“Scheduling note”

• “We now return to our interrupted program” on graphs
  – Last “graph lecture” was lecture 16
    • Shortest-path problem
    • Dijkstra’s algorithm for graphs with non-negative weights

• Why this strange schedule?
  – Needed to do parallelism and concurrency in time for project 3 and homeworks 6 and 7
    – But cannot delay all of graphs because of the CSE312 co-requisite

• So: not the most logical order, but hopefully not a big deal
Minimum Spanning Trees

Given an undirected graph $G=(V,E)$, find a graph $G'=(V, E')$ such that:

– $E'$ is a subset of $E$
– $|E'| = |V| - 1$
– $G'$ is connected

$G'$ is a **minimum spanning tree**.

$\sum_{(u,v) \in E'} c_{uv}$ is minimal

Applications:

• Example: Electrical wiring for a house or clock wires on a chip
• Example: A road network if you cared about asphalt cost rather than travel time
Find the MST

Student Activity
Two Different Approaches

Prim’s Algorithm
Almost identical to Dijkstra’s

Kruskals’s Algorithm
Completely different!
Two Different Approaches

Prim’s Algorithm
Almost identical to Dijkstra’s
One node, grow greedily

Kruskals’s Algorithm
Completely different!
Forest of MSTs, 
Union them together.
I wonder how to union…
Prim’s algorithm

**Idea:** Grow a tree by picking a vertex from the unknown set that has the smallest cost. Here cost = cost of the edge that connects that vertex to the known set. *Pick the vertex with the smallest cost that connects “known” to “unknown.”*

**A node-based greedy algorithm**
Builds MST by greedily adding nodes
Prim’s Algorithm vs. Dijkstra’s

Recall:

Dijkstra picked the unknown vertex with smallest cost where
  \[ \text{cost} = \text{distance to the source}. \]

Prim’s pick the unknown vertex with smallest cost where
  \[ \text{cost} = \text{distance from this vertex to the known set} \]
  (in other words, the cost of the smallest edge connecting this vertex to the known set)

  – Otherwise identical
  – Compare to slides in lecture 16!
Prim’s Algorithm for MST

1. For each node \( v \), set \( v.cost = \infty \) and \( v.known = \text{false} \)
2. Choose any node \( v \). (this is like your “start” vertex in Dijkstra)
   a) Mark \( v \) as known
   b) For each edge \((v, u)\) with weight \( w \):
      set \( u.cost = w \) and \( u.prev = v \)
3. While there are unknown nodes in the graph
   a) Select the unknown node \( v \) with lowest cost
   b) Mark \( v \) as known and add \((v, v.prev)\) to output (the MST)
   c) For each edge \((v, u)\) with weight \( w \),
      \[
      \text{if}(w < u.cost) \{
      \begin{align*}
      u.cost &= w; \\
      u.prev &= v;
      \end{align*}
      \}
      \]
Example: Find MST using Prim’s

Order added to known set:

<table>
<thead>
<tr>
<th>vertex</th>
<th>known?</th>
<th>cost</th>
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</table>
Example: Find MST using Prim’s

Order added to known set: A
Example: Find MST using Prim’s

Order added to known set: A, D

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Example: Find MST using Prim’s

Order added to known set: A, D, C

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Example: Find MST using Prim’s

Order added to known set:
A, D, C, E

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Example: Find MST using Prim’s

Order added to known set:
A, D, C, E, B

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Example: Find MST using Prim’s

Order added to known set:
A, D, C, E, B, F
Example: Find MST using Prim’s

Order added to known set:
A, D, C, E, B, F, G

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**Find MST using Prim’s**

Start with $V_1$

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<thead>
<tr>
<th>V</th>
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<th>Distance</th>
<th>path</th>
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Order Declared Known:

$V_1$

**Total Cost:**
Prim’s Analysis

• Correctness ??
  – A bit tricky
  – Intuitively similar to Dijkstra
  – Might return to this time permitting (unlikely)

• Run-time
  – Same as Dijkstra
  – $O(|E| \log |V|)$ using a priority queue
Kruskal’s MST Algorithm

Idea: Grow a forest out of edges that do not create a cycle. Pick an edge with the smallest weight.
Kruskal’s Algorithm for MST

An edge-based greedy algorithm
Builds MST by greedily adding edges

1. Initialize with
   • empty MST
   • all vertices marked unconnected
   • all edges unmarked

2. While there are still unmarked edges
   a. Pick the lowest cost edge $(u, v)$ and mark it
   b. If $u$ and $v$ are not already connected, add $(u, v)$ to the MST and mark $u$ and $v$ as connected to each other
Aside: Union-Find aka Disjoint Set ADT

- **Union**(x, y) – take the union of two sets named x and y
  - Given sets: \{3, 5, 7\}, \{4, 2, 8\}, \{9\}, \{1, 6\}
  - **Union**(5, 1)
    Result: \{3, 5, 7, 1, 6\}, \{4, 2, 8\}, \{9\},

To perform the union operation, we replace sets x and y by \((x \cup y)\)

- **Find**(x) – return the name of the set containing x.
  - Given sets: \{3, 5, 7, 1, 6\}, \{4, 2, 8\}, \{9\},
  - **Find**(1) returns 5
  - **Find**(4) returns 8

- We can do Union in constant time.
- We can get Find to be *amortized* constant time
  (worst case \(O(\log n)\) for an individual Find operation).
Kruskal’s pseudo code

```cpp
void Graph::kruskal(){
    int edgesAccepted = 0;
    DisjSet s(NUM_VERTICES);

    while (edgesAccepted < NUM_VERTICES - 1){
        e = smallest weight edge not deleted yet;
        // edge e = (u, v)
       uset = s.find(u);
        vset = s.find(v);
        if (uset != vset){
            edgesAccepted++;
            s.unionSets(uset, vset);
        }
    }
}
```
Kruskal’s pseudo code

```c
void Graph::kruskal()
{
    int edgesAccepted = 0;
    DisjSet s(NUM_VERTICES);

    while (edgesAccepted < NUM_VERTICES - 1)
    {
        e = smallest weight edge not deleted yet;
        // edge e = (u, v)
       uset = s.find(u);
        vset = s.find(v);
        if (uset != vset)
        {
            edgesAccepted++;
            s.unionSets(uset, vset);
        }
    }
}
```

On heap of edges
Deletemin = $\log |E|$

$|E|$ heap ops

$2|E|$ finds

One for each vertex in the edge
Find = $\log |V|$

$|V|$ unions

Union = $O(1)$

$O(|E|\log |E| + |E|\log |V| + |V|)$

$O(\log |E| + |E| - O(1)) = O(|E|\log |E|) = O(|E|\log |V|)$

$b/c \log |E| < \log |V|^{2} = 2\log |V|$
Find MST using Kruskal’s

Now find the MST using Prim’s method.
Under what conditions will these methods give the same result?

Total Cost:
Example: Find MST using Kruskal’s

Edges in sorted order:
1: (A,D), (C,D), (B,E), (D,E)
2: (A,B), (C,F), (A,C)
3: (E,G)
5: (D,G), (B,D)
6: (D,F)
10: (F,G)

Output:

Note: At each step, the union/find sets are the trees in the forest
Example: Find MST using Kruskal’s

Edges in sorted order:
1: (A,D), (C,D), (B,E), (D,E)
2: (A,B), (C,F), (A,C)
3: (E,G)
5: (D,G), (B,D)
6: (D,F)
10: (F,G)

Output: (A,D)

Note: At each step, the union/find sets are the trees in the forest
Example: Find MST using Kruskal’s

Edges in sorted order:
1: (A,D), (C,D), (B,E), (D,E)
2: (A,B), (C,F), (A,C)
3: (E,G)
5: (D,G), (B,D)
6: (D,F)
10: (F,G)

Output: (A,D), (C,D)

Note: At each step, the union/find sets are the trees in the forest
Example: Find MST using Kruskal’s

Edges in sorted order:
1: (A,D), (C,D), (B,E), (D,E)
2: (A,B), (C,F), (A,C)
3: (E,G)
5: (D,G), (B,D)
6: (D,F)
10: (F,G)

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

Note: At each step, the union/find sets are the trees in the forest
Example: Find MST using Kruskal’s

Edges in sorted order:
1:  (A,D), (C,D), (B,E), (D,E)
2:  (A,B), (C,F), (A,C)
3:  (E,G)
5:  (D,G), (B,D)
6:  (D,F)
10: (F,G)

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

Note: At each step, the union/find sets are the trees in the forest
Example: Find MST using Kruskal’s

Edges in sorted order:
1:  (A,D), (C,D), (B,E), (D,E)
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Example: Find MST using Kruskal’s

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Example: Find MST using Kruskal’s

Edges in sorted order:
1: (A,D), (C,D), (B,E), (D,E)
2: (A,B), (C,F), (A,C)
3: (E,G)
5: (D,G), (B,D)
6: (D,F)
10: (F,G)

Output: (A,D), (C,D), (B,E), (D,E), (C,F), (E,G)

Note: At each step, the union/find sets are the trees in the forest
Correctness

Kruskal’s algorithm is clever, simple, and efficient
 – But does it generate a minimum spanning tree?
 – How can we prove it?

First: it generates a spanning tree
 – Intuition: Graph started connected and we added every edge that did not create a cycle
 – Proof by contradiction: Suppose $u$ and $v$ are disconnected in Kruskal’s result. Then there’s a path from $u$ to $v$ in the initial graph with an edge we could add without creating a cycle. But Kruskal would have added that edge. Contradiction.

Second: There is no spanning tree with lower total cost…
The inductive proof set-up

Let $F$ (stands for “forest”) be the set of edges Kruskal has added at some point during its execution.

Claim: $F$ is a subset of one or more MSTs for the graph (Therefore, once $|F|=|V|-1$, we have an MST.)

Proof: By induction on $|F|

Base case: $|F|=0$: The empty set is a subset of all MSTs

Inductive case: $|F|=k+1$: By induction, before adding the $(k+1)^{th}$ edge (call it $e$), there was some MST $T$ such that $F\setminus \{e\} \subseteq T$ …
Staying a subset of some MST

Claim: \( F \) is a subset of one or more MSTs for the graph

So far: \( F - \{e\} \subseteq T \)

Two disjoint cases:
- If \( \{e\} \subseteq T \): Then \( F \subseteq T \) and we’re done
- Else \( e \) forms a cycle with some simple path (call it \( p \)) in \( T \)
  - Must be since \( T \) is a spanning tree
Staying a subset of some MST

Claim: F is a subset of one or more MSTs for the graph

So far: F-{e} $\subseteq$ T and e forms a cycle with p $\subseteq$ T

- There must be an edge e2 on p such that e2 is not in F
  - Else Kruskal would not have added e

- Claim: e2.weight == e.weight
Staying a subset of some MST

Claim: $F$ is a subset of one or more MSTs for the graph

So far: $F\{-e\} \subseteq T$
- $e$ forms a cycle with $p \subseteq T$
- $e2$ on $p$ is not in $F$

- Claim: $e2.weight == e.weight$
  - If $e2.weight > e.weight$, then $T$ is not an MST because $T\{-e2\}+\{e\}$ is a spanning tree with lower cost: contradiction
  - If $e2.weight < e.weight$, then Kruskal would have already considered $e2$. It would have added it since $T$ has no cycles and $F\{-e\} \subseteq T$. But $e2$ is not in $F$: contradiction
Staying a subset of some MST

Claim: \( F \) is a subset of one or more MSTs for the graph

So far: \( F - \{ e \} \subseteq T \)
- \( e \) forms a cycle with \( p \subseteq T \)
- \( e_2 \) on \( p \) is not in \( F \)
- \( e_2.\text{weight} == e.\text{weight} \)

- Claim: \( T - \{ e_2 \} + \{ e \} \) is an MST
  - It’s a spanning tree because \( p - \{ e_2 \} + \{ e \} \) connects the same nodes as \( p \)
  - It’s minimal because its cost equals cost of \( T \), an MST
- Since \( F \subseteq T - \{ e_2 \} + \{ e \} \), \( F \) is a subset of one or more MSTs

Done.