ParaMeter: A profiling tool for amorphous data-parallel applications

Now what?

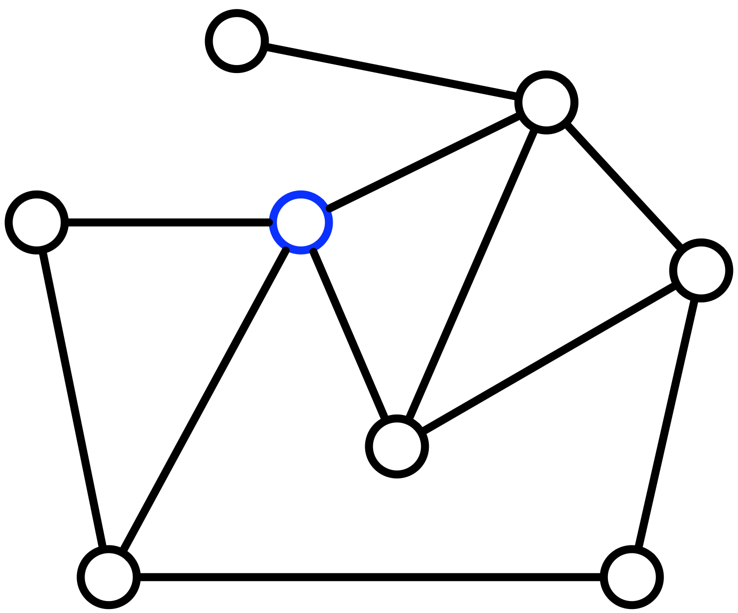
- Simplest thing to do: write your program using the Galois model, then analyze the parallelism

“Available Parallelism”

- How many active nodes can be processed in parallel over time
- Profile the algorithm, not the system
  - Disregard communication/synchronization costs, run-time overheads and locality concerns
- Can expose common structure between algorithms

Example: Spanning Tree

- Problem: given an unweighted graph and a starting node, construct a spanning tree rooted at that node



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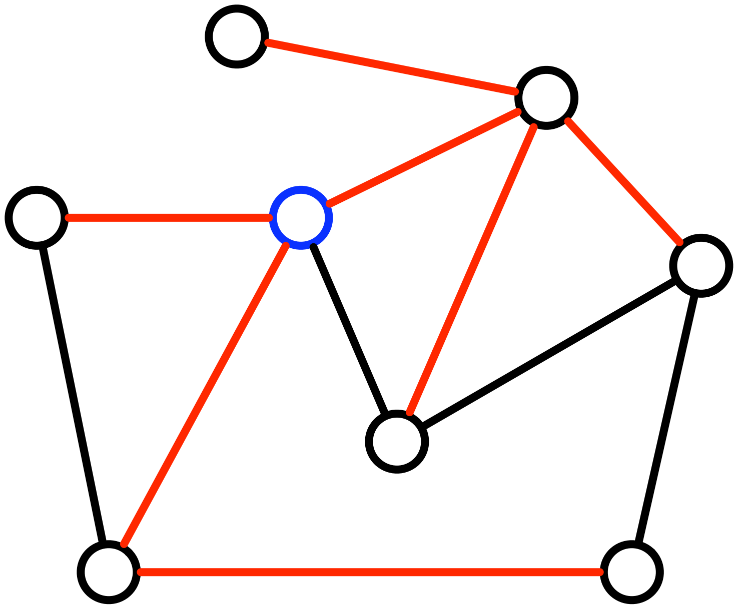

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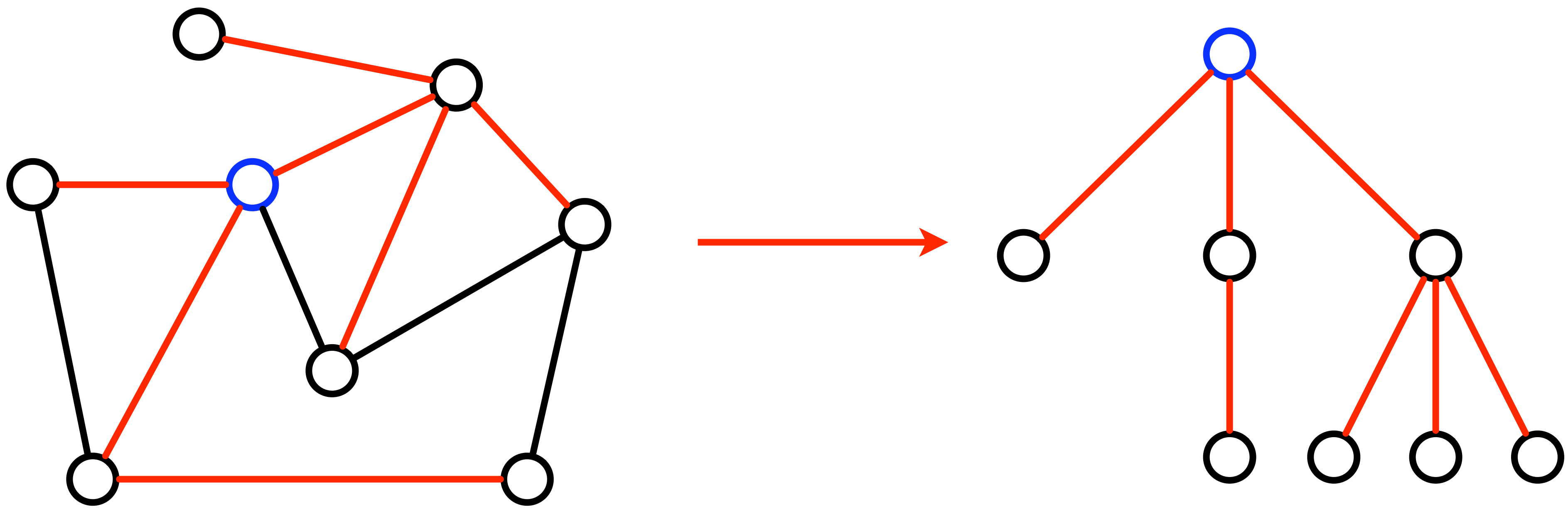


Algorithm + Data Structure

- Algorithm written using Galois foreach operator to represent worklist iteration
  - Specifies whether worklist is ordered or unordered
- Data structures implemented in terms of graph ADT
  - Provided by Galois class library

Algorithm + Data Structure

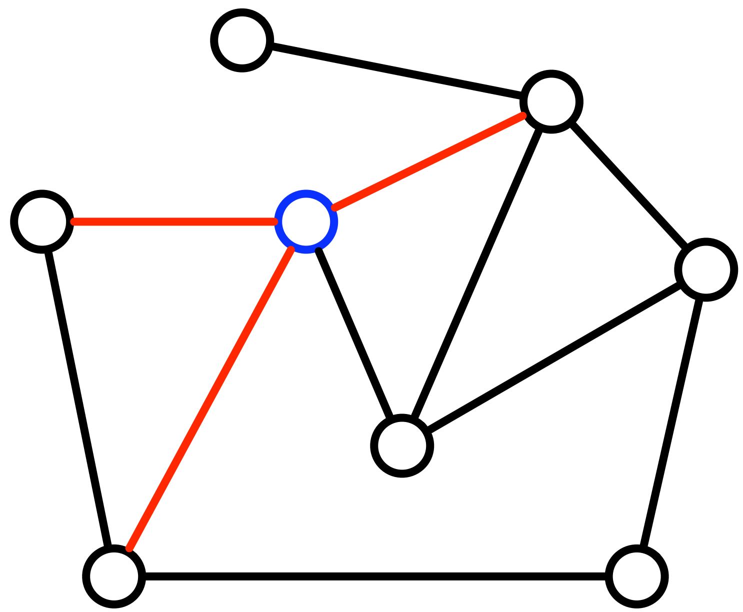
- Algorithm
  - Choose node from worklist
  - Iterate over neighbors
  - If neighbor not in ST, add edge to ST, mark node and add to worklist
- Data structures
  - Graph is a "local computation" graph
  - Spanning tree is a Set of edges

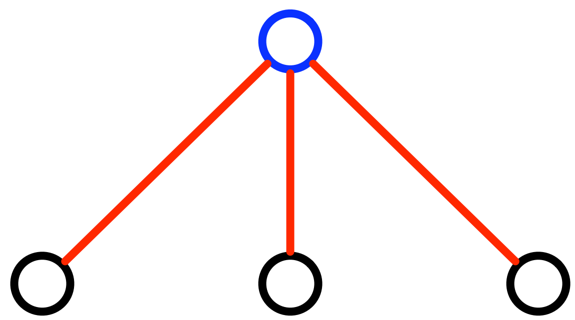
```
Graph graph = read graph from file
Node startNode = pick random node from graph
startNode.inSpanningTree = true
Worklist worklist = create worklist containing startNode
List result = create empty list

foreach src : worklist
    foreach Node dst : src.neighbors
        if not dst.inSpanningTree
            dst.inSpanningTree = true
            Edge edge= new Edge(src,dst)
            result.add(edge)
            worklist.add(dst)
```

Finding Parallelism

- Active nodes: nodes on the frontier of ST (those that have just been added)
- Neighborhood: the immediate neighbors of the active node
- Neighborhoods are small → Can expand ST from several places at the same time





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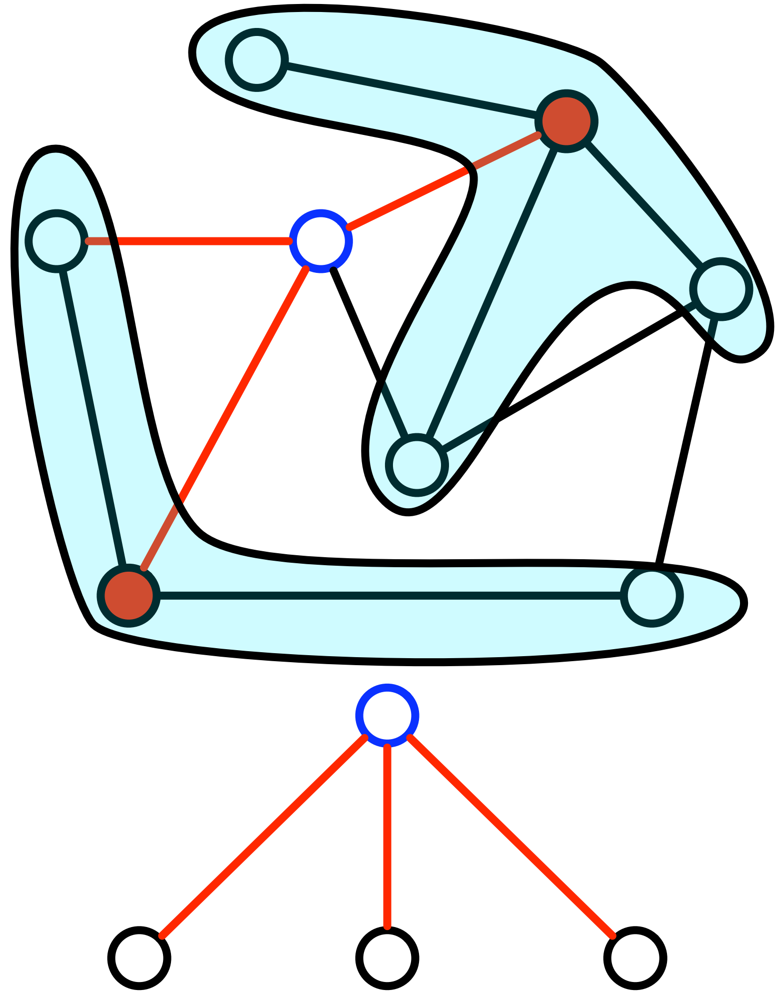

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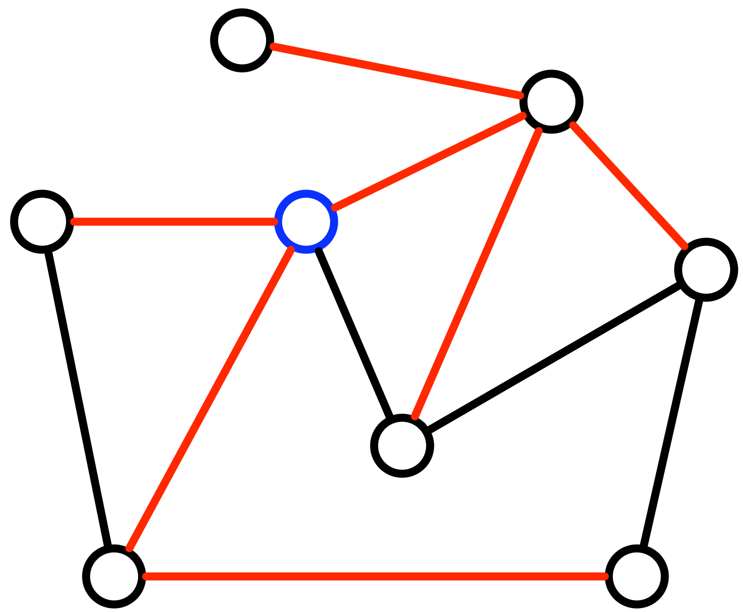
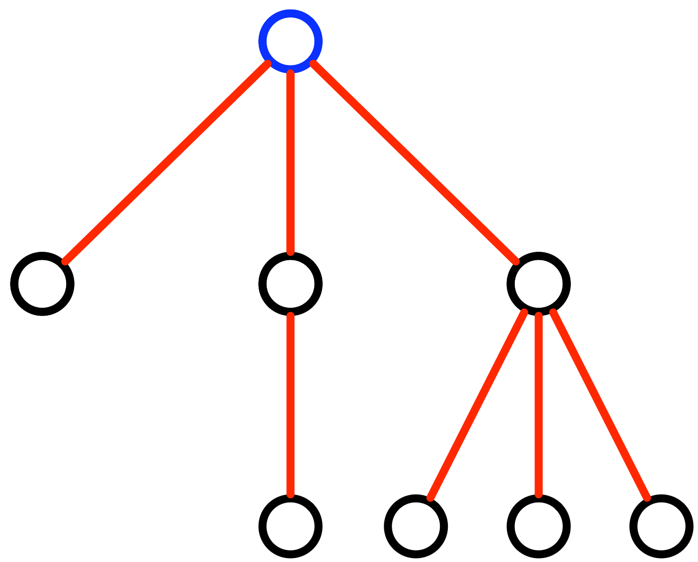
- Parallelism can be seen after the fact in structure of tree

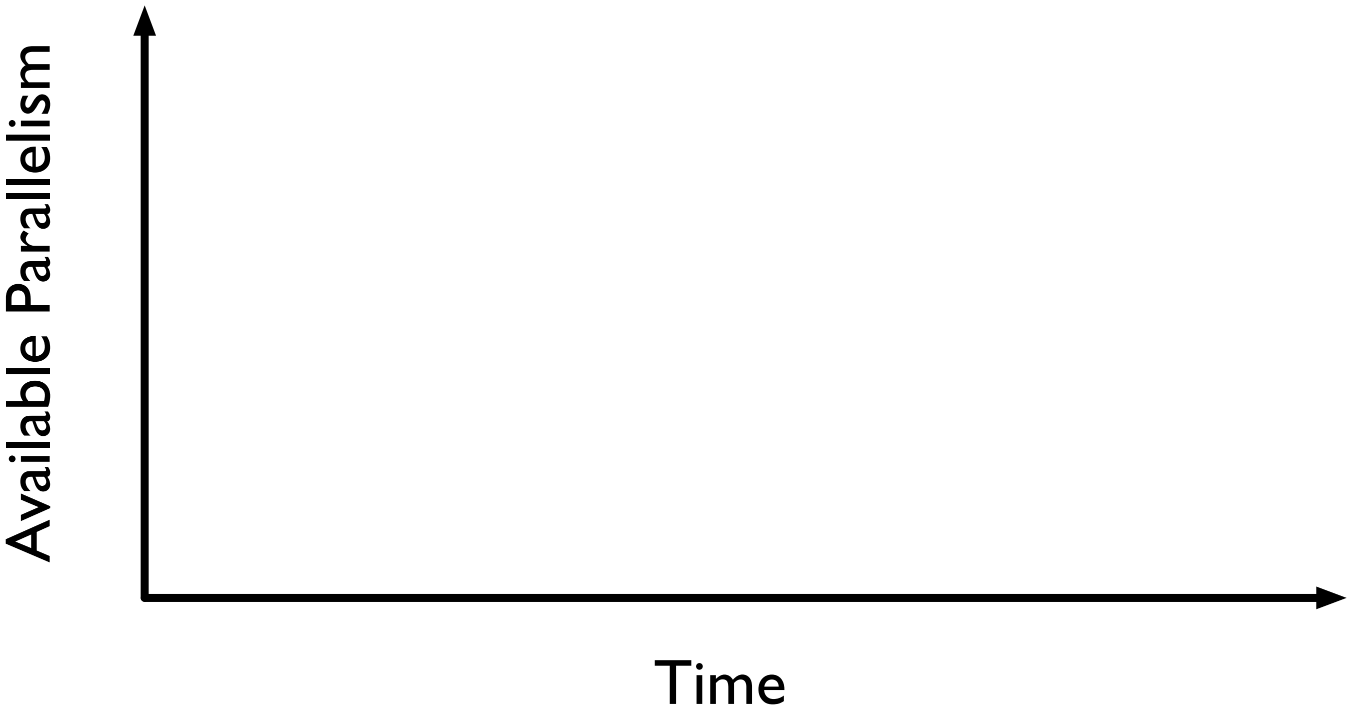




How Much Parallelism is There?

- What would happen if we ran the program on an infinite number of processors?
  - Assume every activity takes the same amount of time (one "step")
  - Assume perfect knowledge of neighborhood and ordering constraints
- How many steps would it take to execute the program?
- How many activities would we be able to execute in one step?
- Computing upper bound on parallelism

A guess:



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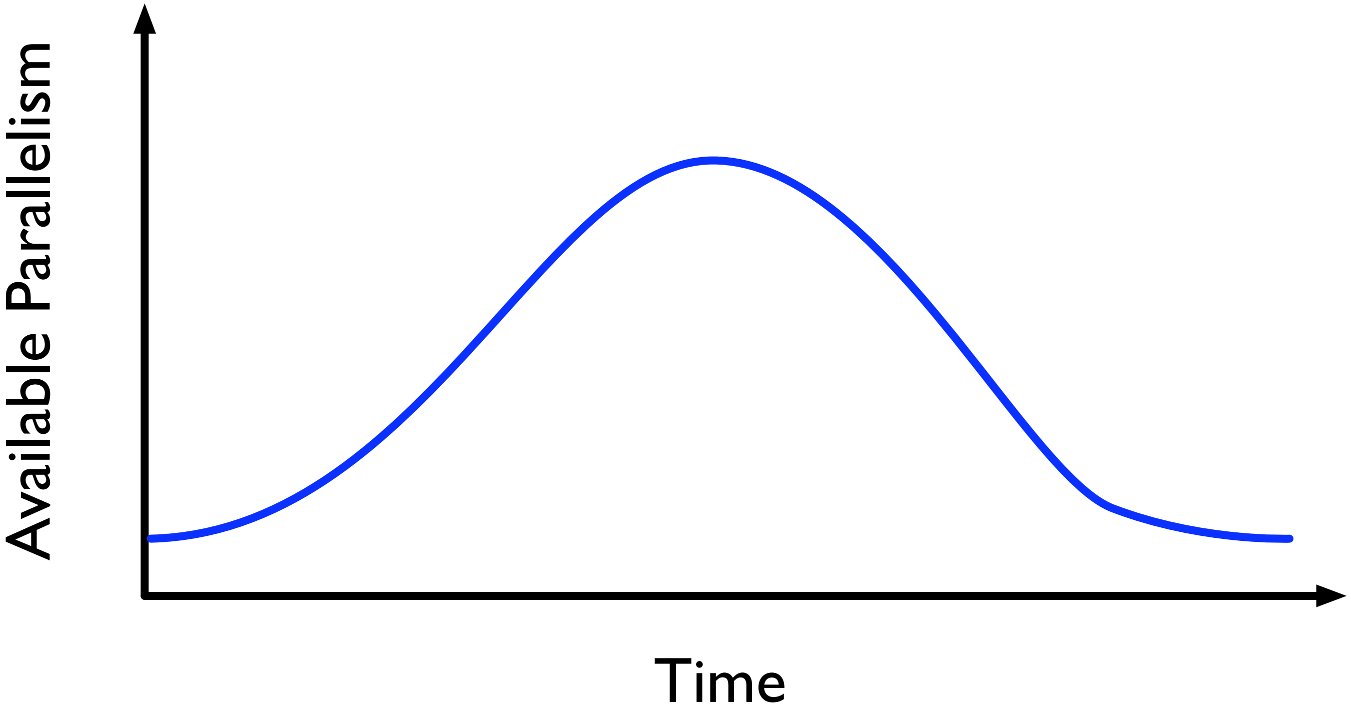

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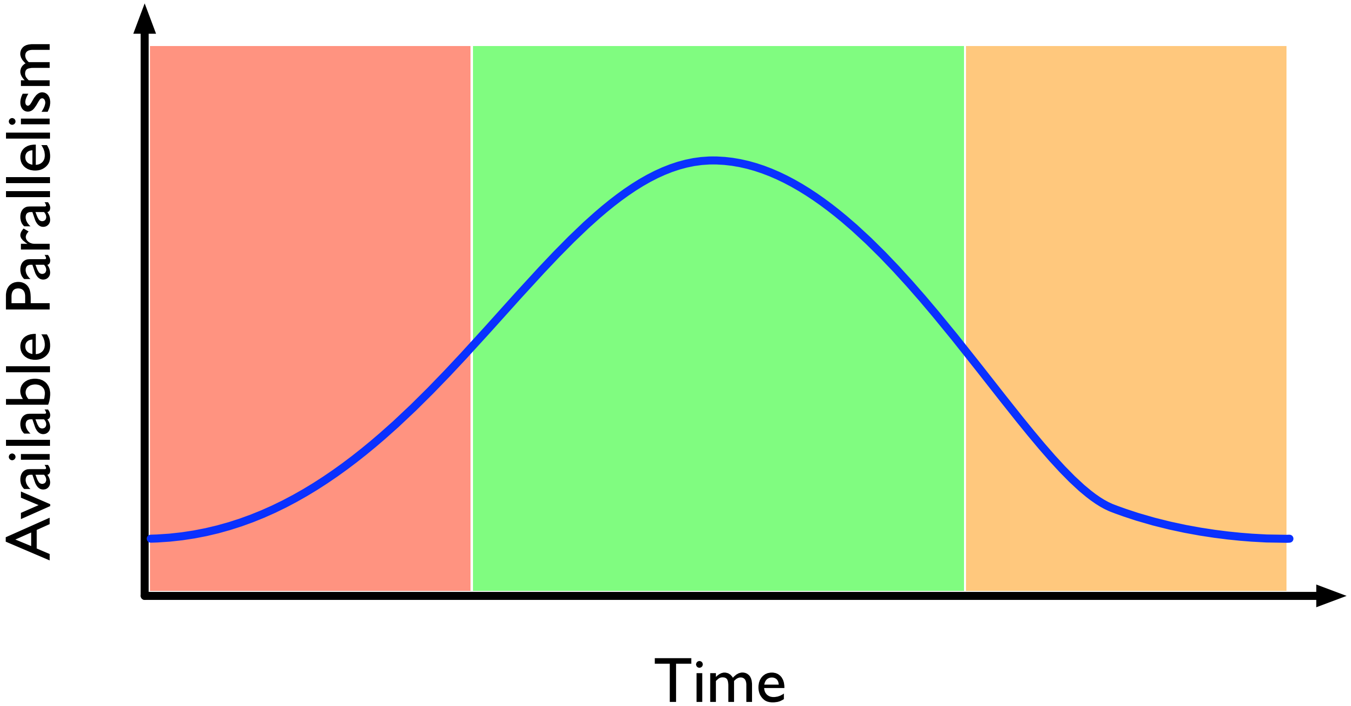


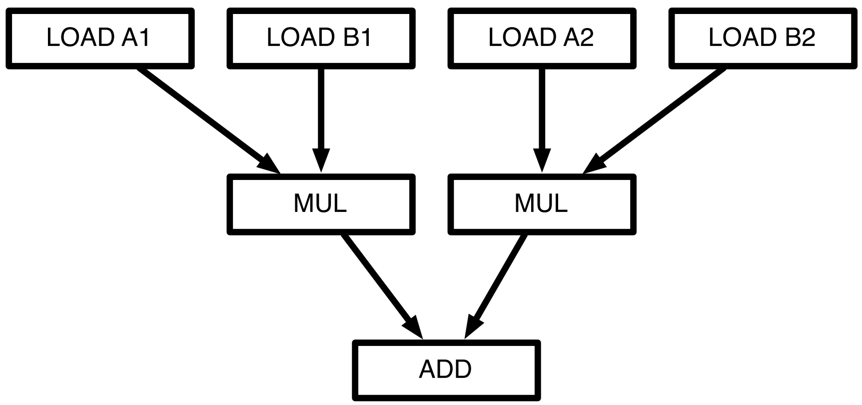
Demo: Spanning tree

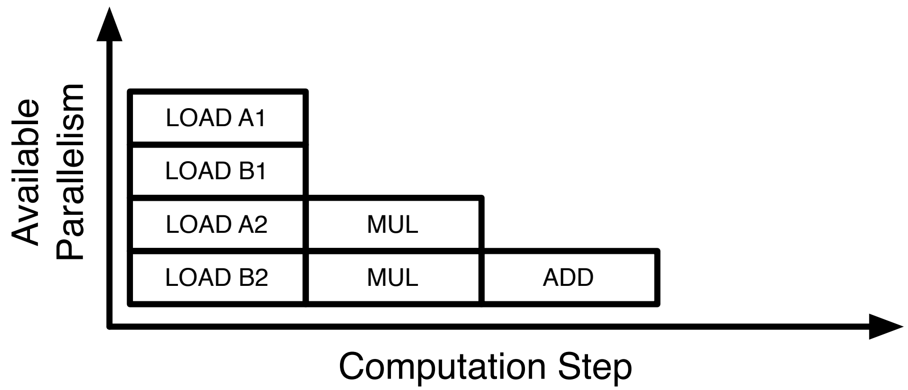
Spanning tree over 120K node graph

So how does this work?

Measuring Parallelism

- Represent program as a DAG
  - Nodes: operations
  - Edges: dependences
- Execution strategy
  - Assume operations take unit time
  - Execute "greedily" – process all ready operations in each step
- Parallelism profile: # of operations executed in each step





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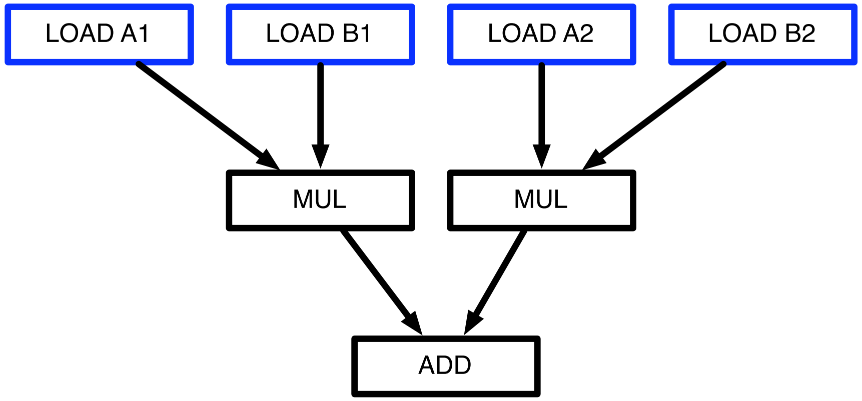

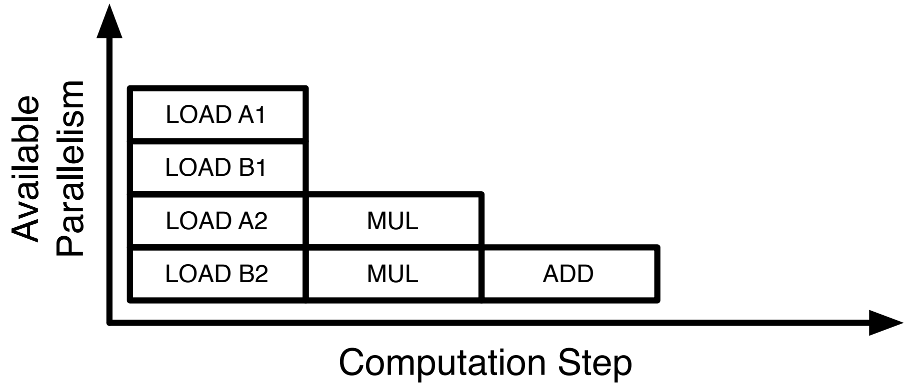

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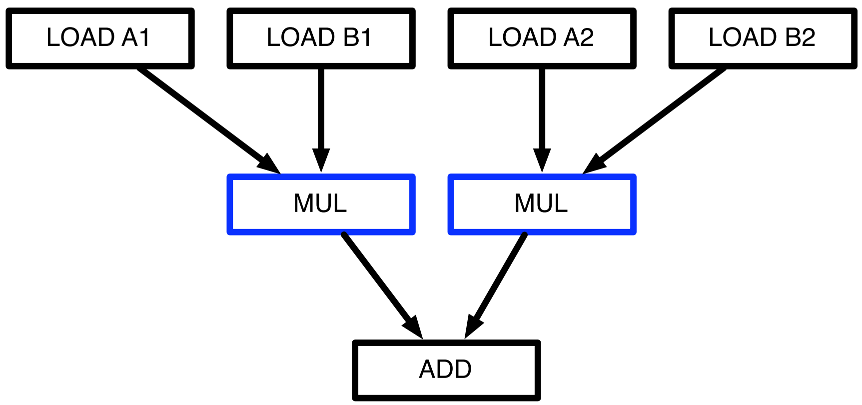

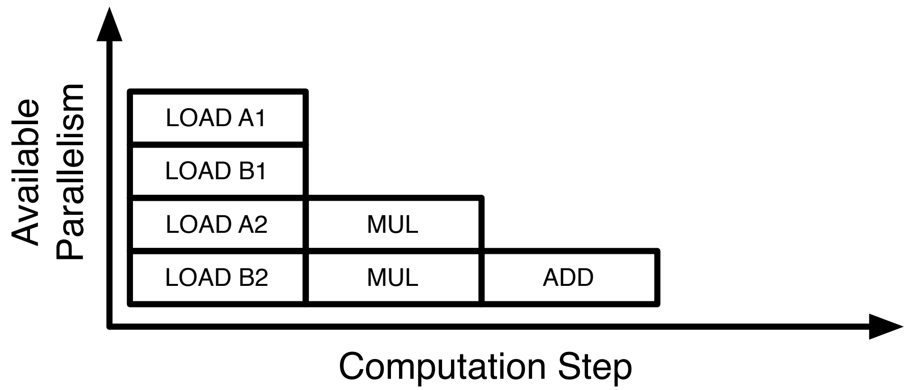

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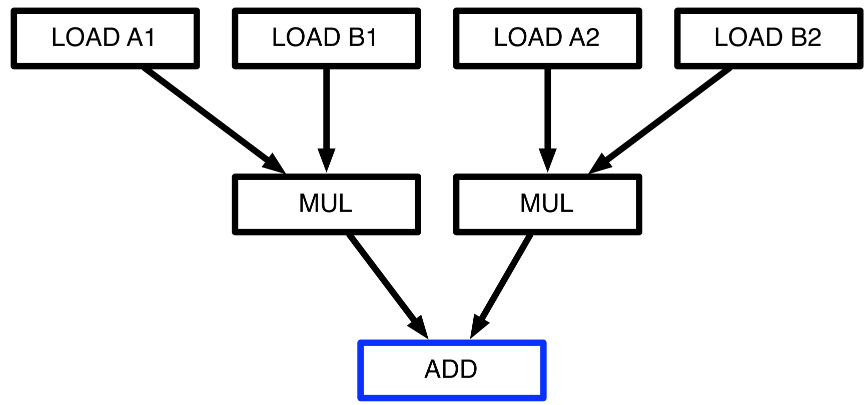
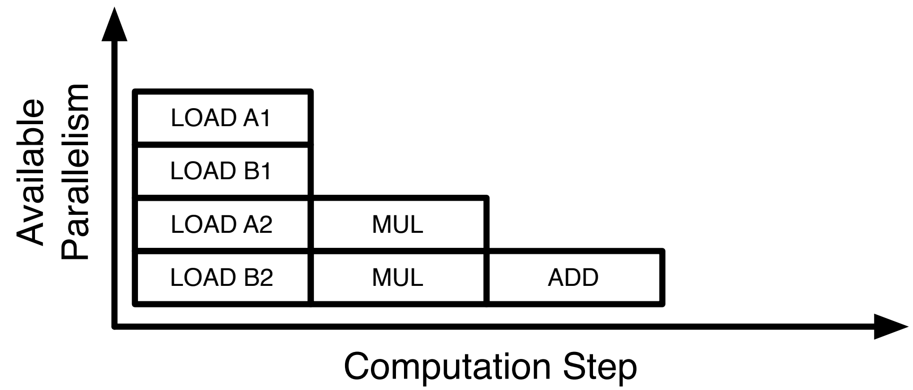
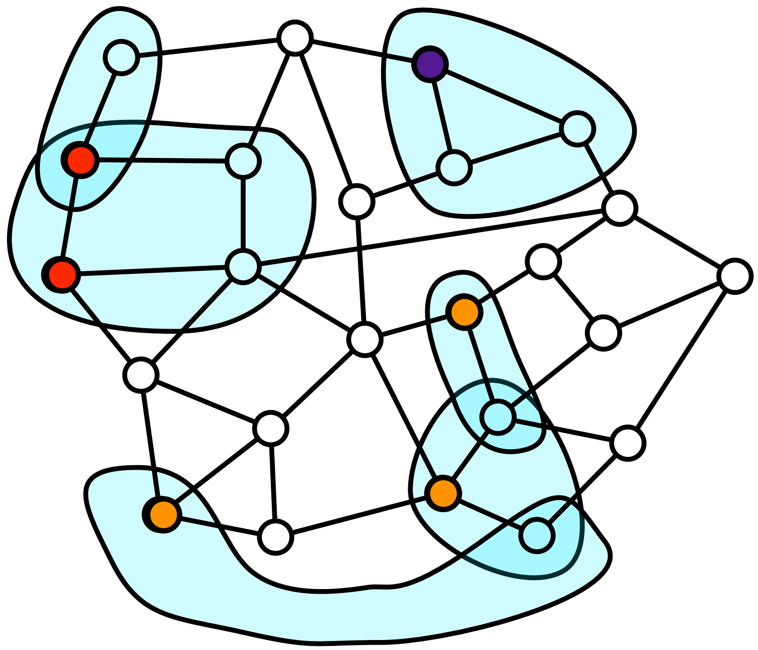




Amorphous Data Parallel Algorithms



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    - Represent program as a graph, not a DAG
- Execution: choose set of independent elements to process
- Different scheduling choices lead to different amounts of parallelism
    - Even with unlimited resources!

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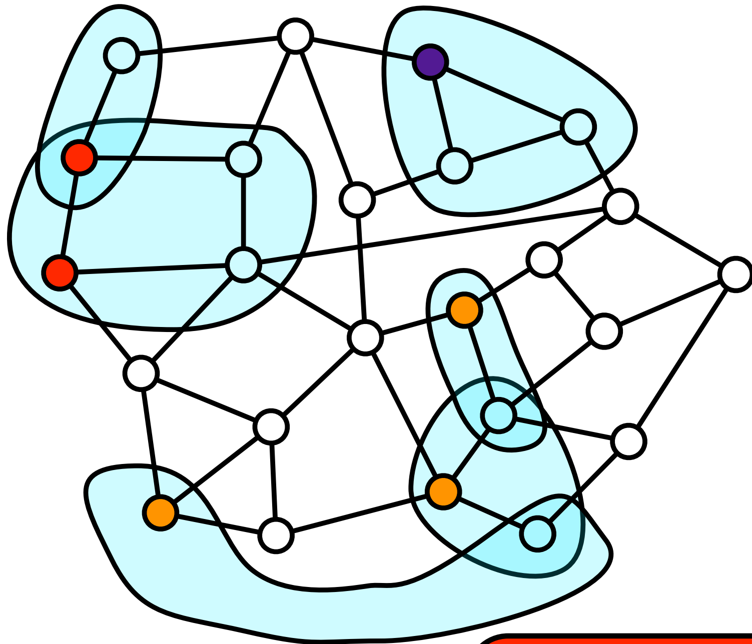
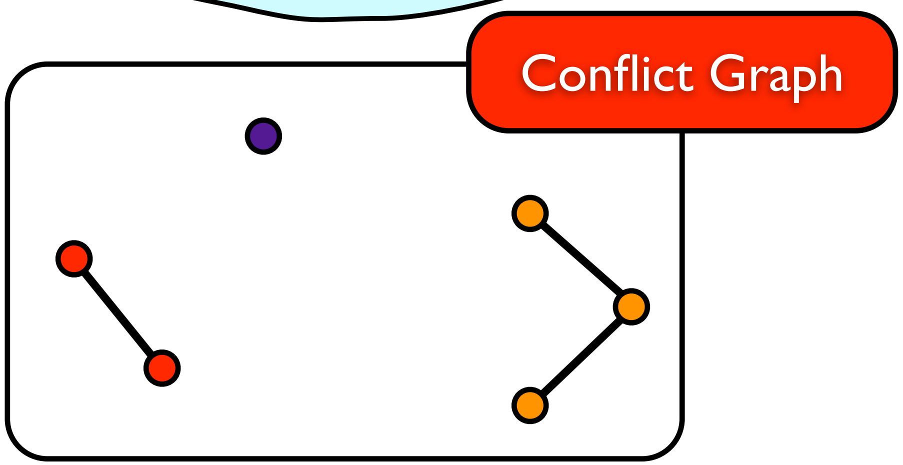




Greedy scheduling

- Finding schedule to maximize parallelism is *NP*-hard

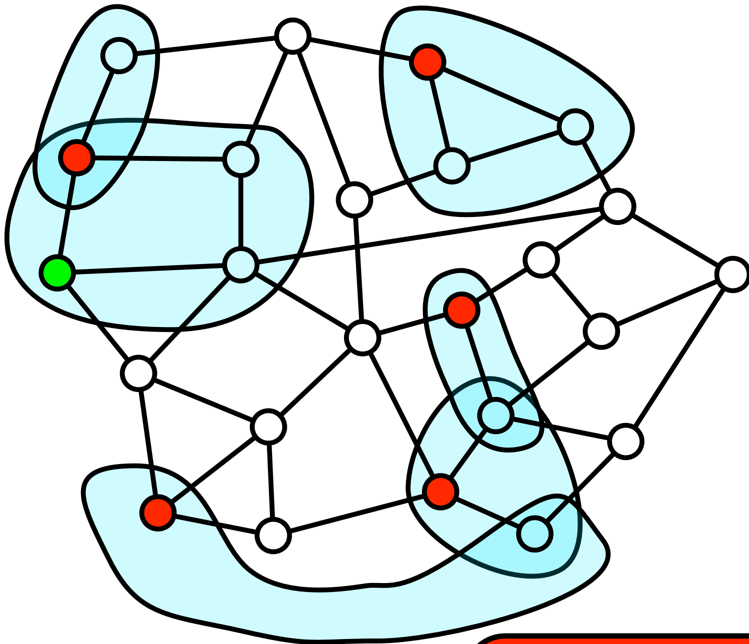
➡ Solution: Schedule greedily

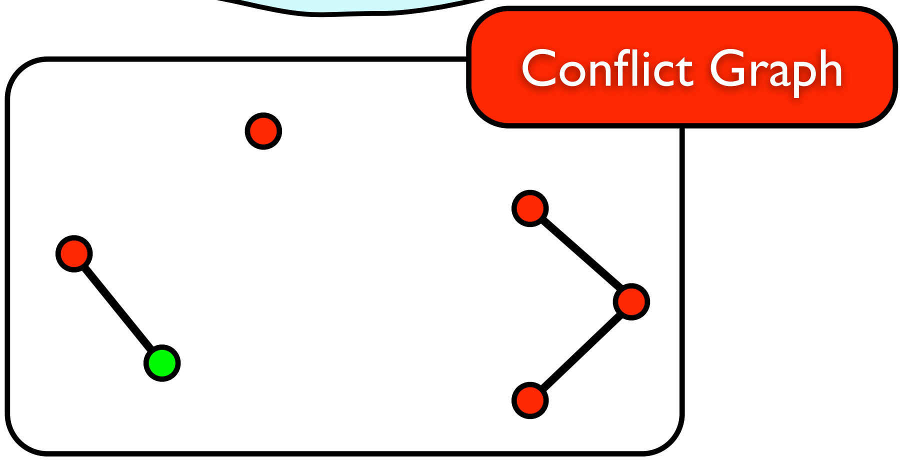
  - Attempt to maximize work done in current step
  - Choose a maximal independent set in conflict graph

Incremental Execution

- Conflict graph can change during execution
  - New work generated
  - New conflicts
- Cannot perform scheduling *a priori*

➡ Solution: execute in stages, recalculate conflict graph after each stage





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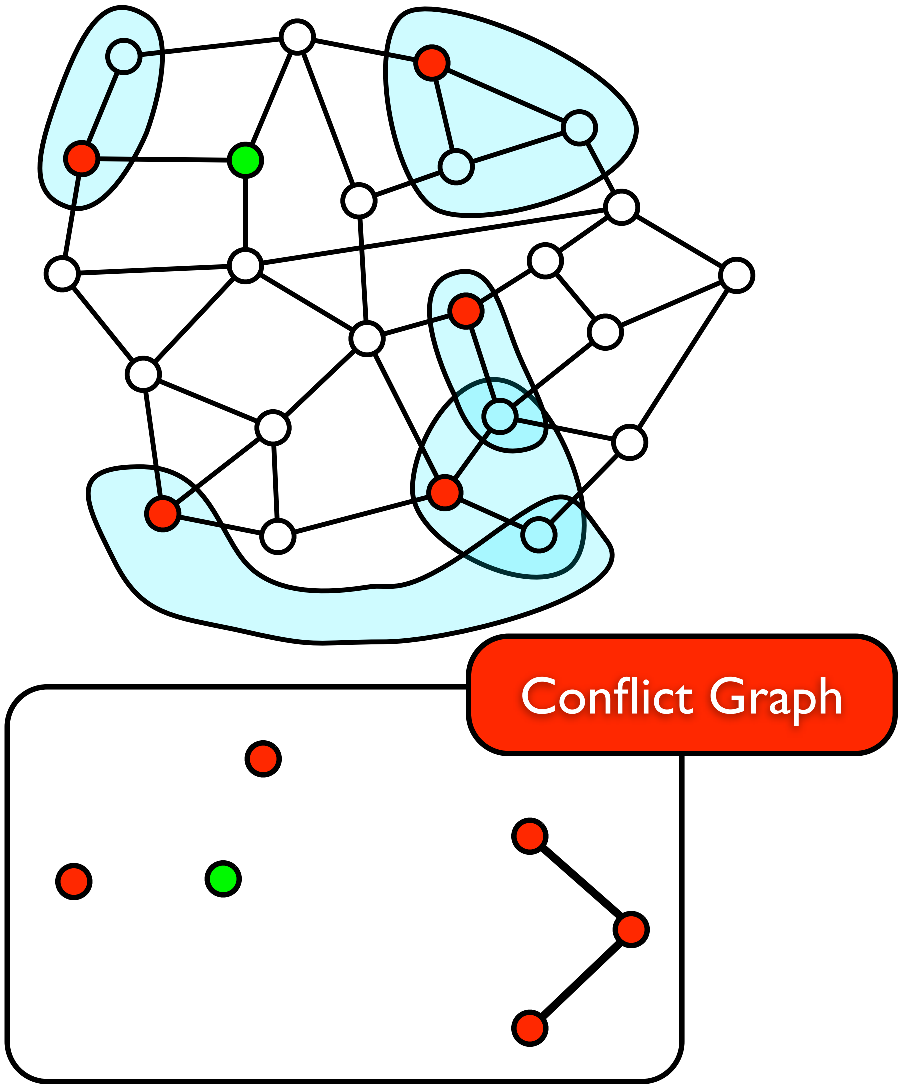

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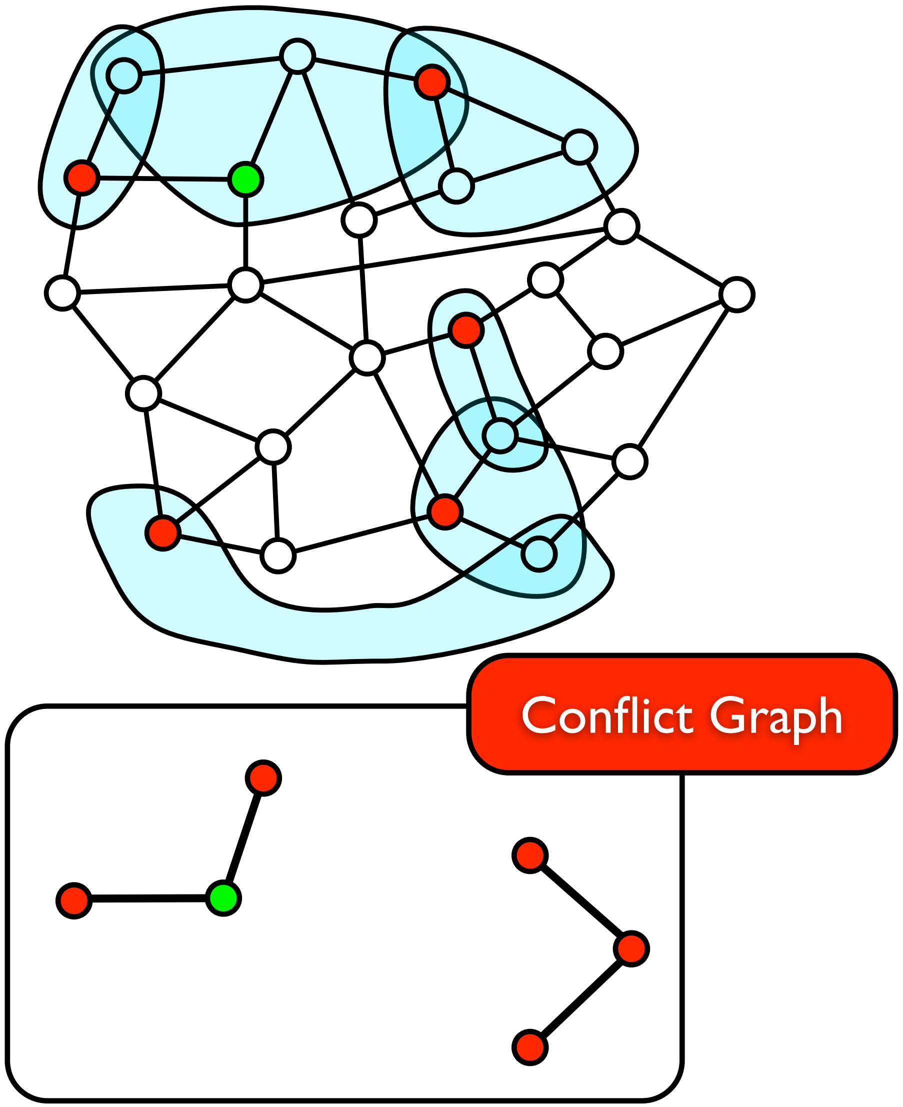

High Level ParaMeter Execution Strategy

- While work left
  - Generate conflict graph for current worklist
  - Execute maximal independent set of nodes in graph
  - Add newly generated work to worklist

High Level ParaMeter Execution Strategy

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  - Gener worklist
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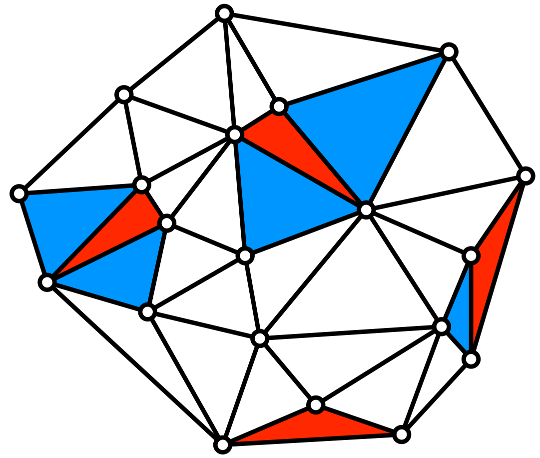
Generate parallelism profile by tracking # of nodes executed in each step

Algorithm classification

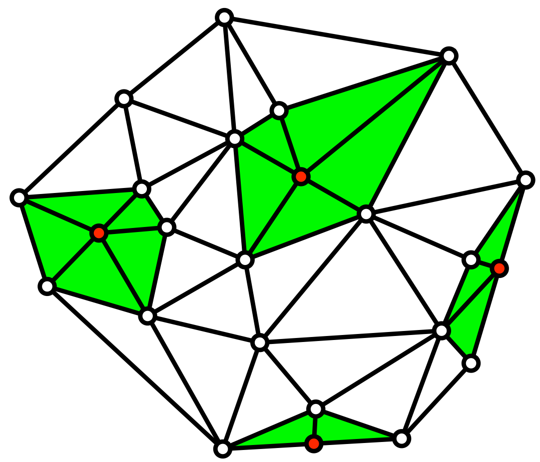
- Spanning tree is a “refinement morph” algorithm
- Typical parallelism profile:
  - Little parallelism to start, as data structure gets refined
  - Most parallelism in the middle, as more activities become independent
  - Little parallelism at the end, as algorithm runs out of work
- Does this pattern hold for other refinement algorithms?

Example: Delaunay mesh refinement

- Active nodes: bad triangles
- Neighborhoods: cavities
- Refinement-like algorithm
  - As bad triangles get fixed, mesh gets larger (fixing a bad triangle replaces N triangles with N+2 triangles)
  - Cavity sizes stay roughly the same (~6 triangles)
  - As mesh grows, cavities less likely to overlap → more parallelism



Before



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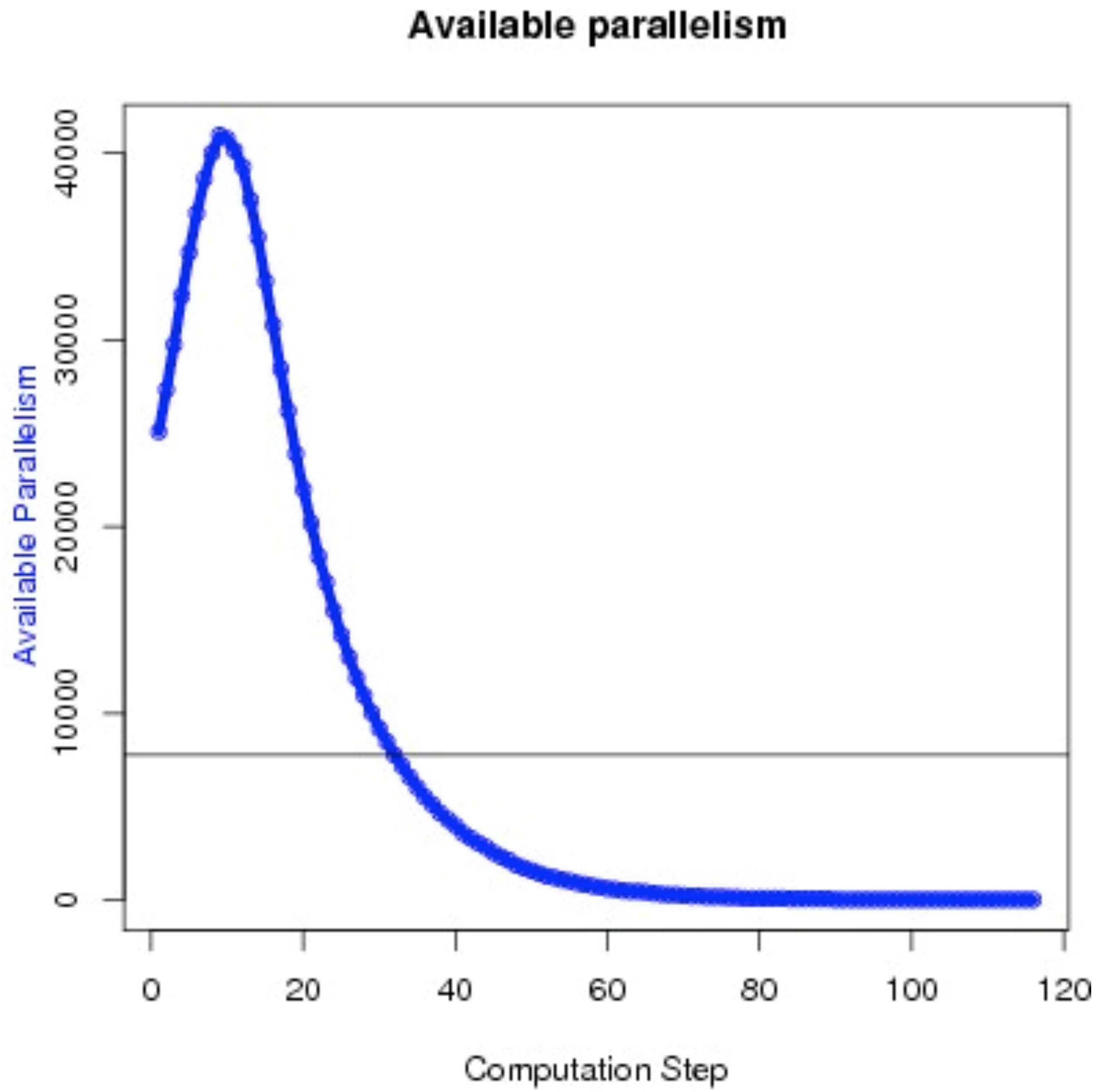
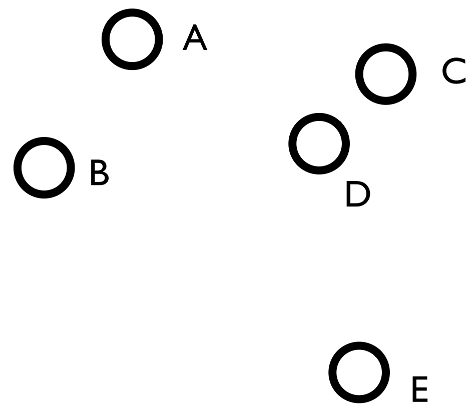


Refine 550K triangle mesh, ~261K badly shaped

Example: Agglomerative clustering

- Goal: cluster a set of points together according to distance to build a *dendrogram*
- Points cluster together if they are one another's nearest neighbor
- Dendrogram is build bottom-up



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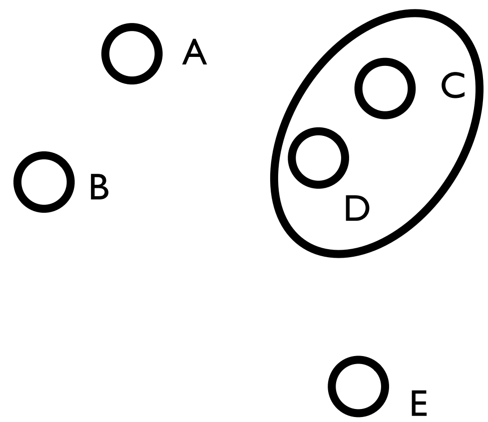

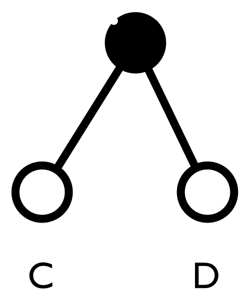

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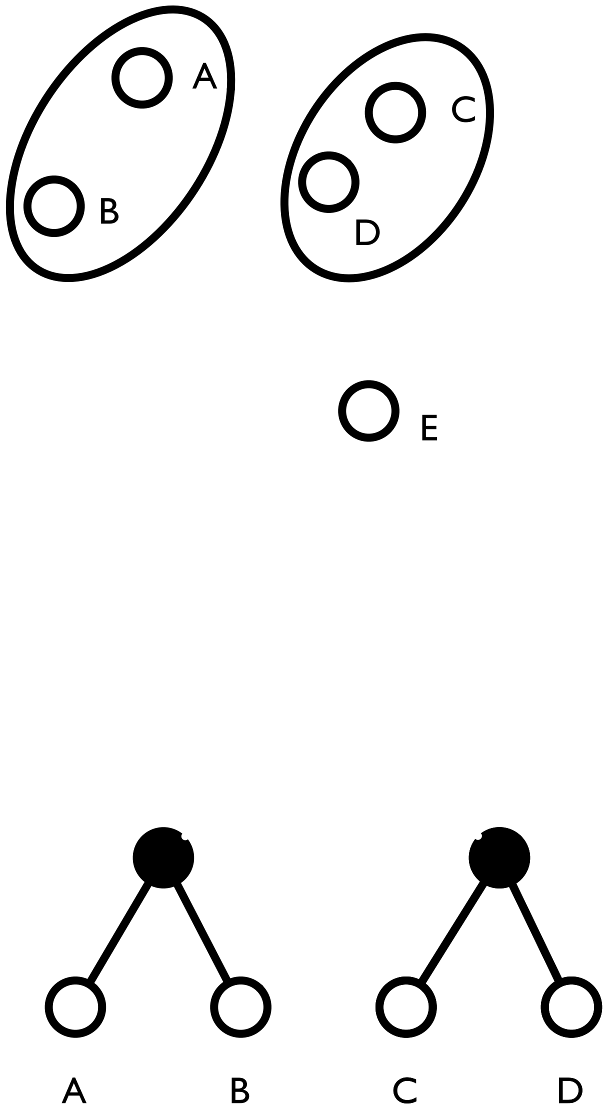

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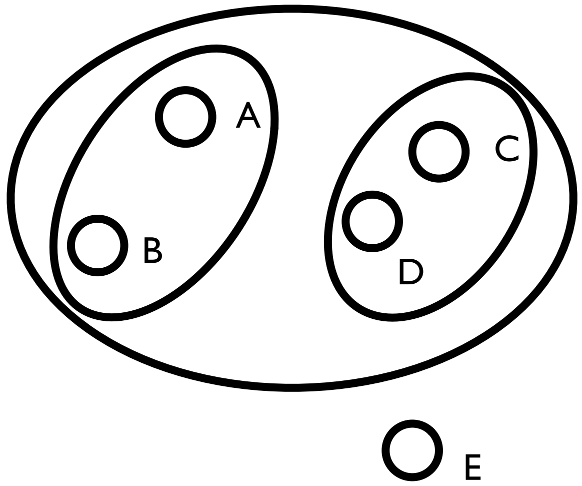

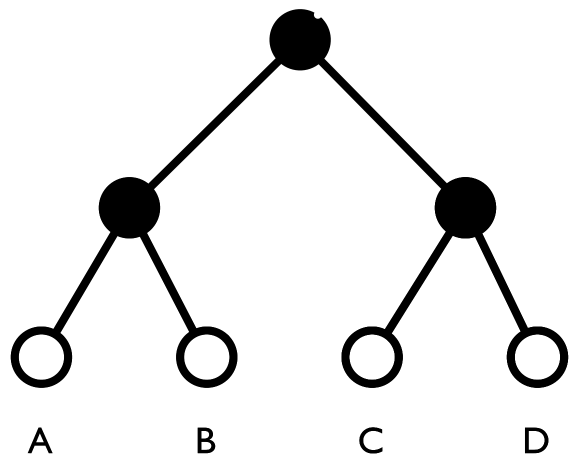

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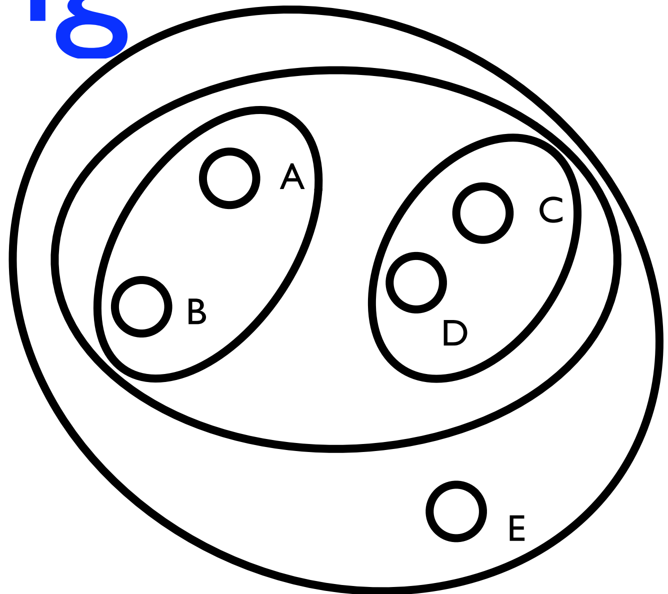
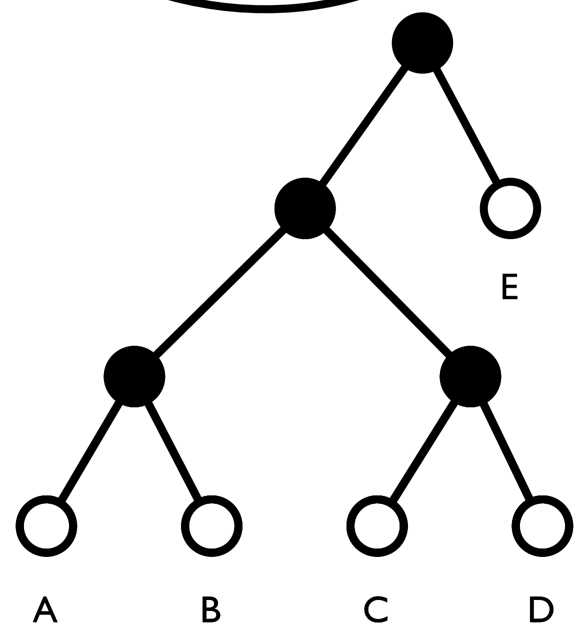
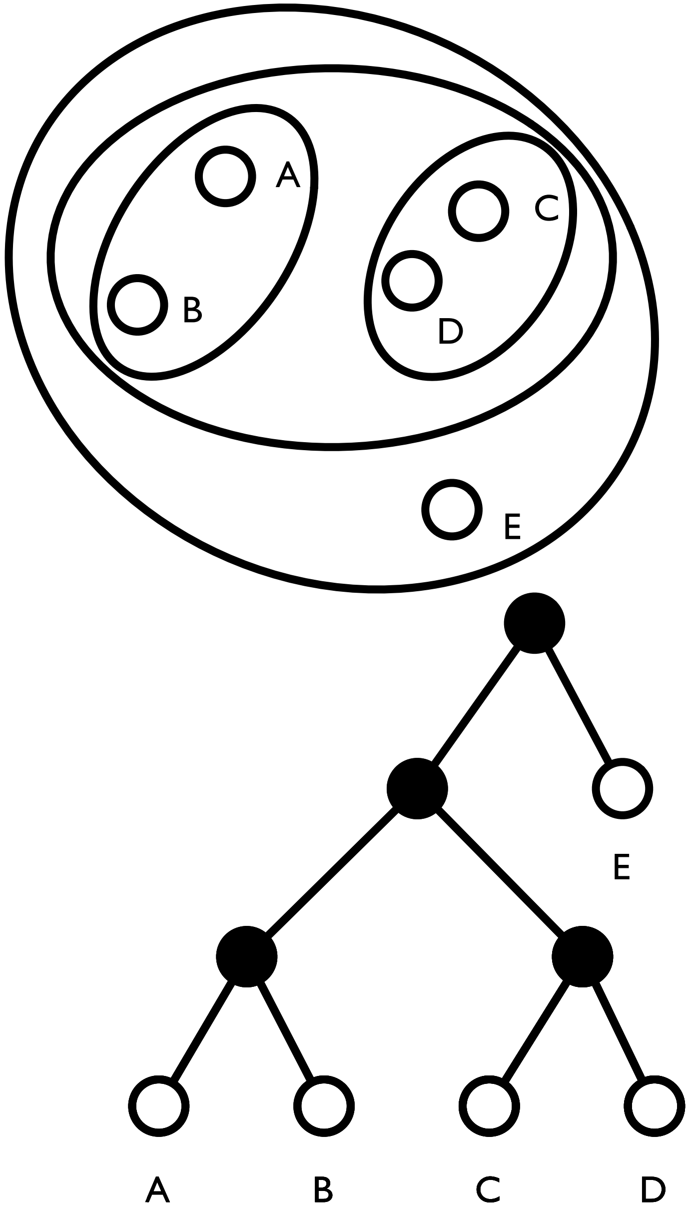
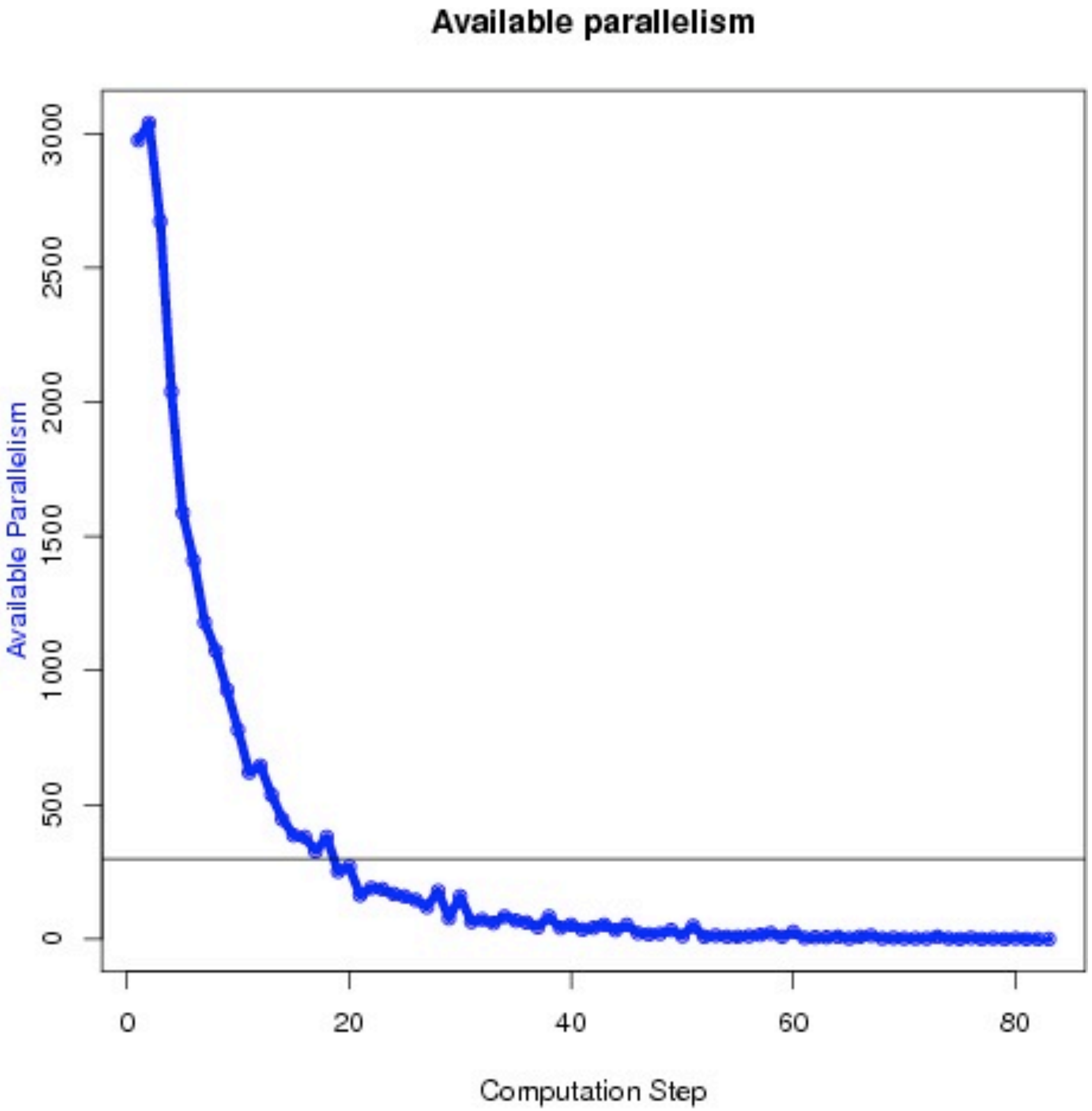




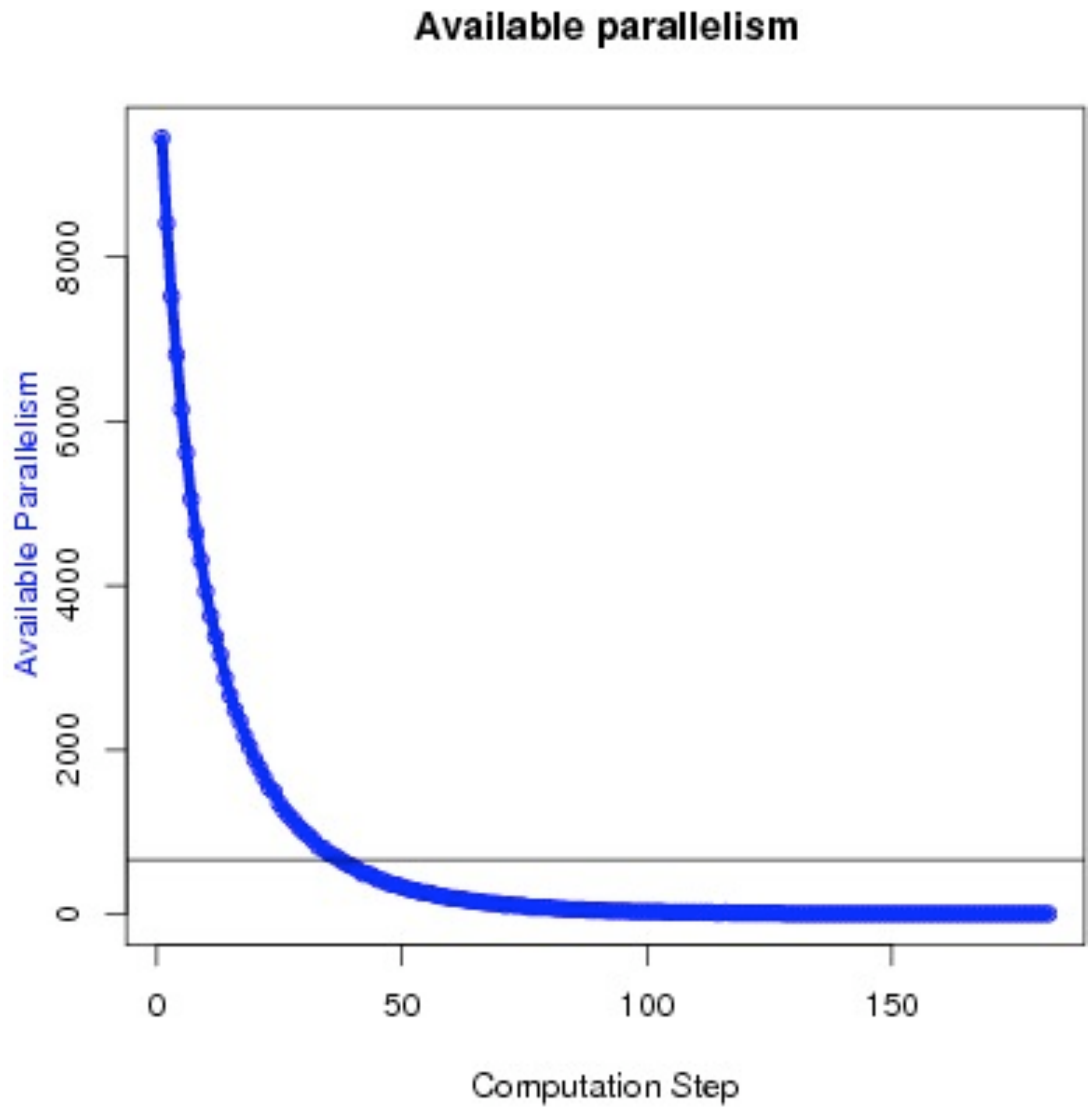
Expected Parallelism

- Expect amount of parallelism to match “bushiness” of dendrogram
  - If dendrogram is long and skinny, not much parallelism
  - If dendrogram is short and bushy, more parallelism
- Dendrogram built bottom-up
  - “Coarsening” morph
  - Expect parallelism to decrease as tree gets connected





Cluster set of 100K randomly generated points



MST over 300x400 2-D grid

Other ParaMeter capabilities

Ordered algorithms

- Can profile parallelism in ordered algorithms
  - Active nodes must be processed in some order
- Intuition: execute nodes as in out-of-order processor, retire in-order through reorder buffer
- ParaMeter tracks when an activity *executes* not when it *retires*
  - *cf* measuring ILP

Other metrics

- Parallelism intensity
  - Measures amount of parallelism relative to worklist size
- Neighborhood statistics
  - Minimum, maximum and average neighborhood sizes

Thank you!

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