

**GRAPH:** a set of OBJECTS with CONNECTIONS

Interesting and useful abstraction

Study of graph algorithms

- challenging branch of computer science

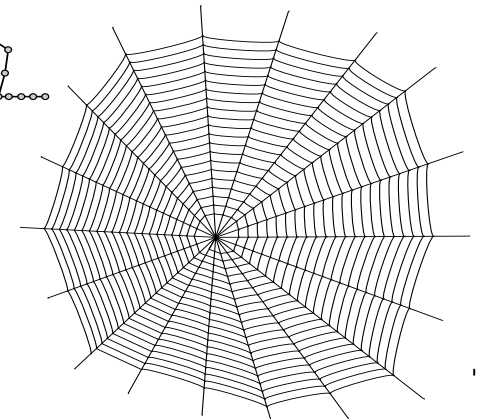
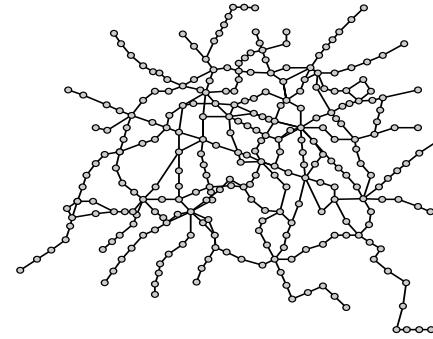
Study of mathematical properties of graphs

- challenging branch of discrete mathematics

Hundreds of interesting graph algorithms known

Important applications abound

- transportation systems
- scheduling
- circuit simulation
- software systems
- web search
- computer vision
- computational biology



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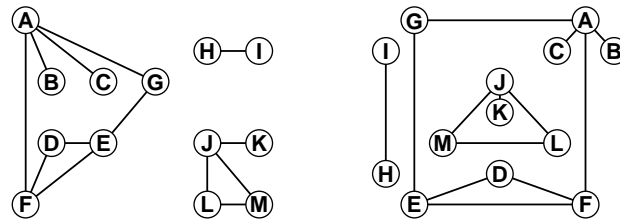
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Glossary of terms

Vertex

Edge

Graph



Dense

Sparse

Path

Cycle, Tour

Tree

Spanning tree

Connected

Connected component

Undirected

Digraph

Weighted

Network

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More graph examples

**CONCRETE** models: direct representations

**Ex:** Transportation network

- cities connected by roads

**Ex:** Electric circuit

- devices connected by wires

**Warning:** geometric intuition may mislead

**Ex:** Airline fares (triangle inequality might not hold)

**ABSTRACT** models: represent other abstractions

**Ex:** Scheduling

- tasks connected by precedence constraints

**Ex:** Programming system

- functions that call one another

**Ex:** CFG

- symbols related by productions

**Ex:** Game graphs

- vertices: board positions; edges: moves

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## Representing graphs

Graphs are abstract mathematical objects  
ADT implementations require specific representations

### AS USUAL

- many different representations possible
- efficiency depends on matching algs to representations

Standard issues apply

- space vs. time
- array vs. linked list
- integers vs. reals
- symbol tables
- duplicate vertices or edges?
- mix of ADT operations

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## Adjacency matrix representation

V-by-V array gives constant-time edge existence test

**VERTEX-INDEXED ARRAY:** one entry for each vertex  
**ADJACENCY MATRIX:**

- vertex-indexed array of vertex-indexed arrays
- 1 in (i, j) AND (j,i) iff edge i-j in graph

	A	B	C	D	E	F	G	H	I	J	K	L	M
A	1	1	1	0	0	1	1	0	0	0	0	0	0
B	1	1	0	0	0	1	1	0	0	0	0	0	0
C	1	0	1	0	0	0	0	0	0	0	0	0	0
D	0	0	0	1	1	1	0	0	0	0	0	0	0
E	0	0	0	1	1	1	1	0	0	0	0	0	0
F	1	1	0	1	1	1	0	0	0	0	0	0	0
G	1	1	0	0	1	0	1	0	0	0	0	0	0
H	0	0	0	0	0	0	0	1	1	0	0	0	0
I	0	0	0	0	0	0	0	1	1	0	0	0	0
J	0	0	0	0	0	0	0	0	0	1	1	1	1
K	0	0	0	0	0	0	0	0	0	1	1	0	0
L	0	0	0	0	0	0	0	0	0	1	0	1	1
M	0	0	0	0	0	0	0	0	0	1	0	1	1

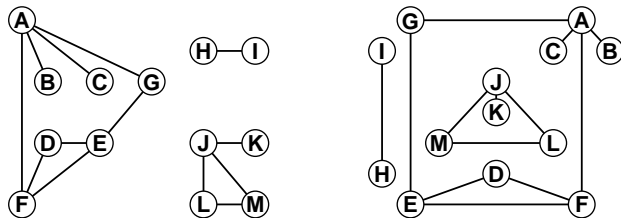
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## Representing graphs

VERTEX NAMES (A B C D E F G H)

- progs use integers between 0 and V-1
- convert via implicit or explicit symbol table

Two drawings that represent the same graph



SET OF EDGES representation

A-B A-G A-C L-M J-M J-L J-K E-D F-D H-I F-E A-F G-E

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## Adjacency lists representation

Array of lists takes space proportional to no. of edges

**ADJACENCY LISTS** representation

A: F C B G  
 B: A  
 C: A  
 D: F E  
 E: G F D  
 F: A E D  
 G: E A  
 H: I  
 I: H  
 J: K L M  
 K: J  
 L: J M  
 M: J L

TWO representations of each edge for UNDIRECTED graphs

## Graph ADT

Standard mechanism to separate clients from implementations  
(plus simple typedef for edges)

GRAPH.h:

```
. typedef struct { int v; int w; } Edge;
. Edge EDGE(int, int);
.
. typedef struct graph *Graph;
. Graph GRAPHinit(int);
. void GRAPHinsertE(Graph, Edge);
```

Typical client program

- calls GRAPHinit to create data structures
- uses Graph handle as arg to graph-processing ADT function
- calls GRAPHinsertE to build graph by adding edges
- calls ADT function to do graph processing

Ex: GRAPHcc computes connected components.

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## Summary of basic costs

E edges, V vertices

Space requirements:

- Adjacency lists:  $V+E$
- Adjacency matrix:  $V^2$
- Set of edges:  $E (+V)$

Choice of representation affects algorithm efficiency

- even for simple primitives

Ex: Is there an edge from A to B?

lists:  $O(E)$

matrix:  $O(1)$

Ex: Is there an edge from A to anywhere?

lists:  $O(1)$

matrix:  $O(V)$

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## Adjacency lists Graph ADT implementation

```
#include "GRAPH.h"
typedef struct node *link;
struct node { int v; link next; };
struct graph { int V; int E; link *adj; };
link NEW(int v, link next)
{ link x = malloc(sizeof *x);
  x->v = v; x->next = next;
  return x;
}
Graph GRAPHinit(int V)
{ int v;
  Graph G = malloc(sizeof *G);
  G->V = V; G->E = 0;
  G->adj = malloc(V*sizeof(link));
  for (v = 0; v < V; v++) G->adj[v] = NULL;
  return G;
}
void GRAPHinsertE(Graph G, Edge e)
{ int v = e.v, w = e.w;
  G->adj[v] = NEW(w, G->adj[v]);
  G->adj[w] = NEW(v, G->adj[w]);
  G->E++;
}
```

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## Basic graph problems (short list)

PATHS

- Is there a path from A to B?

CYCLES

- Does the graph contain a cycle?

CONNECTIVITY (SPANNING TREE)

- Is there a way connect all the vertices?

BICONNECTIVITY

- Is there a vertex whose removal will disconnect the graph?

PLANARITY

- Is there a way to draw the graph without edges crossing?

SHORTEST (LONGEST) PATH

- What is the shortest (longest) way from A to B?

MINIMAL SPANNING TREE

- What is the best way connect the vertices?

HAMILTON TOUR

- Is there a cycle that uses each vertex exactly once?

ISOMORPHISM

- Do two given adj matrices represent the same graph?

## Traversing graphs

Goal: VISIT every vertex in the graph

### Depth-first search (DFS)

- To VISIT a node  $k$   
mark it  
(recursively) VISIT all unmarked  
vertices connected to  $k$
- To TRAVERSE a graph  
initialize all nodes to be unmarked  
VISIT each unmarked node

Solves some simple graph problems

- connectivity
- cycles

basis for solving some difficult graph problems

- biconnectivity
- planarity

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## Traversing a graph's components

Needed for any implementation of VISIT  
UNLESS graph is known to be connected

IF visit( $k$ ) marks all nodes connected to  $k$   
THEN traverse( $G$ ) marks all of  $G$ 's nodes

```
int mark[maxV]; int cnt = 0;
traverse(Graph G)
{ int k;
  for (k = 1; k <= G->V; k++) mark[k] = 0;
  for (k = 1; k <= G->V; k++)
    if (mark[k] == 0) visit(G, k);
}
```

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## DFS implementation

### Adjacency matrix

```
visit(Graph G, int k)
{ int t;
  mark[k] = ++cnt;
  for (t = 1; t <= V; t++)
    if (G->adj[k][t] != 0)
      if (mark[t] == 0) visit(G, t);
}
```

### Adjacency lists

```
visit(Graph G, int k)
{ link t;
  mark[k] = ++cnt;
  for (t = G->adj[k]; t != z; t = t->next)
    if (mark[t->v] == 0) visit(G, t->v);
}
```

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## DFS example (adjacency lists)

visit A

- visit F (first on A's list)  
check A on F's list (been there)  
visit E (second on F's list)  
visit G (first on E's list)  
check E on G's list (been there)  
check A on G's list (been there)  
check F on E's list (been there)  
visit D (third on E's list)  
check F on D's list (been there)  
check E on D's list (been there)  
check D on F's list (done that)
- visit C (second on A's list)
- visit B (third on A's list)
- check G on F's list (done that)
- ...

"been there": currently working on it

"done that": totally finished dealing with it

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## DFS tree (adjacency lists)

Tree structure captures dynamics of DFS

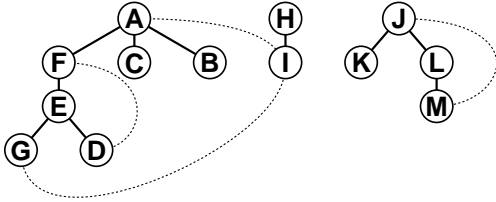
### TREE links

- first encounter: recursive call
- second encounter: been there

### BACK links

- first encounter: been there
- second encounter: done that

A: F C B G  
 B: A  
 C: A  
 D: F E  
 E: G F D  
 F: A E D  
 G: E A  
 H: I  
 I: H  
 J: K L M  
 K: J  
 L: J M  
 M: J L



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## Connected-components ADT functions (DFS)

**GRAPHcc**: preprocessing (DFS)

**GRAPHconnect**: query

**cc**: vertex-indexed array in graph representation

```
void dfsRcc(Graph G, int v, int id)
{ link t;
  G->cc[v] = id;
  for (t = G->adj[v]; t != NULL; t = t->next)
    if (G->cc[t->v] == -1) dfsRcc(G, t->v, id);
}

int GRAPHcc(Graph G)
{ int v, id = 0;
  G->cc = malloc(G->V * sizeof(int));
  for (v = 0; v < G->V; v++)
    G->cc[v] = -1;
  for (v = 0; v < G->V; v++)
    if (G->cc[v] == -1) dfsRcc(G, v, id++);
  return id;
}

int GRAPHconnect(Graph G, int s, int t)
{ return G->cc[s] == G->cc[t]; }
```

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## Connected components ADT function

Is there a path from  $s$  to  $t$ ?

### UNION-FIND (lecture 1)

- query:  $O(\log^* V)$
- preprocessing:  $O(E \log^* V)$
- space:  $O(V)$

### DFS

- query:  $O(1)$
- preprocessing:  $O(E)$
- space:  $O(V)$

UF advantage: can intermix query and edge insertion

DFS advantage: can give client the path

- change arg to pass EDGE taken to visit the vertex
- maintain parent-link representation of DFS tree
- [see text]

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## Graph-search overview

DFS is one of a family of graph-search functions

- all visit all nodes and edges
- strategy to use dictated by problem at hand

### GENERALIZED GRAPH SEARCH

To TRAVERSE a graph

- initialize all nodes to be unmarked
- put some vertex on a generalized queue (GQ)
- while the GQ is nonempty
  - remove a vertex and mark it
  - put all unmarked adjacent vertices on the GQ

ISSUE: duplicate vertices on queue

- ignore the new one or forget the old one?

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## Stack-based graph traversal

Use explicit stack instead of recursive calls

```
visit(Graph G, int k)
{ link t;
  STACKpush(k);
  while (!STACKempty())
  {
    k = STACKpop(); mark[k] = ++id;
    for (t = G->adj[k]; t != z; t = t->next)
      if (mark[t->v] == 0)
        { STACKpush(t->v); mark[t->v] = -1;}
  }
}
```

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## Stack-based search

**NOT** the same as recursive DFS. Why?

Algs differ in treatment of vertices that are adjacent to partially visited vertices

- DFS: visits such a vertex
- stack-based: avoids it  
(it is on the stack and will get visited later)

Nonrecursive DFS: PUSH next node on adj list

- equivalent to disallowing duplicate vertices on stack

No particular reason to use stack

- other ADTs work as well (stay tuned)

**GRAPH SEARCH:** generalized-queue--based traversal

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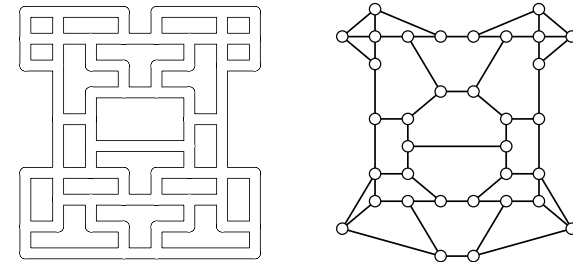
## Stack-based traversal example (adjacency lists)

visit A

- push F, push C, push B, push G
- visit G
  - push E, been to A
  - visit E
    - been to G, been to F, push D
    - visit D
      - been to F, been to E
- visit B
  - been to A
- visit C
  - been to A
- visit F
  - been to A, done with E, done with D

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## Graphs and mazes



vertices: intersections

edges: hallways

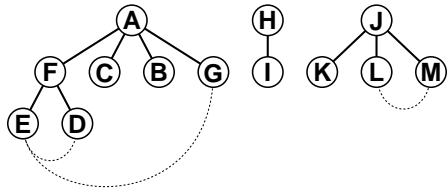
**DFS**

- mark ENTRY and EXIT halls at each vertex
- leave by ENTRY when no unmarked halls

Stack-based?

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### Breadth-first search (BFS)



Put unvisited nodes on a QUEUE, not a stack

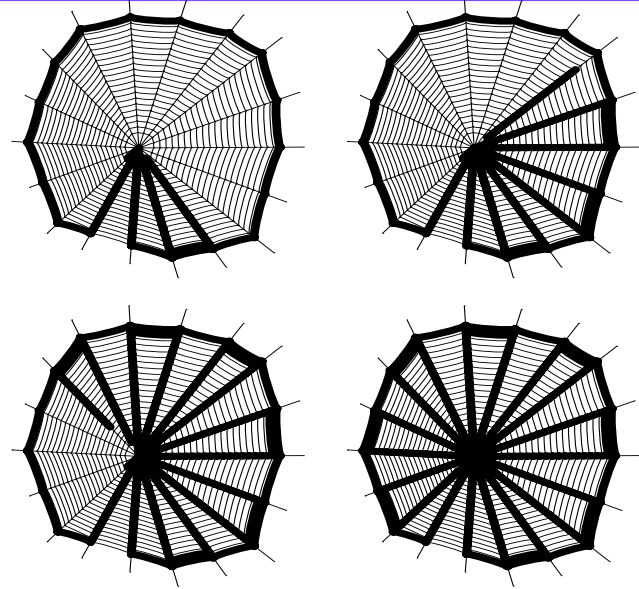
```

visit(Graph G, int k)
{
  link t;
  QUEUEput(k);
  while (!QUEUEempty())
  {
    k = QUEUEget(); mark[k] = ++id;
    for (t = G->adj[k]; t != z; t = t->next)
      if (mark[t->v] == 0)
        { QUEUEput(t->v); mark[t->v] = -1; }
  }
}

```

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### DFS example

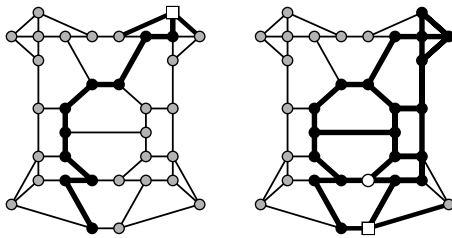


Search order depends on graph representation

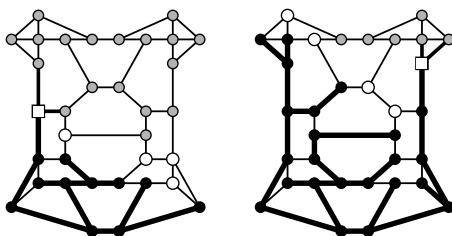
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### BFS vs DFS example

Depth-first search



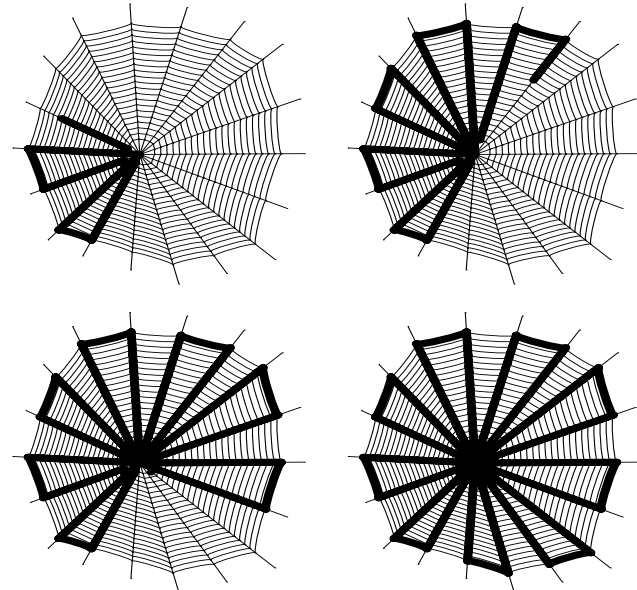
Breadth-first search



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### DFS example (continued)

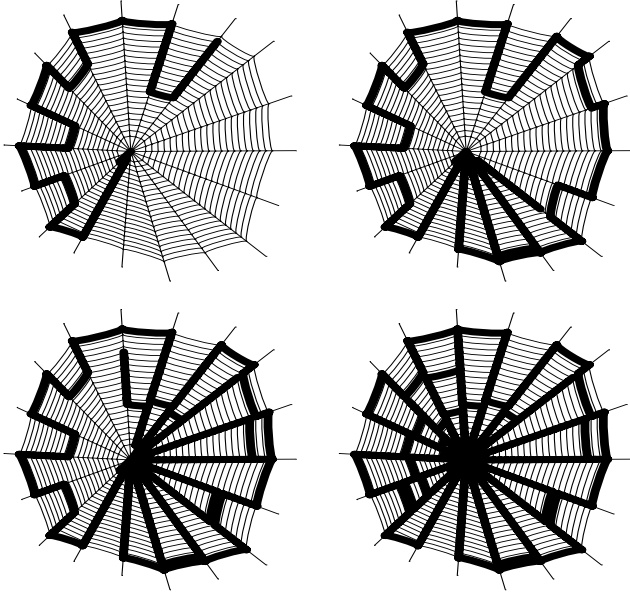
Same graph, different order of edges on adj lists



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## DFS example (continued)

Same graph, random choice of edges on adj lists



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## Graph search and path problems

### Problem: PATHS

- Is there a path from A to B?

**Solution:** DFS, BFS, any graph search

### Problem: SHORTEST PATH

- Find a shortest path (fewest edges) from A to B.

**Solution:** BFS

### Problem: EULER PATH (existence)

- Is there a cycle that uses each EDGE exactly once?

**Solution:** Yes, if degrees of all vertices are

### Problem: EULER TOUR

- Find a cycle that uses all the graph's edges.

**Solution:** interesting exercise [see text]

### Problem: HAMILTON TOUR

- Is there a cycle that uses each VERTEX exactly once?

**Solution:** ?? (NP-complete)

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