Lecture 9

Graphs, BFS and DFS
Announcements!

• HW4 due today.

• You can start taking exam 2 starting tomorrow (<= 36 hours from when you click open on Gradescope).

• HW5 will be released later today. It has some optional parts on topics covered in exam 2 (and other required parts). The solutions to optional parts will be released at the same time.
Roadmap

- Sorting
  - Randomized Algs
  - Asymptotic Analysis
  - Recurrences

- Data structures
  - Randomized Algs
  - Dynamic Programming

- Greedy Algs

- Longest, Shortest, Max and Min...

- MIDTERM

- The Future!

More detailed schedule on the website!
Outline

• Part 0: Graphs and terminology

• Part 1: Depth-first search
  • Application: topological sorting
  • Application: in-order traversal of BSTs

• Part 2: Breadth-first search
  • Application: shortest paths
  • Application (if time): is a graph bipartite?
Part 0: Graphs
Graphs

Graph of the internet (circa 1999...it’s a lot bigger now...)
Graphs

Citation graph of literary theory academic papers
Graphs

Theoretical Computer Science academic communities
Graphs

The Godfather Characters Interaction Network
Graphs
Graphs

Complexity Zoo containment graph
Graphs

Immigration flows
Graphs

Potato trade

World trade in fresh potatoes, flows over 0.1 m US$ average 2005-2009
Graphs

Soybeans

Water
Graphs

Graphical models
Graphs

What eats what in the Atlantic ocean?
Graphs

Neural connections in the brain
Graphs

• There are a lot of graphs.

• We want to answer questions about them.
  • Efficient routing?
  • Community detection/clustering?
  • From pre-lecture exercise:
    • Computing Bacon numbers
    • Signing up for classes without violating pre-req constraints
    • How to distribute fish in tanks so that none of them will fight.

• This is what we’ll do for the next several lectures.
Undirected Graphs

• Has vertices and edges
  • V is the set of vertices
  • E is the set of edges
  • Formally, a graph is $G = (V,E)$

• Example
  • $V = \{1,2,3,4\}$
  • $E = \{\{1,3\}, \{2,4\}, \{3,4\}, \{2,3\}\}$

• The degree of vertex 4 is 2.
  • There are 2 edges coming out
  • Vertex 4’s neighbors are 2 and 3
Directed Graphs

• Has vertices and edges
  • V is the set of vertices
  • E is the set of DIRECTED edges
  • Formally, a graph is $G = (V,E)$

• Example
  • $V = \{1,2,3,4\}$
  • $E = \{ (1,3), (2,4), (3,4), (4,3), (3,2) \}$

• The in-degree of vertex 4 is 2.
• The out-degree of vertex 4 is 1.
• Vertex 4’s incoming neighbors are 2,3
• Vertex 4’s outgoing neighbor is 3.
How do we represent graphs?

• Option 1: adjacency matrix

\[
\begin{bmatrix}
1 & 0 & 1 & 0 \\
0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 \\
0 & 1 & 1 & 0
\end{bmatrix}
\]
How do we represent graphs?

• Option 1: adjacency matrix

\[
\begin{bmatrix}
1 & 0 & 1 & 0 \\
0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 \\
0 & 1 & 1 & 0 \\
\end{bmatrix}
\]
How do we represent graphs?

• Option 1: adjacency matrix

\[
\begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 1 \\
0 & 0 & 1 & 0 \\
\end{bmatrix}
\]
How do we represent graphs?

- Option 2: adjacency lists.

How would you modify this for directed graphs?

4’s neighbors are 2 and 3
In either case

• Vertices can store other information
  • Attributes (name, IP address, ...)
  • Helper info for algorithms that we will perform on the graph

• Want to be able to do the following operations:
  • **Edge Membership**: Is edge e in E?
  • **Neighbor Query**: What are the neighbors of vertex v?
## Trade-offs

Say there are $n$ vertices and $m$ edges.

<table>
<thead>
<tr>
<th>Edge membership</th>
<th>Is $e = {v, w}$ in $E$?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$O(1)$</td>
</tr>
<tr>
<td>$O(1)$</td>
<td>$O(\text{deg}(v))$ or $O(\text{deg}(w))$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neighbor query</th>
<th>Give me a list of $v$’s neighbors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O(n)$</td>
<td>$O(\text{deg}(v))$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Space requirements</th>
<th>$O(n^2)$</th>
<th>$O(n + m)$</th>
</tr>
</thead>
</table>

Generally better for **sparse** graphs (where $m \ll n^2$)

We’ll assume this representation for the rest of the class

---

See Lecture 9 Python notebook for an actual implementation!
Part 1: Depth-first search
How do we explore a graph?

At each node, you can get a list of neighbors, and choose to go there if you want.
Depth First Search

Exploring a labyrinth with chalk and a piece of string

Not been there yet
Been there, haven’t explored all the paths out.
Been there, have explored all the paths out.

start
Depth First Search
Exploring a labyrinth with chalk and a piece of string

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Been there, have explored all the paths out.
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Depth First Search
Exploring a labyrinth with chalk and a piece of string

Labyrinth: EXPLORED!
Depth First Search
Exploring a labyrinth with pseudocode

• Each vertex keeps track of whether it is:
  • Unvisited
  • In progress
  • All done

• Each vertex will also keep track of:
  • The time we first enter it.
  • The time we finish with it and mark it all done.

You might have seen other ways to implement DFS than what we are about to go through. This way has more bookkeeping – the bookkeeping will be useful later!
Depth First Search

currentTime = 0

• **DFS**(w, currentTime):
  • w.startTime = currentTime
  • currentTime += 1
  • Mark w as *in progress*.
  • for v in w.neighbors:
    • if v is *unvisited*:
      • currentTime = **DFS**(v, currentTime)
      • currentTime += 1
    • w.finishTime = currentTime
  • Mark w as *all done*
  • return currentTime
Depth First Search

\[ \text{DFS}(w, \text{currentTime}) : \]

- \( w.\text{startTime} = \text{currentTime} \)
- \( \text{currentTime} += 1 \)
- Mark \( w \) as \textit{in progress}.
- \textbf{for} \( v \) in \( w \).neighbors:
  - \textbf{if} \( v \) is \textit{unvisited}:
    - \( \text{currentTime} = \text{DFS}(v, \text{currentTime}) \)
    - \( \text{currentTime} += 1 \)
  - \( w.\text{finishTime} = \text{currentTime} \)
- Mark \( w \) as \textit{all done}
- \textbf{return} \( \text{currentTime} \)
Depth First Search

\[
\text{currentTime} = 1
\]

- **DFS(w, currentTime):**
  - w.startTime = currentTime
  - currentTime += 1
  - Mark w as \textit{in progress}.
  - \textbf{for} v in w.neighbors:
    - \textbf{if} v is \textit{unvisited}:
      - currentTime = DFS(v, currentTime)
    - currentTime += 1
  - w.finishTime = currentTime
  - Mark w as \textit{all done}
  - \textbf{return} currentTime
Depth First Search

currentTime = 2

- **DFS**(w, currentTime):
  - w.startTime = currentTime
  - currentTime += 1
  - Mark w as **in progress**.
  - **for** v in w.neighbors:
    - **if** v is **unvisited**:
      - currentTime = DFS(v, currentTime)
    - currentTime += 1
  - w.finishTime = currentTime
  - Mark w as **all done**
  - **return** currentTime
Depth First Search

currentTime = 20

• DFS(w, currentTime):
  • w.startTime = currentTime
  • currentTime += 1
  • Mark w as in progress.
  • for v in w.neighbors:
    • if v is unvisited:
      • currentTime = DFS(v, currentTime)
    • currentTime += 1
  • w.finishTime = currentTime
  • Mark w as all done
  • return currentTime

Takes until currentTime = 20

Start: 0

Start: 1

unvisited

in progress

all done
Depth First Search

currentTime = 21

• **DFS**(w, currentTime):
  • w.startTime = currentTime
  • currentTime += 1
  • Mark w as *in progress*.
  • for v in w.neighbors:
    • if v is *unvisited*:
      • currentTime = DFS(v, currentTime)
      • currentTime += 1
    • w.finishTime = currentTime
  • Mark w as *all done*
  • return currentTime

Start: 0

Start: 1

Takes until currentTime = 20

unvisited

in progress

all done
Depth First Search

**DFS**(w, currentTime):
- w.startTime = currentTime
- currentTime += 1
- Mark w as *in progress*.
- for v in w.neighbors:
  - if v is *unvisited*:
    - currentTime
    - = DFS(v, currentTime)
    - currentTime += 1
  - w.finishTime = currentTime
- Mark w as *all done*
- return currentTime
Depth First Search

\[ \text{DFS}(w, \text{currentTime}) : \]
- \( w.\text{startTime} = \text{currentTime} \)
- \( \text{currentTime} += 1 \)
- Mark \( w \) as \textbf{in progress}.
- \textbf{for} \( v \) in \( w.\text{neighbors} \):
  - \textbf{if} \( v \) is \textbf{unvisited}:
    - \( \text{currentTime} = \text{DFS}(v, \text{currentTime}) \)
    - \( \text{currentTime} += 1 \)
  - \( w.\text{finishTime} = \text{currentTime} \)
- Mark \( w \) as \textbf{all done}
- \textbf{return} \( \text{currentTime} \)

\( \text{currentTime} = 22 \)

\( \text{Takes until } \text{currentTime} = 20 \)

\( \text{Start:0} \)

\( \text{Start:1} \text{ End:21} \)

\( \text{etc} \)
This is not the only way to write DFS!

• See the lecture notes for an iterative version (using stacks)! If your graph is large and stack overflow a concern, use this version.

• (Or figure out how to do it yourself!)
DFS finds all the nodes reachable from the starting point

One application of DFS: finding connected components.

In an undirected graph, this is called a **connected component**.
To explore the whole graph

• Do it repeatedly!
Why is it called depth-first?

• We are implicitly building a tree:

  • First, we go as deep as we can.

YOINK!

Call this the “DFS tree”
Running time

To explore just the connected component we started in

• We look at each edge at most twice.
  • Once from each of its endpoints
• And basically, we don’t do anything else.
• So...

\[ O(m) \]
Running time
To explore just the connected component we started in

• Assume we are using the linked-list format for G.
• Say $C = (V', E')$ is a connected component.
• We visit each vertex in $V'$ exactly once.
  • Here, “visit” means “call DFS on”
• At each vertex $w$, we:
  • Do some book-keeping: $O(1)$
  • Loop over $w$’s neighbors and check if they are visited (and then potentially make a recursive call): $O(1)$ per neighbor or $O(\deg(w))$ total.
• Total time:
  • $\sum_{w \in V'}(O(\deg(w)) + O(1))$
  • $= O(|E'| + |V'|)$
  • $= O(|E'|)$

In a connected graph, $|V'| \leq |E'| + 1$. 
Running time

To explore the whole graph

- Explore the connected components one-by-one.
- This takes time $O(n + m)$
  - Same computation as before:
    \[
    \sum_{w \in V}(O(\deg(w)) + O(1)) = O(|E| + |V|) = O(n + m)
    \]

Here the running time is $O(m)$ like before

Here $m=0$ but it still takes time $O(n)$ to explore the graph.
You check:

DFS works fine on directed graphs too!

Only walk to C, not to B.

Siggi the studious stork
Pre-lecture exercise

• How can you sign up for classes so that you never violate the pre-req requirements?

• More practically, how can you install packages without violating dependency requirements?
Application of DFS: topological sorting

• Find an ordering of vertices so that all of the dependency requirements are met.
  • Aka, if v comes before w in the ordering, there is not an edge from w to v.

Suppose the dependency graph has no cycles: it is a **Directed Acyclic Graph (DAG)**
Can’t always eyeball it.
Let’s do DFS

What do you notice about the finish times? Any ideas for how we should do topological sort?

1 minute think
(wait) 1 minute share

### Start and Finish Times

- **tar**: start:7, finish:8
- **coreutils**: start:9, finish:10
- **dpkg**: start:0, finish:11
- **libbz2**: start:1, finish:6
- **multiarch-support**: start:3, finish:4
- **libselinux1**: start:2, finish:5

### Graph Representation

- Tar → Coreutils
- Coreutils → Dpkg
- Dpkg → Libbz2
- Dpkg → Multiarch-support
- Dpkg → Libselinux1
- Libbz2 → Coreutils
- Libbz2 → Dpkg
- Libselinux1 → Dpkg
Finish times seem useful

Claim: In general, we’ll always have:

Suppose the underlying graph has no cycles

To understand why, let’s go back to that DFS tree.
A more general statement
(this holds even if there are cycles)

• If v is a descendant of w in this tree:

  w.start  v.start  v.finish  w.finish

• If w is a descendant of v in this tree:

  v.start  w.start  w.finish  v.finish

• If neither are descendants of each other:

  v.start  v.finish  w.start  w.finish

(or the other way around)
So to prove this →

If A → B
Then B.finishTime < A.finishTime

Suppose the underlying graph has no cycles

- **Case 1**: B is a descendant of A in the DFS tree.

  - Then

    • A.startTime < B.startTime < B.finishTime < A.finishTime
    • aka, B.finishTime < A.finishTime.
So to prove this →

If

Then B.finishTime < A.finishTime

Suppose the underlying graph has no cycles

• **Case 2**: B is a **NOT** descendant of A in the DFS tree.
  - Notice that A can’t be a descendant of B in the DFS tree or else there’d be a cycle; so it looks like this

• Then we must have explored B before A.
  - Otherwise we would have gotten to B from A, and B would have been a descendant of A in the DFS tree.

• Then

  B.finishTime \(\rightarrow\) A.finishTime

  B.startTime \(\rightarrow\) A.startTime

• aka, B.finishTime < A.finishTime.
Theorem

• If we run DFS on a directed acyclic graph,

If

A

B

Then $B.\text{finishTime} < A.\text{finishTime}$
Back to topological sorting

• In what order should I install packages?
• In reverse order of finishing time in DFS!

Suppose the dependency graph has no cycles: it is a **Directed Acyclic Graph (DAG)**
Topological Sorting (on a DAG)

• Do DFS
• When you mark a vertex as **all done**, put it at the **beginning** of the list.

**Example DAG:**

- **dpkg**
- **coreutils**
- **tar**
- **libbz2**
- **libselinux1**
- **multiarch_support**

**Timeline:**
- **start:** 0
  - **finish:** 11
- **start:** 2
  - **finish:** 5
- **start:** 3
  - **finish:** 4
- **start:** 7
  - **finish:** 8
- **start:** 9
  - **finish:** 10
- **start:** 1
  - **finish:** 6
- **start:** 8
  - **finish:** 10
For implementation, see Python notebook.
What did we just learn?

- DFS can help you solve the topological sorting problem
  - That’s the fancy name for the problem of finding an ordering that respects all the dependencies

- Thinking about the DFS tree is helpful.
Example:

This example skipped in class – here for reference.
Example

This example skipped in class – here for reference.

- Unvisited
- In progress
- All done
Example

This example skipped in class – here for reference.

- **A** (Start:0)
- **B**
- **C** (Start:1)
- **D** (Start:2)

Legend:
- Unvisited
- In progress
- All done
This example skipped in class – here for reference.
Example

This example skipped in class – here for reference.
This example skipped in class – here for reference.
Example

This example skipped in class – here for reference.

In progress

Unvisited

All done
Example

Do them in this order:

A  C  D  B

This example skipped in class – here for reference.
Another use of DFS that we’ve already seen

• In-order enumeration of binary search trees

Do DFS and print a node’s label when you are done with the left child and before you begin the right child.
LET'S PLAY
Part 2: breadth-first search
How do we explore a graph?

If we can fly
Breadth-First Search
Exploring the world with a bird’s-eye view

Not been there yet
Can reach there in zero steps
Can reach there in one step
Can reach there in two steps
Can reach there in three steps
Breadth-First Search
Exploring the world with a bird’s-eye view

Not been there yet
Can reach there in zero steps
Can reach there in one step
Can reach there in two steps
Can reach there in three steps
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Breadth-First Search
Exploring the world with a bird’s-eye view

Not been there yet
Can reach there in zero steps
Can reach there in one step
Can reach there in two steps
Can reach there in three steps

start

Diagram showing nodes connected by lines with different colors indicating the number of steps to reach them from the start node.
Breadth-First Search

Exploring the world with a bird’s-eye view

World: EXPLORED!
Breadth-First Search
Exploring the world with pseudocode

- Set $L_i = []$ for $i=1,...,n$
- $L_0 = [w]$, where $w$ is the start node
- Mark $w$ as visited
- For $i = 0, ..., n-1$:
  - For $u$ in $L_i$:
    - For each $v$ which is a neighbor of $u$:
      - If $v$ isn’t yet visited:
        - mark $v$ as visited, and put it in $L_{i+1}$

$L_i$ is the set of nodes we can reach in $i$ steps from $w$

Go through all the nodes in $L_i$ and add their unvisited neighbors to $L_{i+1}$
BFS also finds all the nodes reachable from the starting point.

It is also a good way to find all the connected components.
Running time and extension to directed graphs

• To explore the whole graph, explore the connected components one-by-one.
  • Same argument as DFS: BFS running time is \(O(n + m)\)
• Like DFS, BFS also works fine on directed graphs.

Verify these!
Why is it called breadth-first?

• We are implicitly building a tree:

• First we go as broadly as we can.

YOINK!

Call this the “BFS tree”
Pre-lecture exercise

• What Samuel L. Jackson’s Bacon number?

(Answer: 2)
An example with distance 3

Kevin Bacon

Oliver Sacks

Tilda Swinton

It is really hard to find people with Bacon number 3!
Application of BFS: shortest path

• How long is the shortest path between w and v?
Application of BFS: shortest path

• How long is the shortest path between w and v?

It’s three!
To find the **distance** between \( w \) and all other vertices \( v \)

- Do a BFS starting at \( w \)
- For all \( v \) in \( L_i \)
  - The shortest path between \( w \) and \( v \) has length \( i \).
  - A shortest path between \( w \) and \( v \) is given by the path in the BFS tree.
- If we never found \( v \), the distance is infinite.

The **distance** between two vertices is the number of edges in the shortest path between them.

Modify the BFS pseudocode to return shortest paths!
Prove that this indeed returns shortest paths!

Gauss has no Bacon number.
What have we learned?

• The BFS tree is useful for computing distances between pairs of vertices.
• We can find the shortest path between $u$ and $v$ in time $O(m)$. 
Another application of BFS

• Testing bipartite-ness
Pre-lecture exercise: fish

- You have a bunch of fish and two fish tanks.
- Some pairs of fish will fight if put in the same tank.
  - Model this as a graph: connected fish will fight.
- Can you put the fish in the two tanks so that there is no fighting?
Bipartite graphs

• A bipartite graph looks like this:

Can color the vertices red and orange so that there are no edges between any same-colored vertices

**Example:**
- are in tank A
- are in tank B
- if the fish fight

**Example:**
- are students
- are classes
- if the student is enrolled in the class
Is this graph bipartite?
How about this one?
How about this one?
This one?
Application of BFS: Testing Bipartiteness

- Color the levels of the BFS tree in alternating colors.
- If you never color two connected nodes the same color, then it is bipartite.
- Otherwise, it’s not.

Does DFS work here too?
Breadth-First Search

For testing bipartite-ness

Not been there yet
Can reach there in zero steps
Can reach there in one step
Can reach there in two steps
Can reach there in three steps
Breadth-First Search

For testing bipartite-ness

- Not been there yet
- Can reach there in zero steps
- Can reach there in one step
- Can reach there in two steps
- Can reach there in three steps
Breadth-First Search

For testing bipartite-ness

Not been there yet

Can reach there in zero steps

Can reach there in one step

Can reach there in two steps

Can reach there in three steps

start
Breadth-First Search
For testing bipartite-ness

- Not been there yet
- Can reach there in zero steps
- Can reach there in one step
- Can reach there in two steps
- Can reach there in three steps
Breadth-First Search
For testing bipartite-ness

CLEARLY BIPARTITE!
Breadth-First Search
For testing bipartite-ness

Not been there yet
Can reach there in zero steps
Can reach there in one step
Can reach there in two steps
Can reach there in three steps
Breadth-First Search
For testing bipartite-ness

- Not been there yet
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Breadth-First Search

For testing bipartite-ness

Start

- Not been there yet
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- Can reach there in two steps
- Can reach there in three steps
Breadth-First Search
For testing bipartite-ness

- Not been there yet
- Can reach there in zero steps
- Can reach there in one step
- Can reach there in two steps
- Can reach there in three steps

start
Breadth-First Search
For testing bipartite-ness

WHOA NOT BIPARTITE!
Hang on now.

• Just because this coloring doesn’t work, why does that mean that there is no coloring that works?

I can come up with plenty of bad colorings on this legitimately bipartite graph...
Some proof required

• If BFS colors two neighbors the same color, then it’s found a cycle of odd length in the graph.

There must be an even number of these edges

This one extra makes it odd
Some proof required

• If BFS colors two neighbors the same color, then it’s found a **cycle of odd length** in the graph.

• But you can **never** color an odd cycle with two colors so that no two neighbors have the same color.
  • [Fun exercise!]

• So you can’t legitimately color the whole graph either.

• **Thus it’s not bipartite.**
What have we learned?

BFS can be used to detect bipartite-ness in time $O(n + m)$. 
Outline

• Part 0: Graphs and terminology

• Part 1: Depth-first search
  • Application: topological sorting
  • Application: in-order traversal of BSTs

• Part 2: Breadth-first search
  • Application: shortest paths
  • Application (if time): is a graph bipartite?

Recap
Recap

• Depth-first search
  • Useful for topological sorting
  • Also in-order traversals of BSTs

• Breadth-first search
  • Useful for finding shortest paths
  • Also for testing bipartiteness

• Both DFS, BFS:
  • Useful for exploring graphs, finding connected components, etc
Still open (next few classes)

• We can now find components in undirected graphs...
  • What if we want to find strongly connected components in directed graphs?

• How can we find shortest paths in weighted graphs?

• What is Samuel L. Jackson’s Erdos number?
  • (Or, what if I want everyone’s everyone-else number?)
Next Time

• Strongly Connected Components

Before Next Time

• Pre-lecture exercise: Strongly Connected What-Now?