A graph

The network graph formed by Wikipedia editors (edges) contributing to different Wikipedia language versions (vertices) during one month in summer 2013

Transportation systems

Social networks
Disease transmission network

Transmission of renewable energy


What would we like to solve on graphs?

- Finding paths: which is the shortest route from home to my workplace?
- Flow problems: what is the maximum amount of people that can be transported in Barcelona at rush hours?
- Constraints: how can we schedule the use of the operating room in a hospital to minimize the length of the waiting list?
- Clustering: can we identify groups of friends by analyzing their activity in twitter?

Graph definition

A graph is specified by a set of vertices (or nodes) $V$ and a set of edges $E$.

$$V = \{1,2,3,4,5\}$$

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

Graphs can be directed or undirected. Undirected graphs have a symmetric relation.

Graph representation: adjacency matrix

A graph with $n = |V|$ vertices, $v_1, \ldots, v_n$, can be represented by an $n \times n$ matrix with:

$$a_{i,j} = \begin{cases} 1 & \text{if there is an edge from } v_i \text{ to } v_j \\ 0 & \text{otherwise} \end{cases}$$

$$a = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Space: $O(n^2)$

For undirected graphs, the matrix is symmetric.

Credits

A significant part of the material used in this chapter has been inspired by the book:


(several examples, figures and exercises are taken from the book)
A graph can be represented by $|V|$ lists, one per vertex. The list for vertex $u$ holds the vertices connected to the outgoing edges from $u$.

The lists can be implemented in different ways (vectors, linked lists, ...)

Space: $O(|E|)$

Undirected graphs: use bi-directional edges

Dense and sparse graphs

• A graph with $|V|$ vertices could potentially have up to $|V|^2$ edges (all possible edges are possible).

• We say that a graph is dense when $|E|$ is close to $|V|^2$. We say that a graph is sparse when $|E|$ is close to $|V|$.

• How big can a graph be?

Size of the World Wide Web

• December 2017: 50 billion web pages ($50 \times 10^9$).
• Size of adjacency matrix: $25 \times 10^{20}$ elements. (not enough computer memory in the world to store it).
• Good news: The web is very sparse. Each web page has about half a dozen hyperlinks to other web pages.

Adjacency matrix vs. adjacency list

• Space:
  – Adjacency matrix is $O(|V|^2)$
  – Adjacency list is $O(|E|)$

• Checking the presence of a particular edge $(u, v)$:
  – Adjacency matrix: constant time
  – Adjacency list: traverse $u$’s adjacency list

• Which one to use?
  – For dense graphs $\rightarrow$ adjacency matrix
  – For sparse graphs $\rightarrow$ adjacency list

• For many algorithms, traversing the adjacency list is not a problem, since they require to iterate through all neighbors of each vertex. For sparse graphs, the adjacency lists are usually short (can be traversed in constant time)
Graph usage: example

```cpp
// Declaration of a graph that stores a string (name) for each vertex
Graph<string> G;

// Create the vertices
int a = G.addVertex("a");
int b = G.addVertex("b");
int c = G.addVertex("c");

// Create the edges
G.addEdge(a, a);
G.addEdge(a, b);
G.addEdge(b, c);
G.addEdge(c, b);

// Print all edges of the graph
for (int src = 0; src < G.numVertices(); ++src) {
    for (auto dst : G.succ(src)) {
        cout << G.info(src) << " - " << G.info(dst) << endl;
    }
}
```

Graph implementation
template<typename vertexType>
class Graph {
private:
    struct Vertex {
        vertexType info; // Information of the vertex
        vector<int> succ; // List of successors
        vector<int> pred; // List of predecessors
    };

    vector<Vertex> vertices; // List of vertices

public:
    /** Constructor */
    Graph() {};

    /** Adds a vertex with information associated to the vertex. Returns the index of the vertex */
    int addVertex(const vertexType& info) {
        vertices.push_back(Vertex{info});
        return vertices.size() - 1;
    }

    /** Adds an edge src \(\rightarrow\) dst */
    void addEdge(int src, int dst) {
        vertices[src].succ.push_back(dst);
        vertices[dst].pred.push_back(src);
    }

    /** Returns the number of vertices of the graph */
    int numVertices() const {
        return vertices.size();
    }

    /** Returns the information associated to vertex v */
    const vertexType& info(int v) const {
        return vertices[v].info;
    }

    /** Returns the list of successors of vertex v */
    const vector<int>& succ(int v) const {
        return vertices[v].succ;
    }

    /** Returns the list of predecessors of vertex v */
    const vector<int>& pred(int v) const {
        return vertices[v].pred;
    }
};
```

Reachability: exploring a maze

Which vertices of the graph are reachable from a given vertex?
To explore a labyrinth we need a ball of string and a piece of chalk:
• The chalk prevents looping, by marking the visited junctions.
• The string allows you to go back to the starting place and
visit routes that were not previously explored.

How to simulate the string and the chalk with an algorithm?
• Chalk: a boolean variable for each vertex (visited).
• String: a stack
  o push vertex to unwind at each junction
  o pop to rewind and return to the previous junction

Note: the stack can be simulated with recursion.

Finding the nodes reachable from another node

function explore(G, 𝑣):
// Input: 𝐺 = (𝑉, 𝐸) is a graph
// Output: visited(𝑢) is true for all the
//         nodes reachable from 𝑣

visited(𝑣) = true
previsit(𝑣)
for each edge (𝑣, 𝑢) ∈ 𝐸:
   if not visited(𝑢): explore(G, 𝑢)
postvisit(𝑣)

Notes:
• Initially, visited(𝑣) is assumed to be false for every 𝑣 ∈ 𝑉.
• pre/postvisit functions are not required now.
Finding the nodes reachable from another node

**Function**

```plaintext
function explore(G, v):
  visited(v) = true
  for each edge (v, u) ∈ E:
    if not visited(u): explore(G, u)
```

**Example**

Dotted edges are ignored (back edges): they lead to previously visited vertices.
The solid edges (tree edges) form a tree.

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**Depth-first search**

**Function**

```plaintext
function DFS(G):
  for all v ∈ V:
    visited(v) = false
  for all v ∈ V:
    if not visited(v): explore(G, v)
```

DFS traverses the entire graph.

**Complexity**

- Each vertex is visited only once (thanks to the chalk marks)
- For each vertex:
  - A fixed amount of work (pre/postvisit)
  - All adjacent edges are scanned

**Running time** is \(O(|V| + |E|)\).
Difficult to improve: reading a graph already takes \(O(|V| + |E|)\).

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**Connectivity**

- An undirected graph is connected if there is a path between any pair of vertices.
- A disconnected graph has disjoint connected components.
- Example: this graph has 3 connected components:
  \(\{A, B, E, I, J\}\) \(\{C, D, G, H, K, L\}\) \(\{F\}\).

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**DFS example**

Graph:
- \(A\) \(B\) \(C\) \(D\) \(E\) \(F\) \(G\) \(H\) \(I\) \(J\) \(K\) \(L\)

DFS forest:
- \(A\) \(B\) \(C\) \(D\) \(E\) \(F\) \(G\) \(H\) \(I\) \(J\) \(K\) \(L\)
Connected Components

function explore(G, v, cc):
// Input: G = (V,E) is a graph, cc is a CC number
// Output: ccnum[u] = cc for each vertex u in the same CC as v
ccnum[v] = cc
for each edge (v,u) ∈ E:
    if ccnum[u] == 0: explore(G, u, cc)

function ConnComp(G):
// Input: G = (V,E) is a graph
// Output: Every vertex v has a CC number in ccnum[v]
for all v ∈ V:
    if ccnum[v] = 0: // A new CC starts
        explore(G, v, cc); cc = cc + 1;

• Performs a DFS traversal assigning a CC number to each vertex.
• The outer loop of ConnComp determines the number of CC’s.
• The variable ccnum[v] also plays the role of visited[v].

Revisiting the explore function

function explore(G, v):
    visited(v) = true
    previsit(v)
for each edge (v,u) ∈ E:
    if not visited(u):
        explore(G, u)
    postvisit(v)

function previsit(v):
    pre[v] = clock
    clock = clock + 1

function postvisit(v):
    post[v] = clock
    clock = clock + 1

Let us consider a global variable clock that can determine the occurrence times of previsit and postvisit.

Example of pre/postvisit orderings

DFS in directed graphs: types of edges

• Tree edges: those in the DFS forest.
• Forward edges: lead to a nonchild descendant in the DFS tree.
• Back edges: lead to an ancestor in the DFS tree.
• Cross edges: lead to neither descendant nor ancestor.
**DFS in directed graphs: types of edges**

- **Tree edges**: those in the DFS forest.
- **Forward edges**: lead to a nonchild descendant in the DFS tree.
- **Back edges**: lead to an ancestor in the DFS tree.
- **Cross edges**: lead to neither descendant nor ancestor.

**pre/post ordering for \((u, v)\)**

1. Tree/forward
2. Back
3. Cross

**Cycles in graphs**

A **cycle** is a circular path: 
\[v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_k \rightarrow v_0.\]

Examples:

\[B \rightarrow E \rightarrow F \rightarrow B\]
\[C \rightarrow D \rightarrow A \rightarrow C\]

**Property**: A directed graph has a cycle **iff** its DFS reveals a back edge.

**Proof**:

\(\Leftarrow\) if \((u, v)\) is a back edge, there is a cycle with \((u, v)\) and the path from \(v\) to \(u\) in the search tree.

\(\Rightarrow\) Let us consider a cycle \(v_0 \rightarrow v_1 \rightarrow v_2 \rightarrow \cdots \rightarrow v_k \rightarrow v_0\). Let us assume that \(v_i\) is the first discovered vertex (lowest pre number). All the other \(v_j\) on the cycle are reachable from \(v_i\) and will be its descendants in the DFS tree. The edge \(v_{i-1} \rightarrow v_i\) leads from a vertex to its ancestor and is thus a back edge.

**Getting dressed: DAG representation**

A list of tasks that must be executed in a certain order (cannot be executed if it has cycles).

**Legal task linearizations (or topological sorts):**

- Underwear
- Socks
- Trousers
- Shoes
- Watch
- Shirt
- Belt
- Tie
- Jacket

A **DAG** is a directed graph without cycles.

**Directed Acyclic Graphs (DAGs)**

DAGs are often used to represent causalities or temporal dependencies, e.g., task A must be completed before task C.

- Cyclic graphs cannot be linearized.
- All DAGs can be linearized. **How?**
  - Decreasing order of the post numbers.
  - The only edges \((u, v)\) with \(\text{post}[u] < \text{post}[v]\) are back edges (do not exist in DAGs).
- **Property**: In a DAG, every edge leads to a vertex with a lower post number.
- **Property**: Every DAG has at least one source and at least one sink. (source: highest post number, sink: lowest post number).
Topological sort

function explore(G, v):
visited(v) = true
previsit(v)
for each edge (v, u) ∈ E:
    if not visited(u):
        explore(G, u)
postvisit(v)

Initially: TSort = ∅

function postvisit(v):
TSort.push_front(v)

// After DFS, TSort contains
// a topological sort

Another algorithm:
- Find a source vertex, write it, and delete it (mark) from the graph.
- Repeat until the graph is empty.

It can be executed in linear time. How?

Properties of DFS and SCCs

- **Property:** If the explore function starts at u, it will terminate when all vertices reachable from u have been visited.
  - If we start from a vertex in a sink SCC, it will retrieve exactly that component.
  - If we start from a non-sink SCC, it will retrieve the vertices of several components.

- **Examples:**
  - If we start at K it will retrieve the component \{G, H, I, J, K, L\}.
  - If we start at B it will retrieve all vertices except A.

Strongly Connected Components

The graph is not strongly connected.
Two nodes u and v of a directed graph are connected if there is a path from u to v and a path from v to u.
The connected relation is an equivalence relation and partitions \( V \) into disjoint sets of strongly connected components.

For example, there is no path \( K \rightarrow \cdots \rightarrow C \) or \( E \rightarrow \cdots \rightarrow A \).

Strongly Connected Components
\{A\}
\{B, E\}
\{C, F\}
\{D\}
\{G, H, I, J, K, L\}

This graph is connected (undirected view), but there is no path between any pair of nodes.

Strongly Connected Components
\( \{B, E\} \)
\( \{C, F\} \)
\( \{D\} \)
\( \{G, H, I, J, K, L\} \)

Properties of DFS and SCCs

- **Property:** If the explore function starts at u, it will terminate when all vertices reachable from u have been visited.
  - If we start from a vertex in a sink SCC, it will retrieve exactly that component.
  - If we start from a non-sink SCC, it will retrieve the vertices of several components.

Examples:
- If we start at K it will retrieve the component \{G, H, I, J, K, L\}.
- If we start at B it will retrieve all vertices except A.

Every directed graph can be represented by a meta-graph, where each meta-node represents a strongly connected component.
Properties of DFS and SCCs

• **Intuition for the algorithm:**
  - Find a vertex located in a sink SCC
  - Extract the SCC

• **To be solved:**
  - How to find a vertex in a sink SCC?
  - What to do after extracting the SCC?

• **Property:** If $C$ and $C'$ are SCCs and there is an edge $C \rightarrow C'$, then the highest post number in $C$ is bigger than the highest post number in $C'$.

• **Property:** The vertex with the highest DFS post number lies in a source SCC.

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**Reverse graph ($G^R$)**

**SCC algorithm**

```plaintext
function SCC(G):
    // Input: G(V,E) a directed graph
    // Output: each vertex v has an SCC number in ccnum[v]
    G^R = reverse(G)
    DFS(G^R) // calculates post numbers
    sort V // decreasing order of post number
    ConnComp(G)
```

**Runtime complexity:**

- DFS and ConnComp run in linear time $O(|V| + |E|)$.
- Can we reverse $G$ in linear time?
- Can we sort $V$ by post number in linear time?
### Reversing \( G \) in linear time

**Function SCC(\( G \))**:
// Input: \( G(V,E) \) a directed graph
// Output: each vertex \( v \) has an SCC number in \( ccnum[v] \)
\( G^R = \text{reverse}(G) \)
\( \text{DFS}(G^R) \) // calculates post numbers
\( \text{sort } V \) // decreasing order of post number
\( \text{ConnComp}(G) \)

**Function reverse(G)**:
// Input: \( G(V,E) \) graph represented by an adjacency list
// Output: \( G(V,E^R) \) the reversed graph of \( G \), with the adjacency list \( edgesR[v] \).
for each \( u \in V \):
  for each \( v \in \text{edges}[u] \):
    \( \text{edgesR}[v].\text{insert}(u) \)
return \( (V,\text{edgesR}) \)

### Sorting \( V \) in linear time

**Function SCC(\( G \))**:
// Input: \( G(V,E) \) a directed graph
// Output: each vertex \( v \) has an SCC number in \( ccnum[v] \)
\( G^R = \text{reverse}(G) \)
\( \text{DFS}(G^R) \) // calculates post numbers
\( \text{sort } V \) // decreasing order of post number
\( \text{ConnComp}(G) \)

Use the explore function for topological sort:
- Each time a vertex is post-visited, it is inserted at the top of the list.
- The list is ordered by decreasing order of post number.
- It is executed in linear time.

### Crawling the Web

- Crawling the Web is done using depth-first search strategies.
- The graph is unknown and no recursion is used. A stack is used instead containing the nodes that have already been visited.
- The stack is not exactly a LIFO. Only the most “interesting” nodes are kept (e.g., page rank).
- Crawling is done in parallel (many computers at the same time) but using a central stack.
- How do we know that a page has already been visited? Hashing.
Summary

• Big data is often organized in big graphs (objects and relations between objects)

• Big graphs are usually sparse. Adjacency lists is the most common data structure to represent graphs.

• Connectivity can be analyzed in linear time using depth-first search.

EXERCISES

DFS: stack overflow

• DFS can be implemented with an elegant recursive algorithm, but it may experiment stack overflow problems. Explain why.

• Design an iterative version of DFS.

• Challenge: do not to search in stack overflow

DFS (from [DPV2008])

Perform DFS on the two graphs. Whenever there is a choice of vertices, pick the one that is alphabetically first. Classify each edge as a tree edge, forward edge, back edge or cross edge, and give the pre and post number of each vertex.
Topological ordering (from [DPV2008])

Run the DFS-based topological ordering algorithm on the graph. Whenever there is a choice of vertices to explore, always pick the one that is alphabetically first.

1. Indicate the pre and post numbers of the nodes.
2. What are the sources and sinks of the graph?
3. What topological order is found by the algorithm?
4. How many topological orderings does this graph have?

Streets in Computopia (from [DPV2008])

The police department in the city of Computopia has made all streets one-way. The mayor contends that there is still a way to drive legally from any intersection in the city to any other intersection, but the opposition is not convinced. A computer program is needed to determine whether the mayor is right. However the city elections are coming up soon, and there is just enough time to run a linear-time algorithm.

a) Formulate this problem graph-theoretically, and explain why it can indeed be solved in linear time.

b) Suppose it now turns out that the mayor’s original claim is false. She next claims something weaker: if you start driving from town hall, navigating one-way streets, then no matter where you reach, there is always a way to drive legally back to the town hall. Formulate this weaker property as a graph-theoretic problem, and carefully show how it too can be checked in linear time.

Pouring water (from [DPV2008])

We have three containers whose sizes are 10 pints, 7 pints and 4 pints, respectively. The 7-pint and 4-pint containers start out full of water, but the 10-pint container is initially empty. We are allowed one type of operation: pouring the contents of one container into another, stopping only when the source container is empty or the destination container is full. We want to know if there is a sequence of pourings that leaves exactly 2 pints in the 4-pint container.

a) Model this as a graph problem: give a precise definition of the graph involved and state the specific question about this graph that needs to be answered.

b) What algorithm should be applied to solve the problem?

c) Give a sequence of pourings, if it exists, or prove that it does not exist any sequence.

Hint: A vertex of the graph can be represented by a triple of integers.