Greedy Graph Algorithms

T. M. Murali

September 21, 23, 28, 2021
Algorithm Design

- Start discussion of different ways of designing algorithms.
- Greedy algorithms, divide and conquer, dynamic programming, flow-based approaches.
- Discuss principles that can solve a variety of problem types.
- Design an algorithm, prove its correctness, analyse its complexity.
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- Greedy algorithms, divide and conquer, dynamic programming, flow-based approaches.
- Discuss principles that can solve a variety of problem types.
- Design an algorithm, prove its correctness, analyse its complexity.
- Greedy algorithms: make the current best choice.
  - First discussed greedy algorithms for scheduling (Chapters 4.1 to 4.3).
  - Now we will discuss greedy graph algorithms.
Shortest Paths Problem

- $G(V, E)$ is a connected directed graph. Each edge $e$ has a length $l(e) \geq 0$.
- *Length of a path* $P$ is the sum of the lengths of the edges in $P$. 

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![Graph diagram with nodes s, e, f, b, c, a and edges labeled with lengths 1, 2, 3, 4]
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Goal: compute the shortest path from a specified start node \( s \) to each node in \( V \).

**Shortest Paths**

**INSTANCE:** A directed graph \( G(V, E) \), a function \( l : E \rightarrow \mathbb{R}^+ \), and a node \( s \in V \)

**SOLUTION:** A set \( \{P_u, u \in V\} \) of paths, where \( P_u \) is the shortest path in \( G \) from \( s \) to \( u \).
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**Length of a path** $P$ is the sum of the lengths of the edges in $P$.

Goal: compute the shortest path from a specified start node $s$ to each node in $V$.

Aside: If $G$ is undirected, convert to a directed graph by replacing each edge in $G$ by two directed edges.

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Shortest Paths Problem Instance

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Generalizing BFS

- Shortest Paths
- Minimum Spanning Trees
- Implementation

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Generalizing BFS

Unweighted graph: Use BFS. Process nodes in non-decreasing order of distance.
Weighted graph: Edge weights are integers. Can we make the graph unweighted?
Add dummy nodes: Edge of weight $w$ gets $w - 1$ nodes.
Generalizing BFS

Dummy nodes: BFS computes shortest paths correctly. Running time is
Dummy nodes: BFS computes shortest paths correctly. Running time is \(O(m + n + \sum_{e \in E} l(e))\). Pseudo-polynomial time: depends on input values.
Generalizing BFS to Dijkstra’s Algorithm

Like BFS: explore nodes in non-increasing order of distance from s. Once a node is explored, its distance is fixed.
Generalizing BFS to Dijkstra’s Algorithm

Unlike BFS: Layers are not uniform. Which node to process next? Candidates are nodes with an edge from a explored node.
Generalizing BFS to Dijkstra’s Algorithm

For each unexplored node, determine “best” preceding explored node.
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Generalizing BFS to Dijkstra’s Algorithm

For each unexplored node, determine “best” preceding explored node.
Generalizing BFS to Dijkstra’s Algorithm

Explore node with smallest path length only through explored nodes.
Generalizing BFS to Dijkstra’s Algorithm

Like BFS: Record previous node in the computed path.
Generalizing BFS to Dijkstra’s Algorithm

Follow previous nodes to compute shortest path. Like BFS: these edges form a tree.
**Idea Underlying Dijkstra’s Algorithm**

- Maintain a set $S$ of explored nodes.
  - For each node $u \in S$, compute a value $d(u)$, which (we will prove) is the length of the shortest path from $s$ to $u$.
  - For each node $x \not\in S$, maintain a value $d'(x)$, which is the length of the shortest path from $s$ to $x$ using only the nodes in $S$ (and $x$, of course).
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- “Greedily” add a node $v$ to $S$ that has the smallest value of $d'(v)$ (is closest to $s$ using only nodes in $S$).
Dijkstra’s Algorithm

**Dijkstra’s Algorithm**($G, l, s$)

1. $S = \{s\}$ and $d(s) = 0$
2. **while** $S \neq V$ **do**
3.     **for** every node $x \in V - S$ **do**
4.         Set $d'(x) = \min_{u \in S}(d(u) + l(u, x))$
5.     Set $v = \arg \min_{x \in V - S} d'(x)$
6.     Add $v$ to $S$ and set $d(v) = d'(v)$

To compute the shortest paths: when adding a node $v$ to $S$, store the predecessor $u$ that minimises $d'(v)$.
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- How do we parse \(d'(x) = \min_{(u,x):u \in S} (d(u) + l(u, x))\)?

- For each such edge, we compute the length of the shortest path from \(s\) to \(x\) via \(u\), which is \(d(u) + l(u, x)\).
- We store the smallest of these values in \(d'(x)\).

- Run over all (unexplored) nodes \(x \in V - S\).
- Examine the \(d'(x)\) values for these nodes.
- Return the argument (i.e., the node) that has the smallest value of \(d'(x)\).

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Proof of Correctness

- Let $P_u$ be the path computed by the algorithm for an arbitrary node $u$.
- Claim: $P_u$ is the shortest path from $s$ to $u$.
- Prove by induction on the size of $S$. 
Proof of Correctness

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- Base case: $|S| = 1$. The only node in $S$ is $s$. 
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  - Inductive step: $|S| = k + 1$ because we add the node $v$ to $S$. Could there be a shorter path $P$ from $s$ to $v$? We must prove this cannot be the case.
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![Diagram](image)

**Figure 4.8** The shortest path $P_v$ and an alternate $s$-$v$ path $P$ through the node $y$. 
Comments about Dijkstra’s Algorithm

- Algorithm cannot handle negative edge lengths. We will discuss the Bellman-Ford algorithm in a few weeks.
- Union of shortest paths output by Dijkstra’s algorithm forms a tree. Why?
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- Algorithm cannot handle negative edge lengths. We will discuss the Bellman-Ford algorithm in a few weeks.
- Union of shortest paths output by Dijkstra’s algorithm forms a tree. Why?
- Union of shortest paths from a fixed source $s$ forms a tree; paths not necessarily computed by Dijkstra’s algorithm.
Running time of Dijkstra’s Algorithm

Dijkstra’s Algorithm \( (G, l, s) \)

1: \( S = \{s\} \) and \( d(s) = 0 \)
2: \textbf{while} \( S \neq V \) \textbf{do}
3: \hspace{1em} \textbf{for} every node \( x \in V - S \) \textbf{do}
4: \hspace{2em} Set \( d'(x) = \min_{(u,x):u \in S} (d(u) + l(u,x)) \)
5: \hspace{1em} Set \( \nu = \arg \min_{x \in V - S} d'(x) \)
6: \hspace{1em} Add \( \nu \) to \( S \) and set \( d(\nu) = d'(\nu) \)

- \( V \) has \( n \) nodes and \( E \) has \( m \) edges.
- How many iterations are there of the while loop?
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- \(V\) has \(n\) nodes and \(E\) has \(m\) edges.
- How many iterations are there of the while loop? \(n - 1\).
- In each iteration, for each node \(x \in V - S\), compute \(d'(x) = \min_{(u,x),u \in S} (d(u) + l(u, x))\).
Running time of Dijkstra’s Algorithm

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- How many iterations are there of the while loop? \( n - 1 \).
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\[
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\]

- Running time per iteration is \( O(m) \), since the algorithm processes each edge \( (u, x) \) in the graph exactly once (when computing \( d'(x) \)).
- The overall running time is \( O(nm) \).
A Faster implementation of Dijkstra’s Algorithm

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- Observation: If we add \(v\) to \(S\), \(d'(x)\) changes only if \((v, x)\) is an edge in \(G\) and \(x\) is not in \(S\).

Idea: For each node \(x \in V - S\), store the current value of \(d'(x)\). Upon adding a node \(v\) to \(S\), update \(d'(v)\) only for neighbours of \(v\) that are not in \(S\).
# A Faster implementation of Dijkstra’s Algorithm

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---

**Observation:** If we add $v$ to $S$, $d'(x)$ changes only if $(v, x)$ is an edge in $G$ and $x$ is not in $S$. 

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**Diagram:**
- $d'(w)$ does not change
- $d'(x)$ can change

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**Dijkstra’s Algorithm**($G, I, s$)

1. $S = \{s\}$ and $d(s) = 0$
2. **while** $S \neq V$ **do**
3. \hspace{1em} Set $v = \arg \min_{x \in V - S} d'(x)$
4. \hspace{1em} Add $v$ to $S$ and set $d(v) = d'(v)$
5. \hspace{1em} **for** every node $x \in V - S$ **do**
6. \hspace{2em} Set $d'(x) = \min_{(u, x): u \in S}(d(u) + I(u, x))$

- **Observation:** If we add $v$ to $S$, $d'(x)$ changes only if $(v, x)$ is an edge in $G$ and $x$ is not in $S$.
- **Idea:** For each node $x \in V - S$, store the current value of $d'(x)$. Upon adding a node $v$ to $S$, update $d'$ only for neighbours of $v$ that are not in $S$.
- **How do we efficiently compute $v = \arg \min_{x \in V - S} d'(x)$?**
### A Faster implementation of Dijkstra’s Algorithm

#### Dijkstra’s Algorithm \((G, l, s)\)

1. \(S = \{s\}\) and \(d(s) = 0\)
2. while \(S \neq V\) do
   3. Set \(v = \arg \min_{x \in V - S} d'(x)\)
   4. Add \(v\) to \(S\) and set \(d(v) = d'(v)\)
   5. for every node \(x \in V - S\) do
      6. Set \(d'(x) = \min_{(u, x)}: u \in S (d(u) + l(u, x))\)

- Observation: If we add \(v\) to \(S\), \(d'(x)\) changes only if \((v, x)\) is an edge in \(G\) and \(x\) is not in \(S\).
- Idea: For each node \(x \in V - S\), store the current value of \(d'(x)\). Upon adding a node \(v\) to \(S\), update \(d'()\) only for neighbours of \(v\) that are not in \(S\).
- How do we efficiently compute \(v = \arg \min_{x \in V - S} d'(x)\)?
- Use a priority queue!
Faster Dijkstra’s Algorithm

Dijkstra’s Algorithm \((G, l, s)\)

1: \textsc{Insert}(Q, s, 0).
2: \textbf{while} \(S \neq V\) \textbf{do}
3: \((v, d'(v)) = \textsc{ExtractMin}(Q)\)
4: Add \(v\) to \(S\) and set \(d(v) = d'(v)\)
5: \textbf{for} each node \(x \in V - S\) such that \((v, x)\) is an edge in \(G\) \textbf{do}
6: \textbf{if} \(d(v) + l(v, x) < d'(x)\) \textbf{then}
7: \quad \(d'(x) = d(v) + l(v, x)\)
8: \textsc{ChangeKey}(Q, x, d'(x))

For each node \(x \in V - S\), store the pair \((x, d'(x))\) in a priority queue \(Q\) with \(d'(x)\) as the key.

Determine the next node \(v\) to add to \(S\) using \textsc{ExtractMin} (line 3).

After adding \(v\) to \(S\), for each node \(x \in V - S\) such that there is an edge from \(v\) to \(x\), check if \(d'(x)\) should be updated, i.e., if there is a shortest path from \(s\) to \(x\) via \(v\) (lines 5–8).

In line 8, if \(x\) is not in \(Q\), simply insert it.
Running Time of Faster Dijkstra’s Algorithm

**Dijkstra’s Algorithm**($G, l, s$)

1: \textbf{Insert}($Q, s, 0$).
2: \textbf{while} $S \neq V$ \textbf{do}
3: \hspace{1em}($v, d'(v)$) = \textbf{ExtractMin}($Q$)
4: \hspace{1em}Add $v$ to $S$ and set $d(v) = d'(v)$
5: \hspace{1em}\textbf{for} every node $x \in V - S$ such that $(v, x)$ is an edge in $G$ \textbf{do}
6: \hspace{2em}\textbf{if} $d(v) + l(v, x) < d'(x)$ \textbf{then}
7: \hspace{3em}$d'(x) = d(v) + l(v, x)$
8: \hspace{3em}\textbf{ChangeKey}($Q, x, d'(x)$)

- How many times does the algorithm invoke \textbf{ExtractMin}?
Running Time of Faster Dijkstra’s Algorithm

Dijkstra’s Algorithm($G, l, s$)

1: INSERT($Q, s, 0$).
2: while $S \neq V$ do
3: \hspace{1em} ($v, d'(v)$) = EXTRACTMIN($Q$)
4: \hspace{1em} Add $v$ to $S$ and set $d(v) = d'(v)$
5: \hspace{1em} for every node $x \in V - S$ such that $(v, x)$ is an edge in $G$ do
6: \hspace{2em} if $d(v) + l(v, x) < d'(x)$ then
7: \hspace{3em} $d'(x) = d(v) + l(v, x)$
8: \hspace{3em} CHANGEKEY($Q, x, d'(x)$)

- How many times does the algorithm invoke EXTRACTMIN? $n - 1$ times.
Running Time of Faster Dijkstra’s Algorithm

**Dijkstra’s Algorithm** \((G, l, s)\)

1. **Insert** \((Q, s, 0)\).
2. **while** \(S \neq V \) **do**
3. \((v, d'(v)) = \text{ExtractMin}(Q)\)
4. Add \(v\) to \(S\) and set \(d(v) = d'(v)\)
5. **for** every node \(x \in V - S\) such that \((v, x)\) is an edge in \(G\) **do**
6. **if** \(d(v) + l(v, x) < d'(x)\) **then**
7. \(d'(x) = d(v) + l(v, x)\)
8. **ChangeKey** \((Q, x, d'(x))\)

- How many times does the algorithm invoke **ExtractMin**? \(n - 1\) times.
- For every node \(v\), what is the running time of step 5?
Running Time of Faster Dijkstra’s Algorithm

Dijkstra’s Algorithm \((G, l, s)\)

1: \text{Insert}(Q, s, 0).
2: \textbf{while} \(S \neq V\) \textbf{do}
3: \((v, d'(v)) = \text{ExtractMin}(Q)\)
4: \text{Add} \(v\) \text{to} \(S\) \text{and set} \(d(v) = d'(v)\)
5: \textbf{for} every node \(x \in V - S\) such that \((v, x)\) is an edge in \(G\) \textbf{do}
6: \quad \textbf{if} \(d(v) + l(v, x) < d'(x)\) \textbf{then}
7: \quad d'(x) = d(v) + l(v, x)
8: \quad \text{ChangeKey}(Q, x, d'(x))

- How many times does the algorithm invoke \text{ExtractMin}? \(n - 1\) times.
- For every node \(v\), what is the running time of step 5? \(O(d_v)\), the number of \textit{outgoing} neighbours of \(v\).
Running Time of Faster Dijkstra’s Algorithm

Dijkstra’s Algorithm\((G, l, s)\)

1: \textbf{Insert}(Q, s, 0).
2: \textbf{while }S \neq V \textbf{ do}
3: \quad (v, d'(v)) = \textbf{ExtractMin}(Q)
4: \quad Add v to S and set \(d(v) = d'(v)\)
5: \quad \textbf{for} every node \(x \in V - S\) such that \((v, x)\) is an edge in \(G\) \textbf{ do}
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- How many times does the algorithm invoke \textbf{ExtractMin}? \(n - 1\) times.
- For every node \(v\), what is the running time of step 5? \(O(d_v)\), the number of outgoing neighbours of \(v\).
- What is the total running time of step 5?
Running Time of Faster Dijkstra’s Algorithm

**Dijkstra’s Algorithm** \((G, l, s)\)

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2: while \(S \neq V\) do
3: \((v, d'(v)) = \text{ExtractMin}(Q)\)
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7: \(d'(x) = d(v) + l(v, x)\)
8: \(\text{ChangeKey}(Q, x, d'(x))\)

- How many times does the algorithm invoke \(\text{ExtractMin}\)? \(n - 1\) times.
- For every node \(v\), what is the running time of step 5? \(O(d_v)\), the number of *outgoing* neighbours of \(v\).
- What is the total running time of step 5? \(\sum_{v \in V} O(d_v) = O(m)\).
Running Time of Faster Dijkstra’s Algorithm

Dijkstra’s Algorithm($G, l, s$)

1: Insert($Q, s, 0$).
2: while $S \neq V$ do
3: \hspace{1em} $(v, d'(v)) = \text{ExtractMin}(Q)$
4: \hspace{1em} Add $v$ to $S$ and set $d(v) = d'(v)$
5: \hspace{1em} for every node $x \in V - S$ such that $(v, x)$ is an edge in $G$ do
6: \hspace{2em} if $d(v) + l(v, x) < d'(x)$ then
7: \hspace{3em} $d'(x) = d(v) + l(v, x)$
8: \hspace{2em} ChangeKey($Q, x, d'(x)$)

- How many times does the algorithm invoke ExtractMin? $n - 1$ times.
- For every node $v$, what is the running time of step 5? $O(d_v)$, the number of outgoing neighbours of $v$.
- What is the total running time of step 5? $\sum_{v \in V} O(d_v) = O(m)$.
- How many times does the algorithm invoke ChangeKey?
Running Time of Faster Dijkstra’s Algorithm

Dijkstra’s Algorithm$(G, l, s)$

1: Insert$(Q, s, 0)$.
2: while $S \neq V$ do
3: $(v, d'(v)) = \text{ExtractMin}(Q)$
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- How many times does the algorithm invoke ExtractMin? $n - 1$ times.
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## Running Time of Faster Dijkstra’s Algorithm

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2. while \(S \neq V\) do
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- How many times does the algorithm invoke \text{ExtractMin}\? \(n - 1\) times.
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Running Time of Faster Dijkstra’s Algorithm

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- How many times does the algorithm invoke \text{ExtractMin}? \(n - 1\) times.
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- How many times does the algorithm invoke \text{ChangeKey}? At most \(m\) times.
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Running Time of Faster Dijkstra’s Algorithm

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6: \textbf{if} \(d(v) + l(v, x) < d'(x)\) \textbf{then}
7: \hspace{1cm} \(d'(x) = d(v) + l(v, x)\)
8: \hspace{1cm} \textbf{ChangeKey}(Q, x, d'(x))

- How many times does the algorithm invoke \textbf{ExtractMin}? \(n - 1\) times.
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- What is the total running time of step 5? \(\sum_{v \in V} O(d_v) = O(m)\).
- How many times does the algorithm invoke \textbf{ChangeKey}? At most \(m\) times.
- What is total running time of the algorithm? \(O(m \log n)\).
- State of the art: Fibonacci heaps achieve a running time of \(O(m)\) for all \textbf{ChangeKey} operations, for a running time of \(O(n \log n + m)\).
Network Design

- Connect a set of nodes using a set of edges with certain properties.
- Input is usually a graph and the desired network (the output) should use subset of edges in the graph.
- Example: connect all nodes using a cycle of shortest total length.
Network Design

- Connect a set of nodes using a set of edges with certain properties.
- Input is usually a graph and the desired network (the output) should use subset of edges in the graph.
- Example: connect all nodes using a cycle of shortest total length. This problem is the NP-complete traveling salesman problem.
Minimum Spanning Tree (MST)

- Given an undirected graph $G(V, E)$ with a cost $c(e) > 0$ associated with each edge $e \in E$.
- Find a subset $T$ of edges such that the graph $(V, T)$ is connected and the cost $\sum_{e \in T} c(e)$ is as small as possible.
Minimum Spanning Tree (MST)

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(a) Not connected  
(b) Not connected  
(c) Not smallest cost

(d) Not smallest cost  
(e) Not smallest cost  
(f) Smallest cost
Minimum Spanning Tree (MST)

**INSTANCE:** An undirected graph $G(V, E)$ and a function $c : E \rightarrow \mathbb{R}^+$

**SOLUTION:** A set $T \subseteq E$ of edges such that $(V, T)$ is connected and the cost $\sum_{e \in T} c(e)$ is as small as possible.

Claim: If $T$ is a minimum-cost solution to this problem then $(V, T)$ is a tree.

A subset $T$ of $E$ is a spanning tree of $G$ if $(V, T)$ is a tree.
Minimum Spanning Tree (MST)

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A subset $T$ of $E$ is a *spanning tree* of $G$ if $(V, T)$ is a tree.
Greedy Algorithm for the MST Problem

- Template: process edges in some order. Add an edge to $T$ if tree property is not violated.
Greedy Algorithm for the MST Problem

- **Template:** process edges in some order. Add an edge to $T$ if tree property is not violated.

  - **Increasing cost order** Process edges in increasing order of cost. Discard an edge if it creates a cycle.
  - **Dijkstra-like** Start from a node $s$ and grow $T$ outward from $s$: add the node that can be attached most cheaply to current tree.

  - **Decreasing cost order** Delete edges in order of decreasing cost as long as graph remains connected.
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- Which of these algorithms works?
Greedy Algorithm for the MST Problem

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- **Which of these algorithms works?** All of them!
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- Which of these algorithms works? All of them!

- Simplifying assumption: all edge costs are distinct.
Characterising MSTs

- Does the edge of smallest cost belong to an MST?
Characterising MSTs

Does the edge of smallest cost belong to an MST? Yes. Why?

Wrong proof: because Kruskal's algorithm adds it. We have not yet proved correctness of Kruskal's algorithm!

Correct proof: will work it out soon.

Which edges must belong to an MST?

What happens when we delete an edge from an MST?

MST breaks up into sub-trees.

Which edge should we add to join them?

Which edges cannot belong to an MST?

What happens when we add an edge to an MST?

We obtain a cycle.

Which edge in the cycle can we be sure does not belong to an MST?
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Graph Cuts

- A cut in a graph $G(V, E)$ is a set of edges whose removal disconnects the graph (into two or more connected components).
Graph Cuts

- A *cut* in a graph $G(V, E)$ is a set of edges whose removal disconnects the graph (into two or more connected components).
A **cut** in a graph $G(V, E)$ is a set of edges whose removal disconnects the graph (into two or more connected components).

Every set $S \subset V$ ($S$ cannot be empty or the entire set $V$) has a corresponding cut: $cut(S)$ is the set of edges $(v, w)$ such that $v \in S$ and $w \in V - S$.

$cut(S)$ is a “cut” because deleting the edges in $cut(S)$ disconnects $S$ from $V - S$.  

---

**Polls**
Graph Cuts

- A **cut** in a graph $G(V, E)$ is a set of edges whose removal disconnects the graph (into two or more connected components).
- Every set $S \subset V$ ($S$ cannot be empty or the entire set $V$) has a corresponding cut: $\text{cut}(S)$ is the set of edges $(v, w)$ such that $v \in S$ and $w \in V - S$.
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Graph Cuts

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- $\text{cut}(S)$ is a “cut” because deleting the edges in $\text{cut}(S)$ disconnects $S$ from $V - S$.

(a) Not cut({a, b, d}): (c, g) (b) Is cut({a, b, d}) (c) Not cut({a, b, d}): (a, b) (d) Not cut({a, b, d}): (b, e)
Graph Cuts

- A **cut** in a graph $G(V, E)$ is a set of edges whose removal disconnects the graph (into two or more connected components).
- Every set $S \subset V$ ($S$ cannot be empty or the entire set $V$) has a corresponding cut: $\text{cut}(S)$ is the set of edges $(v, w)$ such that $v \in S$ and $w \in V - S$.
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```latex
table
\begin{tabular}{|c|c|c|c|c|c|}
\hline
a & b & c & d & e & f \\
4 & 5 & 15 & 2 & 11 & 8 & 20 \\
\hline
b & c & h & e & d & f \\
11 & 7 & 12 & 3 & 1 & 6 \\
\hline
g & h & d & e \\
2 & 6 \\
\hline
d & e & f \\
8 & 20 \\
\hline
d & e & f \\
8 & 20 \\
\hline
g & h \\
2 \\
\hline
\end{tabular}
```

T. M. Murali September 21, 23, 28, 2021 Greedy Graph Algorithms
A cut in a graph \( G(V, E) \) is a set of edges whose removal disconnects the graph (into two or more connected components).

Every set \( S \subset V \) (\( S \) cannot be empty or the entire set \( V \)) has a corresponding cut: \( \text{cut}(S) \) is the set of edges \((v, w)\) such that \( v \in S \) and \( w \in V - S \).

\( \text{cut}(S) \) is a “cut” because deleting the edges in \( \text{cut}(S) \) disconnects \( S \) from \( V - S \).
Cut Property

When is it safe to include an edge in an MST?

Claim: For every $S \subset V$, $S \neq \emptyset$, every MST contains the cheapest edge in cut($S$).

Proof by contradiction using exchange argument.

Let $e = (u, v)$ be the cheapest edge in cut($S$).

Proof strategy: If $T$ does not contain $e$, show that there is a tree with smaller cost than $T$ that contains $e$. 

---

Diagram: A graph with nodes labeled a, b, c, d, e, f, g, h and edges with weights labeled on them. The graph includes the edge with weight 4 from a to b, which is part of the cut $S$. The MST includes the edge with weight 8 from d to e, which is not part of the cut $S$. The cut $S$ is highlighted in gray.
**Cut Property**

- When is it safe to include an edge in an MST?
- **Claim:** For every $S \subset V, S \neq \emptyset$, every MST contains the cheapest edge in $\text{cut}(S)$.

Proof strategy: If $T$ does not contain $e = (u, v)$, show that there is a tree with smaller cost than $T$ that contains $e$. 

![Graph Diagram]

The graph shows a network with nodes labeled a through g and edges connecting them with weights. The cut property is illustrated with the green edge, which is the cheapest edge in the cut and is included in the MST.
Cut Property

- When is it safe to include an edge in an MST?
- Claim: For every $S \subset V, S \neq \emptyset$, every MST contains the cheapest edge in cut($S$).
- Proof by contradiction using exchange argument.
Cut Property

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  There is a set \( S \subseteq V \) and an MST \( T \) such that \( T \) does not contain the cheapest edge in \( \text{cut}(S) \).
When is it safe to include an edge in an MST?

Claim: For every $S \subset V, S \neq \emptyset$, every MST contains the cheapest edge in cut($S$).

Proof by contradiction using exchange argument.

How do you state the contradiction to the claim? There is a set $S \subset V$ and an MST $T$ such that $T$ does not contain the cheapest edge in cut($S$).

Let $e = (u, v)$ be the cheapest edge in cut($S$).
**Cut Property**

- When is it safe to include an edge in an MST?
- Claim: For every $S \subset V, S \neq \emptyset$, every MST contains the cheapest edge in $\text{cut}(S)$.
- Proof by contradiction using exchange argument.
- How do you state the contradiction to the claim? There is a set $S \subset V$ and an MST $T$ such that $T$ does not contain the cheapest edge in $\text{cut}(S)$.
  - Let $e = (u, v)$ be the cheapest edge in $\text{cut}(S)$.
- Proof strategy: If $T$ does not contain $e$, show that there is a tree with smaller cost than $T$ that contains $e$. 
Proof of Cut Property

- There is a set $S \subset V$ and an MST $T$ such that $T$ does not contain the cheapest edge in $\text{cut}(S)$.
- Proof strategy: If $T$ does not contain $e$, show that there is a tree with smaller cost than $T$ that contains $e$.
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- Proof strategy: If $T$ does not contain $e$, show that there is a tree with smaller cost than $T$ that contains $e$.

Wrong proof:
- Since $T$ is spanning, it must contain some edge, e.g., $f$, in $\text{cut}(S)$.
- $T - \{f\} \cup \{e\}$ has smaller cost than $T$ but

Correct proof:
- Add $e$ to $T$ forming a cycle.
- This cycle must contain an edge $e'$ in $\text{cut}(S)$.
- Poll $T - \{e'\} \cup \{e\}$ has smaller cost than $T$ and is a spanning tree.
Proof of Cut Property

- There is a set $S \subset V$ and an MST $T$ such that $T$ does not contain the cheapest edge in $\text{cut}(S)$.
- Proof strategy: If $T$ does not contain $e$, show that there is a tree with smaller cost than $T$ that contains $e$.

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- Since $T$ is spanning, it must contain some edge, e.g., $f$, in $\text{cut}(S)$.
- $T - \{f\} \cup \{e\}$ has smaller cost than $T$ but may not be a spanning tree.

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Proof of Cut Property

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- Proof strategy: If \( T \) does not contain \( e \), show that there is a tree with smaller cost than \( T \) that contains \( e \).

Wrong proof:
- Since \( T \) is spanning, it must contain some edge, e.g., \( f \), in \( \text{cut}(S) \).
- \( T - \{f\}\cup\{e\} \) has smaller cost than \( T \) but may not be a spanning tree.

Correct proof:
- Add \( e \) to \( T \) forming a cycle.
- This cycle must contain an edge \( e' \) in \( \text{cut}(S) \).
Proof of Cut Property

There is a set $S \subset V$ and an MST $T$ such that $T$ does not contain the cheapest edge in $\text{cut}(S)$.

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Correct proof:
- Add $e$ to $T$ forming a cycle.
- This cycle must contain an edge $e'$ in $\text{cut}(S)$.
- $T - \{e'\} \cup \{e\}$ has smaller cost than $T$ and is a spanning tree.
Prim’s Algorithm

- Maintain a tree \((S, T)\), i.e. a set of nodes and a set of edges, which we will show will always be a tree.
- Start with an arbitrary node \(s \in S\).
Prim’s Algorithm

- Maintain a tree \((S, T)\), i.e. a set of nodes and a set of edges, which we will show will always be a tree.
- Start with an arbitrary node \(s \in S\).

**Prim’s Algorithm** \((G, c, s)\)

1. \(S = \{s\} \text{ and } T = \emptyset\)
2. while \(S \neq V\) do
3. Compute \((u, v) = \arg \min_{(u, v): u \in S, v \in V - S} c(u, v)\)
4. Add the node \(v\) to \(S\) and add the edge \((u, v)\) to \(T\).
Prim’s Algorithm

- Maintain a tree \((S, T)\), i.e. a set of nodes and a set of edges, which we will show will always be a tree.
- Start with an arbitrary node \(s \in S\).

**Prim’s Algorithm**\((G, c, s)\)

1: \(S = \{s\}\) and \(T = \emptyset\)
2: while \(S \neq V\) do
3: \(\text{Compute } (u, v) = \arg \min_{u \in S, v \in V - S} c(u, v)\)
4: \(\text{Add the node } v \text{ to } S \text{ and add the edge } (u, v) \text{ to } T.\)

- Note that

\[
\arg \min_{(u, v), u \in S, v \in V - S} c(u, v) \equiv \arg \min_{(u, v) \in \text{cut}(S)} c(u, v).
\]

- In other words, in each step, Prim’s algorithm computes and adds the cheapest edge in the current value of \(\text{cut}(S)\).
Example of Prim’s Algorithm
Example of Prim’s Algorithm

Graph:
- a
- b
- c
- d
- e
- f
- g
- h

Edges and Weights:
- a to b: 4
- a to c: 5
- a to g: 15
- b to c: 11
- c to h: 7
- b to d: 12
- c to e: 3
- c to f: 20
- d to e: 8
- e to f: 6
- g to h: 2

Greedy Graph Algorithms

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September 21, 23, 28, 2021
Example of Prim’s Algorithm

Graph:

- Vertices: a, b, c, d, e, f, g, h
- Edges and Weights:
  - (a, b) weight 4
  - (b, c) weight 11
  - (c, f) weight 20
  - (f, g) weight 6
  - (b, e) weight 8
  - (a, c) weight 5
  - (c, h) weight 7
  - (h, g) weight 2
  - (c, d) weight 15
  - (d, e) weight 1
  - (d, b) weight 12

Algorithm steps:
1. Start with vertex a.
2. Add the minimum weight edge from a: (a, b) weight 4.
3. Add the minimum weight edge from b: (b, c) weight 11.
4. Add the minimum weight edge from c: (c, f) weight 20.
5. Add the minimum weight edge from f: (f, g) weight 6.
6. Add the minimum weight edge from g: (g, h) weight 2.
7. Add the minimum weight edge from h: (h, c) weight 7.
8. Add the minimum weight edge from c: (c, d) weight 15.
9. Add the minimum weight edge from d: (d, e) weight 1.
10. Add the minimum weight edge from e: (e, b) weight 8.

The minimum spanning tree includes all vertices and the edges:
- a → b → c → f → g → h → c → d → e → b

Weight of the minimum spanning tree: 76
Example of Prim’s Algorithm

The diagram above illustrates a network of nodes and edges, with weights associated with each edge. Prim’s algorithm can be used to find the minimum spanning tree of this network.
Example of Prim’s Algorithm
Example of Prim’s Algorithm
Example of Prim’s Algorithm

```
a 4 5 15 2
b 11 3 1
  12
  8
d
c
  12 3 1
  11
  8
  8
e
f
  20
  6
  7
  2
  15
g
  1
  7
  2
h
```
Example of Prim’s Algorithm

Graph:

- Vertices: a, b, c, d, e, f, g, h
- Edges with weights:
  - (a, b) = 4
  - (b, c) = 11
  - (b, d) = 12
  - (c, e) = 3
  - (c, h) = 7
  - (d, e) = 8
  - (e, f) = 20
  - (f, g) = 6
  - (g, h) = 2
  - (a, c) = 15

Algorithm:

2. Select the edge with the smallest weight that connects a vertex in the tree to a vertex outside the tree. Let's choose (a, b) with weight 4.
3. Add the new vertex b to the tree.
4. Select the next smallest weight edge that connects a vertex in the tree to a vertex outside the tree. Let's choose (b, c) with weight 11.
5. Add the new vertex c to the tree.
6. Continue this process until all vertices are included in the tree.
Example of Prim’s Algorithm

Graph:
- Nodes: a, b, c, d, e, f, g, h
- Edges with weights:
  - a to b: 4
  - a to c: 5
  - a to b: 11
  - b to d: 12
  - b to c: 3
  - c to e: 1
  - e to f: 20
  - f to g: 6
  - g to h: 2
  - h to c: 7

Prim’s Algorithm implementation example.
Example of Prim’s Algorithm

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Example of Prim’s Algorithm

The diagram above illustrates the steps of Prim’s algorithm for constructing a minimum spanning tree. The algorithm starts with an arbitrary vertex (in this case, vertex a) and then iteratively adds the minimum-weight edge that connects a vertex in the tree to a vertex outside the tree until all vertices are included.

Here are the steps highlighted in blue:
- Starting from vertex a,
- Adding the edge with weight 4 to vertex b,
- Adding the edge with weight 5 to vertex c,
- Adding the edge with weight 15 to vertex g,
- Adding the edge with weight 2 to vertex h,
- Adding the edge with weight 12 to vertex d,
- Adding the edge with weight 3 to vertex e,
- Adding the edge with weight 20 to vertex f.

The minimum spanning tree includes all vertices and edges highlighted in blue.
Example of Prim’s Algorithm

Graph with weighted edges:

- a to b: 4
- a to c: 5
- a to d: 11
- b to c: 12
- b to d: 3
- c to e: 1
- c to f: 20
- d to e: 8
- e to f: 6
- g to h: 2

A minimum spanning tree can be created by selecting edges in order of weight:
1. a to b: 4
2. b to d: 3
3. c to e: 1
4. e to f: 20
5. g to h: 2

Tree edges highlighted in blue.
Example of Prim’s Algorithm
Example of Prim’s Algorithm

```
<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>12</td>
<td>8</td>
<td>20</td>
<td>15</td>
</tr>
</tbody>
</table>
```

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Example of Prim’s Algorithm
Optimality of Prim’s Algorithm

**Prim’s Algorithm** \((G, c, s)\)

1: \(S = \{s\}\) and \(T = \emptyset\)
2: **while** \(S \neq V\) **do**
3: Compute \((u, v) = \arg\min_{(u, v) \in \text{cut}(S)} c(u, v)\)
4: Add the node \(v\) to \(S\) and add the edge \((u, v)\) to \(T\).

- Claim: Prim’s algorithm outputs an MST.
Optimality of Prim’s Algorithm

**Prim’s Algorithm** \((G, c, s)\)

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2: while \(S \neq V\) do
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Claim: Prim’s algorithm outputs an MST.

1. Prove that every edge inserted satisfies the cut property.
2. Prove that the graph constructed is a spanning tree.
Optimality of Prim’s Algorithm

**Prim’s Algorithm**($G, c, s$)

1. $S = \{s\}$ and and $T = \emptyset$
2. while $S \neq V$ do
3. Compute $(u, v) = \arg\min_{(u, v) \in \text{cut}(S)} c(u, v)$
4. Add the node $v$ to $S$ and add the edge $(u, v)$ to $T$.

- **Claim**: Prim’s algorithm outputs an MST.
  1. Prove that every edge inserted satisfies the cut property.
     - By construction, in each iteration $(u, v)$ is the cheapest edge in cut($S$) for the current value of $S$.
  2. Prove that the graph constructed is a spanning tree.
Optimality of Prim’s Algorithm

**Prim’s Algorithm** \((G, c, s)\)

1. \(S = \{s\}\) and \(T = \emptyset\)
2. **while** \(S \neq V\) **do**
3. Compute \((u, v) = \arg \min_{(u, v) \in \text{cut}(S)} c(u, v)\)
4. Add the node \(v\) to \(S\) and add the edge \((u, v)\) to \(T\).

- **Claim:** Prim’s algorithm outputs an MST.
  1. Prove that every edge inserted satisfies the cut property.
     - By construction, in each iteration \((u, v)\) is the cheapest edge in \(\text{cut}(S)\) for the current value of \(S\).
  2. Prove that the graph constructed is a spanning tree.
     - Why are there no cycles in \((V, T)\)?
**Optimality of Prim’s Algorithm**

**Prim’s Algorithm**\((G, c, s)\)

1: \(S = \{s\}\) and \(T = \emptyset\)

2: \textbf{while} \(S \neq V\) \textbf{do}

3: \textbf{Compute} \((u, v) = \arg \min_{(u, v) \in \text{cut}(S)} c(u, v)\)

4: \textbf{Add the node} \(v\) to \(S\) and add the edge \((u, v)\) to \(T\).

---

- **Claim:** Prim’s algorithm outputs an MST.
  1. Prove that every edge inserted satisfies the cut property.
     - By construction, in each iteration \((u, v)\) is the cheapest edge in \(\text{cut}(S)\) for the current value of \(S\).
  2. Prove that the graph constructed is a spanning tree.
     - Why are there no cycles in \((V, T)\)?
     - Why is \((V, T)\) a spanning tree (edges in \(T\) connect all nodes in \(V)\)?
Kruskal’s Algorithm

- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
- Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle. Discard $e$ if it creates a cycle.
Example of Kruskal’s Algorithm

```
<table>
<thead>
<tr>
<th>a</th>
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<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
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<td>12</td>
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<td></td>
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<tr>
<td>8</td>
<td>20</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
```

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Example of Kruskal’s Algorithm

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Example of Kruskal’s Algorithm
Example of Kruskal’s Algorithm
Example of Kruskal’s Algorithm

A graph with weighted edges is shown, where the edges are drawn in blue to indicate they are part of the spanning tree. The weights of the edges are indicated next to the corresponding edges. The algorithm starts by sorting the edges by weight, and then iteratively selects the next lightest edge that does not create a cycle. The resulting graph is a minimum spanning tree.
Example of Kruskal’s Algorithm
Example of Kruskal’s Algorithm
Example of Kruskal’s Algorithm

1. Sort all the edges in the graph in non-decreasing order of their weights.
2. Start with an empty set of edges for the minimum spanning tree.
3. Add the next edge from the sorted list to the set of edges if it does not form a cycle with the edges already in the set.
4. Repeat step 3 until there are (V-1) edges in the set, where V is the number of vertices in the graph.

The resulting set of edges will form a minimum spanning tree.
Example of Kruskal’s Algorithm

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Example of Kruskal’s Algorithm

The image shows a graph with vertices labeled a, b, c, d, e, f, g, and h, and edges with weights indicated. The algorithm starts by selecting the smallest weight edges that do not form a cycle. The selected edges are highlighted in red. The process continues until a minimum spanning tree is formed.
Example of Kruskal’s Algorithm
Example of Kruskal’s Algorithm
Example of Kruskal’s Algorithm

The algorithm proceeds as follows:

1. Sort all the edges in the graph in non-decreasing order of their weights.
2. Start with an empty set of edges to form the minimum spanning tree.
3. Pick the lightest edge that does not form a cycle with the edges already in the set.
4. Repeat step 3 until there are (V-1) edges in the set, where V is the number of vertices in the graph.

The minimum spanning tree for this graph includes the edges with weights 4, 5, 15, 7, 6, 20.
Example of Kruskal’s Algorithm
Optimality of Kruskal’s Algorithm

Kruskal’s algorithm:
- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
- Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle. Discard $e$ if it creates a cycle.

Note: at any iteration, $T$ may contain several connected components and each node in $V$ is in some component.

Claim: Kruskal’s algorithm outputs an MST.

For every edge $e$ added, demonstrate the existence of a set $S \subset V$ (and $V - S$) such that $e$ and $S$ satisfy the cut property, i.e., $e$ is the cheapest edge in cut($S$).

If $e = (u, v)$, let $S$ be the set of nodes connected to $u$ in the current graph $T$.

Why is $e$ the cheapest edge in cut($S$)?

Prove that the algorithm computes a spanning tree.
- ($V, T$) contains no cycles by construction.
- If ($V, T$) is not connected, there exists a subset $S$ of nodes not connected to $V - S$. What is the contradiction?
Optimality of Kruskal’s Algorithm

Kruskal’s algorithm:
- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
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1. For every edge $e$ added, demonstrate the existence of a set $S \subset V$ (and $V - S$) such that $e$ and $S$ satisfy the cut property, i.e., $e$ is the cheapest edge in $\text{cut}(S)$.

2. Prove that the algorithm computes a spanning tree.
Optimality of Kruskal’s Algorithm

Kruskal’s algorithm:

- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
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   - If $e = (u, v)$, let $S$ be the set of nodes connected to $u$ in the current graph $T$.

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Optimality of Kruskal’s Algorithm

- Kruskal’s algorithm:
  - Start with an empty set $T$ of edges.
  - Process edges in $E$ in increasing order of cost.
  - Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle. Discard $e$ if it creates a cycle.

- Note: at any iteration, $T$ may contain several connected components and each node in $V$ is in some component.

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  1. For every edge $e$ added, demonstrate the existence of a set $S \subset V$ (and $V - S$) such that $e$ and $S$ satisfy the cut property, i.e., $e$ is the cheapest edge in cut($S$).
     - If $e = (u, v)$, let $S$ be the set of nodes connected to $u$ in the current graph $T$.
     - Why is $e$ the cheapest edge in cut($S$)?
  2. Prove that the algorithm computes a spanning tree.
Optimality of Kruskal’s Algorithm

- Kruskal’s algorithm:
  - Start with an empty set $T$ of edges.
  - Process edges in $E$ in increasing order of cost.
  - Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle. Discard $e$ if it creates a cycle.
- Note: at any iteration, $T$ may contain several connected components and each node in $V$ is in some component.
- Claim: Kruskal’s algorithm outputs an MST.
  1. For every edge $e$ added, demonstrate the existence of a set $S \subset V$ (and $V - S$) such that $e$ and $S$ satisfy the cut property, i.e., $e$ is the cheapest edge in $\text{cut}(S)$.
    - If $e = (u, v)$, let $S$ be the set of nodes connected to $u$ in the current graph $T$.
    - Why is $e$ the cheapest edge in $\text{cut}(S)$?
  2. Prove that the algorithm computes a spanning tree.
    - $(V, T)$ contains no cycles by construction.
Optimality of Kruskal’s Algorithm

Kruskal’s algorithm:
- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
- Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle. Discard $e$ if it creates a cycle.

Note: at any iteration, $T$ may contain several connected components and each node in $V$ is in some component.

Claim: Kruskal’s algorithm outputs an MST.

1. For every edge $e$ added, demonstrate the existence of a set $S \subset V$ (and $V - S$) such that $e$ and $S$ satisfy the cut property, i.e., $e$ is the cheapest edge in $\text{cut}(S)$.
   - If $e = (u, v)$, let $S$ be the set of nodes connected to $u$ in the current graph $T$.
   - Why is $e$ the cheapest edge in $\text{cut}(S)$?

2. Prove that the algorithm computes a spanning tree.
   - $(V, T)$ contains no cycles by construction.
   - If $(V, T)$ is not connected, there exists a subset $S$ of nodes not connected to $V - S$. What is the contradiction?
Cycle Property

- When can we be sure that an edge cannot be in any MST?
Cycle Property

- When can we be sure that an edge cannot be in any MST?
- Let $C$ be any cycle in $G$ and let $e = (v, w)$ be the most expensive edge in $C$.
- Claim: $e$ does not belong to any MST of $G$. 

Proof: exchange argument. If a supposed MST $T$ contains $e$, show that there is a tree with smaller cost than $T$ that does not contain $e$. 

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When can we be sure that an edge cannot be in any MST?

Let \( C \) be any cycle in \( G \) and let \( e = (v, w) \) be the most expensive edge in \( C \).

Claim: \( e \) does not belong to any MST of \( G \).

Proof: exchange argument. If a supposed MST \( T \) contains \( e \), show that there is a tree with smaller cost than \( T \) that does not contain \( e \).

**Figure 4.11** Swapping the edge \( e' \) for the edge \( e \) in the spanning tree \( T \), as described in the proof of (4.20).
Optimality of the Reverse-Delete Algorithm

- Reverse-Delete algorithm: Maintain a set $E'$ of edges.
  - Start with $E' = E$.
  - Process edges in decreasing order of cost.
  - Delete the next edge $e$ from $E'$ only if $(V, E')$ is connected after deletion.
  - Stop after processing all the edges.

- Claim: the Reverse-Delete algorithm outputs an MST.
Optimality of the Reverse-Delete Algorithm

Reverse-Delete algorithm: Maintain a set $E'$ of edges.

- Start with $E' = E$.
- Process edges in decreasing order of cost.
- Delete the next edge $e$ from $E'$ only if $(V, E')$ is connected after deletion.
- Stop after processing all the edges.

Claim: the Reverse-Delete algorithm outputs an MST.

1. Show that every edge deleted belongs to no MST.
2. Prove that the graph remaining at the end is a spanning tree.
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Optimality of the Reverse-Delete Algorithm

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     - Since the edge is the first encountered by the algorithm, it is the most expensive edge in $C$.
  2. Prove that the graph remaining at the end is a spanning tree.
     - $(V, E')$ is connected at the end, by construction.
     - If $(V, E')$ contains a cycle, consider the costliest edge in that cycle. The algorithm would have deleted that edge.
### Implementing Prim’s Algorithm

**Prim’s Algorithm** $(G, c, s)$

1. $S = \{s\}$ and $T = \emptyset$
2. **while** $S \neq V$ **do**
3. \[ (u, v) = \arg\min_{(u, v) : u \in S, v \in V - S} c(u, v) \]
4. Add the node $v$ to $S$ and add the edge $(u, v)$ to $T$.

- Implementation and analysis are very similar to Dijkstra’s algorithm.
- Maintain $S$ and store attachment costs $a(v) = \min_{e \in \text{cut}(S)} c(e)$ for every node $v \in V - S$ in a priority queue. **Not the same as Dijsktra’s algorithm!**
- At each step, extract the node $v$ with the minimum attachment cost from the priority queue and update the attachment costs of the neighbours of $v$. 
Final Version of Prim’s Algorithm

Prim’s Algorithm\((G, c, s)\)

1: \textbf{Insert}\((Q, s, 0, \emptyset)\)
2: \textbf{while} \(S \neq V\) \textbf{do}
3: \((v, a(v), u) = \textbf{ExtractMin}(Q)\)
4: \textbf{Add} node \(v\) to \(S\) and edge \((u, v)\) to \(T\).
5: \textbf{for} every node \(x \in V - S\) such that \((v, x)\) is an edge in \(G\) \textbf{do}
6: \hspace{1em} \textbf{if} \(c(v, x) < a(x)\) \textbf{then}
7: \hspace{2em} \(a(x) = c(v, x)\)
8: \hspace{2em} \textbf{ChangeKey}(Q, x, a(x), v)

- \(Q\) is a priority queue.
- Each element in \(Q\) is a triple: the node, its attachment cost, and its predecessor in the MST.
- In Step 8, if \(x\) is not already in \(Q\), simply \textbf{Insert} \((x, a(x), v)\) into \(Q\).
**Final Version of Prim’s Algorithm**

**Prim’s Algorithm** \((G, c, s)\)

1. **Insert** \((Q, s, 0, \emptyset)\)
2. **while** \(S \neq V\) **do**
3. \((v, a(v), u) = \text{ExtractMin}(Q)\)
4. **Add node** \(v\) **to** \(S\) **and edge** \((u, v)\) **to** \(T\).
5. **for** every node \(x \in V - S\) such that \((v, x)\) is an edge in \(G\) **do**
6. **if** \(c(v, x) < a(x)\) **then**
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8. **ChangeKey** \((Q, x, a(x), v)\)

- \(Q\) is a priority queue.
- Each element in \(Q\) is a triple: the node, its attachment cost, and its predecessor in the MST.
- In Step 8, if \(x\) is not already in \(Q\), simply **Insert** \((x, a(x), v)\) into \(Q\).
- Total of \(n - 1\) \text{ExtractMin} and \(m\) \text{ChangeKey}/Insert operations, yielding a running time of \(O(m \log n)\).

Skip implementation of Kruskal’s algorithm.
Implementing Kruskal’s Algorithm

- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
- Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle.
Implementing Kruskal’s Algorithm

- Start with an empty set $T$ of edges.
- Process edges in $E$ in increasing order of cost.
- Add the next edge $e$ to $T$ only if adding $e$ does not create a cycle.
- Sorting edges takes $O(m \log n)$ time.
- Key question: “Does adding $e = (u, v)$ to $T$ create a cycle?”
  - Maintain set of connected components of $T$.
  - $\text{FIND}(u)$: return the name of the connected component of $T$ that $u$ belongs to.
  - $\text{UNION}(A, B)$: merge connected components $A$ and $B$. 
Analysing Kruskal’s Algorithm

- How many \texttt{FIND} invocations does Kruskal’s algorithm need?
Analysing Kruskal’s Algorithm

- How many **FIND** invocations does Kruskal’s algorithm need? $2m$.
- How many **UNION** invocations does Kruskal’s algorithm need?
Analysing Kruskal’s Algorithm

- How many `FIND` invocations does Kruskal’s algorithm need? $2m$.
- How many `UNION` invocations does Kruskal’s algorithm need? $n - 1$. 

Textbook describes two implementations of `Union-Find`: (see appendix to this set of slides)

- Each `FIND` takes $O(1)$ time, $k$ invocations of `Union` take $O(k \log k)$ time in total.
- Each `FIND` takes $O(\log n)$ time and each invocation of `Union` takes $O(1)$ time.

Total running time of Kruskal’s algorithm is $O(m \log n)$.
Analysing Kruskal’s Algorithm

- How many **FIND** invocations does Kruskal’s algorithm need? $2m$.
- How many **UNION** invocations does Kruskal’s algorithm need? $n - 1$.
- Textbook describes two implementations of **UNION-FIND**: (see appendix to this set of slides)
  - Each **FIND** takes $O(1)$ time, $k$ invocations of **UNION** take $O(k \log k)$ time in total.
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Analysing Kruskal’s Algorithm

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  - Each `FIND` takes $O(\log n)$ time and each invocation of `UNION` takes $O(1)$ time.
- Total running time of Kruskal’s algorithm is $O(m \log n)$. 
Comments on Union-Find and MST

- The **Union-Find** data structure is useful to maintain the connected components of a graph as edges are added to the graph.
- The data structure does not support edge deletion efficiently.
Comments on MST Algorithms

- To handle multiple edges with the same length, perturb each length by a random infinitesimal amount. Read the textbook.

- *Any* algorithm that constructs a spanning tree by including edges that satisfy the cut property and deleting edges that satisfy the cycle property will yield an MST!

- Current best algorithm for MST runs in $O(m\alpha(m, n))$ time (Chazelle 2000) and $O(m)$ randomised time (Karger, Klein, and Tarjan, 1995).

- Holy grail: $O(m)$ deterministic algorithm for MST.
Appendix: Union-Find

Union-Find Data Structure

- Abstraction of the data structure needed by Kruskal’s algorithm.
- Maintain disjoint subsets of elements from a universe $U$ of $n$ elements.
- Each subset has an name. We will set a set’s name to be the identity of some element in it.
- Support three operations:
  1. \texttt{MAKEUNIONFIND}(U): initialise the data structure with elements in $U$.
  2. \texttt{FIND}(u): return the identity of the subset that contains $u$.
  3. \texttt{UNION}(A, B): merge the sets named $A$ and $B$ into one set.
Union-Find Data Structure: Implementation 1

- Store all the elements of $U$ in an array $COMPONENT$.
  - Assume identities of elements are integers from 1 to $n$.
  - $COMPONENT[s]$ is the name of the set containing $s$.
- Implementing the operations:
Appendix: Union-Find

Union-Find Data Structure: Implementation 1

- Store all the elements of $U$ in an array $\text{COMPONENT}$. 
  - Assume identities of elements are integers from 1 to $n$.
  - $\text{COMPONENT}[s]$ is the name of the set containing $s$.

- Implementing the operations:
  1. $\text{MAKEUNIONFIND}(U)$: For each $s \in U$, set $\text{COMPONENT}[s] = s$ in $O(n)$ time.
  2. $\text{FIND}(s)$: return $\text{COMPONENT}[s]$ in $O(1)$ time.
  3. $\text{UNION}(A, B)$: merge $B$ into $A$ by scanning $\text{COMPONENT}$ and updating each index whose value is $B$ to the value $A$. Takes $O(n)$ time.
Union-Find Data Structure: Implementation 1

- Store all the elements of $U$ in an array $\text{Component}$.
  - Assume identities of elements are integers from 1 to $n$.
  - $\text{Component}[s]$ is the name of the set containing $s$.

- Implementing the operations:
  1. $\text{MakeUnionFind}(U)$: For each $s \in U$, set $\text{Component}[s] = s$ in $O(n)$ time.
  2. $\text{Find}(s)$: return $\text{Component}[s]$ in $O(1)$ time.
  3. $\text{Union}(A, B)$: merge $B$ into $A$ by scanning $\text{Component}$ and updating each index whose value is $B$ to the value $A$. Takes $O(n)$ time.

- $\text{Union}$ is very slow because
Union-Find Data Structure: Implementation 1

- Store all the elements of $U$ in an array $\text{Component}$.
  - Assume identities of elements are integers from 1 to $n$.
  - $\text{Component}[s]$ is the name of the set containing $s$.

Implementing the operations:

1. $\text{MAKEUNIONFIND}(U)$: For each $s \in U$, set $\text{Component}[s] = s$ in $O(n)$ time.
2. $\text{FIND}(s)$: return $\text{Component}[s]$ in $O(1)$ time.
3. $\text{UNION}(A, B)$: merge $B$ into $A$ by scanning $\text{Component}$ and updating each index whose value is $B$ to the value $A$. Takes $O(n)$ time.

$\text{UNION}$ is very slow because we cannot efficiently find the elements that belong to a set.
Union-Find Data Structure: Implementation 2

- Optimisation 1: Use an array \texttt{ELEMENTS}
  - Indices of \texttt{ELEMENTS} range from 1 to \(n\).
  - \texttt{ELEMENTS}[s] stores the elements in the subset named \(s\) in a list.

- Execute \texttt{UNION}(\(A, B\)) by merging \(B\) into \(A\) in two steps:
  1. Updating \texttt{COMPONENT} for elements of \(B\) in \(O(|B|)\) time.
  2. Append \texttt{ELEMENTS}[\(B\)] to \texttt{ELEMENTS}[\(A\)] in \(O(1)\) time.

- \texttt{UNION} takes \(\Omega(n)\) in the worst-case.
Appendix: Union-Find

Union-Find Data Structure: Implementation 2

- Optimisation 1: Use an array `Elements`
  - Indices of `Elements` range from 1 to $n$.
  - `Elements[s]` stores the elements in the subset named $s$ in a list.

- Execute `Union(A, B)` by merging $B$ into $A$ in two steps:
  1. Updating `Component` for elements of $B$ in $O(|B|)$ time.

- `Union` takes $\Omega(n)$ in the worst-case.


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Union-Find Data Structure: Analysis of Implementation

- \textsc{MakeUnionFind}(S) and \textsc{Find}(u) are as before.

- The \textsc{Union}(A, B) operation runs in time proportional to the size of the smaller set, which may be $\Omega(n)$.
- Any sequence of $k$ \textsc{Union} operations takes $O(k \log k)$ time.
- Intuition: the running time of \textsc{Union} is dominated by updates to Component.
- Charge each update to the element being updated and bound the number of charges per element.
- Consider any element $s$. Every time $s$'s set identity is updated, the size of the set containing $s$ at least doubles $\Rightarrow$ $s$'s set can change at most $\log(2^k)$ times $\Rightarrow$ the total work done in $k$ \textsc{Union} operations is $O(k \log k)$.
- \textsc{Find} is fast in the worst case, \textsc{Union} is fast in an amortised sense. Can we make both operations worst-case efficient?
Union-Find Data Structure: Analysis of Implementation

- **MAKEUNIONFIND**$(S)$ and **FIND**$(u)$ are as before.
- **UNION**$(A, B)$: Running time is proportional to the size of the smaller set, which may be $\Omega(n)$.

▶ Any sequence of $k$ **UNION** operations takes $O(k \log k)$ time.
▶ $k$ **UNION** operations touch at most $2k$ elements.
▶ Intuition: running time of **UNION** is dominated by updates to **Component**.
Charge each update to the element being updated and bound number of charges per element.

▶ Consider any element $s$. Every time $s$’s set identity is updated, the size of the set containing $s$ at least doubles $\Rightarrow$ $s$’s set can change at most $\log(2^k)$ times $\Rightarrow$ the total work done in $k$ **UNION** operations is $O(k \log k)$.

**FIND** is fast in the worst case, **UNION** is fast in an amortised sense. Can we make both operations worst-case efficient?
Union-Find Data Structure: Analysis of Implementation

- $\text{MAKEUNIONFIND}(S)$ and $\text{FIND}(u)$ are as before.
- $\text{UNION}(A, B)$: Running time is proportional to the size of the smaller set, which may be $\Omega(n)$.
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Union-Find Data Structure: Analysis of Implementation

- \textsc{MakeUnionFind}(S) and \textsc{Find}(u) are as before.
- \textsc{Union}(A, B): Running time is proportional to the size of the smaller set, which may be \( \Omega(n) \).
- Any sequence of \( k \) \textsc{Union} operations takes \( O(k \log k) \) time.
  - \( k \) \textsc{Union} operations touch at most \( 2k \) elements.
Union-Find Data Structure: Analysis of Implementation

- `MAKEUNIONFIND(S)` and `FIND(u)` are as before.
- `UNION(A, B)`: Running time is proportional to the size of the smaller set, which may be $\Omega(n)$.
- Any sequence of $k$ `UNION` operations takes $O(k \log k)$ time.
  - $k$ `UNION` operations touch at most $2k$ elements.
  - Intuition: running time of `UNION` is dominated by updates to `Component`. Charge each update to the element being updated and bound number of charges per element.
MakeUnionFind\((S)\) and Find\((u)\) are as before.

Union\((A, B)\): Running time is proportional to the size of the smaller set, which may be \(\Omega(n)\).

Any sequence of \(k\) Union operations takes \(O(k \log k)\) time.

- \(k\) Union operations touch at most \(2k\) elements.
- Intuition: running time of Union is dominated by updates to Component.
  Charge each update to the element being updated and bound number of charges per element.
- Consider any element \(s\). Every time \(s\)'s set identity is updated, the size of the set containing \(s\) at least doubles \(\Rightarrow\) \(s\)'s set can change at most \(\log(2k)\) times \(\Rightarrow\) the total work done in \(k\) Union operations is \(O(k \log k)\).

Find is fast in the worst case, Union is fast in an amortised sense. Can we make both operations worst-case efficient?
Appendix: Union-Find

## Union-Find Data Structure: Analysis of Implementation

- **MAKEUNIONFIND(S)** and **FIND(u)** are as before.
- **UNION(A, B)**: Running time is proportional to the size of the smaller set, which may be $\Omega(n)$.
- Any sequence of $k$ **UNION** operations takes $O(k \log k)$ time.
  - $k$ **UNION** operations touch at most $2k$ elements.
  - Intuition: running time of **UNION** is dominated by updates to **COMPONENT**. Charge each update to the element being updated and bound number of charges per element.
  - Consider any element $s$. Every time $s$’s set identity is updated, the size of the set containing $s$ at least doubles $\Rightarrow$ $s$’s set can change at most $\log(2k)$ times $\Rightarrow$ the total work done in $k$ **UNION** operations is $O(k \log k)$.
- **FIND** is fast in the worst case, **UNION** is fast in an amortised sense. Can we make both operations worst-case efficient?
Union-Find Data Structure: Implementation 3

Goal: Implement \texttt{FIND} in \(O(\log n)\) and \texttt{UNION} in \(O(1)\) worst-case time.

- Represent each subset in a tree using pointers:
  - Each tree node contains an element and a pointer to a parent.
  - The identity of the set is the identity of the element at the root.

- Implementing \texttt{FIND}(u):
  - Follow pointers from \(u\) to the root of \(u\)'s tree.

- Implementing \texttt{UNION}(A, B):
  - Make smaller tree's root a child of the larger tree's root. Takes \(O(1)\) time.
Goal: Implement $\text{FIND}$ in $O(\log n)$ and $\text{UNION}$ in $O(1)$ worst-case time.

Represent each subset in a tree using pointers:
- Each tree node contains an element and a pointer to a parent.
- The identity of the set is the identity of the element at the root.

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**Figure 4.12** A Union-Find data structure using pointers. The data structure has only two sets at the moment, named after nodes $v$ and $j$. The dashed arrow from $u$ to $v$ is the result of the last Union operation. To answer a Find query, we follow the arrows until we get to a node that has no outgoing arrow. For example, answering the query Find($i$) would involve following the arrows $i$ to $x$, and then $x$ to $j$. 

The set $\{s, u, w\}$ was merged into $\{t, v, z\}$. 

The diagram shows a tree structure with nodes labeled $u$, $v$, $w$, $s$, $t$, $z$, $j$, $x$, $y$, and $i$. The dashed arrow from $u$ to $v$ indicates the result of the last Union operation.
Union-Find Data Structure: Implementation 3

- Goal: Implement \texttt{FIND} in $O(\log n)$ and \texttt{UNION} in $O(1)$ worst-case time.
- Represent each subset in a tree using pointers:
  - Each tree node contains an element and a pointer to a parent.
  - The identity of the set is the identity of the element at the root.
- Implementing \texttt{FIND}(u): follow pointers from $u$ to the root of $u$'s tree.

![Diagram](image.png)

\textbf{Figure 4.12} A Union–Find data structure using pointers. The data structure has only two sets at the moment, named after nodes $v$ and $j$. The dashed arrow from $u$ to $v$ is the result of the last Union operation. To answer a Find query, we follow the arrows until we get to a node that has no outgoing arrow. For example, answering the query \texttt{Find}(i) would involve following the arrows $i$ to $x$, and then $x$ to $j$. 
Goal: Implement `FIND` in $O(\log n)$ and `UNION` in $O(1)$ worst-case time.

Represent each subset in a tree using pointers:

- Each tree node contains an element and a pointer to a parent.
- The identity of the set is the identity of the element at the root.

Implementing `FIND(u)`: follow pointers from $u$ to the root of $u$’s tree.

Implementing `UNION(A, B)`: make smaller tree’s root a child of the larger tree’s root. Takes $O(1)$ time.

Figure 4.12 A Union–Find data structure using pointers. The data structure has only two sets at the moment, named after nodes $v$ and $j$. The dashed arrow from $u$ to $v$ is the result of the last `Union` operation. To answer a `Find` query, we follow the arrows until we get to a node that has no outgoing arrow. For example, answering the query `Find(i)` would involve following the arrows $i$ to $x$, and then $x$ to $j$. 
Why does $\text{Find}(u)$ take $O(\log n)$ time?

**Figure 4.12** A Union-Find data structure using pointers. The data structure has only two sets at the moment, named after nodes $v$ and $j$. The dashed arrow from $u$ to $v$ is the result of the last Union operation. To answer a Find query, we follow the arrows until we get to a node that has no outgoing arrow. For example, answering the query $\text{Find}(i)$ would involve following the arrows $i$ to $x$, and then $x$ to $j$. 
Why does $\text{FIND}(u)$ take $O(\log n)$ time?

- Number of pointers followed equals the number of times the identity of the set containing $u$ changed.
- Every time $u$’s set’s identity changes, the set at least doubles in size $\Rightarrow$ there are $O(\log n)$ pointers followed.
Every time we invoke $\text{FIND}(u)$, we follow the same set of pointers.
Every time we invoke $\text{FIND}(u)$, we follow the same set of pointers.

Path compression: make all nodes visited by $\text{FIND}(u)$ children of the root.

**Figure 4.12** A Union-Find data structure using pointers. The data structure has only two sets at the moment, named after nodes $v$ and $j$. The dashed arrow from $u$ to $v$ is the result of the last Union operation. To answer a Find query, we follow the arrows until we get to a node that has no outgoing arrow. For example, answering the query $\text{Find}(i)$ would involve following the arrows $i$ to $x$, and then $x$ to $j$. 
Union-Find Data Structure: Improving Implementation

- Every time we invoke $\text{FIND}(u)$, we follow the same set of pointers.
- Path compression: make all nodes visited by $\text{FIND}(u)$ children of the root.
Every time we invoke $\text{FIND}(u)$, we follow the same set of pointers.

- Path compression: make all nodes visited by $\text{FIND}(u)$ children of the root.
- Can prove that total time taken by $n$ $\text{FIND}$ operations is $O(n\alpha(n))$, where $\alpha(n)$ is the inverse of the Ackermann function, and grows extremely slowly with $n$. 

**Figure 4.13** (a) An instance of a Union–Find data structure; and (b) the result of the operation $\text{Find}(u)$ on this structure, using path compression.