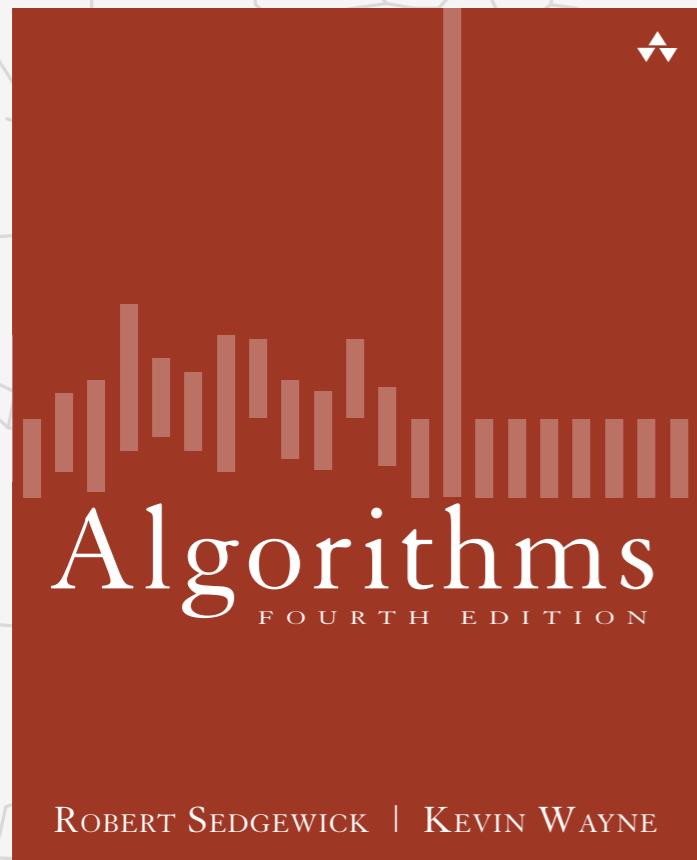


Algorithms

ROBERT SEDGEWICK | KEVIN WAYNE



<http://algs4.cs.princeton.edu>

4.2 DIRECTED GRAPHS

- ▶ *introduction*
- ▶ *digraph API*
- ▶ *digraph search*
- ▶ *topological sort*
- ▶ *strong components*

Algorithms

ROBERT SEDGEWICK | KEVIN WAYNE

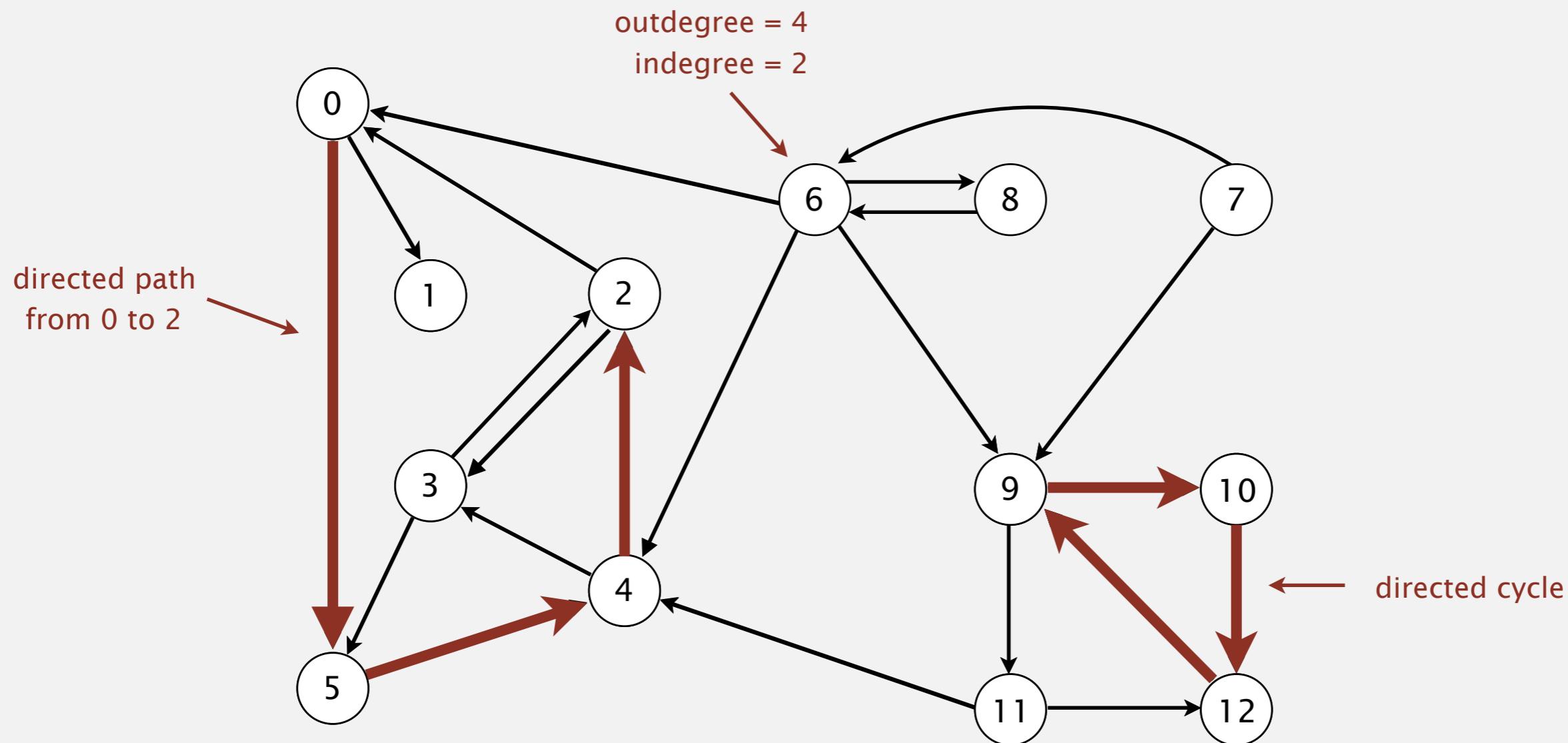
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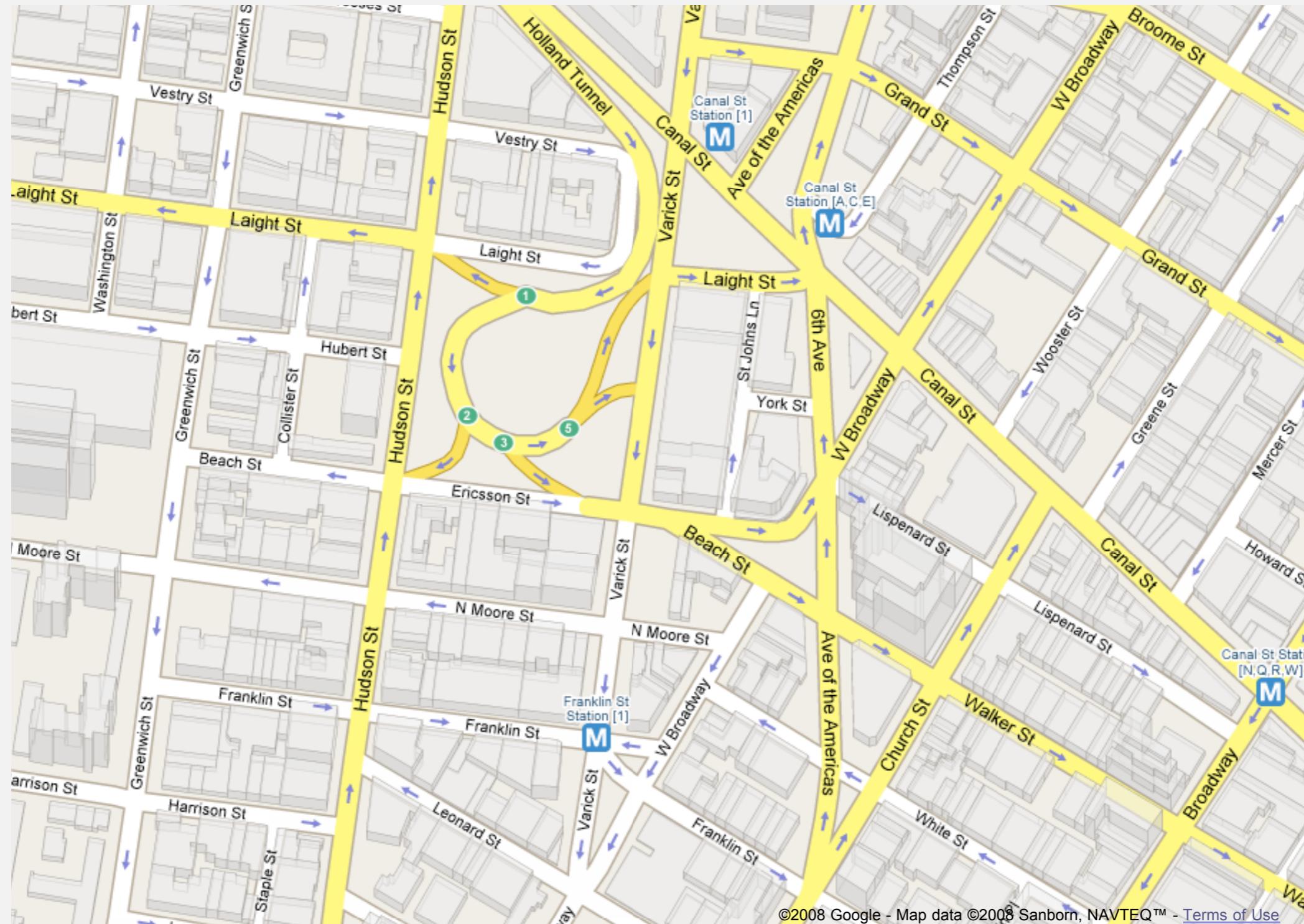
Directed graphs

Digraph. Set of vertices connected pairwise by **directed** edges.



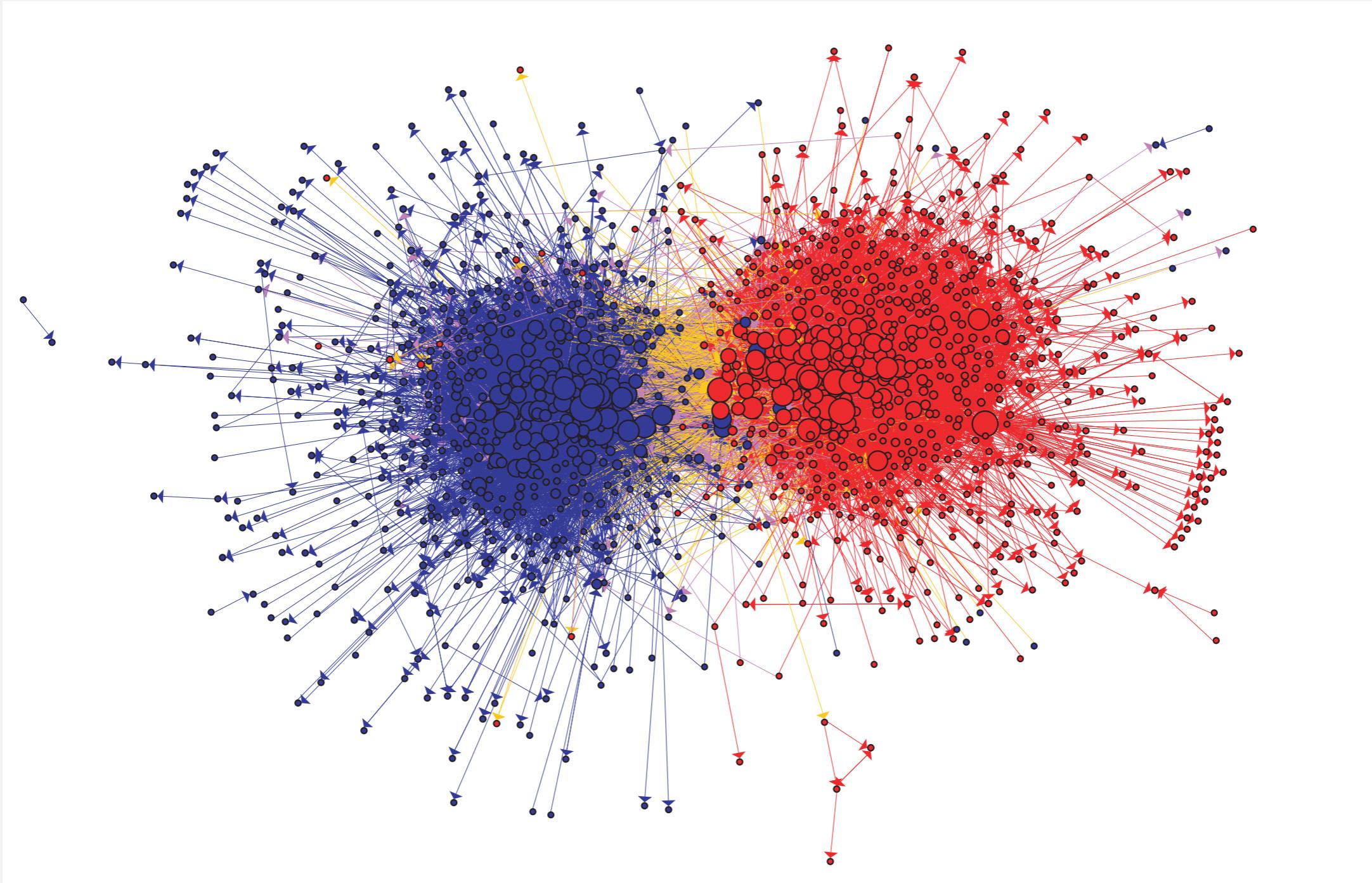
Road network

Vertex = intersection; edge = one-way street.



Political blogosphere graph

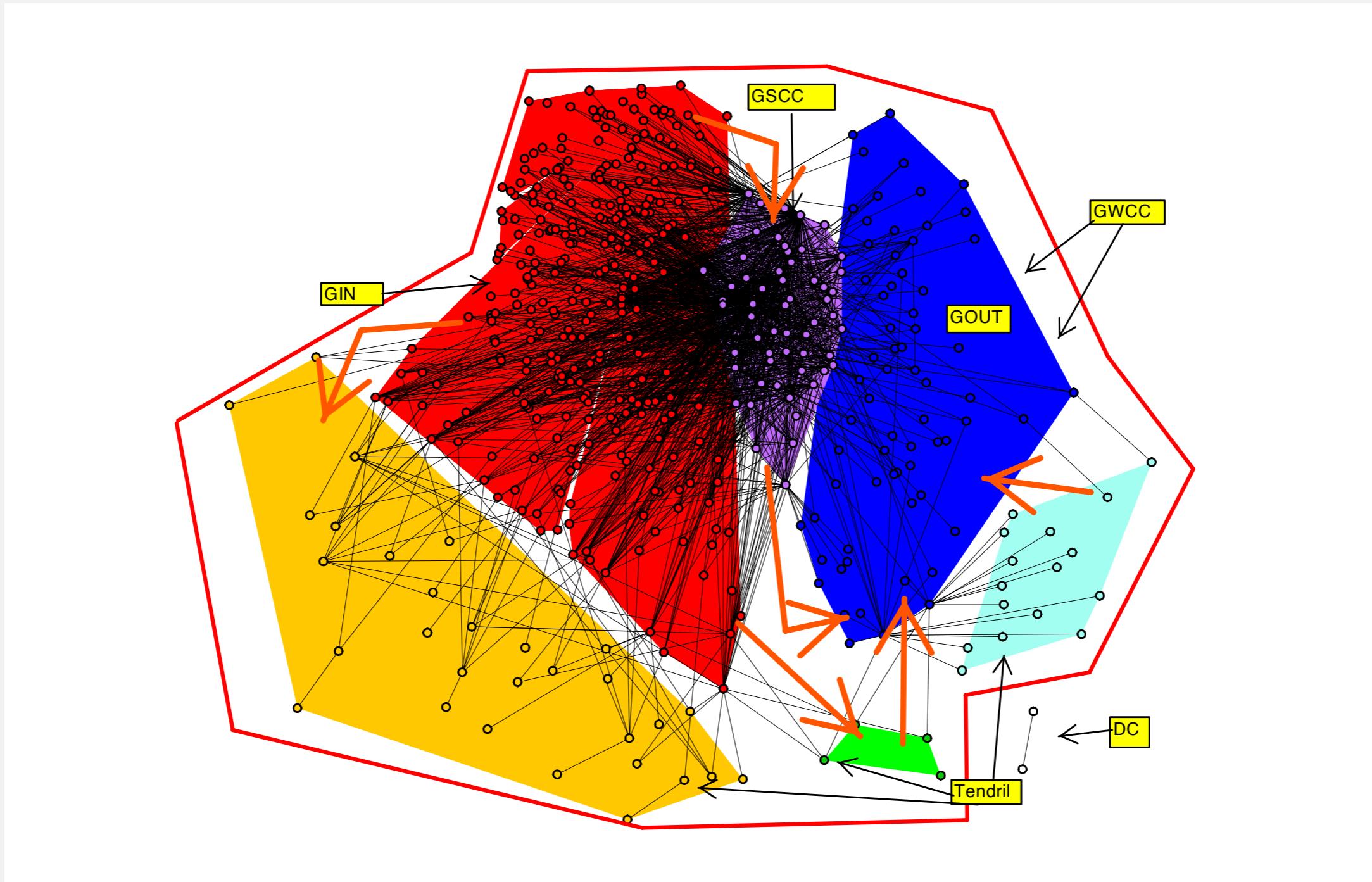
Vertex = political blog; edge = link.



The Political Blogosphere and the 2004 U.S. Election: Divided They Blog, Adamic and Glance, 2005

Overnight interbank loan graph

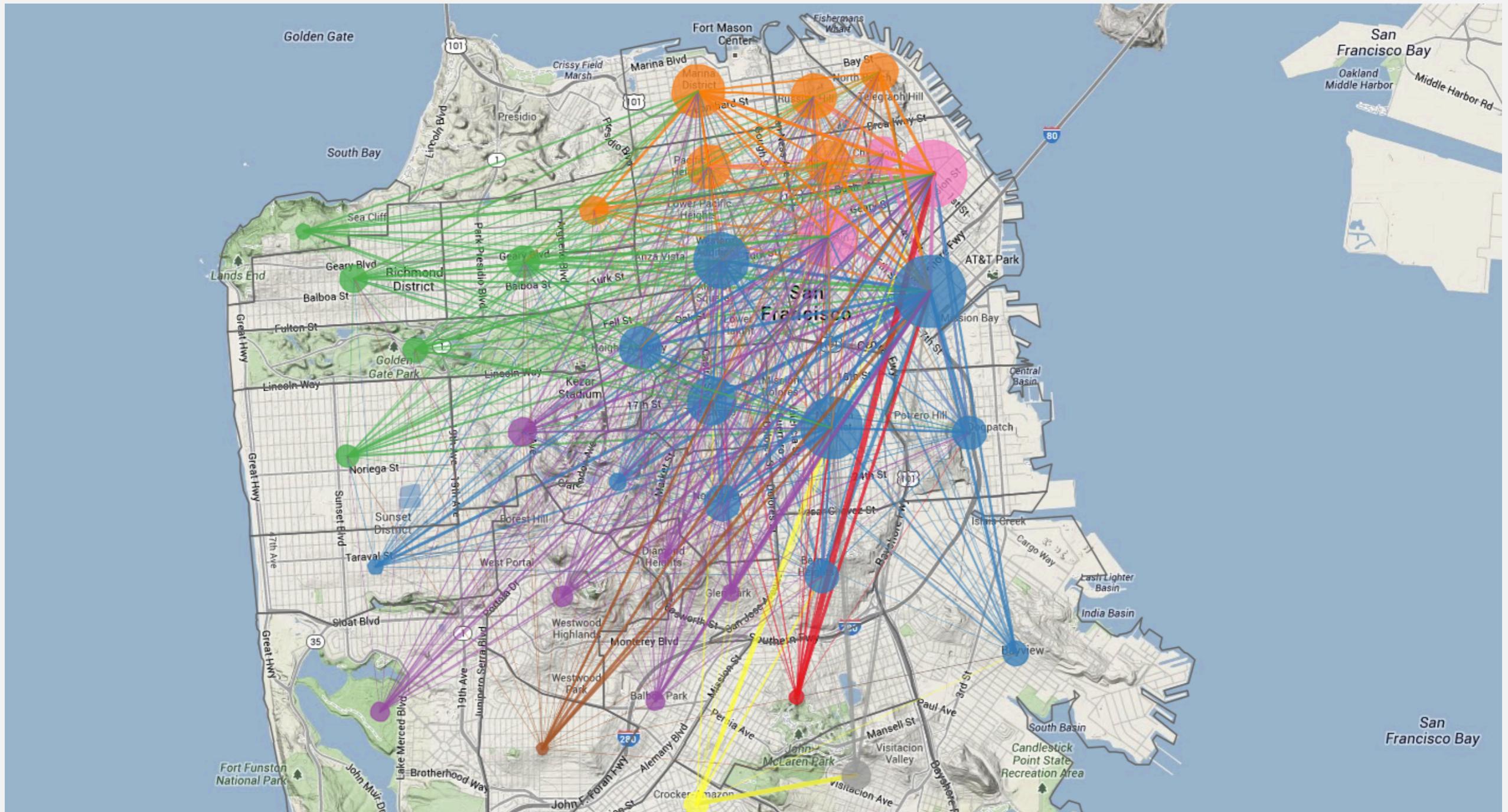
Vertex = bank; edge = overnight loan.



The Topology of the Federal Funds Market, Bech and Atalay, 2008

Uber taxi graph

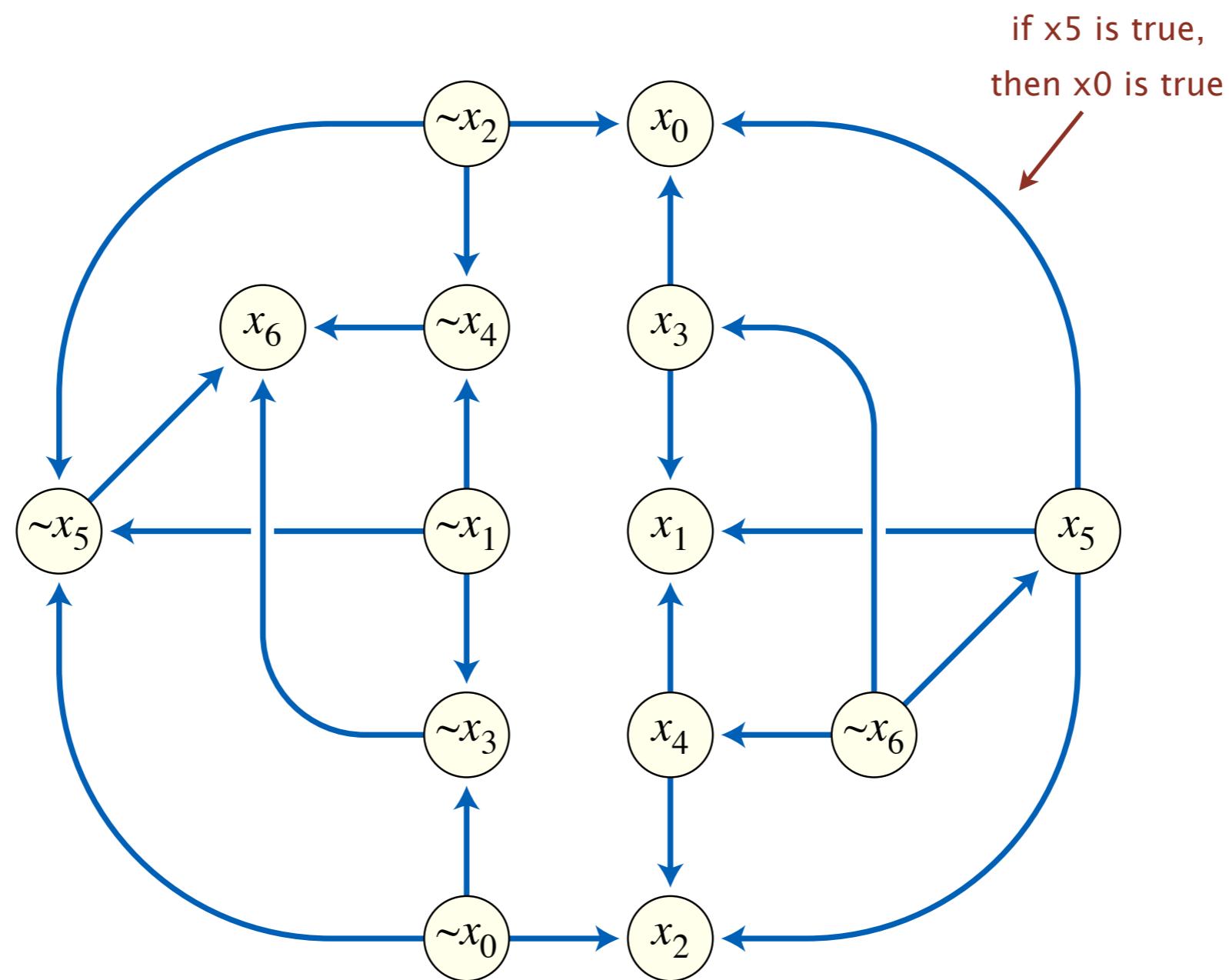
Vertex = taxi pickup; edge = taxi ride.



<http://blog.uber.com/2012/01/09/uberdata-san-franciscomics/>

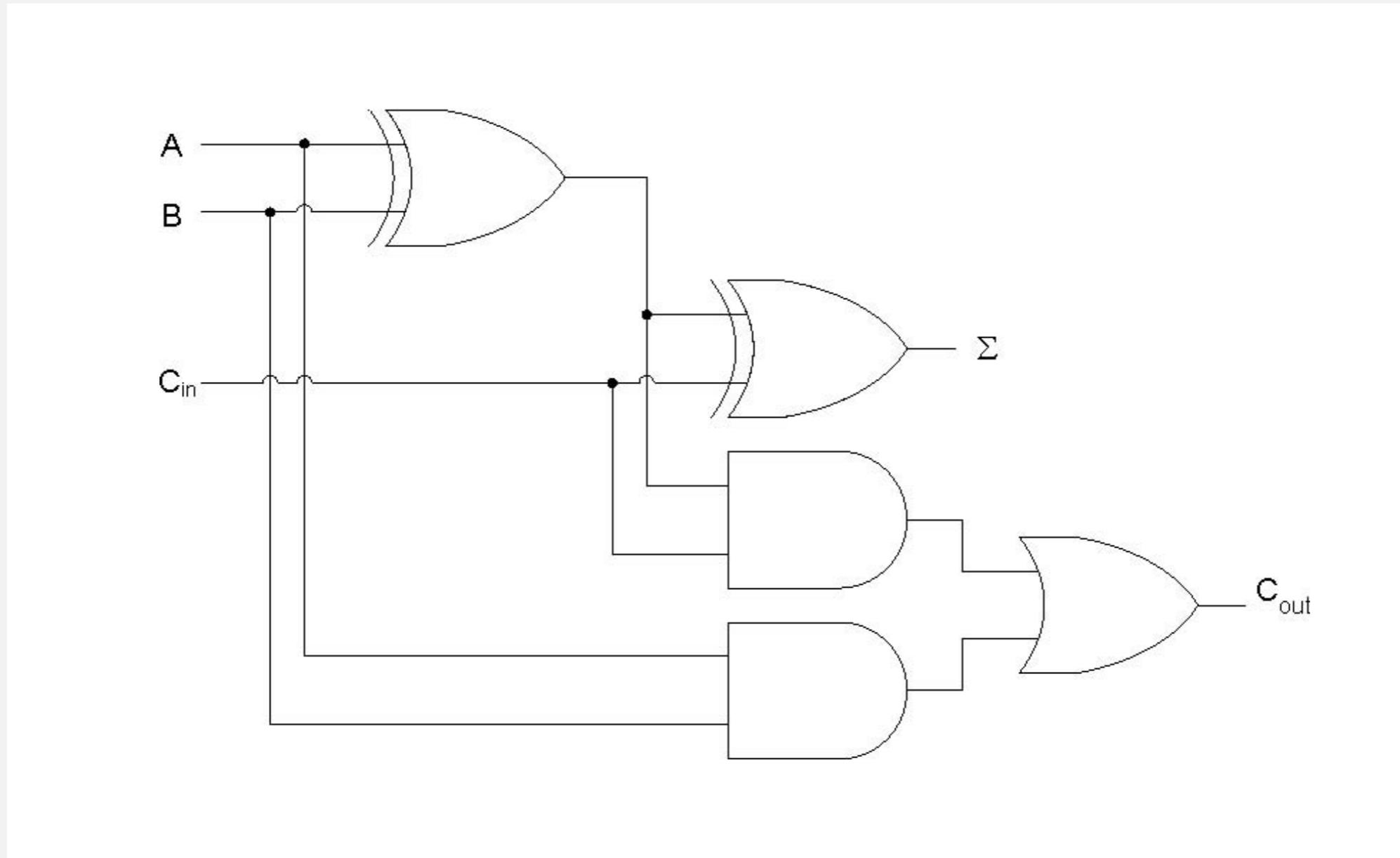
Implication graph

Vertex = variable; edge = logical implication.



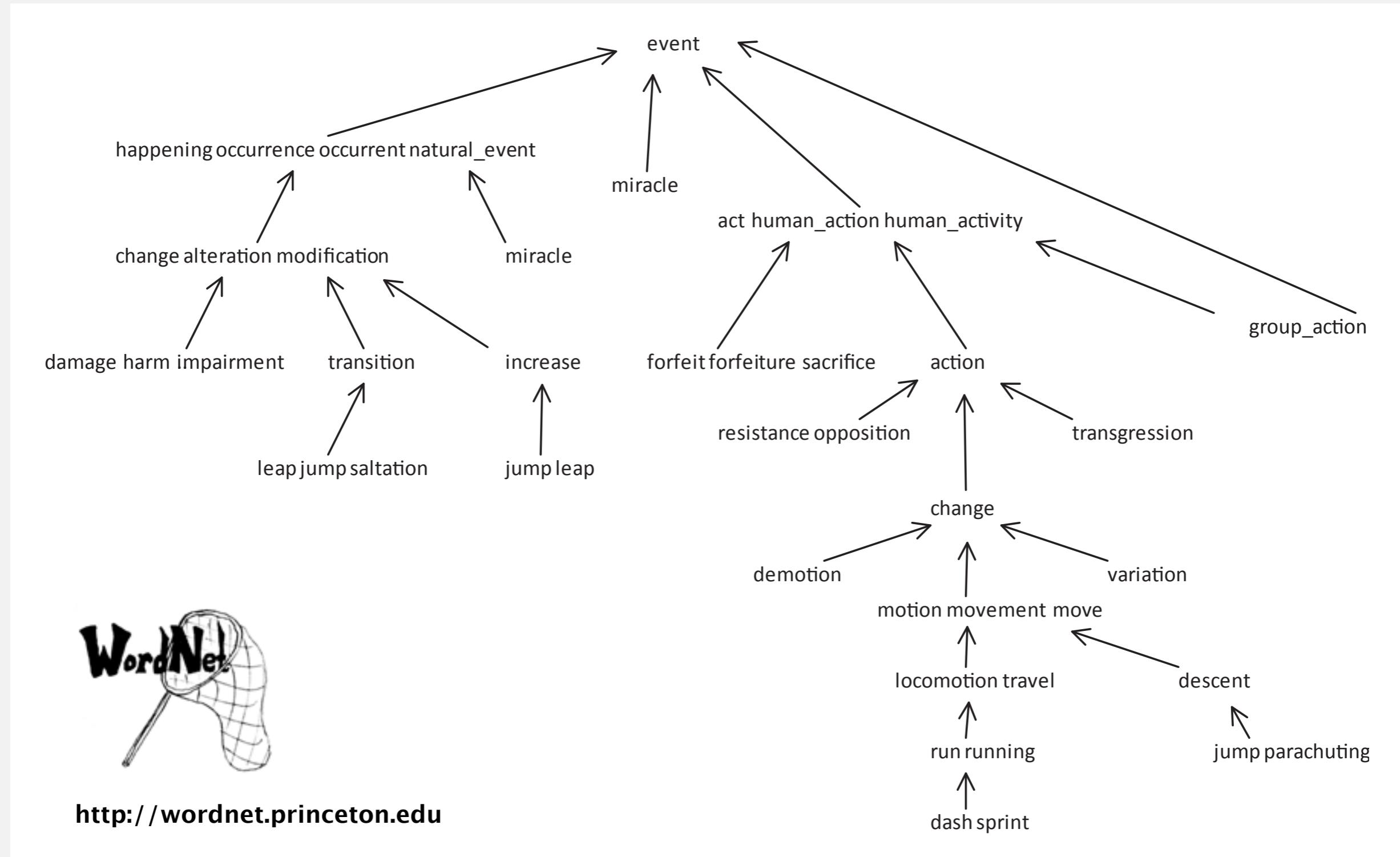
Combinational circuit

Vertex = logical gate; edge = wire.



WordNet graph

Vertex = synset; edge = hypernym relationship.



Digraph applications

digraph	vertex	directed edge
transportation	street intersection	one-way street
web	web page	hyperlink
food web	species	predator-prey relationship
WordNet	synset	hyponym
scheduling	task	precedence constraint
financial	bank	transaction
cell phone	person	placed call
infectious disease	person	infection
game	board position	legal move
citation	journal article	citation
object graph	object	pointer
inheritance hierarchy	class	inherits from
control flow	code block	jump

Some digraph problems

problem	description
s→t path	<i>Is there a path from s to t ?</i>
shortest s→t path	<i>What is the shortest path from s to t ?</i>
directed cycle	<i>Is there a directed cycle in the graph ?</i>
topological sort	<i>Can the digraph be drawn so that all edges point upwards?</i>
strong connectivity	<i>Is there a directed path between all pairs of vertices ?</i>
transitive closure	<i>For which vertices v and w is there a directed path from v to w ?</i>
PageRank	<i>What is the importance of a web page ?</i>

Algorithms

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4.2 DIRECTED GRAPHS

- ▶ *introduction*
- ▶ *digraph API*
- ▶ *digraph search*
- ▶ *topological sort*
- ▶ *strong components*

Digraph API

Almost identical to Graph API.

```
public class Digraph
```

```
    Digraph(int V)
```

create an empty digraph with V vertices

```
    Digraph(In in)
```

create a digraph from input stream

```
    void addEdge(int v, int w)
```

add a directed edge $v \rightarrow w$

```
    Iterable<Integer> adj(int v)
```

vertices pointing from v

```
    int V()
```

number of vertices

```
    int E()
```

number of edges

```
    Digraph reverse()
```

reverse of this digraph

```
    String toString()
```

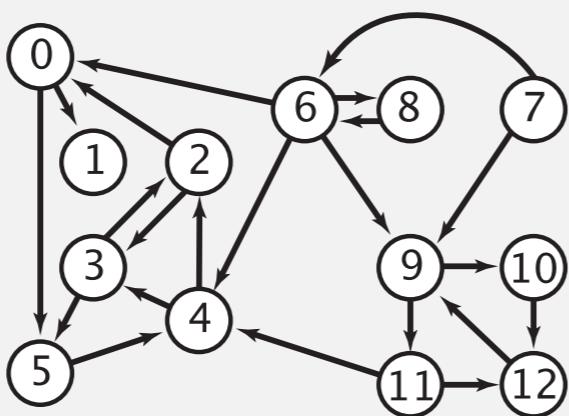
string representation

Digraph API

tinyDG.txt

V → 13
22 ← *E*

4 2
2 3
3 2
6 0
0 1
2 0
11 12
12 9
9 10
9 11
7 9
10 12
11 4
4 3
3 5
6 8
8 6
:



% java Digraph tinyDG.txt

0->5
0->1
2->0
2->3
3->5
3->2
4->3
4->2
5->4
:
11->4
11->12
12->9

```
In in = new In(args[0]);  
Digraph G = new Digraph(in);
```

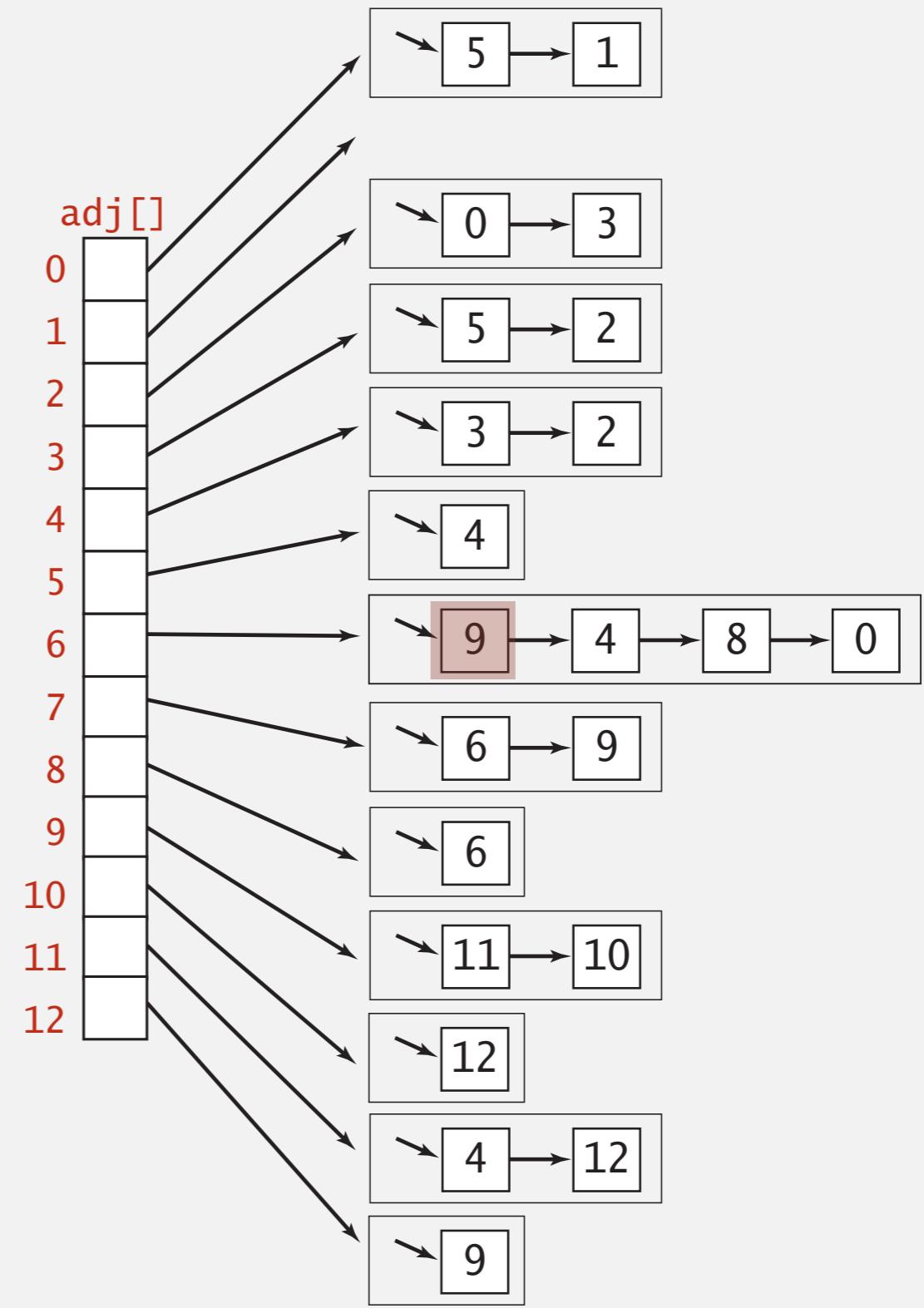
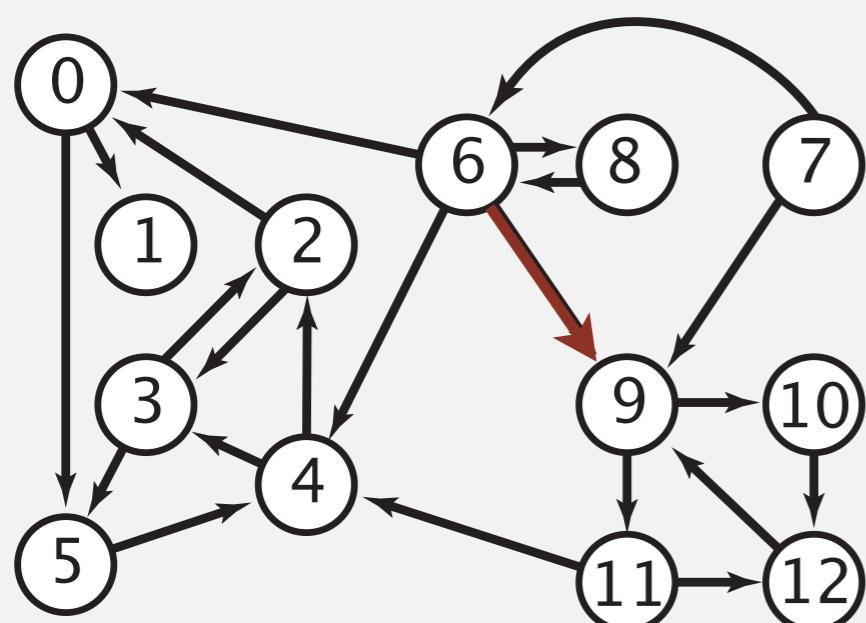
read digraph from
input stream

```
for (int v = 0; v < G.V(); v++)  
    for (int w : G.adj(v))  
        StdOut.println(v + "->" + w);
```

print out each
edge (once)

Digraph representation: adjacency lists

Maintain vertex-indexed array of lists.



Digraph representations

In practice. Use adjacency-lists representation.

- Algorithms based on iterating over vertices pointing from v .
- Real-world digraphs tend to be sparse.

huge number of vertices,
small average vertex degree

representation	space	insert edge from v to w	edge from v to w ?	iterate over vertices pointing from v ?
list of edges	E	1	E	E
adjacency matrix	V^2	1^\dagger	1	V
adjacency lists	$E + V$	1	$outdegree(v)$	$outdegree(v)$

[†] disallows parallel edges

Adjacency-lists graph representation (review): Java implementation

```
public class Graph
{
    private final int V;
    private final Bag<Integer>[] adj; ← adjacency lists

    public Graph(int V)
    {
        this.V = V;
        adj = (Bag<Integer>[]) new Bag[V];
        for (int v = 0; v < V; v++)
            adj[v] = new Bag<Integer>();
    }

    public void addEdge(int v, int w) ← add edge v-w
    {
        adj[v].add(w);
        adj[w].add(v);
    }

    public Iterable<Integer> adj(int v) ← iterator for vertices
    { return adj[v]; } adjacent to v
```

Adjacency-lists digraph representation: Java implementation

```
public class Digraph
{
    private final int V;
    private final Bag<Integer>[] adj; ← adjacency lists

    public Digraph(int V)
    {
        this.V = V;
        adj = (Bag<Integer>[]) new Bag[V]; ← create empty digraph
        for (int v = 0; v < V; v++)
            adj[v] = new Bag<Integer>();
    }

    public void addEdge(int v, int w)
    {
        adj[v].add(w); ← add edge v→w
    }

    public Iterable<Integer> adj(int v) ← iterator for vertices
    { return adj[v]; }                  pointing from v
```

Algorithms

ROBERT SEDGEWICK | KEVIN WAYNE

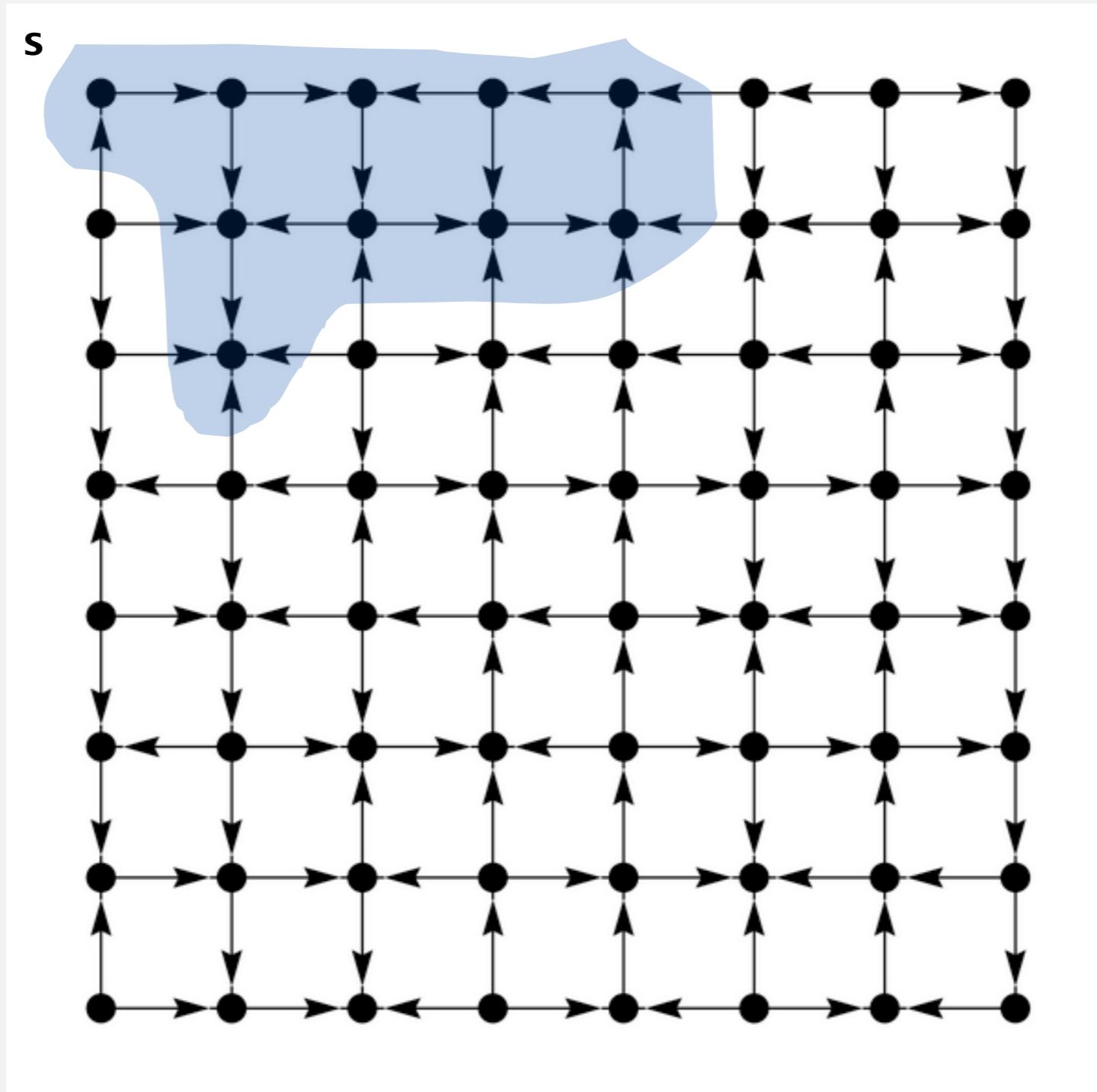
<http://algs4.cs.princeton.edu>

4.2 DIRECTED GRAPHS

- *introduction*
- *digraph API*
- *digraph search*
- *topological sort*
- *strong components*

Reachability

Problem. Find all vertices reachable from s along a directed path.



Depth-first search in digraphs

Same method as for undirected graphs.

- Every undirected graph is a digraph (with edges in both directions).
- DFS is a **digraph** algorithm.

DFS (to visit a vertex v)

Mark v as visited.

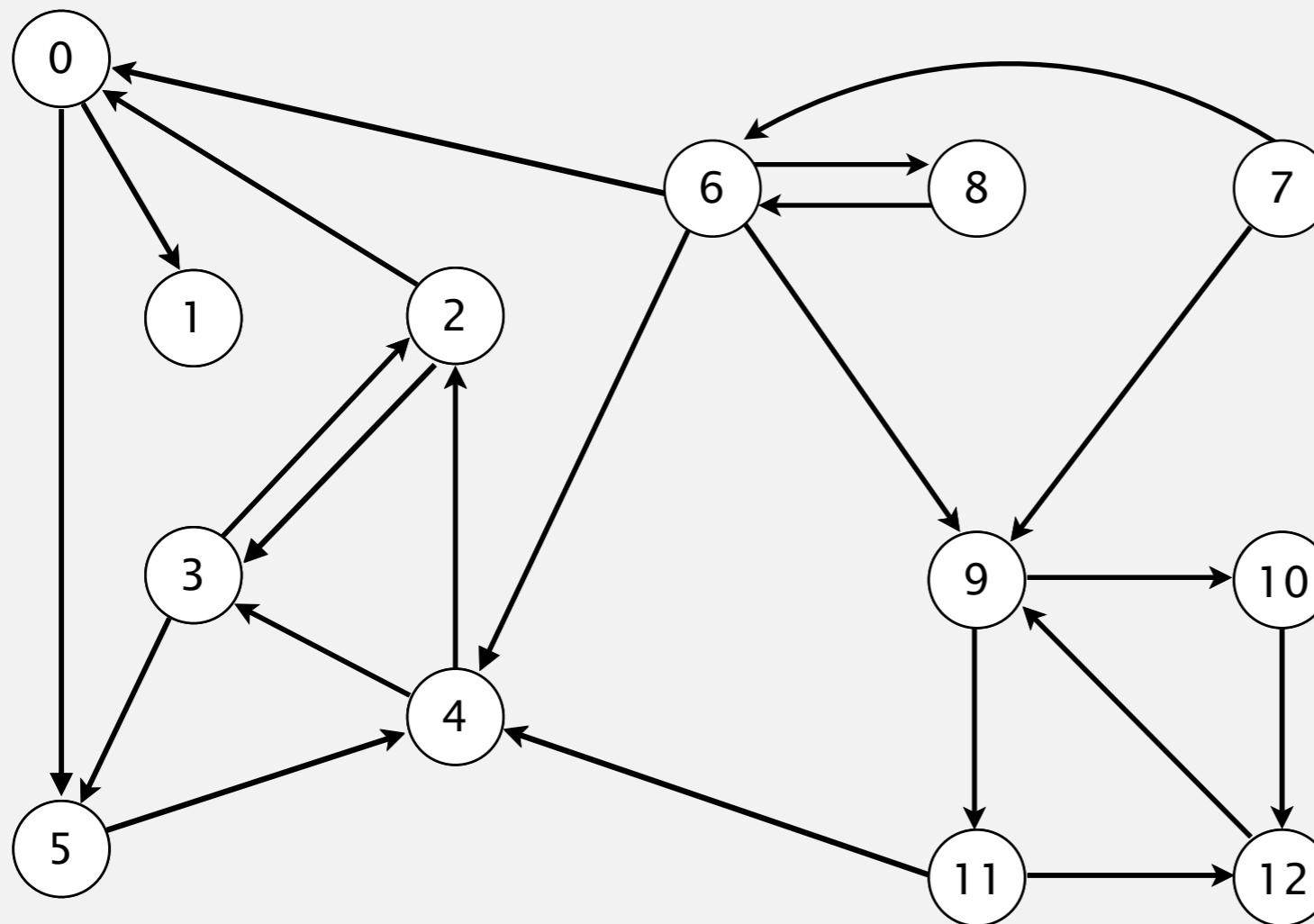
**Recursively visit all unmarked
vertices w pointing from v.**

Depth-first search demo

4→2
2→3
3→2
6→0
0→1
2→0
11→12
12→9
9→10
9→11
8→9
10→12
11→4
4→3
3→5
6→8
8→6
5→4
0→5
6→4
6→9
7→6

To visit a vertex v :

- Mark vertex v as visited.
- Recursively visit all unmarked vertices pointing from v .

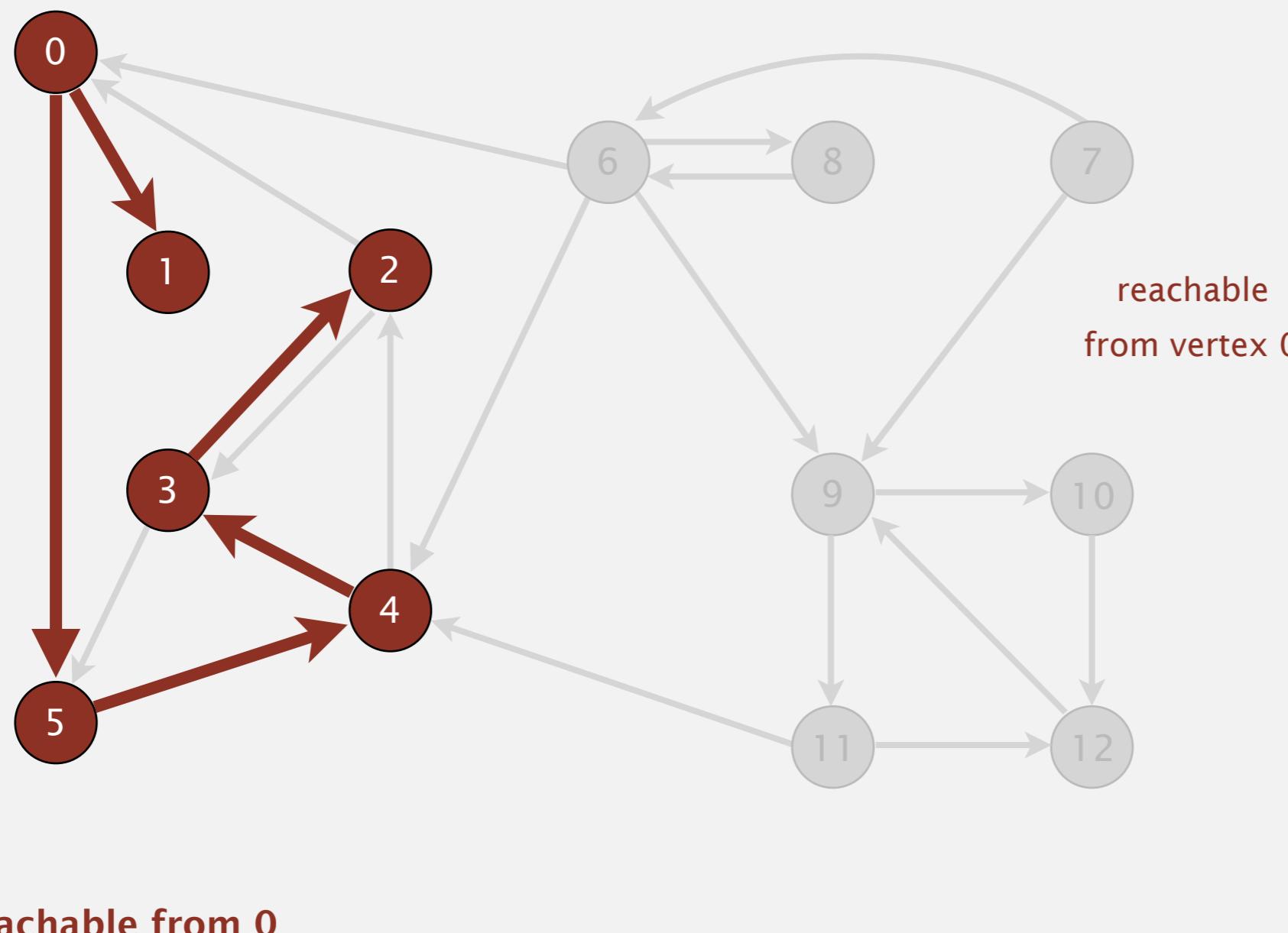


a directed graph

Depth-first search demo

To visit a vertex v :

- Mark vertex v as visited.
- Recursively visit all unmarked vertices pointing from v .



v	marked[]	edgeTo[]
0	T	-
1	T	0
2	T	3
3	T	4
4	T	5
5	T	0
6	F	-
7	F	-
8	F	-
9	F	-
10	F	-
11	F	-
12	F	-

Depth-first search (in undirected graphs)

Recall code for **undirected** graphs.

```
public class DepthFirstSearch
{
    private boolean[] marked;           ← true if connected to s

    public DepthFirstSearch(Graph G, int s)
    {
        marked = new boolean[G.V()];
        dfs(G, s);
    }

    private void dfs(Graph G, int v)   ← recursive DFS does the work
    {
        marked[v] = true;
        for (int w : G.adj(v))
            if (!marked[w]) dfs(G, w);
    }

    public boolean visited(int v)      ← client can ask whether any
    { return marked[v]; }             vertex is connected to s
}
```

Depth-first search (in directed graphs)

Code for **directed** graphs identical to undirected one.

```
public class DirectedDFS
{
    private boolean[] marked;           ← true if path from s

    public DirectedDFS(Digraph G, int s)
    {
        marked = new boolean[G.V()];
        dfs(G, s);
    }

    private void dfs(Digraph G, int v)
    {
        marked[v] = true;               ← recursive DFS does the work
        for (int w : G.adj(v))
            if (!marked[w]) dfs(G, w);
    }

    public boolean visited(int v)
    { return marked[v]; }             ← client can ask whether any
                                    vertex is reachable from s
    }
```

Reachability application: program control-flow analysis

Every program is a digraph.

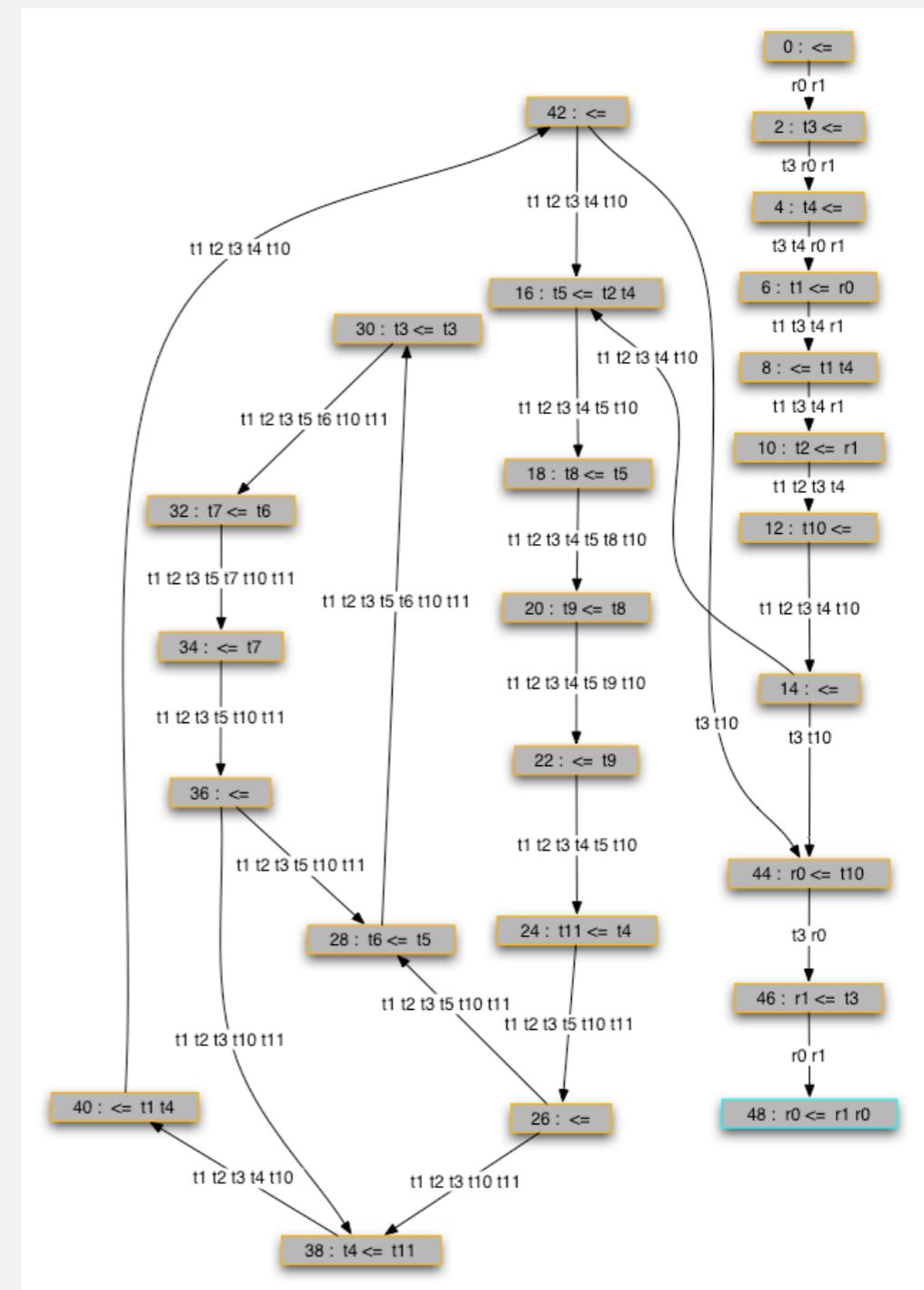
- Vertex = basic block of instructions (straight-line program).
 - Edge = jump.

Dead-code elimination.

Find (and remove) unreachable code.

Infinite-loop detection.

Determine whether exit is unreachable.



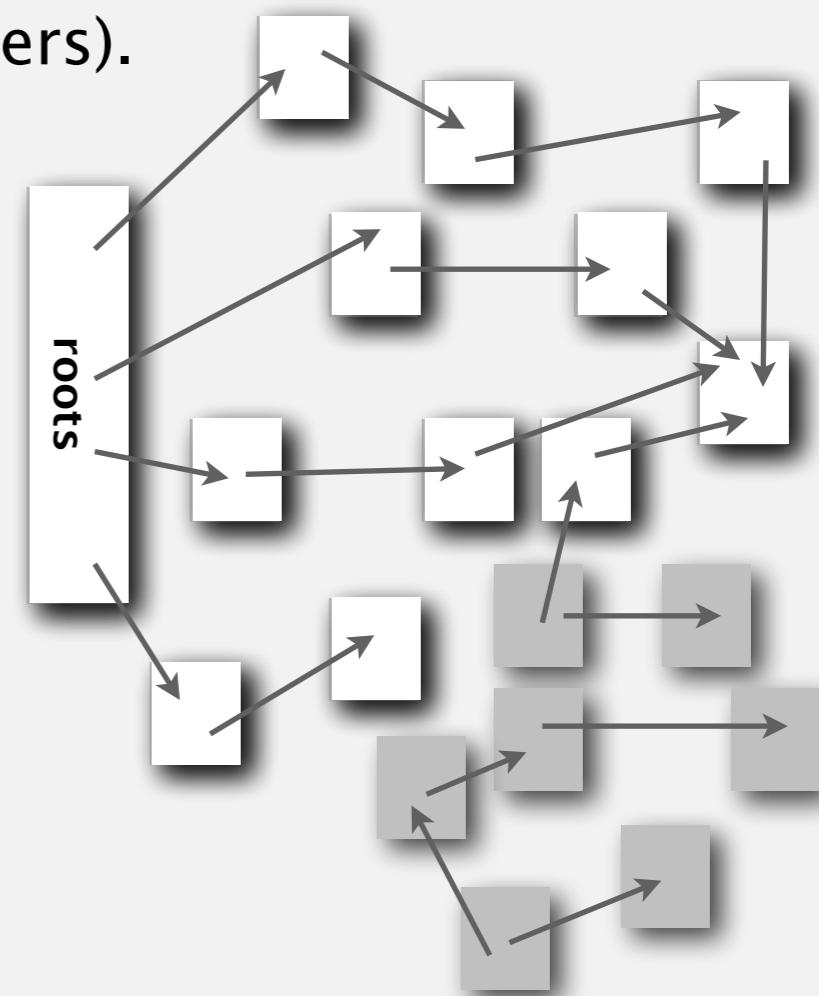
Reachability application: mark-sweep garbage collector

Every data structure is a digraph.

- Vertex = object.
 - Edge = reference.

Roots. Objects known to be directly accessible by program (e.g., stack).

Reachable objects. Objects indirectly accessible by program
(starting at a root and following a chain of pointers).

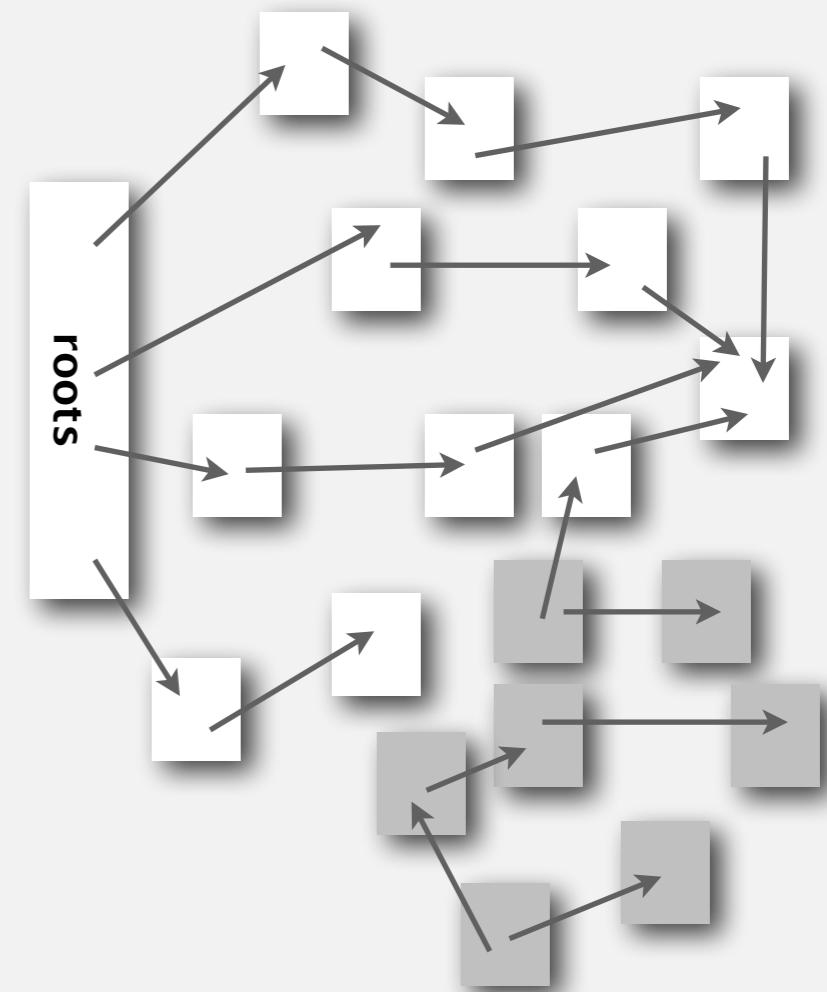


Reachability application: mark-sweep garbage collector

Mark-sweep algorithm. [McCarthy, 1960]

- Mark: mark all reachable objects.
- Sweep: if object is unmarked, it is garbage (so add to free list).

Memory cost. Uses 1 extra mark bit per object (plus DFS stack).



Depth-first search in digraphs summary

DFS enables direct solution of simple digraph problems.

- ✓ • Reachability.
- Path finding.
- Topological sort.
- Directed cycle detection.

Basis for solving difficult digraph problems.

- 2-satisfiability.
- Directed Euler path.
- Strongly-connected components.

SIAM J. COMPUT.
Vol. 1, No. 2, June 1972

DEPTH-FIRST SEARCH AND LINEAR GRAPH ALGORITHMS*

ROBERT TARJAN†

Abstract. The value of depth-first search or “backtracking” as a technique for solving problems is illustrated by two examples. An improved version of an algorithm for finding the strongly connected components of a directed graph and an algorithm for finding the biconnected components of an undirected graph are presented. The space and time requirements of both algorithms are bounded by $k_1 V + k_2 E + k_3$ for some constants k_1, k_2 , and k_3 , where V is the number of vertices and E is the number of edges of the graph being examined.

Breadth-first search in digraphs

Same method as for undirected graphs.

- Every undirected graph is a digraph (with edges in both directions).
- BFS is a **digraph** algorithm.

BFS (from source vertex s)

Put s onto a FIFO queue, and mark s as visited.

Repeat until the queue is empty:

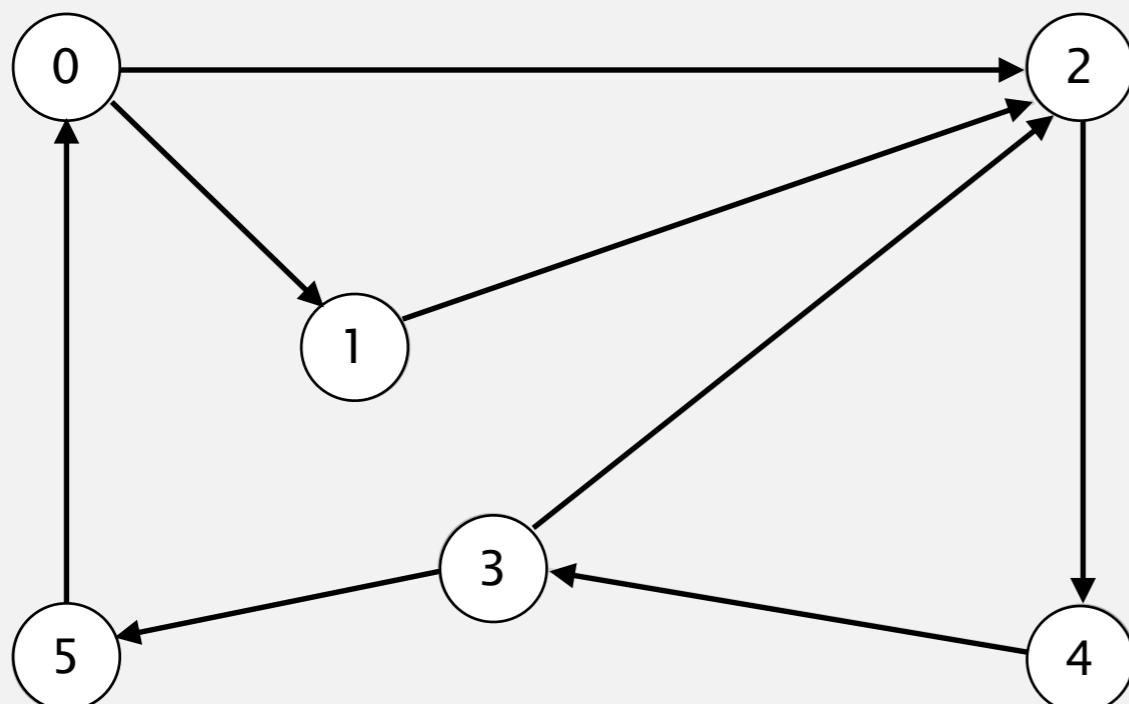
- **remove the least recently added vertex v**
- **for each unmarked vertex pointing from v :**
 - add to queue and mark as visited.**

Proposition. BFS computes shortest paths (fewest number of edges) from s to all other vertices in a digraph in time proportional to $E + V$.

Directed breadth-first search demo

Repeat until queue is empty:

- Remove vertex v from queue.
- Add to queue all unmarked vertices pointing from v and mark them.



tinyDG2.txt

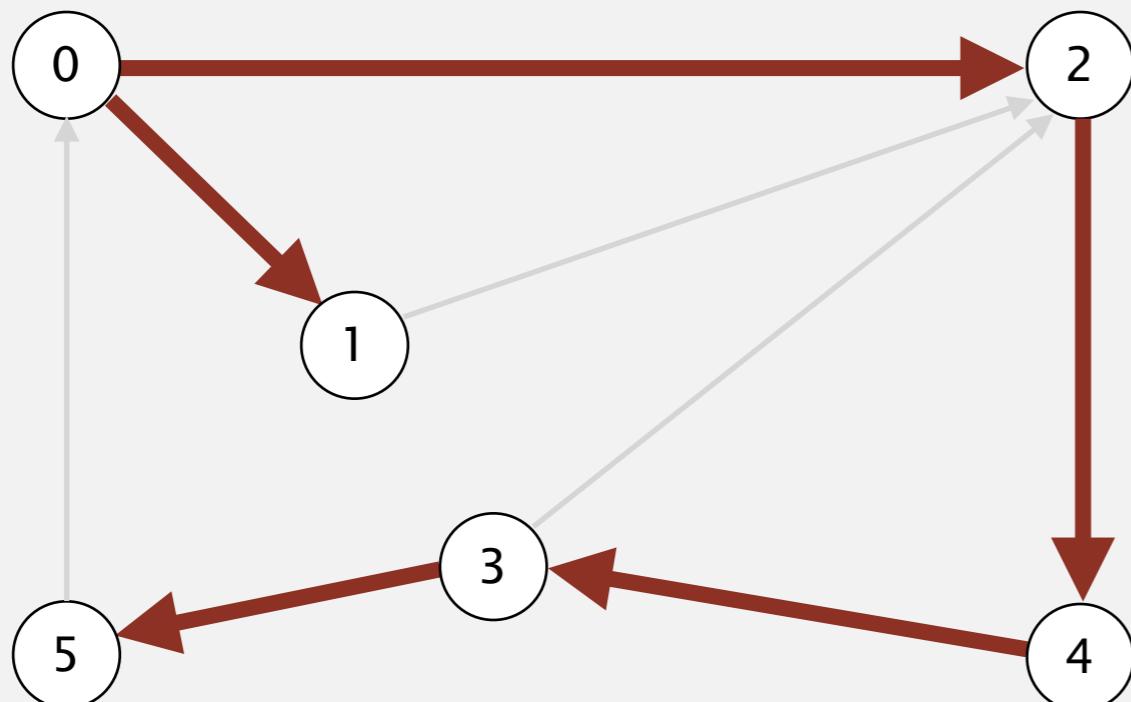
V → 6
E → 8
5 0
2 4
3 2
1 2
0 1
4 3
3 5
0 2

graph G

Directed breadth-first search demo

Repeat until queue is empty:

- Remove vertex v from queue.
- Add to queue all unmarked vertices pointing from v and mark them.



v	edgeTo[]	distTo[]
0	-	0
1	0	1
2	0	1
3	4	3
4	2	2
5	3	4

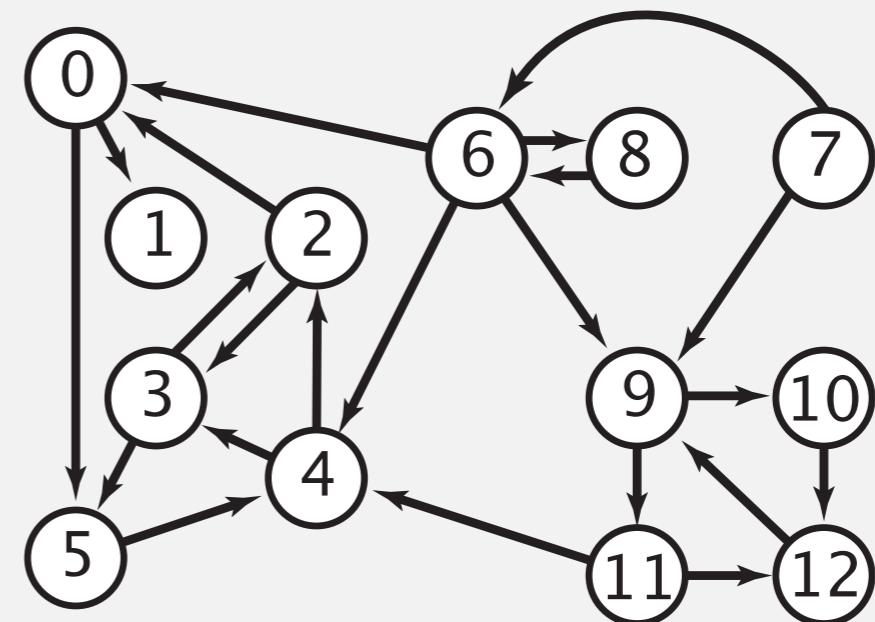
done

Multiple-source shortest paths

Multiple-source shortest paths. Given a digraph and a **set** of source vertices, find shortest path from any vertex in the set to each other vertex.

Ex. $S = \{ 1, 7, 10 \}$.

- Shortest path to 4 is $7 \rightarrow 6 \rightarrow 4$.
- Shortest path to 5 is $7 \rightarrow 6 \rightarrow 0 \rightarrow 5$.
- Shortest path to 12 is $10 \rightarrow 12$.
- ...



Q. How to implement multi-source shortest paths algorithm?

A. Use BFS, but initialize by enqueueing all source vertices.

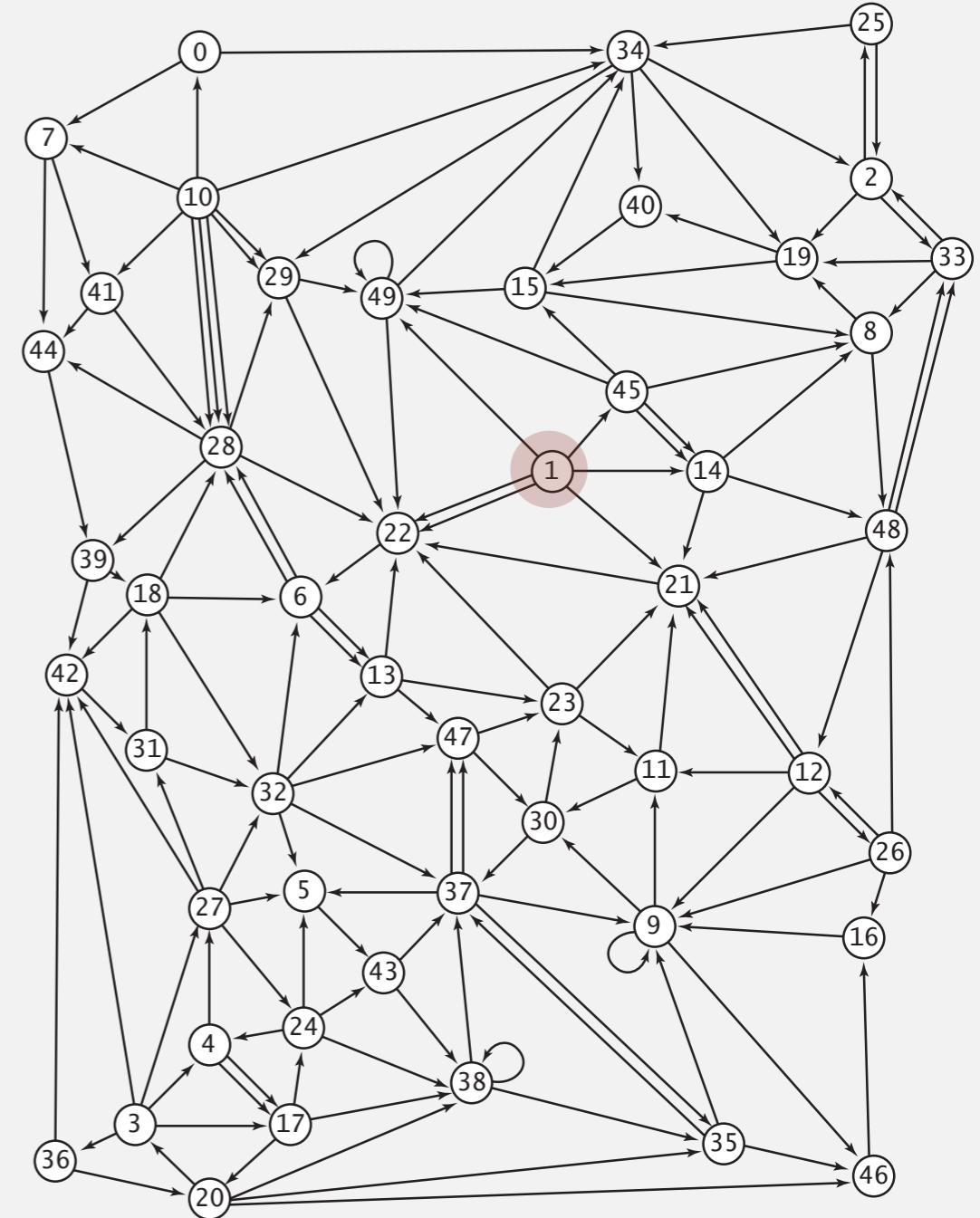
Breadth-first search in digraphs application: web crawler

Goal. Crawl web, starting from some root web page, say www.princeton.edu.

Solution. [BFS with implicit digraph]

- Choose root web page as source s .
- Maintain a Queue of websites to explore.
- Maintain a SET of discovered websites.
- Dequeue the next website and enqueue websites to which it links
(provided you haven't done so before).

Q. Why not use DFS?



Bare-bones web crawler: Java implementation

```
Queue<String> queue = new Queue<String>();           ← queue of websites to crawl
SET<String> marked = new SET<String>();             ← set of marked websites

String root = "http://www.princeton.edu";
queue.enqueue(root);
marked.add(root);                                     ← start crawling from root website

while (!queue.isEmpty())
{
    String v = queue.dequeue();
    StdOut.println(v);
    In in = new In(v);
    String input = in.readAll();                         ← read in raw html from next
                                                          website in queue

    String regexp = "http://(\w+\.\w+)+(\w+)";          ← use regular expression to find all URLs
    Pattern pattern = Pattern.compile(regexp);
    Matcher matcher = pattern.matcher(input);
    while (matcher.find())
    {
        String w = matcher.group();
        if (!marked.contains(w))                         ← if unmarked, mark it and put
        {                                                 on the queue
            marked.add(w);
            queue.enqueue(w);
        }
    }
}
```

Web crawler output

BFS crawl

<http://www.princeton.edu>
<http://www.w3.org>
<http://ogp.me>
<http://giving.princeton.edu>
<http://www.princetonartmuseum.org>
<http://www.goprinctontigers.com>
<http://library.princeton.edu>
<http://helpdesk.princeton.edu>
<http://tigernet.princeton.edu>
<http://alumni.princeton.edu>
<http://gradschool.princeton.edu>
<http://vimeo.com>
<http://princetonusg.com>
<http://artmuseum.princeton.edu>
<http://jobs.princeton.edu>
<http://odoc.princeton.edu>
<http://blogs.princeton.edu>
<http://www.facebook.com>
<http://twitter.com>
<http://www.youtube.com>
<http://deimos.apple.com>
<http://qprize.org>
<http://en.wikipedia.org>
...

DFS crawl

<http://www.princeton.edu>
<http://deimos.apple.com>
<http://www.youtube.com>
<http://www.google.com>
<http://news.google.com>
<http://csi.gstatic.com>
<http://googlenewsblog.blogspot.com>
<http://labs.google.com>
<http://groups.google.com>
<http://img1.blogblog.com>
<http://feeds.feedburner.com>
<http://buttons.googlesyndication.com>
<http://fusion.google.com>
<http://insidesearch.blogspot.com>
<http://agoogleaday.com>
<http://static.googleusercontent.com>
<http://searchresearch1.blogspot.com>
<http://feedburner.google.com>
<http://www.dot.ca.gov>
<http://www.TahoeRoads.com>
<http://www.LakeTahoeTransit.com>
<http://www.laketahoe.com>
<http://ethel.tahoeguide.com>
...

Algorithms

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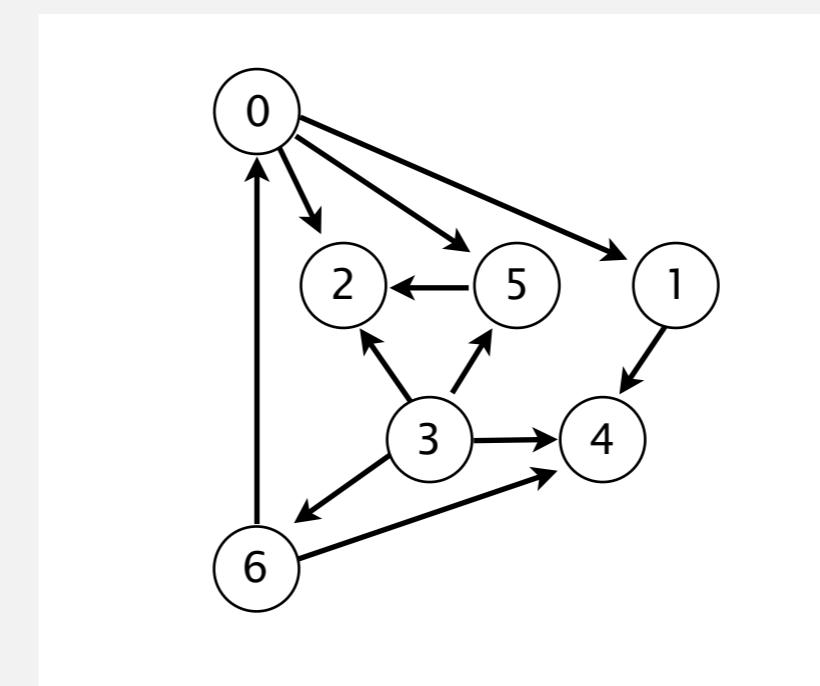
Precedence scheduling

Goal. Given a set of tasks to be completed with precedence constraints, in which order should we schedule the tasks?

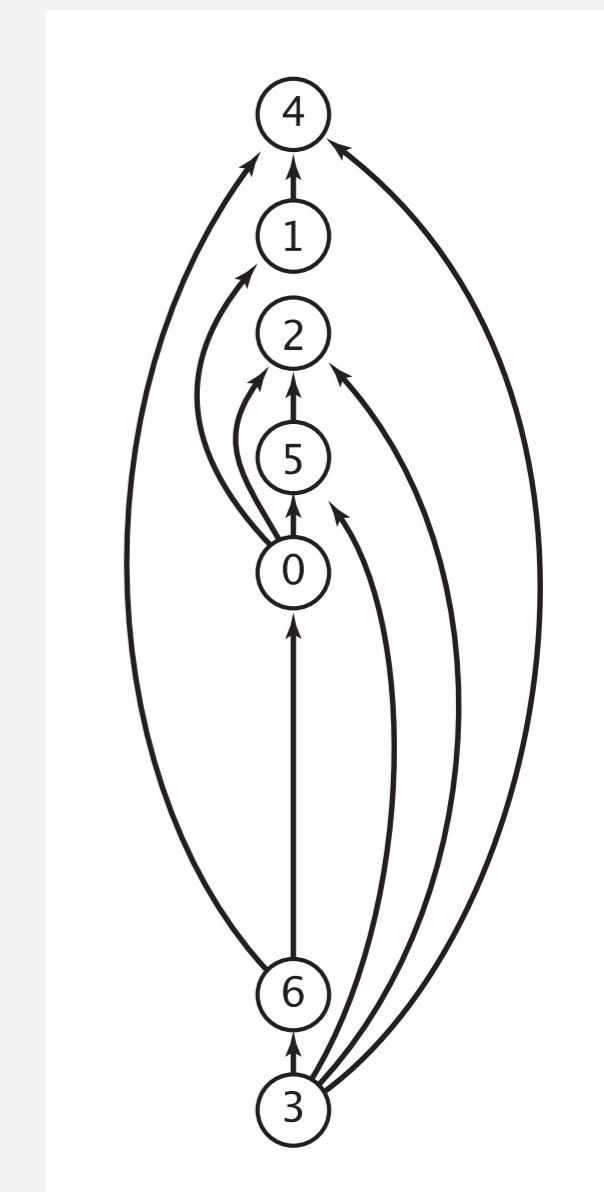
Digraph model. vertex = task; edge = precedence constraint.

- 0. Algorithms
- 1. Complexity Theory
- 2. Artificial Intelligence
- 3. Intro to CS
- 4. Cryptography
- 5. Scientific Computing

tasks



precedence constraint graph



feasible schedule

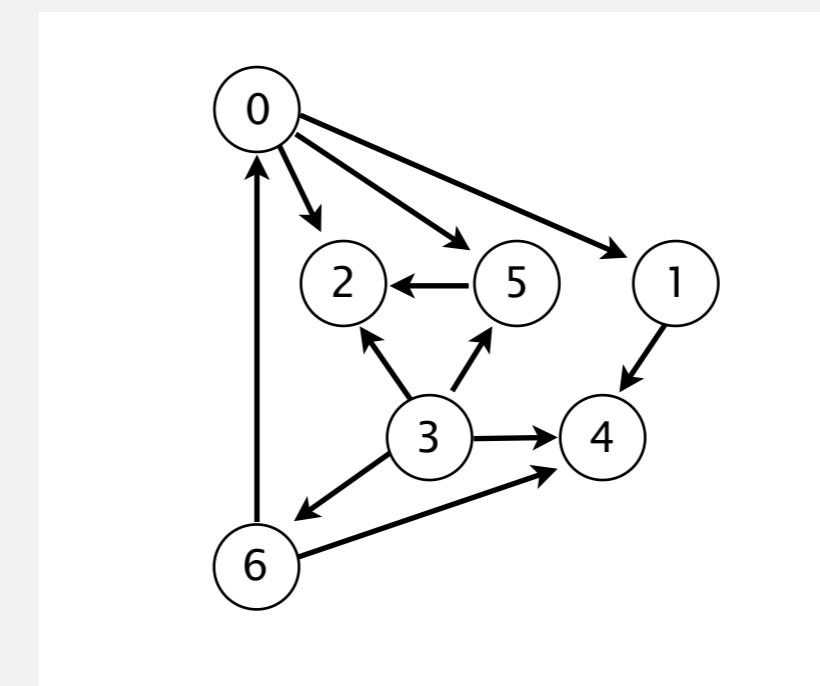
Topological sort

DAG. Directed acyclic graph.

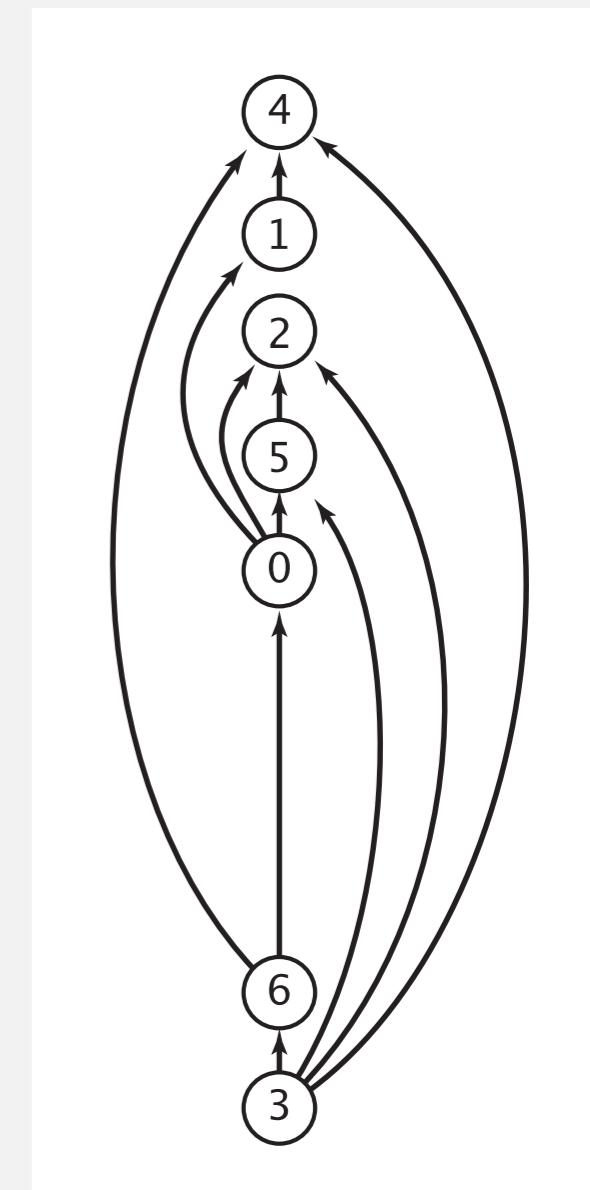
Topological sort. Redraw DAG so all edges point upwards.

$$\begin{array}{ll}
 0 \rightarrow 5 & 0 \rightarrow 2 \\
 0 \rightarrow 1 & 3 \rightarrow 6 \\
 3 \rightarrow 5 & 3 \rightarrow 4 \\
 5 \rightarrow 2 & 6 \rightarrow 4 \\
 6 \rightarrow 0 & 3 \rightarrow 2 \\
 1 \rightarrow 4 &
 \end{array}$$

directed edges



DAG

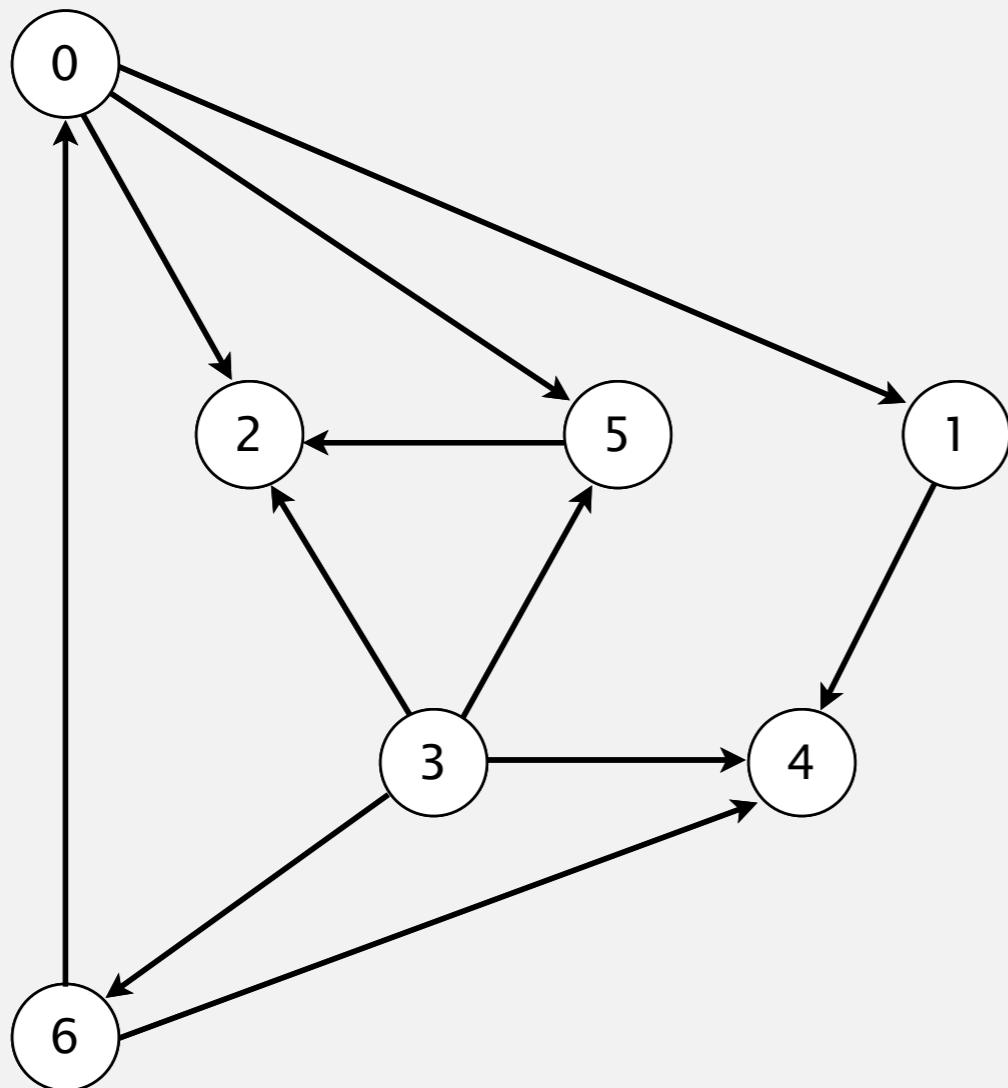


topological order

Solution. DFS. What else?

Topological sort demo

- Run depth-first search.
- Return vertices in reverse postorder.



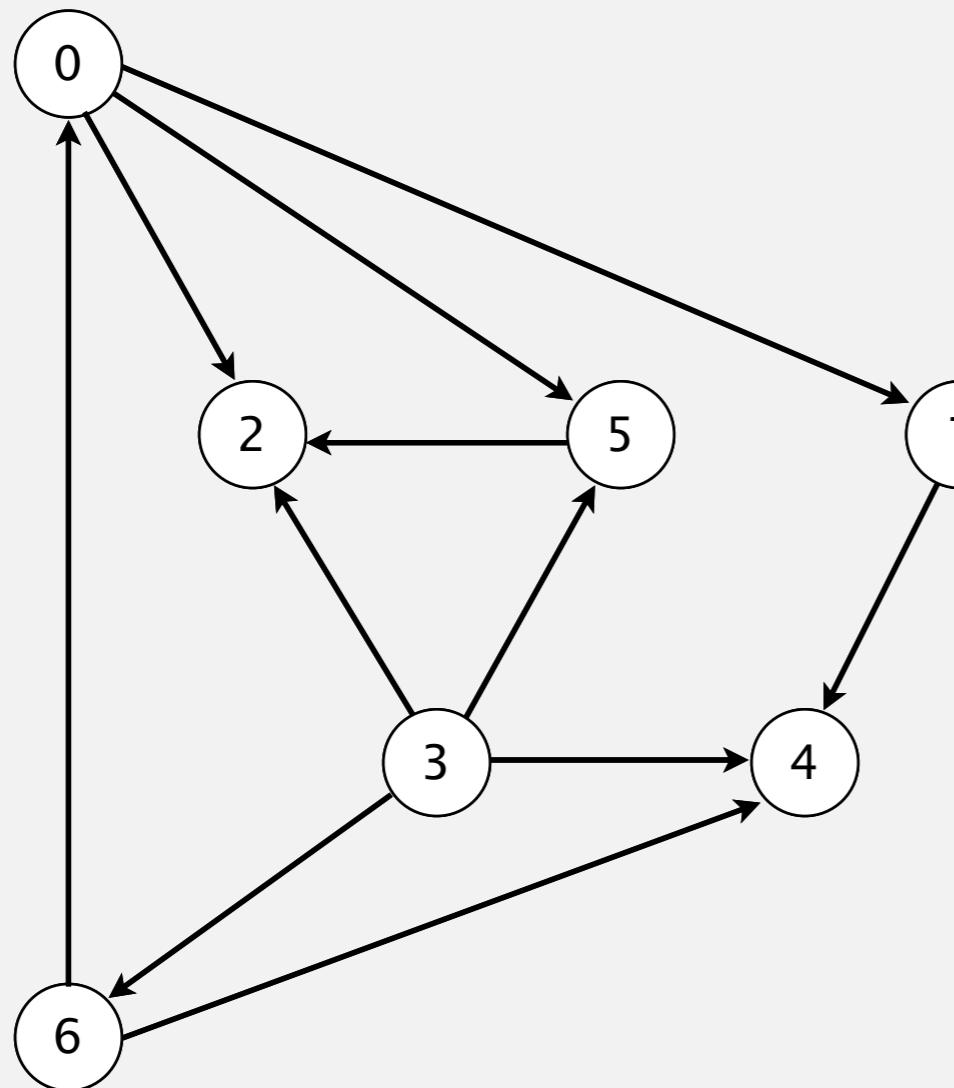
tinyDAG7.txt

7
11
0 5
0 2
0 1
3 6
3 5
3 4
5 2
6 4
6 0
3 2

a directed acyclic graph

Topological sort demo

- Run depth-first search.
- Return vertices in reverse postorder.



postorder

4 1 2 5 0 6 3

topological order

3 6 0 5 2 1 4

done

Depth-first search order

```
public class DepthFirstOrder
{
    private boolean[] marked;
    private Stack<Integer> reversePostorder;

    public DepthFirstOrder(Digraph G)
    {
        reversePostorder = new Stack<Integer>();
        marked = new boolean[G.V()];
        for (int v = 0; v < G.V(); v++)
            if (!marked[v]) dfs(G, v);
    }

    private void dfs(Digraph G, int v)
    {
        marked[v] = true;
        for (int w : G.adj(v))
            if (!marked[w]) dfs(G, w);
        reversePostorder.push(v);
    }

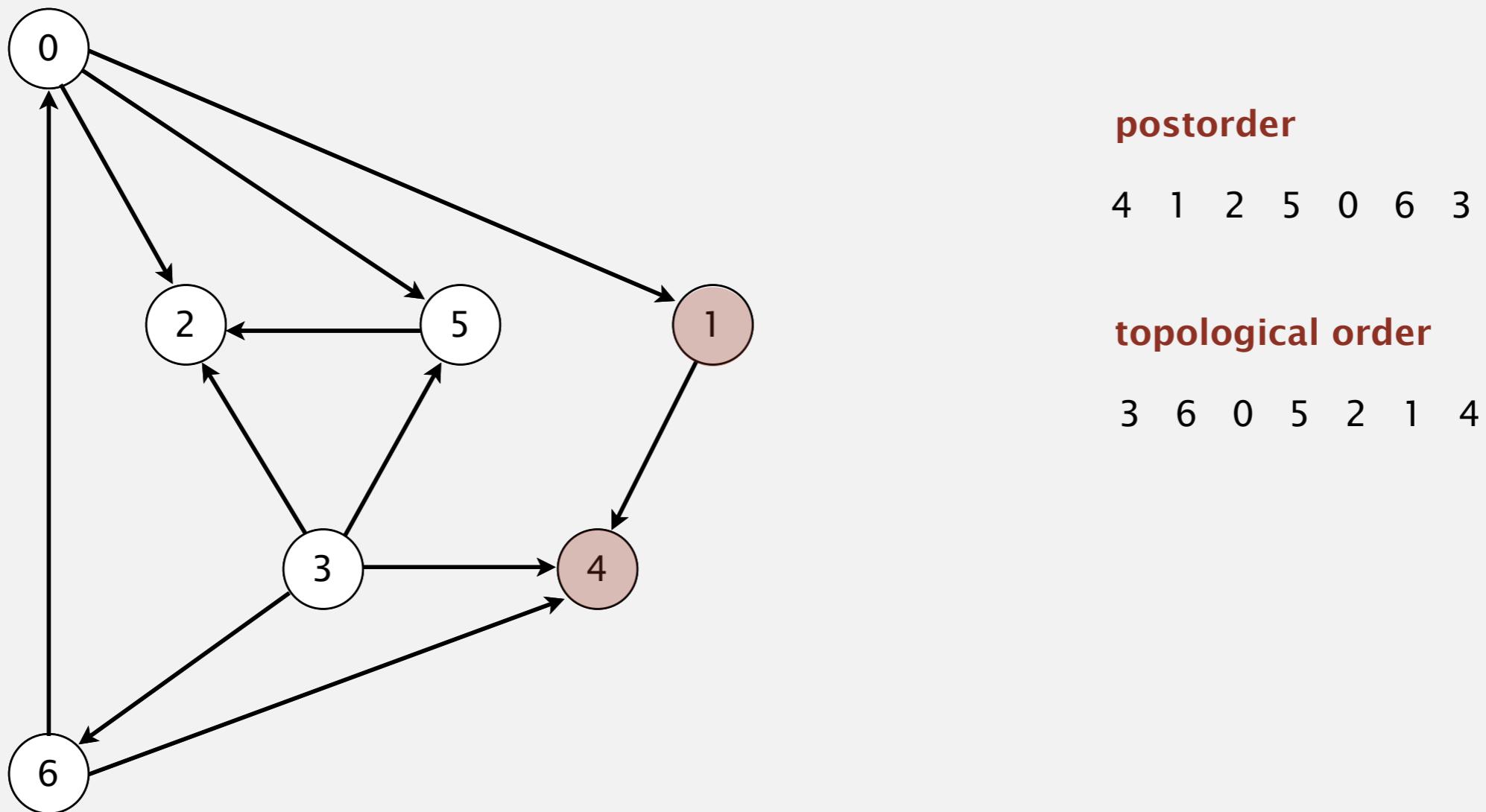
    public Iterable<Integer> reversePostorder()
    { return reversePostorder; }
}
```

returns all vertices in
“reverse DFS postorder”

Topological sort in a DAG: intuition

Why does topological sort algorithm work?

- First vertex in postorder has outdegree 0.
- Second-to-last vertex in postorder can only point to last vertex.
- ...



Topological sort in a DAG: correctness proof

Proposition. Reverse DFS postorder of a DAG is a topological order.

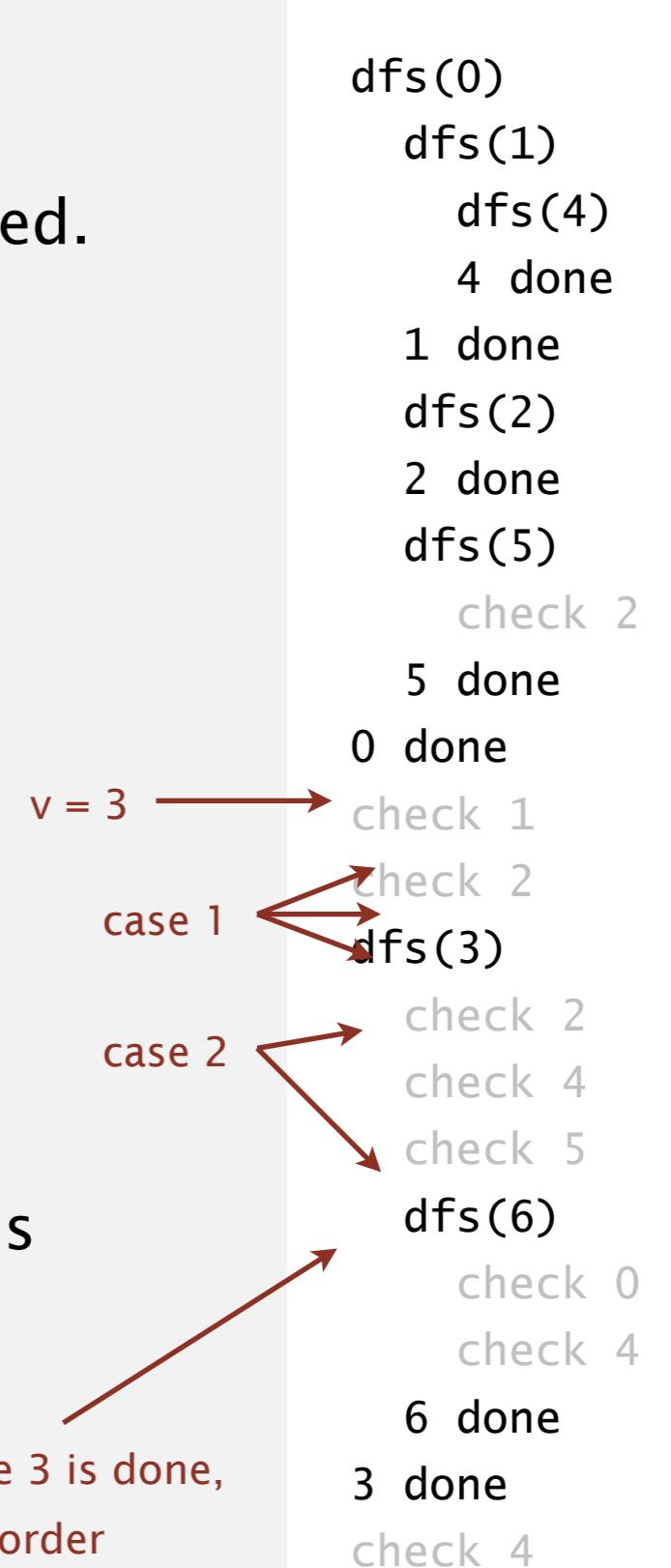
Pf. Consider any edge $v \rightarrow w$. When $\text{dfs}(v)$ is called:

- Case 1: $\text{dfs}(w)$ has already been called and returned.
Thus, w was done before v .

- Case 2: $\text{dfs}(w)$ has not yet been called.
 $\text{dfs}(w)$ will get called directly or indirectly
by $\text{dfs}(v)$ and will finish before $\text{dfs}(v)$.
Thus, w will be done before v .

- Case 3: $\text{dfs}(w)$ has already been called,
but has not yet returned.
Can't happen in a DAG: function call stack contains
path from w to v , so $v \rightarrow w$ would complete a cycle.

all vertices pointing from 3 are done before 3 is done,
so they appear after 3 in topological order

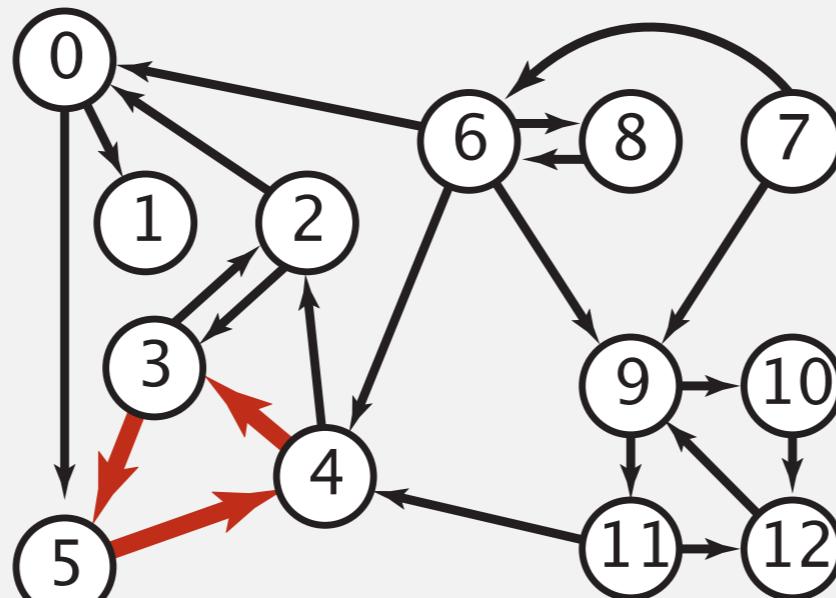


Directed cycle detection

Proposition. A digraph has a topological order iff no directed cycle.

Pf.

- If directed cycle, topological order impossible.
- If no directed cycle, DFS-based algorithm finds a topological order.



a digraph with a directed cycle

Goal. Given a digraph, find a directed cycle.

Solution. DFS. What else? See textbook.

Directed cycle detection application: precedence scheduling

Scheduling. Given a set of tasks to be completed with precedence constraints, in what order should we schedule the tasks?

PAGE 3

DEPARTMENT	COURSE	DESCRIPTION	PREREQS
COMPUTER SCIENCE	CPSC 432	INTERMEDIATE COMPILER DESIGN, WITH A FOCUS ON DEPENDENCY RESOLUTION.	CPSC 432

<http://xkcd.com/754>

Remark. A directed cycle implies scheduling problem is infeasible.

Directed cycle detection application: cyclic inheritance

The Java compiler does cycle detection.

```
public class A extends B
{
    ...
}
```

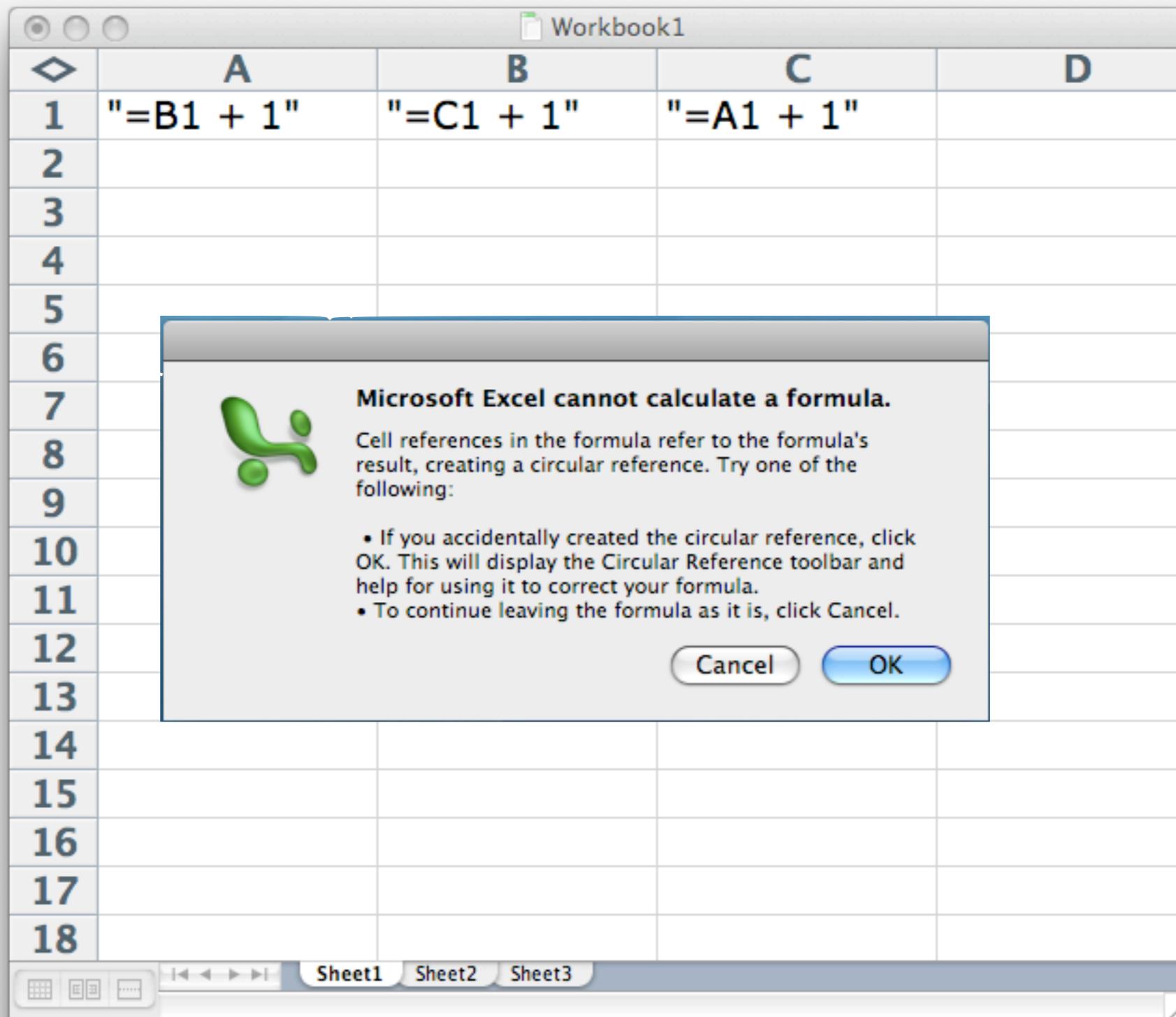
```
public class B extends C
{
    ...
}
```

```
public class C extends A
{
    ...
}
```

```
% javac A.java
A.java:1: cyclic inheritance
involving A
public class A extends B { }
^
1 error
```

Directed cycle detection application: spreadsheet recalculation

Microsoft Excel does cycle detection (and has a circular reference toolbar!)



Depth-first search orders

Observation. DFS visits each vertex exactly once. The order in which it does so can be important.

Orderings.

- Preorder: order in which `dfs()` is called.
- Postorder: order in which `dfs()` returns.
- Reverse postorder: reverse order in which `dfs()` returns.

```
private void dfs(Graph G, int v)
{
    marked[v] = true;
    preorder.enqueue(v);
    for (int w : G.adj(v))
        if (!marked[w]) dfs(G, w);
    postorder.enqueue(v);
    reversePostorder.push(v);
}
```

Algorithms

ROBERT SEDGEWICK | KEVIN WAYNE

<http://algs4.cs.princeton.edu>

4.2 DIRECTED GRAPHS

- ▶ *introduction*
- ▶ *digraph API*
- ▶ *digraph search*
- ▶ *topological sort*
- ▶ ***strong components***

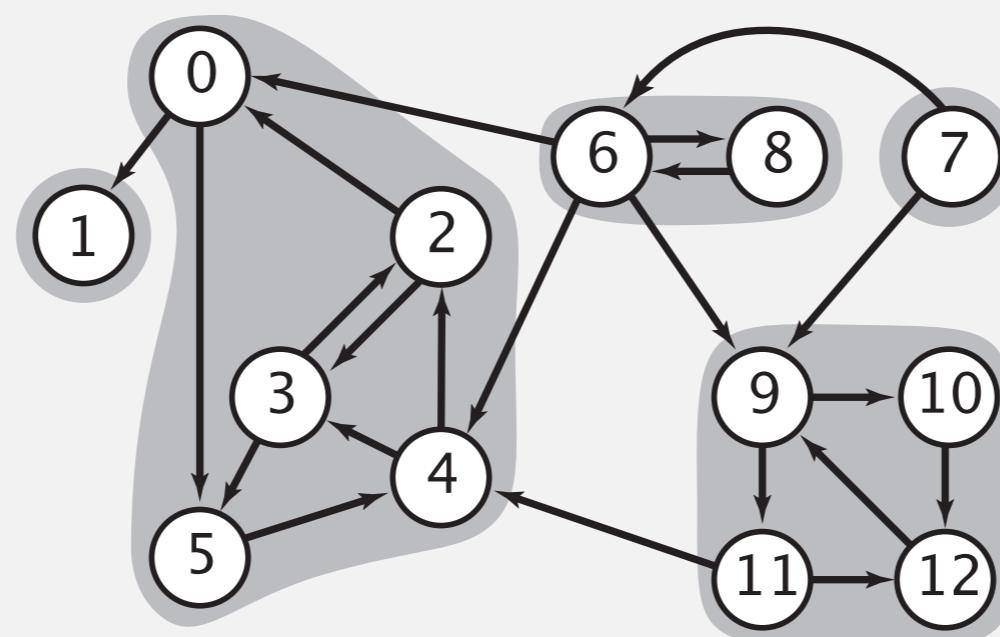
Strongly-connected components

Def. Vertices v and w are **strongly connected** if there is both a directed path from v to w **and** a directed path from w to v .

Key property. Strong connectivity is an **equivalence relation**:

- v is strongly connected to v .
- If v is strongly connected to w , then w is strongly connected to v .
- If v is strongly connected to w and w to x , then v is strongly connected to x .

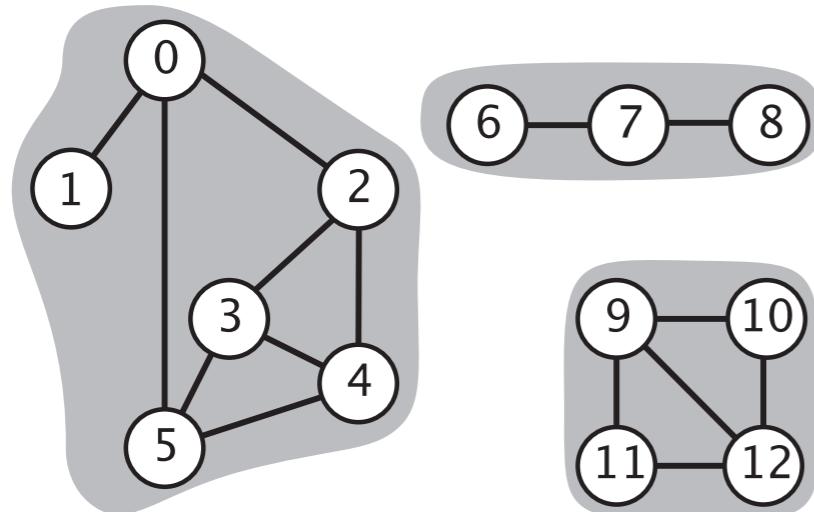
Def. A **strong component** is a maximal subset of strongly-connected vertices.



5 strongly-connected components

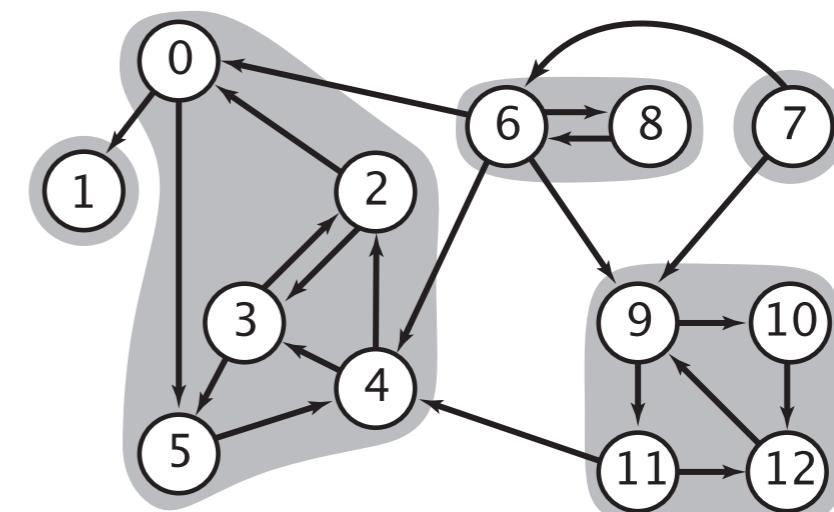
Connected components vs. strongly-connected components

v and w are **connected** if there is a path between v and w



3 connected components

v and w are **strongly connected** if there is both a directed path from v to w and a directed path from w to v



5 strongly-connected components

connected component id (easy to compute with DFS)

0	1	2	3	4	5	6	7	8	9	10	11	12
0	0	0	0	0	0	1	1	1	2	2	2	2

```
public boolean connected(int v, int w)
{ return id[v] == id[w]; }
```

constant-time client connectivity query

strongly-connected component id (how to compute?)

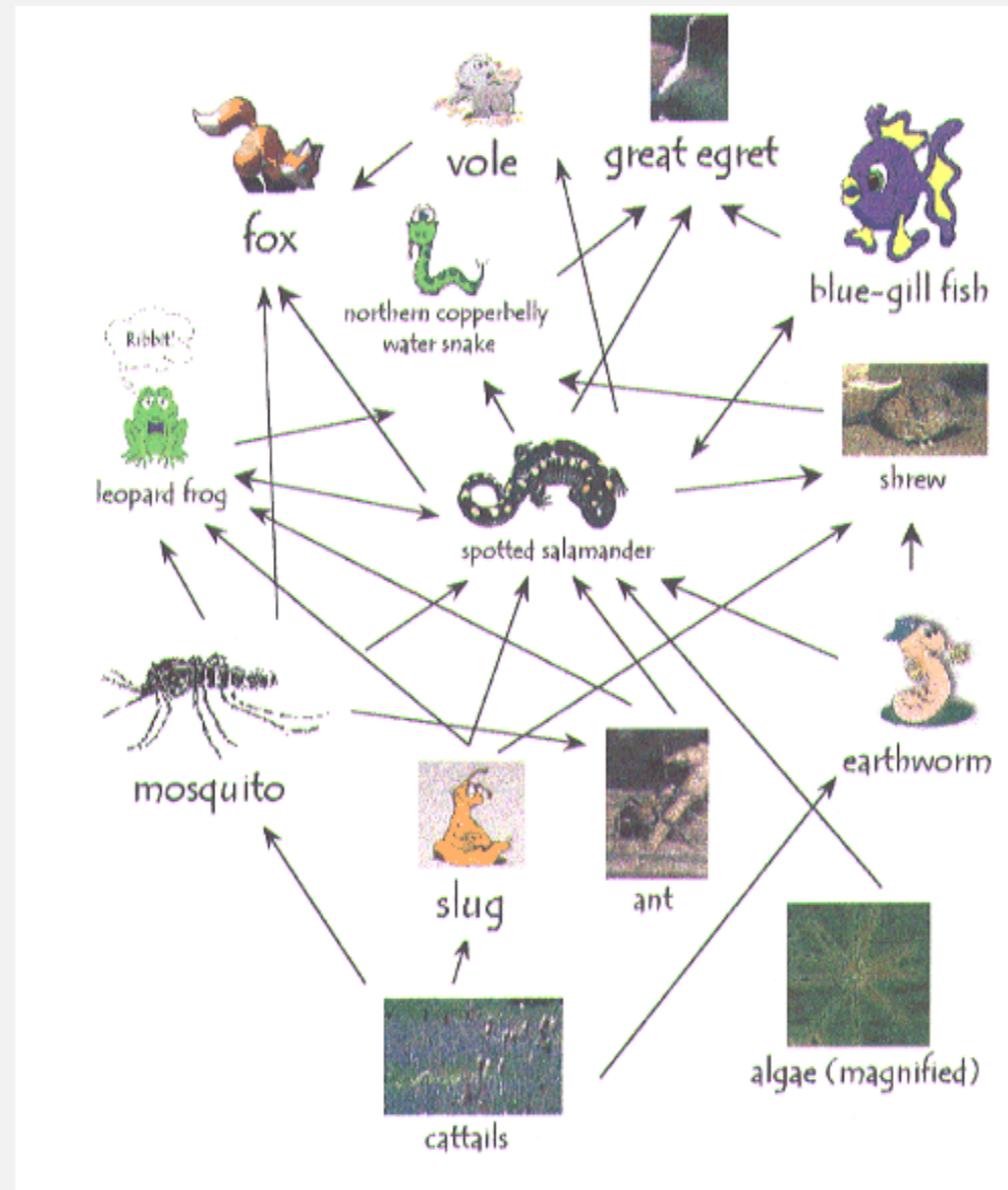
0	1	2	3	4	5	6	7	8	9	10	11	12
1	0	1	1	1	1	3	4	3	2	2	2	2

```
public boolean stronglyConnected(int v, int w)
{ return id[v] == id[w]; }
```

constant-time client strong-connectivity query

Strong component application: ecological food webs

Food web graph. Vertex = species; edge = from producer to consumer.



<http://www.twingroves.district96.k12.il.us/Wetlands/Salamander/SalGraphics/salfoodweb.gif>

Strong component. Subset of species with common energy flow.

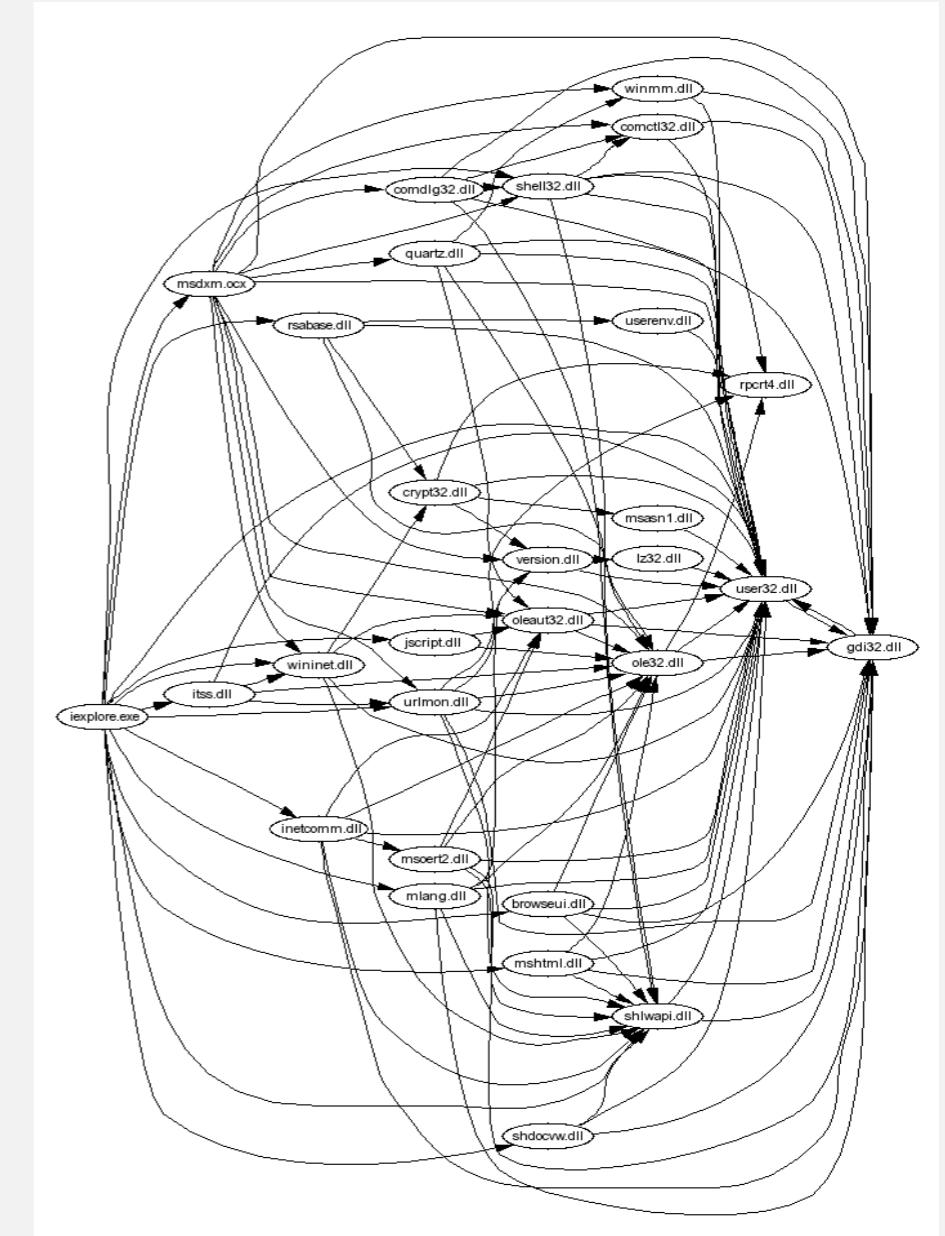
Strong component application: software modules

Software module dependency graph.

- Vertex = software module.
 - Edge: from module to dependency.



Firefox



Internet Explorer

Strong component. Subset of mutually interacting modules.

Approach 1. Package strong components together.

Approach 2. Use to improve design!

Strong components algorithms: brief history

1960s: Core OR problem.

- Widely studied; some practical algorithms.
- Complexity not understood.

1972: linear-time DFS algorithm (Tarjan).

- Classic algorithm.
- Level of difficulty: Algs4++.
- Demonstrated broad applicability and importance of DFS.

1980s: easy two-pass linear-time algorithm (Kosaraju-Sharir).

- Forgot notes for lecture; developed algorithm in order to teach it!
- Later found in Russian scientific literature (1972).

1990s: more easy linear-time algorithms.

- Gabow: fixed old OR algorithm.
- Cheriyan-Mehlhorn: needed one-pass algorithm for LEDA.

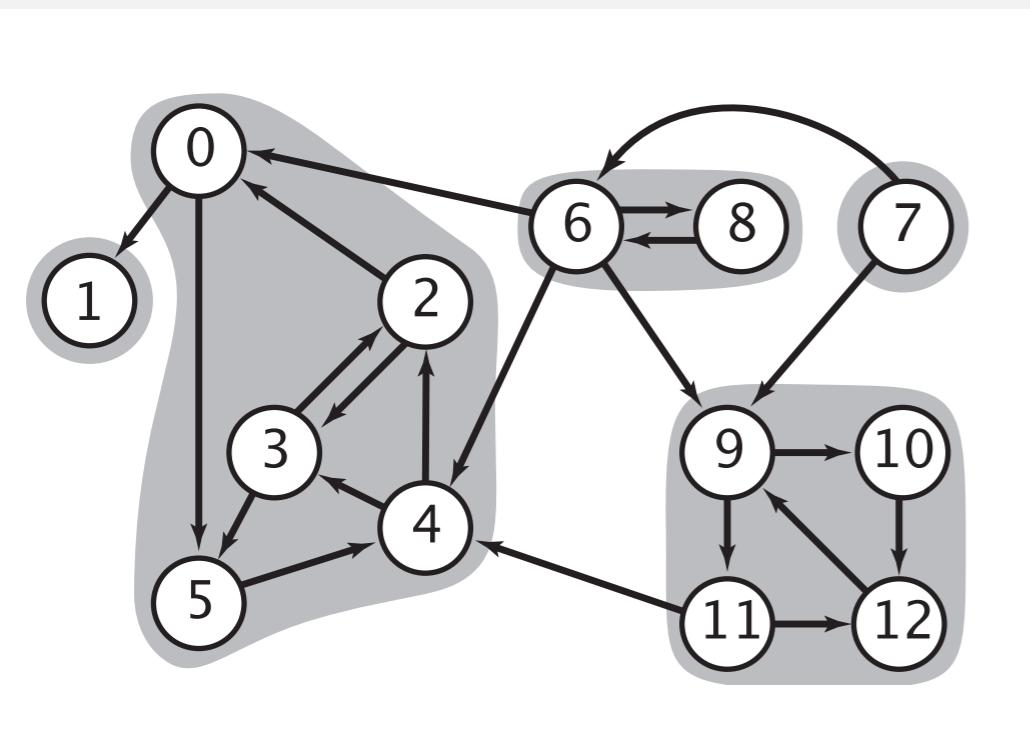
Kosaraju-Sharir algorithm: intuition

Reverse graph. Strong components in G are same as in G^R .

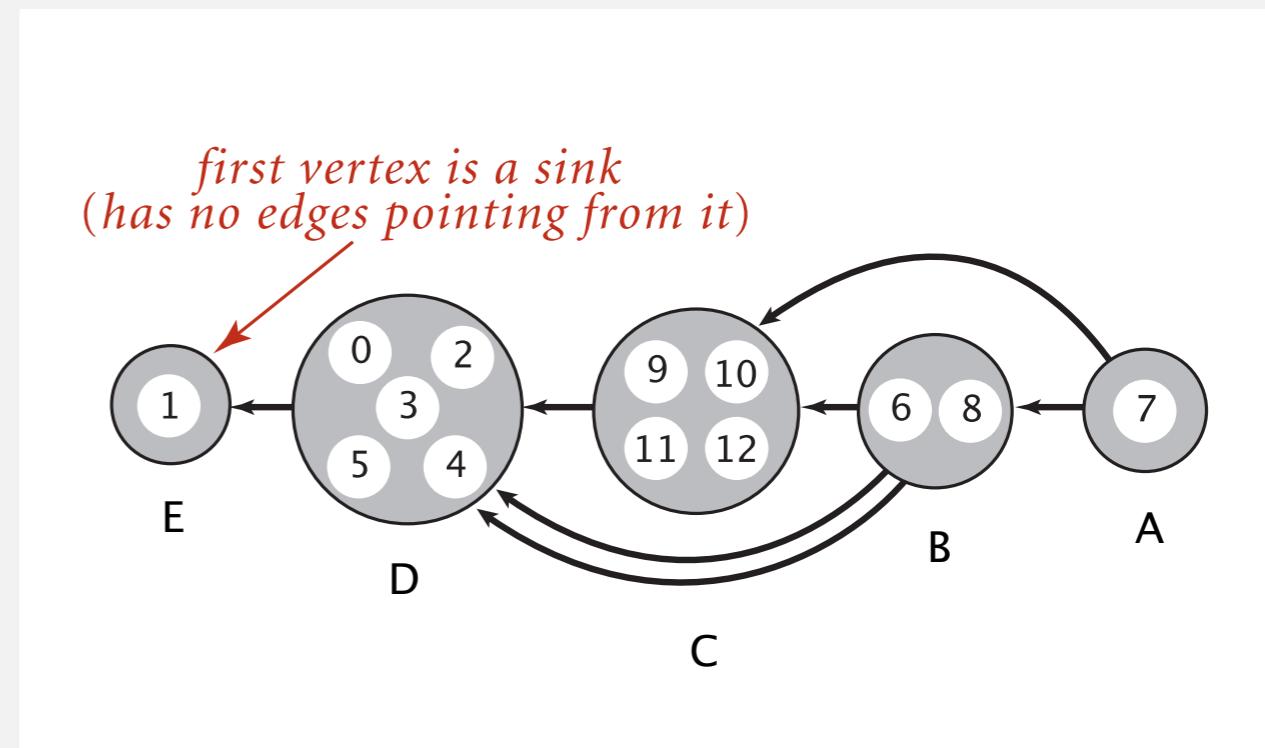
Kernel DAG. Contract each strong component into a single vertex.

Idea.

- Compute topological order (reverse postorder) in kernel DAG.
- Run DFS, considering vertices in reverse topological order.



digraph G and its strong components

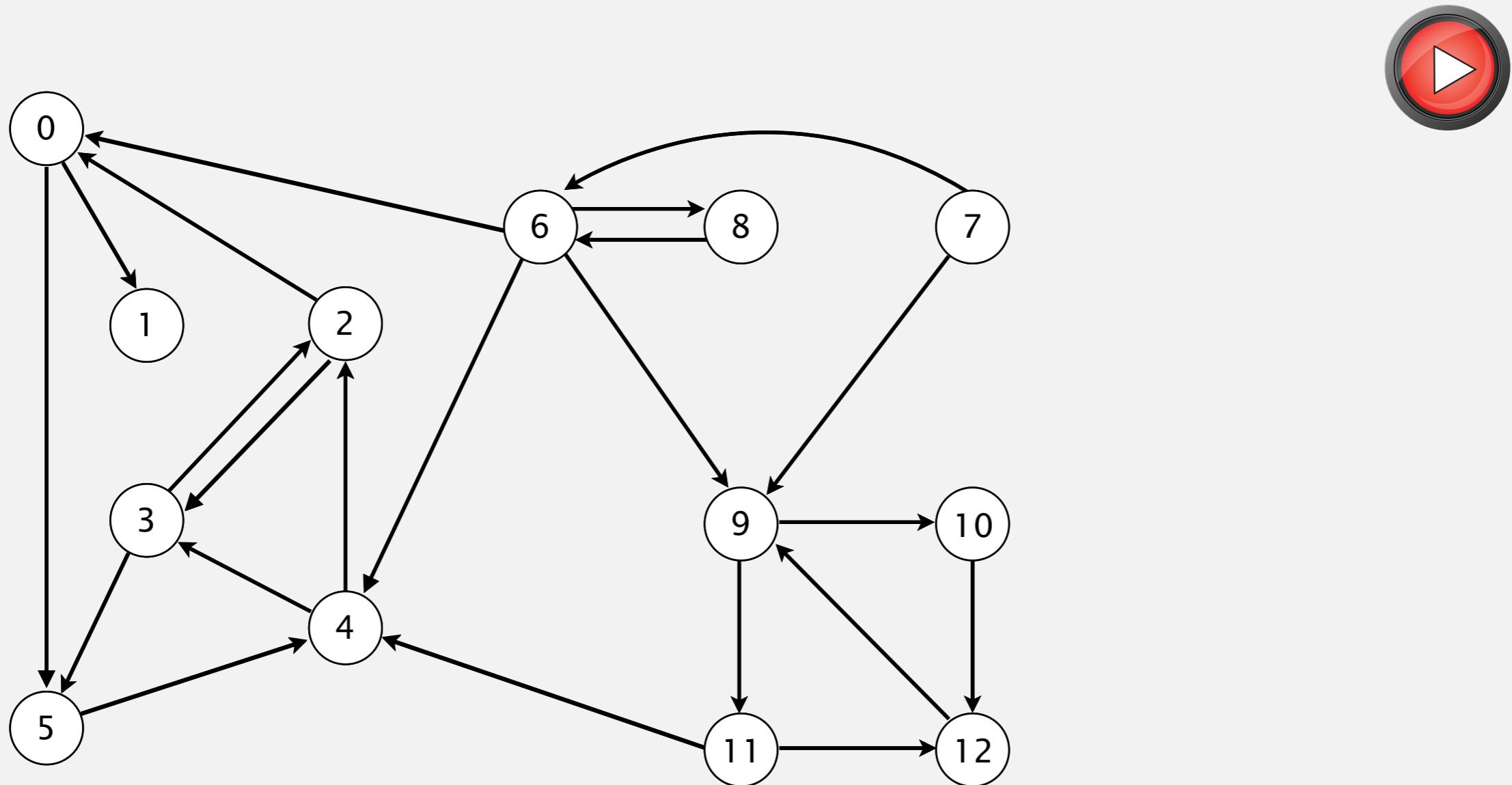


kernel DAG of G (topological order: A B C D E)

Kosaraju-Sharir algorithm demo

Phase 1. Compute reverse postorder in G^R .

Phase 2. Run DFS in G , visiting unmarked vertices in reverse postorder of G^R .

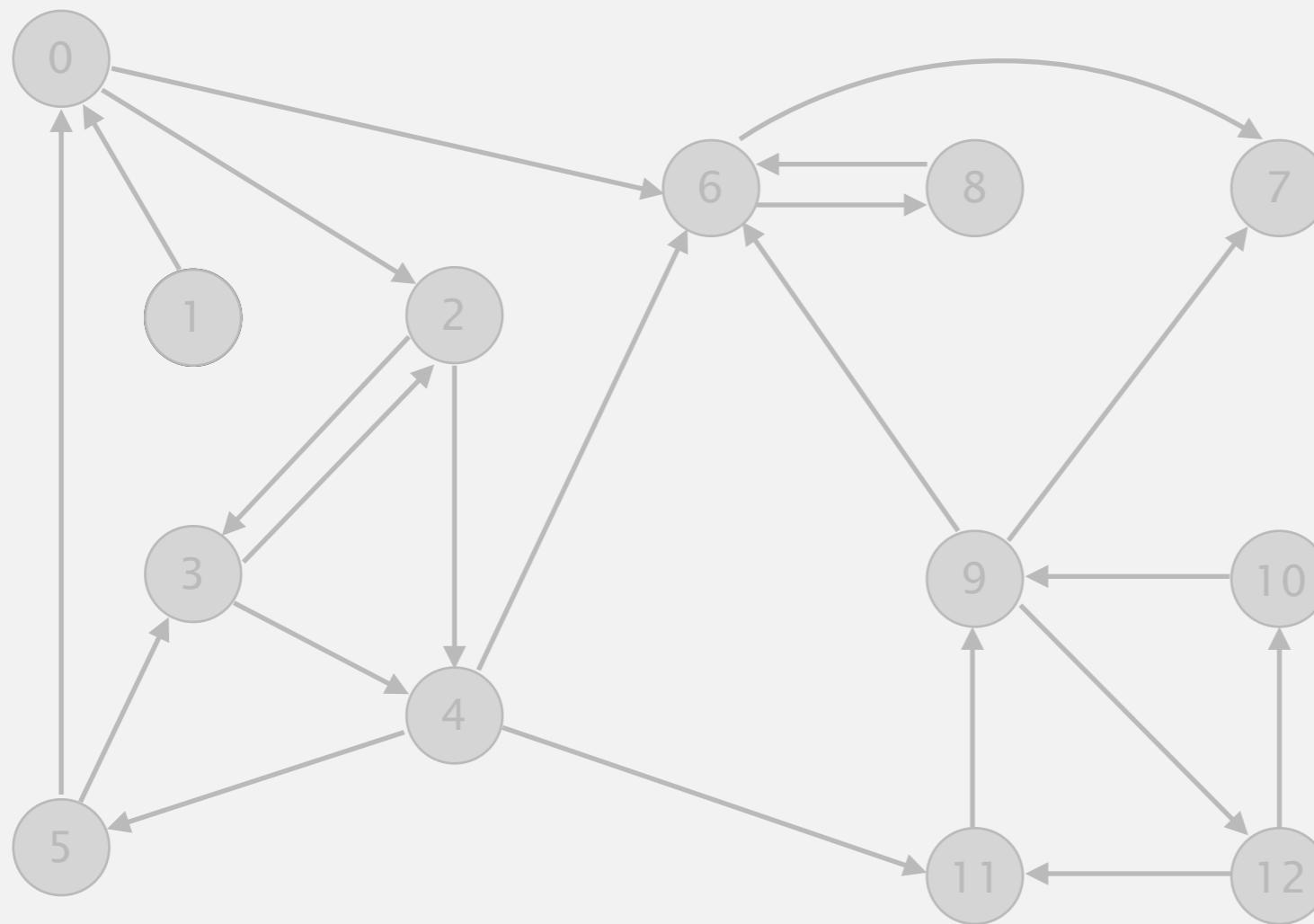


digraph G

Kosaraju-Sharir algorithm demo

Phase 1. Compute reverse postorder in G^R .

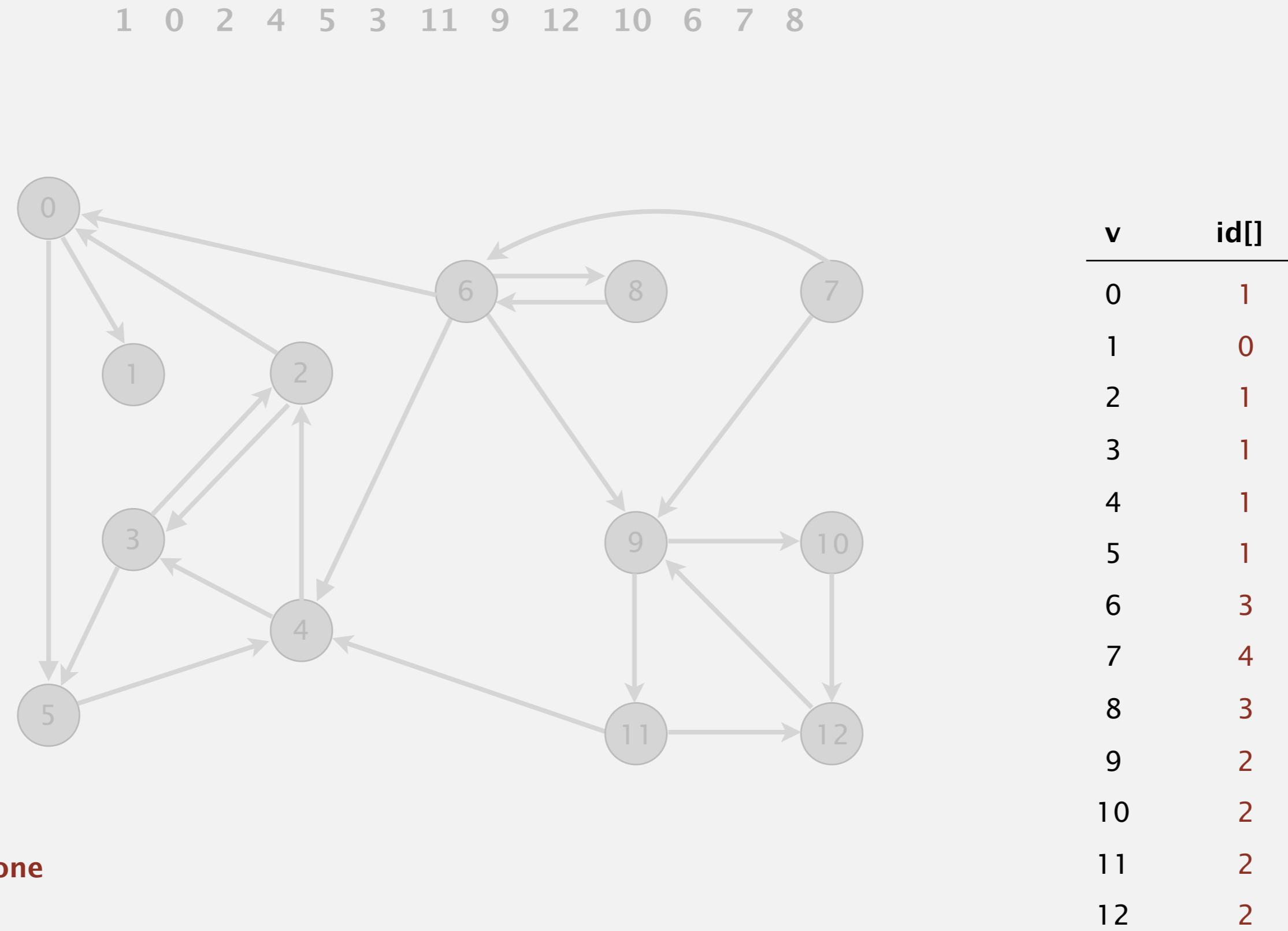
1 0 2 4 5 3 11 9 12 10 6 7 8



reverse digraph G^R

Kosaraju-Sharir algorithm demo

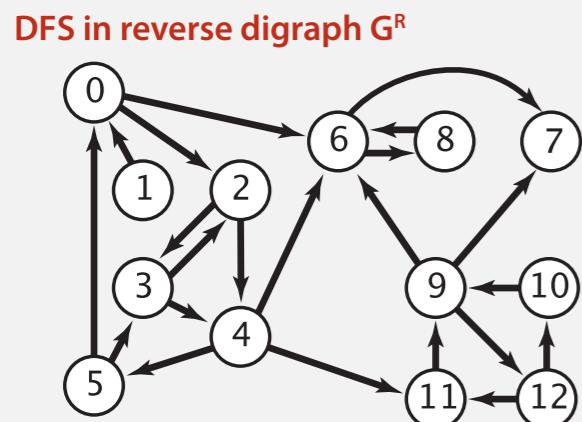
Phase 2. Run DFS in G , visiting unmarked vertices in reverse postorder of G^R .



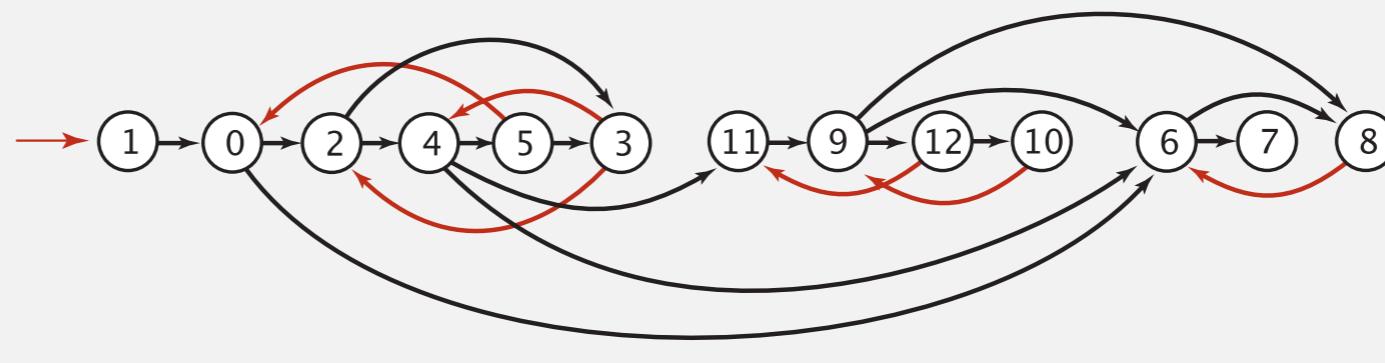
Kosaraju-Sharir algorithm

Simple (but mysterious) algorithm for computing strong components.

- Phase 1: run DFS on G^R to compute reverse postorder.
- Phase 2: run DFS on G , considering vertices in order given by first DFS.



check unmarked vertices in the order
0 1 2 3 4 5 6 7 8 9 10 11 12



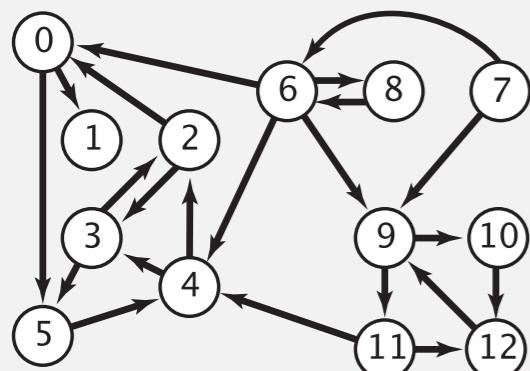
```
dfs(0)
  dfs(6)
    dfs(8)
      | check 6
      8 done
      dfs(7)
        7 done
      6 done
      dfs(2)
        dfs(4)
          dfs(11)
            dfs(9)
              dfs(12)
                | check 11
                dfs(10)
                  | check 9
                  10 done
                12 done
                check 7
                check 6
  ...
  ...
```

Kosaraju-Sharir algorithm

Simple (but mysterious) algorithm for computing strong components.

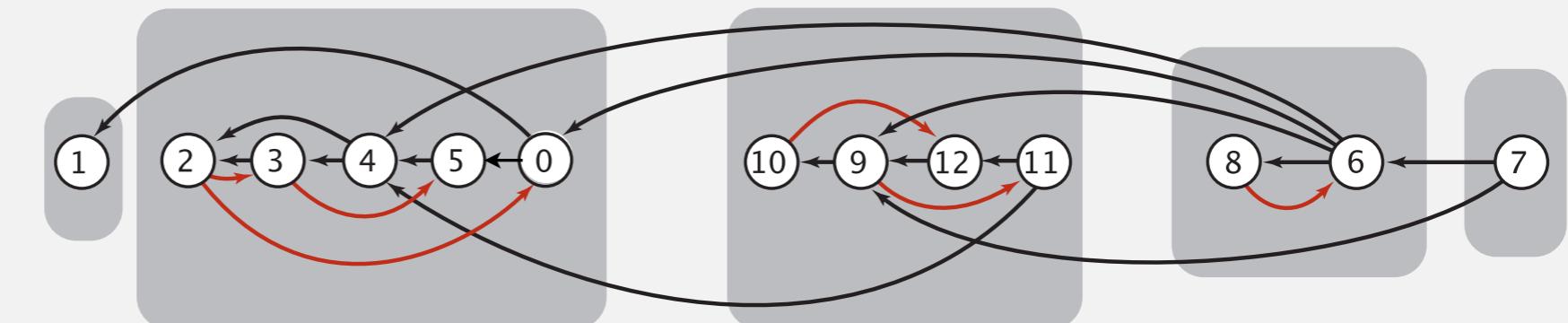
- Phase 1: run DFS on G^R to compute reverse postorder.
- Phase 2: run DFS on G , considering vertices in order given by first DFS.

DFS in original digraph G



check unmarked vertices in the order

1 0 2 4 5 3 11 9 12 10 6 7 8
 ↑↑ ↑ ↑↑



dfs(1)
1 done

dfs(0)
dfs(5)
dfs(4)
dfs(3)
check 5
dfs(2)
check 0
check 3
2 done
3 done
check 2
4 done
5 done
check 1
0 done
check 2
check 4
check 5
check 3

dfs(11)
check 4
dfs(12)
dfs(9)
check 11
dfs(10)
check 12
10 done
9 done
12 done
11 done
check 9
check 12
check 10

dfs(6)
check 9
check 4
dfs(8)
check 6
8 done
check 0
6 done

dfs(7)
check 6
check 9
7 done
check 8

Kosaraju-Sharir algorithm

Proposition. Kosaraju-Sharir algorithm computes the strong components of a digraph in time proportional to $E + V$.

Pf.

- Running time: bottleneck is running DFS twice (and computing G^R).
- Correctness: tricky, see textbook (2nd printing).
- Implementation: easy!

Connected components in an undirected araph (with DFS)

```
public class CC
{
    private boolean marked[];
    private int[] id;
    private int count;

    public CC(Graph G)
    {
        marked = new boolean[G.V()];
        id = new int[G.V()];

        for (int v = 0; v < G.V(); v++)
        {
            if (!marked[v])
            {
                dfs(G, v);
                count++;
            }
        }
    }

    private void dfs(Graph G, int v)
    {
        marked[v] = true;
        id[v] = count;
        for (int w : G.adj(v))
            if (!marked[w])
                dfs(G, w);
    }

    public boolean connected(int v, int w)
    { return id[v] == id[w]; }
}
```

Strong components in a diagraph (with two DFSs)

```
public class KosarajuSharirSCC
{
    private boolean marked[];
    private int[] id;
    private int count;

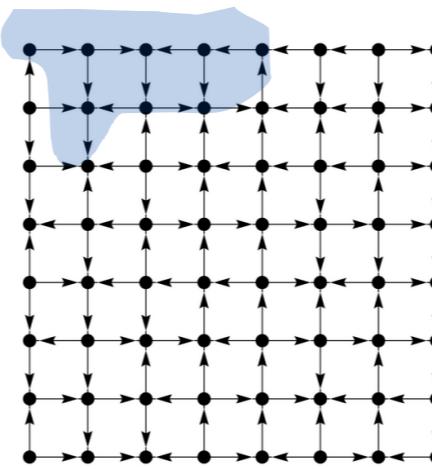
    public KosarajuSharirSCC(Digraph G)
    {
        marked = new boolean[G.V()];
        id = new int[G.V()];
        DepthFirstOrder dfs = new DepthFirstOrder(G.reverse());
        for (int v : dfs.reversePostorder())
        {
            if (!marked[v])
            {
                dfs(G, v);
                count++;
            }
        }
    }

    private void dfs(Digraph G, int v)
    {
        marked[v] = true;
        id[v] = count;
        for (int w : G.adj(v))
            if (!marked[w])
                dfs(G, w);
    }

    public boolean stronglyConnected(int v, int w)
    { return id[v] == id[w]; }
```

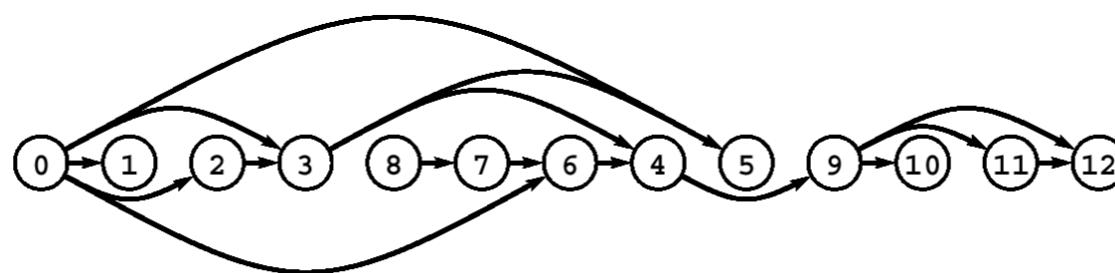
Digraph-processing summary: algorithms of the day

**single-source
reachability
in a digraph**



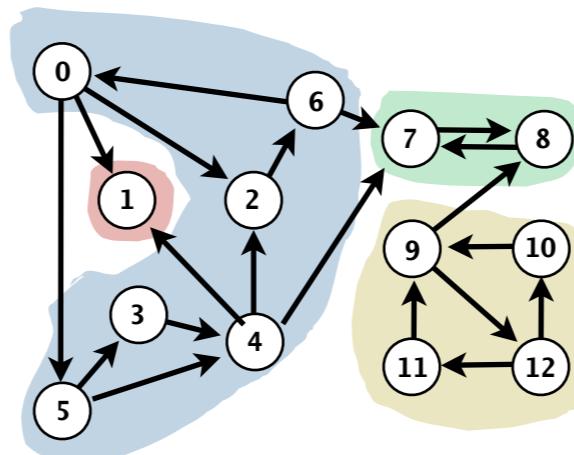
DFS

**topological sort
in a DAG**



DFS

**strong
components
in a digraph**



Kosaraju-Sharir
DFS (twice)