries info of $boss_1$
4. When $boss_2 = find(v_2)$, align parent pointers of bosses

- Effectively we are constructing a forest of inverted trees; each tree is a unique connected component
- Root of a tree = Representative of the component

Our algorithm

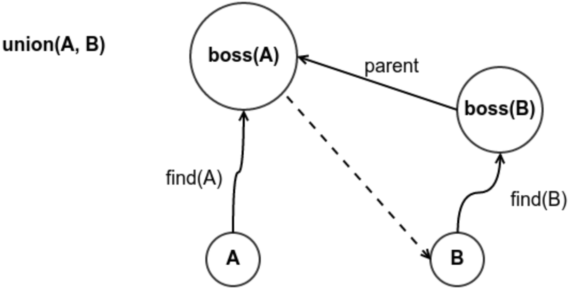
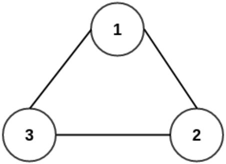


Figure 2: Asynchronous union-find algorithm

Outline

Challenges



Consider 3 PEs, one chare on each PE

union(1, 2) on chare 0
union(2, 3) on chare 1
union(3, 1) on chare 2

Too much symmetry

Solution

- Simplicity is the best way of dealing with complexity
- Enforce a strict ordering in the union operation, say based on vertex ID
- Brings in an additional min-heap like property to the inverted trees
  - ID of a parent node is always lesser than IDs of its children
  - A possible cycle edge can be detected if a node with lower ID is asked to point to node with higher ID
  - We reprocess the union-request by flipping the order to comply with the ordering

Solution - 3 Functions

```
union_request(v1, v2) {
    if (v1.ID > v2.ID)
        union_request(v2, v1)
    else
        find_boss1(v1, v2)
}
```

Listing 1: union_request

Solution - 3 Functions

```
union_request(v1, v2) {
    if (v1.ID > v2.ID)
        union_request(v2, v1)
    else
        find_boss1(v1, v2)
}
```

Listing 1: union_request

```
find_boss1(v1, v2) {
    if (v1.parent == -1)
        find_boss2(v2, boss1)
    else
        find_boss1(v1.parent, v2)
}
```

Listing 2: find_boss1

Solution - 3 Functions

```
union_request(v1, v2) {
    if (v1.ID > v2.ID)
        union_request(v2, v1)
    else
        find_boss1(v1, v2)
}
```

Listing 1: union_request

```
find_boss1(v1, v2) {
    if (v1.parent == -1)
        find_boss2(v2, boss1)
    else
        find_boss1(v1.parent, v2)
}
```

Listing 2: find_boss1

```
find_boss2(v2, boss1) {
    if (v2.parent == -1) {
        if (boss1.ID > v2.ID)
            union_request(v2, boss1)
        else
            v2.parent = boss1
    }
    else
        find_boss2(v2.parent, boss1)
}
```

Listing 3: find_boss2

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4. **Optimizations**
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Optimizations

Motivation to optimize:

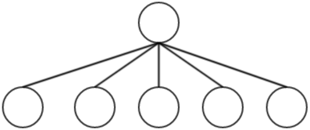
- Tree construction is very communication-intensive
- Lots of tiny messages ($\sim$1.5 billion messages for 16 million vertices, 6 million edges)
- We also found the trees to be very deep
  - Sequentially, path compression is used to get optimal performance
- Climbing long tree paths for each request slowed down tree construction

Optimizations

1. **Locality-based tree climbing**
   - Sequentially traverse the tree path until the next vertex lies on a different chare
   - This increases work per chare but drastically reduces number of messages
   - Observed 25x speedup in tree construction

Optimizations

1. **Locality-based tree climbing**
   - Sequentially traverse the tree path until the next vertex lies on a different chare
   - This increases work per chare but drastically reduces number of messages
   - Observed 25x speedup in tree construction
2. **Local path compression**
   - Make the local tree constructed in every chare completely shallow
   - Provides a one-hop access to bosses



More optimization if extended to PE-level or node-level

Outline

Current Status

- Library designed using bound-array concept
- Connected components detection
  - **Phase 1** : Build the forest of inverted trees using our asynchronous union-find algorithm
  - **Phase 2** : Identify the bosses of each component and label all vertices in that component
  - **Phase 3** : Prune out insignificant components
- Tested and verified with real-world graphs (protein structures from PDB)
- Large scale testing with probabilistic mesh concept

Probabilistic Mesh

- A class of graphs motivated by cluster dynamics in computational physics[1] (2D Ising model)
- A random graph built on a lattice structure
- Edge between two lattice points (vertices) is determined by calculating a probability value using coordinate positions

Advantages:

- Easy to scale the size of graph
- Easy to verify results and catch race conditions
  - Fixed probability and lattice size produces same graph
  - Play with the number of chares and PEs

[1] S. S. Lumetta, A. Krishnamurthy, and D. E. Culler. "Towards Modeling the Performance of a Fast Connected Components Algorithm on Parallel Machines". In: *Proceedings of the IEEE/ACM SC95 Conference*. 1995, pp. 32–32.

Experiments

Experiments performed:

1. Phase runtime evaluation
   - Mesh configurations : 1024^2 (1M), 2048^2 (4M), 4096^2 (16M), 8192^2 (64M)
   - Probabilities : 2D00, 2D40, 2D60
   - Problem size per chare fixed at : 64x64 mesh piece
2. Scaling performance
   - Mesh configuration : 2048^2, 2D40
   - Problem size per chare : 2x2 mesh piece
   - Number of physical nodes : 2, 4, 8, 16, 32, 64

Results - Phase runtime

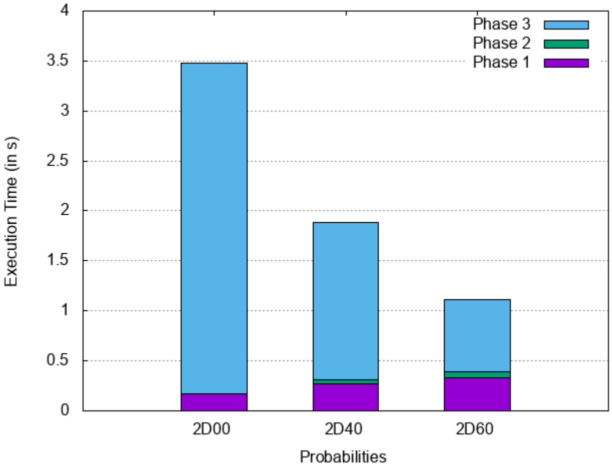


Figure 4: Mesh size 1024x1024 on 2 nodes

Results - Phase runtime

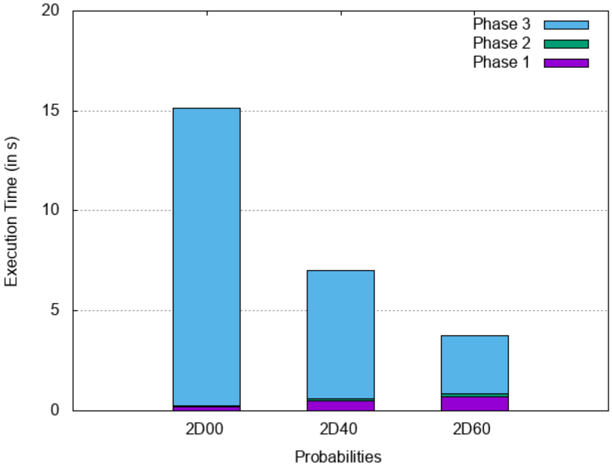


Figure 5: Mesh size 2048x2048 on 2 nodes

Results - Phase runtime

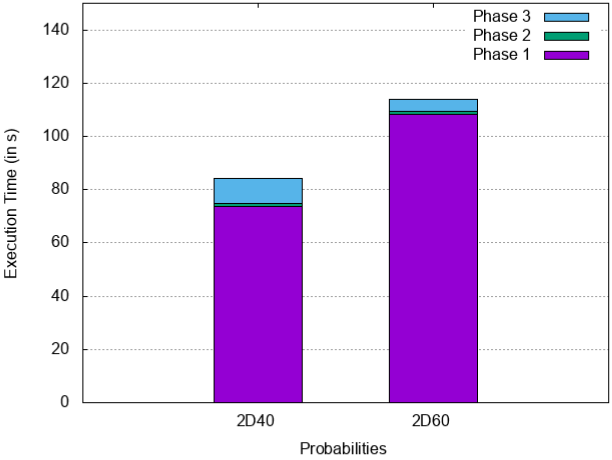


Figure 6: Mesh size 4096x4096 on 16 nodes

Results - Phase runtime

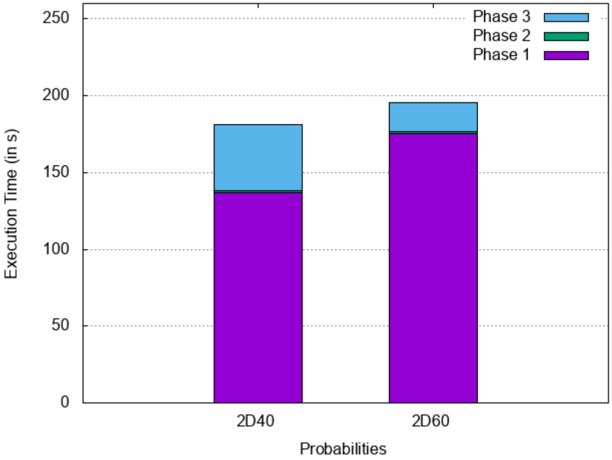
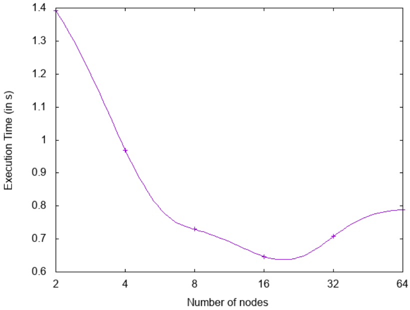
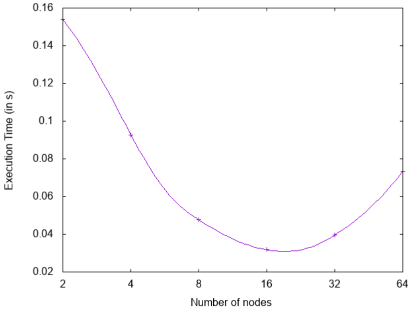


Figure 7: Mesh size 8192x8192 on 32 nodes

Results - Scaling runs



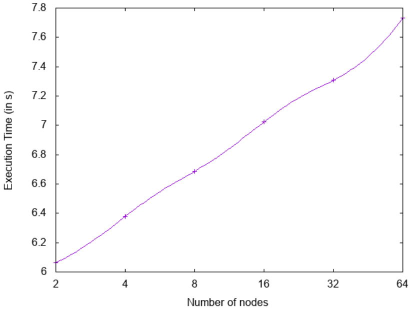
Phase 1



Phase 2

Figure 8: Scaling runs on mesh size 2048x2048

Results - Scaling runs



Phase 3

Figure 9: Scaling runs on mesh size 2048x2048

Outline

Future Work

On the to-do list:

- Optimizing Phase 1 for very large graphs (planning on sub-phases)
- Priority for particular kinds of messages
- Global level path compression which is PE and node-aware
- Use TRAM library in Charm++
- Target ChaNGa for friends-of-friends based galaxy detection

Code and examples on Gerrit: users/karthik/unionFind

Thank You

It's banquet time!