How Much Parallelism is There in Irregular Applications?

Milind Kulkarni, Martin Burtscher, Rajasekhar Inkulu and Keshav Pingali

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Introduction

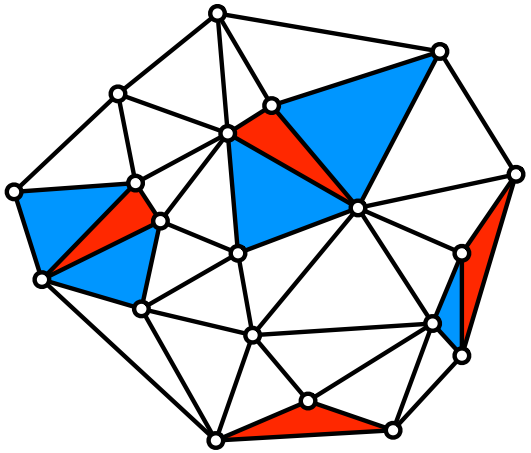
- We understand parallelism in regular algorithms
  - e.g., in N×N matrix-matrix multiply, can do N^3 multiplications concurrently
- What about irregular algorithms?
  - Operate on complex, pointer-based data structures such as graphs, trees, etc.
  - Is there much parallelism?

Example Algorithms

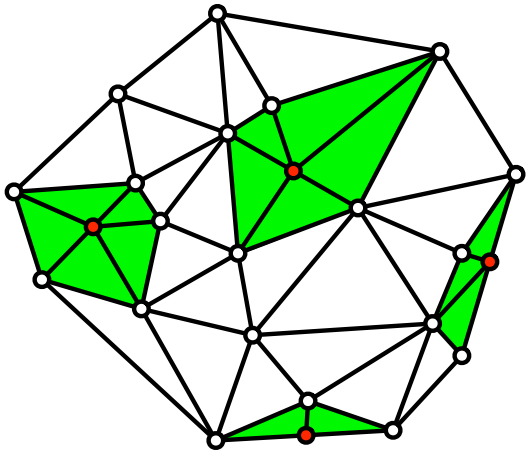
Application Domain	Algorithms
Data-mining	Agglomerative clustering, k-means
Bayesian inference	Belief propagation, survey propagation
Compilers	Iterative dataflow, Elimination-based dataflow
Functional interpreters	Graph reduction, static/dynamic dataflow
Maxflow	Preflow-push, augmenting paths
Minimum spanning trees	Prim's, Kruskal's Boruvka's
N-body methods	Barnes-Hut, fast multipole
Graphics	Ray-tracing
Linear solvers	Sparse MVM, sparse Cholesky factorization
Event-driven simulation	Time warp, Chandy-Misra-Bryant
Meshing	Delaunay mesh refinement, triangulation

Example: Delaunay mesh refinement

- Worklist of bad triangles
- Process bad triangles by removing "cavity" and re-triangulating
  - May create new bad triangles
- Triangles can be processed in any order
- Algorithm terminates when worklist is empty



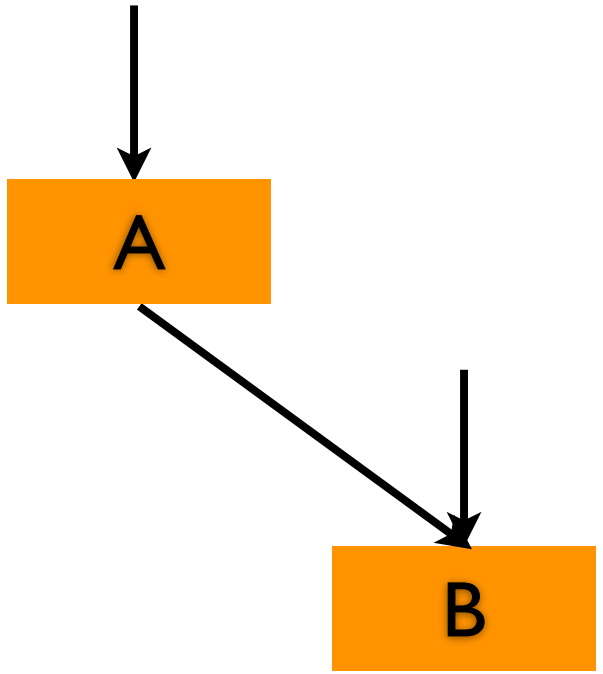
Before



After

Example: Event-driven Simulation

- Network of nodes
- Worklist of events, ordered by timestamp
- Nodes process events, can generate new events to send to other nodes
- Events must be processed in global time order



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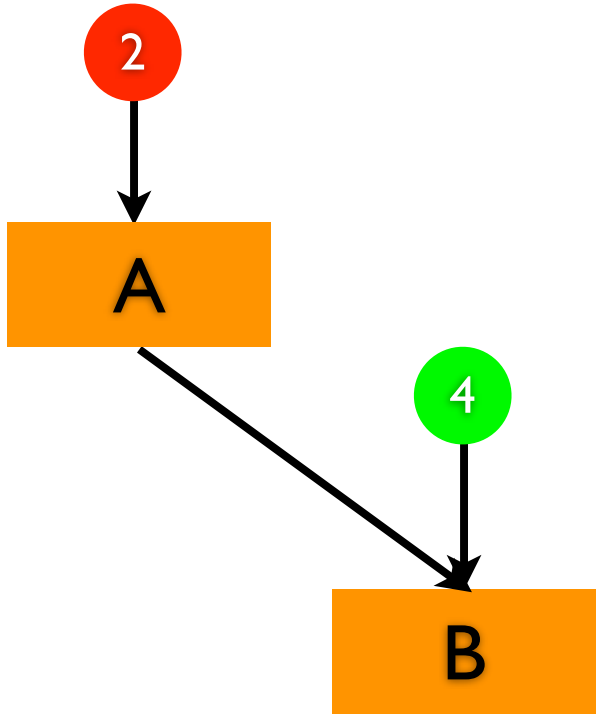

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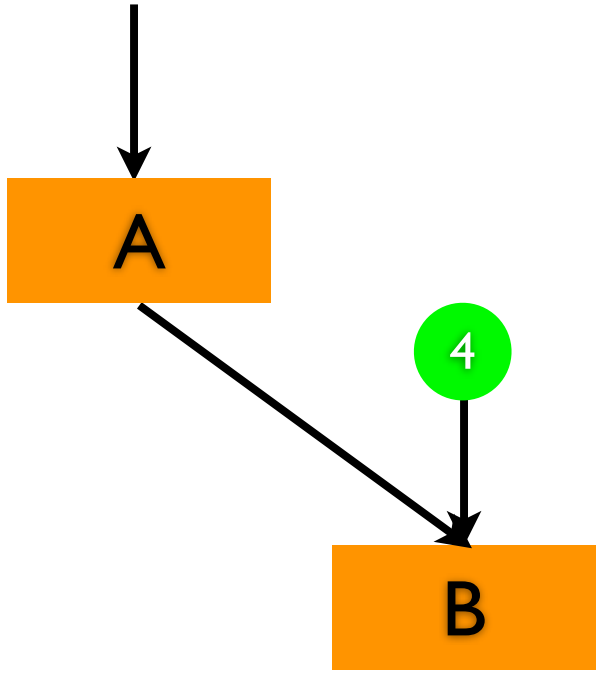

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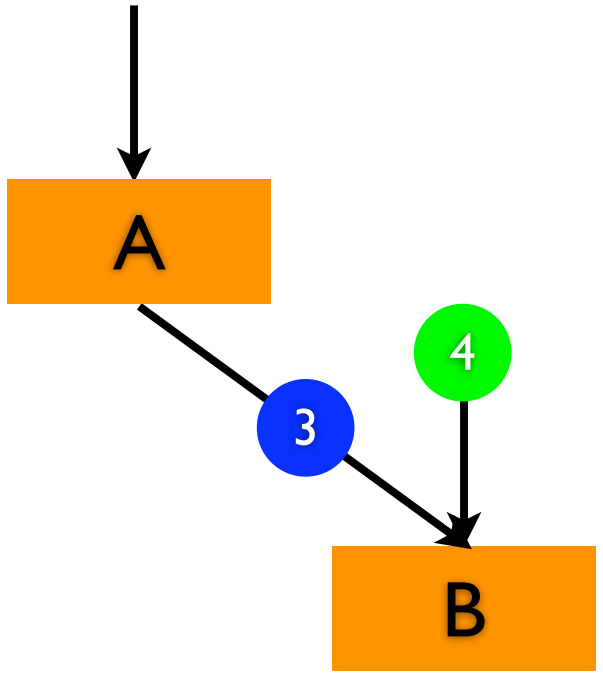

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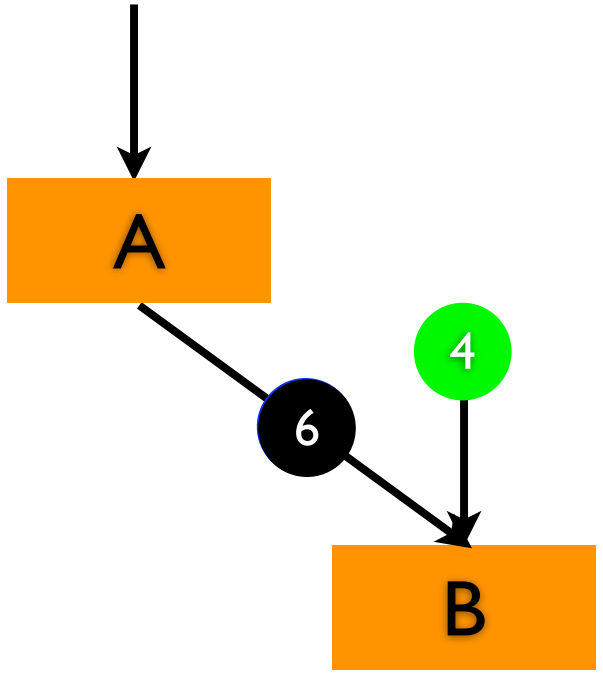
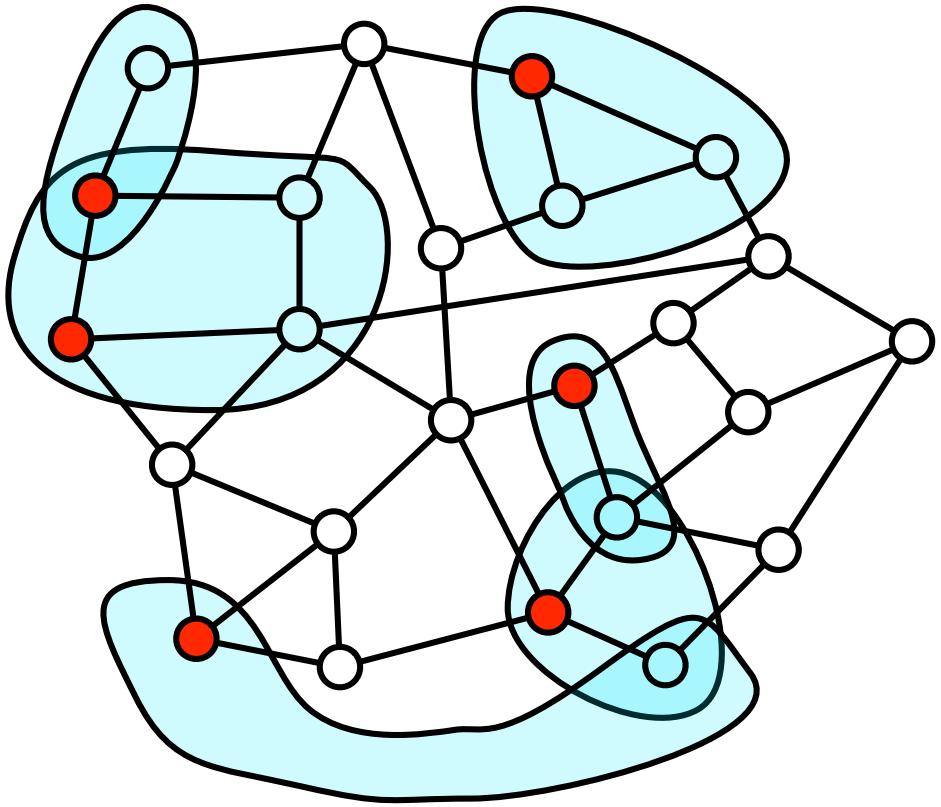


Amorphous Data Parallelism



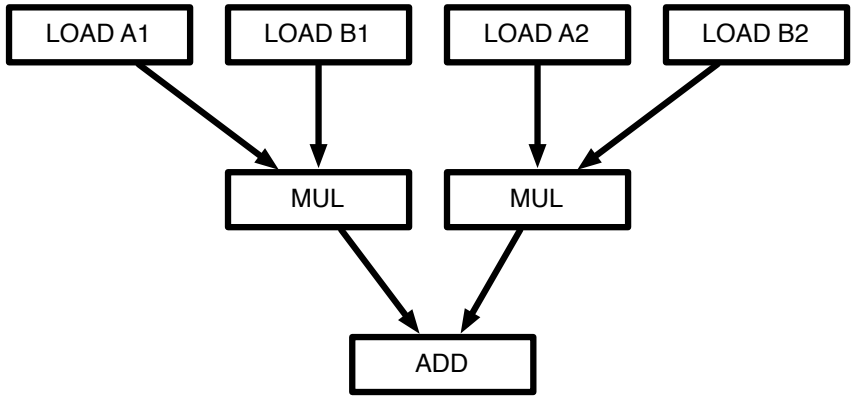
- Data structure: graph
- Operate over ordered or unordered worklists of *active nodes*
- Process an active node by accessing *neighborhood*
  - May generate new active nodes
- Can process nodes with non-overlapping neighborhoods in parallel
- Ordered worklists: must respect ordering constraints

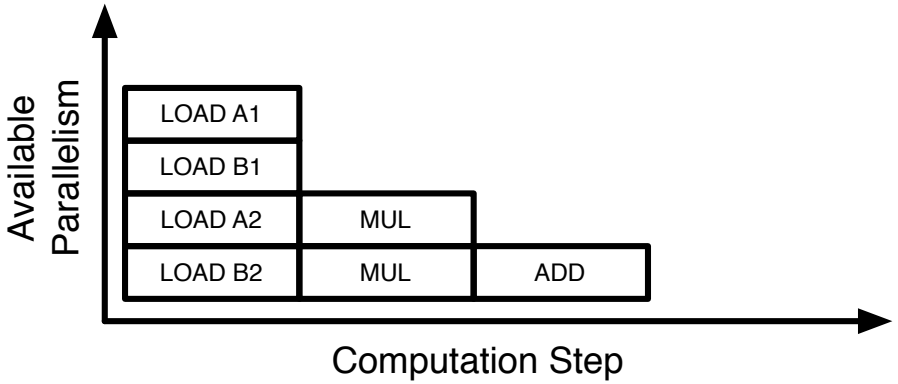
“Available Parallelism”

- A measure of the maximum amount of parallelism that can be extracted from a program
- Profile the algorithm, not the system
  - Disregard communication/synchronization costs, run-time overheads and locality concerns

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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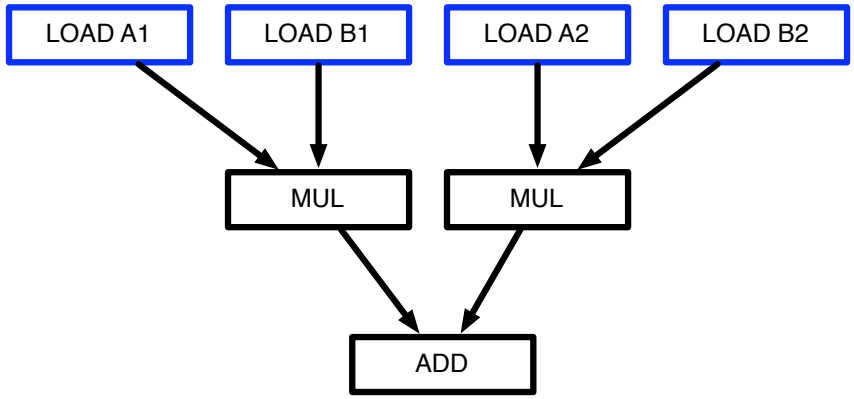

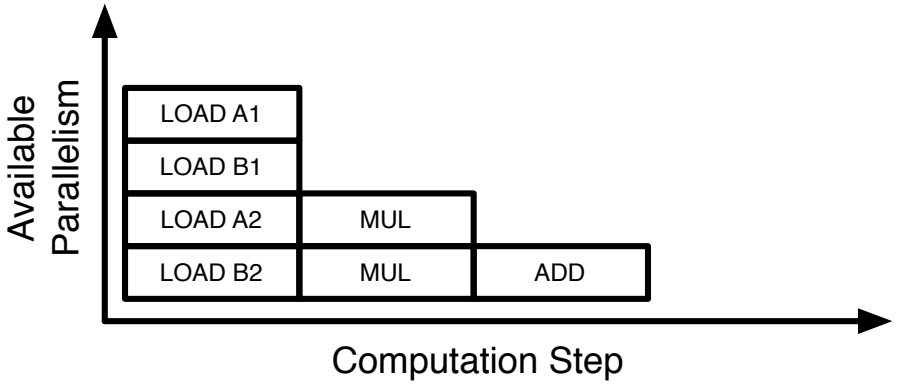

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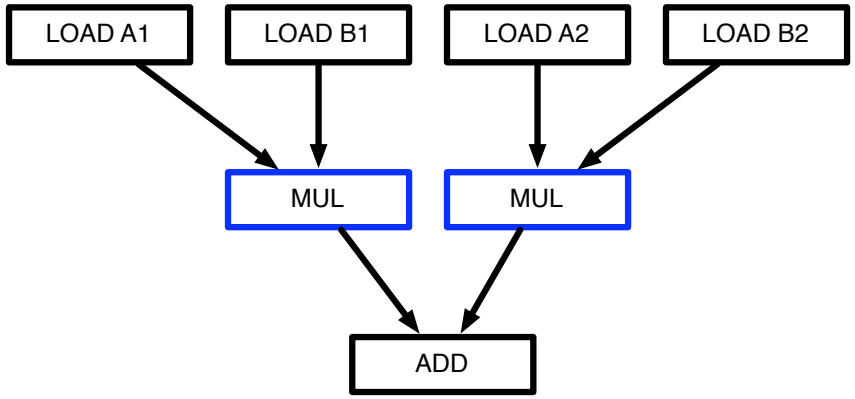

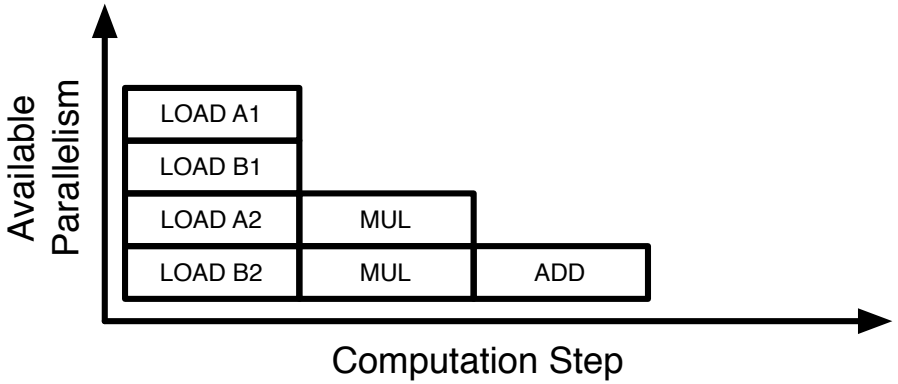

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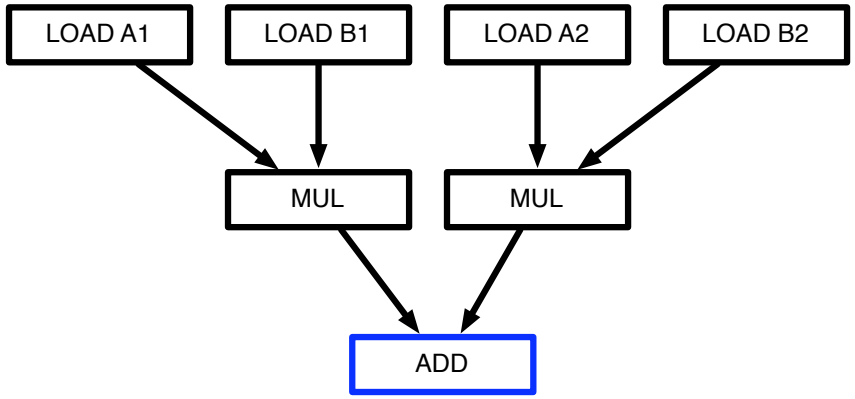
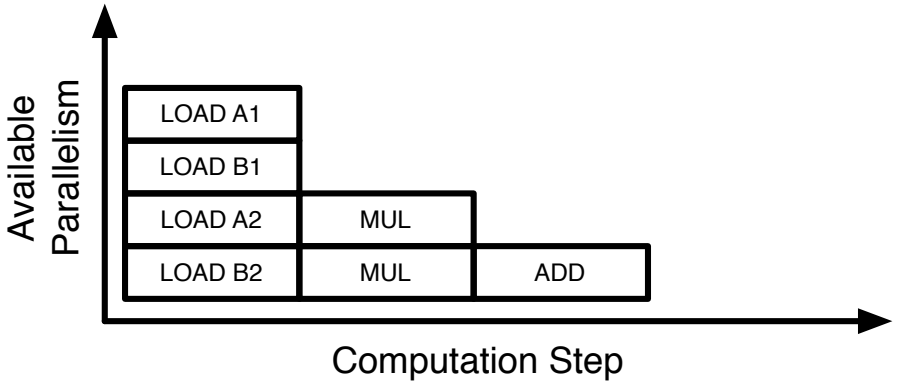
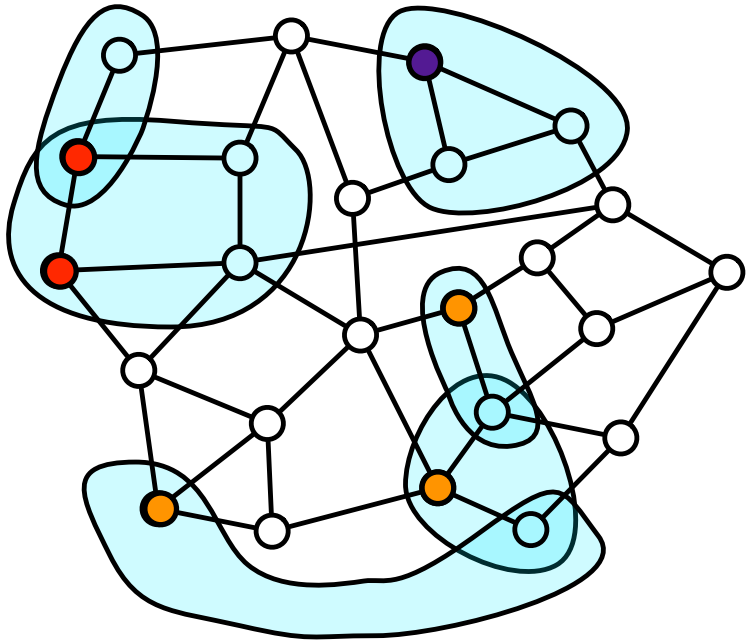




Amorphous Data Parallel Algorithms

- No notion of ordering
  - 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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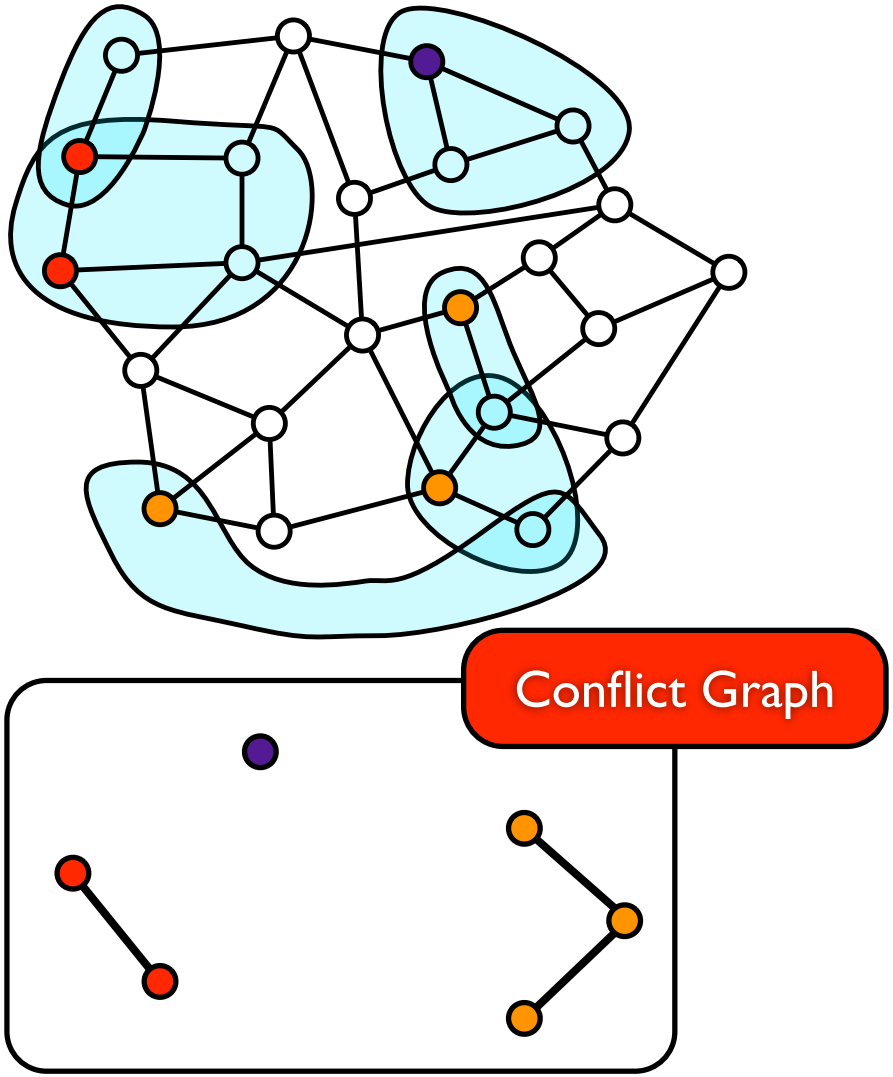


Greedy scheduling

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

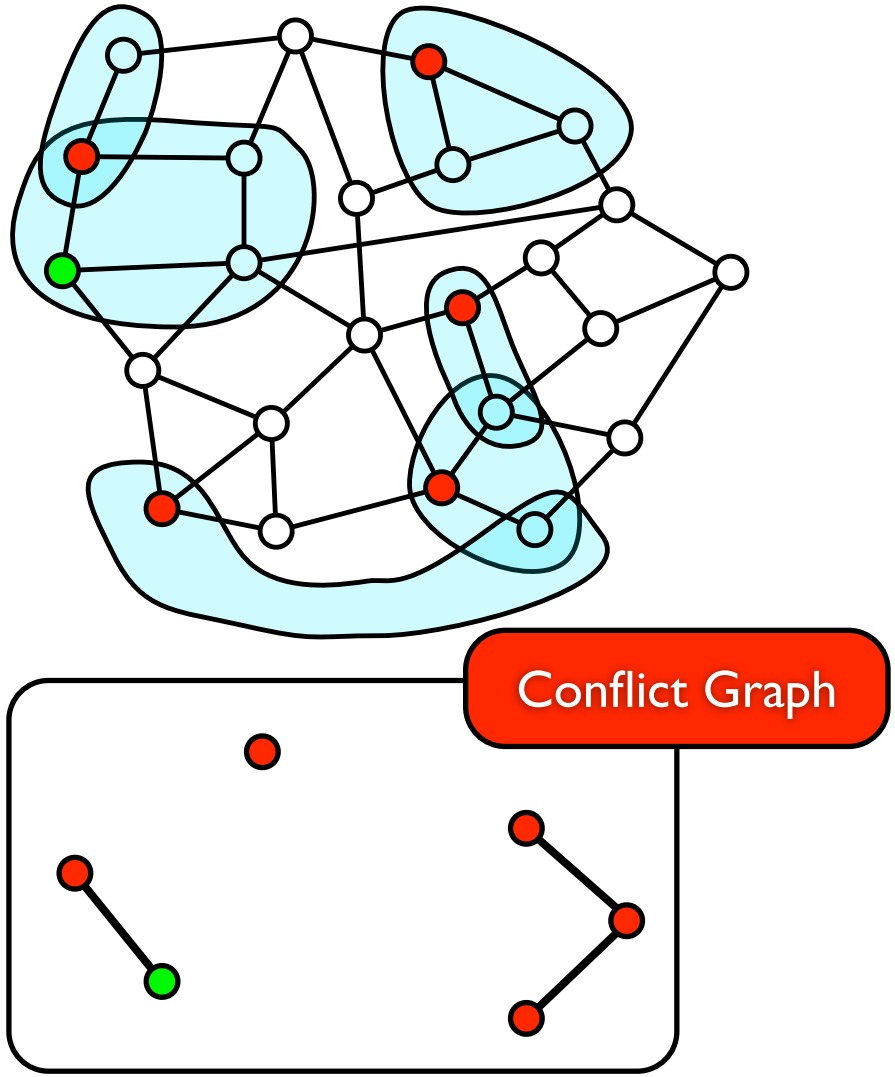
➡ Solution: Schedule greedily

  - 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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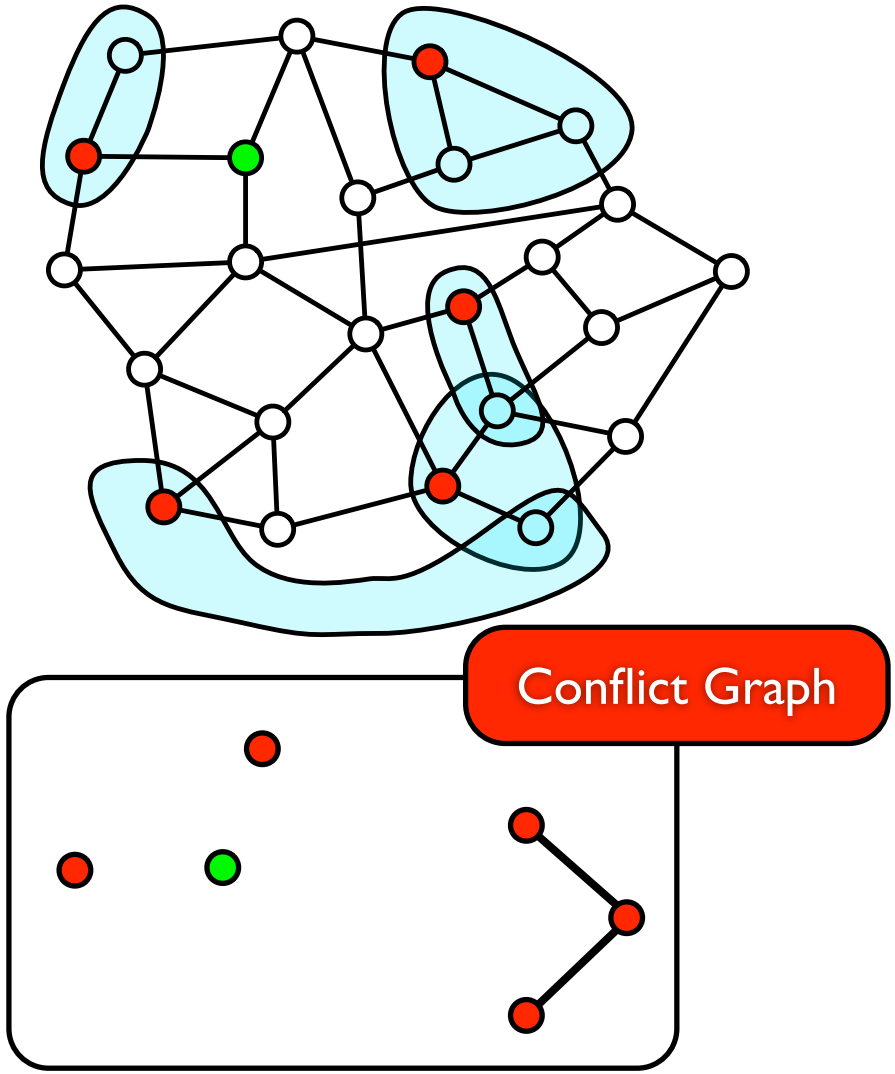

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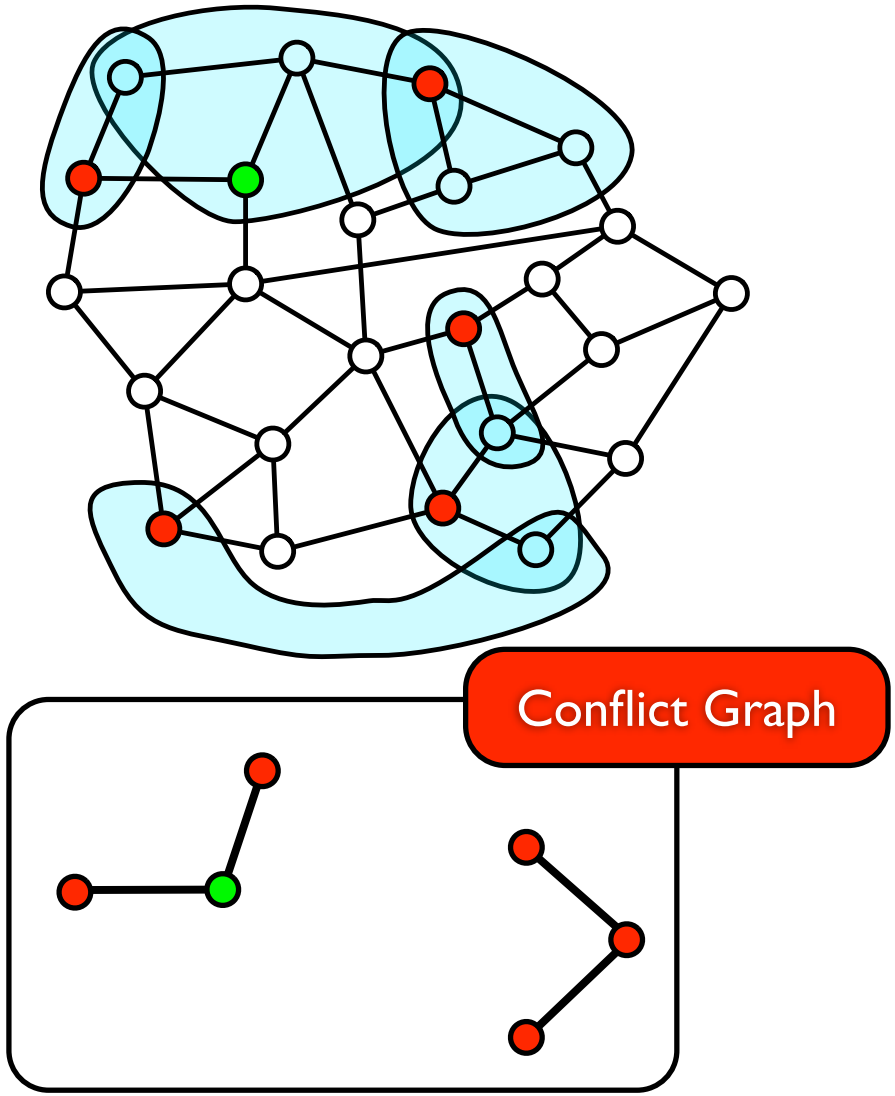


ParaMeter

- Tool to generate parallelism profiles for amorphous data-parallel applications
- Uses *greedy scheduling* and *incremental execution* to handle dynamic nature of computation

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

ParaMeter Execution Strategy

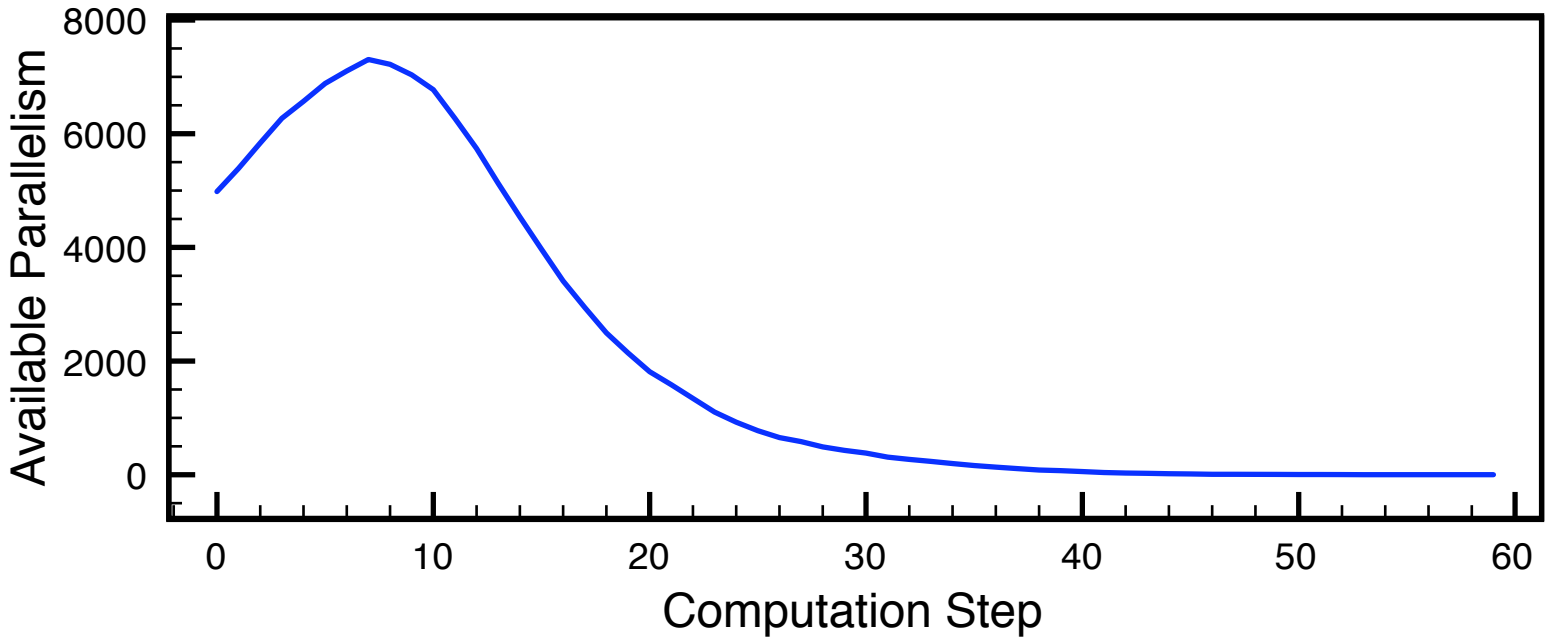
- While work left
  - Gener
    workl
  - Execute maximal independent set of nodes in graph
  - Add newly generated work to worklist

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

Experiments

- Profiled 7 applications:
  - Delaunay mesh refinement
  - Delaunay triangulation
  - Augmenting paths maxflow
  - Preflow push maxflow
  - Survey propagation
  - Agglomerative clustering (unordered)
  - Agglomerative clustering (ordered)

Delaunay Mesh Refinement

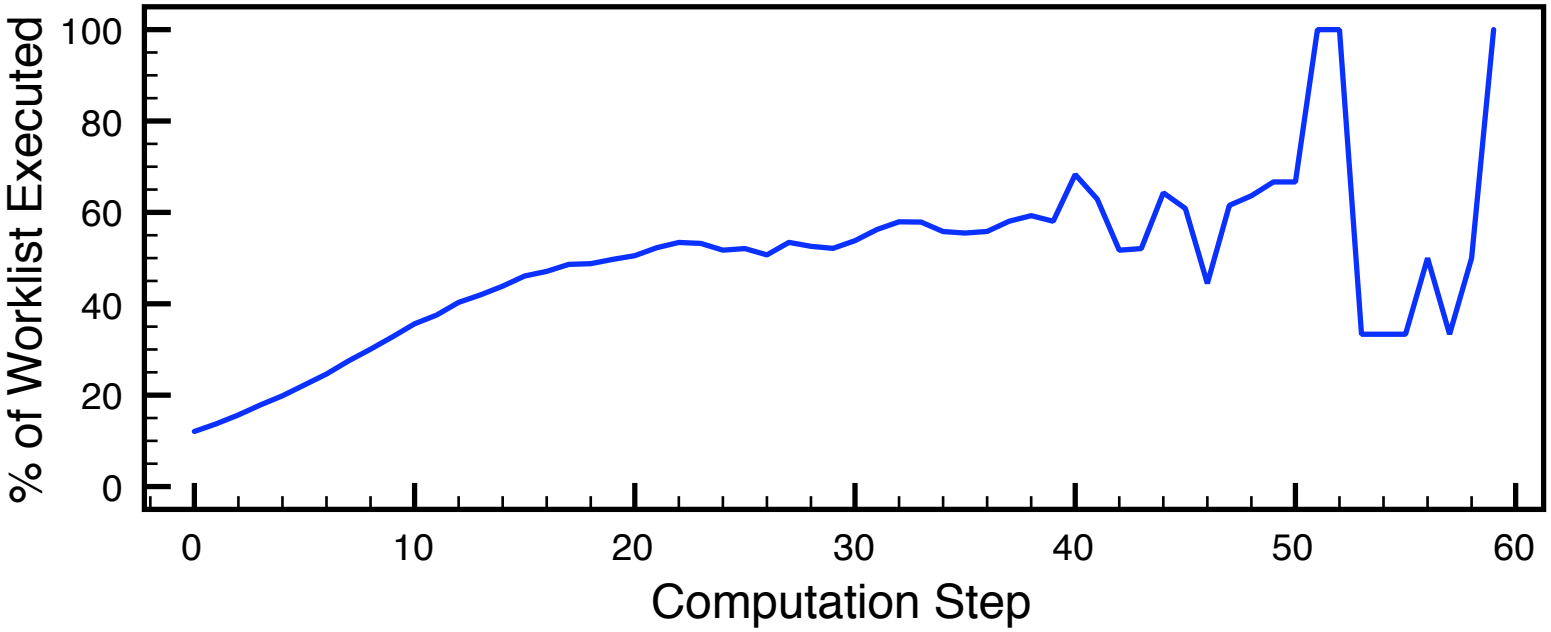


Input: 100,000 triangle mesh, 47,000 bad triangles

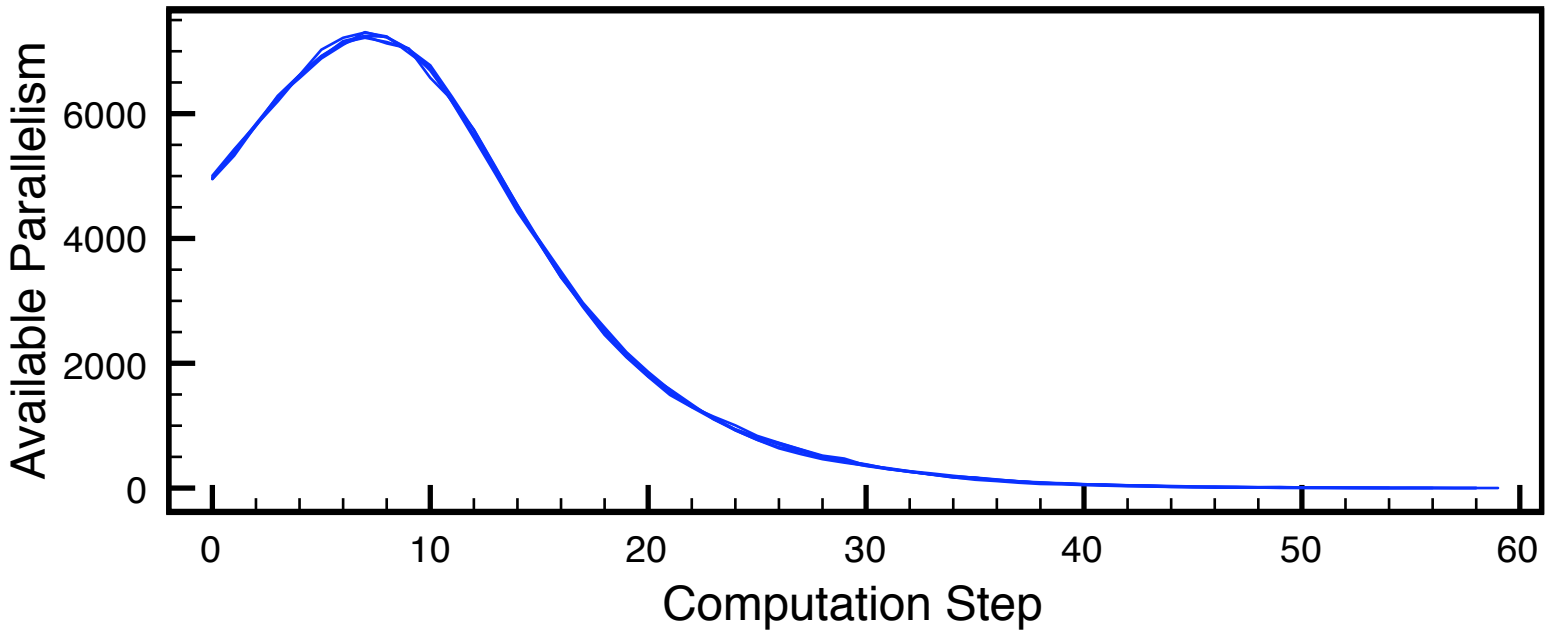
Parallelism Intensity

- Available parallelism shows absolute amount of parallelism in program
  - Is parallelism low because there is little work? Or many conflicts?
- Parallelism intensity: measure what percentage of worklist is executed in parallel

Mesh Refinement: Parallelism Intensity



Effects of Scheduling on Parallelism



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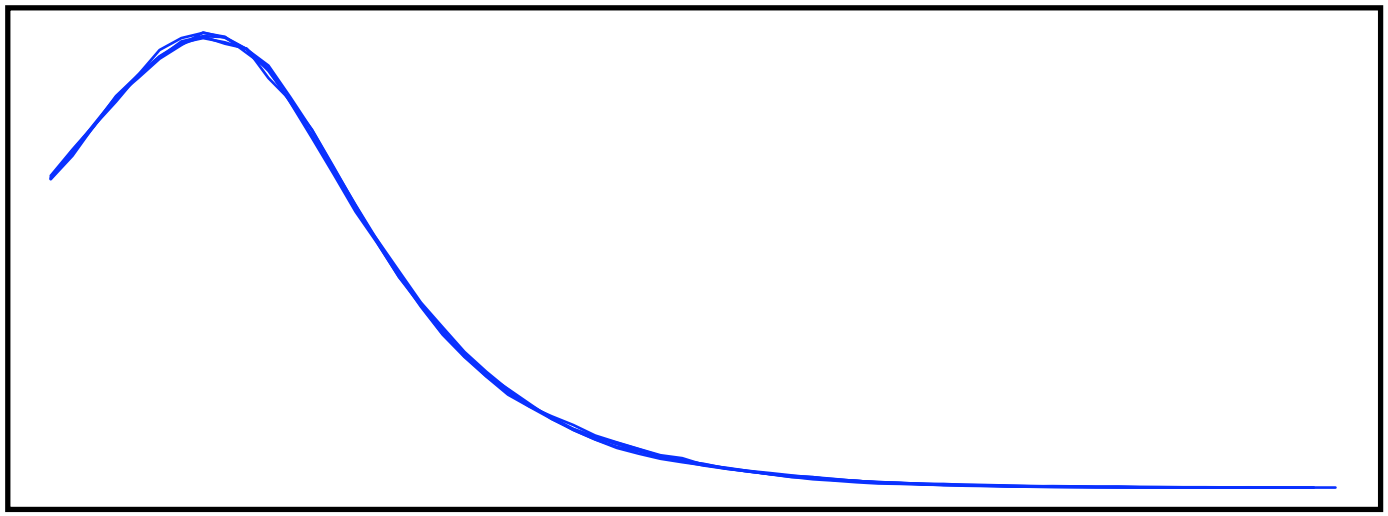

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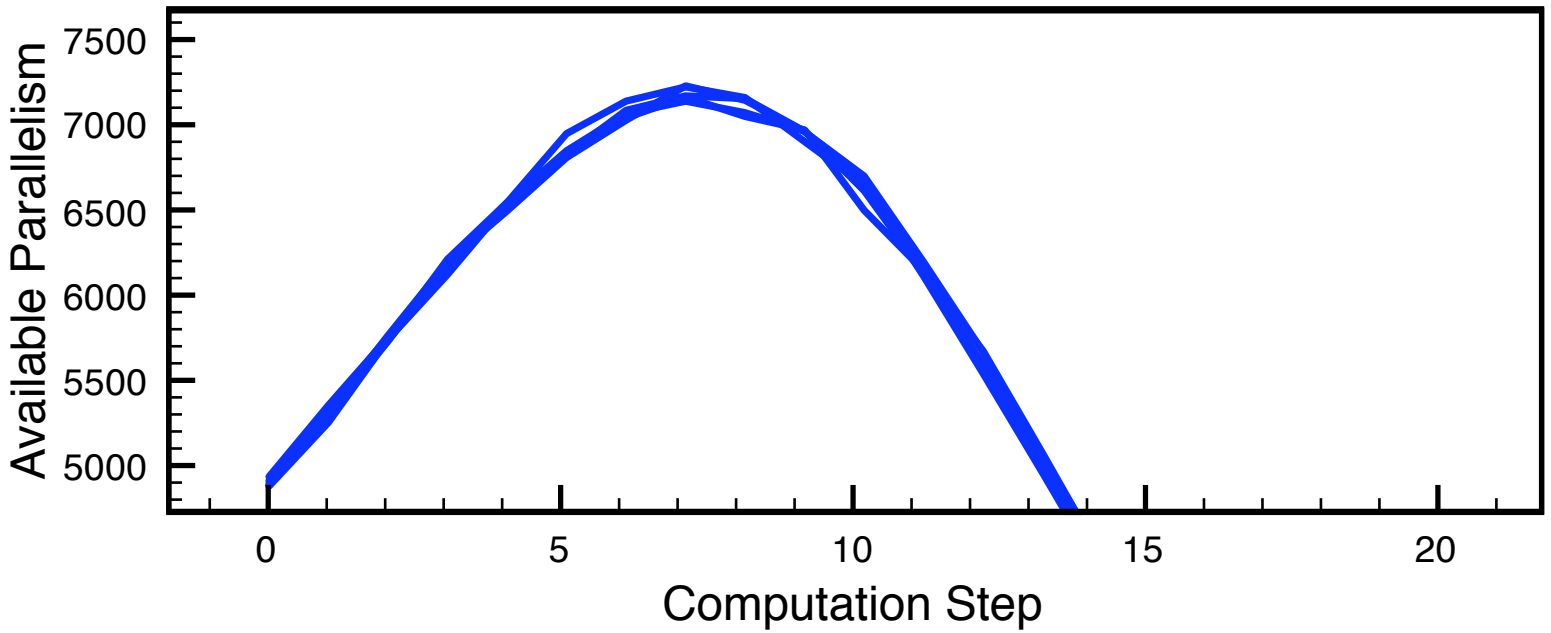
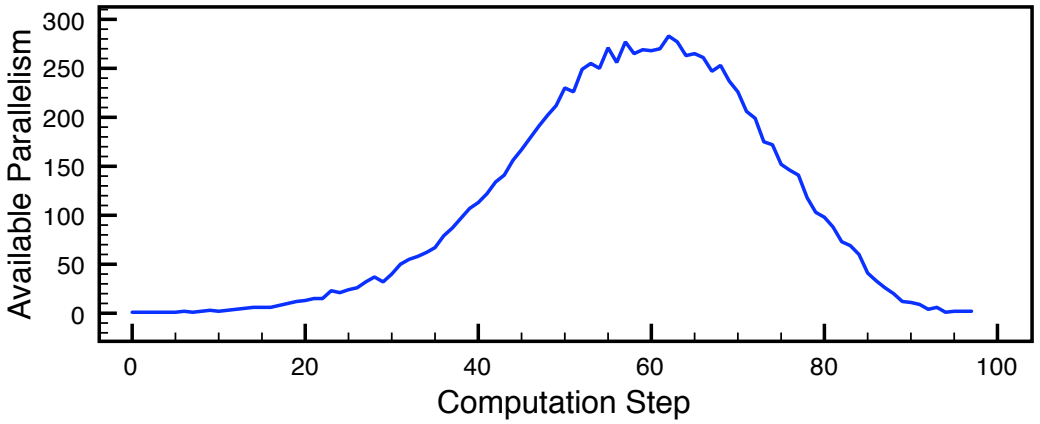
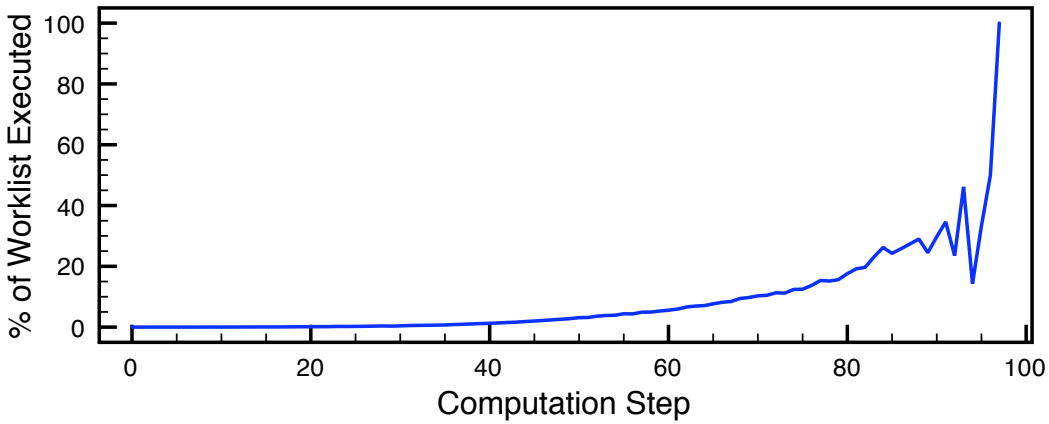


Input: 100,000 triangle mesh, 47,000 bad triangles

Delaunay Triangulation

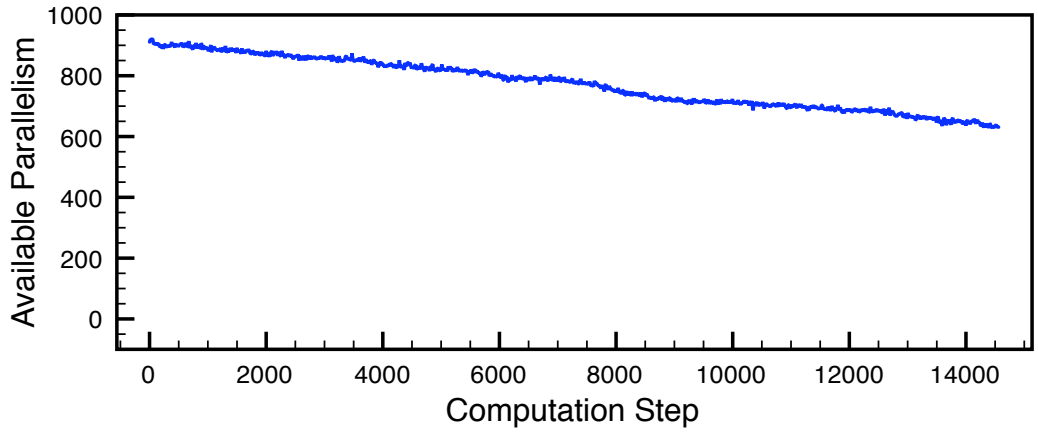
- Build a Delaunay mesh given a set of points
- Points in an unordered worklist
- Insert points by splitting triangles, flipping edges
- Input: 10,000 points

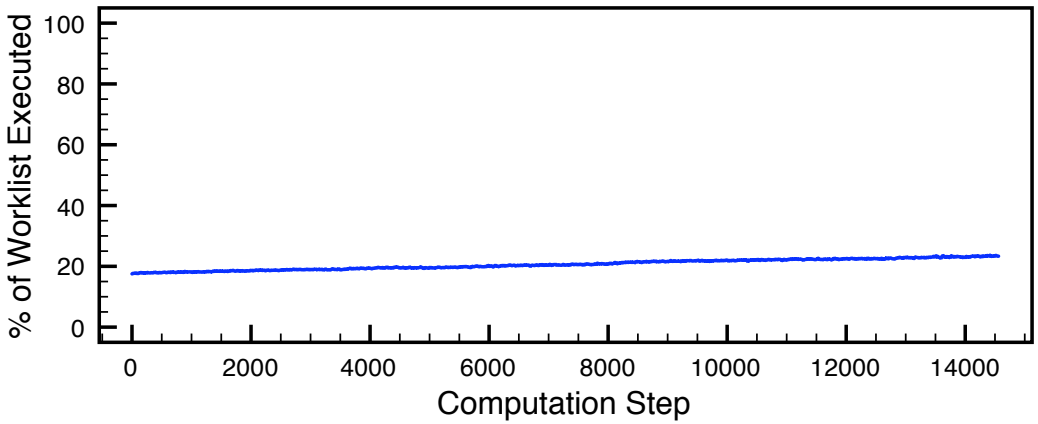




Survey Propagation

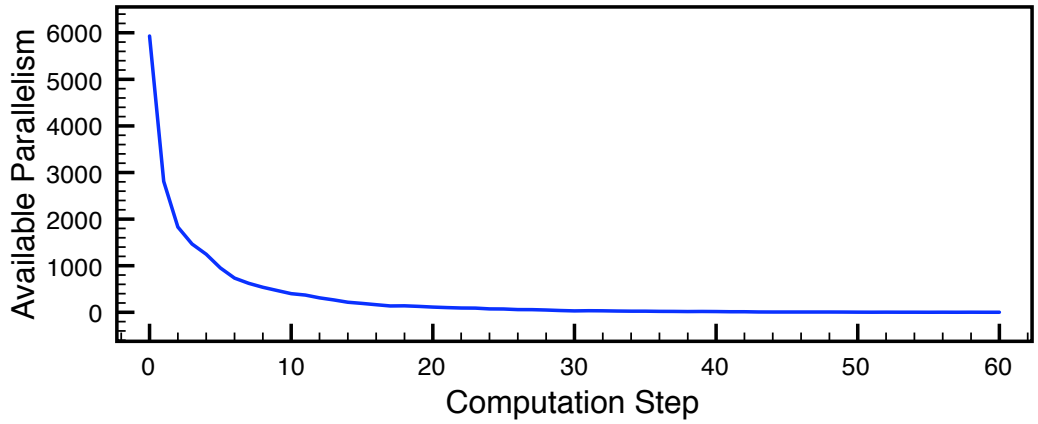
- Heuristic approach to solving SAT problems
- Bipartite graph of clauses and variables
- Iteratively update variables with possible truth values
- Input: formula with 1000 variables, 4200 clauses

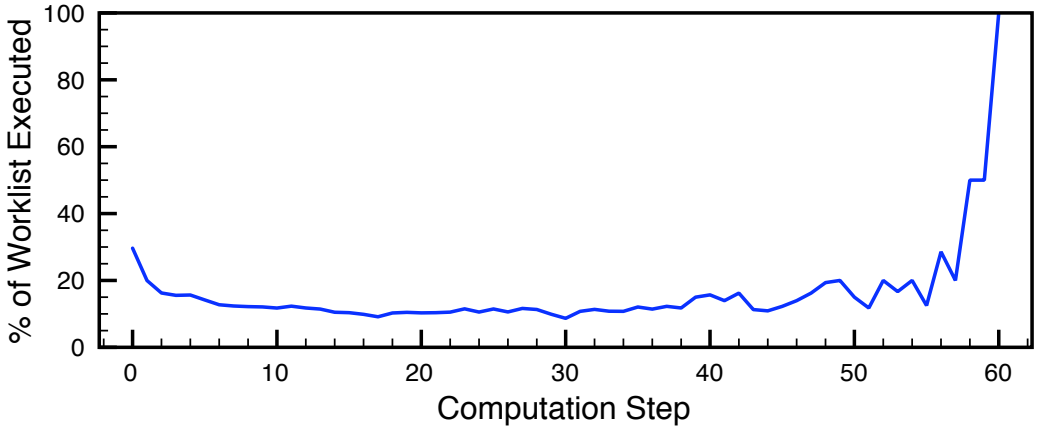




Agglomerative Clustering

- Cluster a set of points based on similarity
- Unordered worklist of point clusters
- Builds a tree bottom-up
- Input: 20,000 points





Conclusions

- ParaMeter: first tool to measure parallelism in irregular algorithms
  - Provides insight into an *algorithm*, rather than a particular parallel *implementation*
  - Also: ordered worklists, constrained parallelism (details in paper)
- ParaMeter shows that important irregular algorithms have significant parallelism
  - Mesh algorithms, SAT solvers, data mining algorithms, maxflow algorithms ...
- Parallelism varies during execution → adaptive control of number of threads may be useful

Thank you!

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