CS101 Algorithms and Data Structures

Graphs

Textbook Ch B.4, B.5.1, 22.1

Outline

- Definitions
  - Undirected graphs
  - Directed graph
- Representation
  - Adjacency matrix
  - Adjacency list

Undirected Graphs

We will define an Undirected Graph ADT as a collection of *vertices*

$$V = \{v_1, v_2, ..., v_n\}$$

- The number of vertices is denoted by

$$|V| = n$$

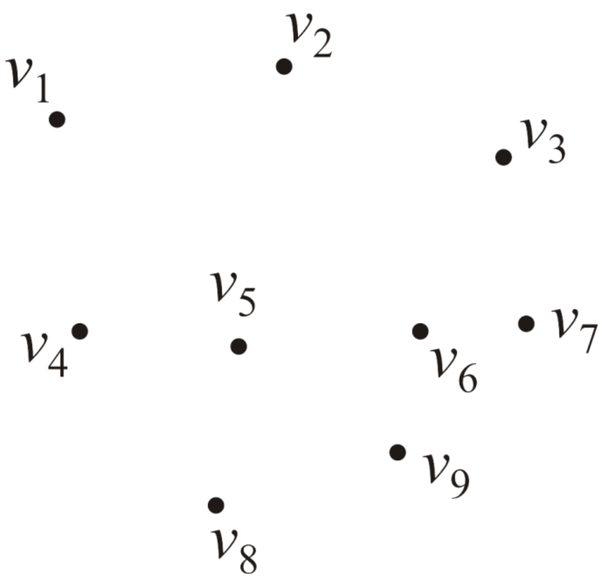
- Associated with this is a collection E of <u>unordered</u> pairs $\{v_i, v_j\}$ termed *edges* which connect the vertices

Undirected Graphs

Consider this collection of vertices

$$V = \{v_1, v_2, ..., v_9\}$$

where $|V| = n = 9$

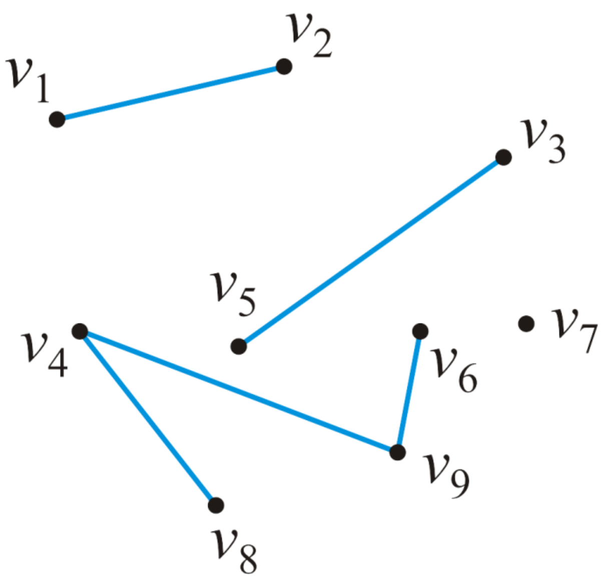


Undirected graphs

Associated with these vertices are $|E| = 5$ edges

$$E = \{\{v_1, v_2\}, \{v_3, v_5\}, \{v_4, v_8\}, \{v_4, v_9\}, \{v_6, v_9\}\}$$

- The pair $\{v_j , v_k\}$ indicates that both vertex v_j is adjacent to vertex v_k and vertex v_k is adjacent to vertex v_j



Undirected graphs

We will assume that a vertex is never adjacent to itself

– For example, $\{v_1, v_1\}$ will not define an edge

The maximum number of edges in an undirected graph is

$$|E| \le \binom{|V|}{2} = \frac{|V|\left(|V|-1\right)}{2} = \mathrm{O}\left(|V|^2\right)$$

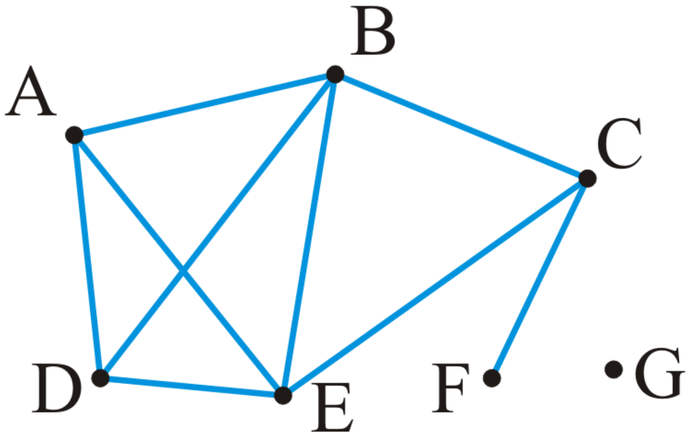
An undirected graph

Example: given the $|V| = 7$ vertices

$$V = \{A, B, C, D, E, F, G\}$$

and the $|E| = 9$ edges

$$E = \{\{A, B\}, \{A, D\}, \{A, E\}, \{B, C\}, \{B, D\}, \{B, E\}, \{C, E\}, \{C, F\}, \{D, E\}\}$$



Degree

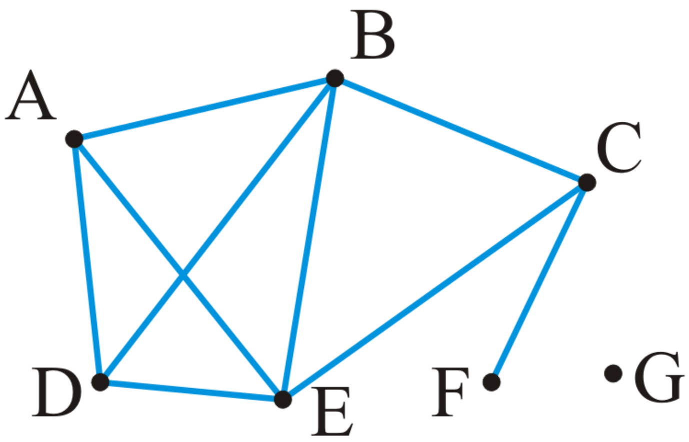
The degree of a vertex is defined as the number of adjacent vertices

degree(A) = degree(D) = degree(C) = 3

degree(B) = degree(E) = 4

degree(F) = 1

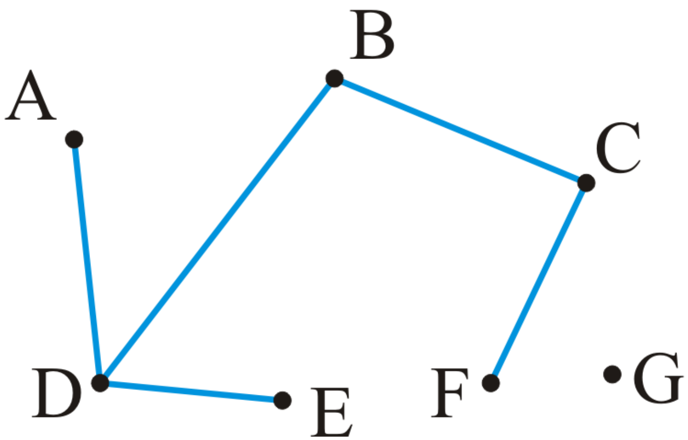
degree(G) = 0

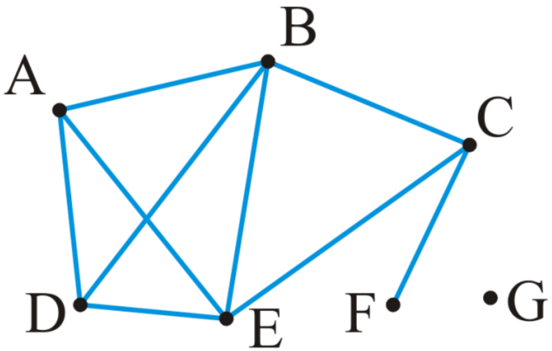


Those vertices adjacent to a given vertex are its *neighbors*

Sub-graphs

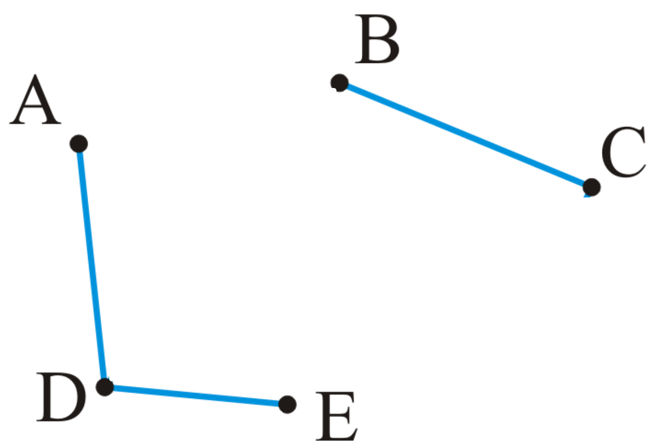
A *sub-graph* of a graph contains a subset of the vertices and a subset of the edges that connect the subset of the vertices in the original graph

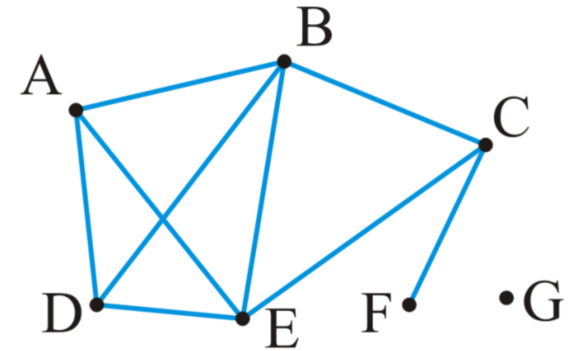




Sub-graphs

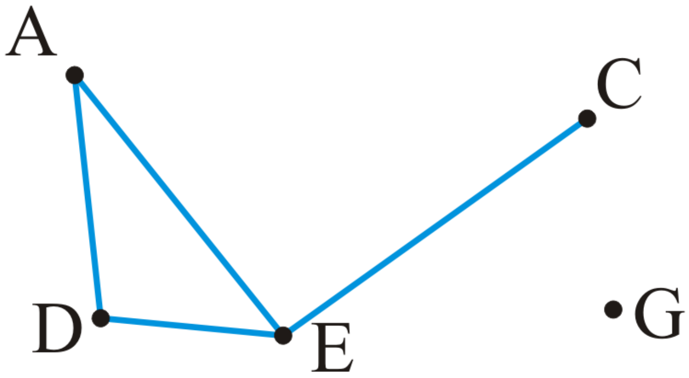
A *sub-graph* of a graph contains a subset of the vertices and a subset of the edges that connect the subset of the vertices in the original graph

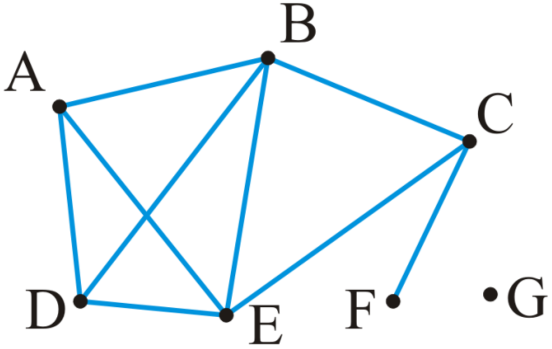




Vertex-induced sub-graphs

A *vertex-induced sub-graph* contains a subset of the vertices and all the edges in the original graph between those vertices





Paths

A path in an undirected graph is an ordered sequence of vertices

$(v_0, v_1, v_2, ..., v_k)$

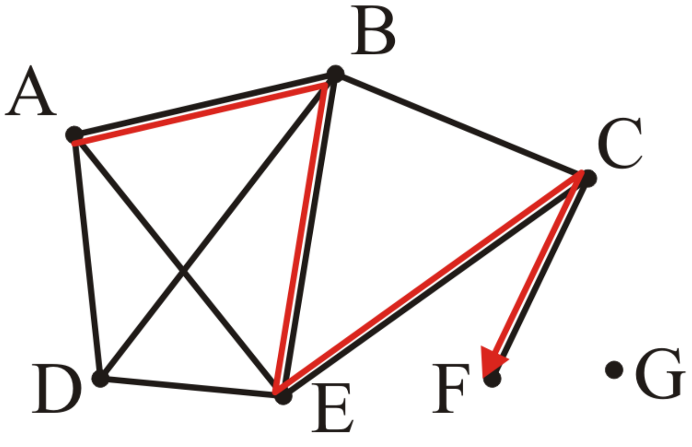
where $\{v_{j-1}, v_j\}$ is an edge for $j = 1, ..., k$

- Termed *a path from* v_0 *to* v_k
- The length of this path is k

Paths

A path of length 4:

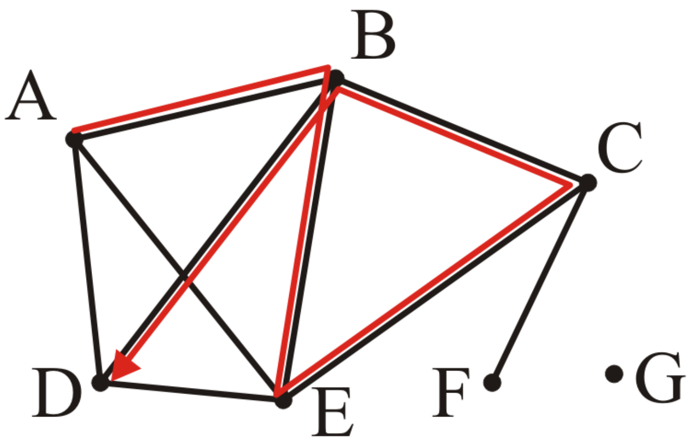
(A, B, E, C, F)



Paths

A path of length 5:

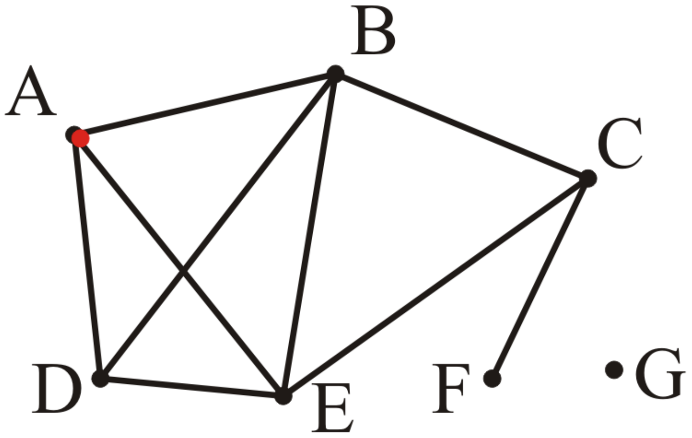
(A, B, E, C, B, D)



Paths

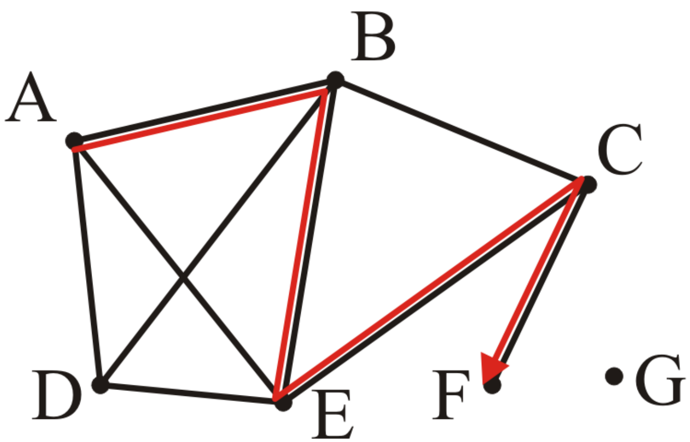
A *trivial* path of length 0:

(A)

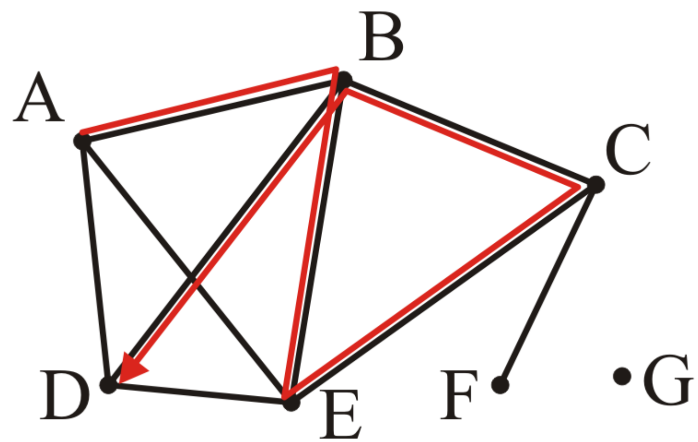


Simple path

A *simple path* has no repetitions (other than perhaps the first and last vertices)



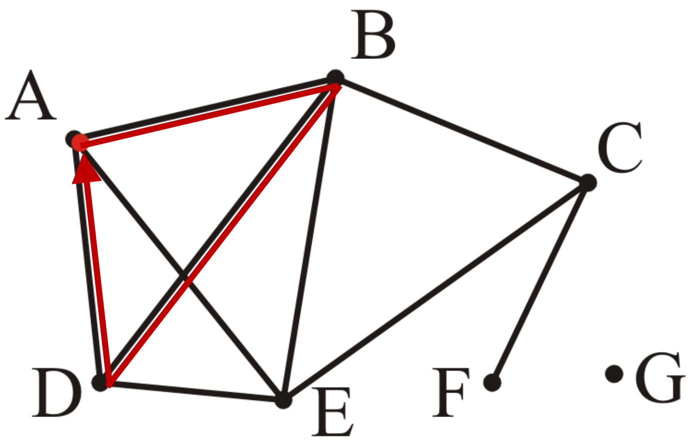
(A, B, E, C, F)



(A, B, E, C, B, D)

Simple cycle

A *simple cycle* is a simple path of at least two vertices with the first and last vertices equal

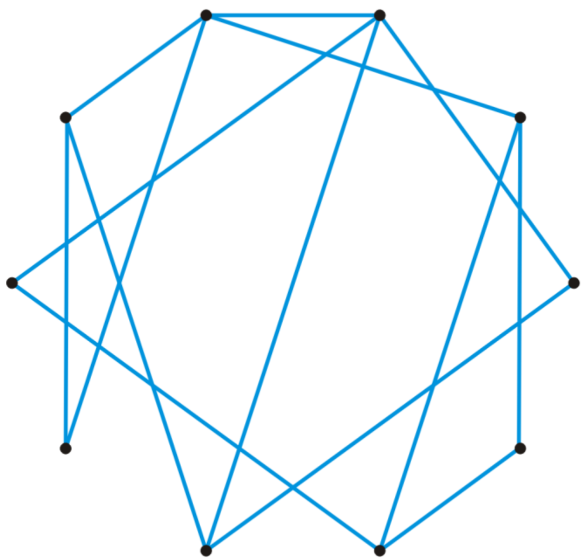


(A, B, D, A)

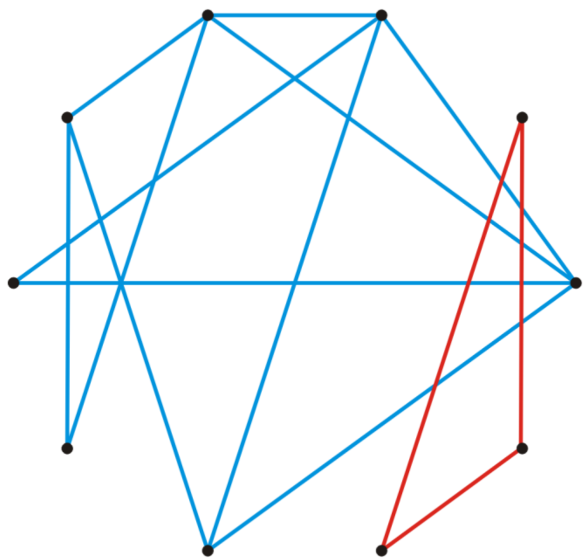
Connectedness

Two vertices v_i, v_j are said to be *connected* if there exists a path from v_i to v_j

A graph is connected if there exists a path between any two vertices



A connected graph

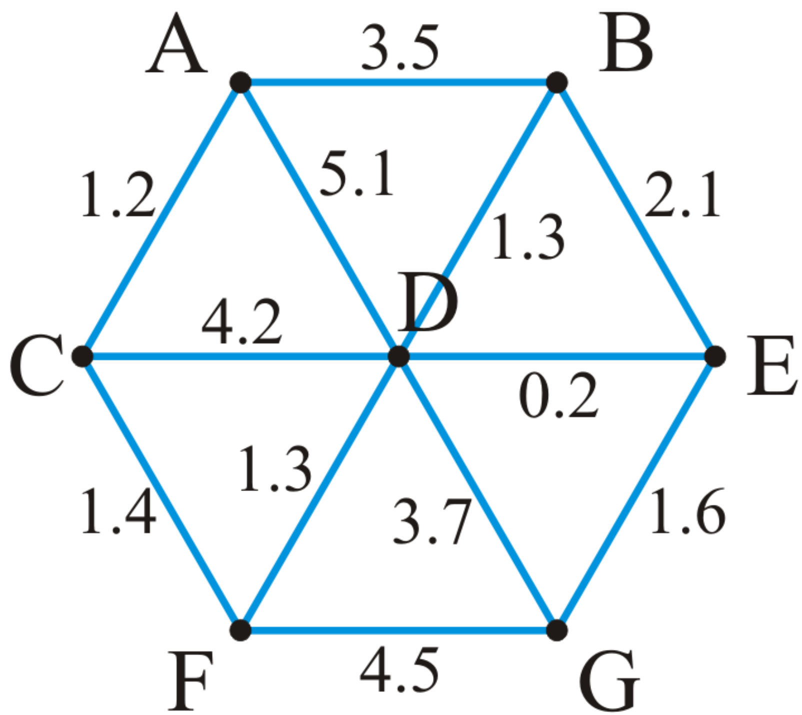


An unconnected graph

Weighted graphs

A weight may be associated with each edge in a graph

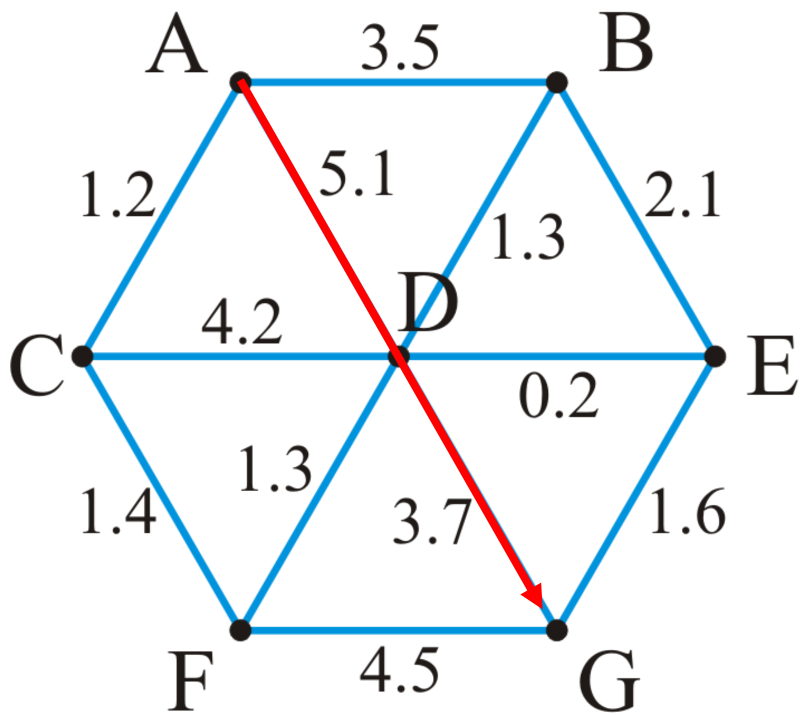
- This could represent distance, energy consumption, cost, etc.
- Such a graph is called a *weighted graph*



Weighted graphs

The *length* of a path within a weighted graph is the sum of all of the edges which make up the path

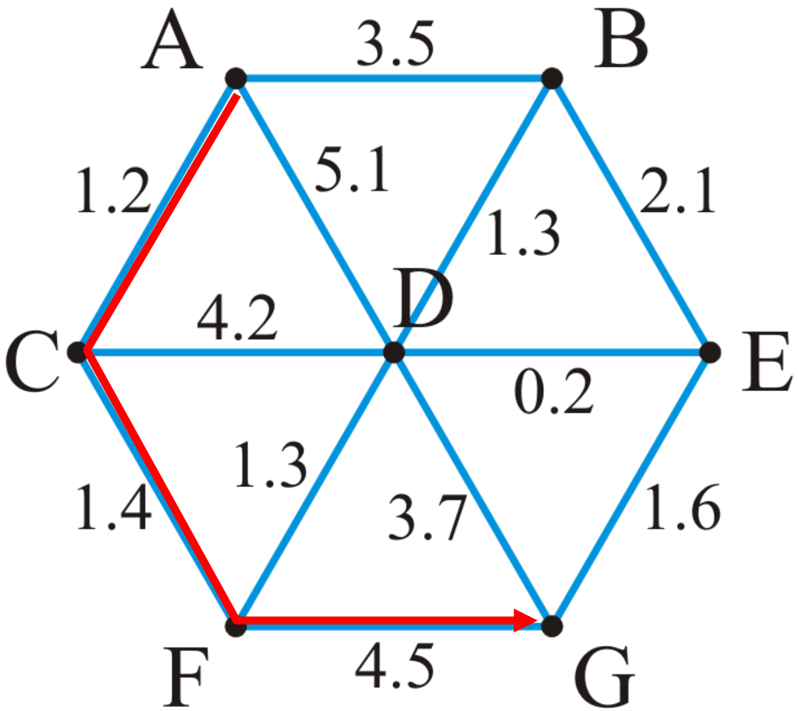
- The length of the path (A, D, G) in the following graph is $5.1 + 3.7 = 8.8$



Weighted graphs

Different paths may have different weights

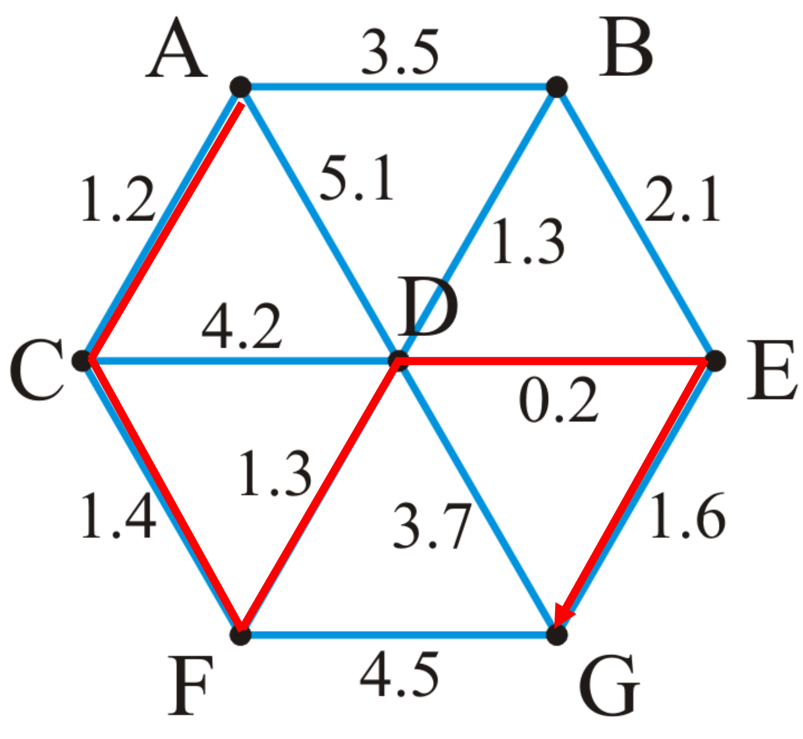
- Another path is (A, C, F, G) with length $1.2 + 1.4 + 4.5 = 7.1$



Weighted graphs

Problem: find the shortest path between two vertices

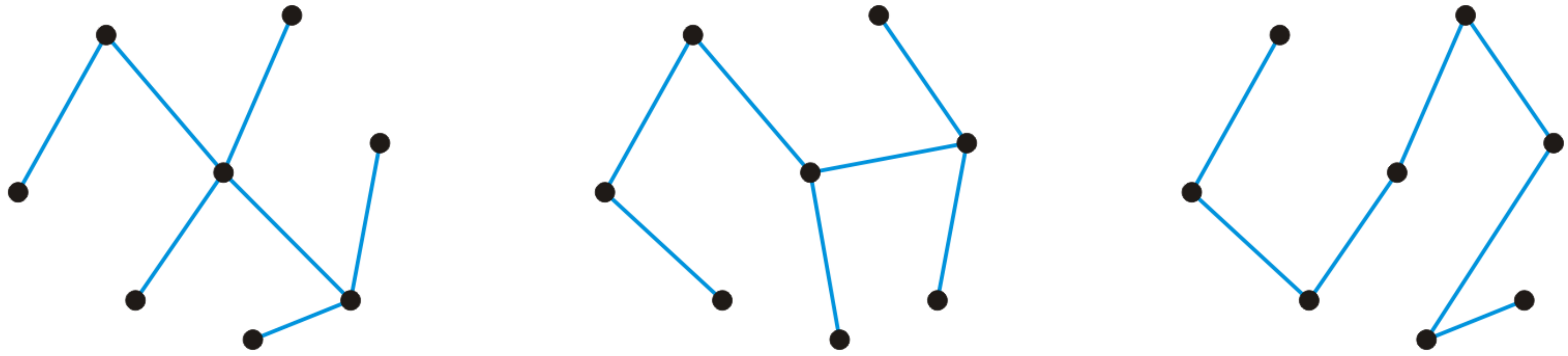
- Here, the shortest path from A to G is (A, C, F, D, E, G) with length 5.7



Trees

A graph is a tree if it is connected and there is a unique path between any two vertices

- Example: three trees on the same eight vertices



Properties:

- The number of edges is $|E| = |V| - 1$
- The graph is *acyclic*, that is, it does not contain any cycles
- Adding one more edge must create a cycle
- Removing any one edge creates two unconnected sub-graphs

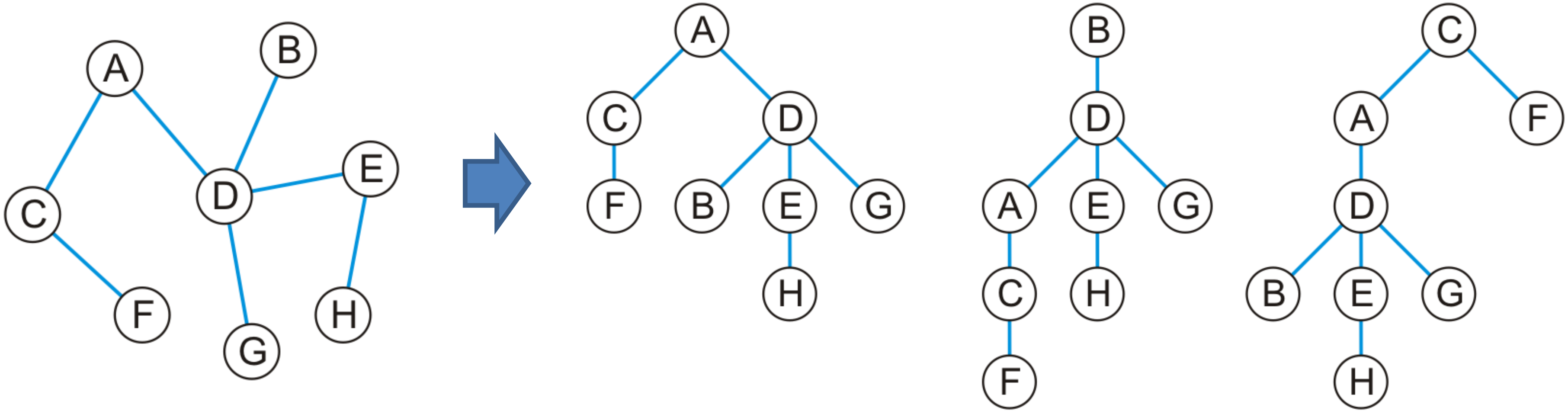
Trees

Any tree can be converted into a rooted tree by:

– Choosing any vertex to be the root
– Defining its neighboring vertices as its children

and then recursively defining:

– All neighboring vertices other than that one designated its parent to be its children



Forests

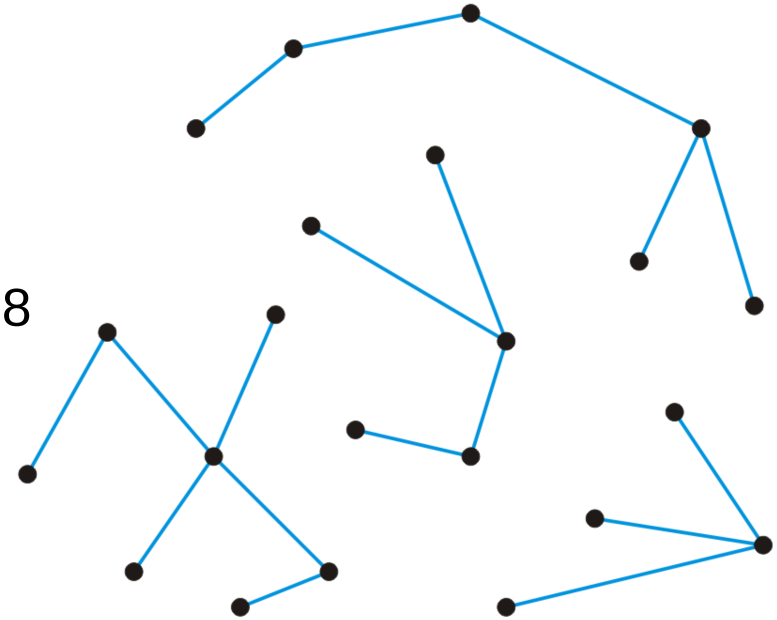
A forest is any graph that has no cycles

Consequences:

- The number of edges is $|E| < |V|$
- The number of trees is $|V| - |E|$
- Removing any one edge adds one more tree to the forest

Here is a forest with 22 vertices and 18 edges

- There are four trees



Outline

- Definitions
  - Undirected graphs
  - Directed graph
- Representation
  - Adjacency matrix
  - Adjacency list

Directed graphs

In a *directed graph*, the edges on a graph are be associated with a direction

- Edges are ordered pairs (v_j, v_k) denoting a connection from v_j to v_k
- The edge (v_j, v_k) is different from the edge (v_k, v_j)

Streets are directed graphs:

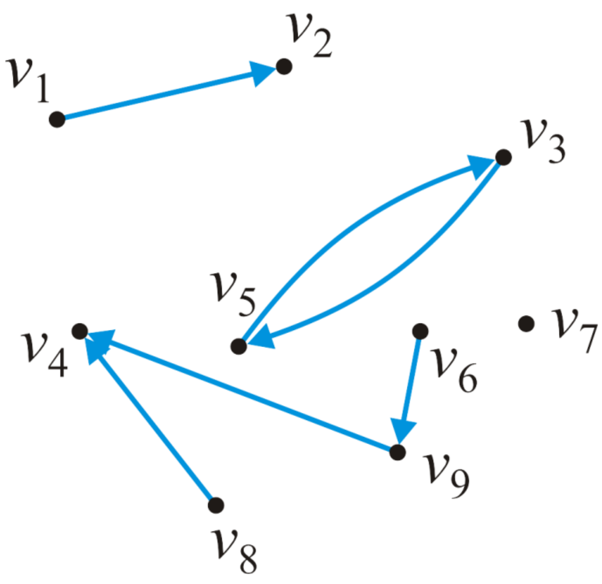
- In most cases, you can go two ways unless it is a one-way street

Directed graphs

Given a graph of nine vertices $V = \{v_1, v_2, \ldots v_9\}$

– These six pairs (v_j, v_k) are *directed edges*

$$E = \{(v_1, v_2), (v_3, v_5), (v_5, v_3), (v_6, v_9), (v_8, v_4), (v_9, v_4)\}$$



Directed graphs

The maximum number of directed edges in a directed graph is

$$|E| \le 2\binom{|V|}{2} = 2\frac{|V|\left(|V|-1\right)}{2} = |V|\left(|V|-1\right) = \mathrm{O}\left(|V|^2\right)$$

In and out degrees

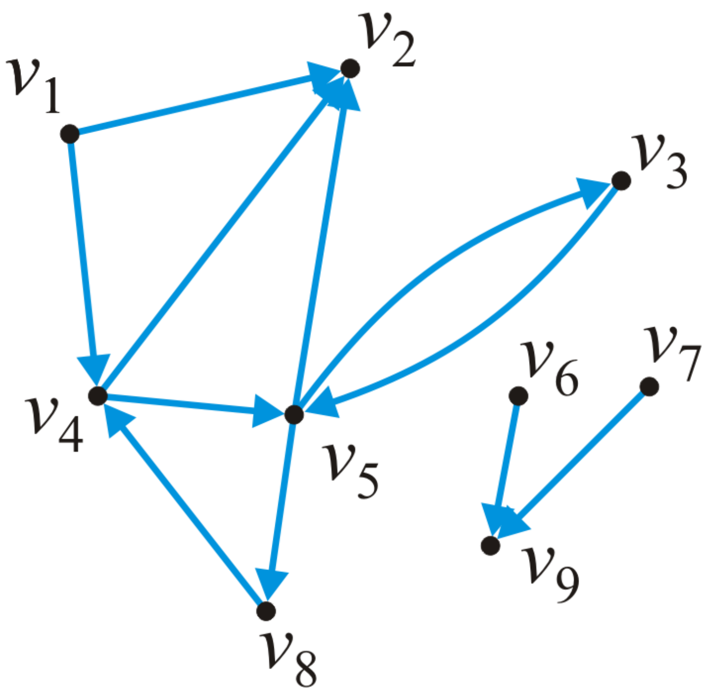
The degree of a vertex in a directed graph:

- The *out-degree* of a vertex is the number of outward edges from the vertex
- The *in-degree* of a vertex is the number of inward edges to the vertex

In this graph:

in_degree(v_1) = 0   out_degree(v_1) = 2

in_degree(v_5) = 2   out_degree(v_5) = 3



Sources and sinks

Definitions:

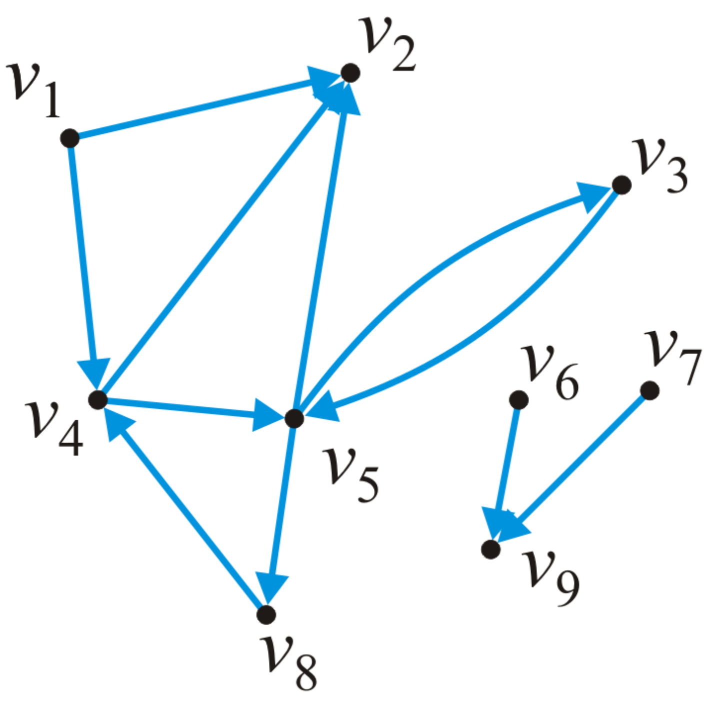
– Vertices with an in-degree of zero are described as *sources*

– Vertices with an out-degree of zero are described as *sinks*

In this graph:

– Sources: v_1, v_6, v_7

– Sinks: v_2, v_9



Paths

A path in a directed graph is an ordered sequence of vertices

$(v_0, v_1, v_2, ..., v_k)$

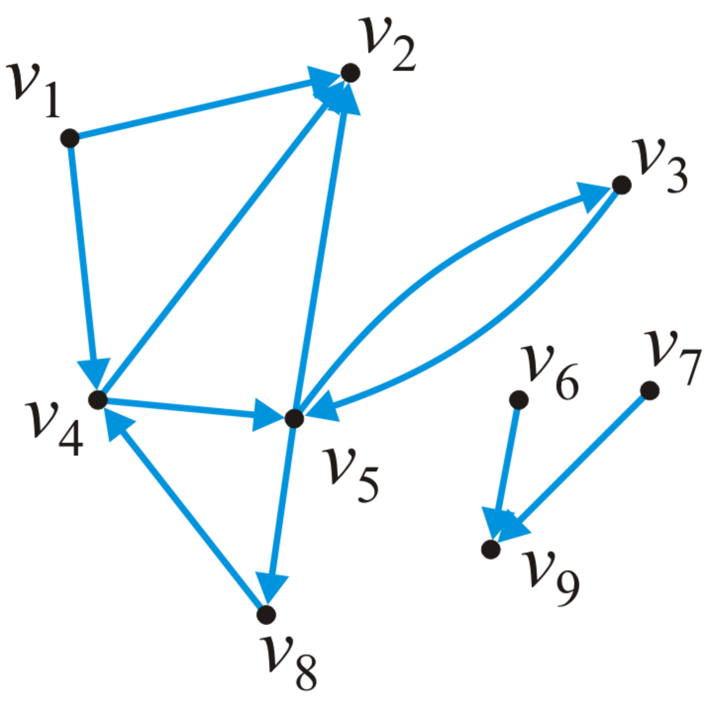
where (v_{j-1}, v_j) is an edge for $j = 1, ..., k$

A path of length 5 in this graph is

$(v_1, v_4, v_5, v_3, v_5, v_2)$

A simple cycle of length 3 is

(v_8, v_4, v_5, v_8)



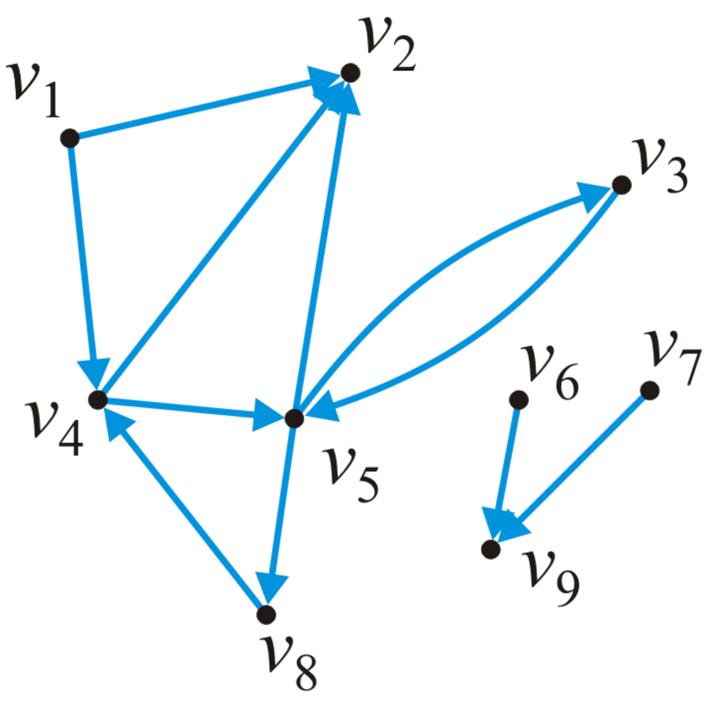
Connectedness

Two vertices v_j, v_k are said to be *connected* if there exists a path from v_j to v_k

- A graph is *strongly connected* if there exists a directed path between any two vertices
- A graph is *weakly connected* there exists a path between any two vertices that ignores the direction

In this graph:

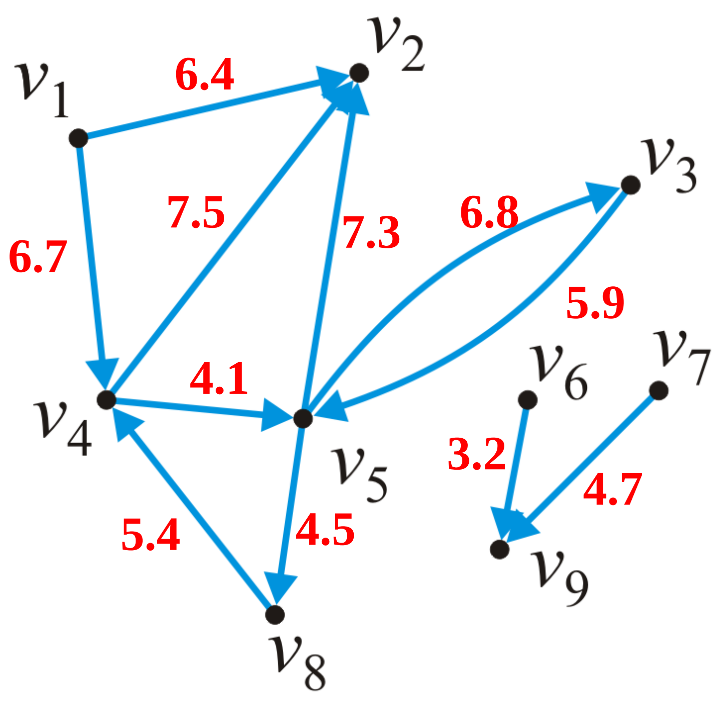
- The sub-graph $\{v_3, v_4, v_5, v_8\}$ is strongly connected
- The sub-graph $\{v_1, v_2, v_3, v_4, v_5, v_8\}$ is weakly connected



Weighted directed graphs

In a weighted directed graphs, each edge is associated with a value

If both (v_j, v_k) and (v_k, v_j) are edges, it is not required that they have the same weight



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  - Adjacency list

The Graph ADT

The Graph ADT describes a container storing an adjacency relation

- Queries include:
  - The number of vertices
  - The number of edges
  - List the vertices adjacent to a given vertex
  - Are two vertices adjacent?
  - Are two vertices connected?

- Modifications include:
  - Inserting or removing an edge
  - Inserting or removing a vertex (and all edges containing that vertex)

The run-time of these operations will depend on the representation

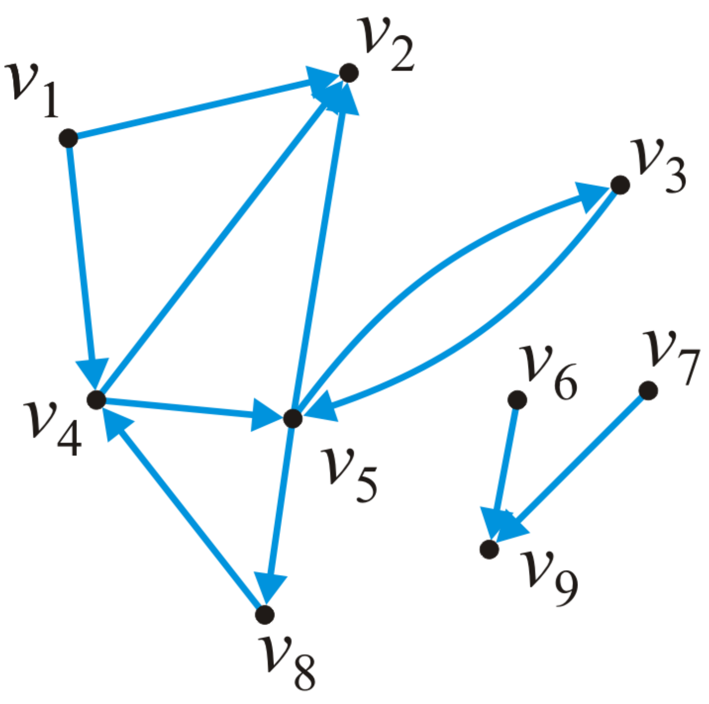
Binary-relation list

The most inefficient is a relation list:

- A container storing the edges

  $\{(1, 2), (1, 4), (3, 5), (4, 2), (4, 5), (5, 2), (5, 3), (5, 8), (6, 9), (7, 9), (8, 4)\}$

- Requires $\Theta(|E|)$ memory
- Determining if v_j is adjacent to v_k is $O(|E|)$
- Finding all neighbors of v_j is $\Theta(|E|)$

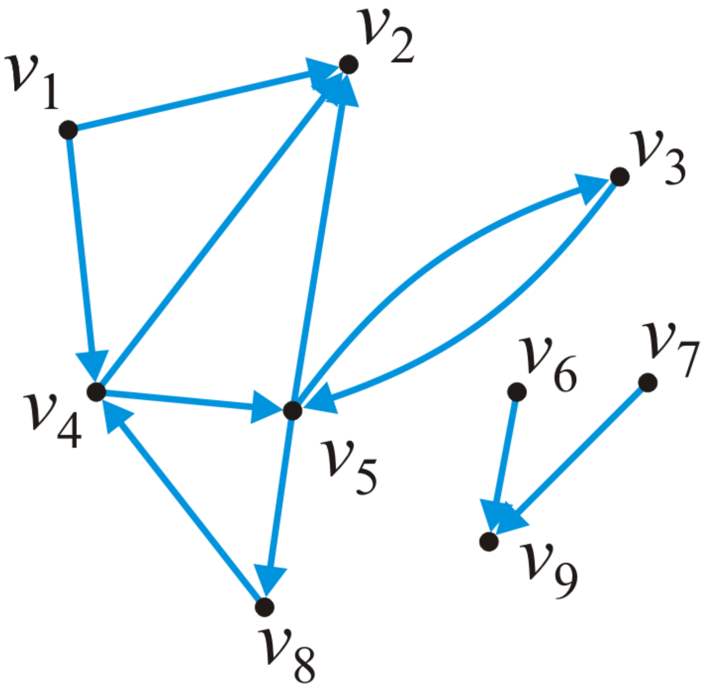


Adjacency matrix

Requiring more memory but also faster, an adjacency matrix

– The matrix entry (j, k) is set to true if there is an edge (v_j, v_k)

	1	2	3	4	5	6	7	8	9
1		T		T					
2									
3					T				
4		T			T				
5		T	T					T	
6									T
7									T
8				T					
9									



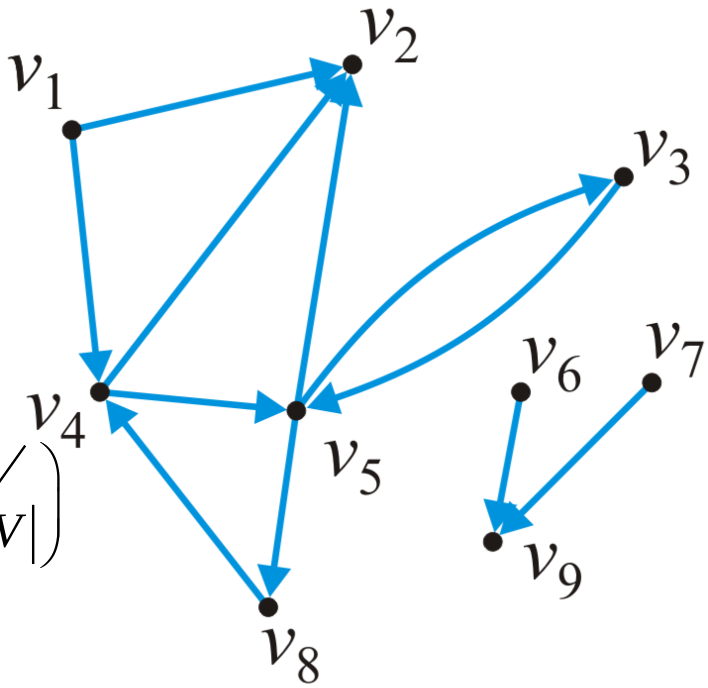
– Requires $\Theta(|V|^2)$ memory
– Determining if v_j is adjacent to v_k is $O(1)$
– Finding all neighbors of v_j is $\Theta(|V|)$

Adjacency list

Most efficient for algorithms is an adjacency list

- Each vertex is associated with a list of its neighbors

$$\begin{array}{ll} 1 & \bullet \rightarrow 2 \rightarrow 4 \\ 2 & \bullet \\ 3 & \bullet \rightarrow 5 \\ 4 & \bullet \rightarrow 2 \rightarrow 5 \\ 5 & \bullet \rightarrow 2 \rightarrow 3 \rightarrow 8 \\ 6 & \bullet \rightarrow 9 \\ 7 & \bullet \rightarrow 9 \\ 8 & \bullet \rightarrow 4 \\ 9 & \bullet \end{array}$$



- Requires $\Theta(|V| + |E|)$ memory
- On average:
  - Determining if v_j is adjacent to v_k is $O\left(\frac{|E|}{|V|}\right)$
  - Finding all neighbors of v_j is $\Theta\left(\frac{|E|}{|V|}\right)$

Adjacency Matrix

A graph of n vertices may have up to

$$\binom{n}{2} = \frac{n(n-1)}{2} = \mathbf{O}(n^2)$$

edges

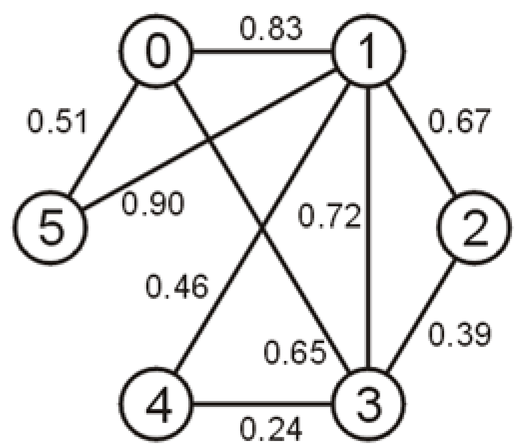
The first straight-forward implementation is an adjacency matrix

Adjacency Matrix

Define an $n \times n$ matrix $\mathbf{A} = (a_{ij})$ and if the vertices v_i and v_j are connected with weight w, then set $a_{ij} = w$ and $a_{ji} = w$

That is, the matrix is symmetric, *e.g.*,

	0	1	2	3	4	5
0		0.83		0.65		0.51
1	0.83		0.67	0.72	0.46	0.90
2		0.67		0.39		
3	0.65	0.72	0.39		0.24	
4		0.46		0.24		
5	0.51	0.90				

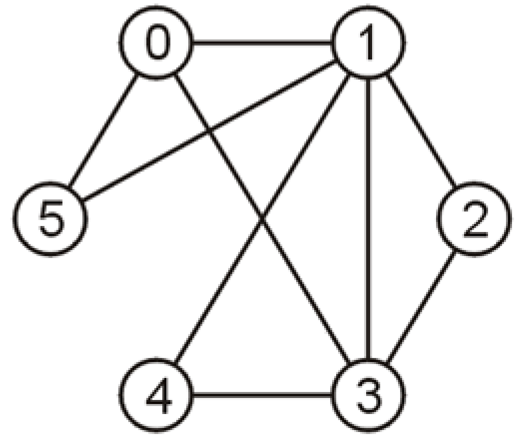


Adjacency Matrix

An unweighted graph may be saved as an array of Boolean values

– vertices v_i and v_j are connected then set
  $a_{ij} = a_{ji} = true$

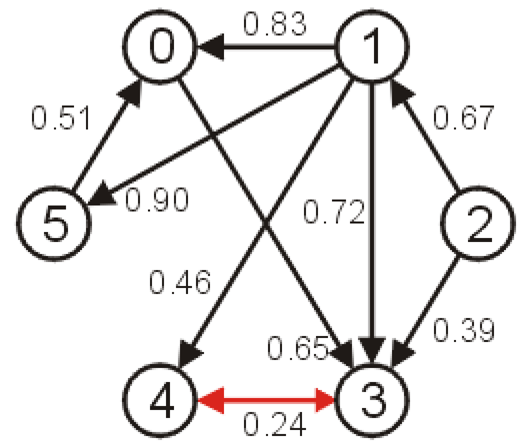
	0	1	2	3	4	5
0		T	F	T	F	T
1	T		T	T	T	T
2	F	T		T	F	F
3	T	T	T		T	F
4	F	T	F	T		F
5	T	T	F	F	F	



Adjacency Matrix

If the graph was directed, then the matrix would not necessarily be symmetric

	0	1	2	3	4	5
0				0.65		
1	0.83			0.72	0.46	0.90
2		0.67		0.39		
3					0.24	
4				0.24		
5	0.51					



Adjacency Matrix

First we must allocate memory for a two-dimensional array

C++ does not have native support for anything more than one-dimensional arrays, thus how do we store a two-dimensional array?

- as an array of arrays

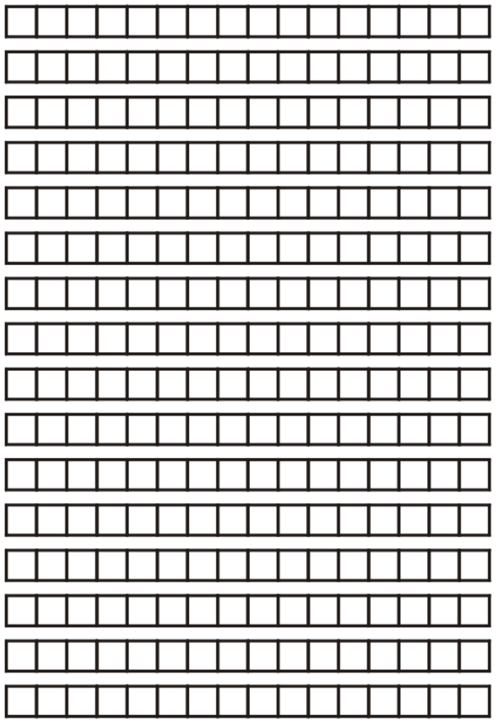
Adjacency Matrix

Suppose we require a 16 × 16 matrix of double-precision floating-point numbers

Each row of the matrix can be represented by an array

The address of the first entry must be stored in a pointer to a double:

```
double *
```



Adjacency Matrix

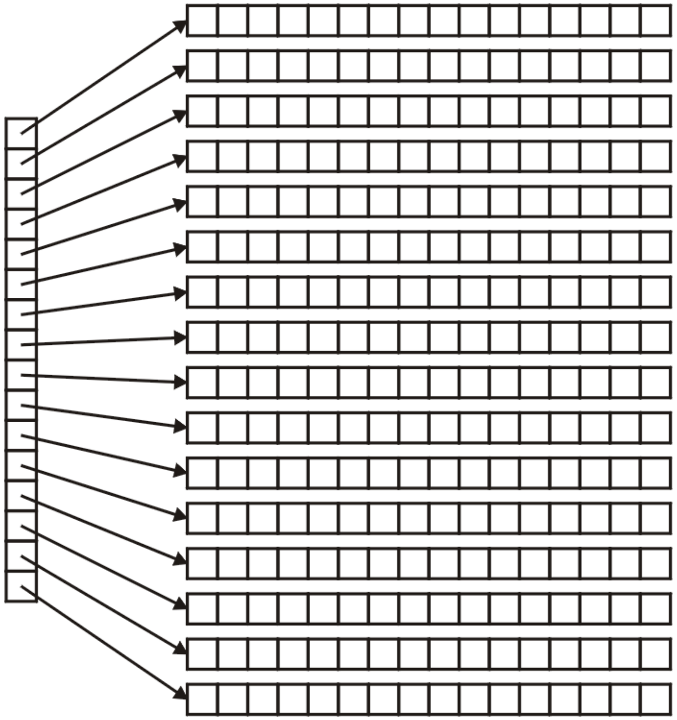
However, because we must store 16 of these pointers-to-doubles, it makes sense that we store these in an array

What is the declaration of this array?

Well, we must store a

pointer to a pointer to a double

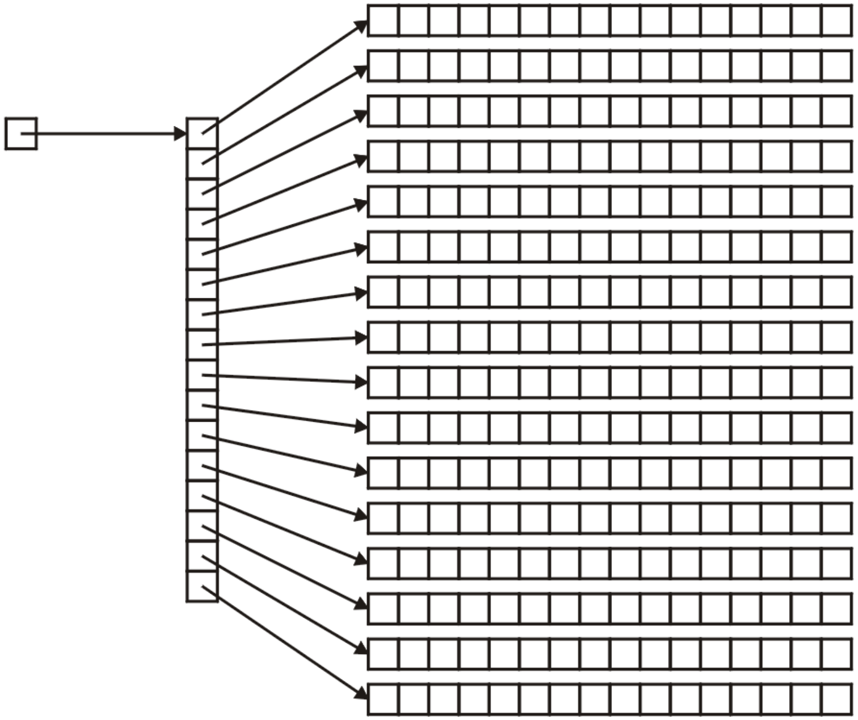
That is: `double **`



Adjacency Matrix

Thus, the address of the first array must be declared to be:

```
double **matrix;
```



Default Values

Question: what do we do about vertices which are not connected?

- the value 0
- a negative number, *e*.*g*., -1
- positive infinity: ∞

The last is the most logical, in that it makes sense that two vertices which are not connected have an infinite distance between them

The distance from a node to itself is `0`

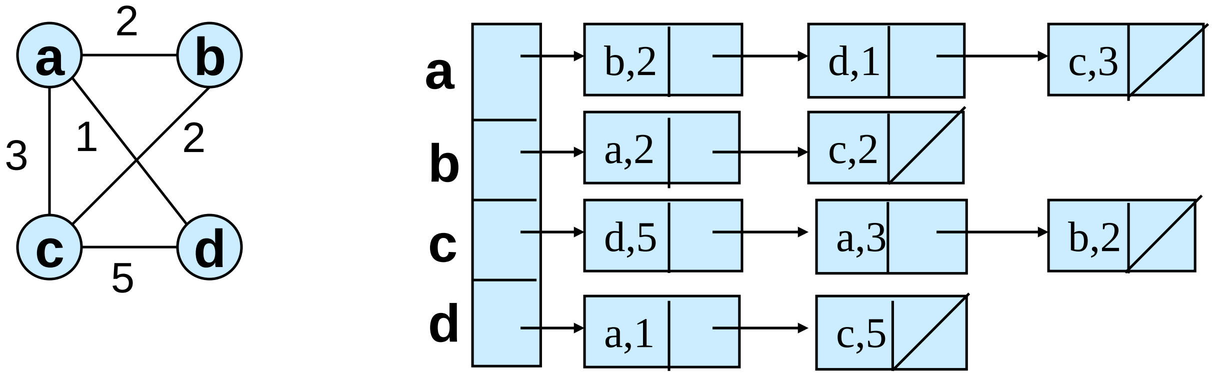
Sparse Matrices

- The memory required for creating an $n \times n$ matrix using a 2D array is $\Theta(n^2)$ bytes
- This could potentially waste a significant amount of memory:
  – Consider a friendship graph: nodes represent persons and edges represent friendship
  – The world population is 7.4 billion => the size of the matrix is $(7.4\times10^9)^2 \approx 55\times10^{18}$
  – However, each person on average has, say, 100 friends. Hence only $\frac{100}{7.4\times10^9}$ of the matrix elements are true. The other elements are the default value: false.

Adjacency list

- For an undirected graph, use an array of linked lists to store edges
  - Each vertex has a linked list that stores all the edges connected to the vertex
  - Each node in a linked list must store two items of information: the connecting vertex and the weight

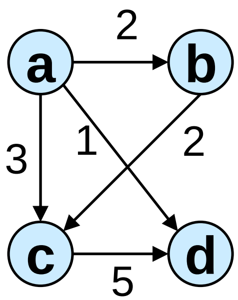
Adjacency list

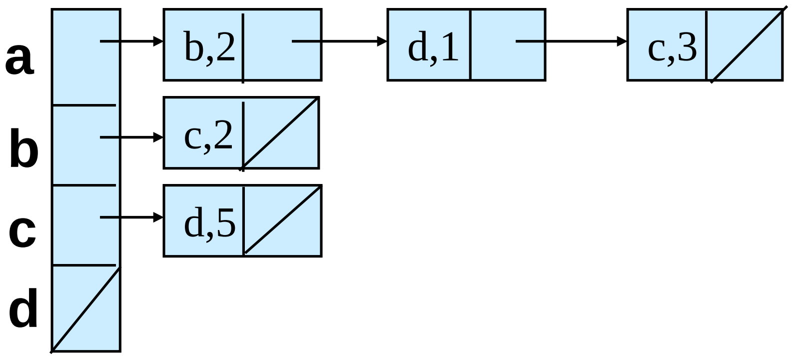


Adjacency list

- To store a directed graph
  - Each vertex has a linked list that stores all the edges originated from the vertex
  - Each node in a linked list stores two items of information: the vertex that the edge connects to, the weight

Adjacency list





Summary

- Definitions
  - Undirected graphs
  - Directed graph
- Representation
  - Adjacency matrix
  - Adjacency list