

4.2 DIRECTED GRAPHS

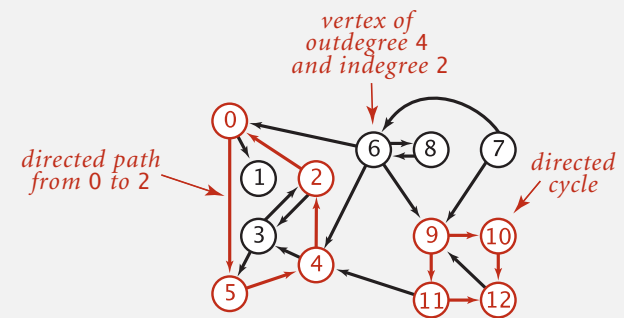


- ▶ digraph API
- ▶ digraph search
- ▶ topological sort
- ▶ strong components

Algorithms, 4th Edition · Robert Sedgwick and Kevin Wayne · Copyright © 2002–2012 · March 28, 2012 12:27:10 PM

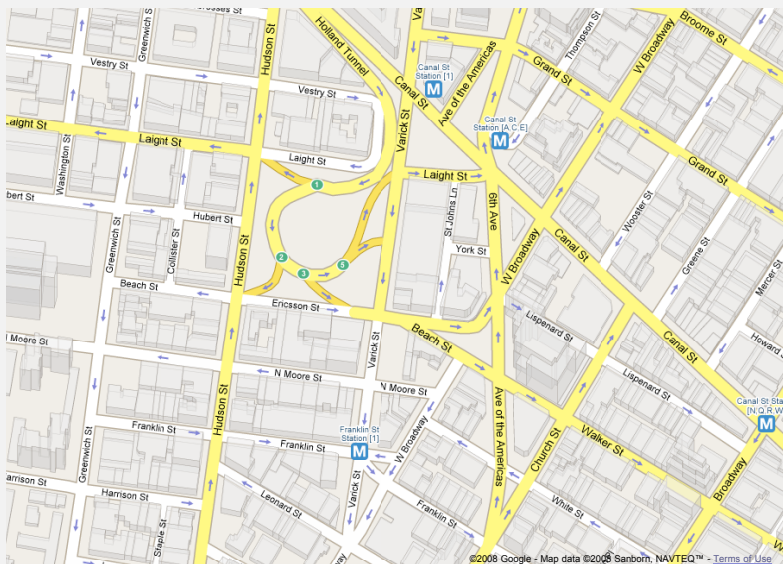
Directed graphs

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



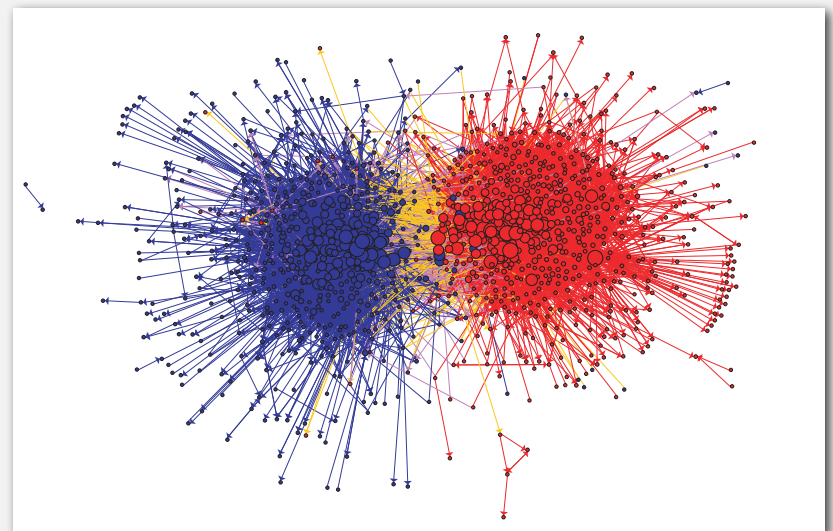
Road network

Vertex = intersection; edge = one-way street.



Political blogosphere graph

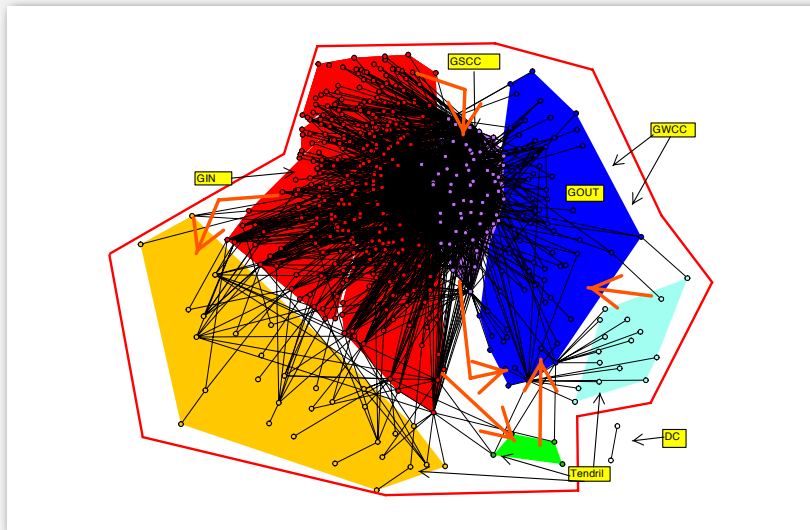
Vertex = political blog; edge = link.



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.

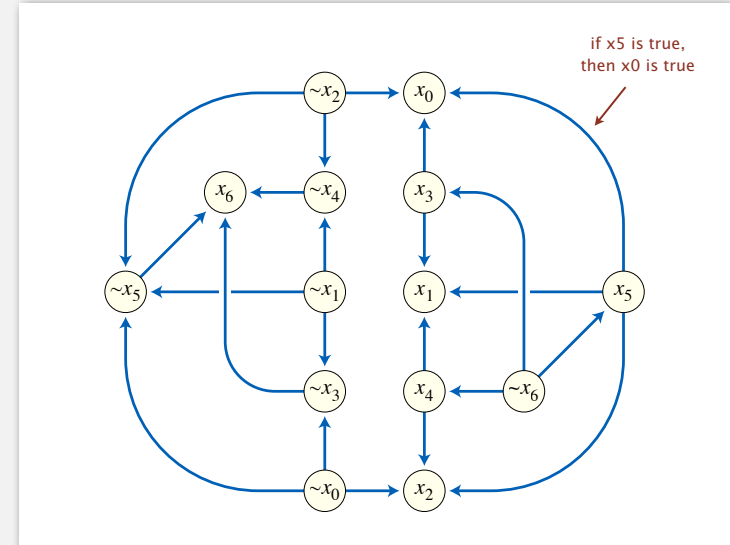


The Topology of the Federal Funds Market, Bech and Atalay, 2008

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Implication graph

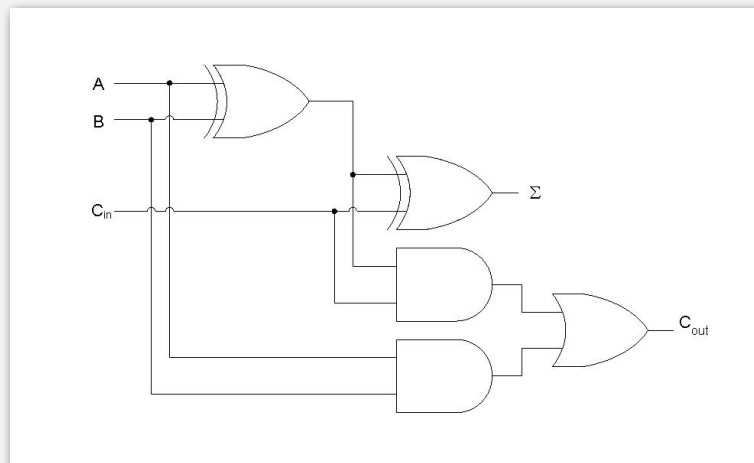
Vertex = variable; edge = logical implication.



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Combinational circuit

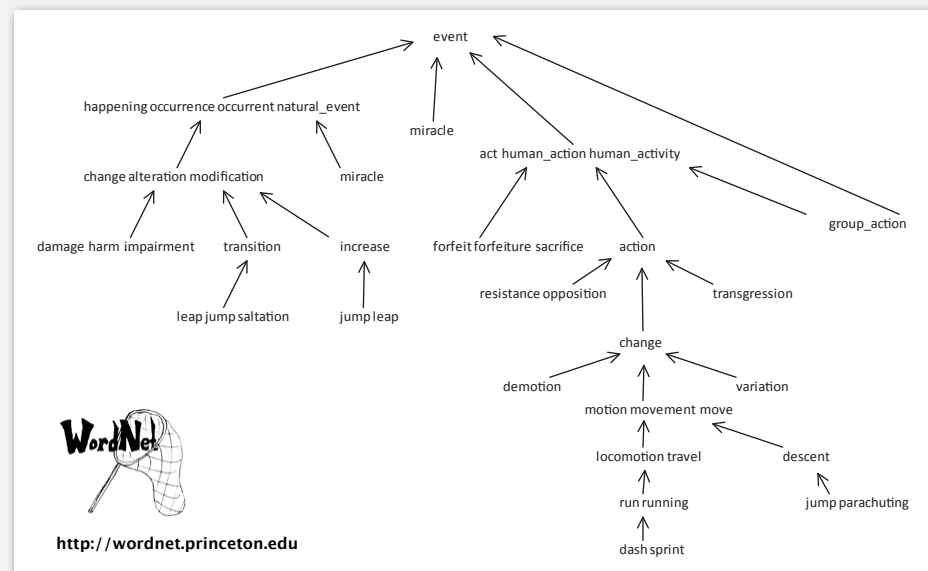
Vertex = logical gate; edge = wire.



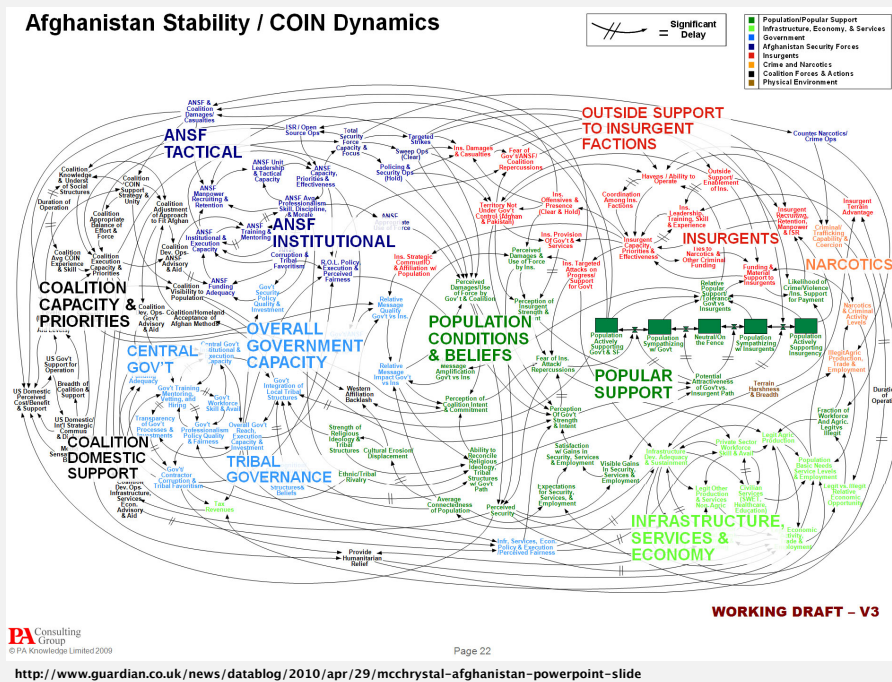
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WordNet graph

Vertex = synset; edge = hypernym relationship.



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digraph	vertex	directed edge
transportation	street intersection	one-way street
web	web page	hyperlink
food web	species	predator-prey relationship
WordNet	synset	hypernym
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

Path. Is there a directed path from s to t ?

Shortest path. What is the shortest directed path from s to t ?

Topological sort. Can you draw the digraph so that all edges point upwards?

Strong connectivity. Is there a directed path between all pairs of vertices?

Transitive closure. For which vertices v and w is there a path from v to w ?

PageRank. What is the importance of a web page?

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

Digraph 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→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
    
```

```

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)

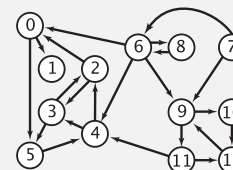
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Digraph API

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

```

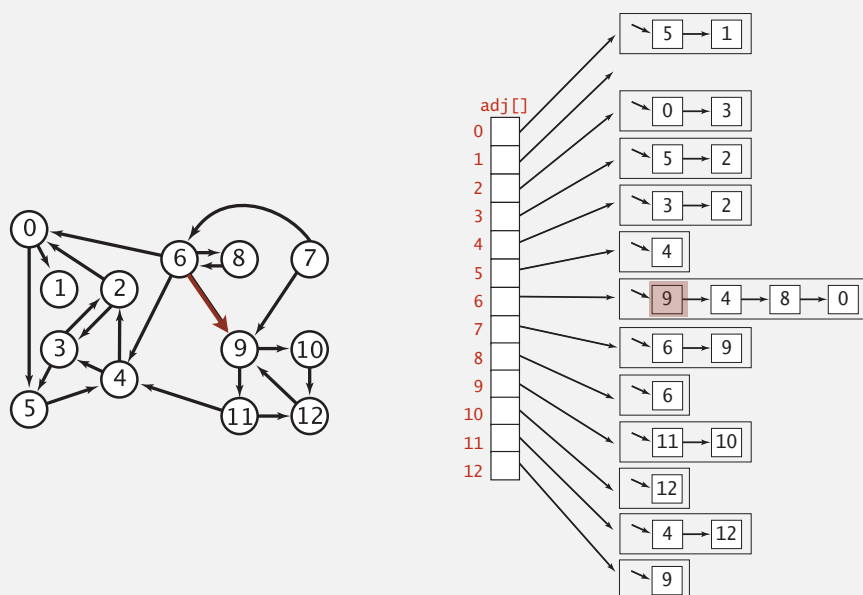
for (int v = 0; v < G.V(); v++)
    for (int w : G.adj(v))
        StdOut.println(v + "->" + w);
    
```

← print out each edge (once)

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Adjacency-lists digraph representation

Maintain vertex-indexed array of lists.



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Adjacency-lists graph representation: 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>();
    }
    
```

← create empty graph with V vertices

```

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

← add edge v-w

```

    public Iterable<Integer> adj(int v)
    { return adj[v]; }
    }
    
```

← iterator for vertices adjacent to v

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```
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];
    for (int v = 0; v < V; v++)
        adj[v] = new Bag<Integer>();
}
```

create empty digraph with V vertices

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

```
{
    adj[v].add(w);
}
```

add edge v→w

```
    public Iterable<Integer> adj(int v)
    { return adj[v]; }
```

iterator for vertices pointing from v

```
}
```

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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 †	1	V
adjacency lists	$E + V$	1	outdegree(v)	outdegree(v)

† disallows parallel edges

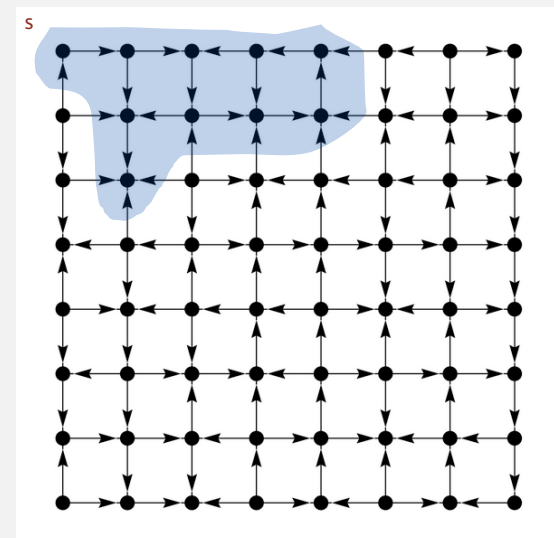
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- digraph API
- digraph search
- topological sort
- strong components

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Reachability

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



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Depth-first search in digraphs

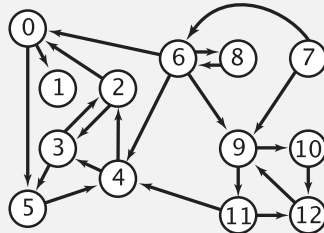
Same method as for undirected graphs.

- 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 .



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Depth-first search demo

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Depth-first search (in undirected graphs)

Recall code for **undirected** graphs.

```
public class DepthFirstSearch
{
    private boolean[] marked;

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

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

    public boolean visited(int v)
    { return marked[v]; }
}
```

← true if path to s

← constructor marks
vertices connected to s

← recursive DFS does the work

← client can ask whether any
vertex is connected to s

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Depth-first search (in directed graphs)

Code for **directed** graphs identical to undirected one.
[substitute Digraph for Graph]

```
public class DirectedDFS
{
    private boolean[] marked;

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

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

    public boolean visited(int v)
    { return marked[v]; }
}
```

← true if path from s

← constructor marks
vertices reachable from s

← recursive DFS does the work

← client can ask whether any
vertex is reachable from s

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Reachability application: program control-flow analysis

Every program is a digraph.

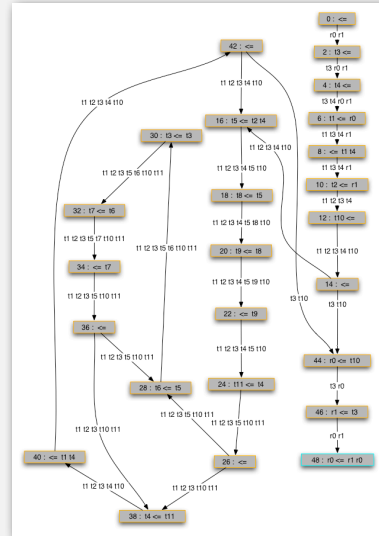
- Vertex = basic block of instructions (straight-line program).
- Edge = jump.

Dead-code elimination.

Find (and remove) unreachable code.

Infinite-loop detection.

Determine whether exit is unreachable.



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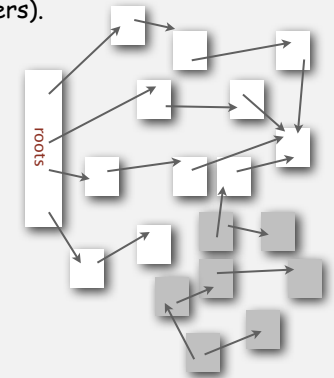
Reachability application: mark-sweep garbage collector

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).



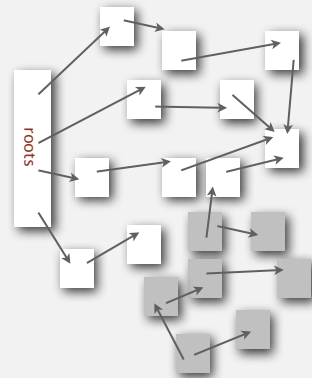
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Reachability application: mark-sweep garbage collector

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).



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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.

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Breadth-first search in digraphs

Same method as for undirected graphs.

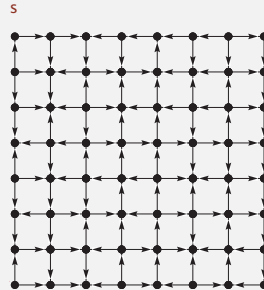
- Every undirected graph is a digraph (with edges in both directions).
- BFS is a **digraph** algorithm.

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.

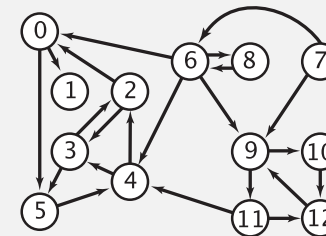


Proposition. BFS computes shortest paths (fewest number of edges).

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. Shortest path from $\{1, 7, 10\}$ to 5 is $7 \rightarrow 6 \rightarrow 4 \rightarrow 3 \rightarrow 5$.



Q. How to implement multi-source constructor?

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

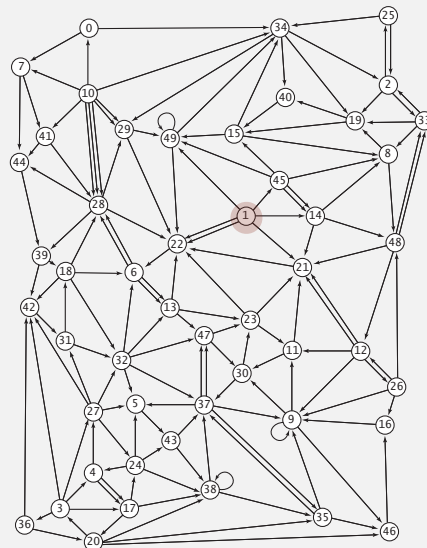
Breadth-first search in digraphs application: web crawler

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

Solution. BFS with implicit graph.

BFS.

- 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>();
SET<String> discovered = new SET<String>();

String root = "http://www.princeton.edu";
queue.enqueue(root);
discovered.add(root);

while (!queue.isEmpty())
{
    String v = queue.dequeue();
    StdOut.println(v);
    In in = new In(v);
    String input = in.readAll();

    String regexp = "http://(\\w+\\.)* (\\w+)";
    Pattern pattern = Pattern.compile(regexp);
    Matcher matcher = pattern.matcher(input);
    while (matcher.find())
    {
        String w = matcher.group();
        if (!discovered.contains(w))
        {
            discovered.add(w);
            queue.enqueue(w);
        }
    }
}
```

queue of websites to crawl

set of discovered websites

start crawling from root website

read in raw html from next website in queue

use regular expression to find all URLs in website of form `http://xxx.yyy.zzz` [crude pattern misses relative URLs]

if undiscovered, mark it as discovered and put on queue

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

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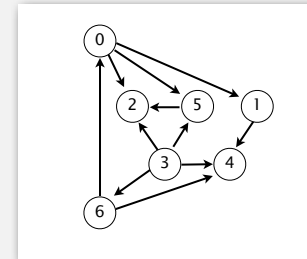
Precedence scheduling

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

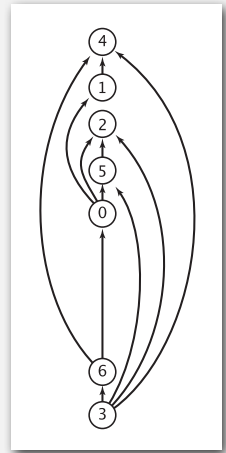
Digraph model. vertex = task; edge = precedence constraint.

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

tasks



precedence constraint graph



feasible schedule

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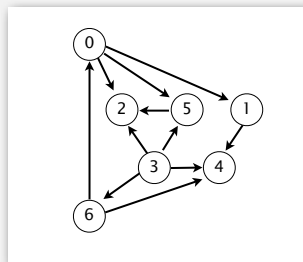
Topological sort

DAG. Directed **acyclic** graph.

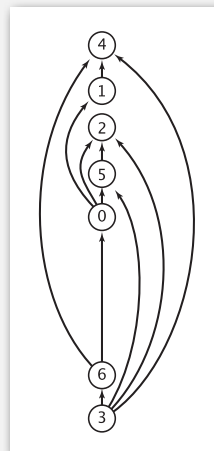
Topological sort. Redraw DAG so all edges point upwards.

0 → 5 0 → 2
 0 → 1 3 → 6
 3 → 5 3 → 4
 5 → 4 6 → 4
 6 → 0 3 → 2
 1 → 4

directed edges



DAG



topological order

Solution. DFS. What else?

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Topological sort demo

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Depth-first search order

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

    public DepthFirstOrder(Digraph G)
    {
        reversePost = 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);
        reversePost.push(v);
    }

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

returns all vertices in
"reverse DFS postorder"

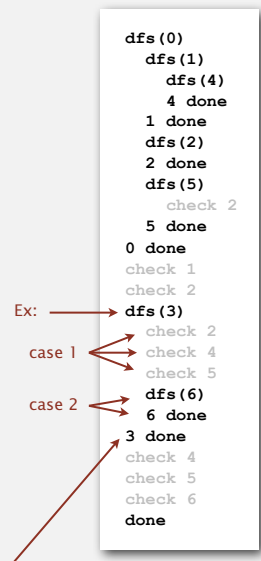
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Topological sort in a DAG: correctness proof

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

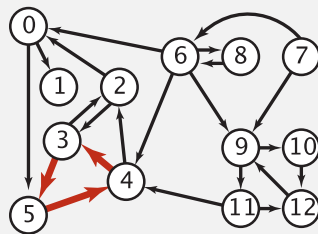
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Directed cycle detection

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.

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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.

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The Java compiler does cycle detection.

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

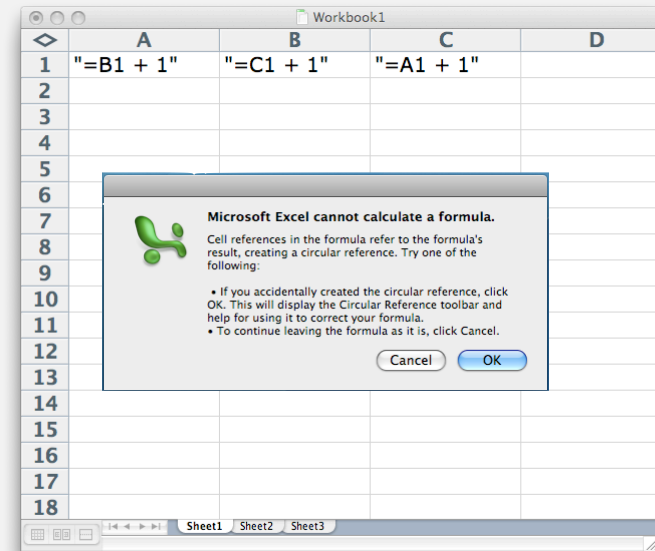
```
public class B extends C
{
    ...
}
```

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

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

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



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- ▶ digraph API
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- ▶ strong components

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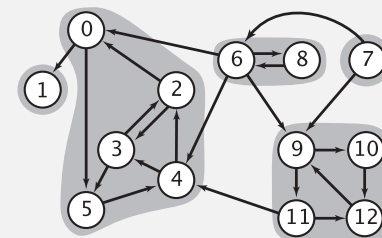
Strongly-connected components

Def. Vertices v and w are **strongly connected** if there is 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 .

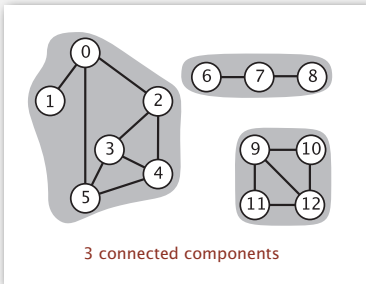
Def. A **strong component** is a maximal subset of strongly-connected vertices.



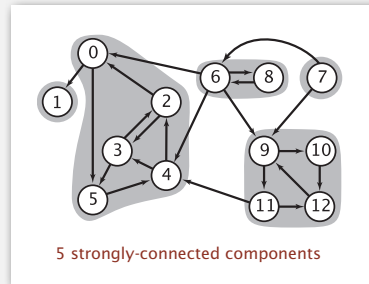
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Connected components vs. strongly-connected components

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



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



connected component id (easy to compute with DFS)

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

```
public int connected(int v, int w)
{ return cc[v] == cc[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
scc[]	1	0	1	1	1	1	3	4	3	2	2	2	2

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

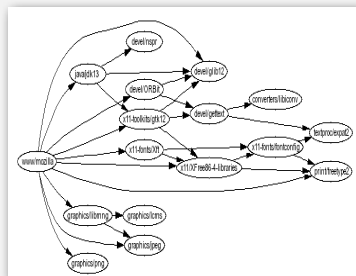
constant-time client strong-connectivity query

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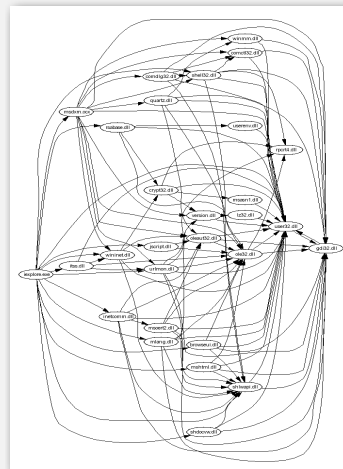
Strong component application: software modules

Software module dependency graph.

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



Firefox



Internet Explorer

Strong component. Subset of mutually interacting modules.

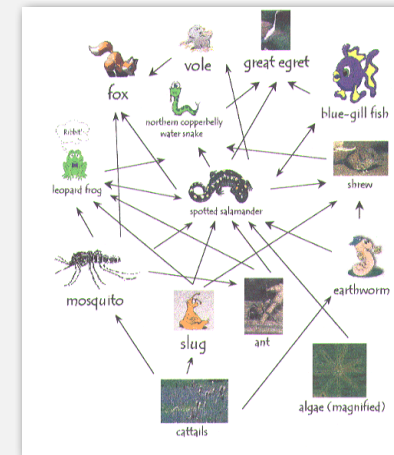
Approach 1. Package strong components together.

Approach 2. Use to improve design!

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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.

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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.

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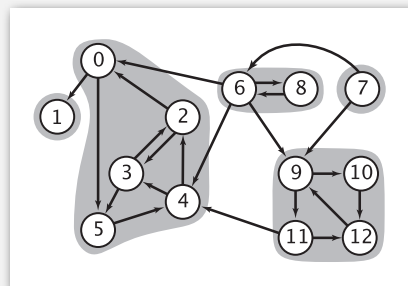
Kosaraju's algorithm: intuition

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

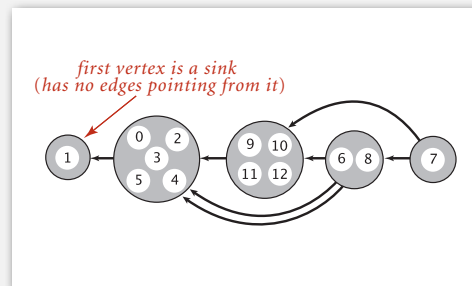
Kernel DAG. Contract each strong component into a single vertex.

Idea.

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



digraph G and its strong components



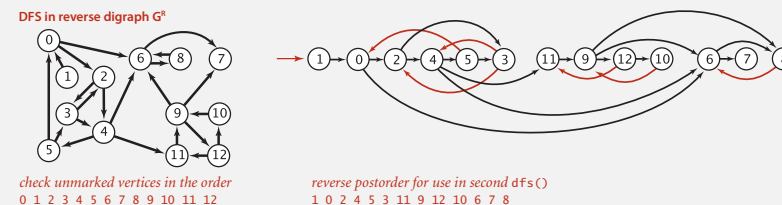
kernel DAG of G (in reverse topological order)

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Kosaraju's algorithm

Simple (but mysterious) algorithm for computing strong components.

- Run DFS on G^R to compute reverse postorder.
- 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

reverse postorder for use in second dfs()
1 0 2 4 5 3 11 9 12 10 6 7 8

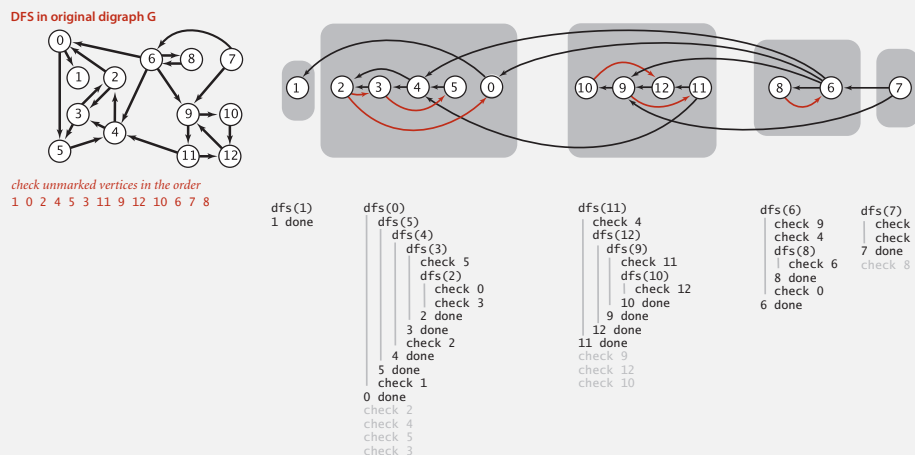
```
dfs(0)
  dfs(6)
    dfs(8)
      check 6
      8 done
    dfs(7)
      7 done
    6 done
  dfs(2)
    dfs(4)
      dfs(11)
        dfs(9)
          dfs(12)
            check 11
          dfs(10)
            check 9
            10 done
          12 done
        check 7
        check 6
      ...
```

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Kosaraju's algorithm

Simple (but mysterious) algorithm for computing strong components.

- Run DFS on G^R to compute reverse postorder.
- Run DFS on G , considering vertices in order given by first DFS.



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)
      check 5
      5 done
    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)
    check 11
    11 done
  check 9
  check 12
  12 done
  check 10
  10 done
  9 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
```

Proposition. Second DFS gives strong components. (!!)

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Connected components in an undirected graph (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];
  }
}
```

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Strong components in a digraph (with two DFSs)

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

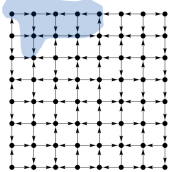
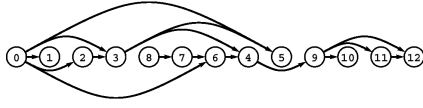
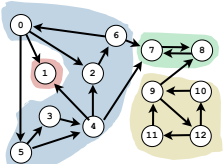
    public KosarajuSCC(Digraph G)
    {
        marked = new boolean[G.V()];
        id = new int[G.V()];
        DepthFirstOrder dfs = new DepthFirstOrder(G.reverse());
        for (int v : dfs.reversePost())
        {
            if (!marked[v])
            {
                dfs(G, v);
                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]; }
}
```

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Digraph-processing summary: algorithms of the day

single-source reachability		DFS
topological sort (DAG)		DFS
strong components		Kosaraju DFS (twice)

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