Kruskal’s Algorithm

Start with an empty tree $A$

Add to $A$ the lowest-weight edge that does not create a cycle
Cut Theorem

If a set of edges $A$ is a subset of a minimum spanning tree $T$, let $(S, V - S)$ be any cut which $A$ respects. Let $e$ be the least-weight edge which crosses $(S, V - S)$. $A \cup \{e\}$ is also a subset of a minimum spanning tree.
Cut Theorem

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Proof of Kruskal’s Algorithm

Start with an empty tree $A$
Repeat $V - 1$ times:
   Add the min-weight edge that doesn’t cause a cycle

Proof: Suppose we have some arbitrary set of edges $A$ that Kruskal’s has already selected to include in the MST. $e = (F, G)$ is the edge Kruskal’s selects to add next

We know that there cannot exist a path from $F$ to $G$ using only edges in $A$ because $e$ does not cause a cycle

We can cut the graph therefore into 2 disjoint sets:
• nodes reachable from $G$ using edges in $A$
• All other nodes

$e$ is the minimum cost edge that crosses this cut, so by the Cut Theorem, Kruskal’s is optimal!
Kruskal’s Algorithm Runtime

Start with an empty tree $A$
Repeat $V - 1$ times:

Add the min-weight edge that doesn’t cause a cycle

Keep edges in a Disjoint-set data structure (very fancy) $O(E \log V)$
General MST Algorithm

Start with an empty tree \( A \).

Repeat \( V - 1 \) times:

- Pick a cut \((S, V - S)\) which \( A \) respects (typically implicitly).
- Add the min-weight edge which crosses \((S, V - S)\).
Prim’s Algorithm

Start with an empty tree $A$

Repeat $V - 1$ times:

Pick a cut $(S, V - S)$ which $A$ respects

Add the min-weight edge which crosses $(S, V - S)$

$S$ is all endpoint of edges in $A$

e is the min-weight edge that grows the tree
Prim’s Algorithm
Start with an empty tree $A$
Pick a start node
Repeat $V - 1$ times:
Add the min-weight edge which connects to node in $A$ with a node not in $A$
Prim’s Algorithm
Start with an empty tree $A$
Pick a start node
Repeat $V - 1$ times:
Add the min-weight edge which connects to node in $A$ with a node not in $A$
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Prim’s Algorithm
Start with an empty tree $A$
Pick a start node
Repeat $V - 1$ times:
Add the min-weight edge which connects to node in $A$ with a node not in $A$
int dijkstras(graph, start, end){
    PQ = new minheap();
    PQ.insert(0, start);  // priority=0, value=start
    start.distance = 0;
    while (!PQ.isEmpty){
        current = PQ.extractmin();
        if (current.known){ continue;}
        current.known = true;
        for (neighbor : current.neighbors){
            if (!neighbor.known){
                new_dist = current.distance + weight(current,neighbor);
                if(neighbor.dist != ∞){ PQ.insert(new_dist, neighbor);}
                else if (new_dist < neighbor.distance){
                    neighbor.distance = new_dist;
                    PQ.decreaseKey(new_dist,neighbor); }
            }
        }
    }
    return end.distance;
}
Prim’s Algorithm

```java
int dijkstras(graph, start, end){
PQ = new minheap();
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            else if (new_dist < neighbor.distance){
                neighbor.distance = new_dist;
                PQ.decreaseKey(new_dist,neighbor); } }
    }
}
return end.distance;
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            }
        }
    }
    return end.distance;
}
Prim’s Algorithm

int dijkstras(graph, start, end) {
    PQ = new minheap();
    PQ.insert(0, start); // priority=0, value=start
    start.distance = 0;
    while (!PQ.isEmpty) {
        current = PQ.extractmin();
        if (current.known) continue;
        current.known = true;
        for (neighbor : current.neighbors) {
            if (!neighbor.known) {
                new_dist = weight(current, neighbor);
                if (neighbor.dist != ∞) PQ.insert(new_dist, neighbor);
                else if (new_dist < neighbor.distance) {
                    neighbor.distance = new_dist;
                    PQ.decreaseKey(new_dist, neighbor);
                }
            }
        }
    }
    return end.distance;
}
The Pregel River runs through the city of Koenigsberg, creating 2 islands. Among these 2 islands and the 2 sides of the river, there are 7 bridges. Is there any path starting at one landmass which crosses each bridge exactly once?
Euler Path Problem

• Path:
  • A sequence of nodes $v_1, v_2, \ldots$ such that for every consecutive pair are connected by an edge (i.e. $(v_i, v_{i+1})$ is an edge for each $i$ in the path)

• Euler Path:
  • A path such that every edge in the graph appears exactly once
    • If the graph is not simple then some pairs need to appear multiple times!

• Euler path problem:
  • Given an undirected graph $G = (V, E)$, does there exist an Euler path for $G$?
Examples

Which of the graphs below have an Euler path?

- No Euler path exists!
- Euler path exists!

No Euler path exists!
Euler path exists!

A, B, D, A, C, D
A, B, C, D, A, C, B, D
Euler’s Theorem

• A graph has an Euler Path if and only if it is connected and has exactly 0 or 2 nodes with odd degree.
Algorithm for the Euler Path Problem

• Given an undirected graph $G = (V, E)$, does there exist an Euler path for $G$?

• Algorithm:
  • Check if the graph is connected
  • Check the degree of each node
  • If the number of nodes with odd degree is 0 or 2, return true
  • Otherwise return false

• Running time?
A Seemingly Similar Problem

• Hamiltonian Path:
  • A path that includes every node in the graph exactly once

• Hamiltonian Path Problem:
  • Given a graph $G = (V, E)$, does that graph have a Hamiltonian Path?

True!
$A, B, C, E, G, H, F, D$
Algorithms for the Hamiltonian Path Problem

• Option 1:
  • Explore all possible simple paths through the graph
  • Check to see if any of those are length $V$

• Option 2:
  • Write down every sequence of nodes
  • Check to see if any of those are a path

• Both options are examples of an Exhaustive Search ("Brute Force") algorithm
Option 2: List all sequences, look for a path

• Running time:
  • \( G = (V, E) \)
  • Number of permutations of \( V \) is \( |V|! \)
    • \( n! = n \cdot (n - 1) \cdot (n - 2) \cdot ... \cdot 2 \cdot 1 \)
  • How does \( n! \) compare with \( 2^n \)?
    • \( n! \in \Omega(2^n) \)
  • Exponential running time!
Option 1: Explore all simple paths, check for one of length $V$

- **Running time:**
  - $G = (V, E)$
  - Number of paths
    - Pick a first node ($|V|$ choices)
    - Pick a neighbor (up to $|V| - 1$ choices)
    - Pick a neighbor (up to $|V| - 2$ choices)
    - .... Repeat $|V| - 1$ total times
    - Overall: $|V|!$ paths
  - Exponential running time
Running Times

Running times we’ve seen:
• $\Theta(1)$
• $\Theta(\log n)$
• $\Theta(n)$
• $\Theta(n \log n)$
• $\Theta(n^2)$
• $\Theta(2^n)$
## Running Times

Table 2.1 The running times (rounded up) of different algorithms on inputs of increasing size, for a processor performing a million high-level instructions per second. In cases where the running time exceeds $10^{25}$ years, we simply record the algorithm as taking a very long time.

<table>
<thead>
<tr>
<th>n</th>
<th>$n \log_2 n$</th>
<th>$n^2$</th>
<th>$n^3$</th>
<th>$1.5^n$</th>
<th>$2^n$</th>
<th>$n!$</th>
</tr>
</thead>
<tbody>
<tr>
<td>n = 10</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>4 sec</td>
</tr>
<tr>
<td>n = 30</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>18 min</td>
</tr>
<tr>
<td>n = 50</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>11 min</td>
<td>36 years</td>
</tr>
<tr>
<td>n = 100</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>1 sec</td>
<td>12,892 years</td>
<td>$10^{17}$ years</td>
</tr>
<tr>
<td>n = 1,000</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>1 sec</td>
<td>18 min</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>n = 10,000</td>
<td>&lt; 1 sec</td>
<td>&lt; 1 sec</td>
<td>2 min</td>
<td>12 days</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>n = 100,000</td>
<td>&lt; 1 sec</td>
<td>2 sec</td>
<td>3 hours</td>
<td>32 years</td>
<td>very long</td>
<td>very long</td>
</tr>
<tr>
<td>n = 1,000,000</td>
<td>&lt; 1 sec</td>
<td>20 sec</td>
<td>12 days</td>
<td>31,710 years</td>
<td>very long</td>
<td>very long</td>
</tr>
</tbody>
</table>
Tractability

- **Tractable:**
  - Feasible to solve in the “real world”

- **Intractable:**
  - Infeasible to solve in the “real world”

- Whether a problem is considered “tractable” or “intractable” depends on the use case
  - For machine learning, big data, etc. tractable might mean $O(n)$ or even $O(\log n)$
  - For most applications it’s more like $O(n^3)$ or $O(n^2)$

- A strange pattern:
  - Most “natural” problems are either done in small-degree polynomial (e.g. $n^2$) or else exponential time (e.g. $2^n$)
  - It’s rare to have problems which require a running time of $n^5$, for example
Complexity Classes

- A Complexity Class is a set of problems (e.g. sorting, Euler path, Hamiltonian path)
  - The problems included in a complexity class are those whose most efficient algorithm has a specific upper bound on its running time (or memory use, or...)
- Examples:
  - The set of all problems that can be solved by an algorithm with running time $O(n)$
    - Contains: Finding the minimum of a list, finding the maximum of a list, buildheap, summing a list, etc.
  - The set of all problems that can be solved by an algorithm with running time $O(n^2)$
    - Contains: everything above as well as sorting, Euler path
  - The set of all problems that can be solved by an algorithm with running time $O(n!)$
    - Contains: everything we’ve seen in this class so far
Complexity Classes and Tractability

• To explore what problems are and are not tractable, we give some complexity classes special names:

• Complexity Class $\mathbf{P}$:
  • Stands for “Polynomial”
  • The set of problems which have an algorithm whose running time is $O(n^p)$ for some choice of $p \in \mathbb{R}$.
  • We say all problems belonging to $\mathbf{P}$ are “Tractable”

• Complexity Class $\mathbf{EXP}$:
  • Stands for “Exponential”
  • The set of problems which have an algorithm whose running time is $O(2^{np})$ for some choice of $p \in \mathbb{R}$
  • We say all problems belonging to $\mathbf{EXP} - \mathbf{P}$ are “Intractable”
    • Disclaimer: Really it’s all problems outside of $\mathbf{P}$, and there are problems which do not belong to $\mathbf{EXP}$, but we’re not going to worry about those in this class
\( EXP \) and \( P \)

**Important!**

\( P \subset EXP \)

Every problem within \( P \) is also within \( EXP \)
The intractable ones are the problems within \( EXP \) but NOT \( P \)
Important!
Some of the problems listed in EXP could also be members of P.
Since membership is determined by a problem's most efficient algorithm, knowing if a problem belongs to P requires knowing the best algorithm possible!
Studying Complexity and Tractability

• Organizing problems into complexity classes helps us to reason more carefully and flexibly about tractability

• The goal for each problem is to either
  • Find an efficient algorithm if it exists
    • i.e. show it belongs to $P$
  • Prove that no efficient algorithm exists
    • i.e. show it does not belong to $P$

• Complexity classes allow us to reason about sets of problems at a time, rather than each problem individually
  • If we can find more precise classes to organize problems into, we might be able to draw conclusions about the entire class
  • It may be easier to show a problem belongs to class $C$ than to $P$, so it may help to show that $C \subseteq P$
Some problems in $EXP$ seem “easier”

• There are some problems that we do not have polynomial time algorithms to solve, but provided answers are easy to check

• Hamiltonian Path:
  • It’s “hard” to look at a graph and determine whether it has a Hamiltonian Path
  • It’s “easy” to look at a graph and a candidate path together and determine whether THAT path is a Hamiltonian Path
    • It’s easy to verify whether a given path is a Hamiltonian path
Class $NP$

• $NP$
  • The set of problems for which a candidate solution can be verified in polynomial time
  • Stands for “Non-deterministic Polynomial”
    • Corresponds to algorithms that can guess a solution (if it exists), that solution is then verified to be correct in polynomial time
    • Can also think of as allowing a special operation that allows the algorithm to magically guess the right choice at each step of an exhaustive search
  
• $P \subseteq NP$
  • Why?
$EXP \supset NP \supseteq P$

- **$P$**
  - Polynomial
  - Upper bounded by $n^p$

- **$NP$**
  - Nondeterministic Polynomial
  - Verified in $n^p$ time

- **$EXP$**
  - Exponential
  - Upper bounded by $2^{n^p}$

**Gap?**

**Unknown!**
Solving and Verifying Hamiltonian Path

• Give an algorithm to solve Hamiltonian Path
  • Input: $G = (V, E)$
  • Output: True if $G$ has a Hamiltonian Path
  • Algorithm: Check whether each permutation of $V$ is a path.
    • Running time: $|V|!$, so does not show whether it belongs to $P$

• Give an algorithm to verify Hamiltonian Path
  • Input: $G = (V, E)$ and a sequence of nodes
  • Output: True if that sequence of nodes is a Hamiltonian Path
  • Algorithm:
    • Check that each node appears in the sequence exactly once
    • Check that the sequence is a path
    • Running time: $O(V \cdot E)$, so it belongs to $NP$
Party Problem

Draw Edges between people who don’t get along
How many people can I invite to a party if everyone must get along?
Independent Set

• Independent set:
  • $S \subseteq V$ is an independent set if no two nodes in $S$ share an edge

• Independent Set Problem:
  • Given a graph $G = (V, E)$ and a number $k$, determine whether there is an
    independent set $S$ of size $k$
Example

Independent set of size 6
Solving and Verifying Independent Set

• Give an algorithm to solve independent set
  • Input: $G = (V, E)$ and a number $k$
  • Output: True if $G$ has an independent set of size $k$

• Give an algorithm to verify independent set
  • Input: $G = (V, E)$, a number $k$, and a set $S \subseteq V$
  • Output: True if $S$ is an independent set of size $k$
Generalized Baseball
Generalized Baseball

Need to place defenders on bases such that every edge is defended

How many defenders would suffice?
Vertex Cover

• Vertex Cover:
  • $C \subseteq V$ is a vertex cover if every edge in $E$ has one of its endpoints in $C$

• Vertex Cover Problem:
  • Given a graph $G = (V, E)$ and a number $k$, determine if there is a vertex cover $C$ of size $k$
Example

Vertex cover of size 5
Solving and Verifying Vertex Cover

• Give an algorithm to solve vertex cover
  • Input: $G = (V, E)$ and a number $k$
  • Output: True if $G$ has a vertex cover of size $k$

• Give an algorithm to verify vertex cover
  • Input: $G = (V, E)$, a number $k$, and a set $S \subseteq E$
  • Output: True if $S$ is a vertex cover of size $k$
\[ \text{EXP} \supset \text{NP} \supseteq \text{P} \]

\[ P = \text{NP} \text{ or } P \subset \text{NP} \]

- **Exponential**
  - Upper bounded by \(2^{n^p}\)

- **NP**
  - Nondeterministic Polynomial
  - Verified in \(n^p\) time
  - Contains: Checkers, Go, Chess

- **P**
  - Polynomial
  - Upper bounded by \(n^p\)
  - Contains: Sorting, Shortest Path, Euler Path

- **EXP**
  - Exponential

**Unknown Gap?**
Way Cool!

$S$ is an independent set of $G$ iff $V - S$ is a vertex cover of $G$
Way Cool!

\[ S \text{ is an independent set of } G \text{ iff } V - S \text{ is a vertex cover of } G \]
Solving Vertex Cover and Independent Set

• Algorithm to solve vertex cover
  • Input: $G = (V, E)$ and a number $k$
  • Output: True if $G$ has a vertex cover of size $k$
    • Check if there is an Independent Set of $G$ of size $|V| - k$

• Algorithm to solve independent set
  • Input: $G = (V, E)$ and a number $k$
  • Output: True if $G$ has an independent set of size $k$
    • Check if there is a Vertex Cover of $G$ of size $|V| - k$

Either both problems belong to $P$, or else neither does!
NP-Complete

• A set of “together they stand, together they fall” problems
• The problems in this set either all belong to $P$, or none of them do
• Intuitively, the “hardest” problems in NP
• Collection of problems from $NP$ that can all be “transformed” into each other in polynomial time
  • Like we could transform independent set to vertex cover, and vice-versa
  • We can also transform vertex cover into Hamiltonian path, and Hamiltonian path into independent set, and ...
$\mathit{EXP} \supset \mathit{NP-Complete} \supseteq \mathit{NP} \supseteq \mathit{P}$

$P = \mathit{NP}$ iff some problem from $\mathit{NP-Complete}$ belongs to $\mathit{P}$
Overview

• Problems not belonging to $P$ are considered intractable
• The problems within $NP$ have some properties that make them seem like they might be tractable, but we’ve been unsuccessful with finding polynomial time algorithms for many
• The class $NP - Complete$ contains problems with the properties:
  • All members are also members of $NP$
  • All members of $NP$ can be transformed into every member of $NP - Complete$
  • Therefore if any one member of $NP - Complete$ belongs to $P$, then $P = NP$
Why should YOU care?

• If you can find a polynomial time algorithm for any $NP - Complete$ problem then:
  • You will win $1million
  • You will win a Turing Award
  • You will be world famous
  • You will have done something that no one else on Earth has been able to do in spite of the above!

• If you are told to write an algorithm a problem that is $NP - Complete$
  • You can tell that person everything above to set expectations
  • Change the requirements!
  • **Approximate the solution:** Instead of finding a path that visits every node, find a path that visits at least 75% of the nodes
  • **Add Assumptions:** problem might be tractable if we can assume the graph is acyclic, a tree
  • **Use Heuristics:** Write an algorithm that’s “good enough” for small inputs, ignore edge cases