Three Lectures on Parallel Programming

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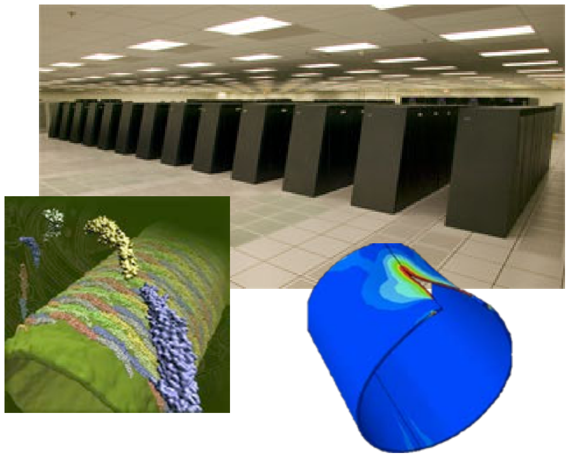
My background

- UT Austin
  - Professor in CS and ECE departments
  - Member of Institute for Computational Engineering and Science (ICES)
- Cornell University
  - Professor in CS and ECE departments
- MIT
  - ScD (Advisor: Arvind)
- IIT Kanpur, India
  - B.Tech.

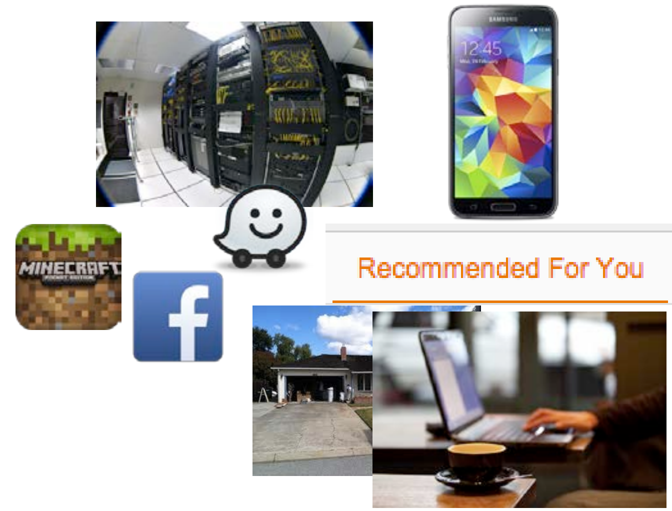
Intelligent Software Systems group (ISS)

- Faculty
  - Keshav Pingali, CS/ECE/ICES
- Research associates
  - Swarnendu Biswas
  - Vishwesh Jatala
- PhD students
  - Roshan Dathathri
  - Gurbinder Gill
  - Michael He
  - Ian Hendrickson
  - Loc Hoang
  - Yi-Shan Lu
  - Sepideh Maliki
  - Francis Pei
- Visitors from France, India, Norway, Poland, Portugal
- Home page: http://iss.ices.utexas.edu
- Funding: DARPA, NSF, BAE, HP, NEC, NVIDIA…

Parallel computing is changing



Old World

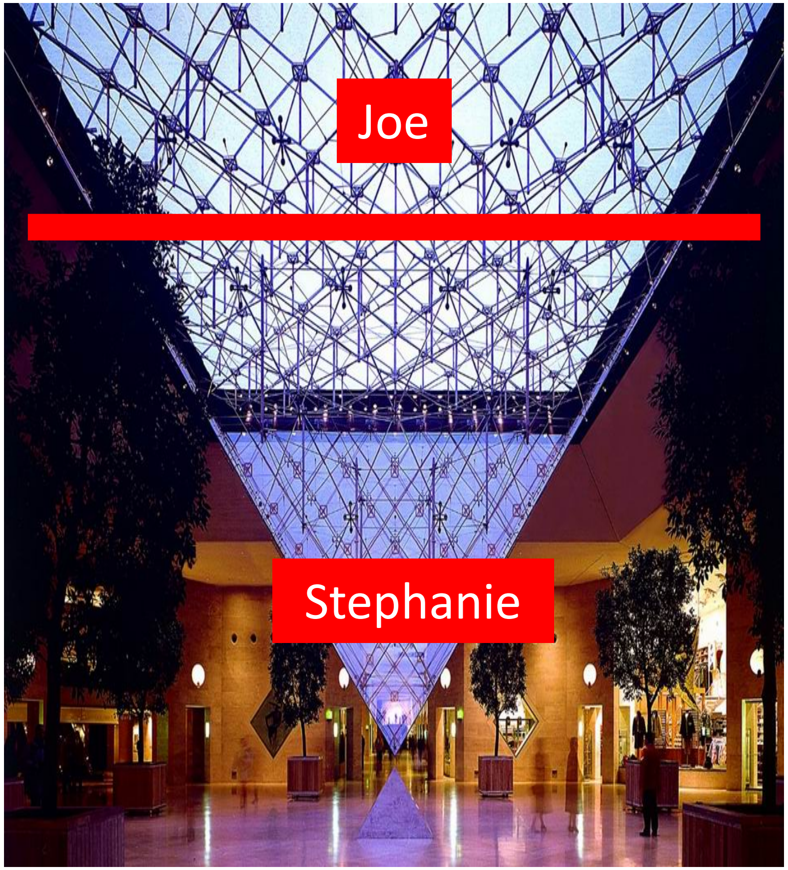


New World

- Platforms
  - Dedicated clusters versus cloud, mobile
- People
  - Small number of scientists and engineers versus large number of self-trained parallel programmers
- Data
  - Structured (vector, dense matrix) versus unstructured, sparse

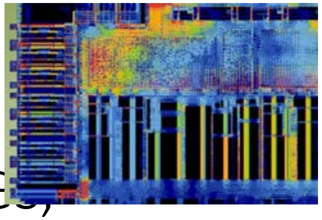
The Search for "Scalable" Parallel Programming Models

- Tension between productivity and performance
  - support large number of application programmers with small number of expert parallel programmers
  - performance comparable to hand-optimized codes
- Galois project
  - data-centric abstractions for parallelism and locality
  - operator formulation of algorithms



Some projects using Galois

- BAE Systems (RIPE DARPA program)
  - intrusion detection in computer networks
  - data-mining in hierarchical interaction graphs
- HP Enterprise
  - [ICPE 2016,MASCOTS 2016] workloads for designing enterprise systems
- FPGA tools
  - [DAC'14] "Parallel FPGA Routing based on the Operator Formulation", Moctar and Brisk
  - [IWLS'18] "Parallel AIG Rewriting" Andre Reis et al. (UFRGS, Brazil), Alan Mishchenko (UCB), et al.



- Multi-frontal finite-elements for fracture problems
  - Maciej Paszynski, Krakow
- 2017 DARPA HIVE Graph Challenge Champion

Data-centric abstractions

Parallelism: Old world

- Functional languages
  - map f $(e_1, e_2, \ldots, e_n)$
- Imperative languages

```
for i = 1, N
    y[i] = a*x[i] +y[i]
for i = 1, N
    y[i] =a*x[i] + y[i-1]
for i = 1,N
     y[2*i] = a*x[i] + y[2*i-1]
```

- Key idea
  - find parallelism by analyzing algorithm or program text
  - major success: auto-vectorization in compilers (Kuck, UIUC)

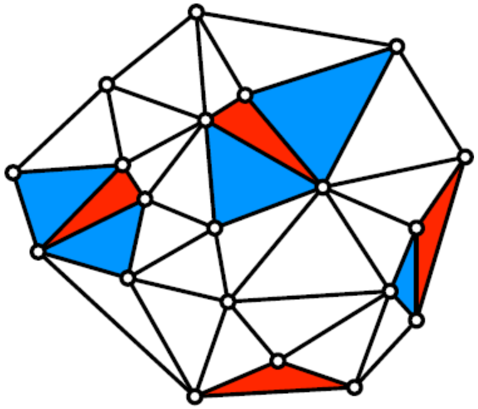
Parallelism: Old world (contd.)

```
Mesh m = /* read in mesh */
WorkList wl;
wl.add(m.badTriangles());
while (true) {
  if (wl.empty()) break;
  Element e = wl.get();
  if (e no longer in mesh)
    continue;
  Cavity c = new  Cavity();
  c.expand();
  c.retriangulate();
  m.update(c);//update mesh
  wl.add(c.badTriangles());
}
```

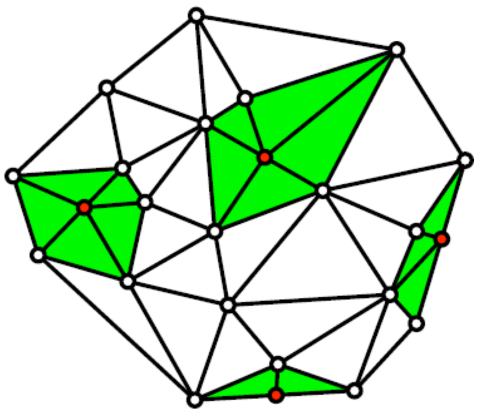
- Static analysis techniques
  - points-to and shape analysis
- Fail to find parallelism
  - may be there is no parallelism in program?
  - may be we need better static analysis techniques?

Computation-centric view of parallelism

Parallelism: New world



Before



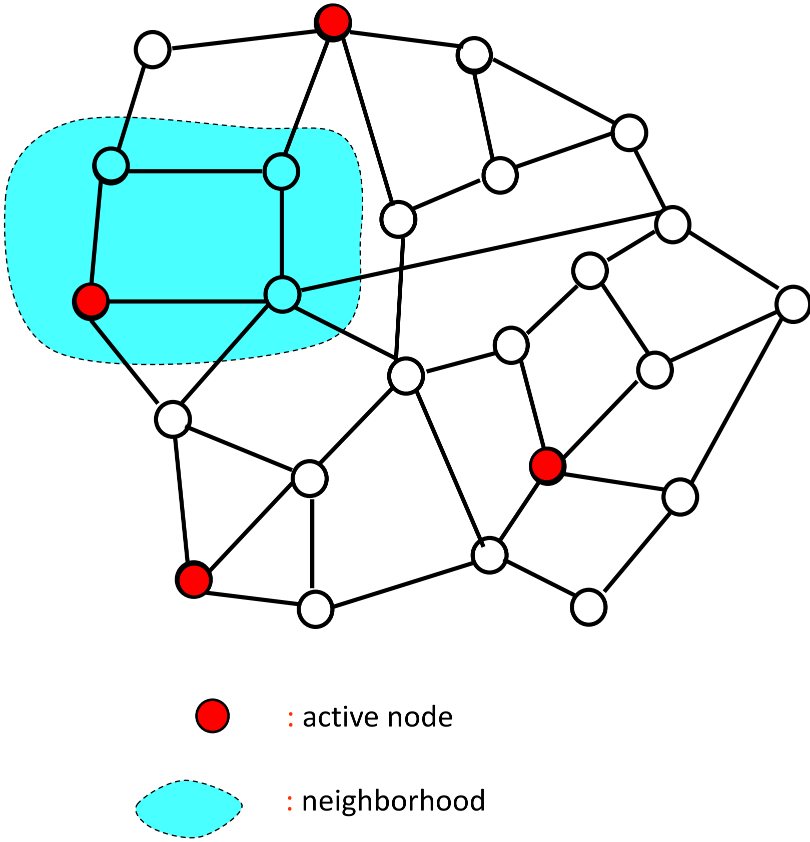
After

Delaunay mesh refinement
Red Triangle: badly shaped triangle
Blue triangles: cavity of bad triangle

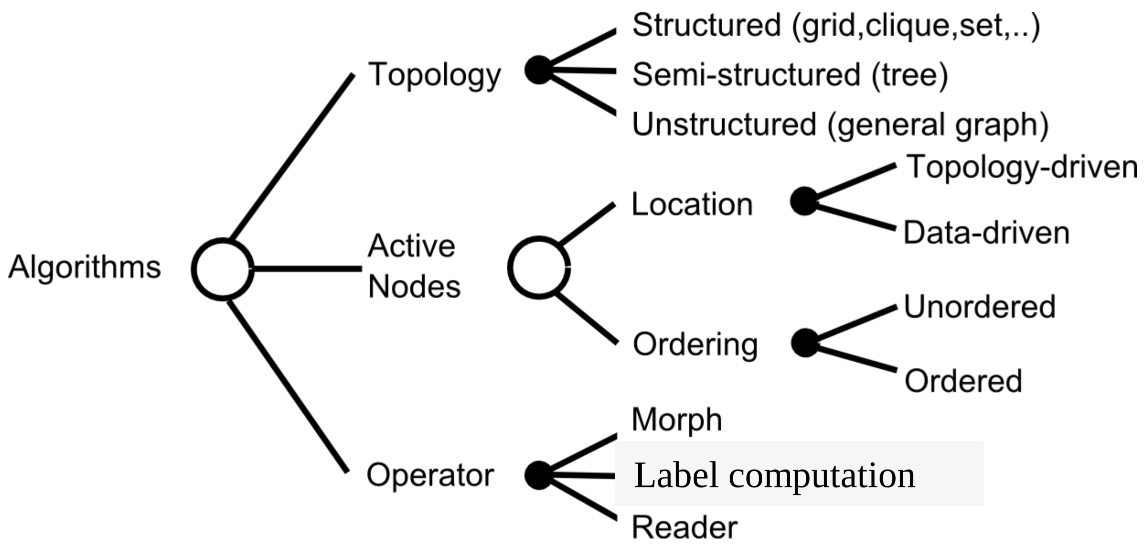
- Parallelism:
  - Bad triangles whose cavities do not overlap can be processed in parallel
  - Parallelism must be found at runtime
- Data-centric view of algorithm
  - Active elements: bad triangles
  - Operator: local view
    {Find cavity of bad triangle (blue);
    Remove triangles in cavity;
    Retriangulate cavity and update mesh;}
  - Schedule: global view
    Processing order of active elements
  - Algorithm = Operator + Schedule
- Parallel data structures
  - Graph
  - Worklist of bad triangles

Operator formulation of algorithms

- Active node/edge:
  - site where computation is needed
- Operator:
  - local view of algorithm
  - computation at active node/edge
- Schedule:
  - global view of algorithm
  - unordered algorithms:
    - active nodes can be processed in any order
    - all schedules produce the same answer but performance may vary
  - ordered algorithms:
    - problem-dependent order on active nodes



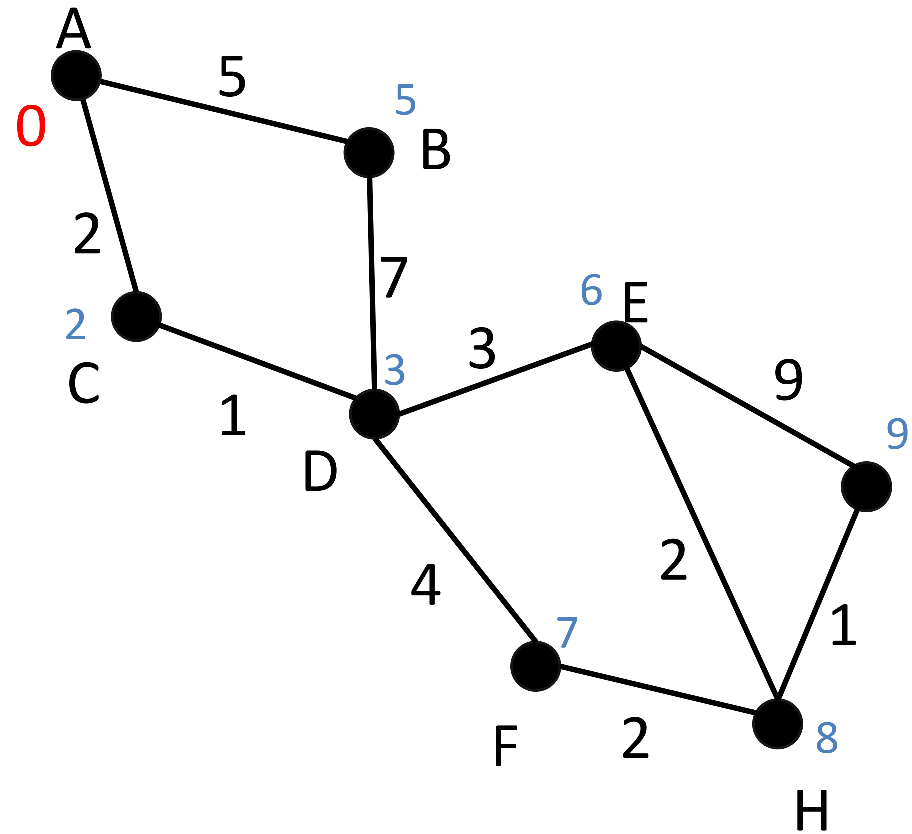
TAO terminology for algorithms



- Active nodes
  - Topology-driven algorithms
    - Algorithm is executed in rounds
    - In each round, all nodes/edges are initially active
    - Iterate till convergence
  - Data-driven algorithms
    - Some nodes/edges initially active
    - Applying operator to active node may create new active nodes
    - Terminate when no more active nodes/edges in graph
- Operator
  - Morph: may change the graph structure by adding/removing nodes/edges
  - Label computation: updates labels on nodes/edges w/o changing graph structure
  - Reader: makes no modification to graph

Graph problem:SSSP

- Problem: single-source shortest-path (SSSP) computation
- Formulation:
  - Given an undirected graph with positive weights on edges, and a node called the source
  - Compute the shortest distance from source to every other node
- Variations:
  - Negative edge weights but no negative weight cycles
  - All-pairs shortest paths
  - Breadth-first search: all edge weights are 1
- Applications:
  - GPS devices for driving directions
  - social network analyses: centrality metrics



Node A is the source

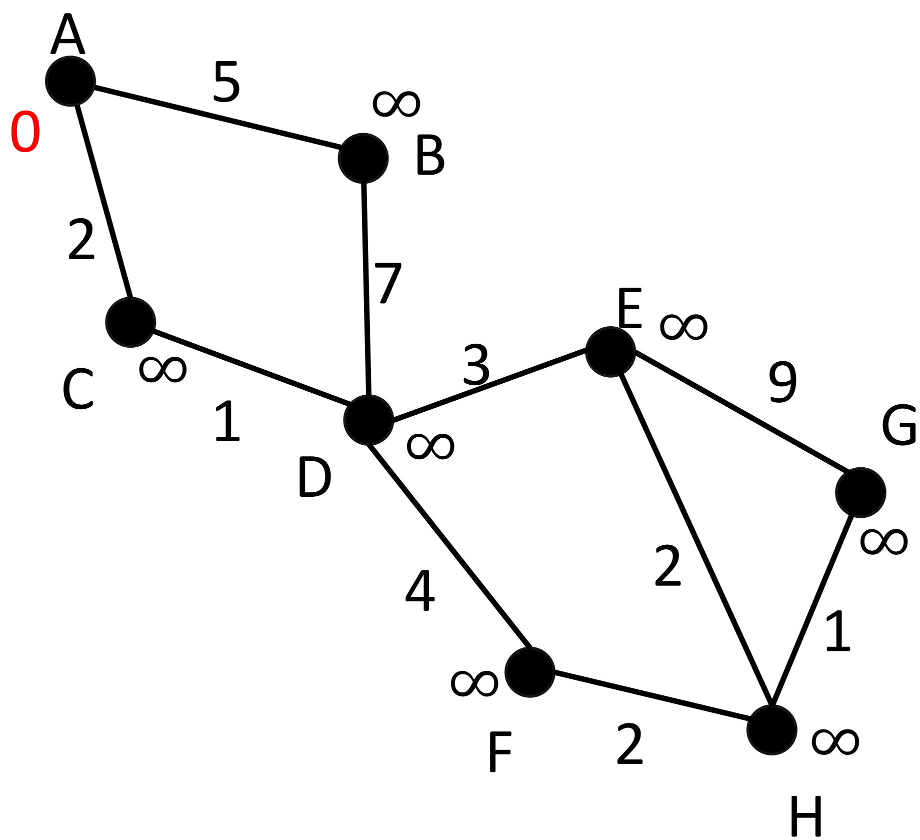
SSSP Problem

- Many algorithms
  - Dijkstra (1959)
  - Bellman-Ford (1957)
  - Chaotic relaxation (1969)
  - Delta-stepping (1998)
- In textbook presentations, they seem unrelated to each other
- Common structure:
  - Each node has a label d that is updated repeatedly
    - initialized to 0 for source and ∞ for all other nodes
    - during algorithm: shortest known distance to that node from source
    - termination: shortest distance from source
  - All of them use the same *operator*

    relax-edge(u,v):
      if d[v] > d[u]+w(u,v)
    then d[v] ← d[u]+w(u,v)

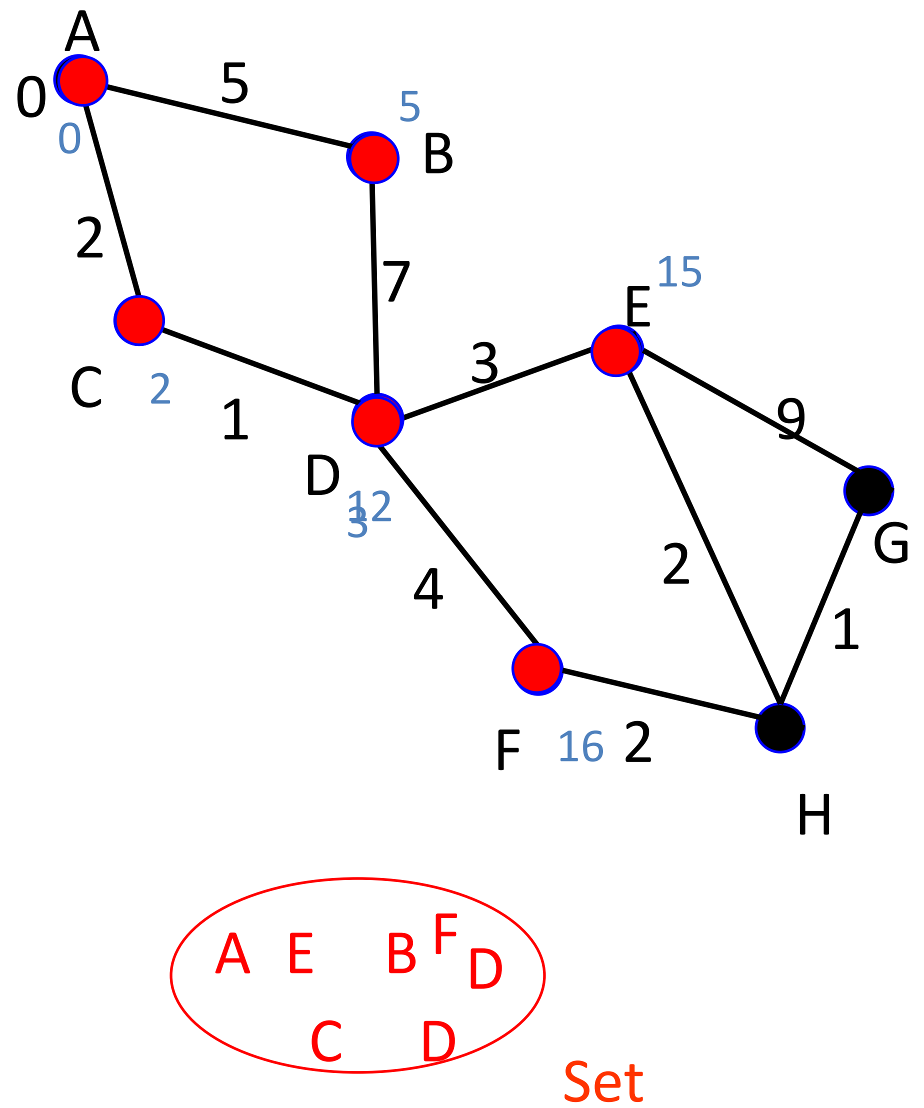
    relax-node(u):
      relax all edges connected to u

  - Differences between algorithms: schedule



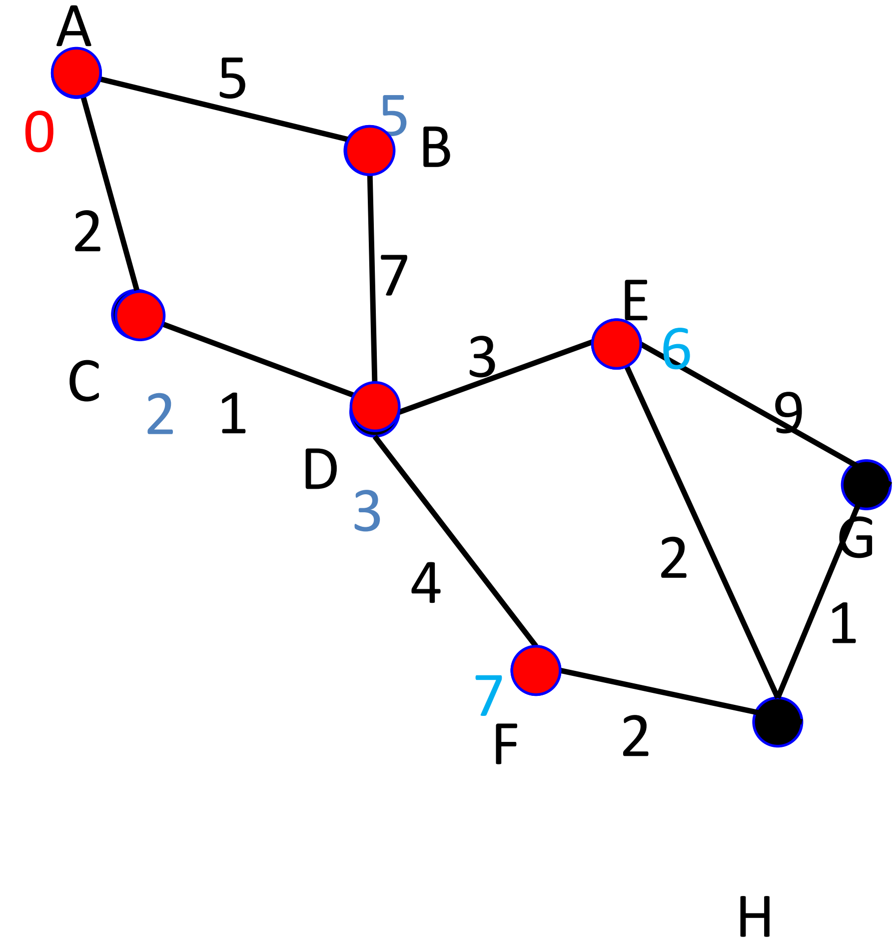
Chaotic relaxation (1969)

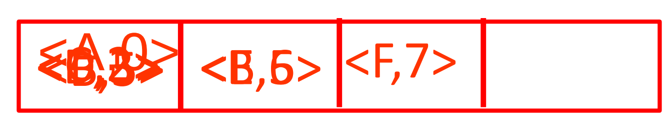
- Active node
  - node whose label has been updated
  - initially, only source is active
- Schedule
  - pick active node at random
  - use a (work)-set or multiset to track active nodes
- TAO: unordered, data-driven algorithm
- Main inefficiency:
  - number of node relaxations depends on the schedule
  - can be exponential in the size of graph



Dijkstra’s algorithm (1959)

- Active nodes
  - node whose label has been updated
  - initially, only source is active
- Schedule for processing nodes
  - ordered by increasing label
- Implementation of work-set
  - priority queue ordered by node label
- Work-efficient ordered algorithm
  - node is relaxed just once
  - O(|E|*lg(|V|))
- Main inefficiency:
  - there is little parallelism for most graphs

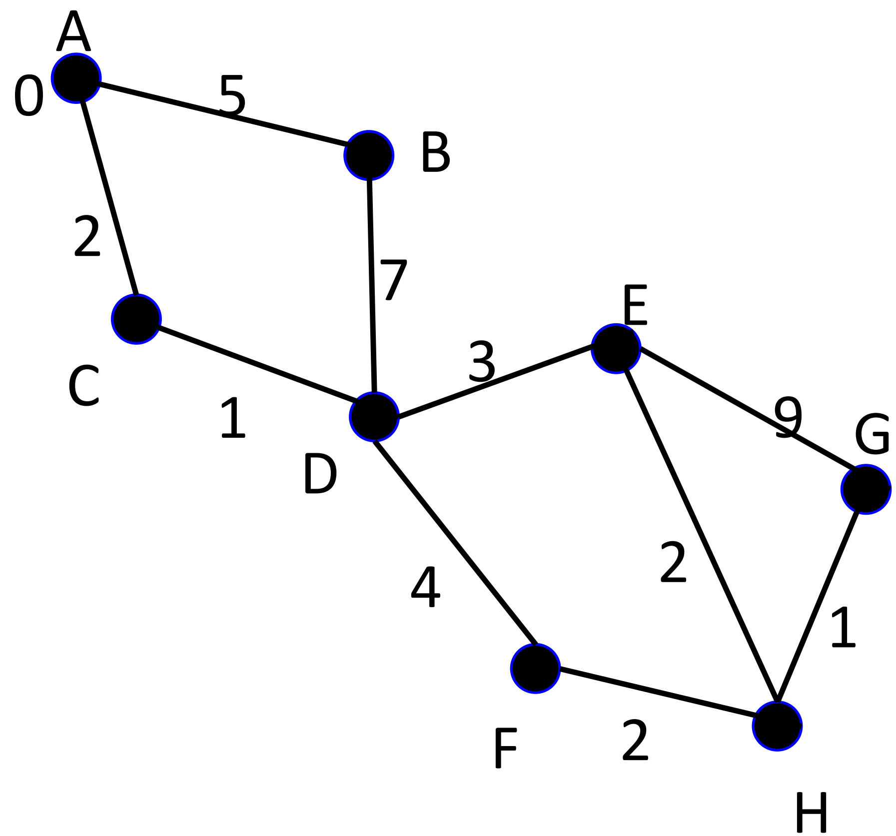


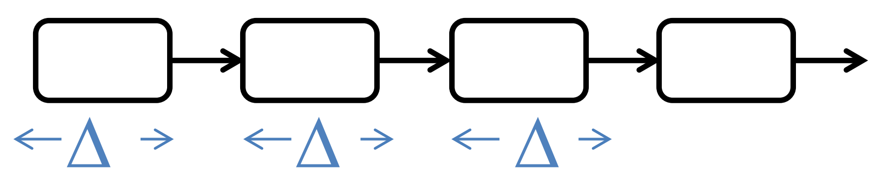


Priority queue

Delta-stepping (1998)

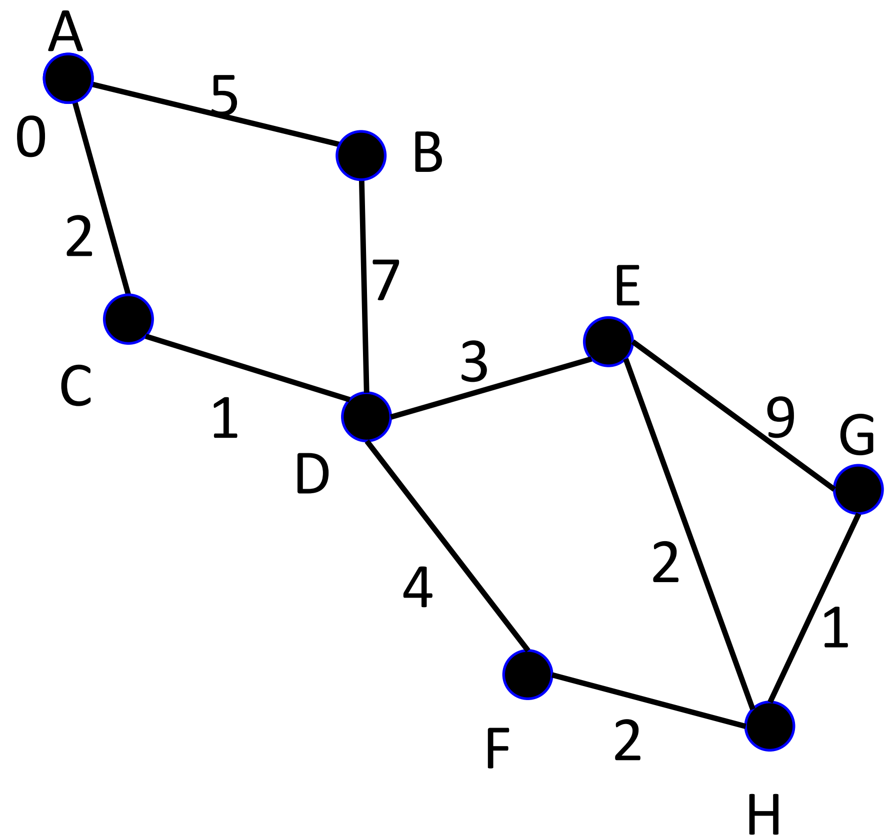
- Controlled chaotic relaxation
  - Exploit the fact that SSSP is robust to priority inversions
  - “soft” priorities
- Implementation of work-set:
  - parameter: Δ
  - sequence of sets
  - nodes whose current distance is between $n\Delta$ and $(n+1)\Delta$ are put in the n^{th} set
  - nodes in set n are completed before processing of nodes in set (n+1) are started
- $\Delta = 1$: Dijkstra
- $\Delta = \infty$: Chaotic relaxation
- Picking an optimal Δ :
  - depends on graph and machine
  - high-diameter graph → large Δ
  - find experimentally





Bellman-Ford (1957)

- Algorithm:
  - execute algorithm in rounds
  - in each round, iterate over all nodes and apply relaxation operator
  - terminate rounds when no node changes value in a round
- Work-efficiency:
  - O(|E|*|V|)
  - in each round, we may visit many nodes where there is no work to do
  - however, we do not need a worklist, so there is one less problem for the implementation to worry about
- TAO analysis:
  - topology-driven
  - each round is unordered

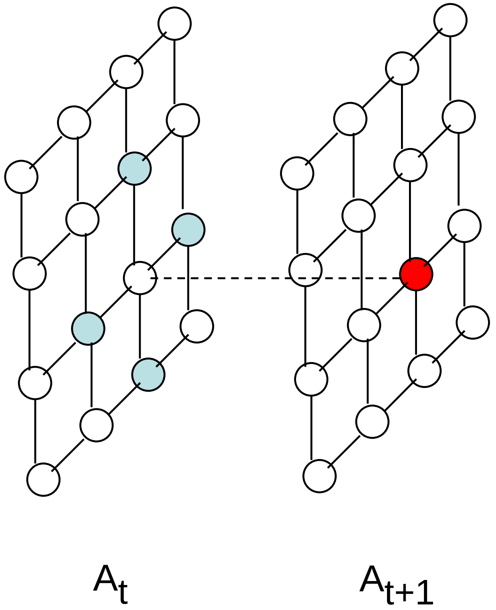


Summary of SSSP Algorithms

- Chaotic relaxation
  - unordered, data-driven algorithm
    - use sets/multisets for work-set
  - amount of work depends on schedule: can be exponential in size of graph
- Dijkstra's algorithm
  - ordered, data-driven algorithm
    - use priority queue for work-set
  - O(|V|log(|E|)): work-efficient but little parallelism
- Delta-stepping
  - controlled chaotic relaxation: parameter Δ
  - Δ permits trade-off between parallelism and work-efficiency
- Bellman-Ford algorithm
  - unordered, topology-driven algorithm
  - O(|V||E|) time
- Operator formulation brings out commonality and differences
  - useful even if you do not care about parallelism

Stencil computation

- Active nodes
  - nodes in A_{t+1}
- Operator
  - five-point stencil
- Different schedules have different locality
- Regular application
  - grid structure and active nodes known statically
  - application can be parallelized using static analysis



Jacobi iteration, 5-point stencil

```
//Jacobi iteration with 5-point stencil
//initialize array A
for time = 1, nsteps
    for <i,j> in [2,n-1]x[2,n-1]
        temp(i,j)=0.25*(A(i-1,j)+A(i+1,j)+A(i,j-1)+A(i,j+1))
    for <i,j> in [2,n-1]x[2,n-1]:
        A(i,j) = temp(i,j)
```

Machine learning

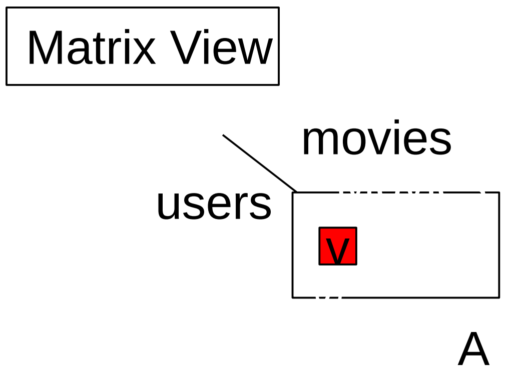
- Examples:
  - Page rank: used to rank webpages to answer Internet search queries
  - Recommender systems: used to make recommendations to users in Netflix, Amazon, Facebook etc.

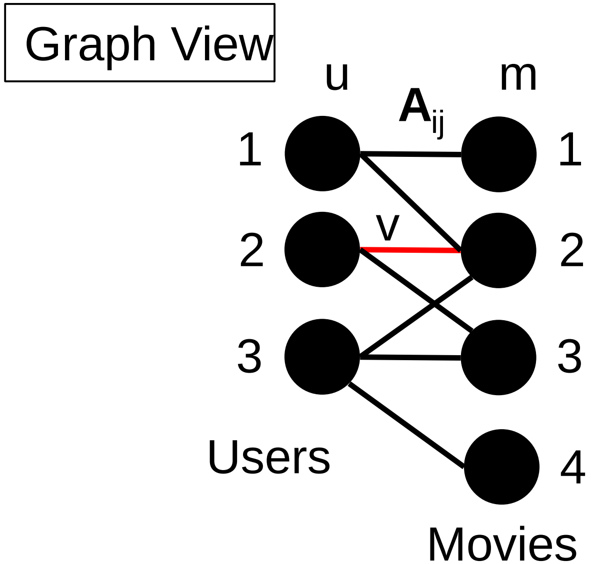
Recommender system

- Problem
  - given a database of users, items, and ratings given by each user to some of the items
  - predict ratings that user might give to items he has not rated yet (usually, we are interested only in the top few items in this set)
- Netflix challenge
  - in 2006, Netflix released a subset of their database and offered $1 million prize to anyone who improved their algorithm by 10%
  - triggered a lot of interest in recommender systems
  - prize finally given to BellKor's Pragmatic Chaos team in 2009

Data structure for database

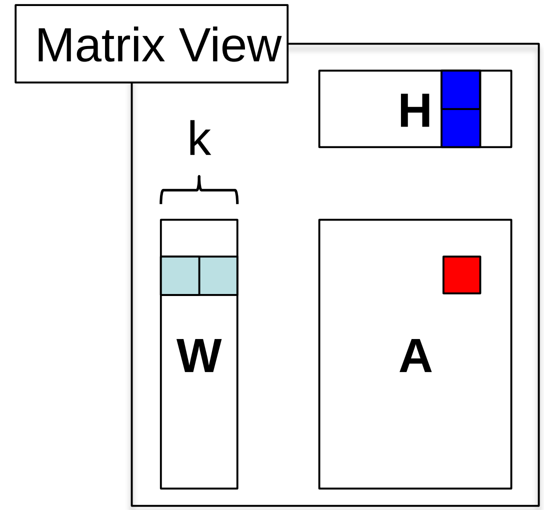
- Sparse matrix view:
  - rows are users
  - columns are movies
  - A(u,m) = v is user u has given rating v to movie m
- Graph view:
  - bipartite graph
  - two sets of nodes, one for users, one for movies
  - edge (u,m) with label v
- Recommendation problem:
  - predict missing entries in sparse matrix
  - predict labels of missing edges in bipartite graph

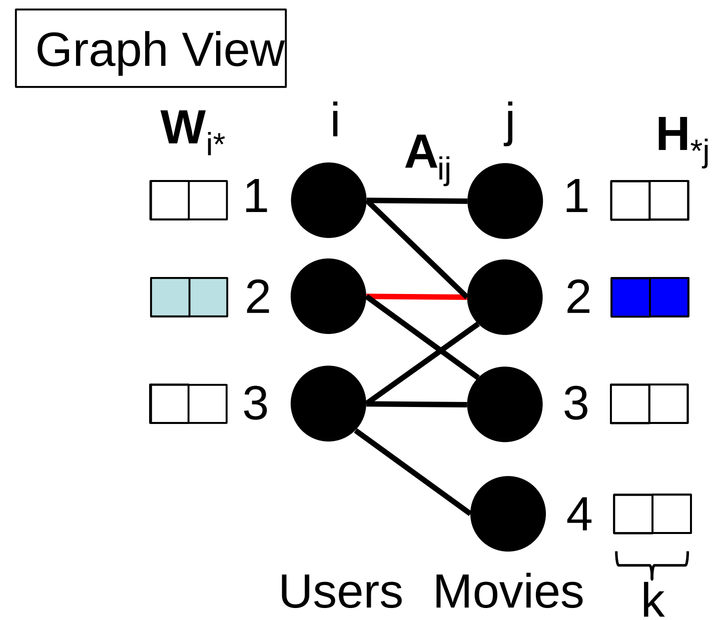




One approach: matrix completion

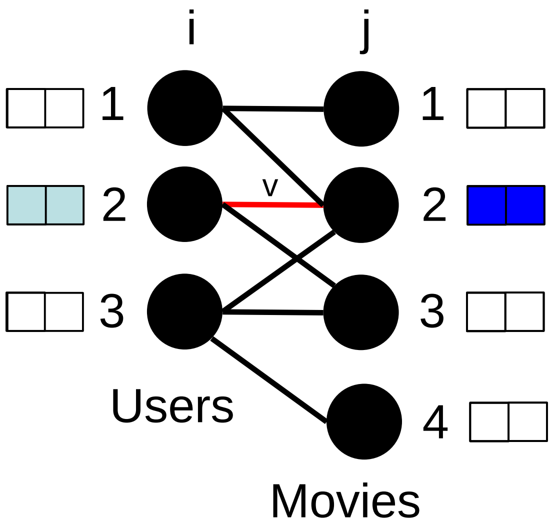
- Optimization problem
  - Find m×k matrix **W** and k×n matrix **H** (k << min(m,n)) such that **A** ≈ **WH**
  - Low-rank approximation
  - **H** and **W** are dense so all missing values are predicted
- Graph view
  - Label of user nodes i is vector corresponding to row W_{i*}
  - Label of movie node j is vector corresponding to column H_{*j}
  - If graph has edge (u,m), inner product of labels on u and m must be approximately equal to label on edge





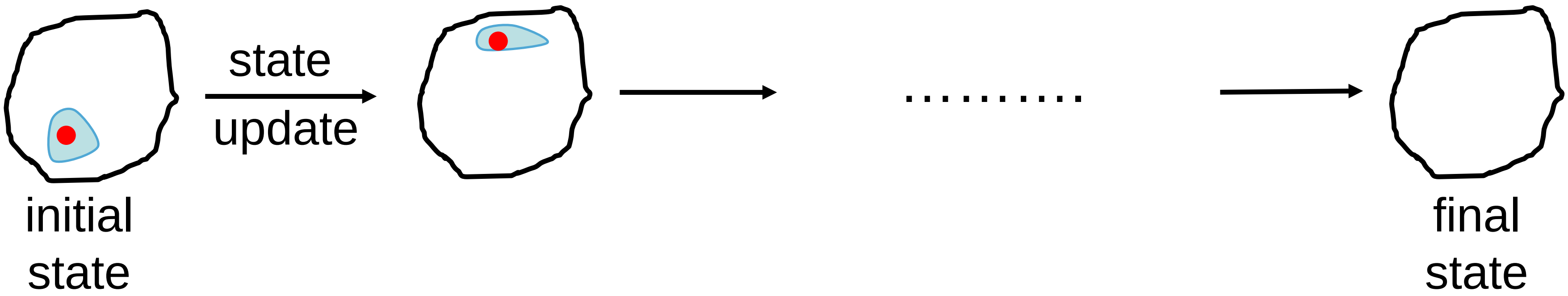
One algorithm:SGD

- Stochastic gradient descent (SGD)
- Iterative algorithm:
  - initialize all node labels to some arbitrary values
  - iterate until convergence
    - visit all edges (u,m) in some order and update node labels at u and m based on the residual
- TAO analysis:
  - topology-driven, unordered



Summary of discussion of algorithms

von Neumann programming model



Program Execution

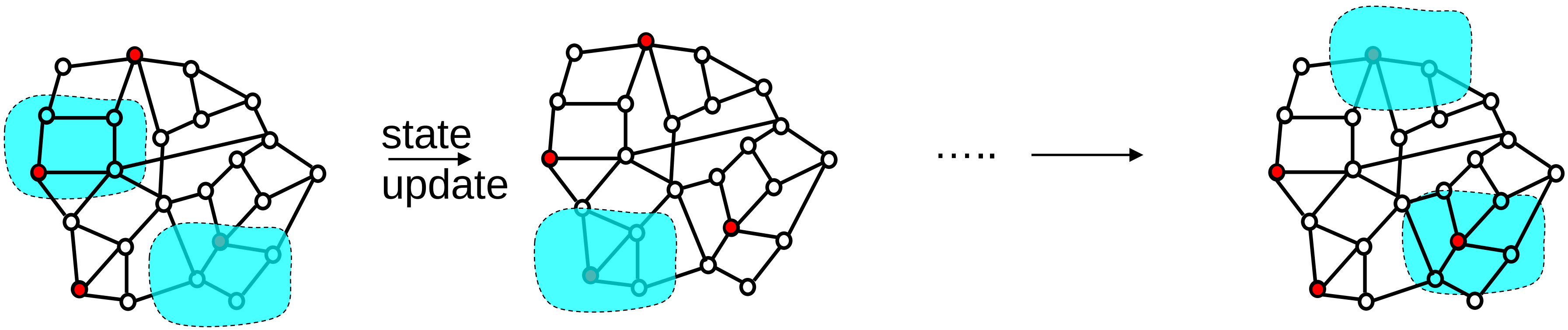
where — Program counter

what — State update: assignment statement
(local view)

when — Schedule: control-flow constructs
(global view)

von Neumann bottleneck [Backus 79]

Data-centric programming model



Program Execution

where — Active nodes

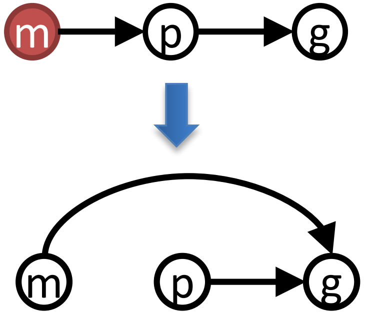
what — State update: operator
(local view)

when — Schedule: ordering between active nodes
(global view)

von Neumann bottleneck [Backus 79]

Connections

- Functional languages: λ-calculus
  - operator: β-reduction
  - schedule: applicative order, normal order,…
- Unity (Chandy and Misra)
  - atomic state updates
  - fair-scheduling for unordered algorithms
- Transactional memory (Herlihy and Moss)
  - operators have transactional semantics
- Stencil programs (Steele), Halide (Amarasinghe)
  - finite-differences, image processing
  - do not handle irregular graph algorithms
- Vertex programs (Pregel, GraphLab,Ligra)
  - neighborhood restricted to immediate neighbors of active node: not adequate for pointer-jumping algorithms
  - graph structure cannot be modified



Questions

- How do we implement this model?
  - Shared-memory machines
  - GPUs
  - Distributed-memory machines
- What structure can we exploit for efficiency?
  - (e.g.) Why can we find parallelism statically in finite-differences but not in Delaunay mesh-refinement?
  - Locality

Graph Algorithms

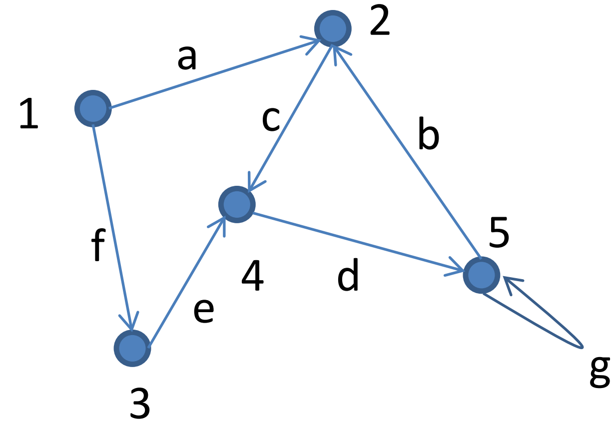
Overview

- Graph: abstract data type
  - G = (V,E) where V is set of nodes, E is set of edges $\subseteq$ VxV
- Structural properties of graphs
  - Power-law graphs, uniform-degree graphs
- Graph representations: concrete data type
  - Compressed-row/column, coordinate, adjacency list
- Graph algorithms
  - Operator formulation: abstraction for algorithms
  - Algorithms for single-source shortest-path (SSSP) problem
- Machine learning algorithms
  - Page-rank
  - Matrix-completion for recommendation systems

Structural properties of graphs

Graph-matrix duality

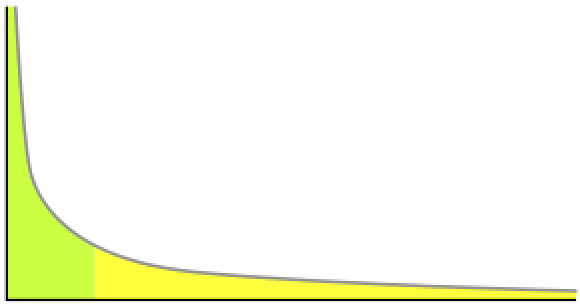
- Graph (V,E) as a matrix
  - Choose an ordering of vertices
  - Number them sequentially
  - Fill in |V|x|V| matrix
    - A(i,j) is w if graph has edge from node i to node j with label w
  - Called *adjacency matrix* of graph
  - Edge (u → v):
    - v is *out-neighbor* of u
    - u is in-neighbor of v
- Observations:
  - Diagonal entries: weights on self-loops
  - Symmetric matrix ←→ undirected graph
  - Lower triangular matrix ←→ no edges from lower numbered nodes to higher numbered nodes
  - Dense matrix ←→ clique (edge between every pair of nodes)



$$
\begin{array}{c|c}
\text{from} \backslash \text{to} & \begin{matrix} 1 & 2 & 3 & 4 & 5 \end{matrix} \\
\begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{matrix} & \begin{bmatrix} 0 & a & f & 0 & 0 \\ 0 & 0 & 0 & c & 0 \\ 0 & 0 & 0 & e & 0 \\ 0 & 0 & 0 & 0 & d \\ 0 & b & 0 & 0 & g \end{bmatrix}
\end{array}
$$

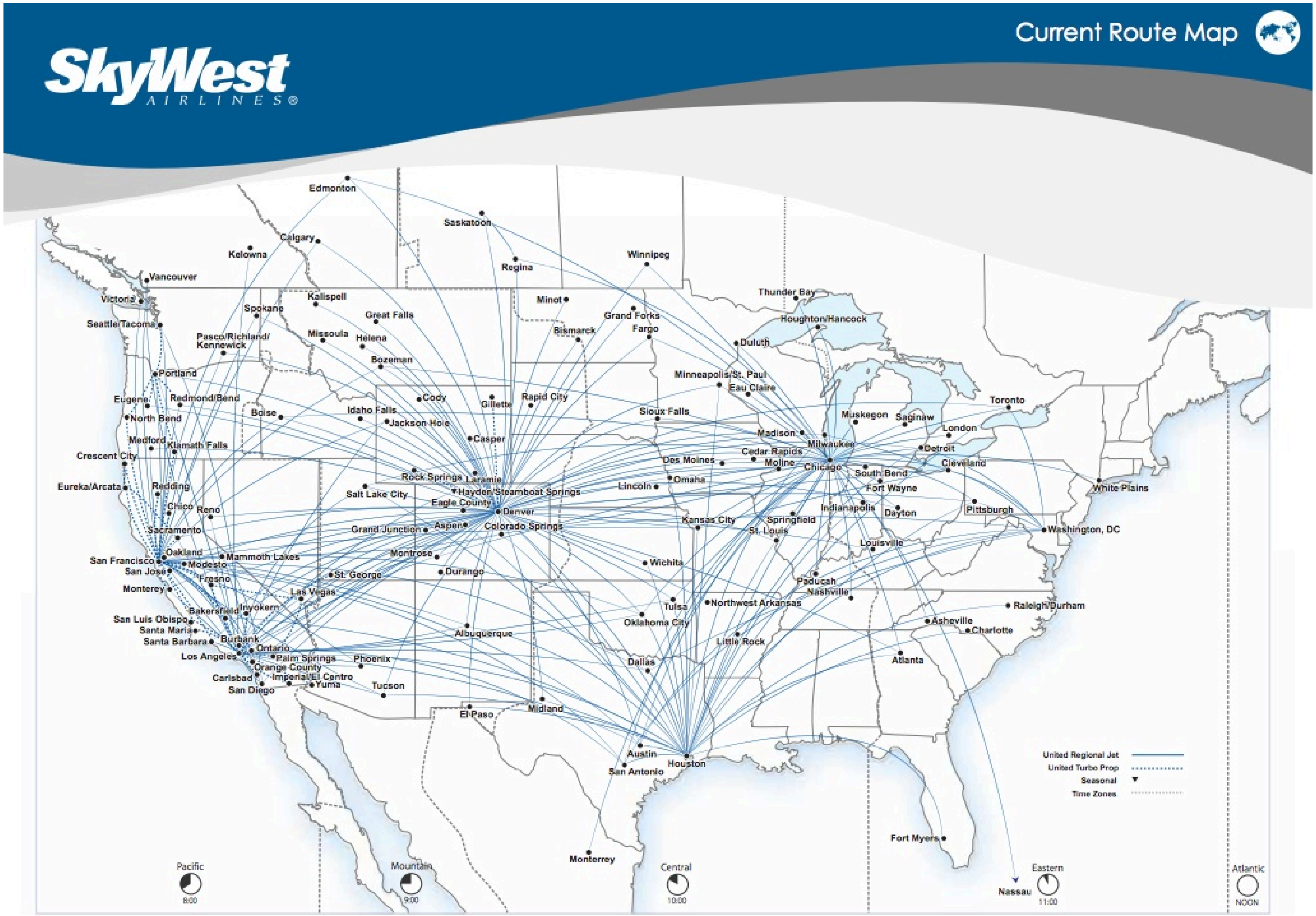
Sparse graphs

- Terminology:
  - Degree of node: number of edges connected to it
  - (Average) diameter of graph: average number of hops between two nodes
- Power-law graphs
  - small number of very high degree nodes (see next slide for example)
  - low diameter
    - "six degrees of separation" (Karinthy 1929, Milgram 1967), on Facebook, it is 4.74
  - typical of social network graphs like the Internet graph or the Facebook graph
- Uniform-degree graphs
  - nodes have roughly same degree
  - high diameter
  - road networks, IC circuits, finite-element meshes
- Random (Erdös-Rènyi) graphs
  - constructed by random insertion of edges
  - mathematically interesting but few real-life examples



Node degree distribution of power-law graphs

Airline route map: power-law graph



UNITED EXPRESS

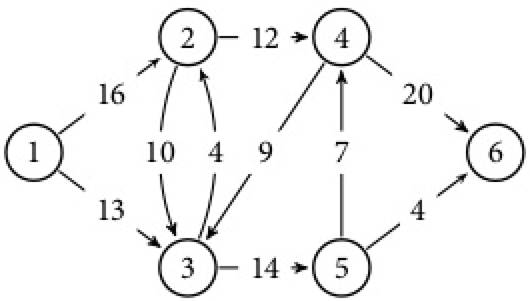
Road map: uniform-degree graph

Graph representations:
how to store graphs in memory

Three storage formats:CSR,CSC,COO

Coordinate storage

1	**2**	**4**	**5**	**3**	**1**	**2**	**3**	**4**	**5**
2	4	6	6	5	3	3	2	3	4
16	12	20	4	15	13	10	4	9	7



Compressed sparse row

rp	1	3	5	7	9	11	11				
ci	2	3	3	4	2	5	3	6	4	6	∅
ai	16	13	10	12	4	14	9	20	7	4	

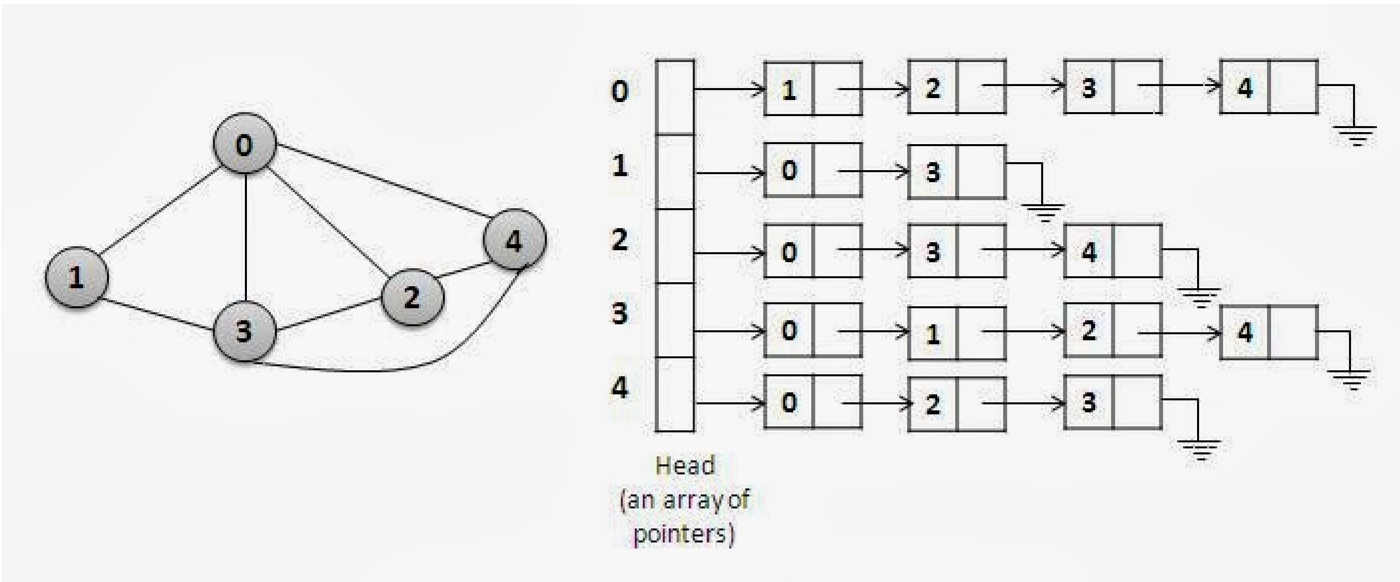
$$\begin{bmatrix} 0 & 16 & 13 & 0 & 0 & 0 \\ 0 & 0 & 10 & 12 & 0 & 0 \\ 0 & 4 & 0 & 0 & 14 & 0 \\ 0 & 0 & 9 & 0 & 0 & 20 \\ 0 & 0 & 0 & 7 & 0 & 4 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Compressed sparse column

cp	1	1	3	6	8	9	11				
ri	1	3	1	2	4	2	5	3	4	5	∅
ai	16	4	13	10	9	12	7	14	20	4	

Labels on nodes are stored in a separate vector (not shown)

Adjacency list representation



Adjacency List Representation of Graph

From: https://www.thecrazyprogrammer.com

Permits you to add and remove edges from graph

Deleting edges: often it is more efficient to just to mark an edge as deleted rather than delete it physically from the list

Graph algorithms

Overview

- Algorithms: usually specified by pseudocode
- We take a different approach:
  - operator formulation of algorithms
  - data-centric abstraction in which data structures play central role
- Advantages of operator formulation abstraction:
  - Connections between seemingly unrelated algorithms
  - Sources of parallelism and locality become evident
  - Suggests common set of mechanisms for exploiting parallelism and locality for all algorithms

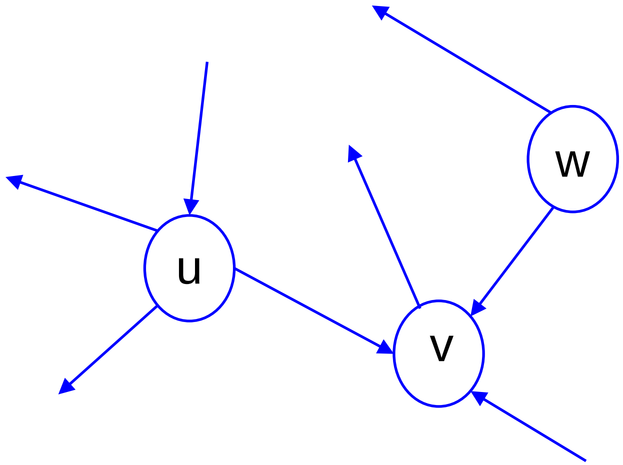
Web search

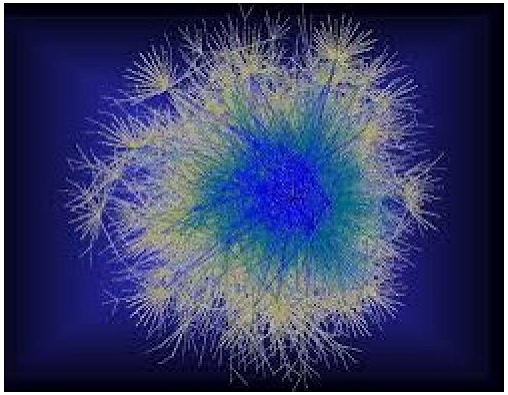
- When you type a set of keywords to do an Internet search, which web-pages should be returned and in what order?
- Basic idea:
  - offline:
    - crawl the web and gather webpages into data center
    - build an index from keywords to webpages
  - online:
    - when user types keywords, use index to find all pages containing the keywords
  - key problem:
    - usually you end up with tens of thousands of pages
    - how do you rank these pages for the user?

Ranking pages

- Manual ranking
  - Yahoo did something like this initially, but this solution does not scale
- Word counts
  - order webpages by how many times keywords occur in webpages
  - problem: easy to mess with ranking by having lots of meaningless occurrences of keyword
- Citations
  - analogy with citations to articles
  - if lots of webpages point to a webpage, rank it higher
  - problem: easy to mess with ranking by creating lots of useless pages that point to your webpage
- PageRank
  - extension of citations idea
  - weight link from webpage A to webpage B by “importance” of A
  - if A has few links to it, its links are not very “valuable”
  - how do we make this into an algorithm?

Web graph



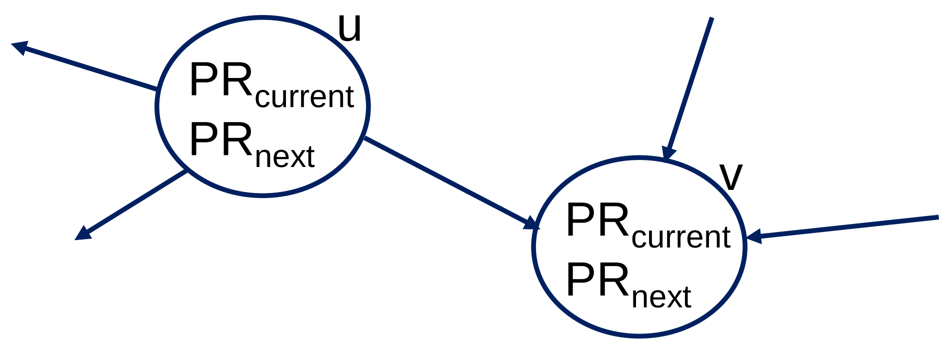


Webgraph from commoncrawl.org

- Directed graph: nodes represent webpages, edges represent links
  - edge from u to v represents a link in page u to page v
- Size of graph: commoncrawl.org (2012)
  - 3.5 billion nodes
  - 128 billion links
- Intuitive idea of pageRank algorithm:
  - each node in graph has a weight (pageRank) that represents its importance
  - assume all edges out of a node are equally important
  - importance of edge is scaled by the pageRank of source node

PageRank (simple version)

Graph G = (V,E)
|V| = N



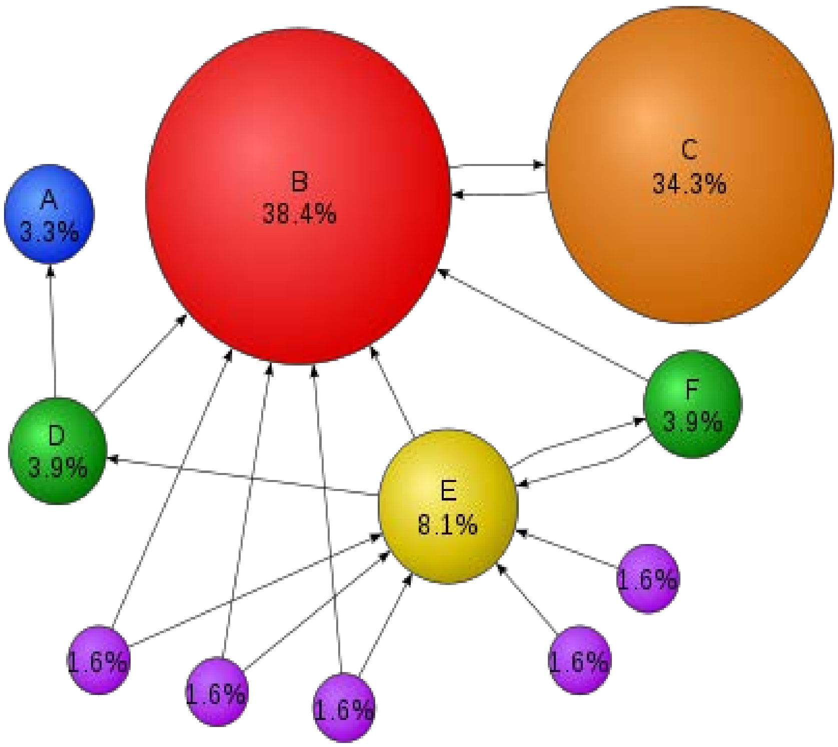
- Iterative algorithm:
  - compute a series PR_0, PR_1, PR_2, … of node labels
- Iterative formula:
  - $\forall v \in V.\ PR_0(v) = 1/N$
  - $\forall v \in V.\ PR_{i+1}(v) = \sum_{u \in in-neighbors(v)} \frac{PR_i(u)}{out-degree(u)}$
- Implement with two fields $PR_{current}$ and PR_{next} in each node

Page Rank (contd.)

- Small twist needed to handle nodes with no outgoing edges
- Damping factor: d
  - small constant: 0.85
  - assume each node may also contribute its pageRank to a randomly selected node with probability (1-d)
- Iterative formula
  - $\forall v \in V.\ PR_0(v) = \frac{1}{N}$
  - $\forall v \in V.\ PR_{i+1}(v) = \frac{1-d}{N} + d * \sum_{u \in in-neighbors(v)} \frac{PR_i(u)}{out-degree(u)}$
- Convergence
  - $\forall v \in V.\ PR(v) = \frac{1-d}{N} + d * \sum_{u \in in-neighbors(v)} \frac{PR(u)}{out-degree(u)}$

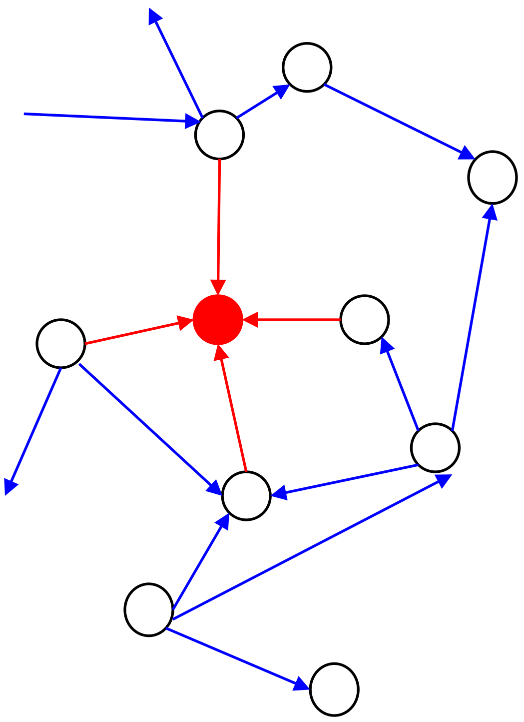
PageRank example

- Nice example from Wikipedia
- Note
  - B and E have many in-edges but pageRank of B is much greater
  - C has only one in-edge but high pageRank because its in-edge is very valuable
- Caveat:
  - search engines use many criteria in addition to pageRank to rank webpages



PageRank discussion

- TAO:
  - Topology: unstructured graph
  - Active nodes
    - Topology-driven
    - Unordered
  - Operator
    - Label computation operator
    - Pull-style
- Interesting application of TAO
  - Can you think of a data-driven version of pageRank?



What we have learned

- Operator formulation:
  - data-centric view of algorithms
- TAO classification
- Location of active nodes
  - Topology-driven algorithms
  - Data-driven algorithms
  - Data-driven algorithm may be more work-efficient than topology-driven one
- Ordering of active nodes
  - Unordered algorithms
  - Ordered algorithms
- Some problems
  - have both ordered and unordered algorithms (e.g. SSSP)
  - have both topology-driven and data-driven algorithms (e.g. SSSP, pageRank)