

Week 02b: Graph Data Structures

Graph Definitions

Graphs

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Many applications require

- a collection of *items* (i.e. a set)
- *relationships/connections* between items

Examples:

- maps: items are cities, connections are roads
- web: items are pages, connections are hyperlinks

Collection types you're familiar with

- lists ... linear sequence of items (last week; COMP9021)
- trees ... branched hierarchy of items (COMP9021)

Graphs are more general ... allow arbitrary connections

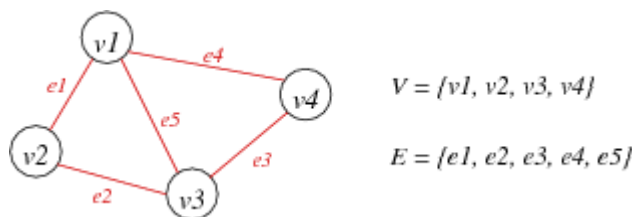
... Graphs

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A graph $G = (V, E)$

- V is a set of *vertices*
- E is a set of *edges* (subset of $V \times V$)

Example:



... Graphs

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A real example: Australian road distances

Distance	Adelaide	Brisbane	Canberra	Darwin	Melbourne	Perth	Sydney
Adelaide	-	2055	1390	3051	732	2716	1605
Brisbane	2055	-	1291	3429	1671	4771	982
Canberra	1390	1291	-	4441	658	4106	309
Darwin	3051	3429	4441	-	3783	4049	4411
Melbourne	732	1671	658	3783	-	3448	873

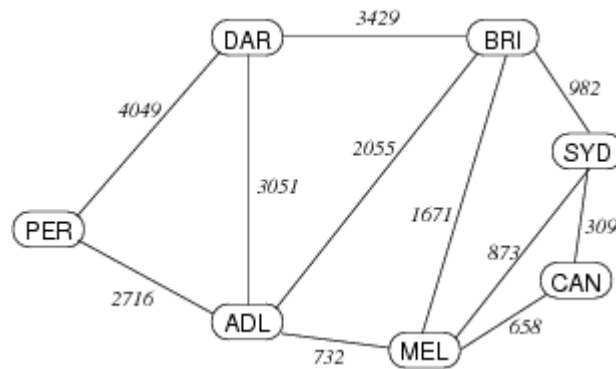
Perth	2716	4771	4106	4049	3448	-	3972
Sydney	1605	982	309	4411	873	3972	-

Notes: vertices are cities, edges are distance between cities, symmetric

... Graphs

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Alternative representation of above:



... Graphs

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Questions we might ask about a graph:

- is there a way to get from item A to item B?
- what is the best way to get from A to B?
- which items are connected?

Graph algorithms are generally more complex than tree/list ones:

- no implicit order of items
- graphs may contain cycles
- concrete representation is less obvious
- algorithm complexity depends on connection complexity

Properties of Graphs

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Terminology: $|V|$ and $|E|$ (cardinality) normally written just as V and E .

A graph with V vertices has at most $V(V-1)/2$ edges.

The ratio $E:V$ can vary considerably.

- if E is closer to V^2 , the graph is *dense*
- if E is closer to V , the graph is *sparse*
 - Example: web pages and hyperlinks

Knowing whether a graph is sparse or dense is important

- may affect choice of data structures to represent graph
- may affect choice of algorithms to process graph

Exercise #1: Number of Edges

The edges in a graph represent pairs of connected vertices. A graph with V has V^2 such pairs.

Consider $V = \{1,2,3,4,5\}$ with all possible pairs:

$$E = \{ (1,1), (1,2), (1,3), (1,4), (1,5), (2,1), (2,2), \dots, (4,5), (5,5) \}$$

Why do we say that the maximum #edges is $V(V-1)/2$?

... because

- (v,w) and (w,v) denote the same edge (in an undirected graph)
- we do not consider loops (v,v)

Graph Terminology

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For an edge e that connects vertices v and w

- v and w are *adjacent* (neighbours)
- e is *incident* on both v and w

Degree of a vertex v

- number of edges incident on v

Synonyms:

- vertex = node, edge = arc = link (Note: some people use arc for *directed* edges)

... Graph Terminology

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Path: a sequence of vertices where

- each vertex has an edge to its predecessor 前任

Simple path: a path where

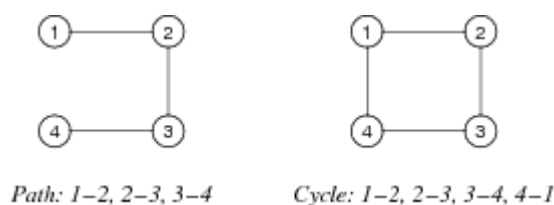
- all vertices and edges are different

Cycle: a path

- that is simple except last vertex = first vertex

Length of path or cycle:

- #edges



... Graph Terminology

Connected graph

- there is a *path* from each vertex to every other vertex
- if a graph is not connected, it has ≥ 2 *connected components*

Complete graph K_V

- there is an *edge* from each vertex to every other vertex
- in a complete graph, $E = V(V-1)/2$



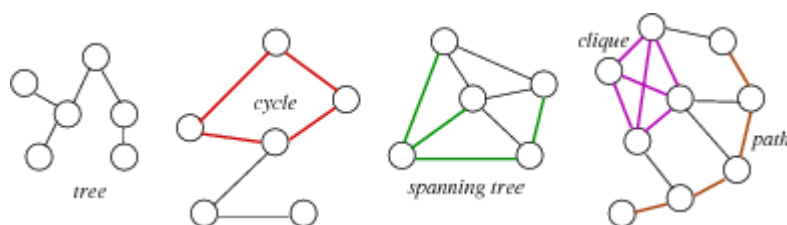
... Graph Terminology

Tree: connected (sub)graph with no cycles

Spanning tree: tree containing all vertices

Clique: complete subgraph

Consider the following single graph:



This graph has 26 vertices, 33 edges, and 4 connected components

Note: The entire graph has no spanning tree; what is shown in green is a spanning tree of the third connected component

... Graph Terminology

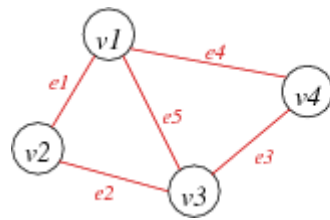
A *spanning tree* of connected graph $G = (V, E)$

- is a **subgraph** of G containing all of V
- and is a single tree (connected, no cycles)

A *spanning forest* of non-connected graph $G = (V, E)$

- is a subgraph of G containing all of V
- and is a set of trees (not connected, no cycles),
 - with one tree for each *connected component*

Exercise #2: Graph Terminology



$$V = \{v1, v2, v3, v4\}$$

$$E = \{e1, e2, e3, e4, e5\}$$

1. How many edges to remove to obtain a spanning tree?
2. How many different spanning trees?

1. 2

2. $\frac{5 \cdot 4}{2} - 2 = 8$ spanning trees (no spanning tree if we remove $\{e1, e2\}$ or $\{e3, e4\}$)

... Graph Terminology

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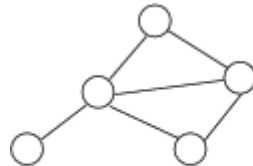
Undirected graph

- $edge(u, v) = edge(v, u)$, no self-loops (i.e. no $edge(v, v)$)

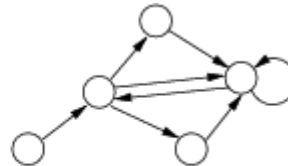
Directed graph

- $edge(u, v) \neq edge(v, u)$, can have self-loops (i.e. $edge(v, v)$)

Examples:



Undirected graph



Directed graph

... Graph Terminology

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Other types of graphs ...

Weighted graph

- each edge has an associated value (weight)
- e.g. road map (weights on edges are distances between cities)

Multi-graph

- allow multiple edges between two vertices
- e.g. function call graph ($f()$ calls $g()$ in several places)

Graph Data Structures

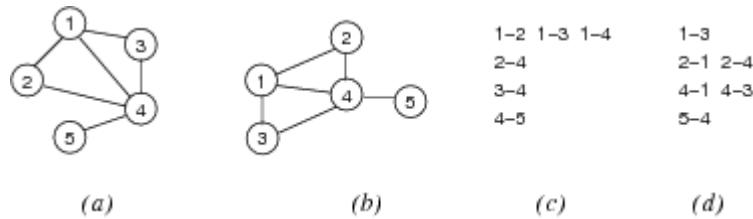
Graph Representations

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Defining graphs:

- need some way of identifying vertices
- could give diagram showing edges and vertices
- could give a list of edges

E.g. four representations of the same graph:



... Graph Representations

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We will discuss three different graph data structures:

1. Array of edges
2. Adjacency matrix
3. Adjacency list

Array-of-edges Representation

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Edges are represented as an array of Edge values (= pairs of vertices)

- space efficient representation
- adding and deleting edges is slightly complex
- undirected: order of vertices in an Edge doesn't matter
- directed: order of vertices in an Edge encodes direction



For simplicity, we always assume vertices to be numbered $0 \dots V-1$

... Array-of-edges Representation

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Graph initialisation

```
newGraph(V):
    Input   number of nodes V
    Output new empty graph

    g.nV = V    // #vertices (numbered 0..V-1)
    g.nE = 0    // #edges
    allocate enough memory for g.edges[]
    return g
```

How much is enough? ... No more than $V(V-1)/2$... Much less in practice (sparse graph)

... Array-of-edges Representation

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Edge insertion

```
insertEdge(g, (v,w)) :
|   Input graph g, edge (v,w)
|
|   g.edges[g.nE] = (v,w)
|   g.nE = g.nE + 1
```

... Array-of-edges Representation

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Edge removal

```
removeEdge(g, (v,w)) :
|   Input graph g, edge (v,w)
|
|   i = 0
|   while (v,w) ≠ g.edges[i] do
|       i = i + 1
|   end while
|   g.edges[i] = g.edges[g.nE - 1] // replace (v,w) by last edge in array
|   g.nE = g.nE - 1
```

Cost Analysis

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Storage cost: $O(E)$

Cost of operations:

- initialisation: $O(1)$
- insert edge: $O(1)$ (assuming edge array has space)
- find/delete edge: $O(E)$ (need to find edge in edge array)

If array is full on insert

- allocate space for a bigger array, copy edges across $\Rightarrow O(E)$

If we maintain edges in order

- use binary search to insert/find edge $\Rightarrow O(\log E)$

Exercise #3: Array-of-edges Representation

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Assuming an array-of-edges representation ...

Write an algorithm to output all edges of the graph

```
show(g) :
|   Input graph g
|
```

```

|   for all i=0 to g.nE-1 do
|       print g.edges[i]
|   end for

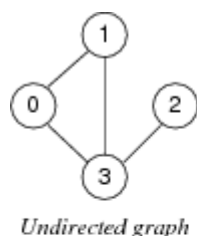
```

Time complexity: $O(E)$

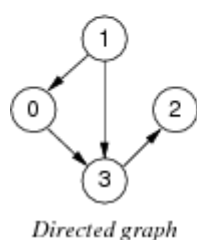
Adjacency Matrix Representation

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Edges represented by a $V \times V$ matrix



A	0	1	2	3
0	0	1	0	1
1	1	0	0	1
2	0	0	0	1
3	1	1	1	0



A	0	1	2	3
0	0	0	0	1
1	1	0	0	1
2	0	0	0	0
3	0	0	1	0

... Adjacency Matrix Representation

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Advantages

- easily implemented as 2-dimensional array
- can represent graphs, digraphs and weighted graphs
 - graphs: symmetric boolean matrix
 - digraphs: non-symmetric boolean matrix
 - weighted: non-symmetric matrix of weight values

Disadvantages:

- if few edges (sparse) \Rightarrow memory-inefficient

... Adjacency Matrix Representation

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Graph initialisation

```

newGraph(V):
|   Input   number of nodes V
|   Output new empty graph

|   g.nV = V    // #vertices (numbered 0..V-1)
|   g.nE = 0    // #edges
|   allocate memory for g.edges[][]
|   for all i,j=0..V-1 do
|       g.edges[i][j]=0    // false
|   end for
|   return g

```


... Adjacency Matrix Representation

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Edge insertion

```

insertEdge(g, (v,w)) :
|   Input graph g, edge (v,w)
|
|   if g.edges[v][w]=0 then    // (v,w) not in graph
|       g.edges[v][w]=1        // set to true
|       g.edges[w][v]=1
|       g.nE=g.nE+1
|   end if

```

... Adjacency Matrix Representation

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Edge removal

```

removeEdge(g, (v,w)) :
|   Input graph g, edge (v,w)
|
|   if g.edges[v][w]≠0 then    // (v,w) in graph
|       g.edges[v][w]=0        // set to false
|       g.edges[w][v]=0
|       g.nE=g.nE-1
|   end if

```

Exercise #4: Show Graph

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Assuming an adjacency matrix representation ...

Write an algorithm to output all edges of the graph (no duplicates!)

... Adjacency Matrix Representation

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```

show(g) :
|   Input graph g
|
|   for all i=0 to g.nV-2 do
|       for all j=i+1 to g.nV-1 do
|           if g.edges[i][j] then
|               print i-"-"j
|           end if
|       end for
|   end for

```

Time complexity: $O(V^2)$

Exercise #5:

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Analyse storage cost and time complexity of adjacency matrix representation

Storage cost: $O(V^2)$

If the graph is sparse, most storage is wasted.

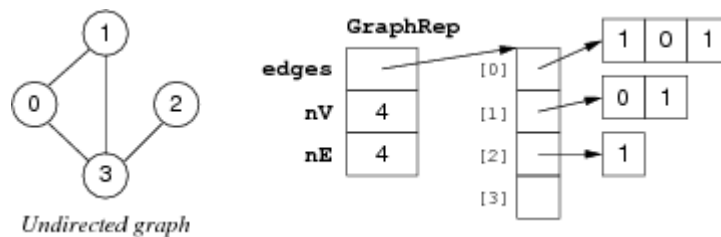
Cost of operations:

- initialisation: $O(V^2)$ (initialise $V \times V$ matrix)
- insert edge: $O(1)$ (set two cells in matrix)
- delete edge: $O(1)$ (unset two cells in matrix)

... Adjacency Matrix Representation

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A storage optimisation: store only top-right part of matrix.



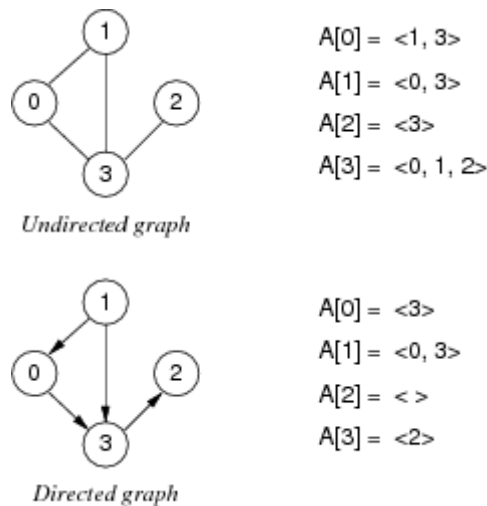
New storage cost: $V-1$ int ptrs + $V(V+1)/2$ ints (but still $O(V^2)$)

Requires us to always use edges (v,w) such that $v < w$.

Adjacency List Representation

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For each vertex, store linked list of adjacent vertices:



... Adjacency List Representation

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Advantages

- relatively easy to implement in languages like C
- can represent graphs and digraphs
- memory efficient if $E:V$ relatively small

Disadvantages:

- one graph has many possible representations
(unless lists are ordered by same criterion e.g. ascending)

... Adjacency List Representation

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Graph initialisation

```
newGraph(V):
|   Input   number of nodes V
|   Output new empty graph
|
|   g.nV = V    // #vertices (numbered 0..V-1)
|   g.nE = 0    // #edges
|   allocate memory for g.edges[]
|   for all i=0..V-1 do
|       g.edges[i]=NULL    // empty list
|   end for
|   return g
```

... Adjacency List Representation

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Edge insertion:

```
insertEdge(g, (v,w)):
|   Input   graph g, edge (v,w)
|
|   insertLL(g.edges[v],w)
|   insertLL(g.edges[w],v)
|   g.nE=g.nE+1
```

... Adjacency List Representation

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Edge removal:

```
removeEdge(g, (v,w)):
|   Input   graph g, edge (v,w)
|
|   deleteLL(g.edges[v],w)
|   deleteLL(g.edges[w],v)
|   g.nE=g.nE-1
```

Exercise #6:

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Analyse storage cost and time complexity of adjacency list representation

Storage cost: $O(V+E)$ (V list pointers, total of $2 \cdot E$ list elements)

Cost of operations:

- initialisation: $O(V)$ (initialise V lists)
- insert edge: $O(1)$ (insert one vertex into list)
 - if you don't check for duplicates
- find/delete edge: $O(V)$ (need to find vertex in list)

If vertex lists are sorted

- insert requires search of list $\Rightarrow O(V)$
- delete always requires a search, regardless of list order

Comparison of Graph Representations

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	array of edges	adjacency matrix	adjacency list
space usage	E	V^2	$V+E$
initialise	I	V^2	V
insert edge	I	I	I
find/delete edge	E	I	V

Other operations:

	array of edges	adjacency matrix	adjacency list
disconnected(v)?	E	V	I
isPath(x,y)?	$E \cdot \log V$	V^2	$V+E$
copy graph	E	V^2	E
destroy graph	I	V	E

To check if a graph is connected, we need to traverse all of the vertices to see if they got neighbors. Am I right? Then it should be $O(V)$. Why is it $O(1)$?

I don't know why for this block

Graph Abstract Data Type

Graph ADT

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Data:

- set of edges, set of vertices

Operations:

- building: create graph, add edge
- deleting: remove edge, drop whole graph
- scanning: check if graph contains a given edge

Things to note:

- set of vertices is fixed when graph initialised
- we treat vertices as `ints`, but could be arbitrary `Items`

... Graph ADT

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Graph ADT interface **graph.h**

```
// graph representation is hidden
typedef struct GraphRep *Graph;

// vertices denoted by integers 0..N-1
typedef int Vertex;

// edges are pairs of vertices (end-points)
typedef struct Edge { Vertex v; Vertex w; } Edge;

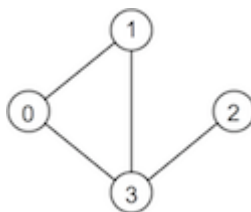
// operations on graphs
Graph newGraph(int V); // new graph with V vertices
void insertEdge(Graph, Edge);
void removeEdge(Graph, Edge);
bool adjacent(Graph, Vertex, Vertex); /* is there an edge
                                         between two vertices */
void freeGraph(Graph);
```

Exercise #7: Graph ADT Client

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Write a program that uses the graph ADT to

- build the graph depicted below
- print all the nodes that are incident to vertex 1 in ascending order



```
#include <stdio.h>
#include "Graph.h"

#define NODES 4
#define NODE_OF_INTEREST 1

int main(void) {
    Graph g = newGraph(NODES);

    Edge e;
    e.v = 0; e.w = 1; insertEdge(g,e);
    e.v = 0; e.w = 3; insertEdge(g,e);
    e.v = 1; e.w = 3; insertEdge(g,e);
    e.v = 3; e.w = 2; insertEdge(g,e);

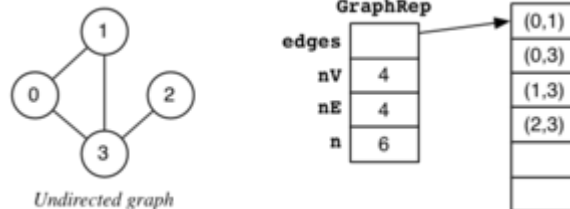
    int v;
    for (v = 0; v < NODES; v++) {
        if (adjacent(g, v, NODE_OF_INTEREST))
            printf("%d\n", v);
    }

    freeGraph(g);
    return 0;
}
```

Graph ADT (Array of Edges)

Implementation of GraphRep (array-of-edges representation)

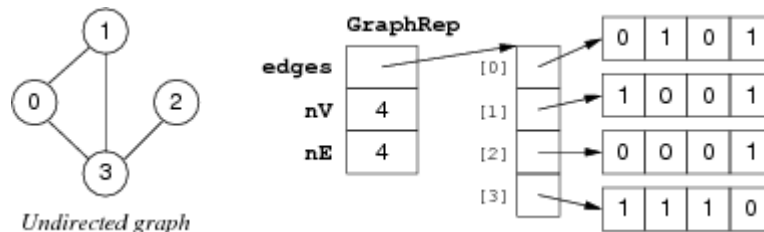
```
typedef struct GraphRep {
    Edge *edges; // array of edges
    int    nV;    // #vertices (numbered 0..nV-1)
    int    nE;    // #edges
    int    n;     // size of edge array
} GraphRep;
```



Graph ADT (Adjacency Matrix)

Implementation of GraphRep (adjacency-matrix representation)

```
typedef struct GraphRep {
    int **edges; // adjacency matrix
    int    nV;    // #vertices
    int    nE;    // #edges
} GraphRep;
```



... Graph ADT (Adjacency Matrix)

Implementation of graph initialisation (adjacency-matrix representation)

```
Graph newGraph(int V) {
    assert(V >= 0);
    int i;

    Graph g = malloc(sizeof(GraphRep));    assert(g != NULL);
    g->nV = V; g->nE = 0;

    // allocate memory for each row
    g->edges = malloc(V * sizeof(int *));    assert(g->edges != NULL);
    // allocate memory for each column and initialise with 0
    for (i = 0; i < V; i++) {
        g->edges[i] = calloc(V, sizeof(int)); assert(g->edges[i] != NULL);
    }
}
```

```
    return g;
}
```

standard library function `calloc(size_t nelems, size_t nbytes)`

- allocates a memory block of size `nelems*nbytes`
- and sets all bytes in that block to *zero*

... Graph ADT (Adjacency Matrix)

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Implementation of edge insertion/removal (adjacency-matrix representation)

```
// check if vertex is valid in a graph
bool validV(Graph g, Vertex v) {
    return (g != NULL && v >= 0 && v < g->nV);
}

void insertEdge(Graph g, Edge e) {
    assert(g != NULL && validV(g,e.v) && validV(g,e.w));

    if (!g->edges[e.v][e.w]) { // edge e not in graph
        g->edges[e.v][e.w] = 1;
        g->edges[e.w][e.v] = 1;
        g->nE++;
    }
}

void removeEdge(Graph g, Edge e) {
    assert(g != NULL && validV(g,e.v) && validV(g,e.w));

    if (g->edges[e.v][e.w]) { // edge e in graph
        g->edges[e.v][e.w] = 0;
        g->edges[e.w][e.v] = 0;
        g->nE--;
    }
}
```

Exercise #8: Checking Neighbours (i)

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Assuming an adjacency-matrix representation ...

Implement a function to check whether two vertices are directly connected by an edge

```
bool adjacent(Graph g, Vertex x, Vertex y) { ... }
```

```
bool adjacent(Graph g, Vertex x, Vertex y) {
    assert(g != NULL && validV(g,x) && validV(g,y));

    return (g->edges[x][y] != 0);
}
```

Graph ADT (Adjacency List)

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Implementation of GraphRep (adjacency-list representation)

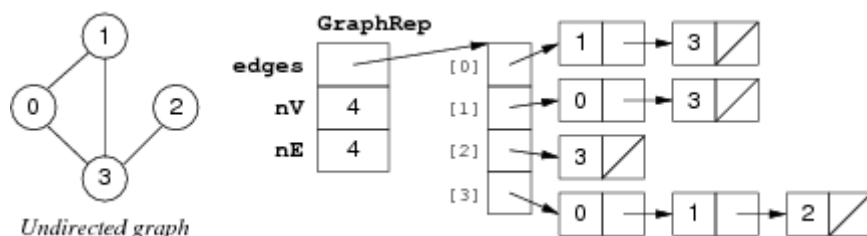
```
typedef struct GraphRep {
    Node **edges; // array of lists
```

```

int    nV;      // #vertices
int    nE;      // #edges
} GraphRep;

typedef struct Node {
    Vertex    v;
    struct Node *next;
} Node;

```



Exercise #9: Checking Neighbours (ii)

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Assuming an adjacency list representation ...

Implement a function to check whether two vertices are directly connected by an edge

```
bool adjacent(Graph g, Vertex x, Vertex y) { ... }
```

```

bool adjacent(Graph g, Vertex x, Vertex y) {
    assert(g != NULL && validV(g,x));

    return inLL(g->edges[x], y);
}

```

inLL() checks if linked list contains an element

Problems on Graphs

Problems on Graphs

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What kind of problems do we want to solve on/via graphs?

- is the graph fully-connected?
- can we remove an edge and keep it fully-connected?
- is one vertex reachable starting from some other vertex?
- which vertices are reachable from v ? (transitive closure)
- is there a cycle that passes through all vertices? (circuit)
- what is the cheapest cost path from v to w ?
- is there a tree that links all vertices? (spanning tree)
- what is the minimum spanning tree?
- what is the maximal flow through a graph?
- ...
- can a graph be drawn in a plane with no crossing edges? (planar graphs)
- are two graphs "equivalent"? (isomorphism)

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Graph Algorithms

In this course we examine algorithms for

- graph traversal (simple graphs)
- reachability (directed graphs)
- minimum spanning trees (weighted graphs)
- shortest path (weighted graphs)
- maximum flow (weighted graphs)

Graph Traversal

Finding a Path

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Questions on paths:

- is there a path between two given vertices ($src, dest$)?
- what is the sequence of vertices from src to $dest$?

Approach to solving problem:

- examine vertices adjacent to src
- if any of them is $dest$, then done
- otherwise try vertices two edges from src
- repeat looking further and further from src

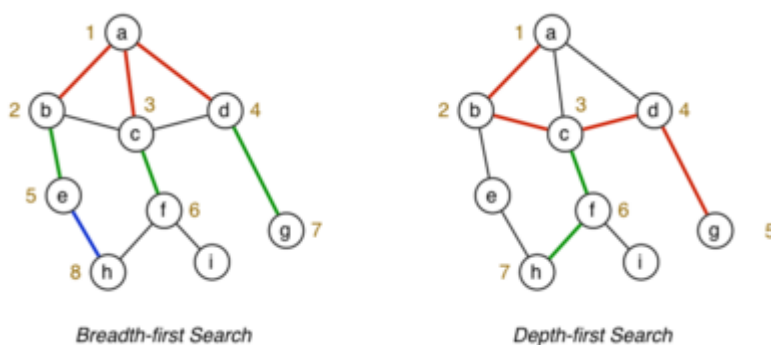
Two strategies for graph traversal/search: *depth-first*, *breadth-first*

- DFS follows one path to completion before considering others
- BFS "fans-out" from the starting vertex ("spreading" subgraph)

... Finding a Path

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Comparison of BFS/DFS search for checking if there is a path from a to h ...



Both approaches ignore some edges by remembering previously visited vertices.

Depth-first Search

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Depth-first search can be described recursively as

depthFirst(G,v):

1. mark v as visited
2. for each $(v,w) \in \text{edges}(G)$ do
 - if w has not been visited then
 - depthFirst(w)**

The recursion induces *backtracking*

... Depth-first Search

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Recursive DFS path checking

```

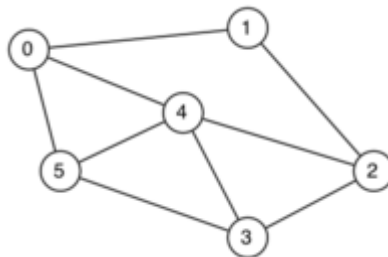
hasPath(G,src,dest):
|   Input  graph G, vertices src,dest
|   Output true if there is a path from src to dest in G,
|           false otherwise
|
|   mark all vertices in G as unvisited
|   return dfsPathCheck(G,src,dest)

dfsPathCheck(G,v,dest):
|   mark v as visited
|   if v=dest then           // found dest
|       return true
|   else
|       for all (v,w)∈edges(G) do
|           if w has not been visited then
|               return dfsPathCheck(G,w,dest) // found path via w to dest
|           end if
|       end for
|   end if
|   return false           // no path from v to dest
  
```

Exercise #10: Depth-first Traversal (i)

69/106

Trace the execution of `dfsPathCheck(G,0,5)` on:



Consider neighbours in ascending order

Answer:

0 - 1 - 2 - 3 - 4 - 5

... Depth-first Search

Cost analysis:

- all vertices marked as unvisited, each vertex visited at most once \Rightarrow cost = $O(V)$
- visit all edges incident on visited vertices \Rightarrow cost = $O(E)$
 - assuming an adjacency list representation

Time complexity of DFS: $O(V+E)$ (adjacency list representation)

- the larger of V, E determines the complexity

... Depth-first Search

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Note how different graph data structures affect cost:

- **array-of-edges representation**
 - visit all edges incident on visited vertices \Rightarrow cost = $O(V \cdot E)$
 - cost of DFS: $O(V \cdot E)$
- **adjacency-matrix representation**
 - visit all edges incident on visited vertices \Rightarrow cost = $O(V^2)$
 - cost of DFS: $O(V^2)$

For *dense graphs* ... $E \cong V^2 \Rightarrow O(V+E) = O(V^2)$

For *sparse graphs* ... $E \cong V \Rightarrow O(V+E) = O(E)$

... Depth-first Search

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Knowing whether a path exists can be useful

Knowing what the path is even more useful

\Rightarrow record the previously visited node as we search through the graph (so that we can then trace path through graph)

Make use of global variable:

- `visited[]` ... array to store previously visited node, for each node being visited

... Depth-first Search

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`visited[]` // store previously visited node, for each vertex $0..nV-1$

```
findPath(G,src,dest):
|   Input graph G, vertices src,dest
|
|   for all vertices v∈G do
|       visited[v]=-1
|   end for
|   visited[src]=src                                // starting node of the path
|   if dfsPathCheck(G,src,dest) then                // show path in dest..src order
|       v=dest
|       while v≠src do
|           print v "-"
|           v=visited[v]
|       end while
```

```

|   |   print src
|   |   end if

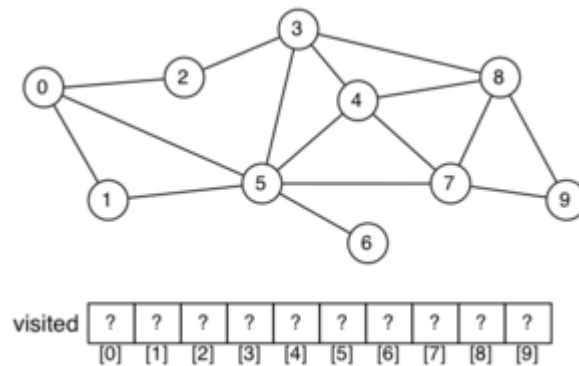
dfsPathCheck(G,v,dest):
|   if v=dest then                // found edge from v to dest
|       return true
|   else
|       for all (v,w)∈edges(G) do
|           if visited[w]=-1 then
|               visited[w]=v
|               if dfsPathCheck(G,w,dest) then
|                   return true    // found path via w to dest
|               end if
|           end if
|       end for
|   end if
|   return false                  // no path from v to dest

```

Exercise #11: Depth-first Traversal (ii)

75/106

Show the DFS order in which we visit vertices in this graph when searching for a path from 0 to 6:



Consider neighbours in ascending order

0	0	3	5	3	1	5	4	7	8
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]

Path: 6-5-1-0

... Depth-first Search

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DFS can also be described non-recursively (via a *stack*):

```

hasPath(G,src,dest):
|   Input  graph G, vertices src,dest
|   Output true if there is a path from src to dest in G,
|           false otherwise
|
|   mark all vertices in G as unvisited
|   push src onto new stack s
|   found=false
|   while not found and s is not empty do

```

```

pop v from s
mark v as visited
if v=dest then
    found=true
else
    for each (v,w)∈edges(G) such that w has not been visited
        push w onto s
    end for
end if
end while
return found

```

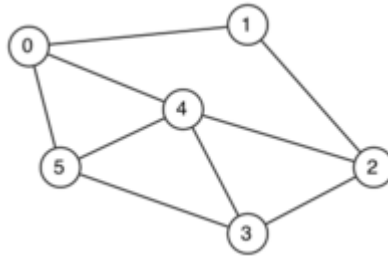
Uses standard stack operations (push, pop, check if empty)

Time complexity is the same: $O(V+E)$ (each vertex added to stack once, each element in vertex's adjacency list visited once)

Exercise #12: Depth-first Traversal (iii)

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Show how the stack evolves when executing `findPathDFS(g, 0, 5)` on:



Push neighbours in *descending* order ... so they get popped in ascending order

						4	5
				3	5	5	5
	1	2	4	4	4	4	4
	4	4	4	4	4	4	4
(empty)	→ 0	→ 5	→ 5	→ 5	→ 5	→ 5	→ 5

Breadth-first Search

80/106

Basic approach to breadth-first search (BFS):

- visit and mark current vertex
- visit all neighbours of current vertex
- then consider neighbours of neighbours

Notes:

- tricky to describe recursively
- a minor variation on non-recursive DFS search works
⇒ switch the *stack* for a *queue*

... Breadth-first Search

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BFS algorithm (records visiting order, marks vertices as visited when put *on* queue):

visited[] // array of visiting orders, indexed by vertex 0..nV-1

```

findPathBFS(G,src,dest):
    Input graph G, vertices src,dest

    for all vertices v∈G do
        visited[v]=-1
    end for
    enqueue src into new queue q
    visited[src]=src
    found=false
    while not found and q is not empty do
        dequeue v from q
        if v=dest then
            found=true
        else
            for each (v,w)∈edges(G) such that visited[w]=-1 do
                enqueue w into q
                visited[w]=v
            end for
        end if
    end while
    if found then
        display path in dest..src order
    end if

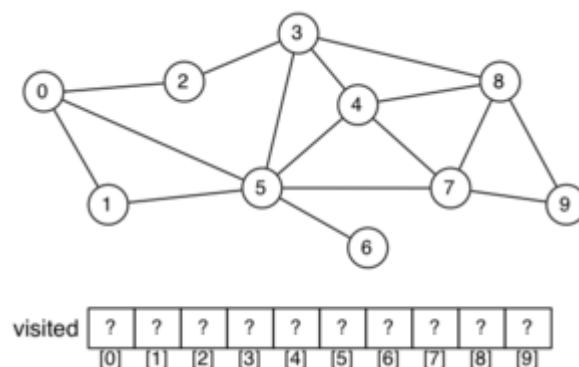
```

Uses standard queue operations (enqueue, dequeue, check if empty)

Exercise #13: Breadth-first Traversal

82/106

Show the BFS order in which we visit vertices in this graph when searching for a path from 0 to 6:



Consider neighbours in ascending order

0	0	0	2	5	0	5	5	3	-1
[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]

Path: 6-5-0

... Breadth-first Search

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Time complexity of BFS: $O(V+E)$ (adjacency list representation, same as DFS)

BFS finds a "shortest" path

- based on minimum # edges between *src* and *dest*.
- stops with first-found path, if there are multiple ones

In many applications, edges are weighted and we want path

- based on minimum sum-of-weights along path *src* .. *dest*

We discuss weighted/directed graphs later.

Other DFS Examples

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Other problems to solve via DFS graph search

- checking for the existence of a cycle
- determining which connected component each vertex is in



Graph with two connected components, a path and a cycle

Exercise #14: Buggy Cycle Check

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A graph has a cycle if

- it has a path of length > 1
- with start vertex *src* = end vertex *dest*
- and without using any edge more than once

We are not required to give the path, just indicate its presence.

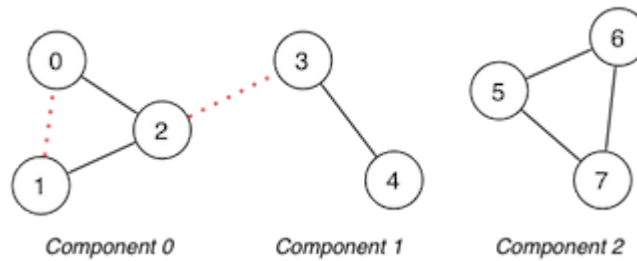
The following DFS cycle check has two bugs. Find them.

```
hasCycle(G):
|   Input  graph G
|   Output true if G has a cycle, false otherwise
|
|   choose any vertex v ∈ G
|   return dfsCycleCheck(G, v)

dfsCycleCheck(G, v):
|   mark v as visited
|   for each (v, w) ∈ edges(G) do
|       if w has been visited then    // found cycle
|           return true
|       else if dfsCycleCheck(G, w) then
```


Trace the execution of the algorithm

1. on the graph shown below
2. on the same graph but with the dotted edges added



Consider neighbours in ascending order

1.

[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]
-1	-1	-1	-1	-1	-1	-1	-1
0	-1	-1	-1	-1	-1	-1	-1
0	-1	0	-1	-1	-1	-1	-1
0	0	0	-1	-1	-1	-1	-1
0	0	0	1	-1	-1	-1	-1
...							
0	0	0	1	1	2	2	2

2.

[0]	[1]	[2]	[3]	[4]	[5]	[6]	[7]
-1	-1	-1	-1	-1	-1	-1	-1
0	-1	-1	-1	-1	-1	-1	-1
0	0	-1	-1	-1	-1	-1	-1
0	0	0	-1	-1	-1	-1	-1
...							
0	0	0	0	0	1	1	1

Hamiltonian and Euler Paths

Hamiltonian Path and Circuit

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Hamiltonian path problem:

- find a path connecting two vertices v, w in graph G
- such that the path includes each *vertex* exactly once

If $v = w$, then we have a *Hamiltonian circuit*

Simple to state, but difficult to solve (*NP*-complete)

Many real-world applications require you to visit all vertices of a graph:

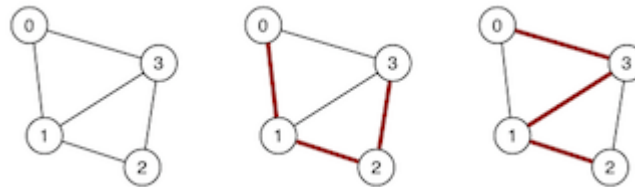
- Travelling salesman
- Bus routes
- ...

Problem named after Irish mathematician, physicist and astronomer Sir William Rowan Hamilton (1805 — 1865)

... Hamiltonian Path and Circuit

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Graph and two possible Hamiltonian paths:



... Hamiltonian Path and Circuit

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Approach:

- generate all possible simple paths (using e.g. DFS)
- keep a counter of vertices visited in current path
- stop when find a path containing V vertices

Can be expressed via a recursive DFS algorithm

- similar to simple path finding approach, except
 - keeps track of path length; succeeds if length = v
 - resets "visited" marker after unsuccessful path

... Hamiltonian Path and Circuit

96/106

Algorithm for finding Hamiltonian path:

`visited[]` // array `[0..nV-1]` to keep track of visited vertices

```
hasHamiltonianPath(G,src,dest):
|   for all vertices v∈G do
|       visited[v]=false
|   end for
|   return hamiltonR(G,src,dest,#vertices(G)-1)

hamiltonR(G,v,dest,d):
|   Input G      graph
|           v      current vertex considered
|           dest  destination vertex
|           d      distance "remaining" until path found
|
|   if v=dest then
|       if d=0 then return true else return false
|   else
|       mark v as visited
|       for each unvisited neighbour w of v in G do
|           if hamiltonR(G,w,dest,d-1) then
```

```

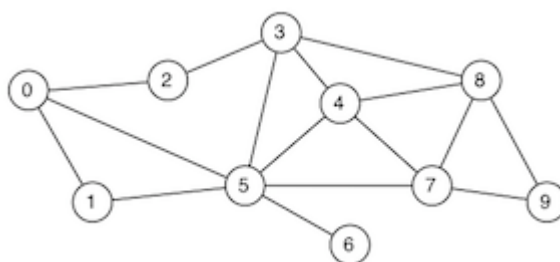
    return true
  end if
end for
end if
mark v as unvisited      // reset visited mark
return false

```

Exercise #16: Hamiltonian Path

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Trace the execution of the algorithm when searching for a Hamiltonian path from 1 to 6:



Consider neighbours in ascending order

1-0-2-3-4-5-6	$d \neq 0$
1-0-2-3-4-5-7-8-9	no unvisited neighbour
1-0-2-3-4-5-7-9-8	no unvisited neighbour
1-0-2-3-4-7-5-6	$d \neq 0$
1-0-2-3-4-7-8-9	no unvisited neighbour
1-0-2-3-4-7-9-8	no unvisited neighbour
1-0-2-3-4-8-7-5-6	$d \neq 0$
1-0-2-3-4-8-7-9	no unvisited neighbour
1-0-2-3-4-8-9-7-5-6	✓

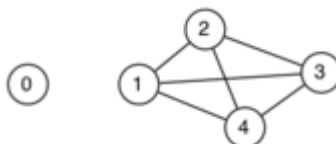
Repeat on your own with `src=0` and `dest=6`

... Hamiltonian Path and Circuit

99/106

Analysis: worst case requires $(V-1)!$ paths to be examined

Consider a graph with isolated vertex and the rest fully-connected



Checking `hasHamiltonianPath(g, x, 0)` for any x

- requires us to consider every possible path
- e.g 1-2-3-4, 1-2-4-3, 1-3-2-4, 1-3-4-2, 1-4-2-3, ...
- starting from any x , there are $3!$ paths $\Rightarrow 4!$ total paths
- there is no path of length 5 in these $(V-1)!$ possibilities

There is no known simpler algorithm for this task \Rightarrow *NP*-hard.

Note, however, that the above case could be solved in constant time if we had a fast check for 0 and x being in the same connected component

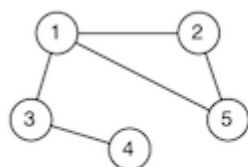
Euler Path and Circuit

100/106

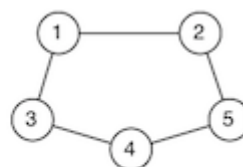
Euler path problem:

- find a path connecting two vertices v, w in graph G
- such that the path includes each *edge* exactly once
(note: the path does not have to be simple \Rightarrow can visit vertices more than once)

If $v = w$, then we have an *Euler circuit*



Euler Path: 4-3-1-5-2-1



Euler Circuit: 1-2-5-4-3-1

Many real-world applications require you to visit all edges of a graph:

- Postman
- Garbage pickup
- ...

Problem named after Swiss mathematician, physicist, astronomer, logician and engineer Leonhard Euler (1707 — 1783)

... Euler Path and Circuit

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One possible "brute-force" approach:

- check for each path if it's an Euler path
- would result in factorial time performance

Can develop a better algorithm by exploiting:

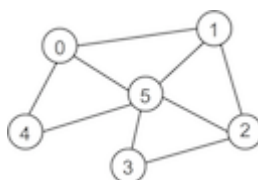
Theorem. A graph has an Euler circuit if and only if it is connected and all vertices have even degree

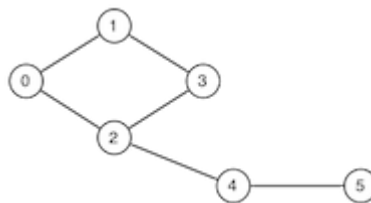
Theorem. A graph has a non-circuitous Euler path if and only if it is connected and exactly two vertices have odd degree

Exercise #17: Euler Paths and Circuits

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Which of these two graphs have an Euler path? an Euler circuit?





No Euler circuit

Only the second graph has an Euler path, e.g. 2-0-1-3-2-4-5

... Euler Path and Circuit

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Assume the existence of $\text{degree}(g, v)$ (degree of a vertex, cf. week 5 problem set)

Algorithm to check whether a graph has an Euler path:

```

hasEulerPath(G, src, dest):
  Input  graph G, vertices src, dest
  Output true if G has Euler path from src to dest
         false otherwise

  if src ≠ dest then           // non-circuitous path
    if degree(G, src) or degree(G, dest) is even then
      return false
    end if
  else if degree(G, src) is odd then // circuit
    return false
  end if
  for all vertices v ∈ G do
    if v ≠ src and v ≠ dest and degree(G, v) is odd then
      return false
    end if
  end for
  return true
  
```

... Euler Path and Circuit

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Analysis of hasEulerPath algorithm:

- assume that connectivity is already checked
- assume that degree is available via $O(1)$ lookup
- single loop over all vertices $\Rightarrow O(V)$

If degree requires iteration over vertices

- cost to compute degree of a single vertex is $O(V)$
- overall cost is $O(V^2)$

\Rightarrow problem tractable, even for large graphs (unlike Hamiltonian path problem)

For the keen, a linear-time (in the number of edges, E) algorithm to compute an Euler path is described in [Sedgewick] Ch.17.7.

Summary

- Graph terminology
 - vertices, edges, vertex degree, connected graph, tree
 - path, cycle, clique, spanning tree, spanning forest
- Graph representations
 - array of edges
 - adjacency matrix
 - adjacency lists
- Graph traversal
 - depth-first search (DFS)
 - breadth-first search (BFS)
 - cycle check, connected components
 - Hamiltonian paths/circuits, Euler paths/circuits
- Suggested reading (Sedgewick):
 - graph representations ... Ch. 17.1-17.5
 - Hamiltonian/Euler paths ... Ch. 17.7
 - graph search ... Ch. 18.1-18.3, 18.7

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