

# Lecture 15

## Minimum Spanning Trees

# Announcements

- HW7 Due Wednesday
- HW8 Out Wednesday
  - HW8 is short! Nearly there!

# Last time

- Greedy algorithms
  - Make a series of choices.
    - Choose this activity, then that one, ..
    - Never backtrack.
  - Show that, at each step, your choice does not rule out success.
    - At every step, there exists an optimal solution consistent with the choices we've made so far.
  - At the end of the day:
    - you've built only one solution,
    - never having ruled out success,
    - so your solution must be correct.

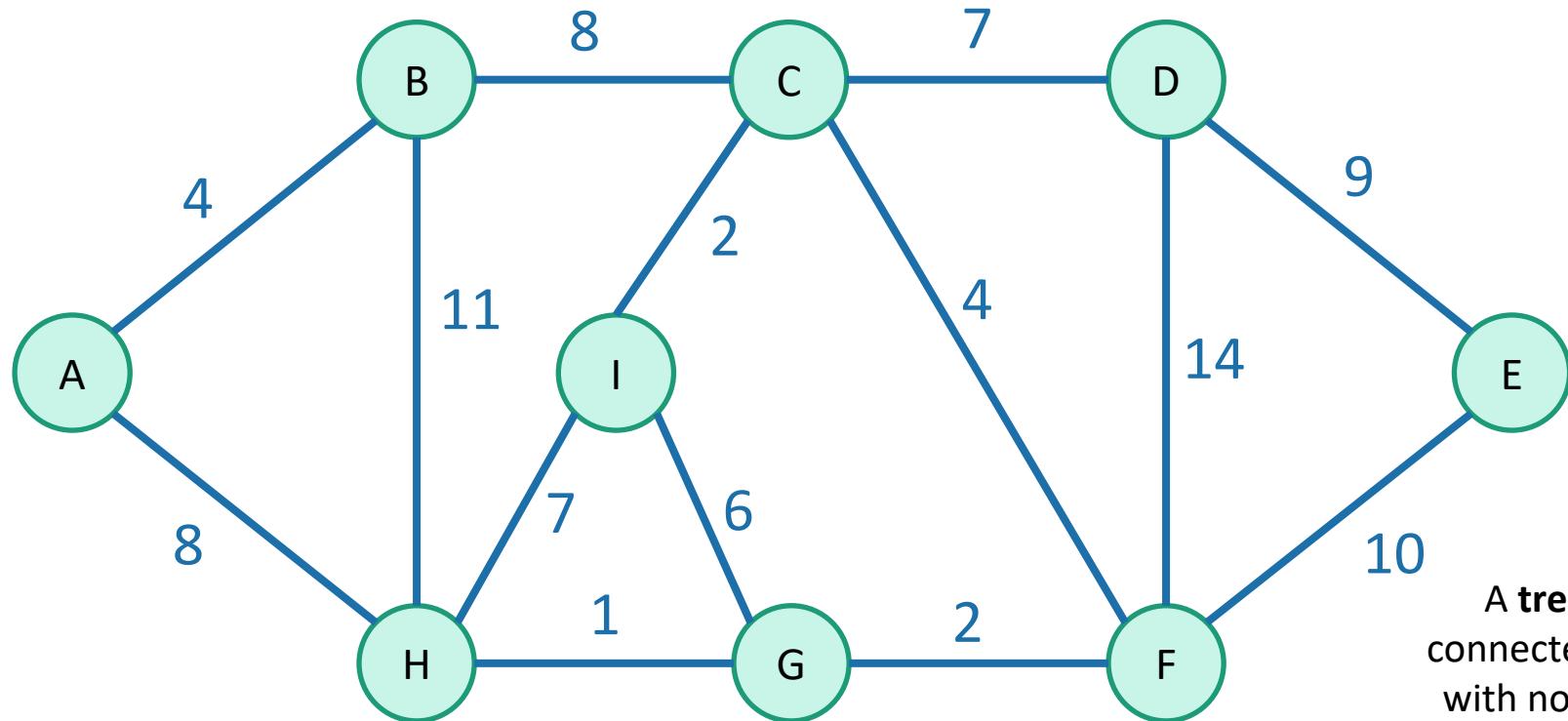
# Today

- Greedy algorithms for Minimum Spanning Tree.
- Agenda:
  1. What is a Minimum Spanning Tree?
  2. Short break to introduce some graph theory tools
  3. Prim's algorithm
  4. Kruskal's algorithm

For today, we will focus on connected graphs!

# Minimum Spanning Tree

Say we have an undirected weighted graph



A **tree** is a connected graph with no cycles!

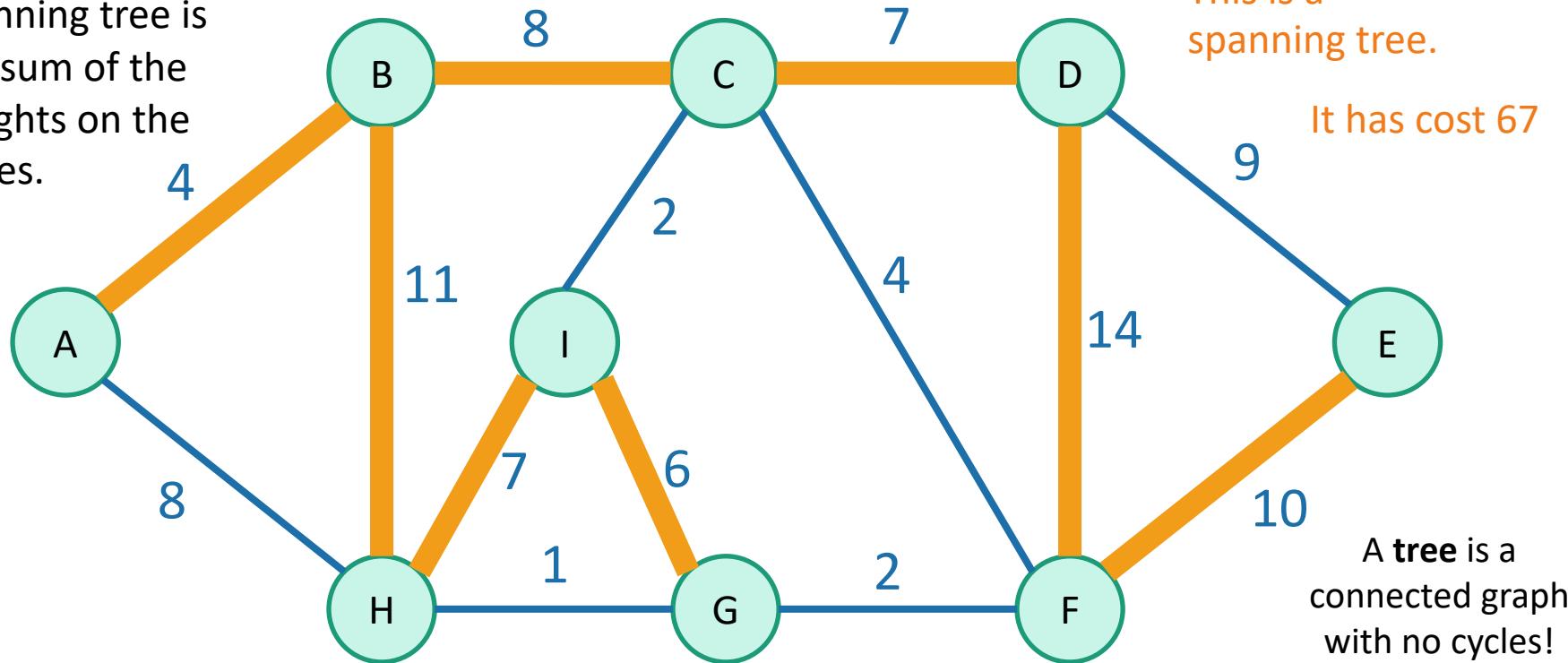
A **spanning tree** is a **tree** that connects all of the vertices.



# Minimum Spanning Tree

Say we have an undirected weighted graph

The **cost** of a spanning tree is the sum of the weights on the edges.

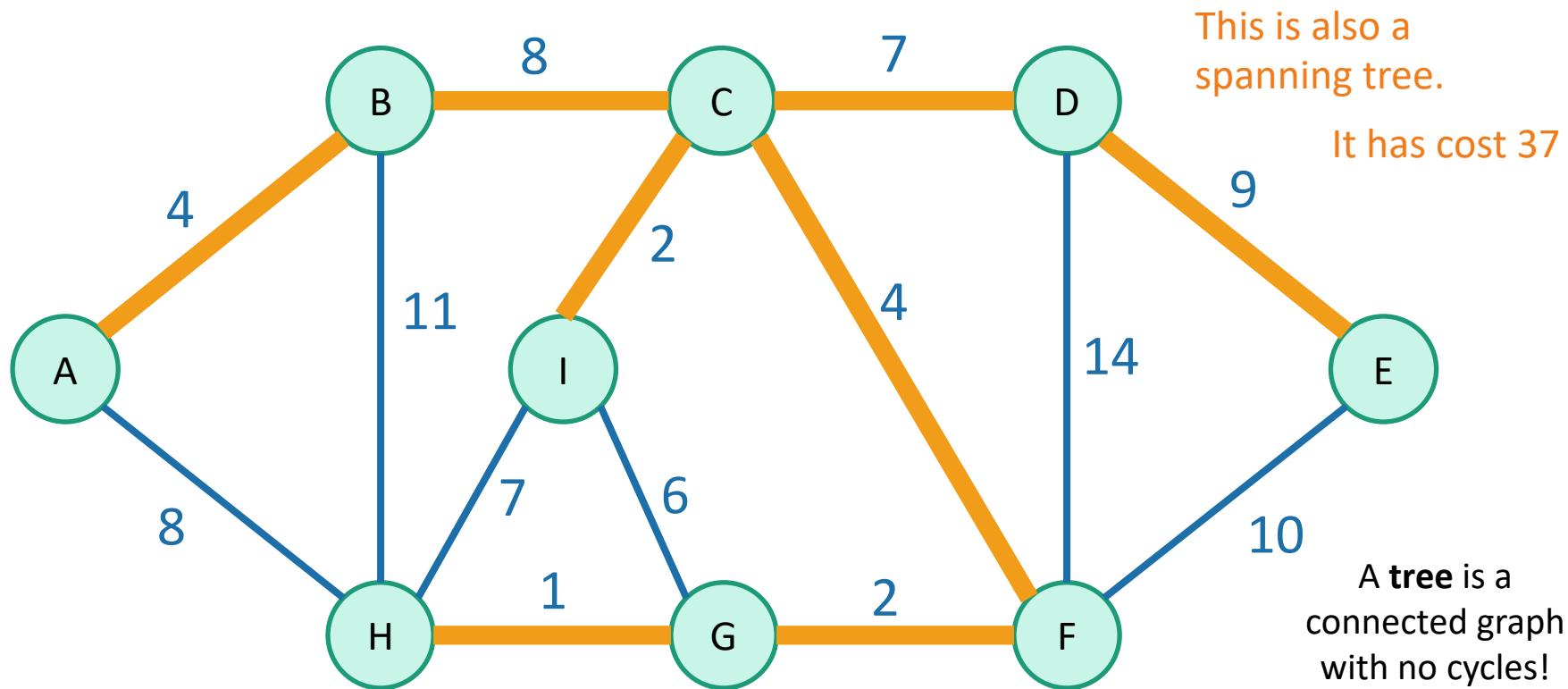


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# Minimum Spanning Tree

Say we have an undirected weighted graph

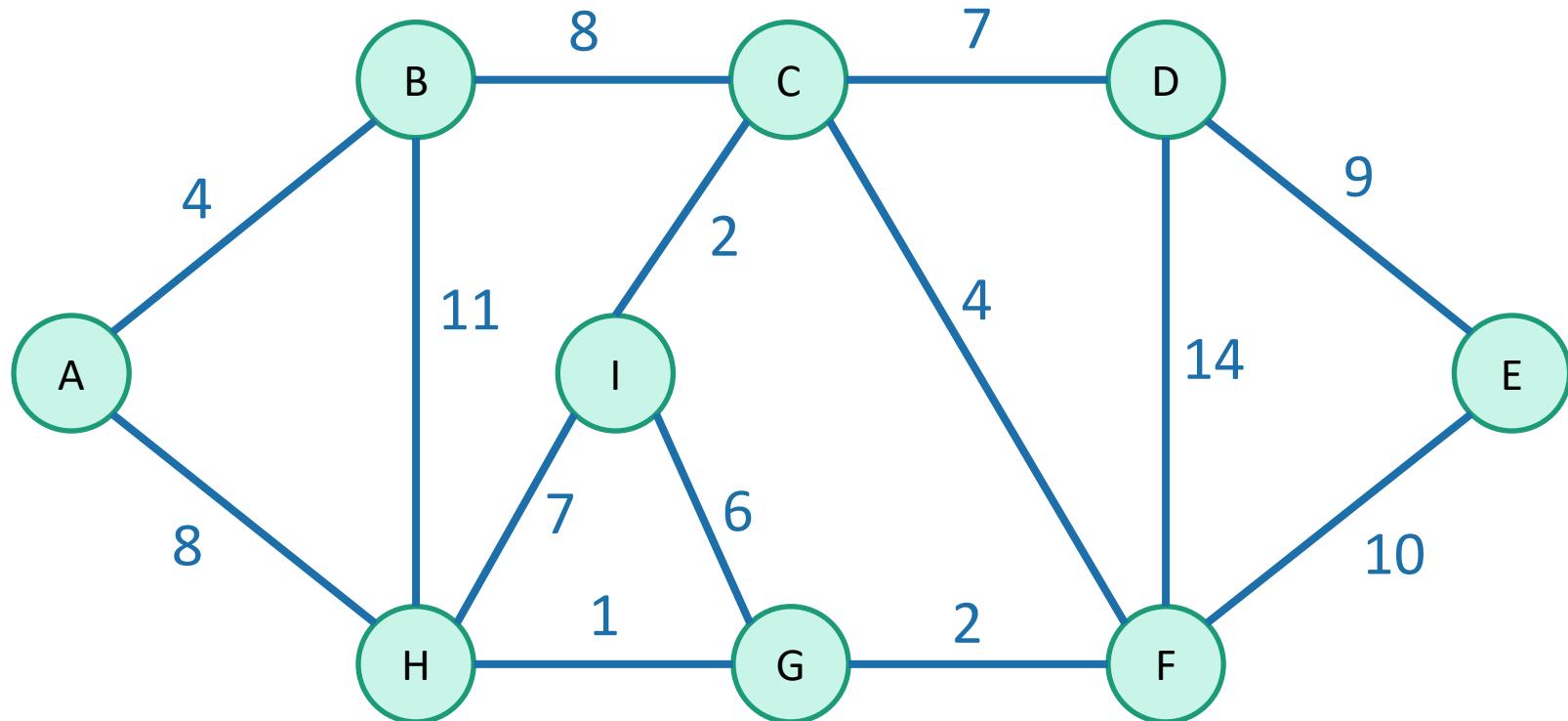


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# Minimum Spanning Tree

Say we have an undirected weighted graph



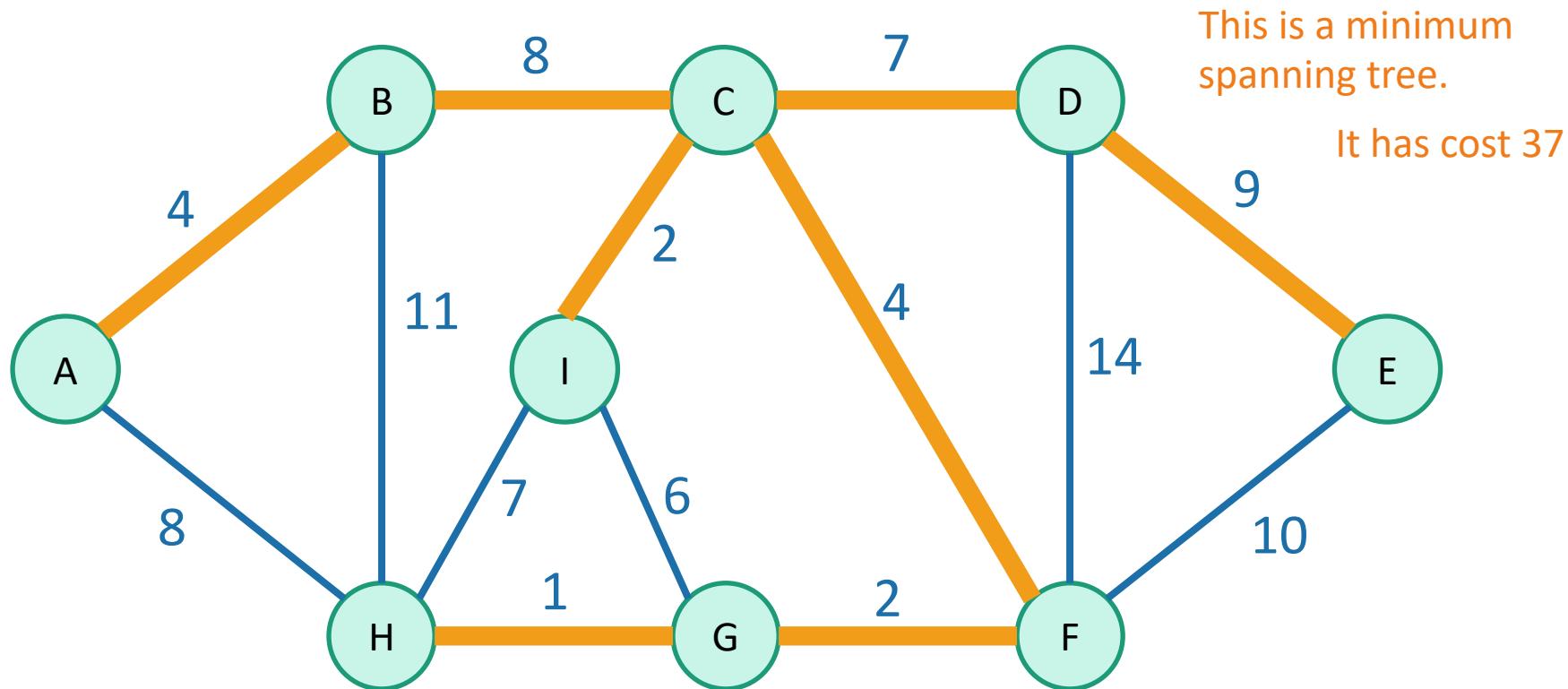
**minimum**

**of minimum cost**

A spanning tree is a **tree** that connects all of the vertices.

# Minimum Spanning Tree

Say we have an undirected weighted graph



**minimum**

A spanning tree is a **tree** that connects all of the vertices.

This is a minimum spanning tree.

It has cost 37

**of minimal cost**

# Why MSTs?



- Network design
    - Connecting cities with roads/electricity/telephone/...
  - cluster analysis
    - eg, genetic distance
  - image processing
    - eg, image segmentation
  - Useful primitive
    - for other graph algs

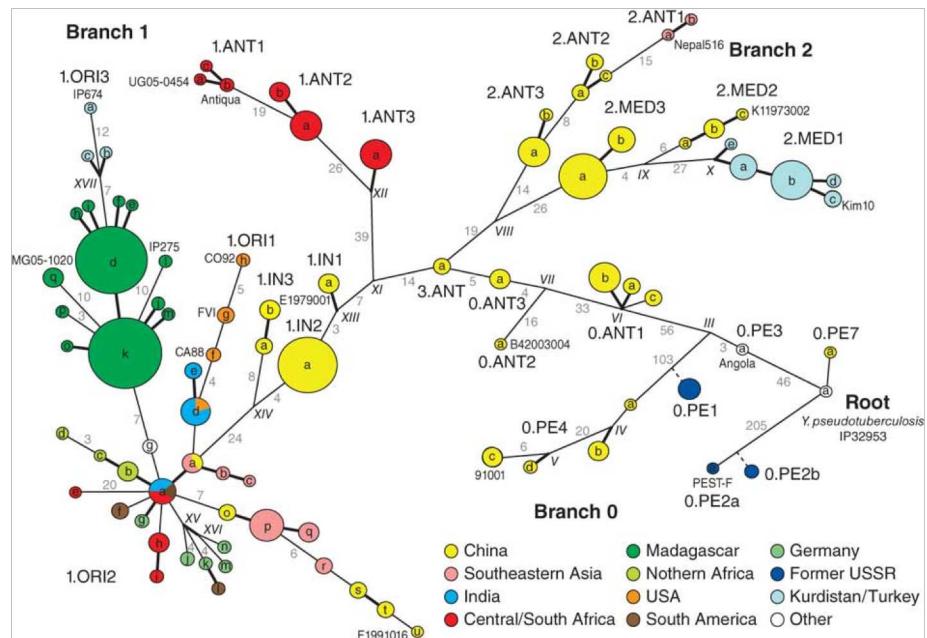
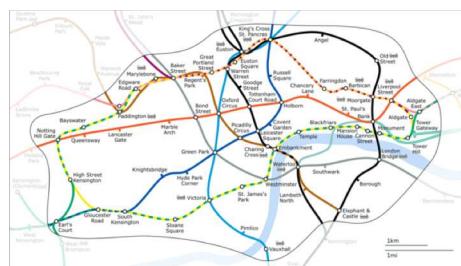


Figure 2: Fully parsimonious minimal spanning tree of 933 SNPs for 282 isolates of *Y. pestis* colored by location.  
**Morelli et al. Nature genetics 2010**

# How to find an MST?

- Today we'll see two greedy algorithms.
- In order to prove that these greedy algorithms work, we'll show something like:

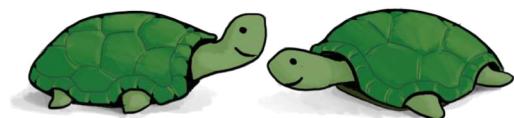
*Suppose that our choices so far  
are consistent with an MST.*

*Then the next greedy choice that we make  
is still consistent with an MST.*

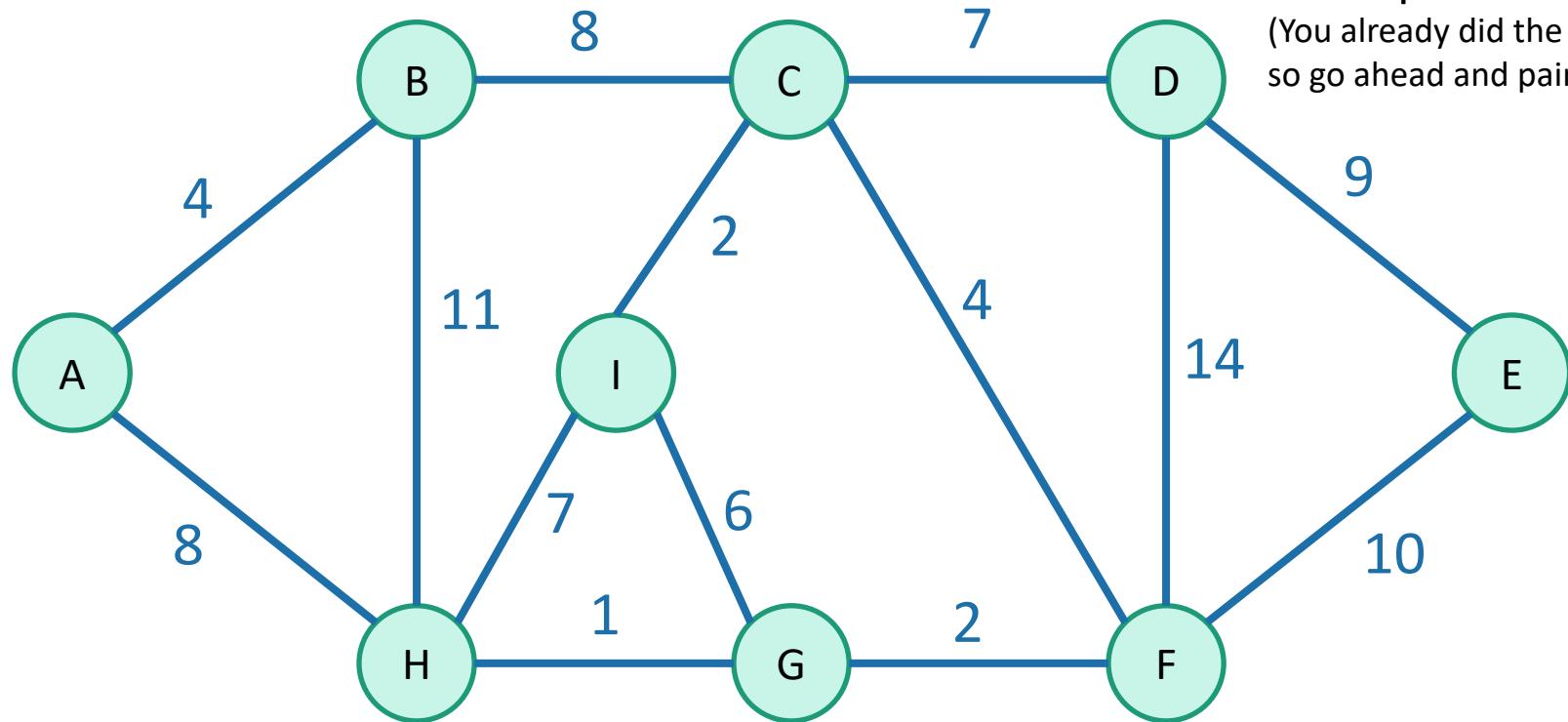
- This is not the only way to prove that these algorithms work!
  - See a different way in the Algorithms Illuminated reading.

Following your pre-lecture exercise...

# Let's brainstorm some greedy algorithms!



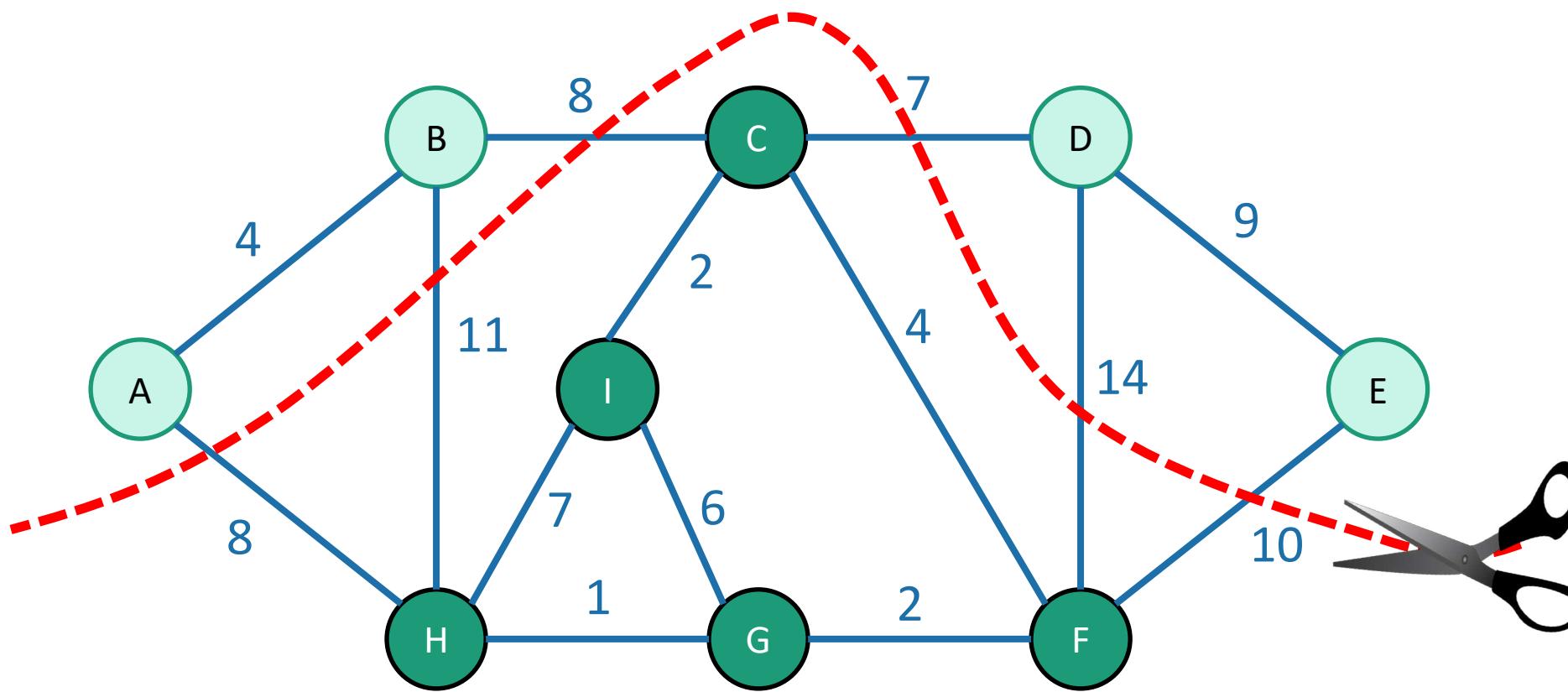
Think-pair-share!  
(You already did the thinking,  
so go ahead and pair+share).



Brief aside  
for a discussion of cuts in graphs!

# Cuts in graphs

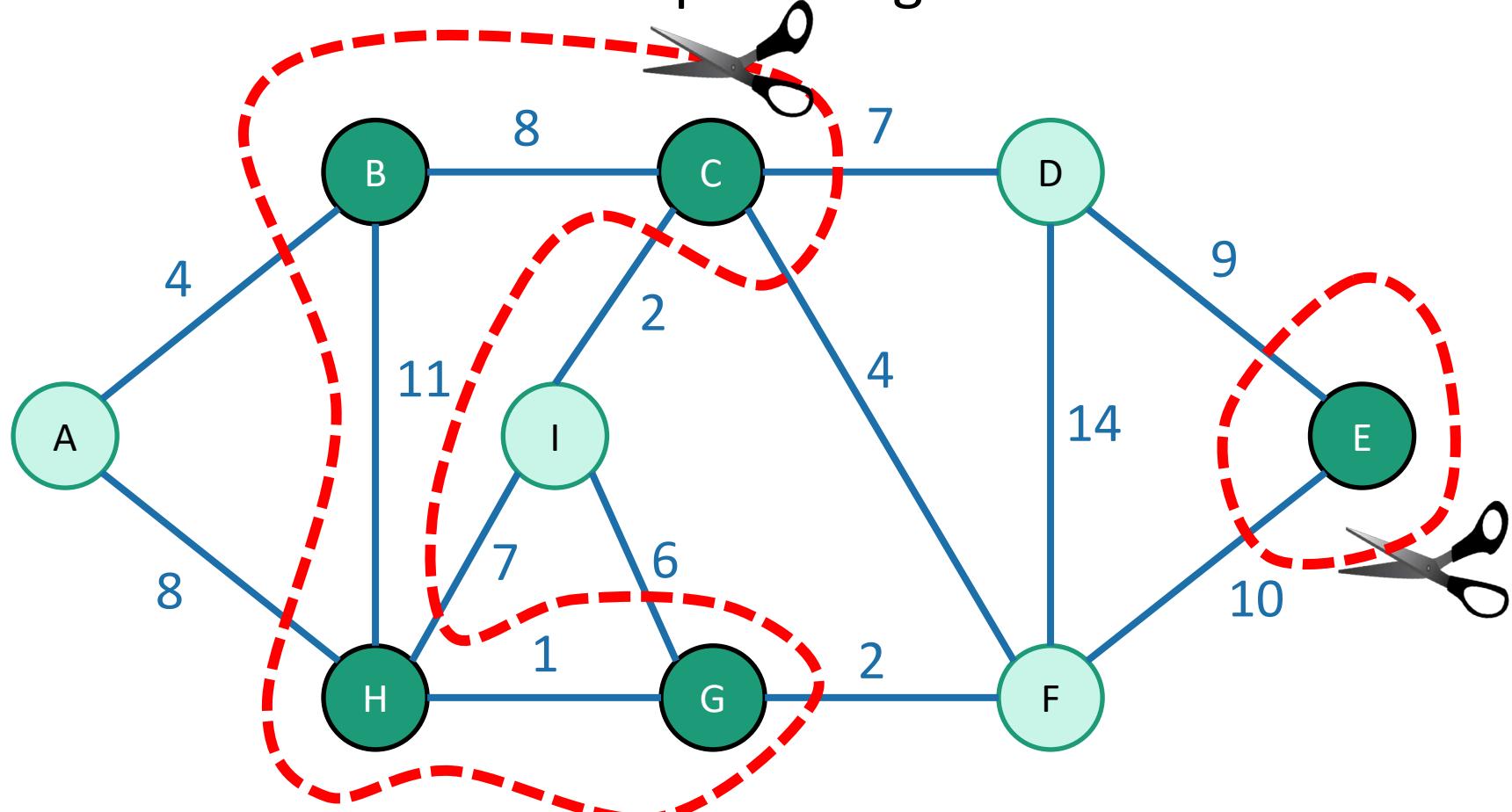
- A **cut** is a partition of the vertices into two parts:



This is the cut “ $\{A, B, D, E\}$  and  $\{C, I, H, G, F\}$ ”

# Cuts in graphs

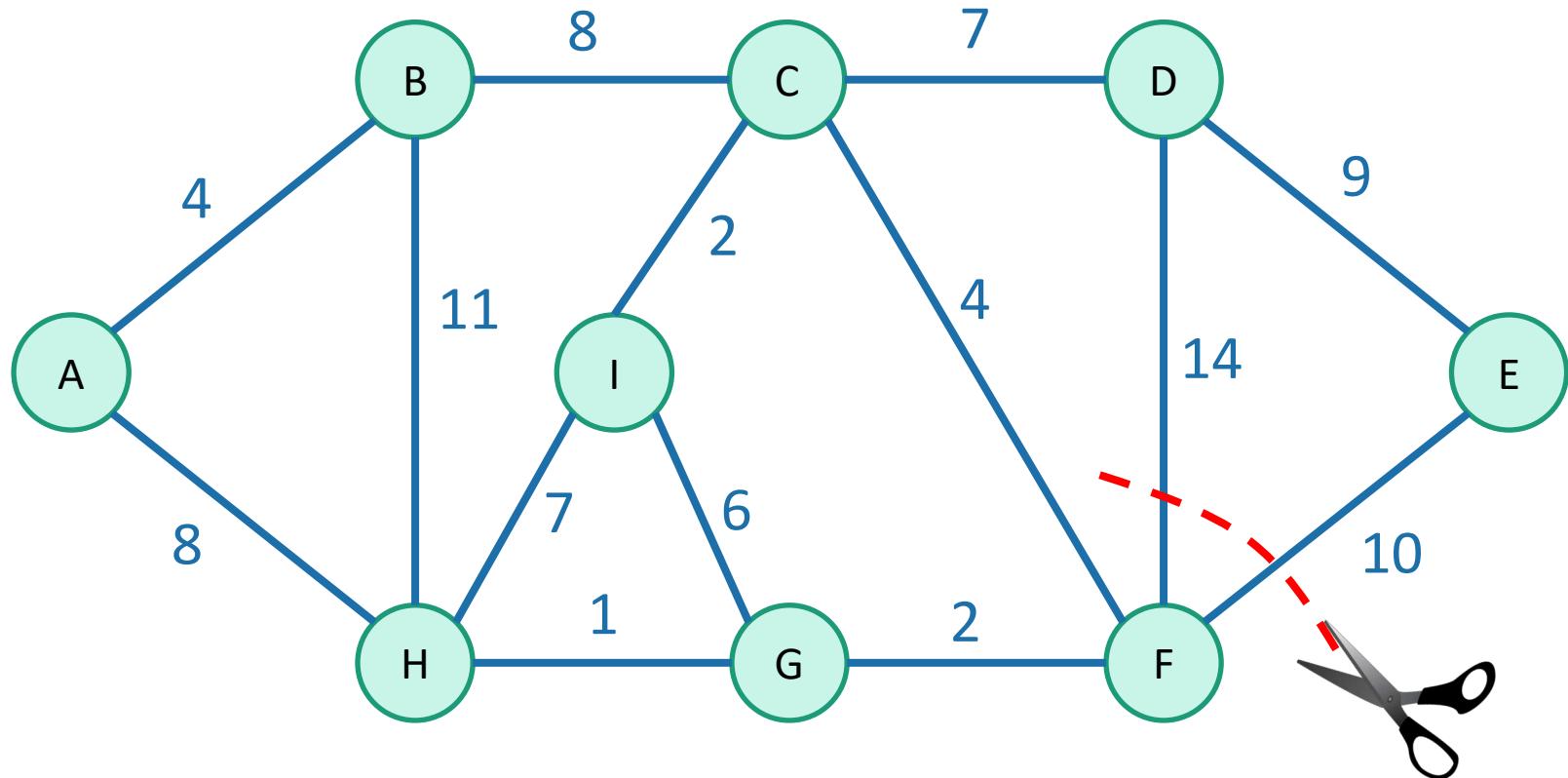
- One or both of the two parts might be disconnected.



This is the cut “ $\{B,C,E,G,H\}$  and  $\{A,D,I,F\}$ ”

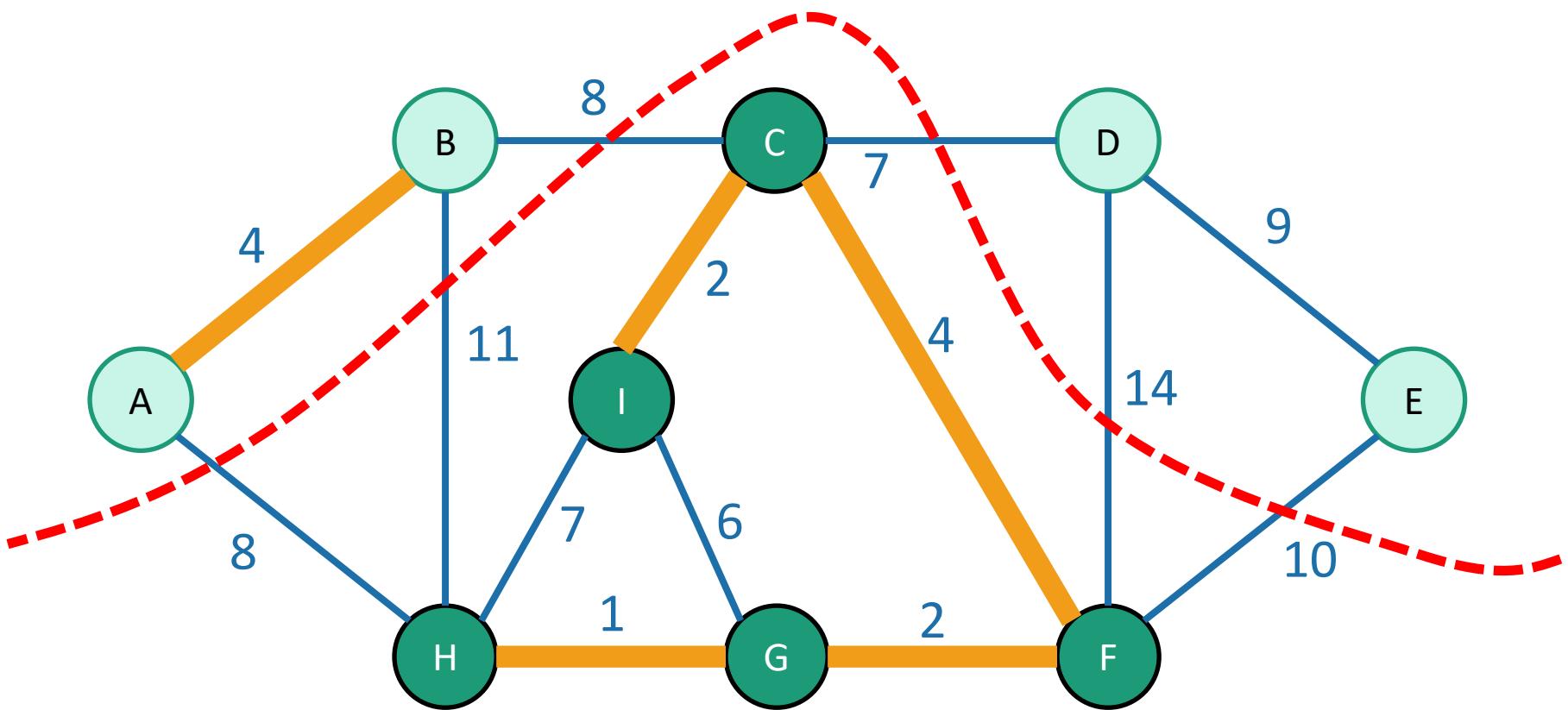
# Cuts in graphs

- This is *not* a cut. Cuts are partitions of vertices.



# Let $S$ be a set of edges in $G$

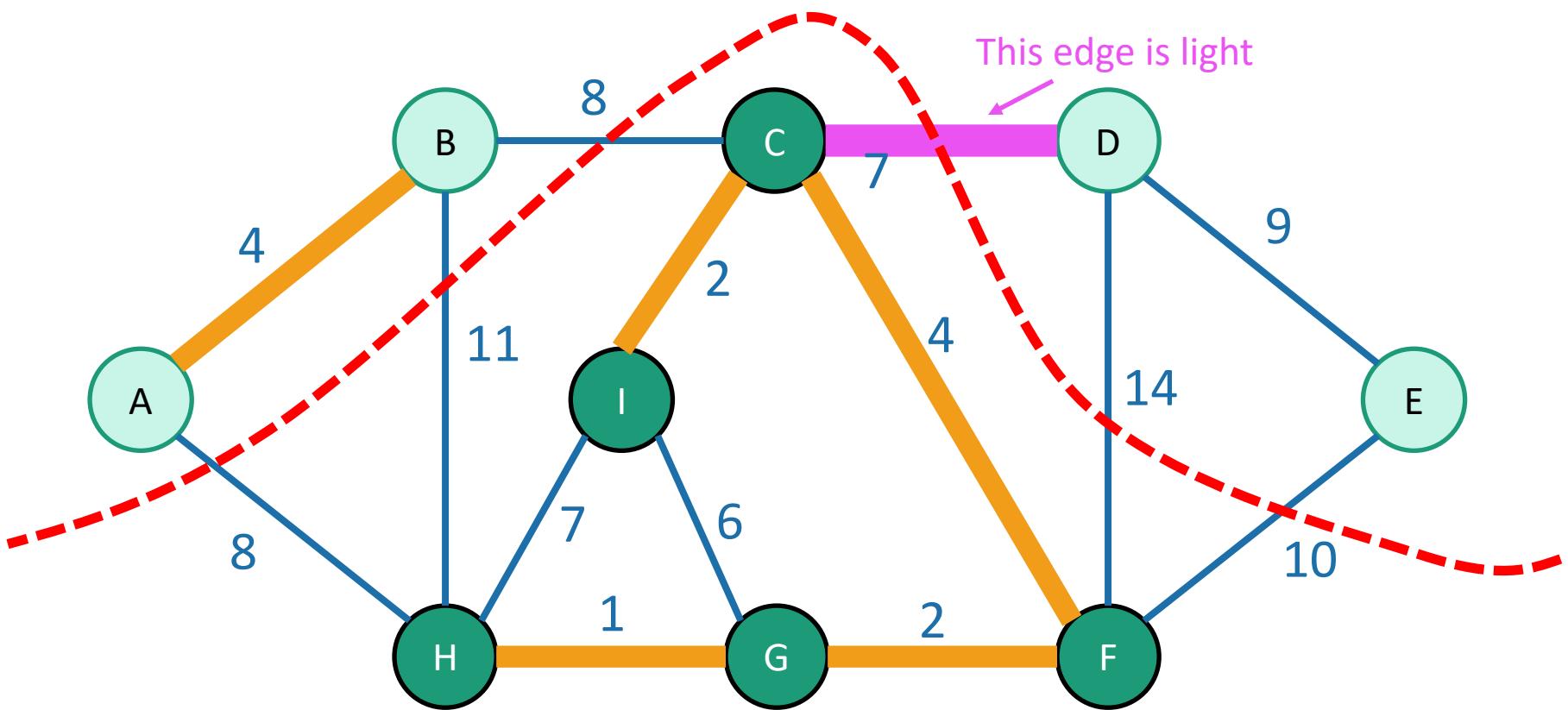
- We say a cut **respects**  $S$  if no edges in  $S$  cross the cut.
- An edge crossing a cut is called **light** if it has the smallest weight of any edge crossing the cut.



$S$  is the set of **thick orange** edges

# Let $S$ be a set of edges in $G$

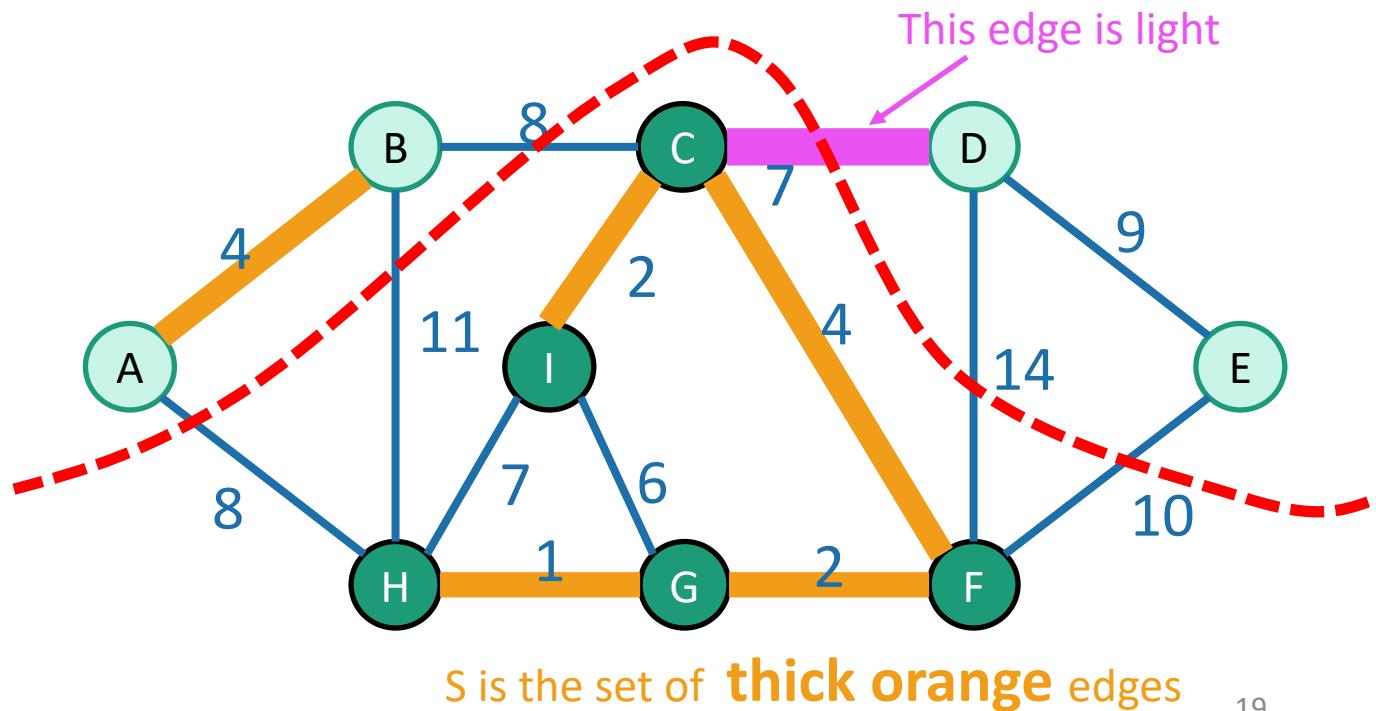
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$S$  is the set of **thick orange** edges

# Lemma

- Let  $S$  be a set of edges, and consider a cut that respects  $S$ .
- Suppose there is an MST containing  $S$ .
- Let  $\{u,v\}$  be a light edge.
- Then there is an MST containing  $S \cup \{\{u,v\}\}$

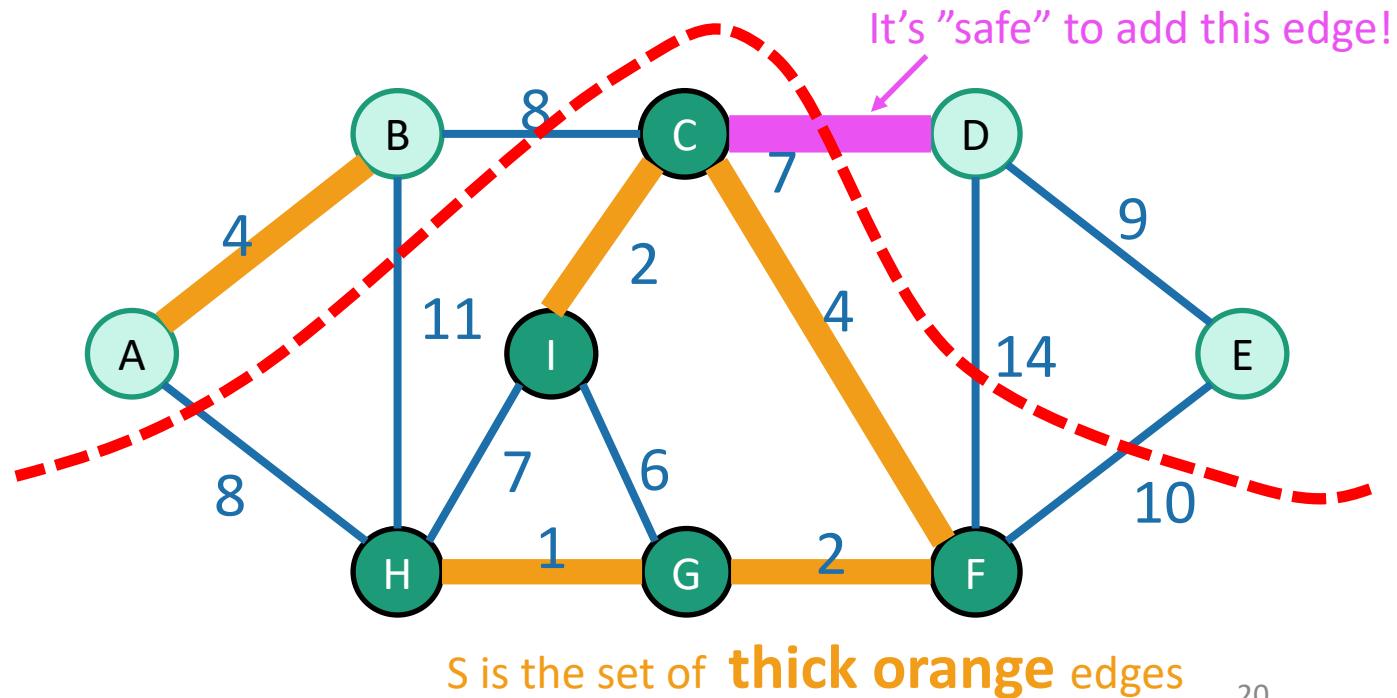


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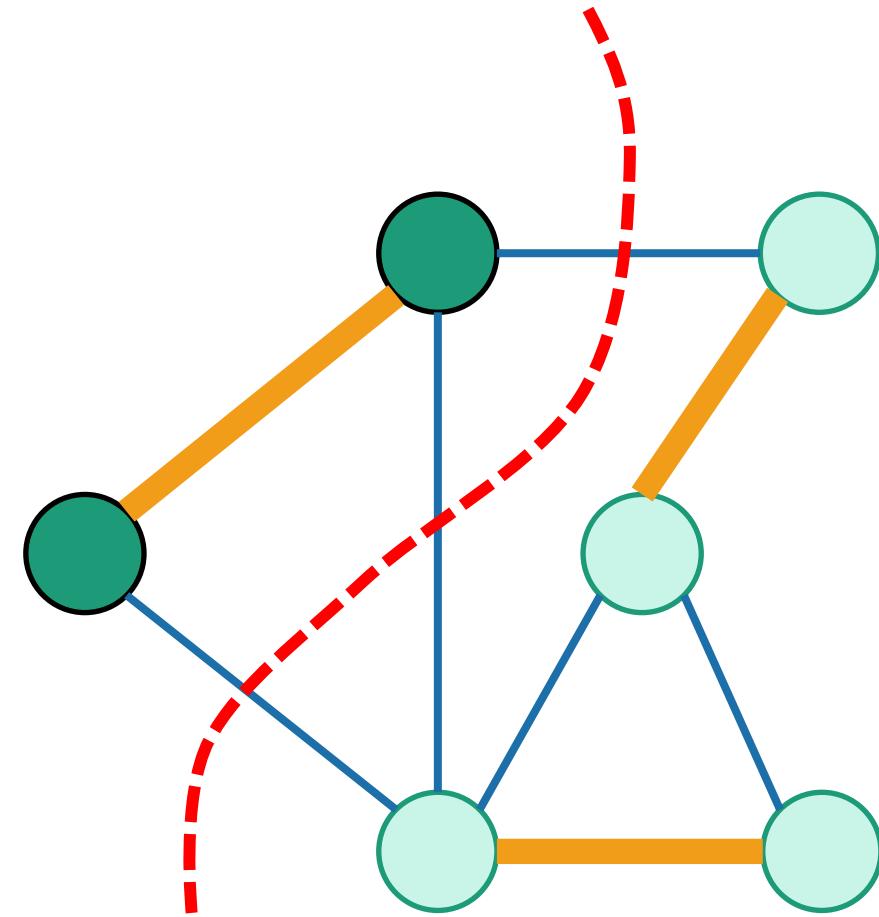
Aka:

If we haven't ruled out the possibility of success so far, then adding a light edge still won't rule it out.



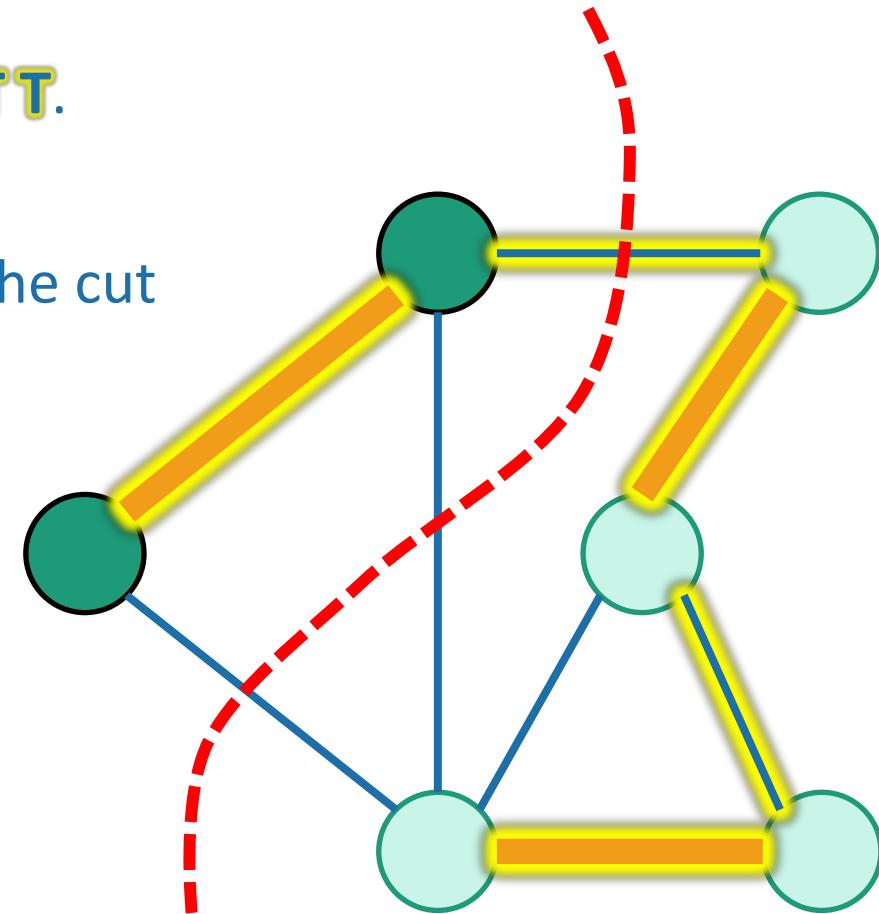
# Proof of Lemma

- Assume that we have:
  - a **cut** that respects **S**



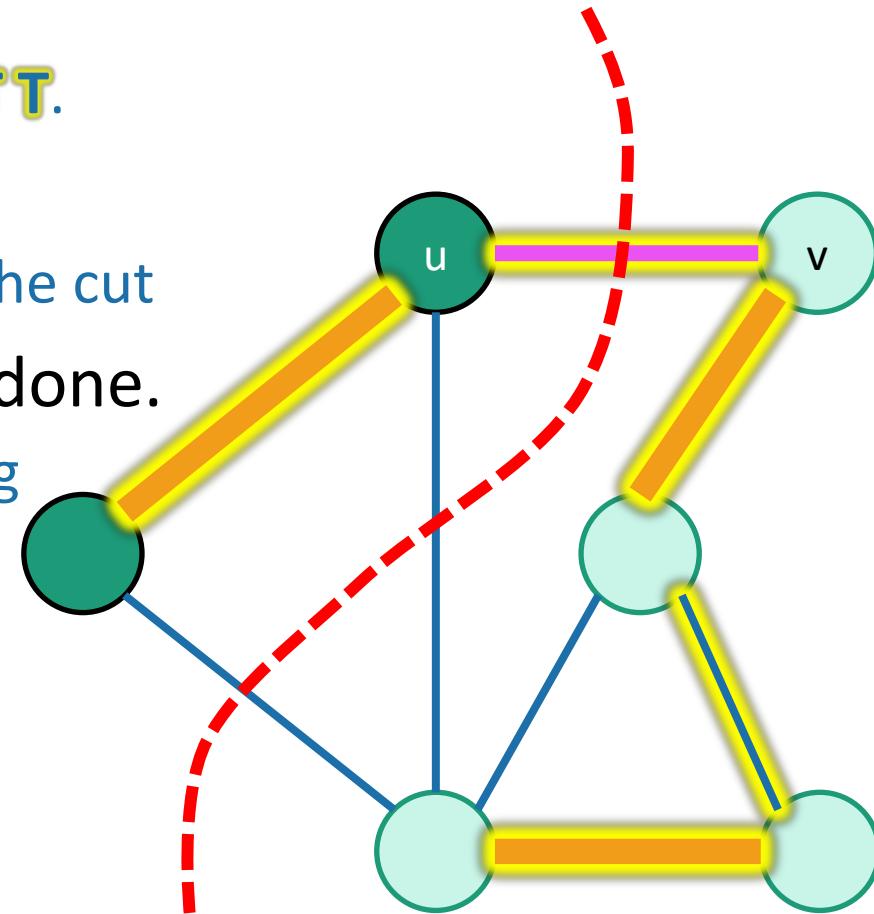
# Proof of Lemma

- Assume that we have:
  - a **cut** that respects **S**
  - **S** is part of some **MST T**.
- Say that  $\{u, v\}$  is light.
  - lowest cost crossing the cut



# Proof of Lemma

- Assume that we have:
  - a **cut** that respects **S**
  - **S** is part of some **MST T**.
- Say that  $\{u,v\}$  is light.
  - lowest cost crossing the cut
- If  $\{u,v\}$  is in **T**, we are done.
  - **T** is an MST containing both  $\{u,v\}$  and **S**.

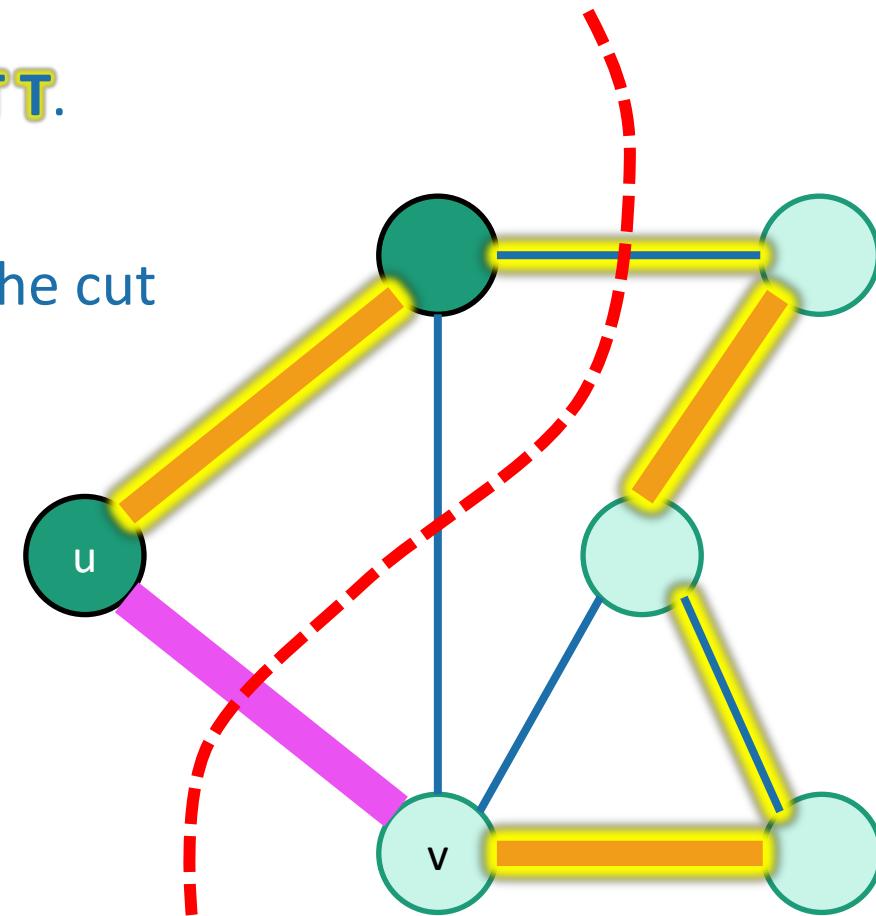


# Proof of Lemma

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  - **S** is part of some **MST T**.
- Say that  $\{u,v\}$  is light.
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- Say  $\{u,v\}$  is not in **T**.
- Note that adding  $\{u,v\}$  to **T** will make a cycle.

**Claim:** Adding any additional edge to a spanning tree will create a cycle.

**Proof:** Both endpoints are already in the tree and connected to each other.

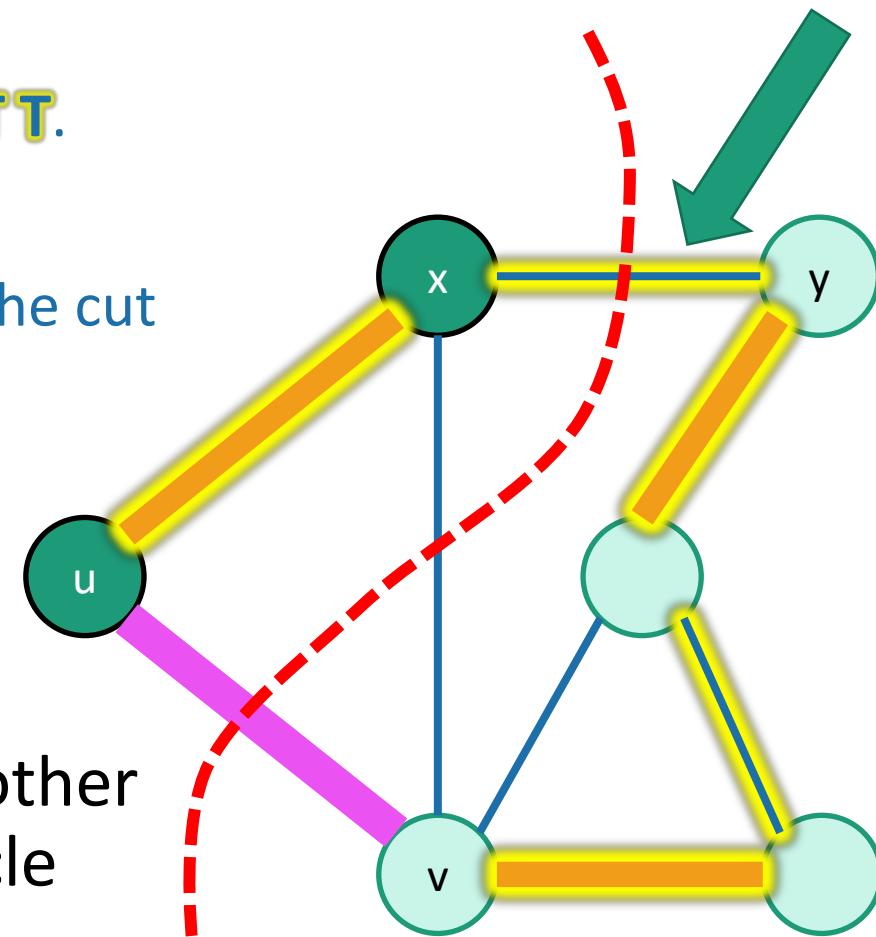


# Proof of Lemma

- Assume that we have:
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  - lowest cost crossing the cut
- Say  $\{u,v\}$  is not in **T**.
- Note that adding  $\{u,v\}$  to **T** will make a cycle.
- There is at least one other edge,  $\{x,y\}$ , in this cycle crossing the cut.

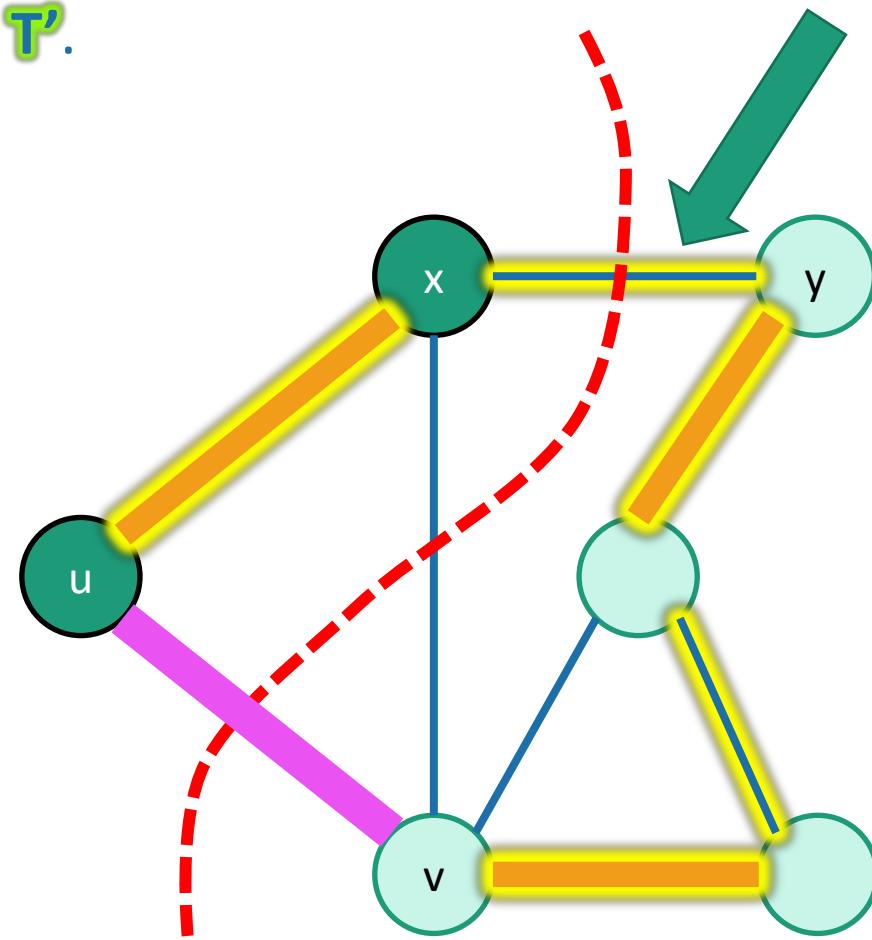
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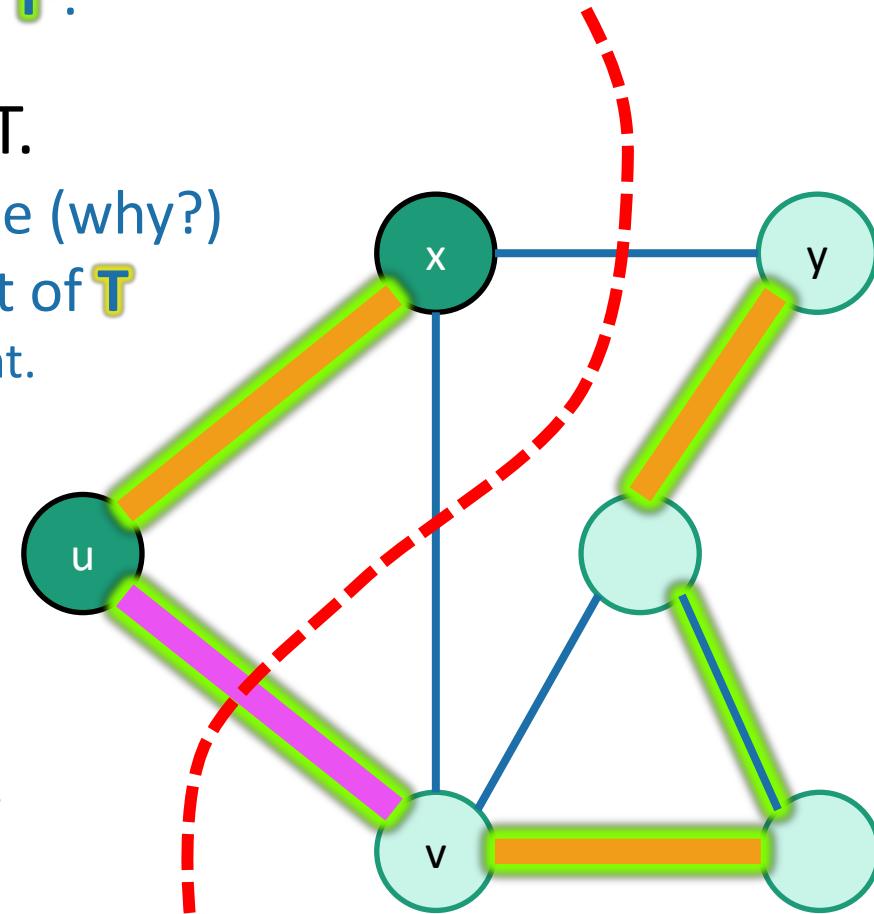
# Proof of Lemma ctd.

- Consider swapping  $\{u,v\}$  for  $\{x,y\}$  in  $T$ .
  - Call the resulting tree  $T'$ .



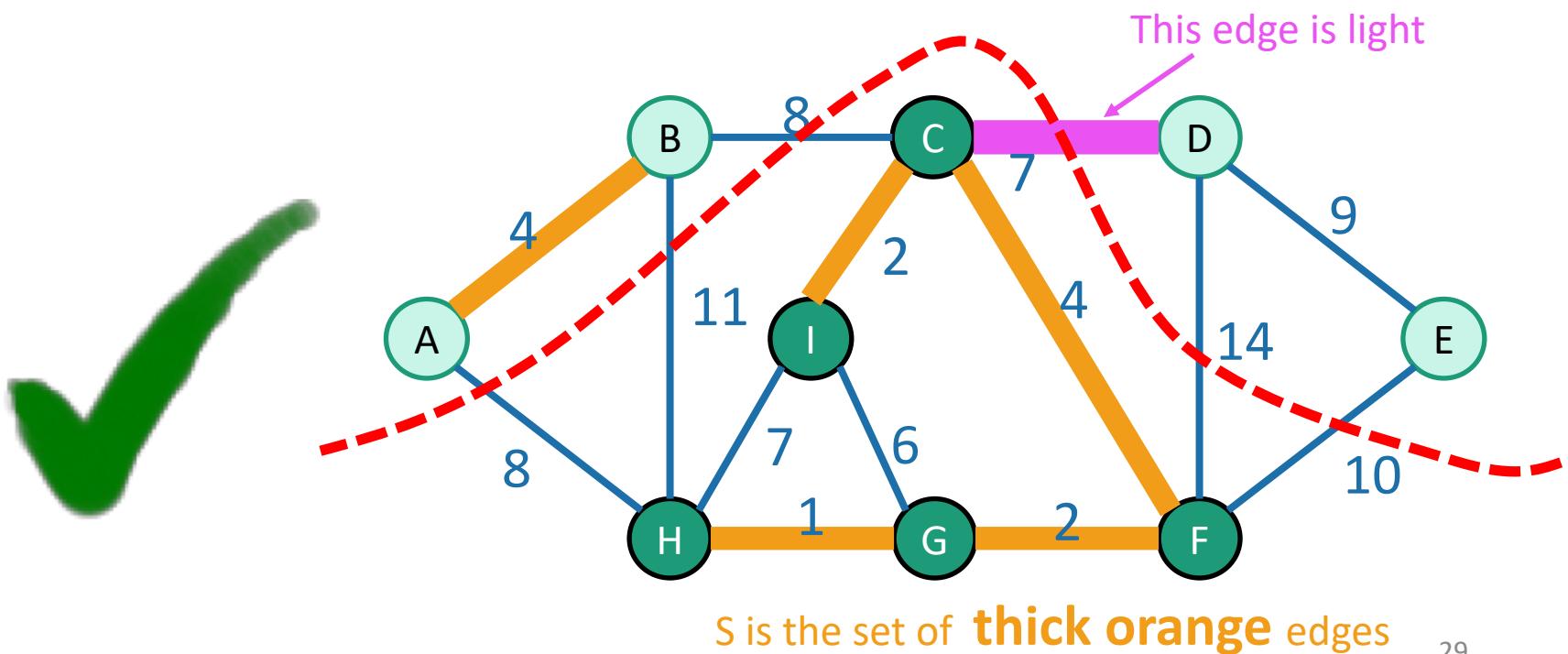
# Proof of Lemma ctd.

- Consider swapping  $\{u,v\}$  for  $\{x,y\}$  in  $T$ .
  - Call the resulting tree  $T'$ .
- **Claim:**  $T'$  is still an MST.
  - It is still a spanning tree (why?)
  - It has cost at most that of  $T$ 
    - because  $\{u,v\}$  was light.
  - $T$  had minimal cost.
  - So  $T'$  does too.
- So  $T'$  is an MST containing  $S$  and  $\{u,v\}$ .
  - This is what we wanted.



# Lemma

- Let  $S$  be a set of edges, and consider a cut that respects  $S$ .
- Suppose there is an MST containing  $S$ .
- Let  $\{u,v\}$  be a light edge.
- Then there is an MST containing  $S \cup \{\{u,v\}\}$



# End aside

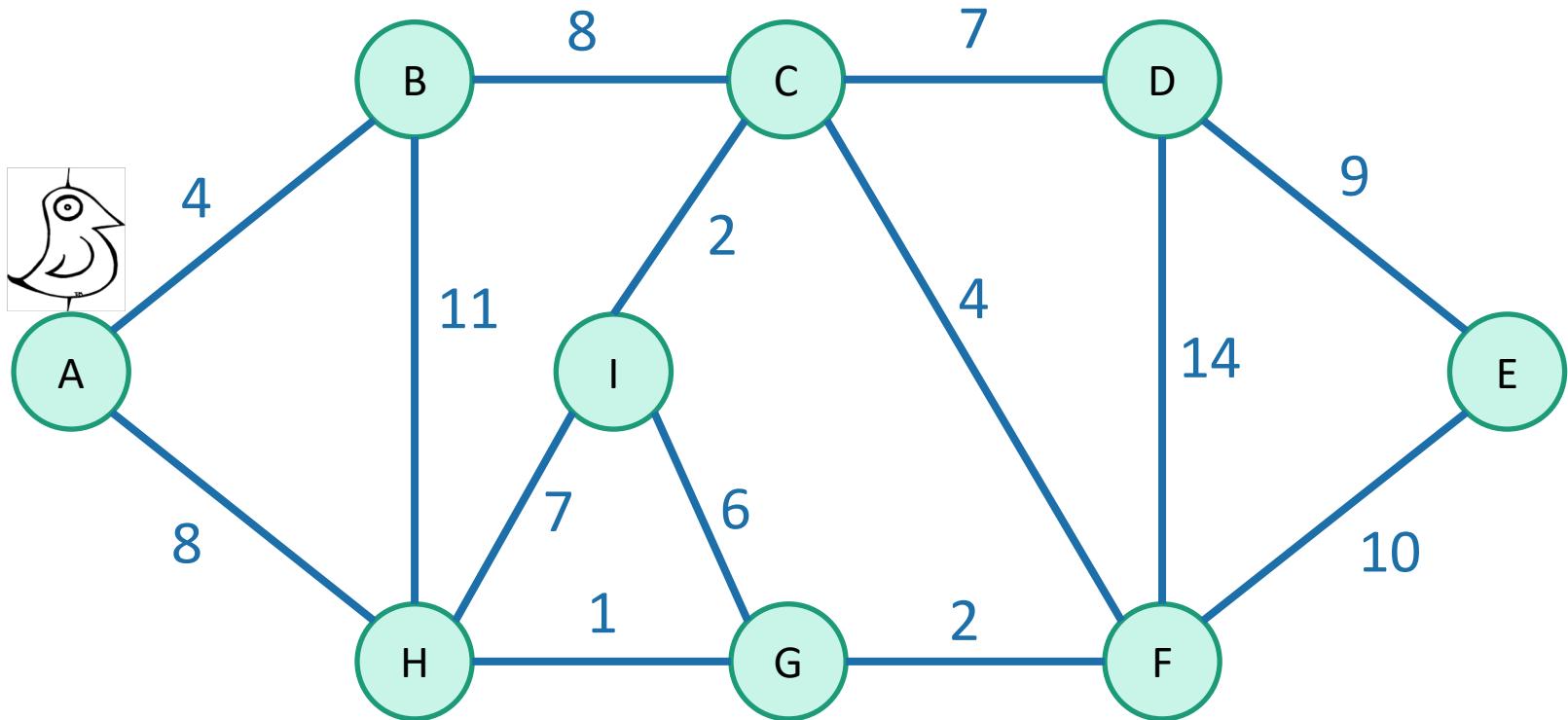
Back to MSTs!

# Back to MSTs

- How do we find one?
- Today we'll see **two greedy algorithms.**
- The strategy:
  - Make a **series of choices**, adding edges to the tree.
  - Show that each edge we add is **safe to add**:
    - we do not rule out the possibility of success
    - we will choose **light edges** crossing **cuts** and **use the Lemma**.
  - **Keep going** until we have an MST.

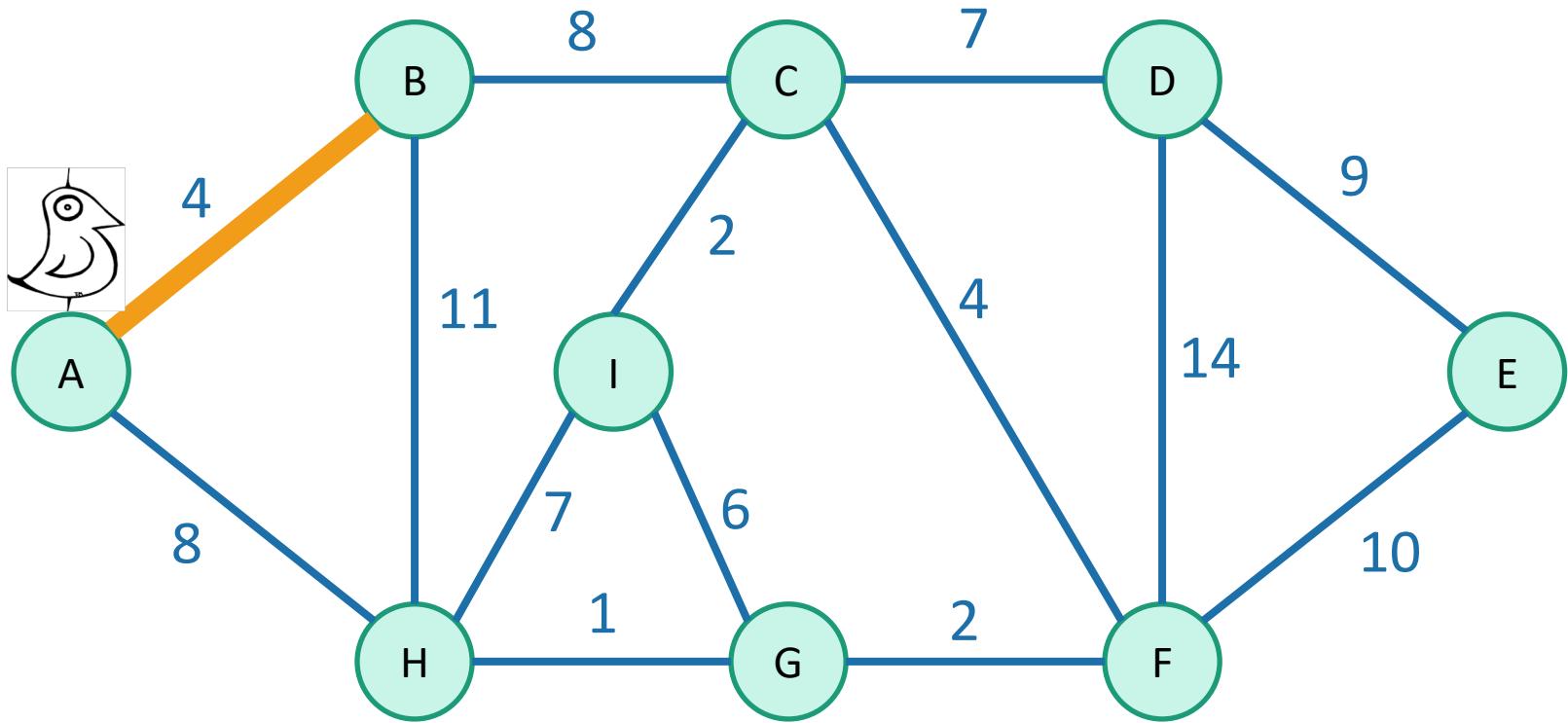
# Idea 1

Start growing a tree, greedily add the shortest edge we can to grow the tree.



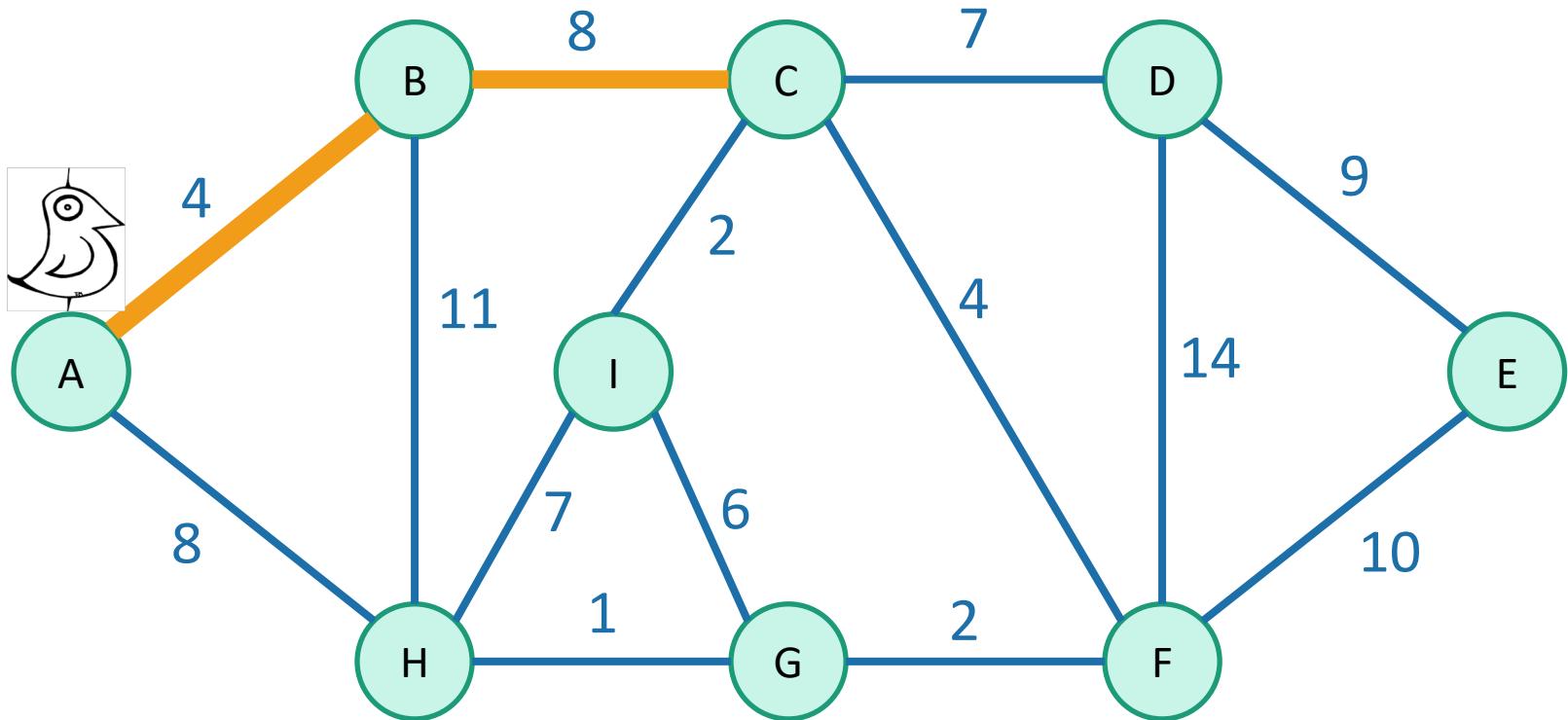
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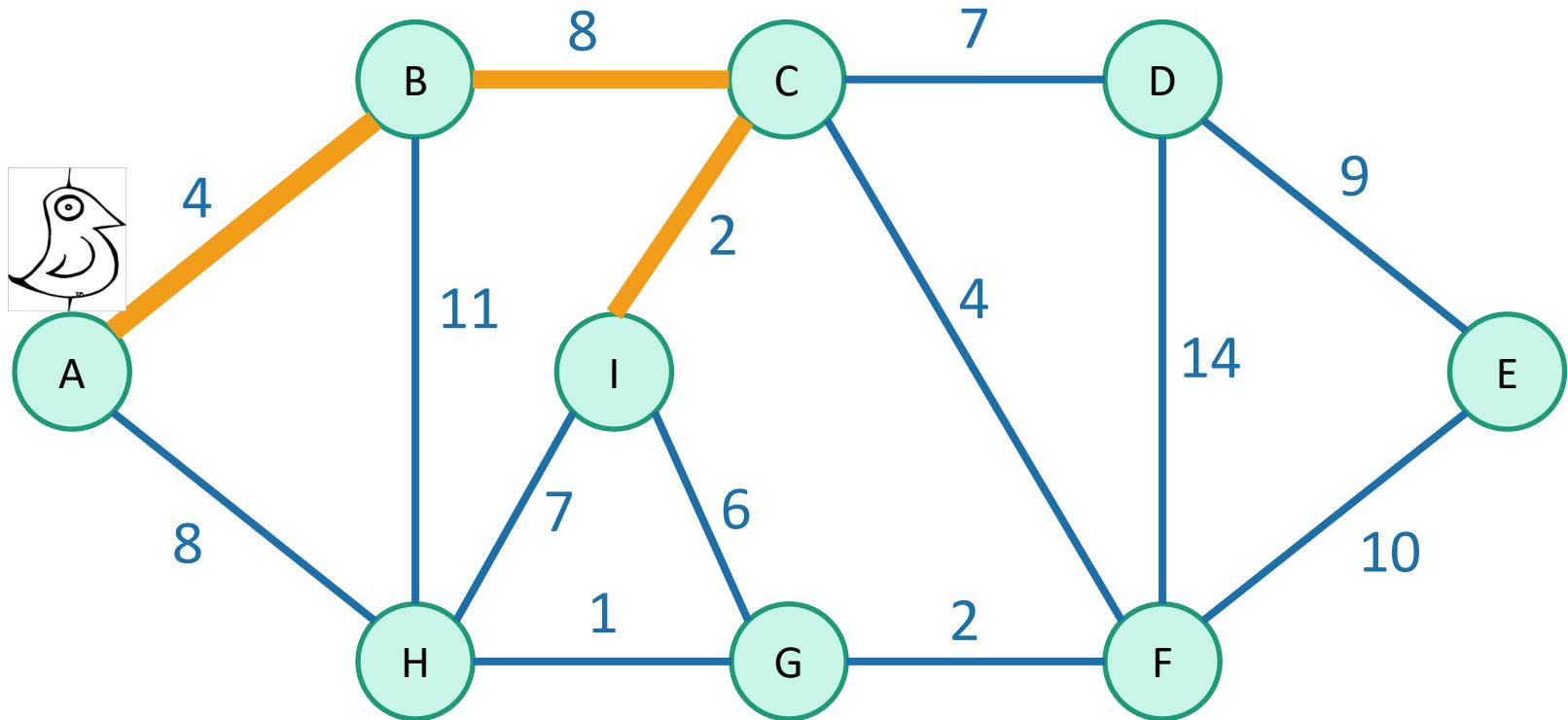
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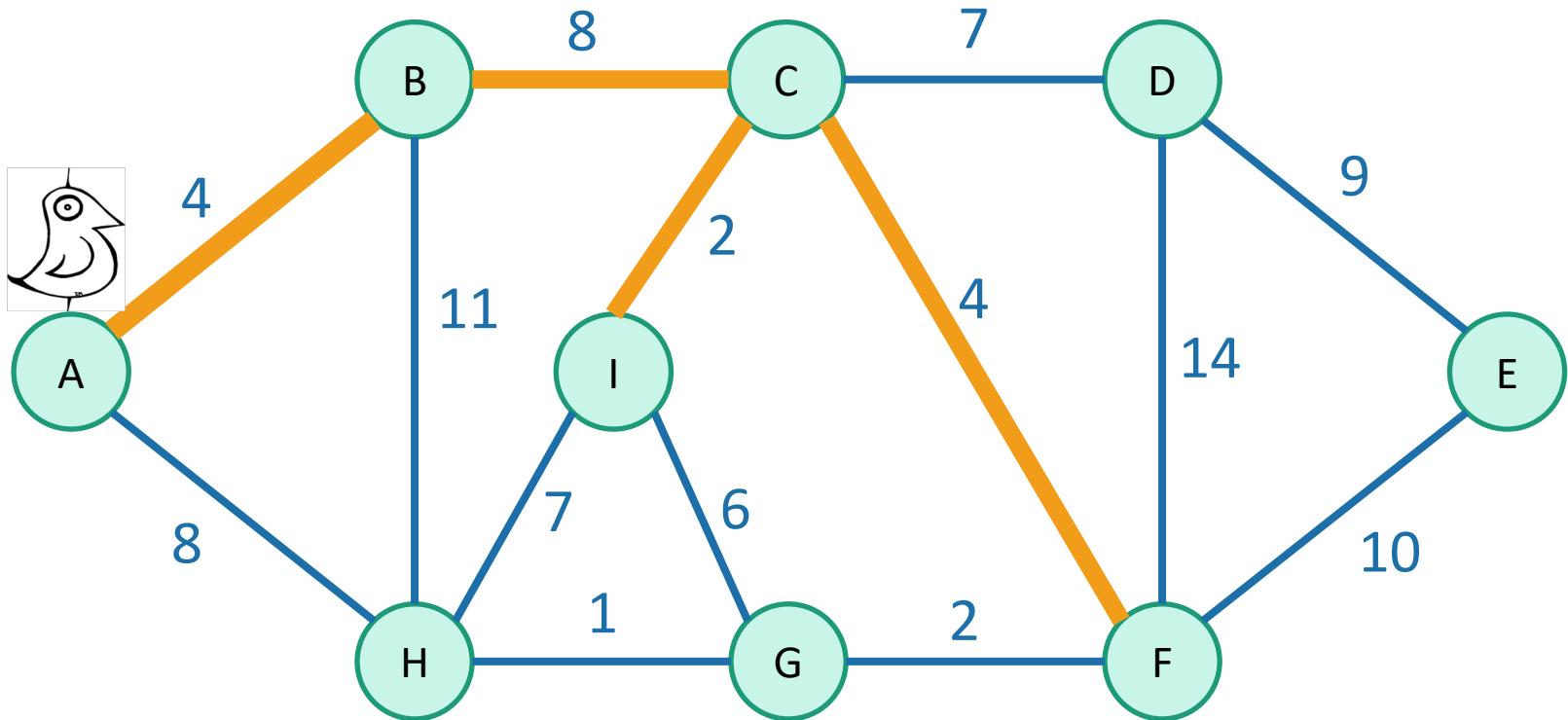
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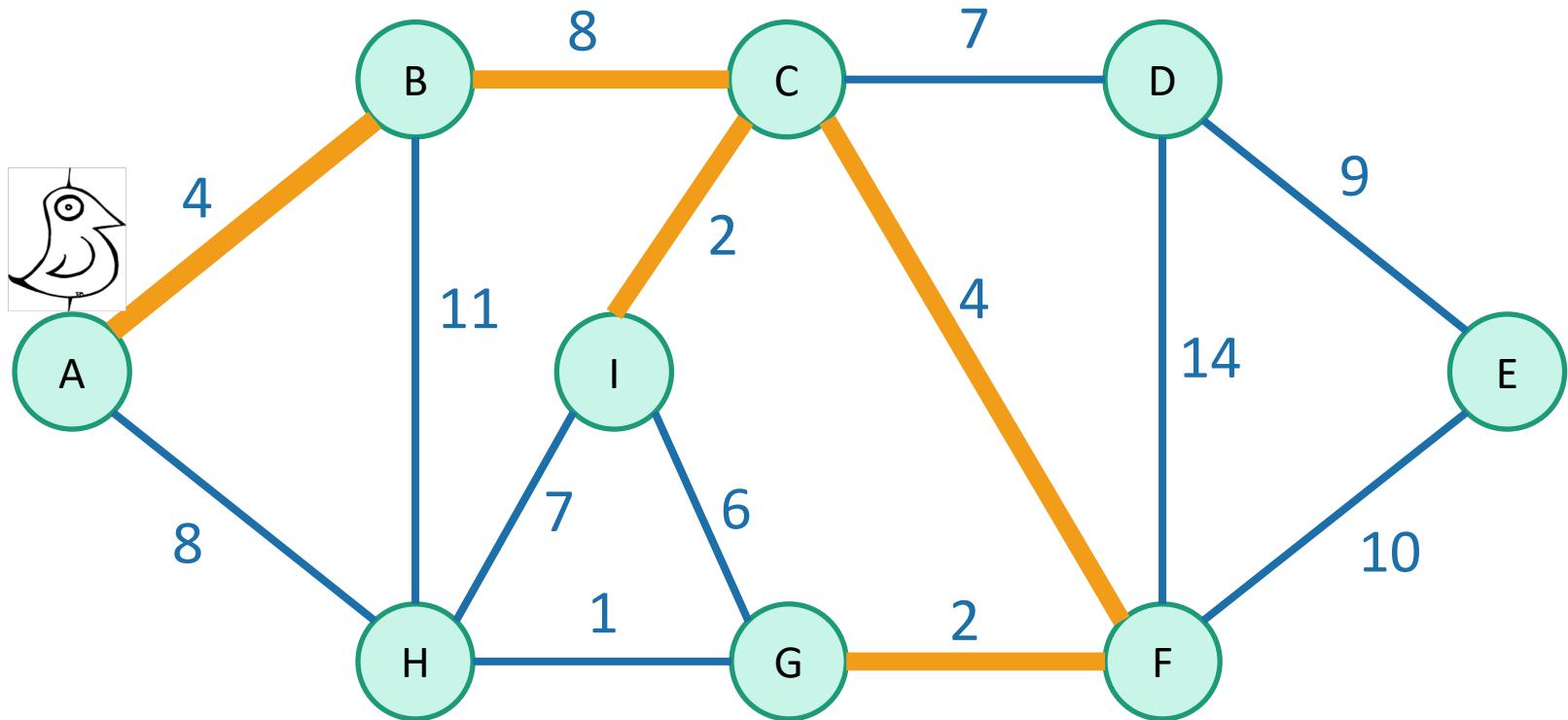
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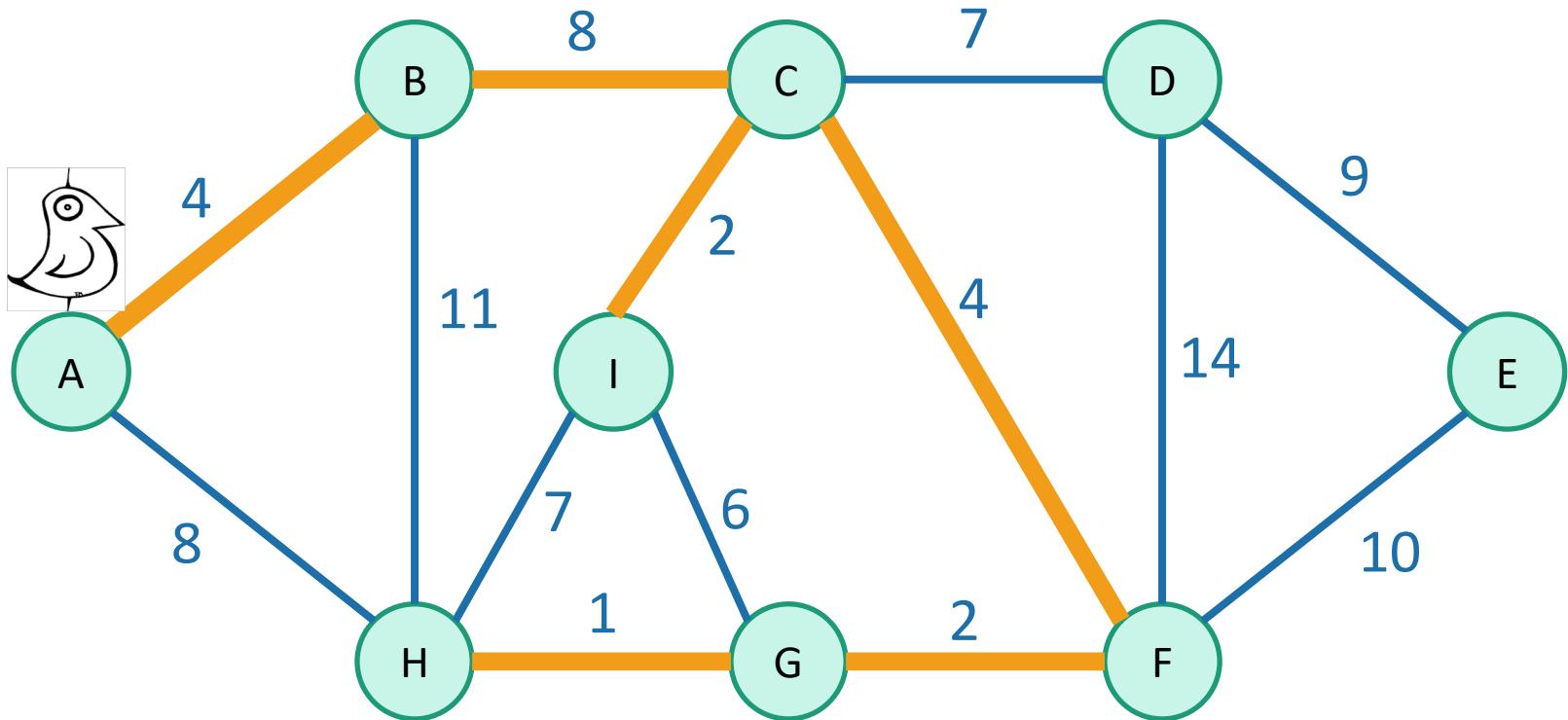
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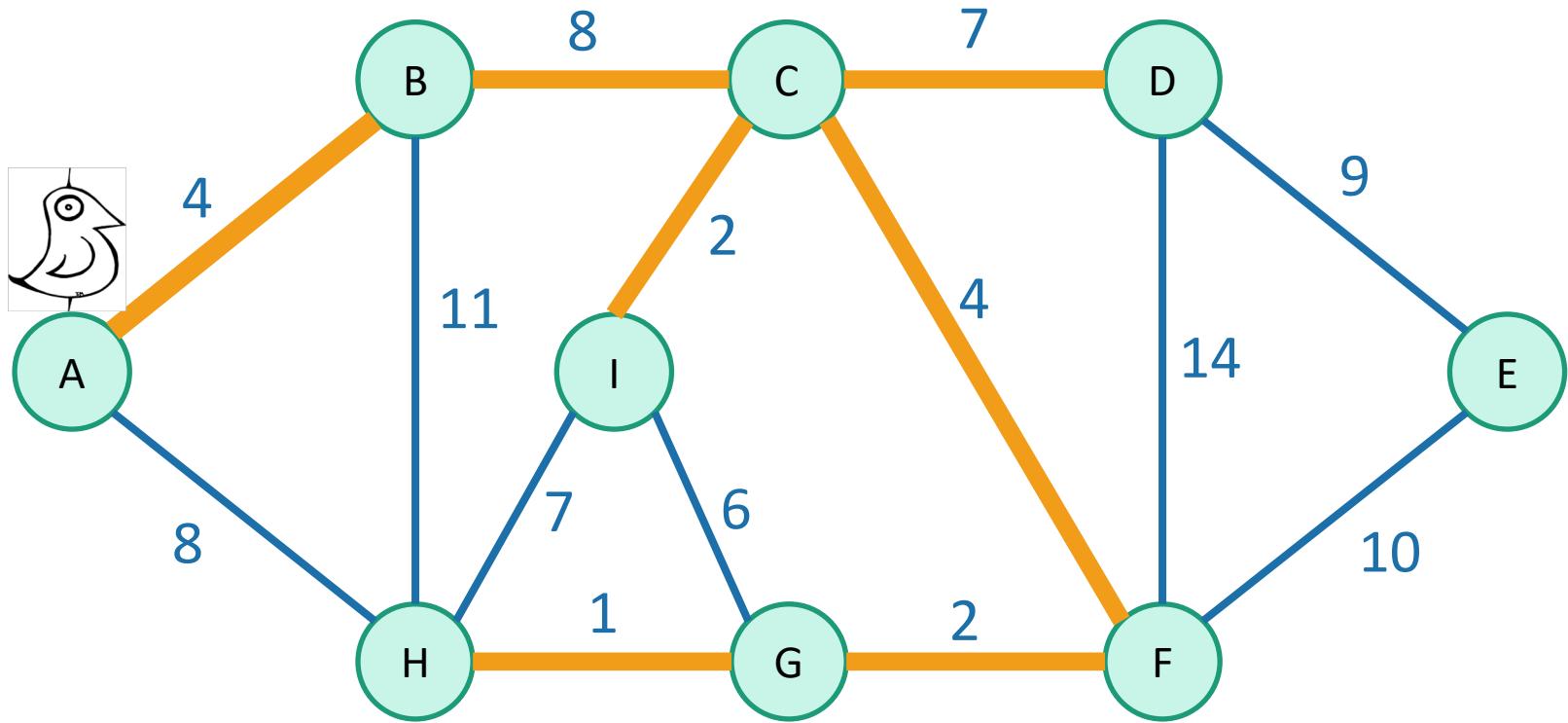
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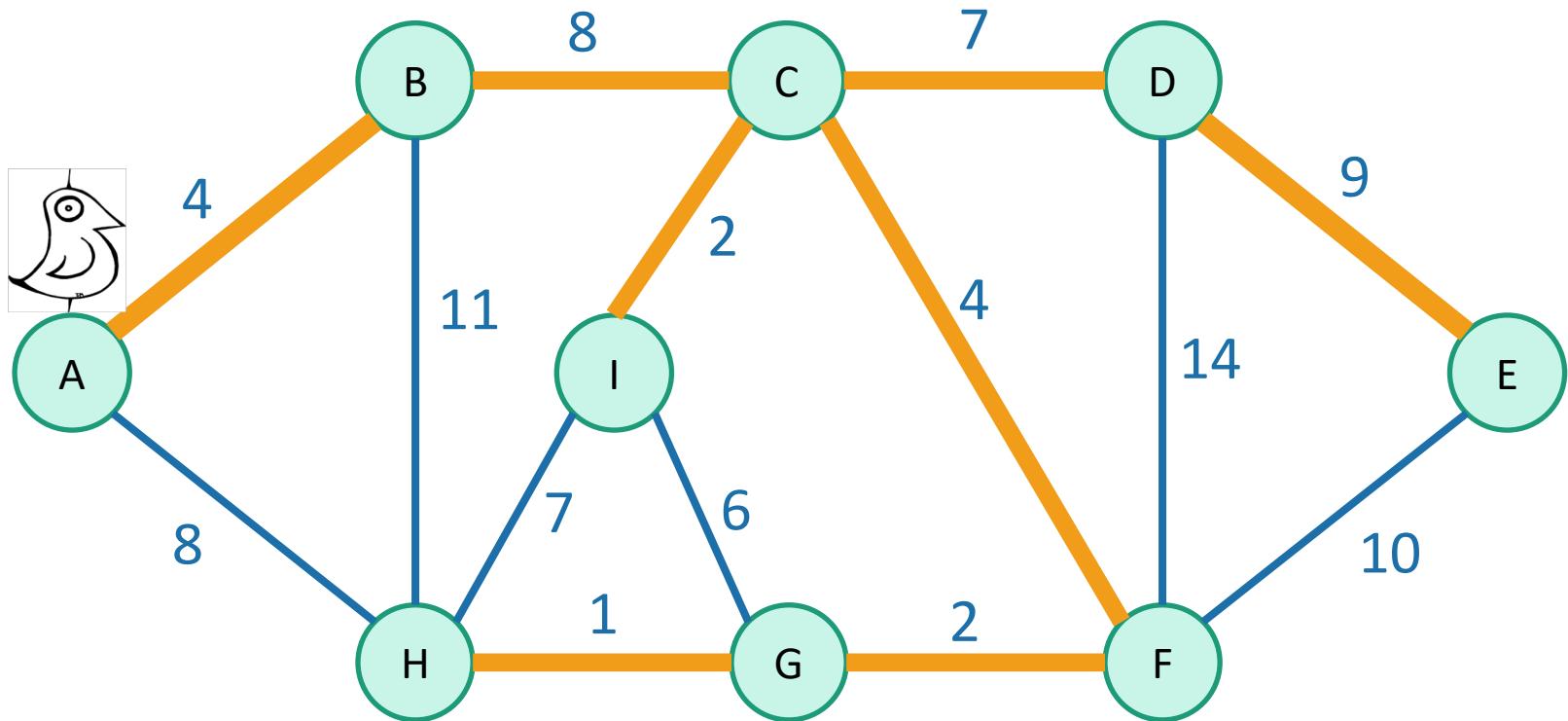
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# We've discovered Prim's algorithm!

- **slowPrim( G = (V,E), starting vertex s ):**
  - Let  $(s,u)$  be the lightest edge coming out of  $s$ .
  - $MST = \{ (s,u) \}$
  - $\text{verticesVisited} = \{ s, u \}$
  - **while**  $|\text{verticesVisited}| < |V|$ :
    - find the lightest edge  $\{x,v\}$  in  $E$  so that:
      - $x$  is in  $\text{verticesVisited}$
      - $v$  is not in  $\text{verticesVisited}$
    - add  $\{x,v\}$  to  $MST$
    - add  $v$  to  $\text{verticesVisited}$
  - **return**  $MST$

At most  $n$   
iterations of this  
while loop.

Time at most  $m$  to  
go through all the  
edges and find the  
lightest.

Naively, the running time is  $O(nm)$ :

- For each of  $\leq n$  iterations of the while loop:
  - Go through all the edges.

# Two questions

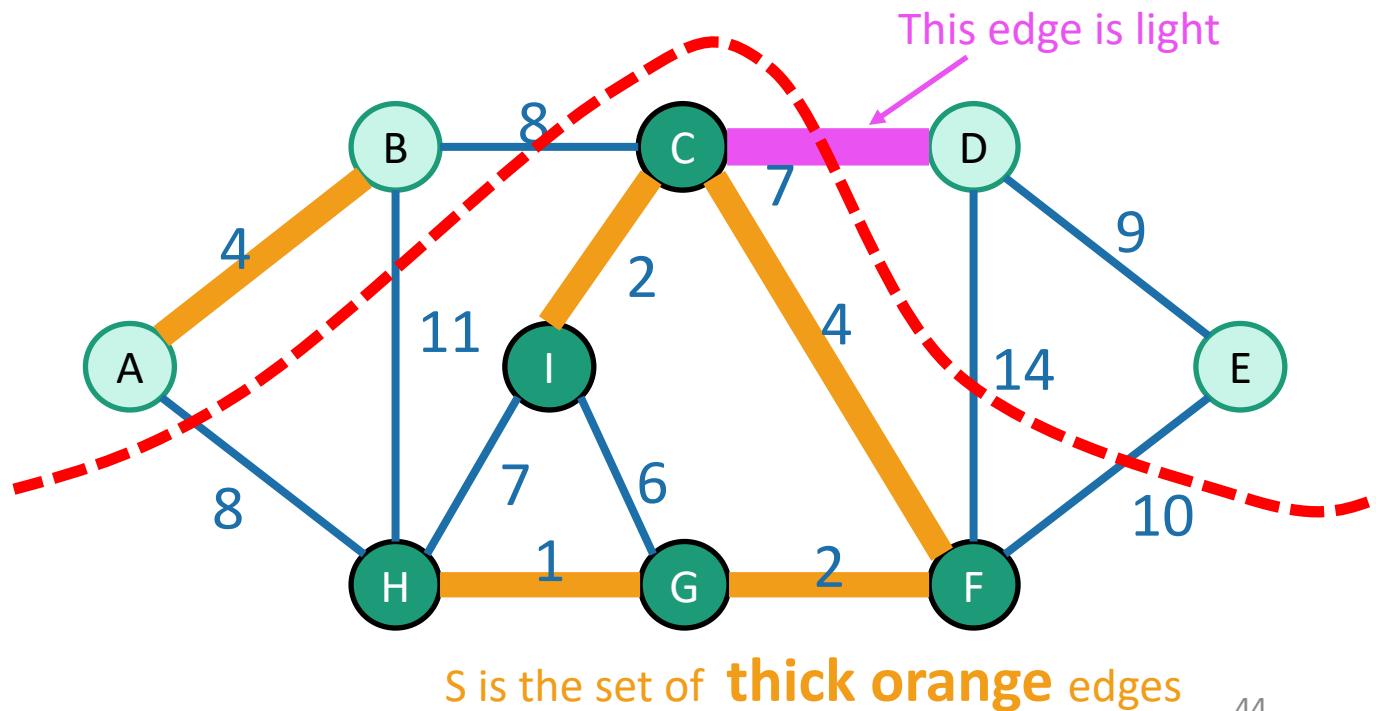
1. Does it work?
  - That is, does it actually return a MST?
2. How do we actually implement this?
  - the pseudocode above says “slowPrim”...

# Does it work?

- We need to show that our greedy choices **don't rule out success**.
- That is, at every step:
  - If there exists an MST that contains all of the edges  $S$  we have added so far...
  - ...then when we make our next choice  $\{u,v\}$ , there is still an MST containing  $S$  and  $\{u,v\}$ .
- Now it is time to use our lemma!

# Lemma

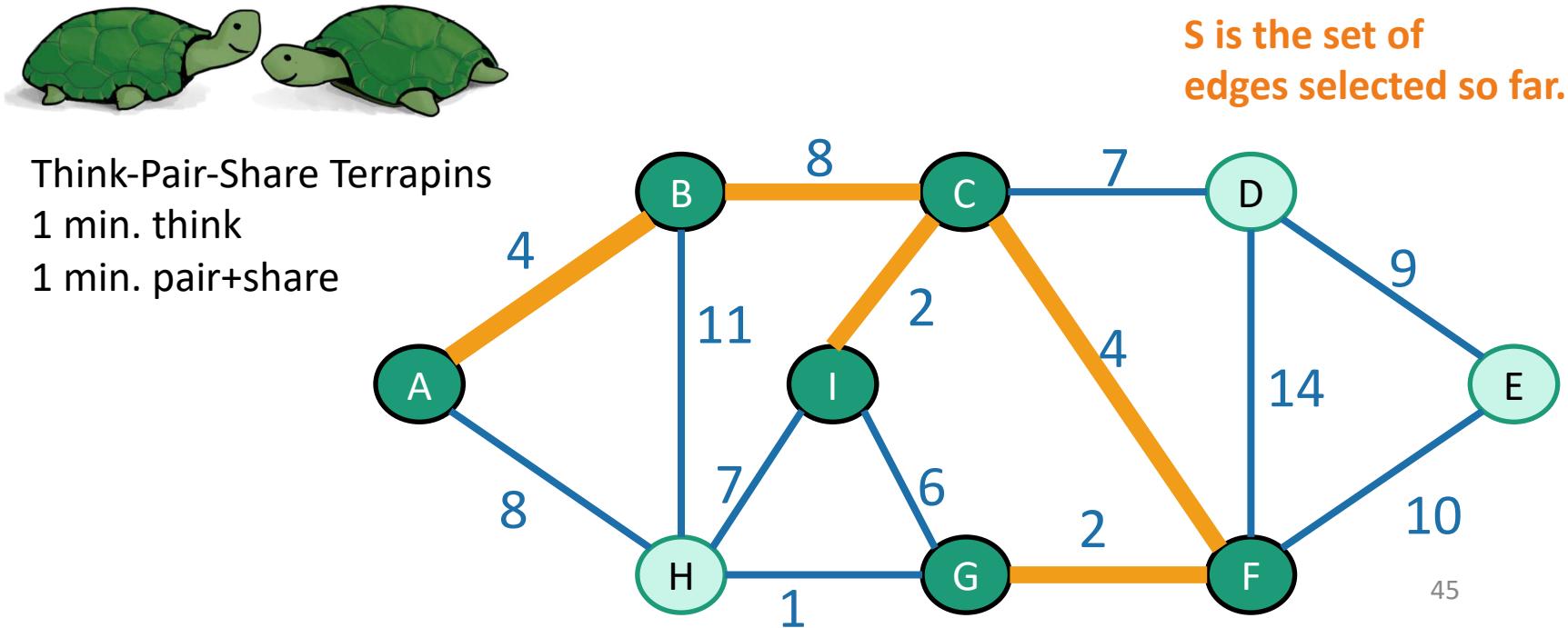
- Let  $S$  be a set of edges, and consider a cut that respects  $S$ .
- Suppose there is an MST containing  $S$ .
- Let  $\{u,v\}$  be a light edge.
- Then there is an MST containing  $S \cup \{\{u,v\}\}$



# Partway through Prim

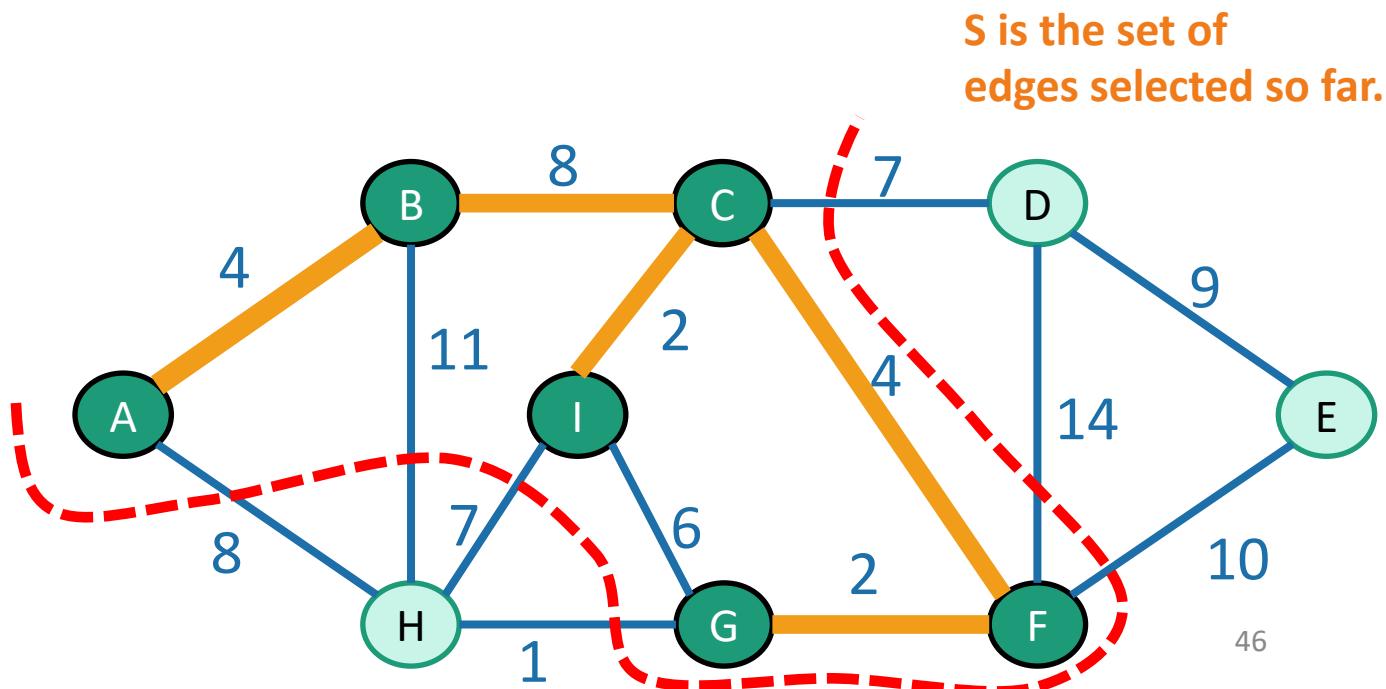
- Assume that our choices **S** so far don't rule out success
  - There is an MST consistent with those choices

How can we use our lemma to show that our next choice also does not rule out success?



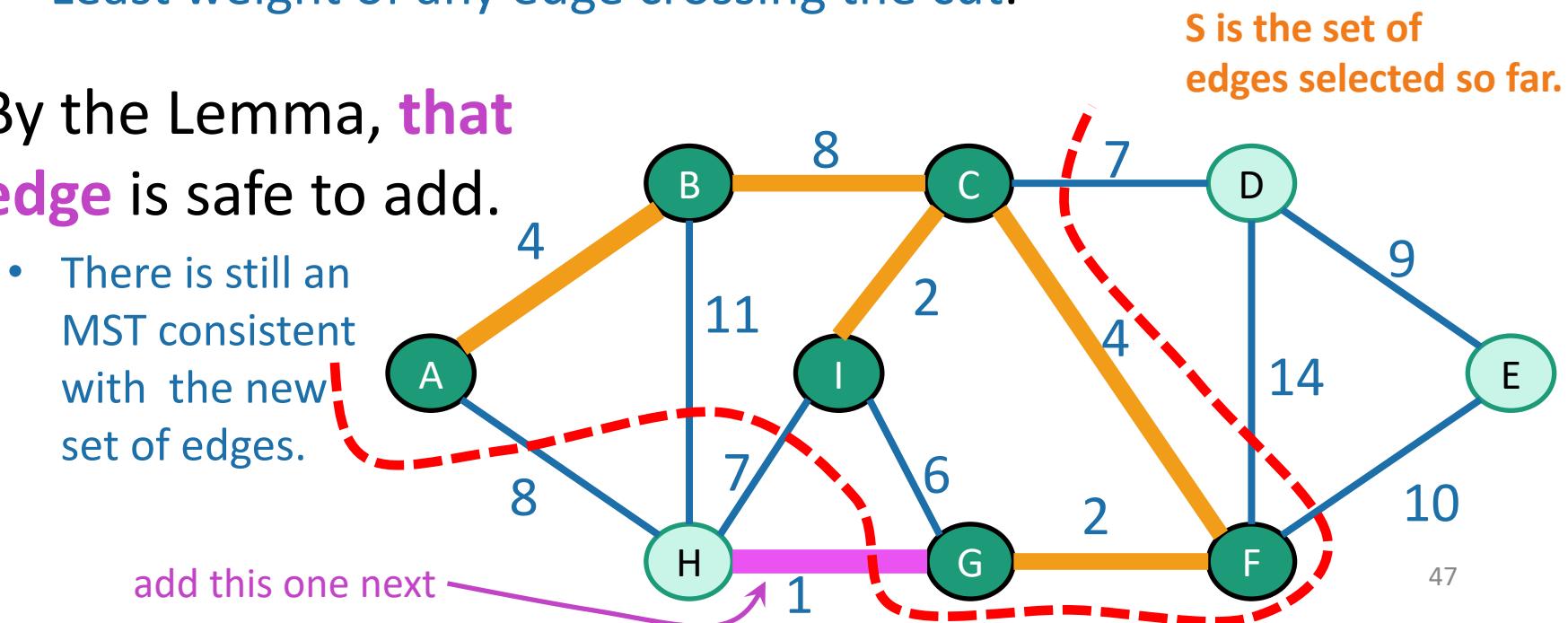
# Partway through Prim

- Assume that our choices  $S$  so far don't rule out success
  - There is an MST consistent with those choices
- Consider the cut  $\{\text{visited}, \text{unvisited}\}$ 
  - This cut respects  $S$ .



# Partway through Prim

- Assume that our choices  $S$  so far don't rule out success
  - There is an MST consistent with these choices
- Consider the cut  $\{\text{visited}, \text{unvisited}\}$ 
  - This cut respects  $S$ .
- The edge we add next is a **light edge**.
  - Least weight of any edge crossing the cut.
- By the Lemma, **that edge** is safe to add.



# Hooray!

- Our greedy choices **don't rule out success.**
- This is enough (along with an argument by induction) to guarantee correctness of Prim's algorithm.



# Formally(ish)

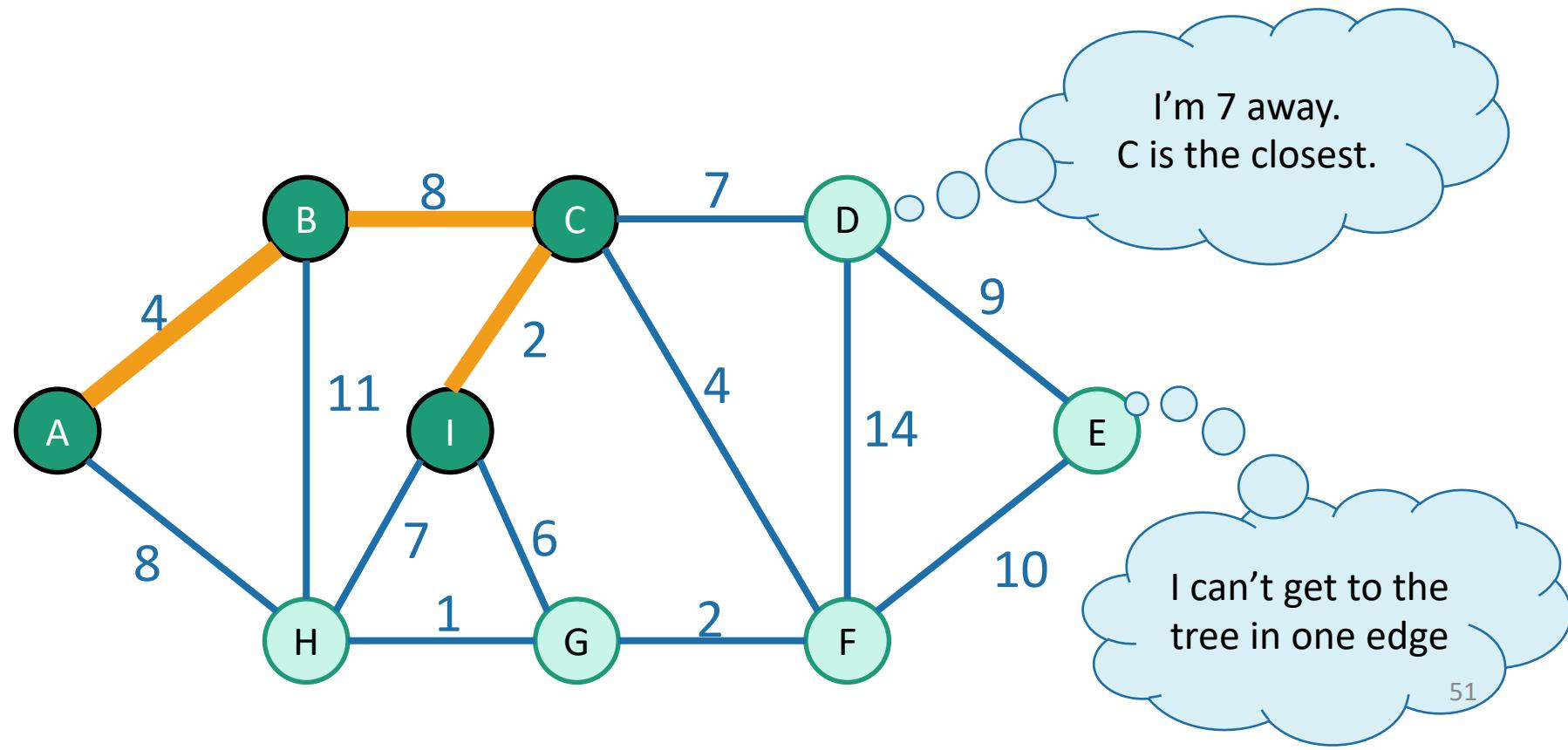
- Inductive hypothesis:
  - After adding the  $t$ 'th edge, there exists an MST with the edges added so far.
- Base case:
  - After adding the 0'th edge, there exists an MST with the edges added so far. YEP.
- Inductive step:
  - If the inductive hypothesis holds for  $t$  (aka, the choices so far are safe), then it holds for  $t+1$  (aka, the next edge we add is safe).
  - **That's what we just showed.**
- Conclusion:
  - After adding the  $n-1$ 'st edge, there exists an MST with the edges added so far.
  - At this point we have a spanning tree, so it better be minimal.

# Two questions

1. Does it work?
  - That is, does it actually return a MST?
    - Yes!
2. How do we actually implement this?
  - the pseudocode above says “slowPrim”...

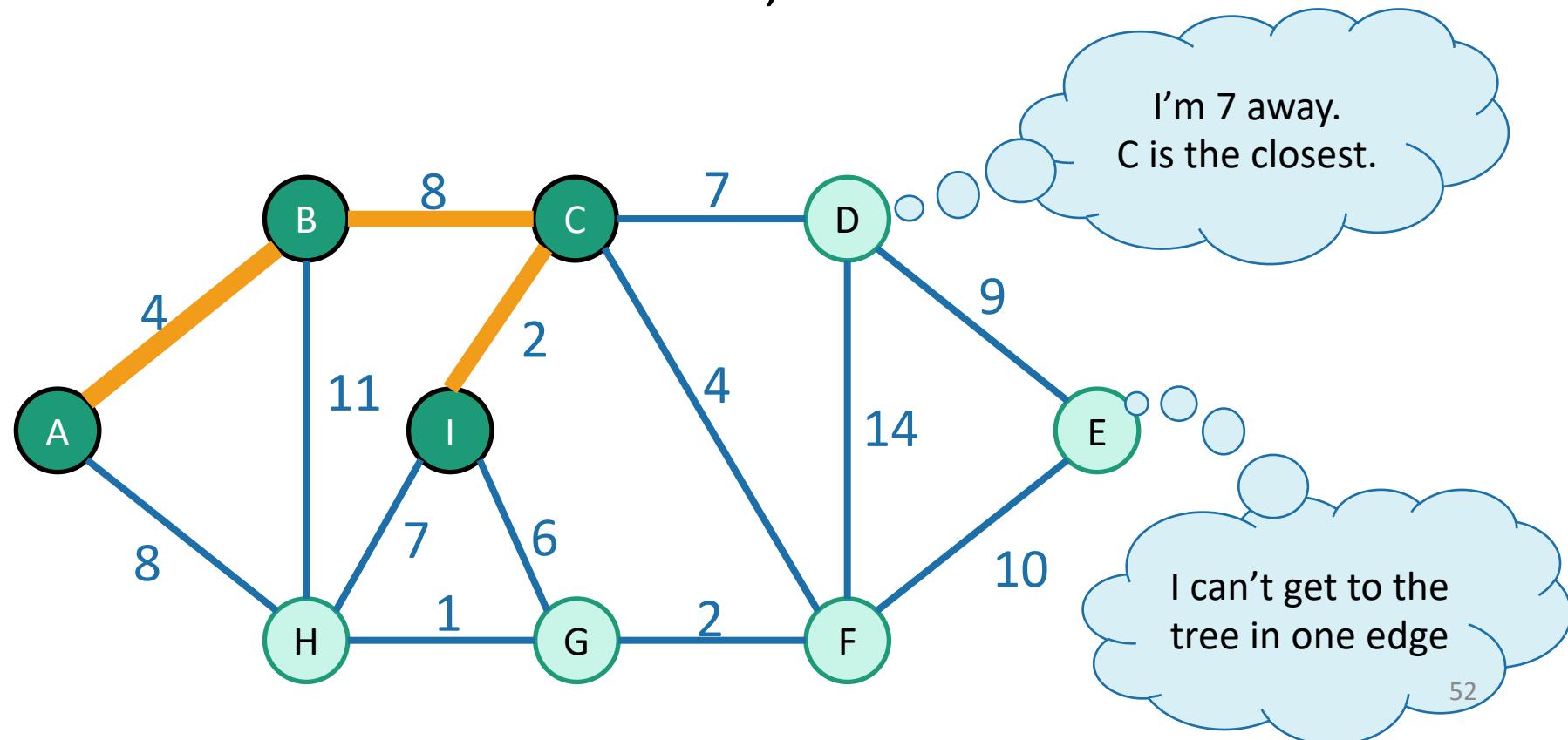
# How do we actually implement this?

- Each vertex keeps:
  - the **distance** from itself to the **growing spanning tree** if you can get there in one edge.
  - **how to get there.**



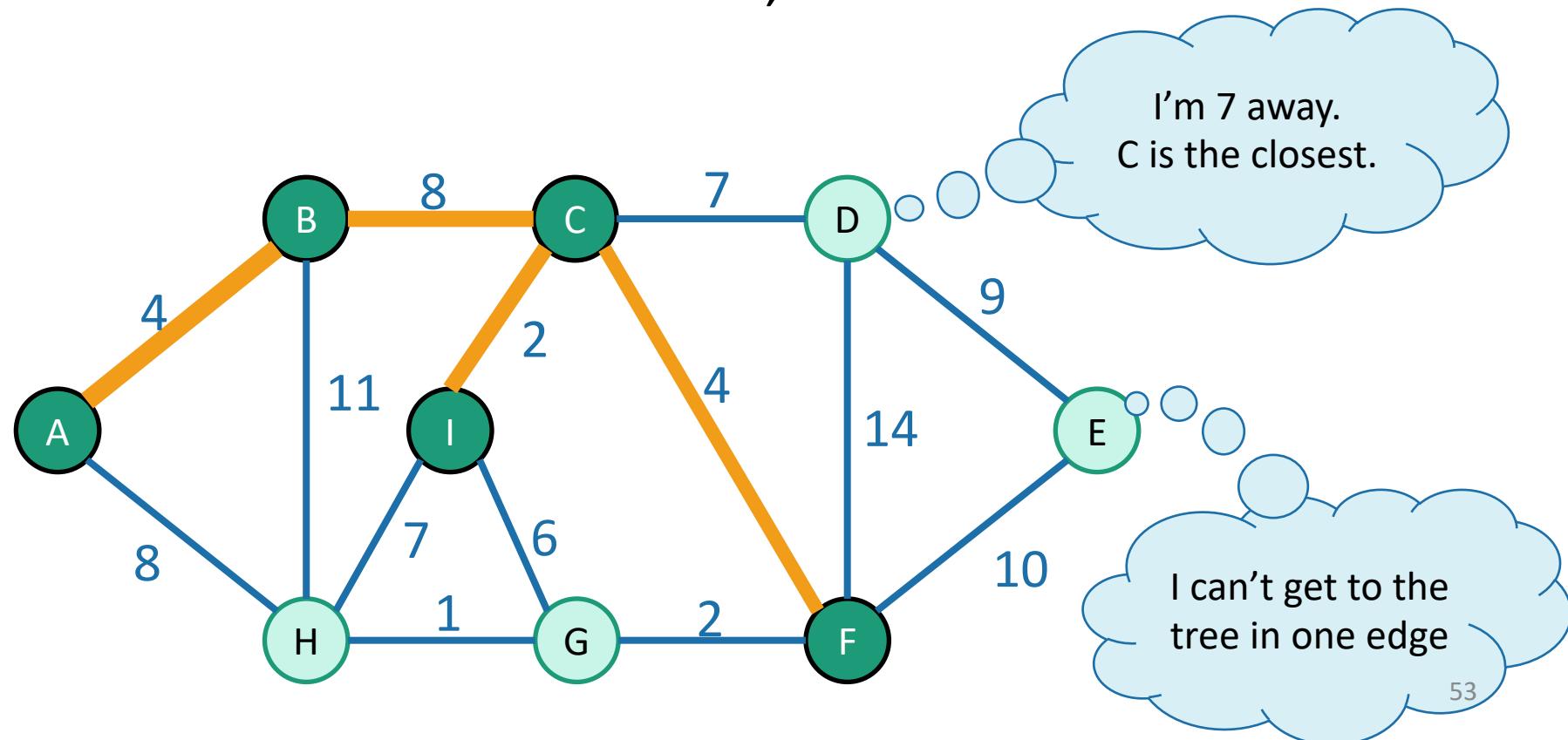
# How do we actually implement this?

- Each vertex keeps:
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- Choose the closest vertex, add it.



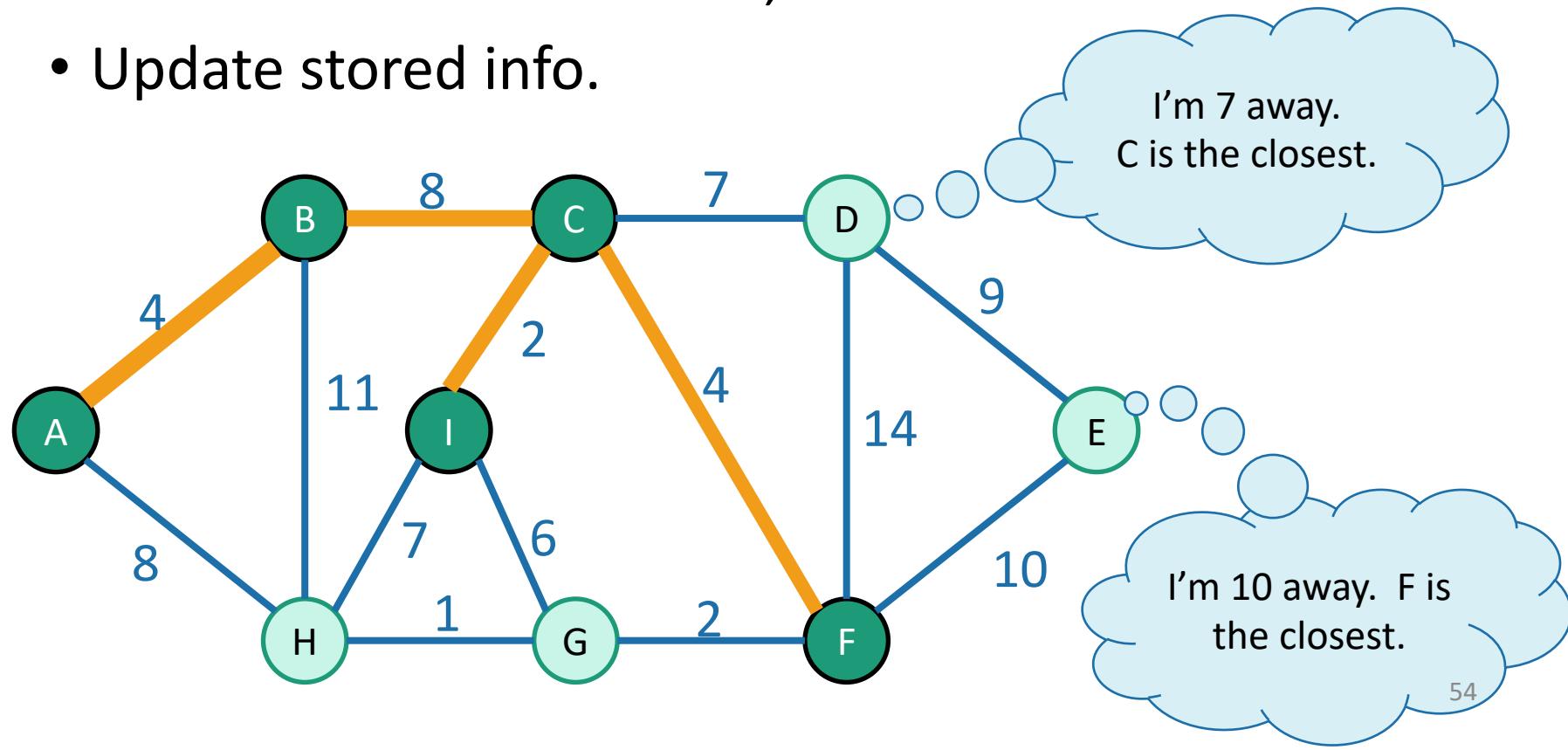
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# How do we actually implement this?

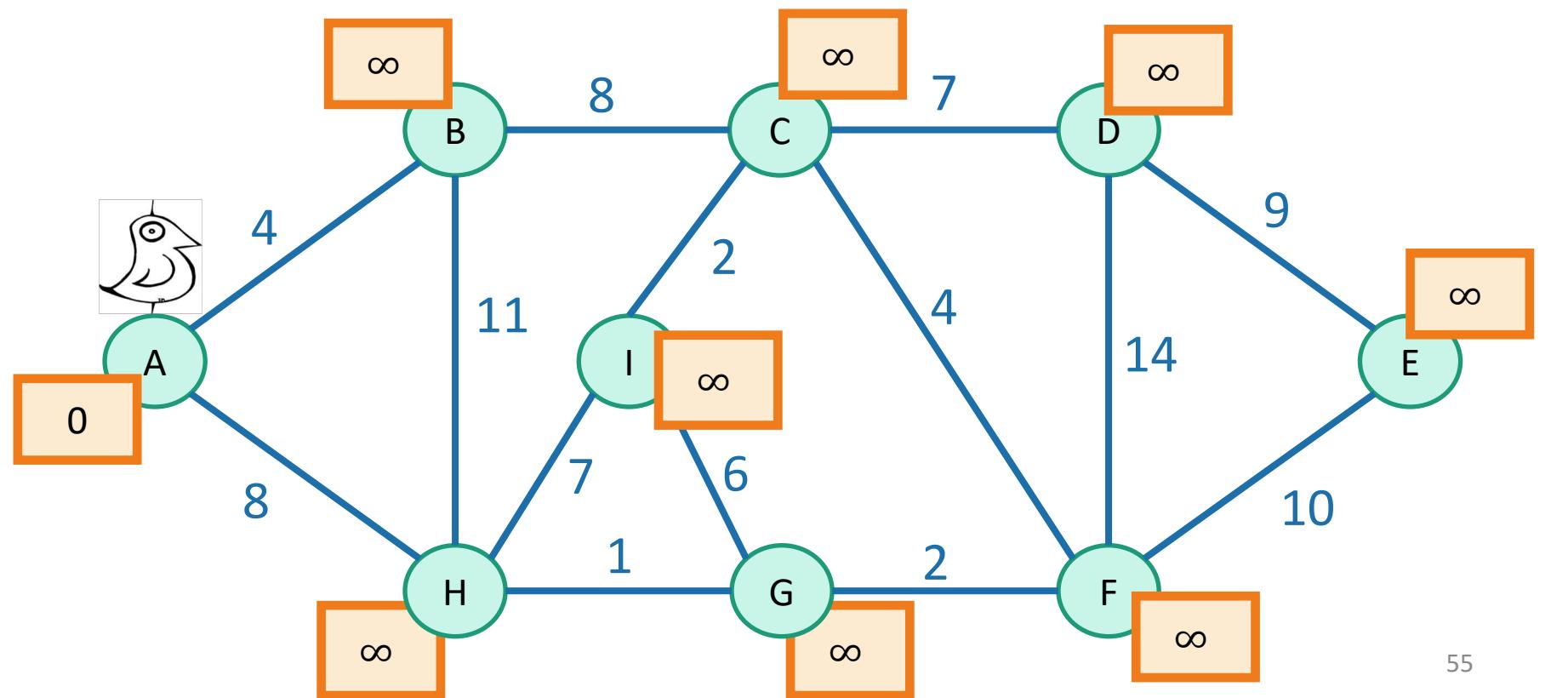
- Each vertex keeps:
  - the **distance** from itself to the **growing spanning tree** if you can get there in one edge.
  - **how to get there.**
- Choose the closest vertex, add it.
- Update stored info.



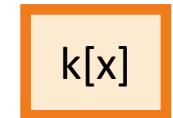
# Efficient implementation

Every vertex has a key and a parent

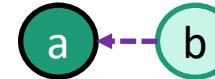
Until all the vertices are reached:



Can't reach  $x$  yet  
 $x$  is “active”  
Can reach  $x$



$k[x]$  is the distance of  $x$  from the growing tree



$p[b] = a$ , meaning that  $a$  was the vertex that  $k[b]$  comes from.

# Efficient implementation

Every vertex has a key and a parent

Until all the vertices are reached:

- Activate the unreached vertex  $u$  with the smallest key.



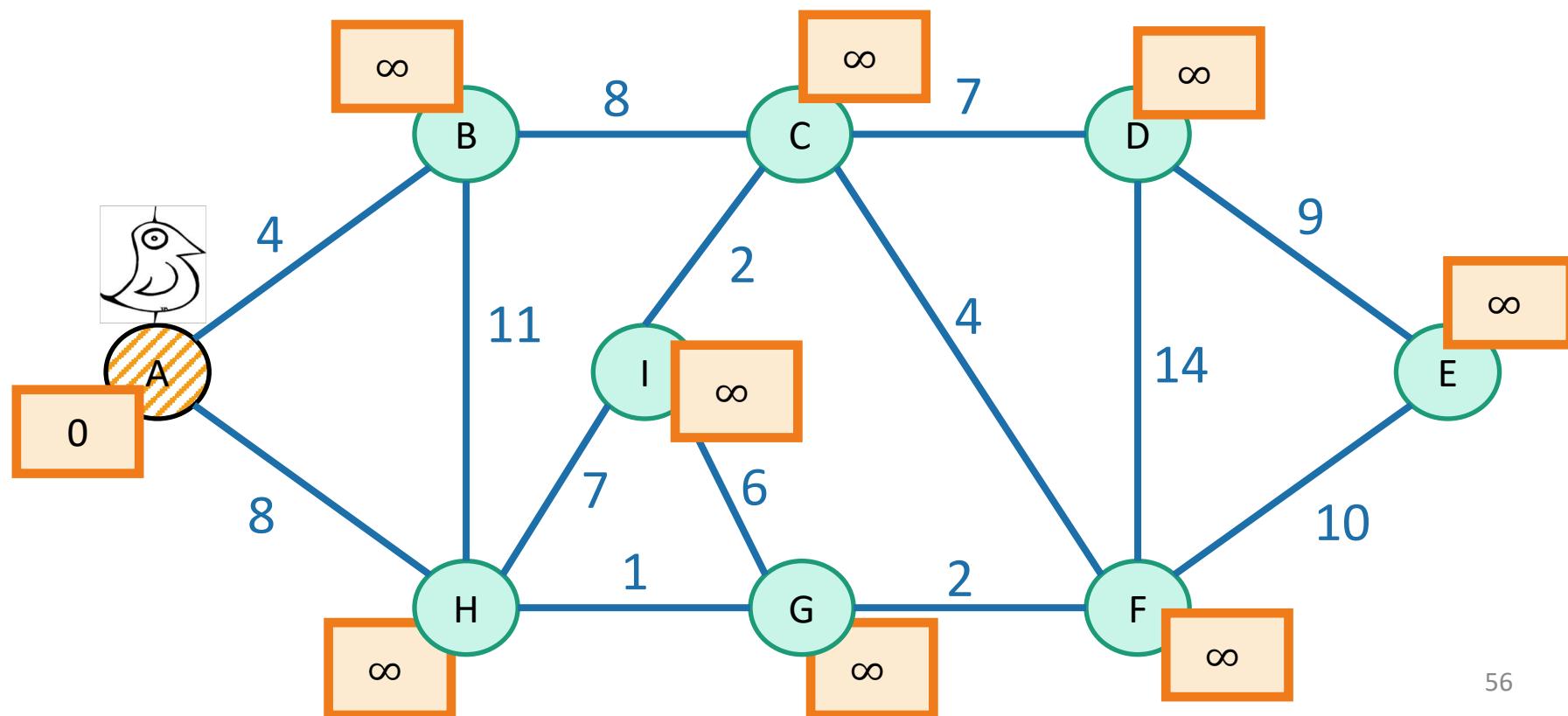
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$k[x]$

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# Efficient implementation

Every vertex has a key and a parent

Until all the vertices are reached:

- Activate the **unreached** vertex  $u$  with the **smallest key**.
- for each of  $u$ 's unreached neighbors  $v$ :
  - $k[v] = \min(k[v], \text{weight}(u,v))$
  - if  $k[v]$  updated,  $p[v] = u$



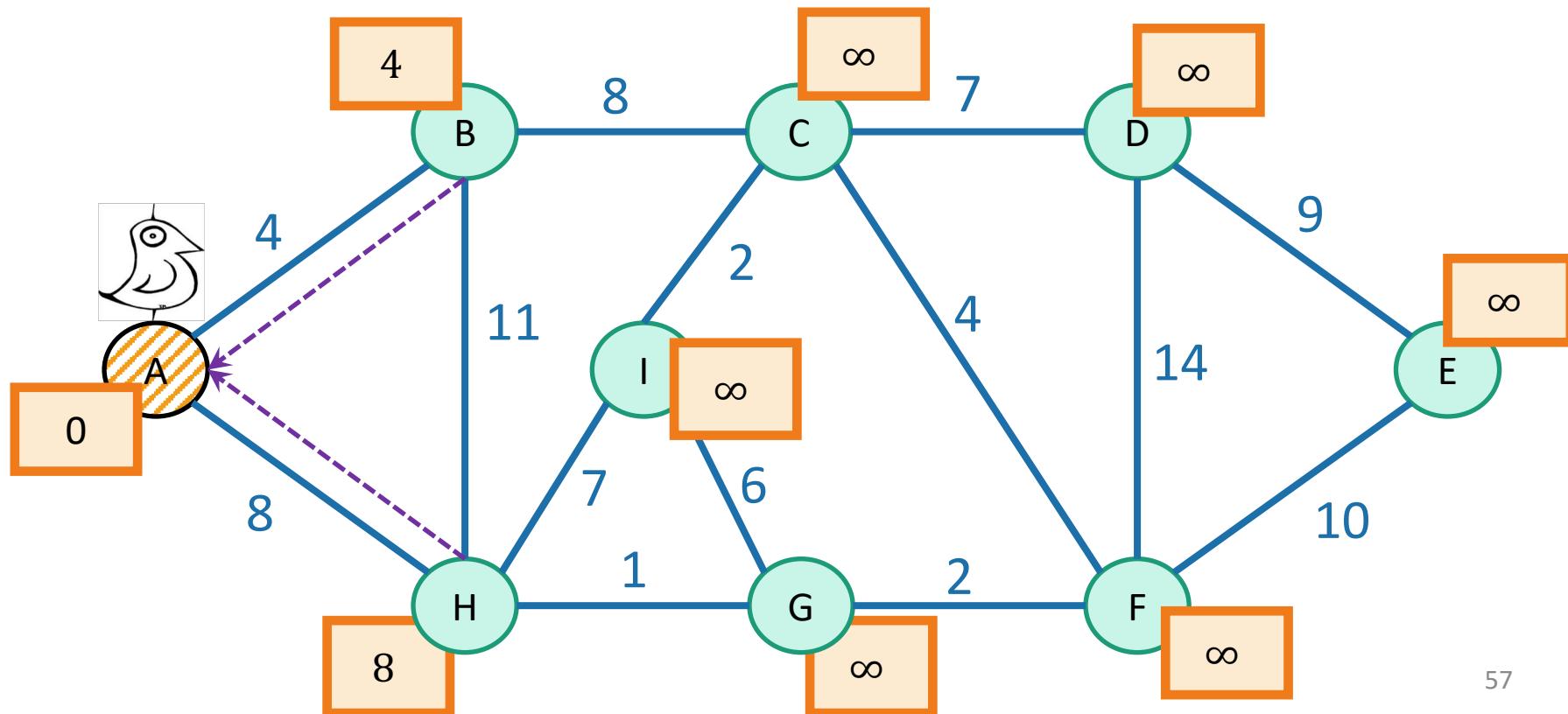
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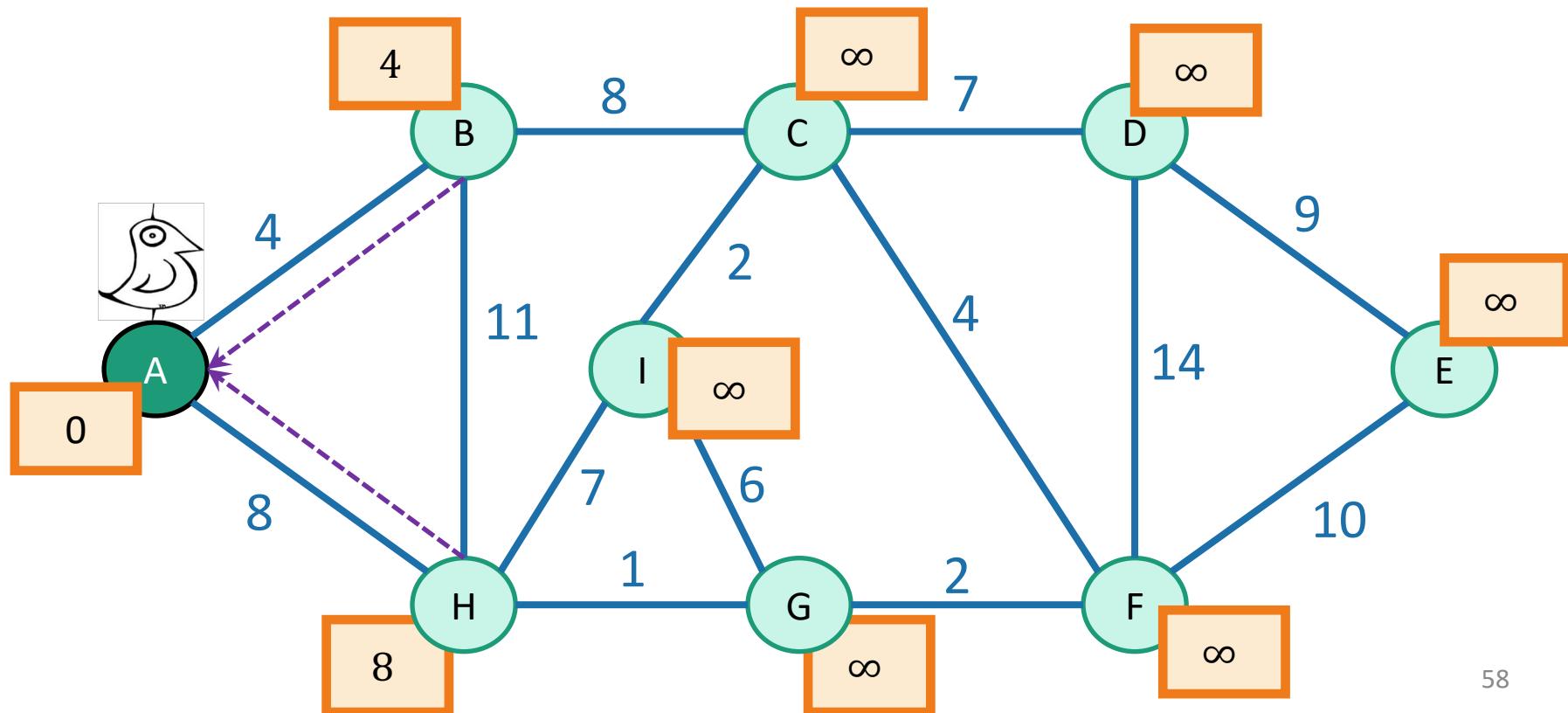
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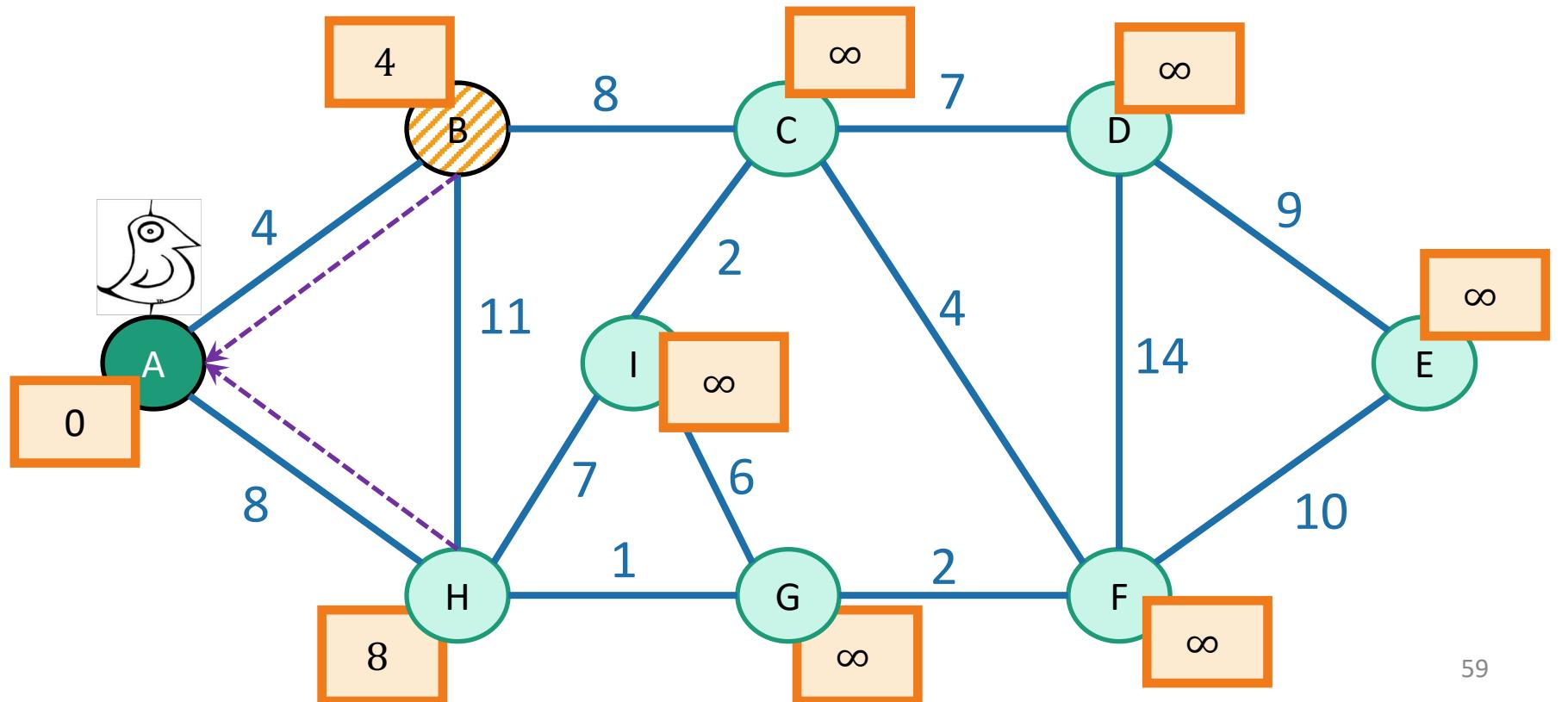


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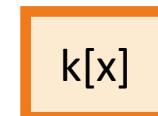
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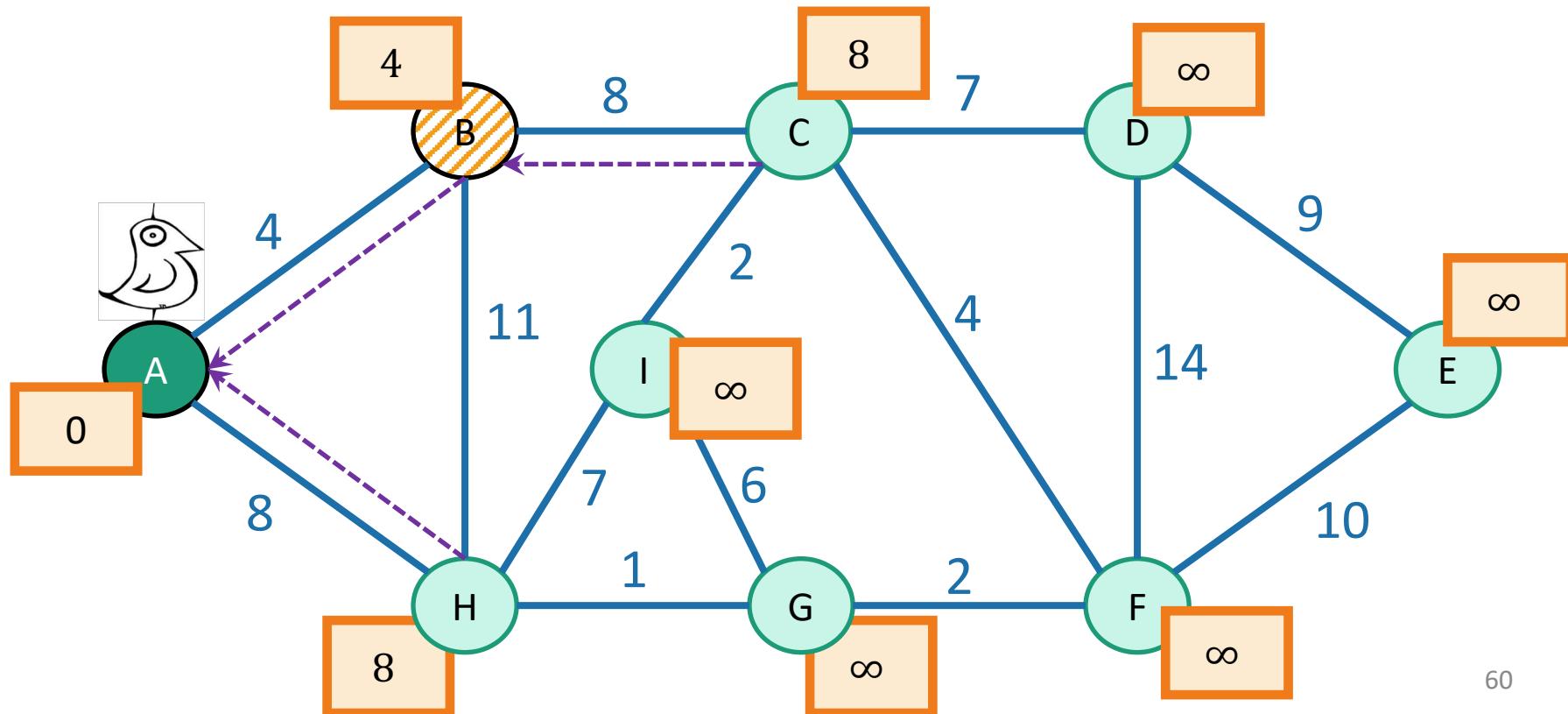
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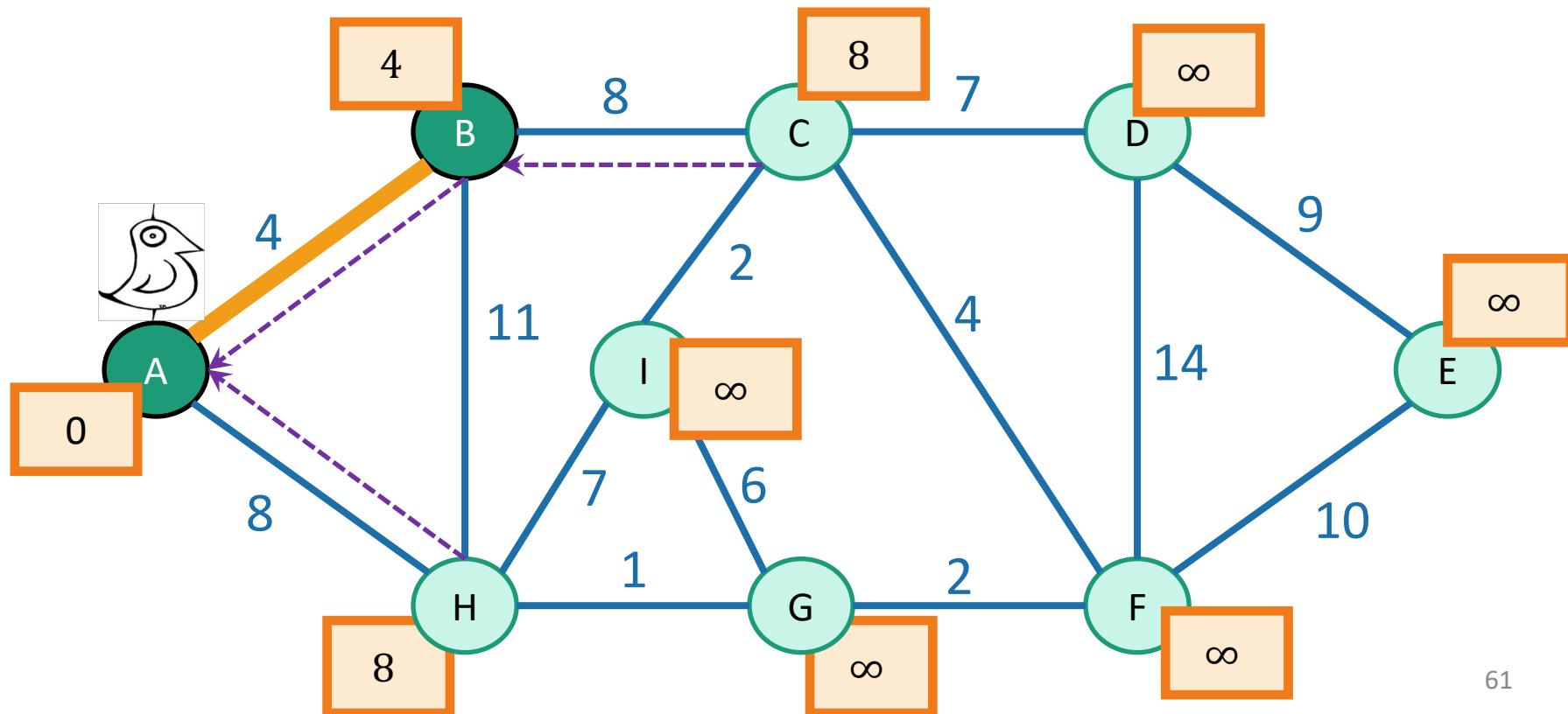
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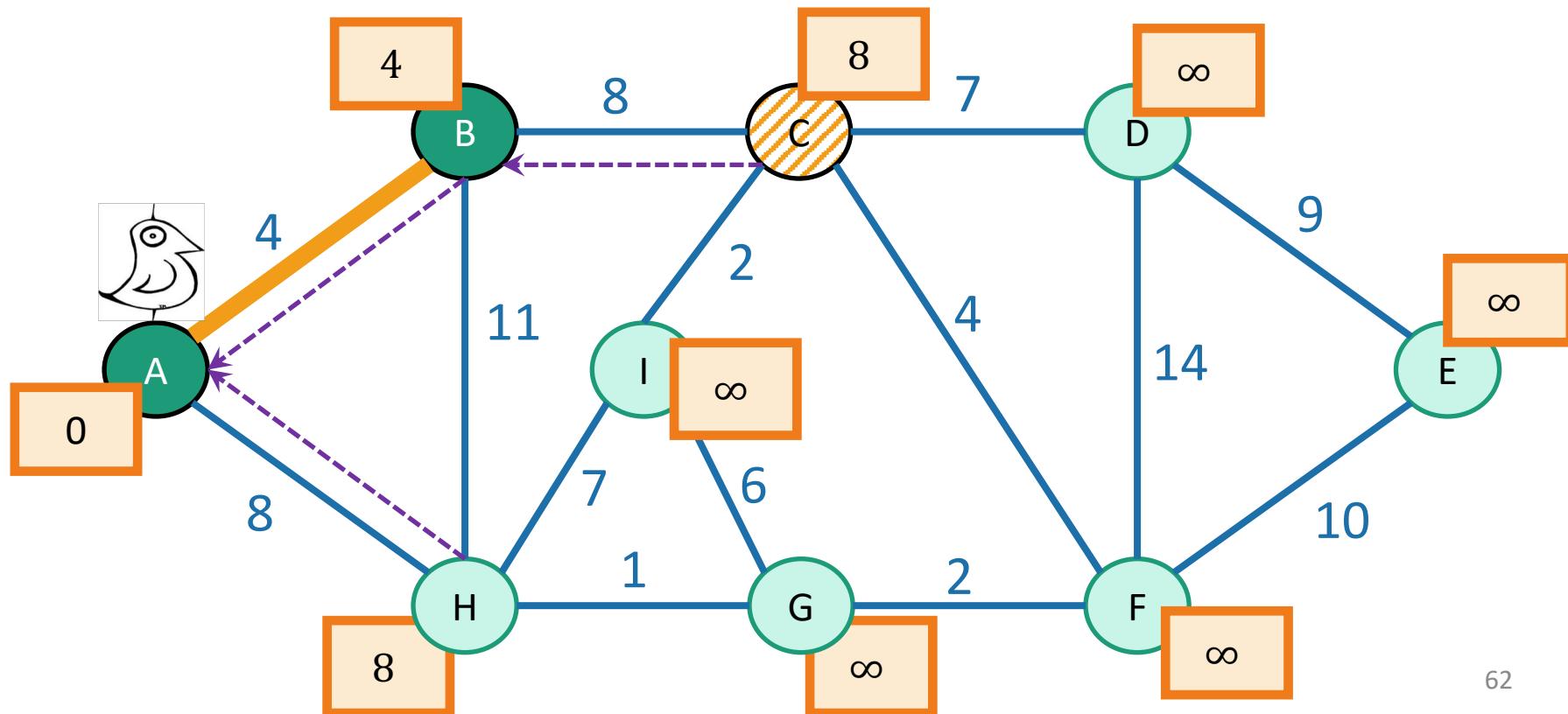
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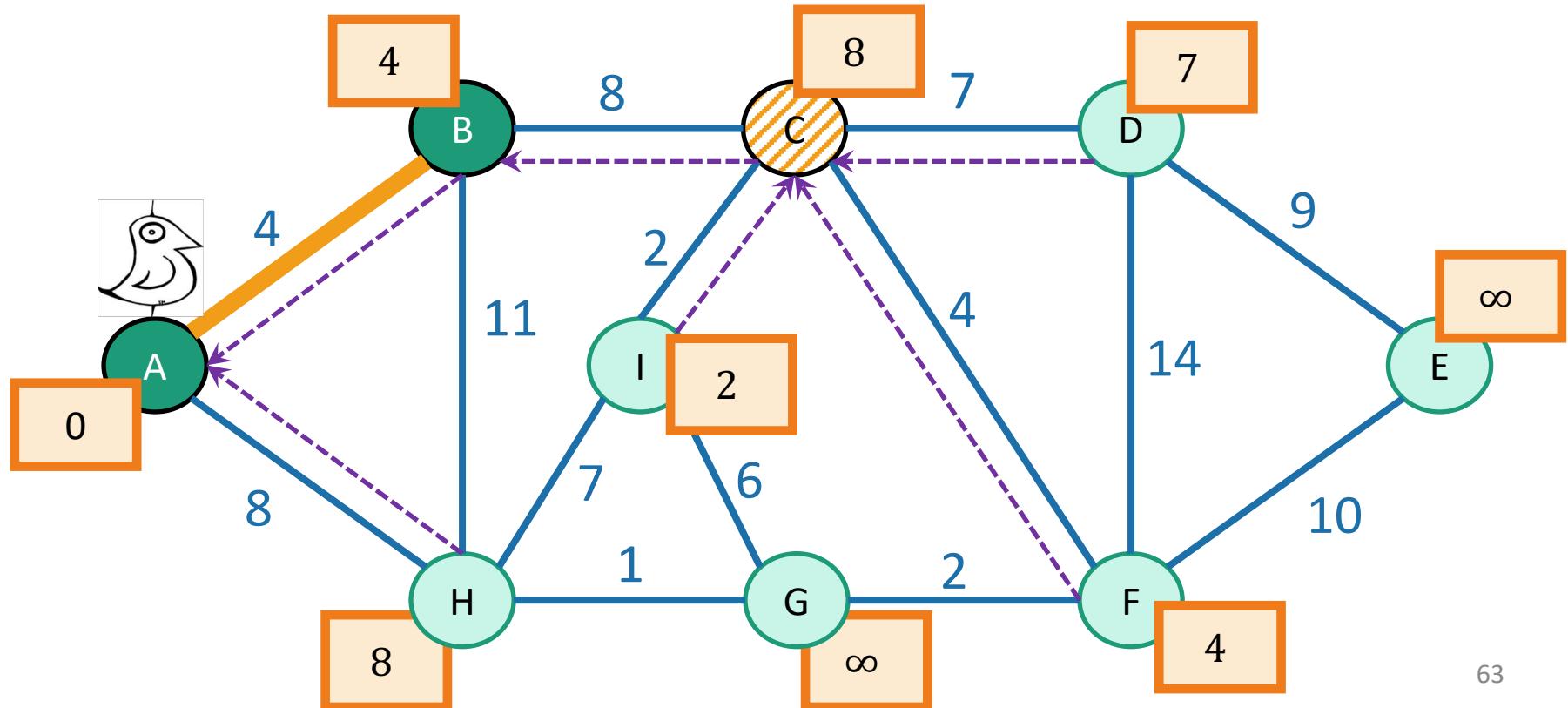


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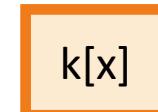
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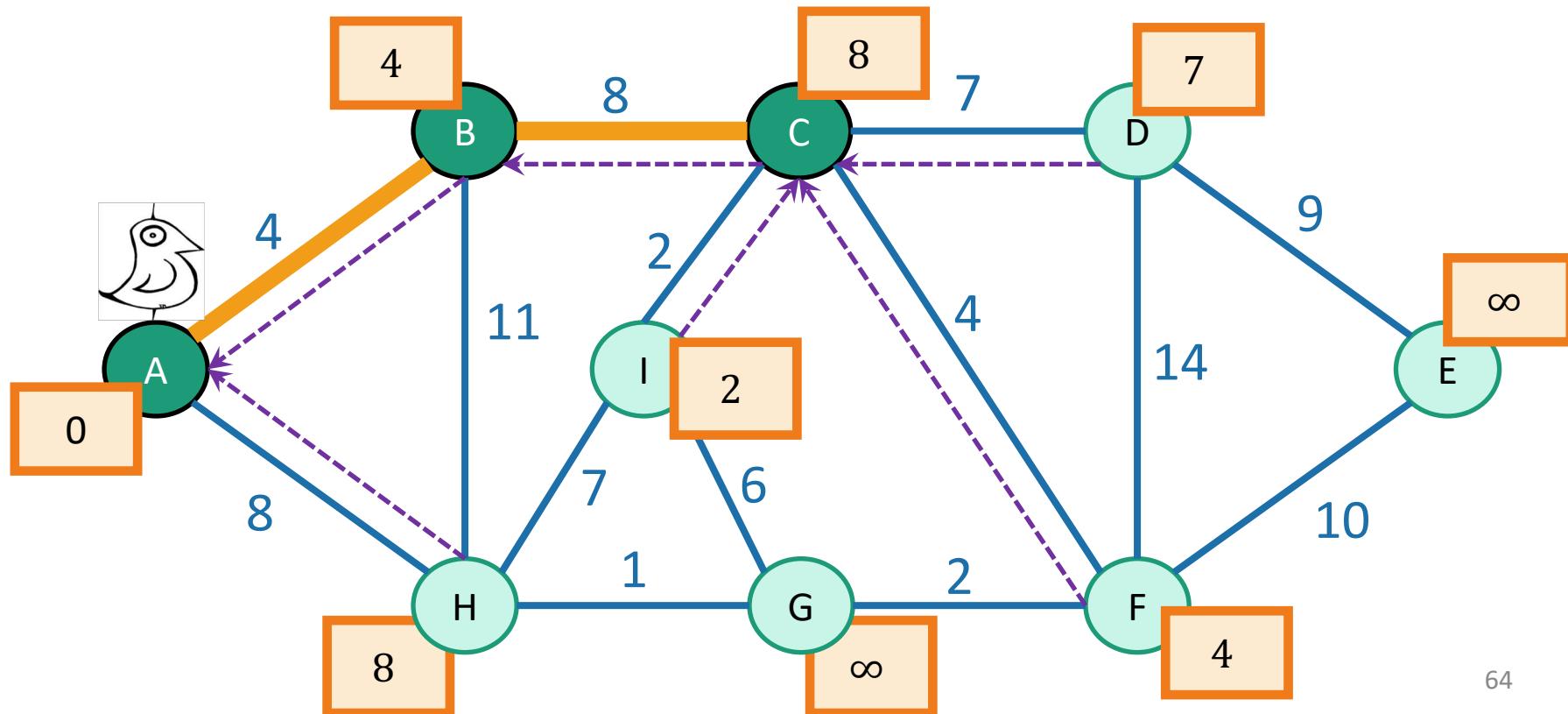
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# Efficient implementation

Every vertex has a key and a parent

**Until** all the vertices are **reached**:

- Activate the **unreached** vertex  $u$  with the **smallest key**.
  - **for each** of  $u$ 's unreached neighbors  $v$ :
    - $k[v] = \min(k[v], \text{weight}(u,v))$
    - if  $k[v]$  updated,  $p[v] = u$
  - Mark  $u$  as **reached**, and **add  $(p[u], u)$  to MST.**



Can't reach x yet  
x is “active”  
Can reach x

$k[x]$  is the distance of  $x$  from the growing tree

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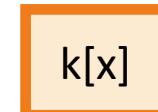
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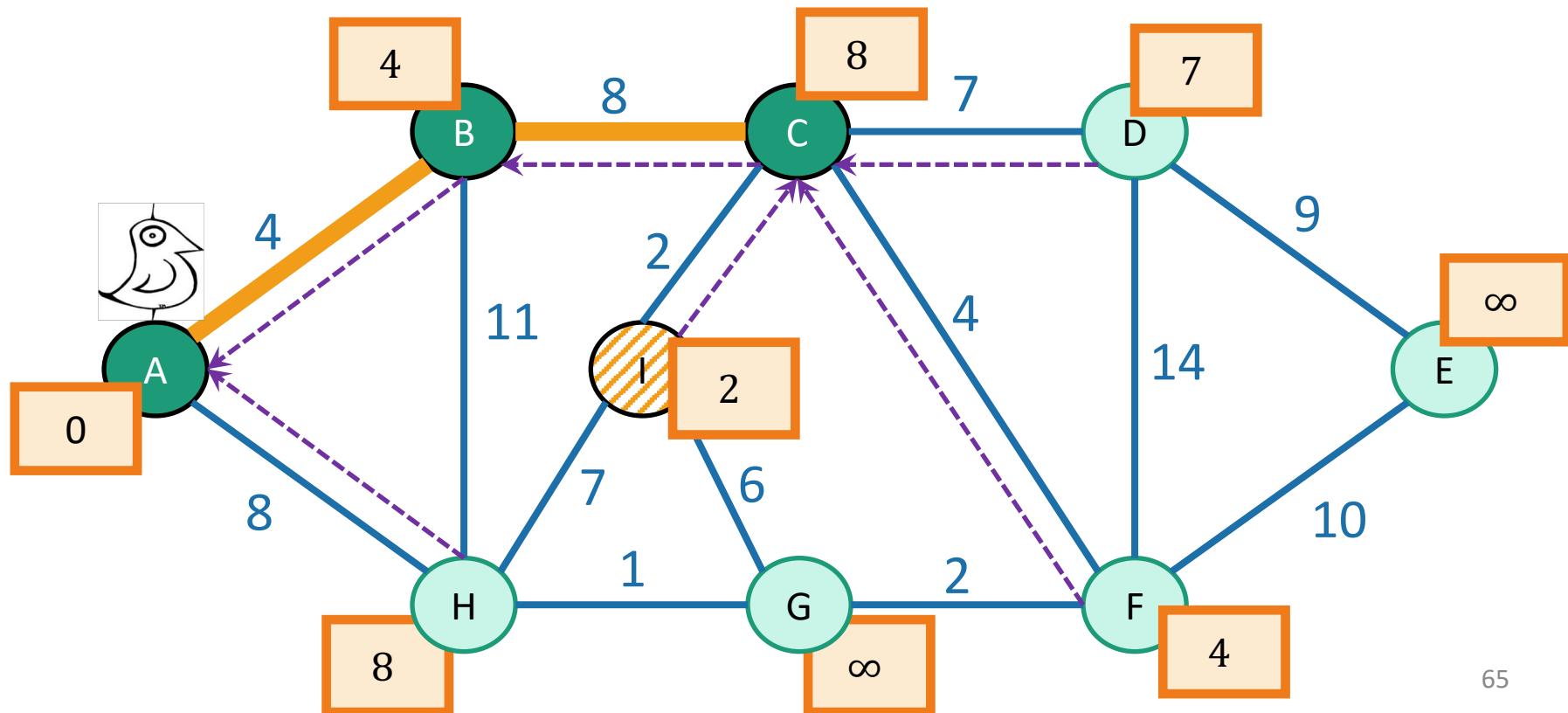
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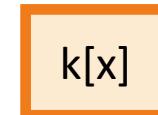
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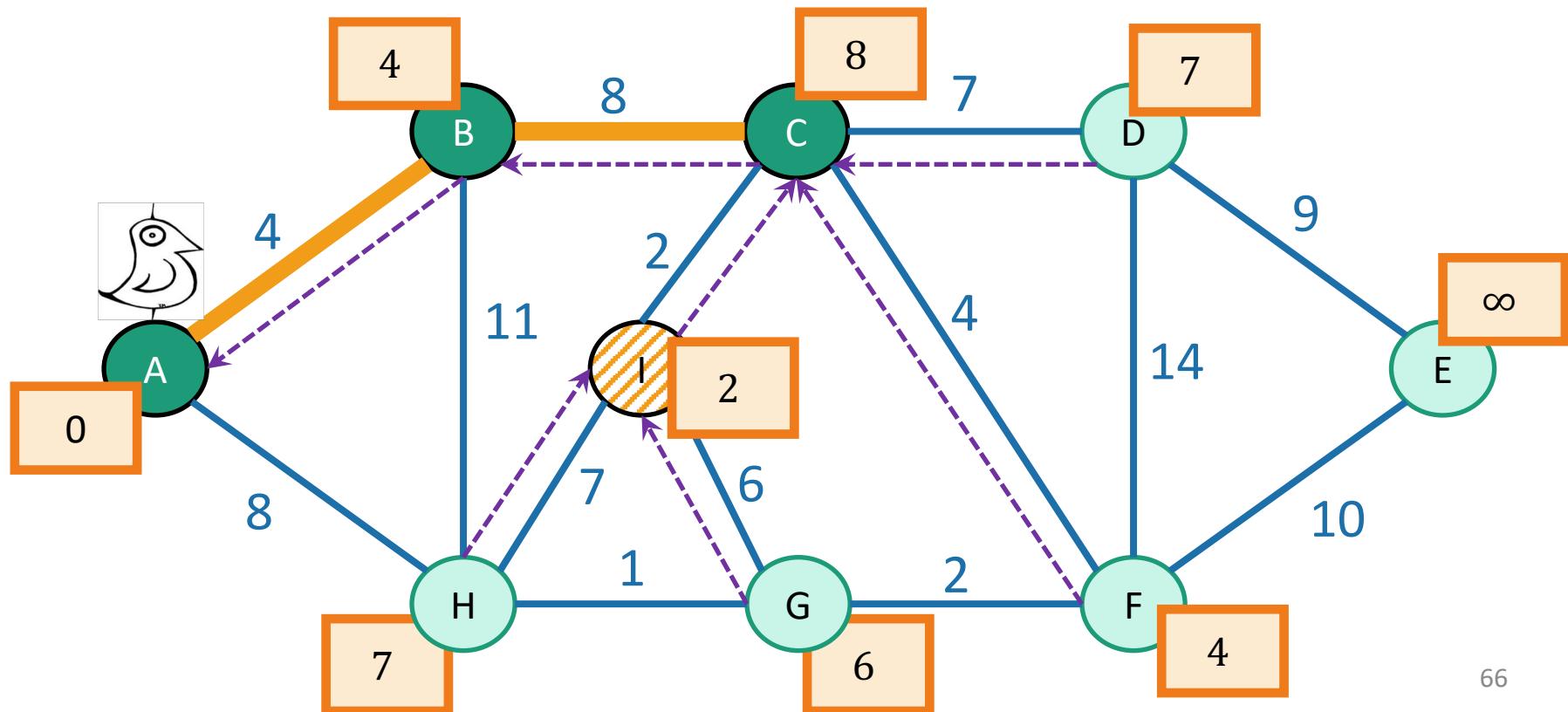
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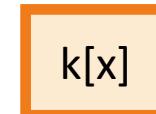
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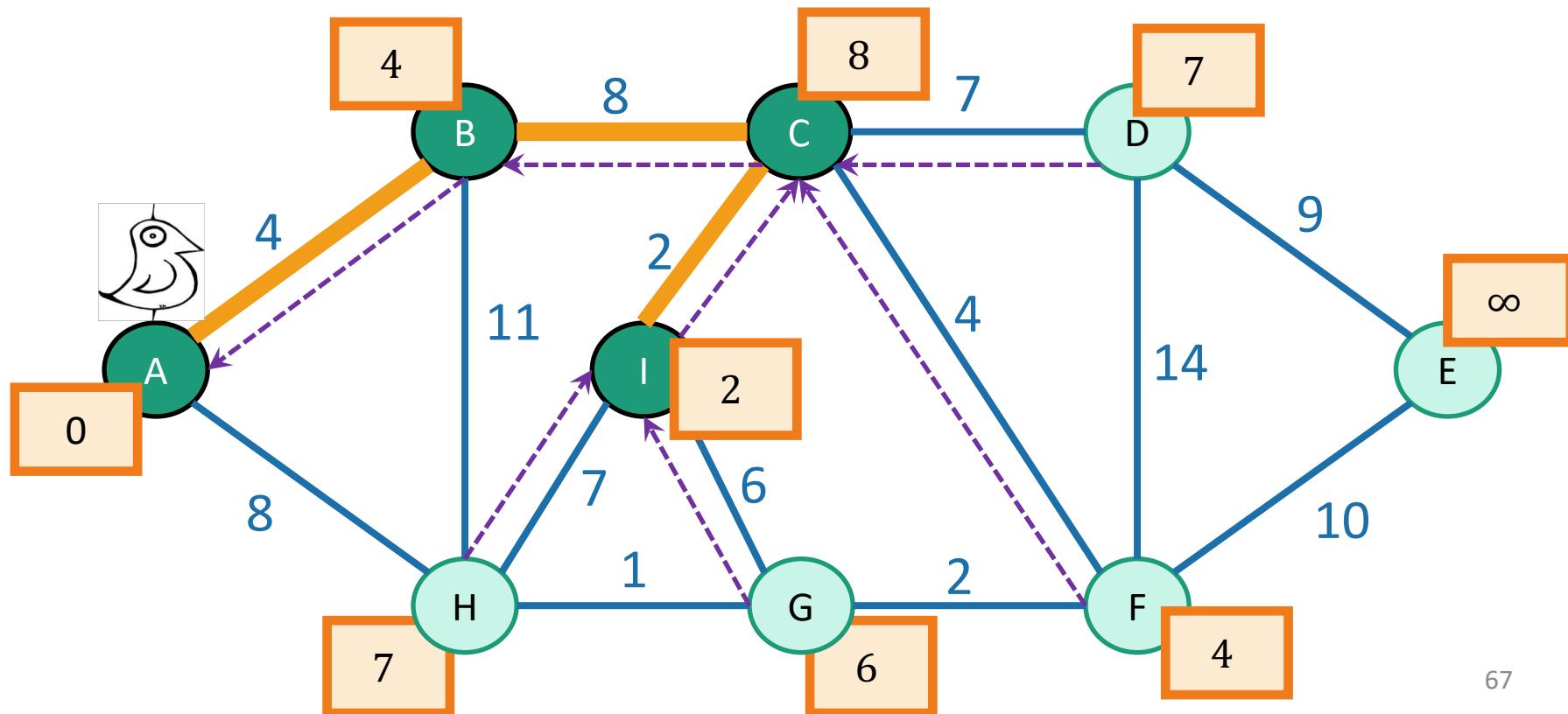
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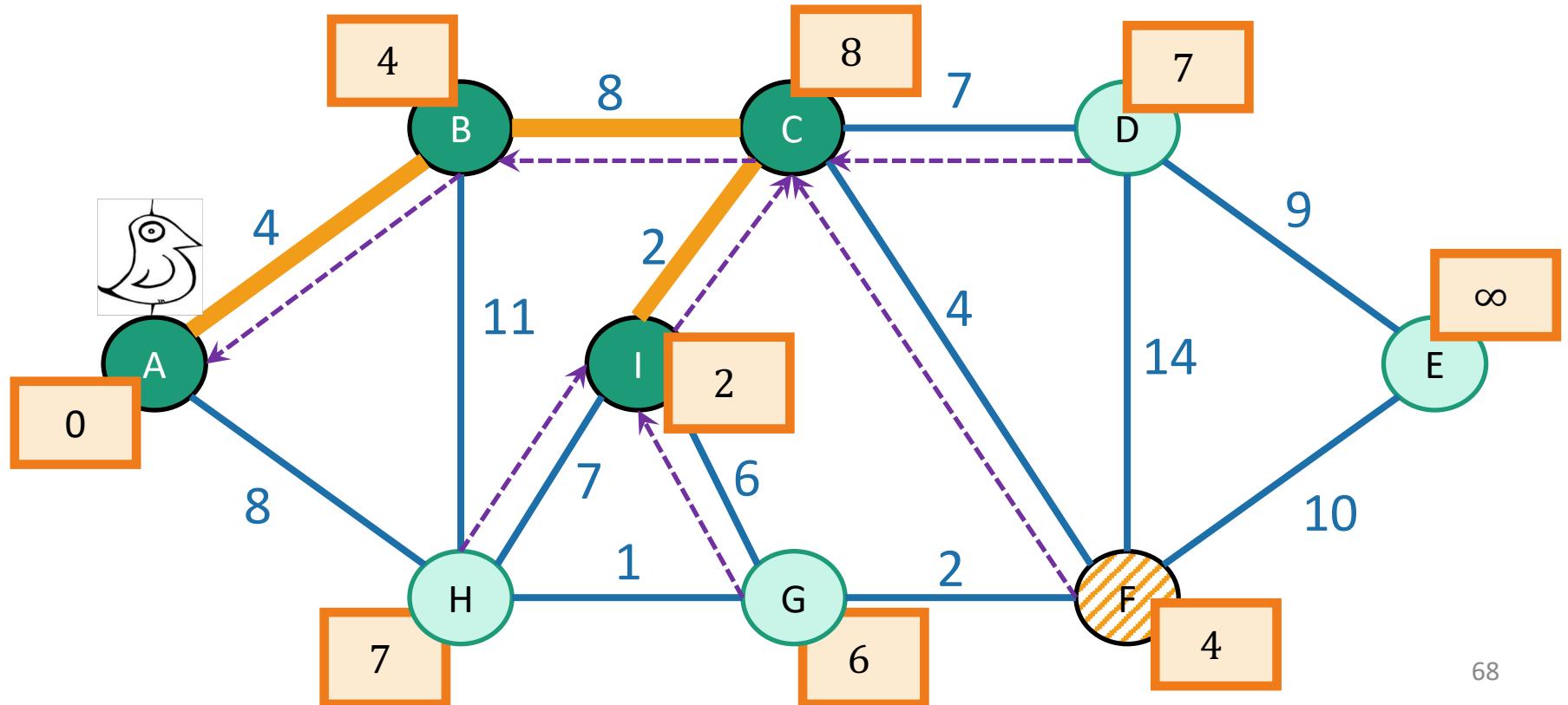


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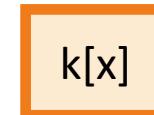
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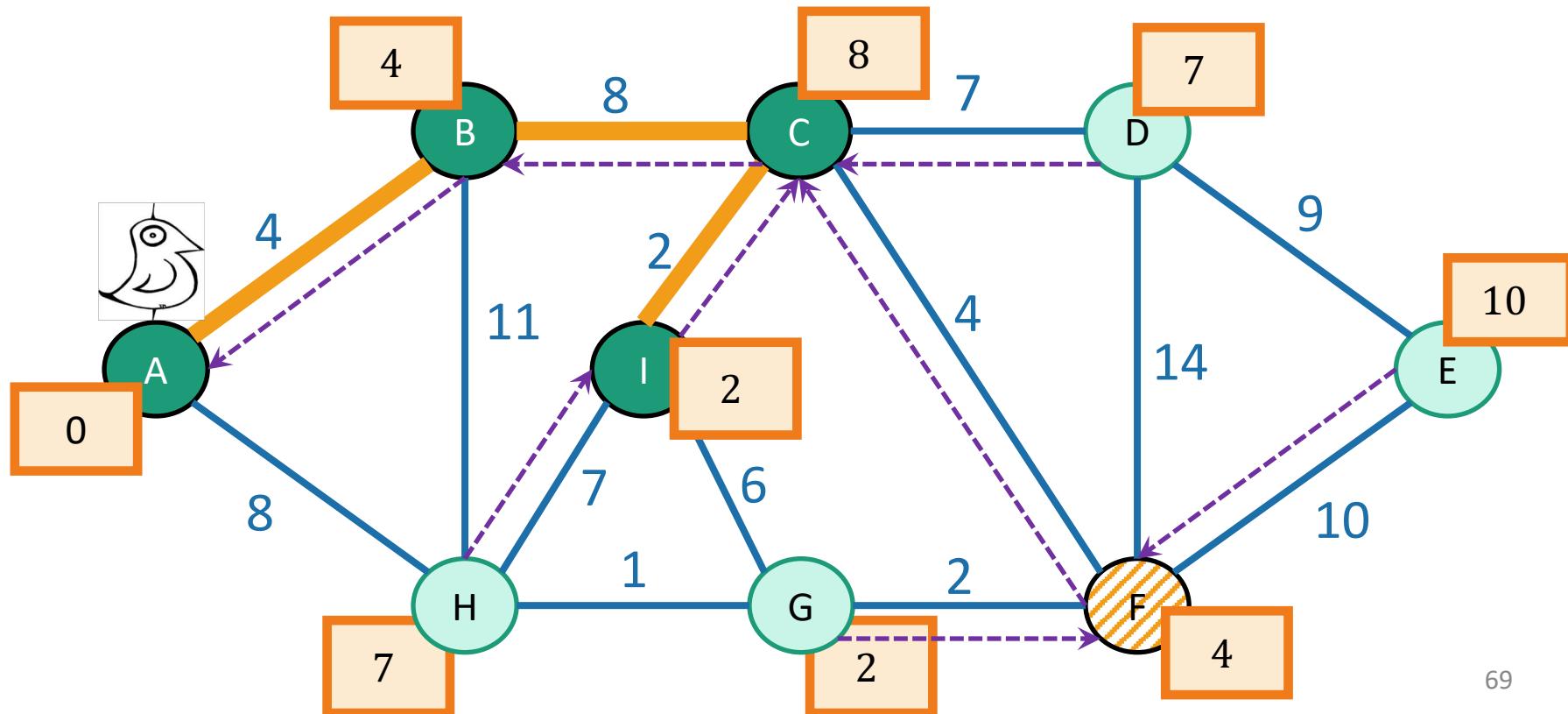
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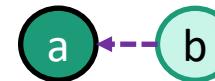
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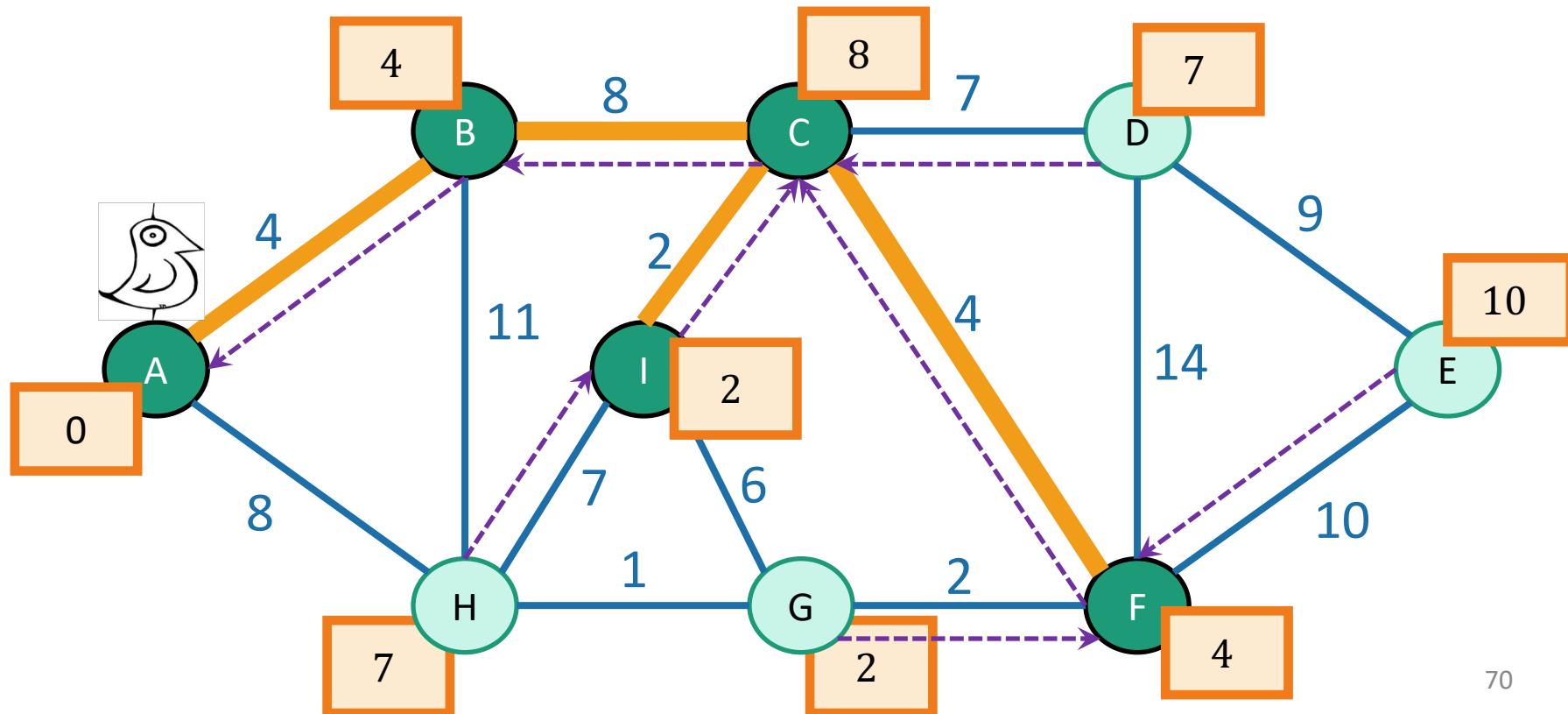
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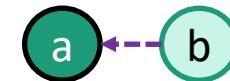
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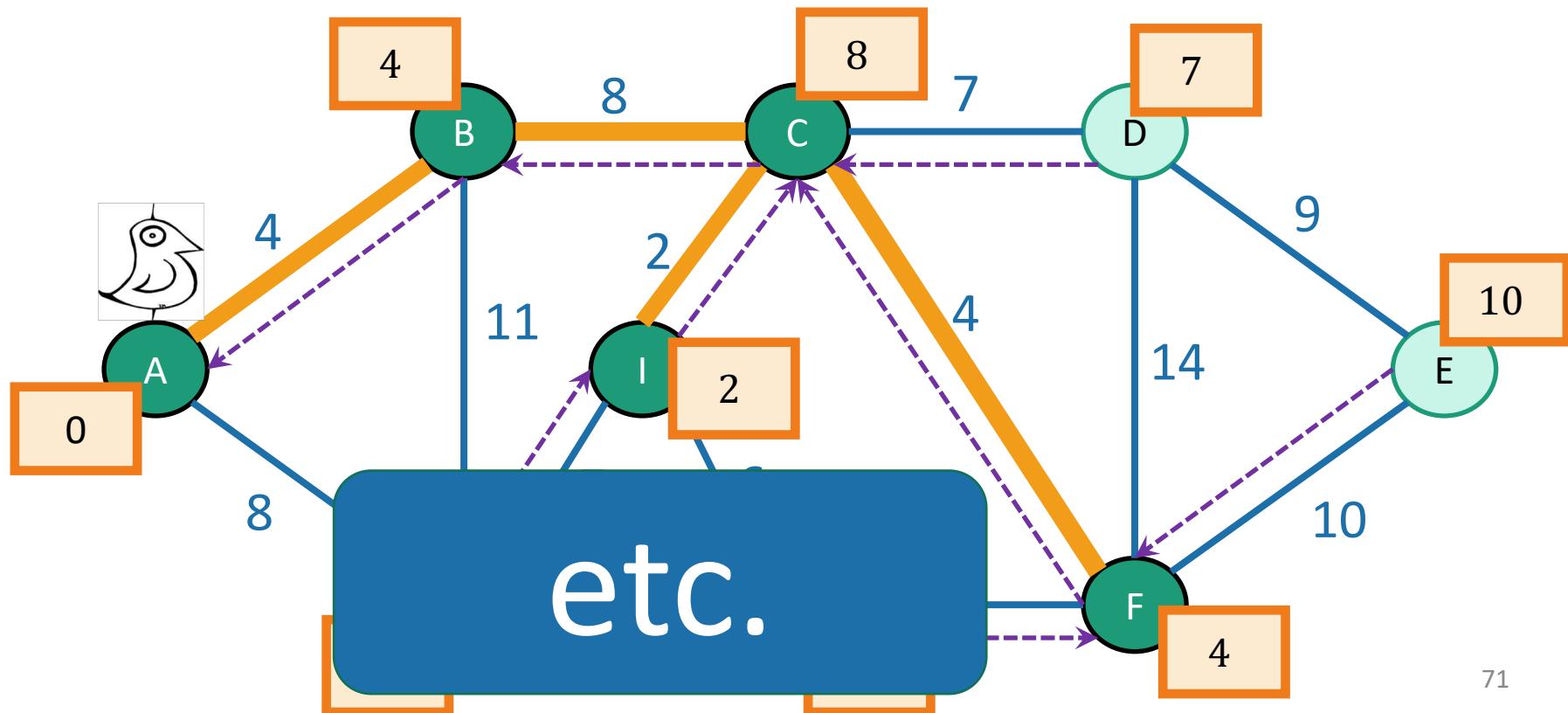
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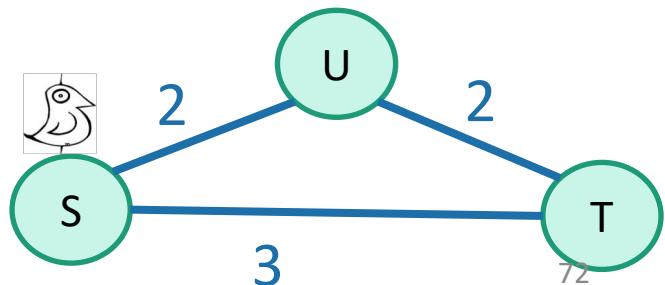


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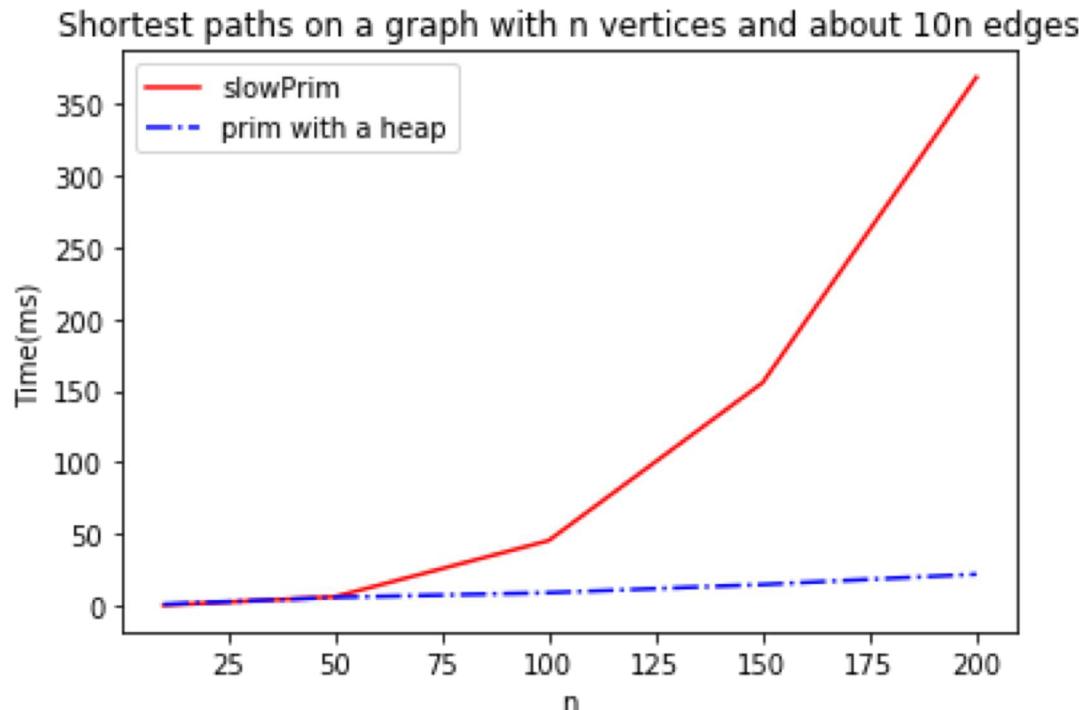
# This should look pretty familiar

- Very similar to Dijkstra's algorithm!
- **Differences:**
  1. Keep track of  $p[v]$  in order to return a tree at the end
    - But Dijkstra's can do that too, that's not a big difference.
  2. Instead of  $d[v]$  which we update by
    - $d[v] = \min( d[v], d[u] + w(u,v) )$we keep  $k[v]$  which we update by
    - $k[v] = \min( k[v], w(u,v) )$
- To see the difference, consider:



# One thing that is similar: Running time

- Exactly the same as Dijkstra:
  - $O(m \log(n))$  using a Red-Black tree as a priority queue.
  - $O(m + n \log(n))$  amortized time if we use a Fibonacci Heap\*.



# Two questions

1. Does it work?
  - That is, does it actually return a MST?
    - Yes!
2. How do we actually implement this?
  - the pseudocode above says “slowPrim”...
    - **Implement it basically the same way we'd implement Dijkstra!**
    - See IPython notebook for an implementation.

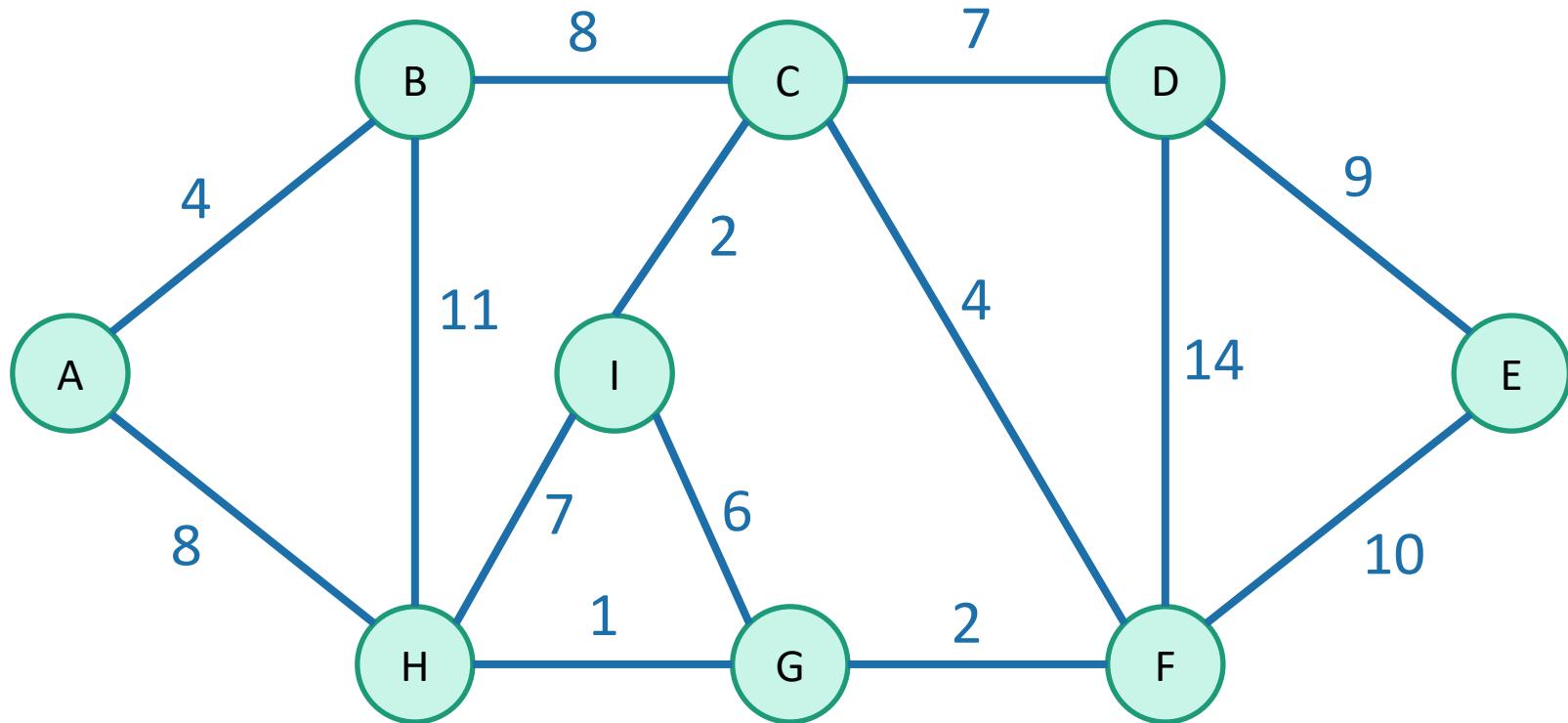
# What have we learned?

- Prim's algorithm greedily grows a tree
  - smells a lot like Dijkstra's algorithm
- It finds a Minimum Spanning Tree!
  - in time  $O(m \log(n))$  if we implement it with a Red-Black Tree.
  - In amortized time  $O(m + n \log(n))$  with a Fibonacci heap.
- To prove it worked, we followed the same recipe for greedy algorithms we saw last time.
  - Show that, at every step, we **don't rule out success**.

That's not the only greedy  
algorithm for MST!

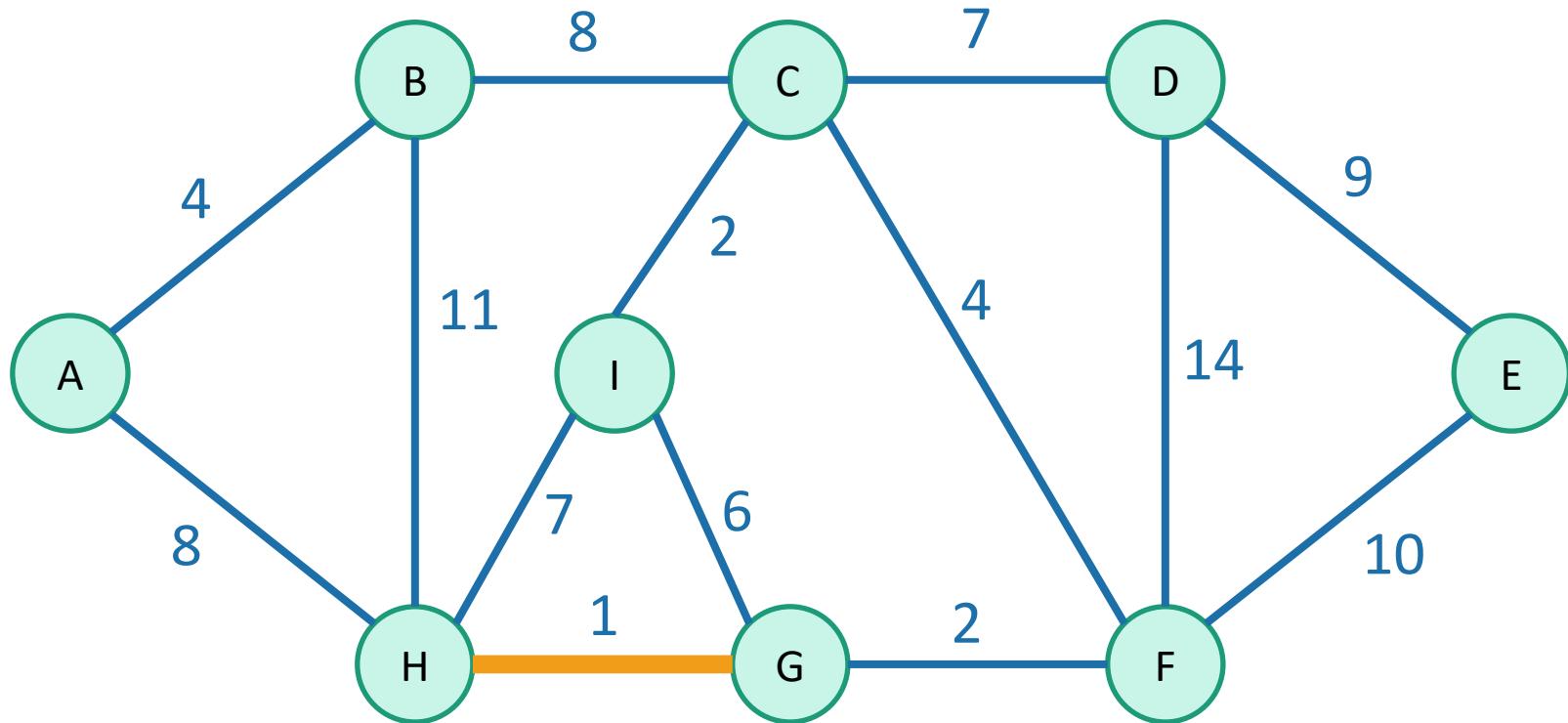
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what if we just always take the cheapest edge?  
whether or not it's connected to what we have so far?



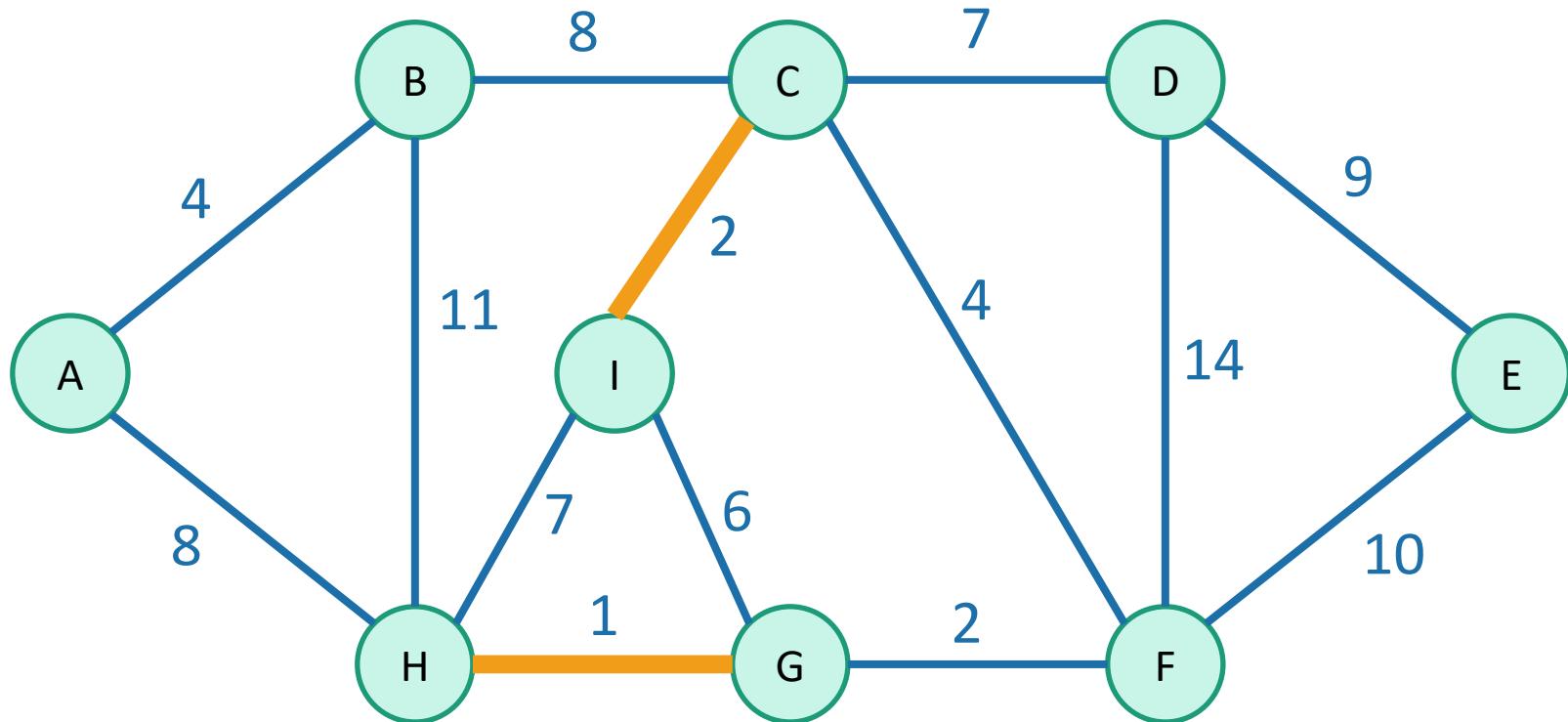
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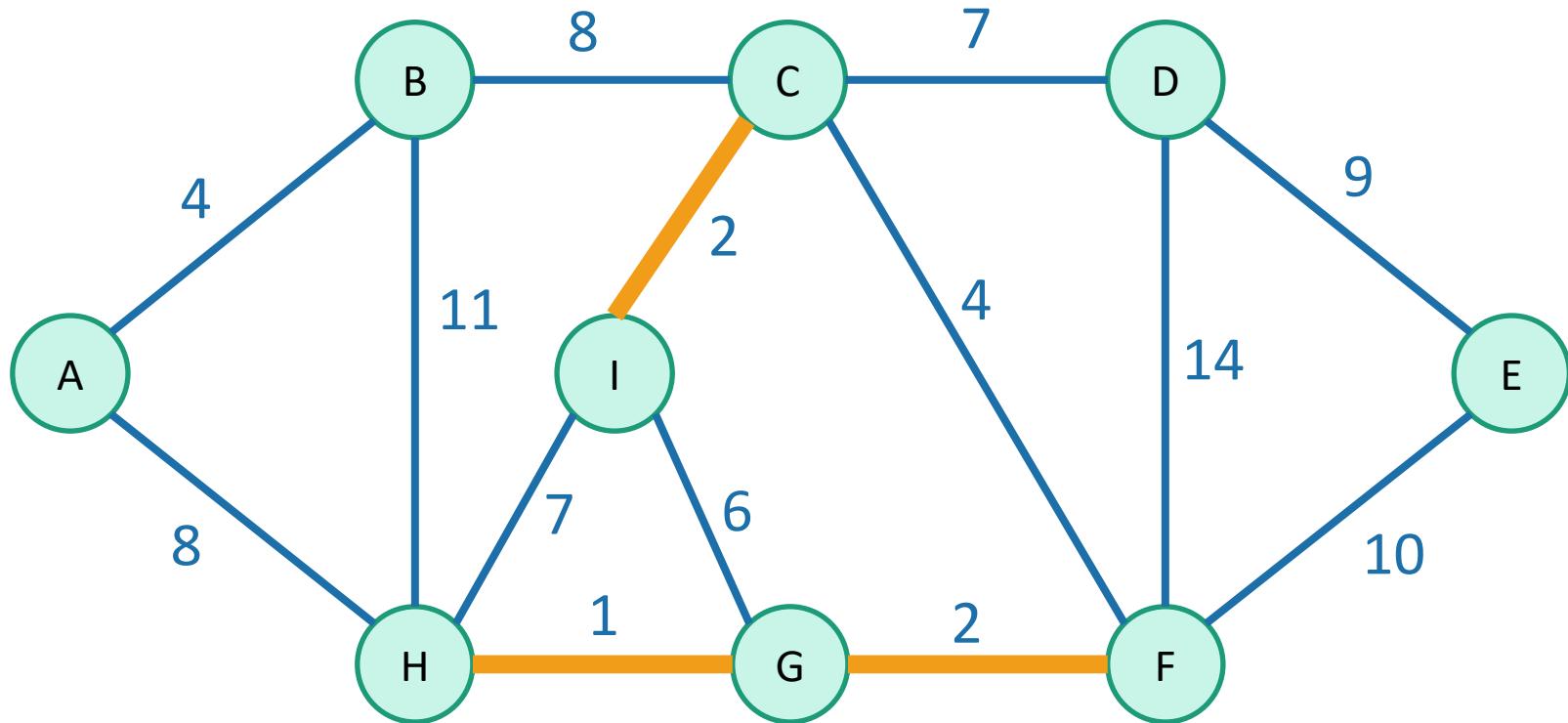
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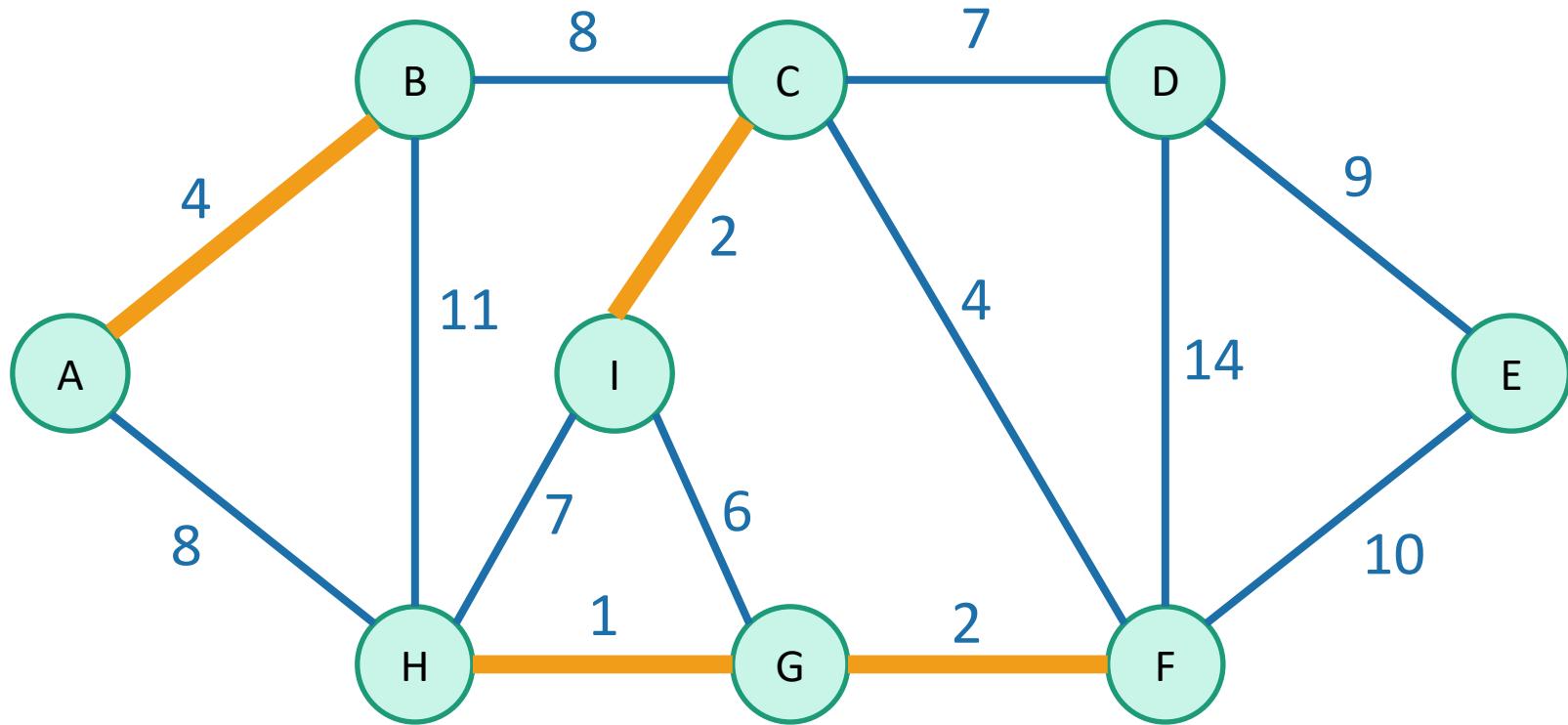
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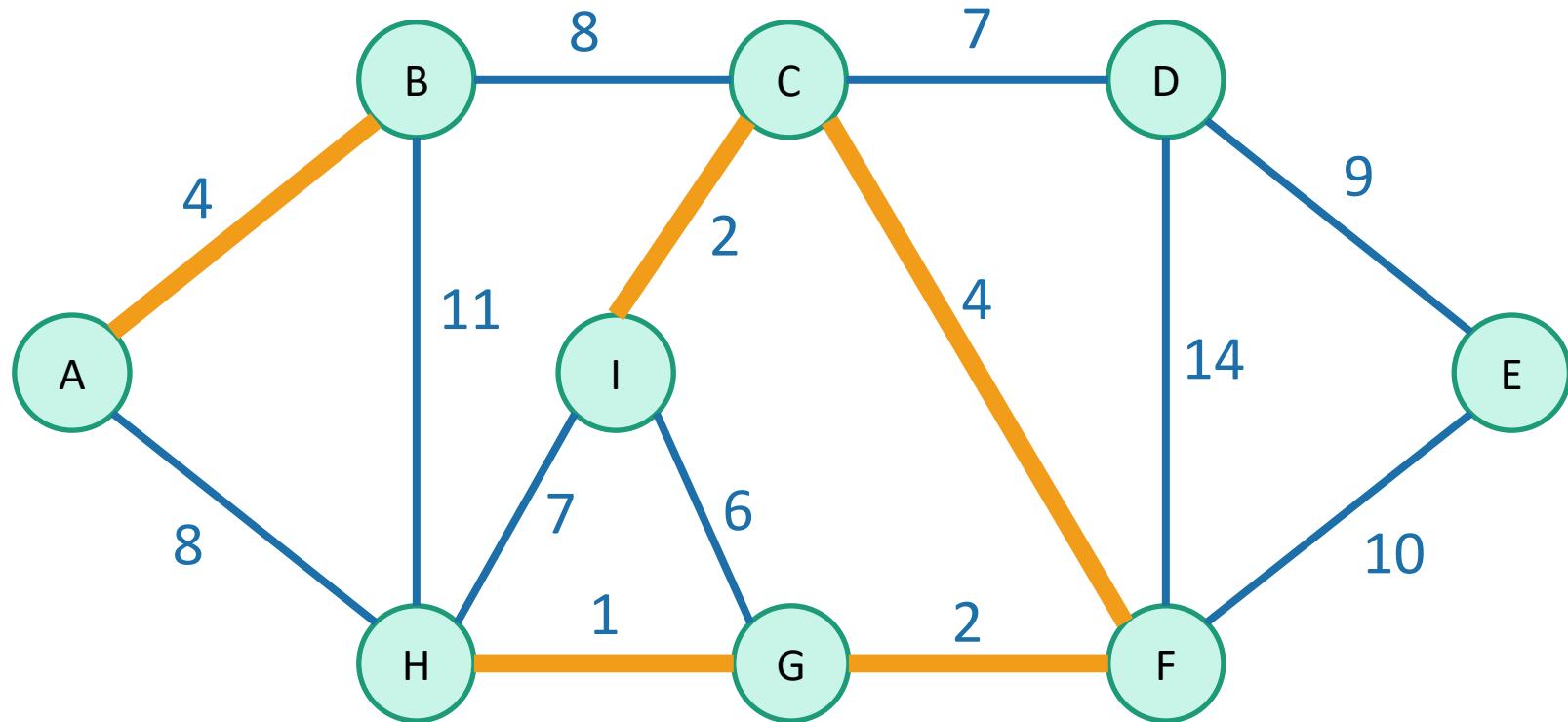
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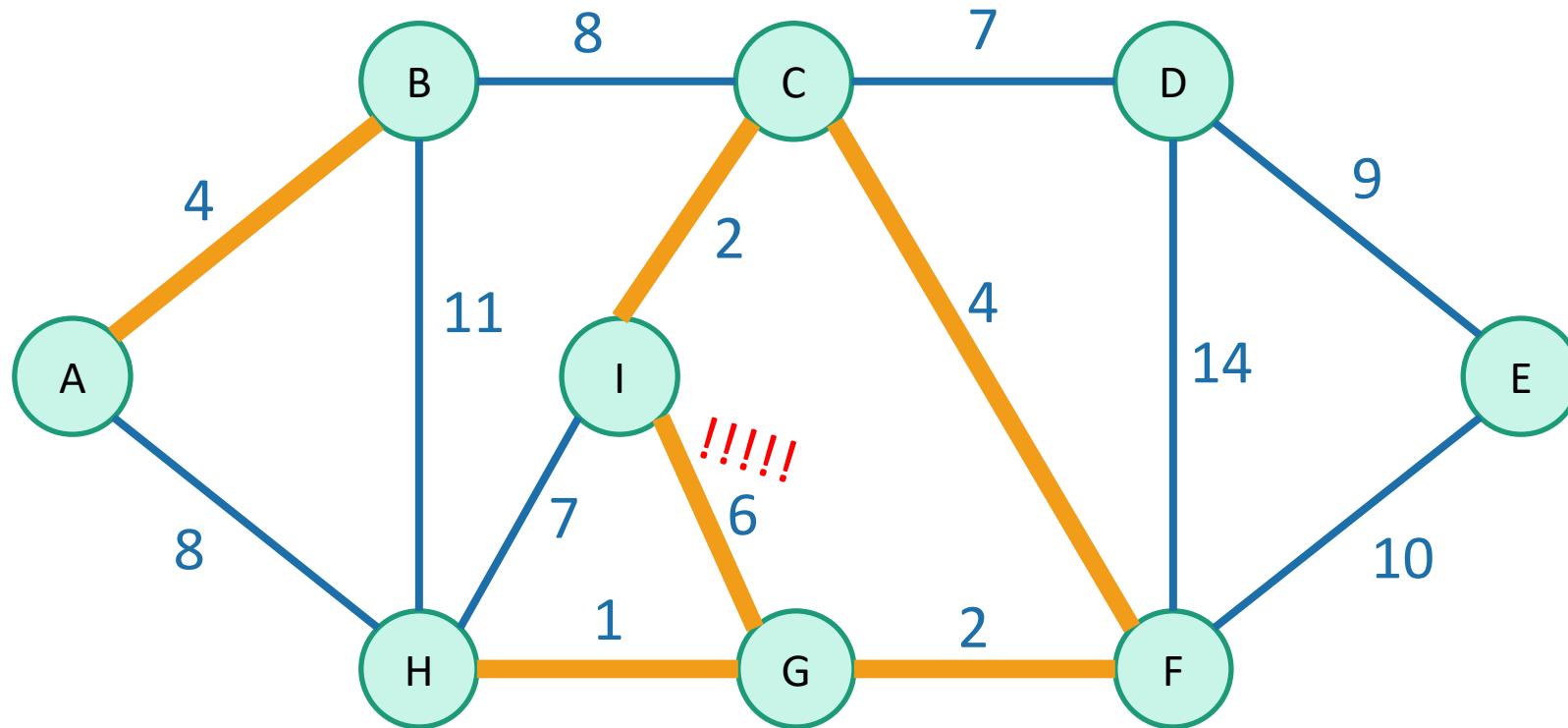


# That's not the only greedy algorithm

what if we just always take the cheapest edge?

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That won't  
cause a cycle

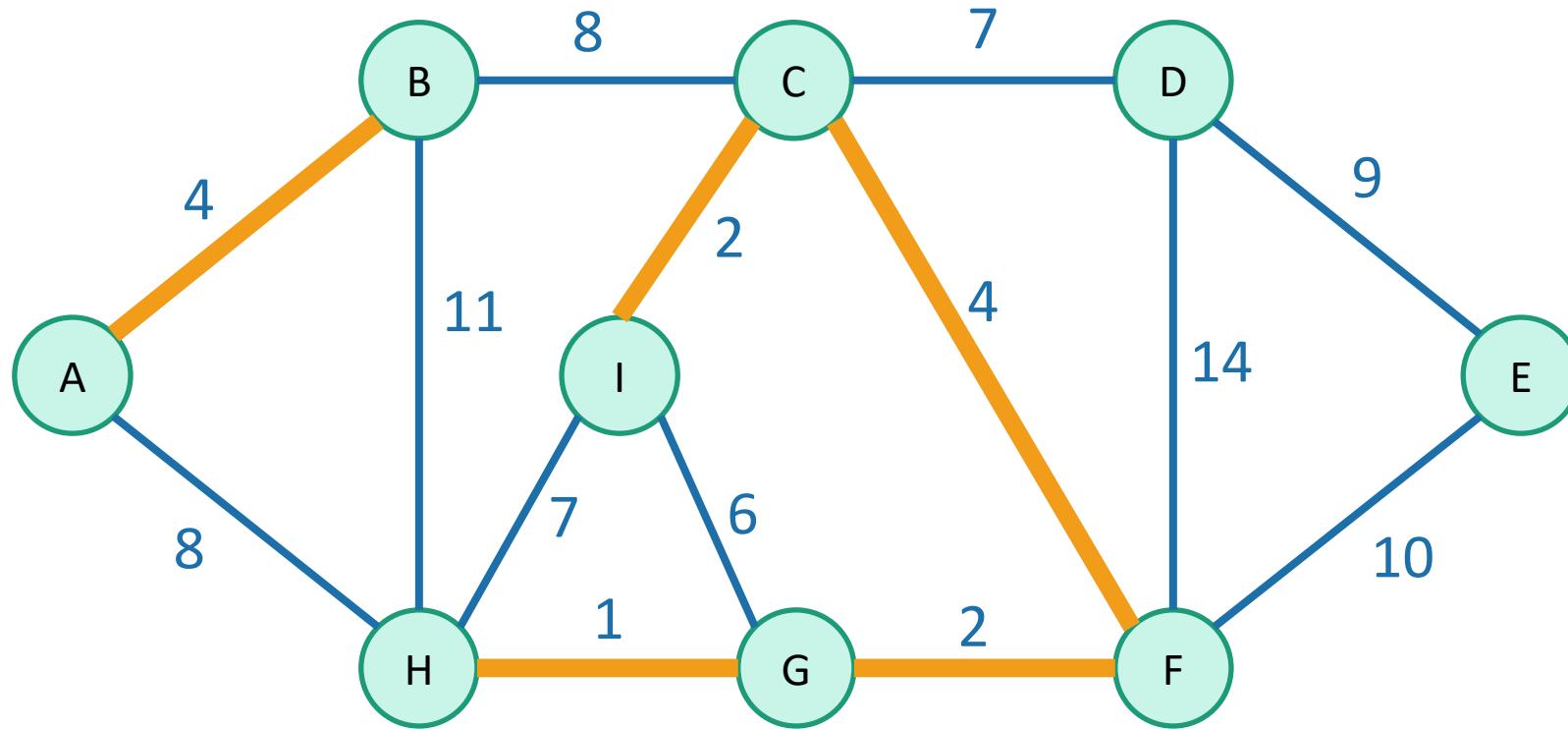


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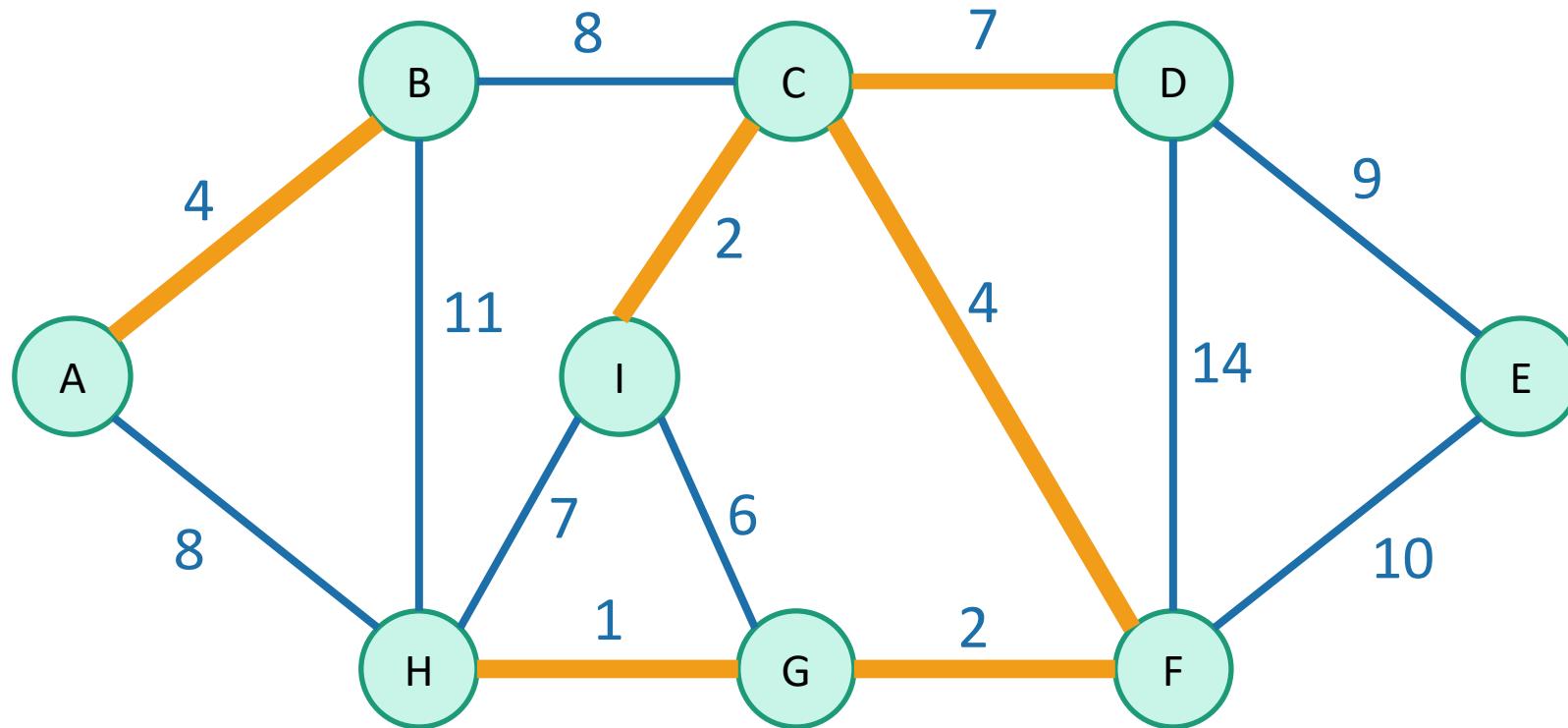


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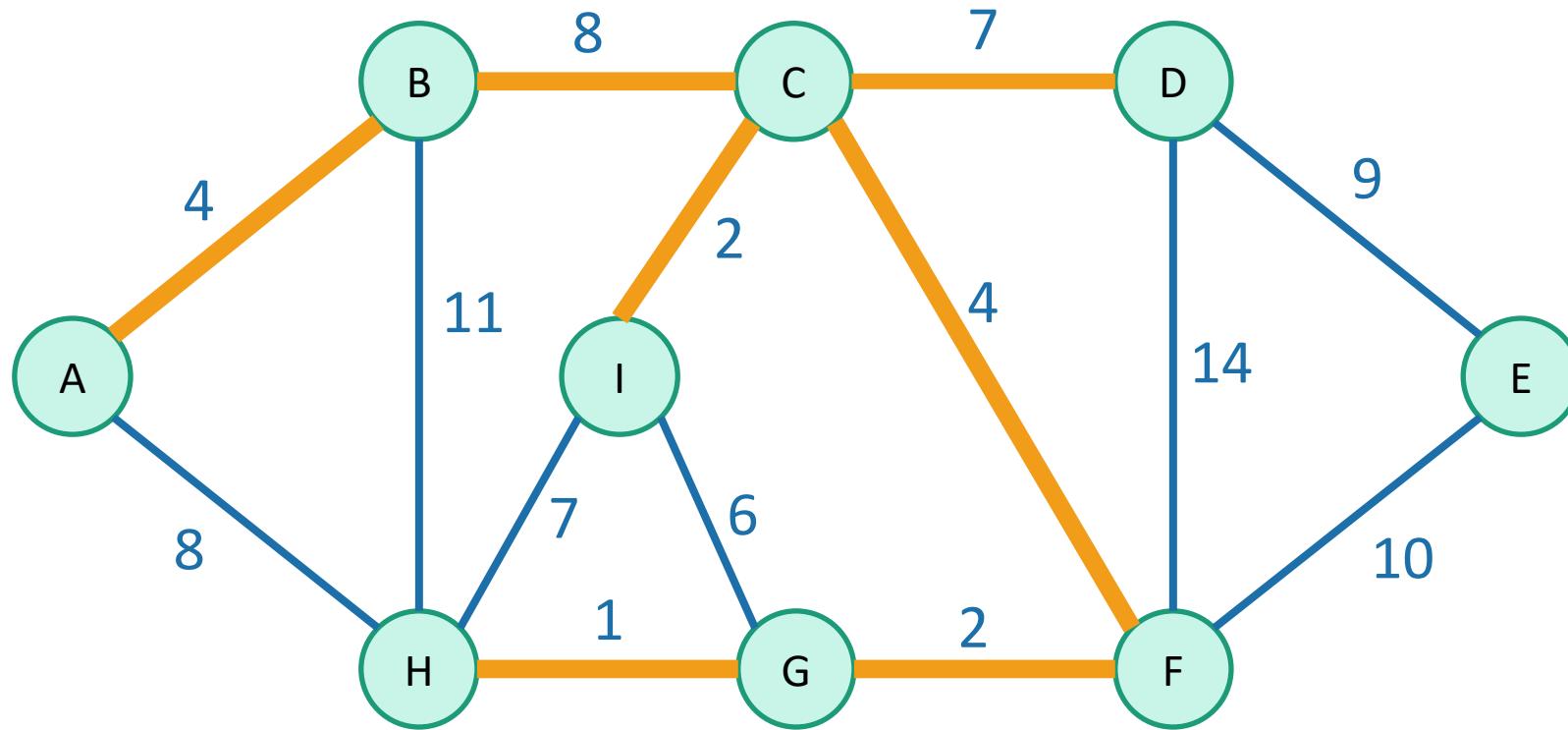


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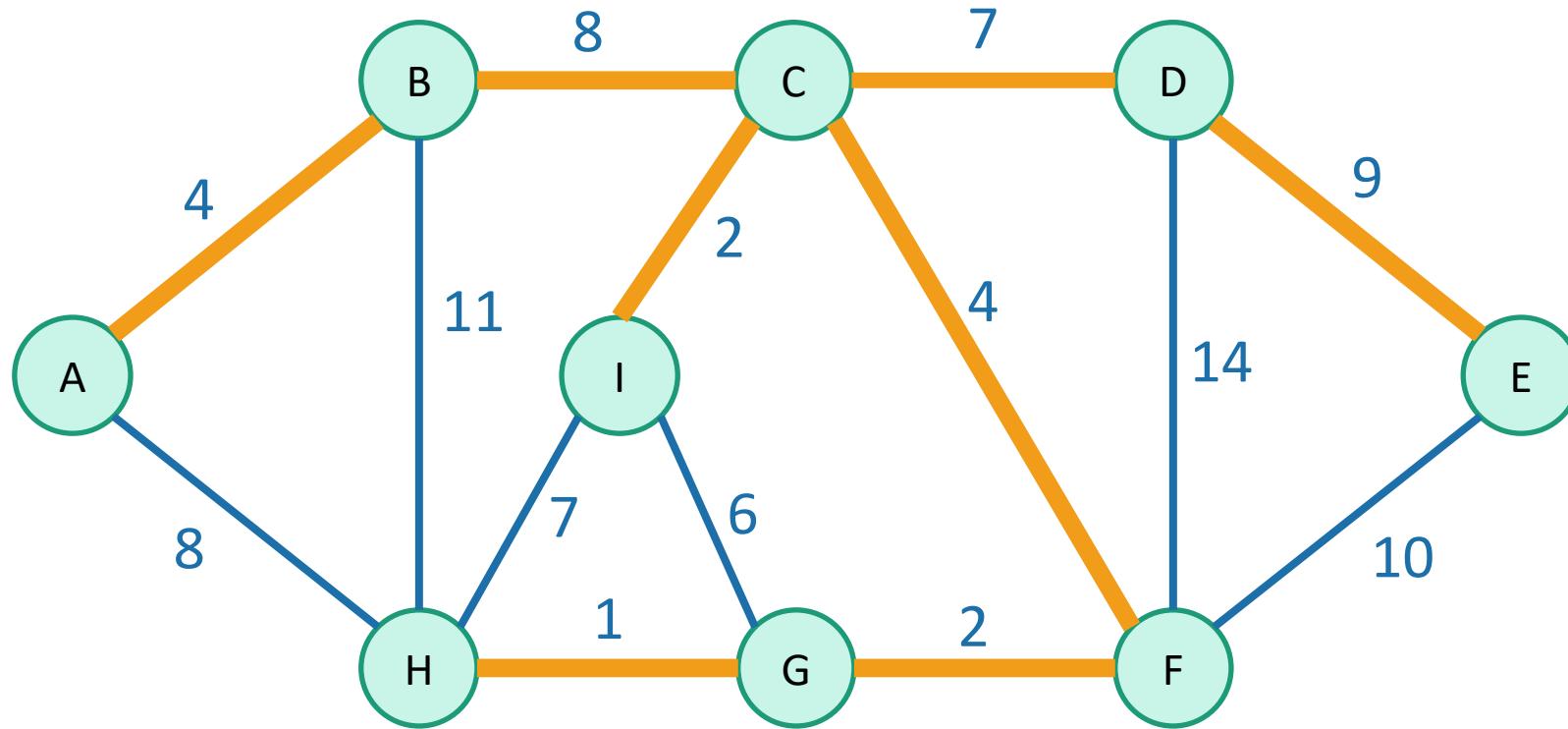


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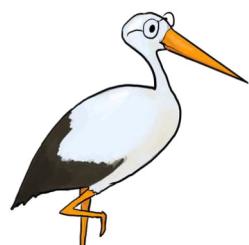
whether or not it's connected to what we have so far?

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# We've discovered Kruskal's algorithm!

- **slowKruskal( $G = (V, E)$ ):**
  - Sort the edges in  $E$  by non-decreasing weight.
  - $MST = \{\}$
  - **for**  $e$  in  $E$  (in sorted order):
    - **if** adding  $e$  to  $MST$  won't cause a cycle:
      - add  $e$  to  $MST$ .
  - **return**  $MST$



How would you figure out if added  $e$  would make a cycle in this algorithm?

m iterations through this loop

How do we check this?

Naively, the running time is ???:

- For each of  $m$  iterations of the for loop:
  - Check if adding  $e$  would cause a cycle...

# Two questions

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  - That is, does it actually return a MST?

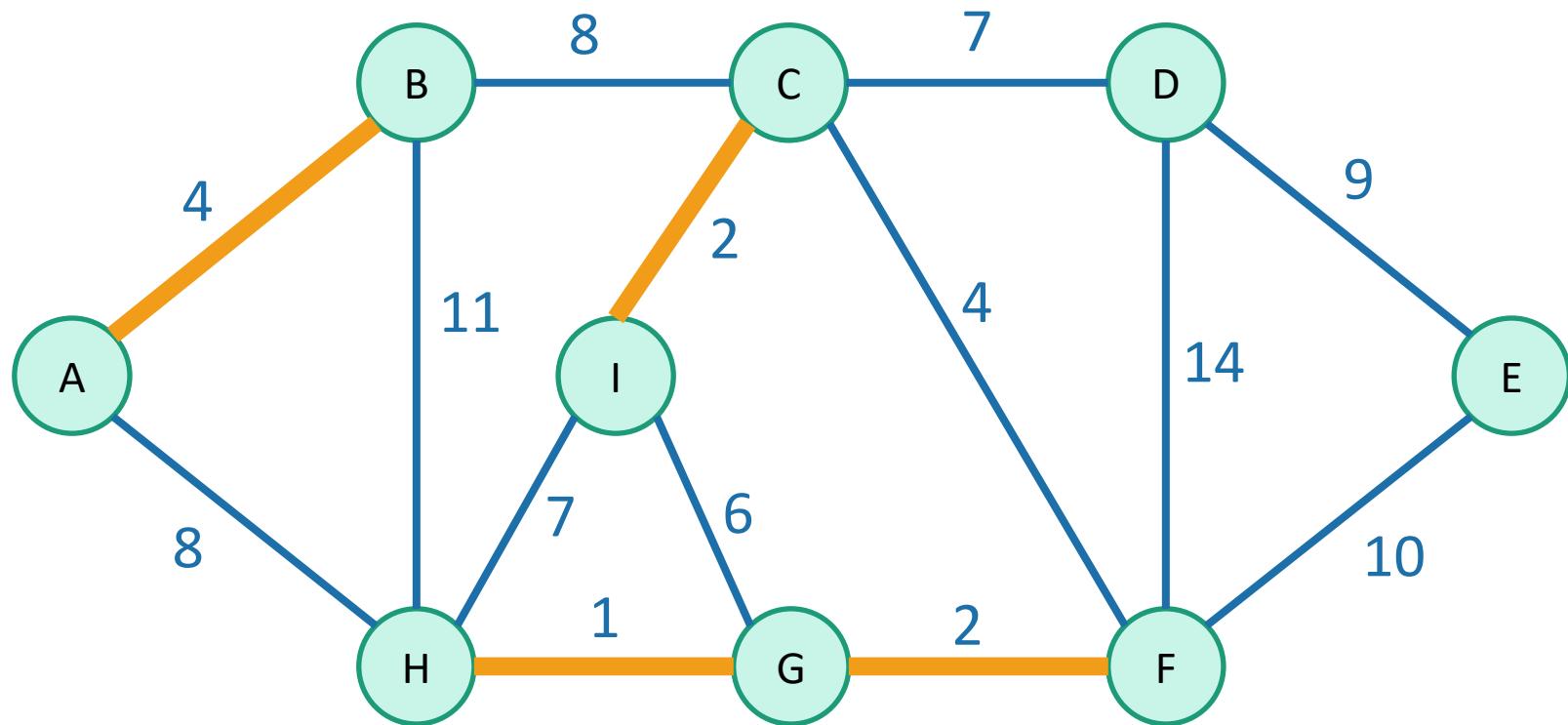
2. How do we actually implement this?
  - the pseudocode above says “slowKruskal”...



Let's do this  
one first

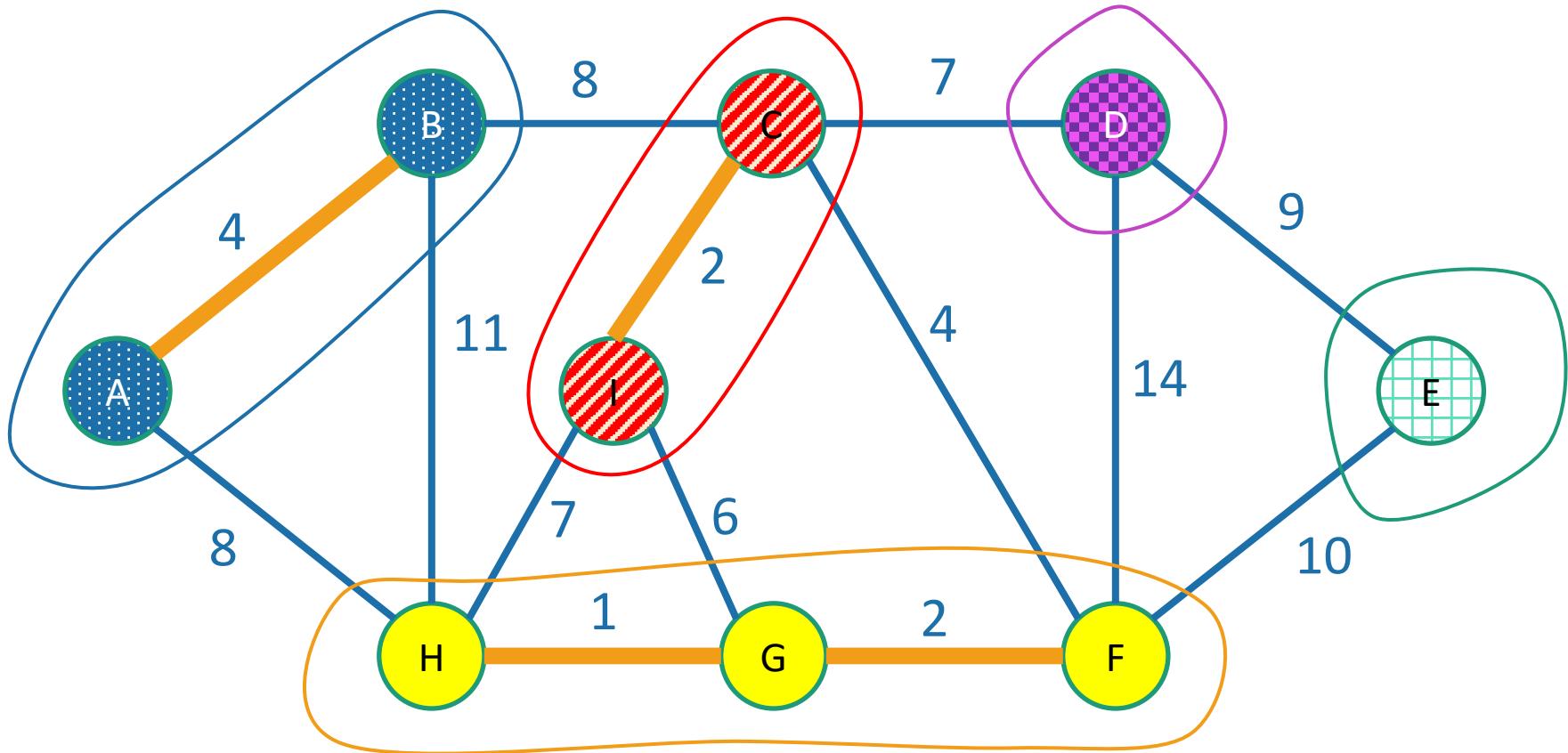
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we are maintaining a forest.

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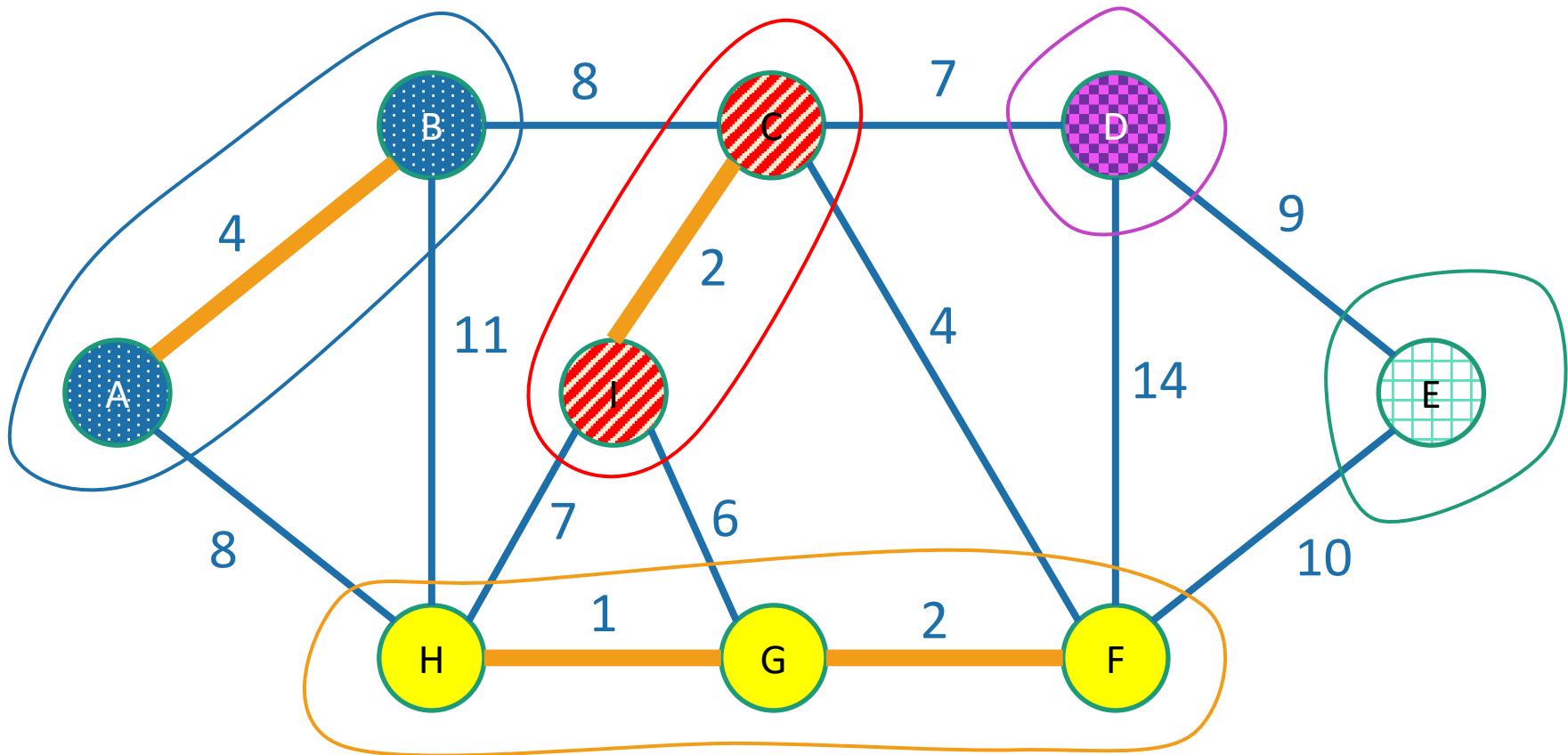


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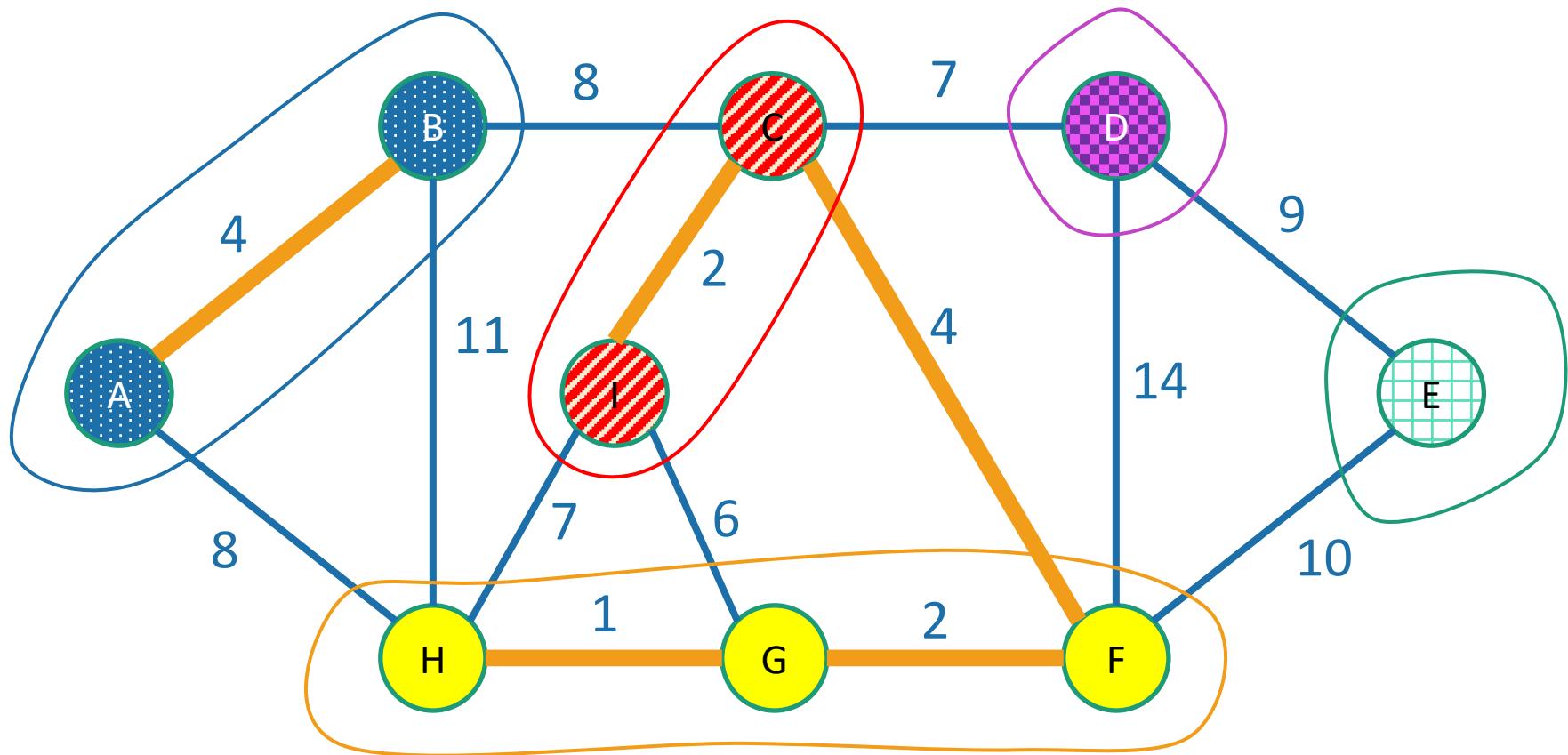


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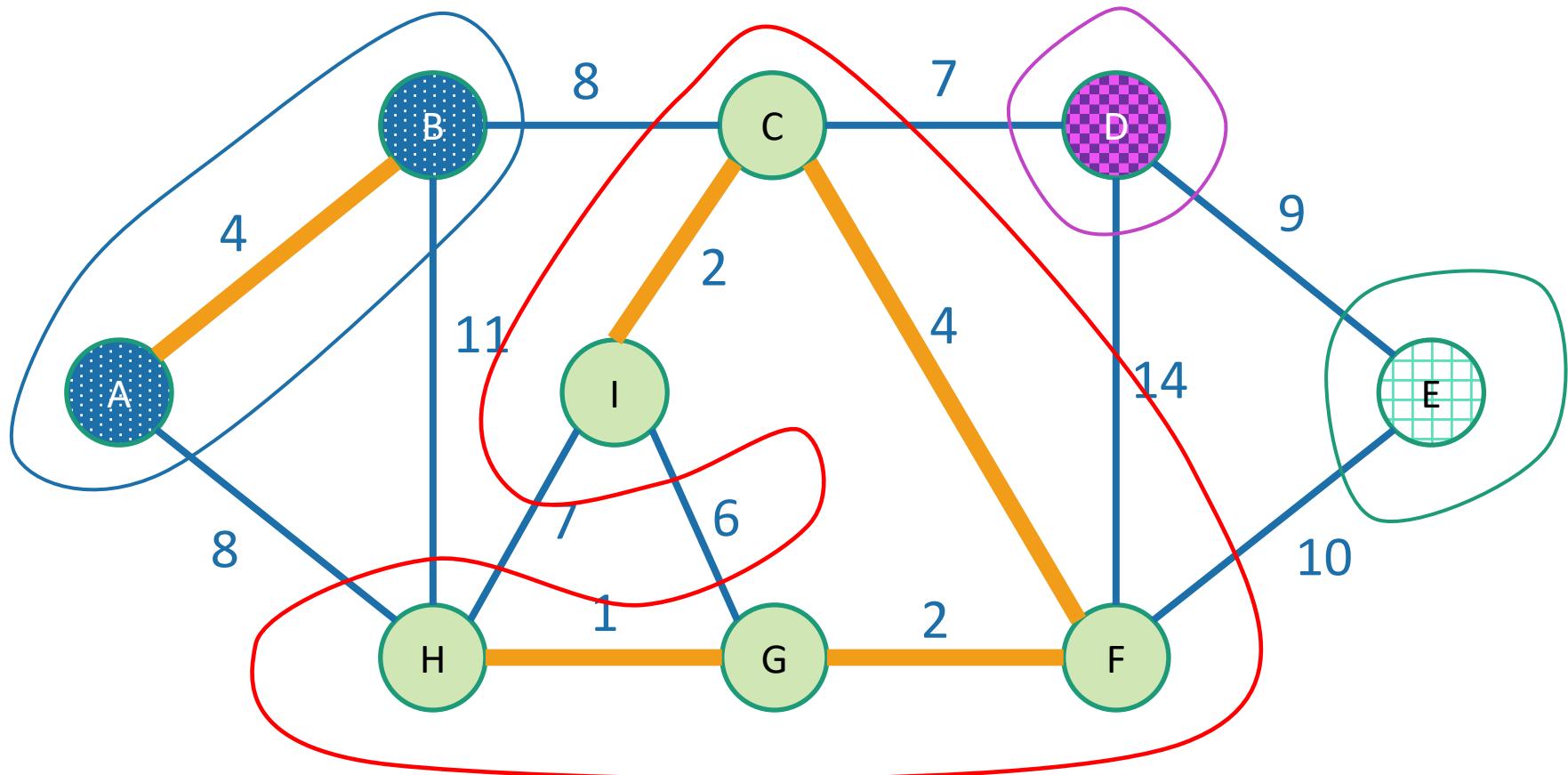


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When we add an edge, we merge two trees:



We never add an edge within a tree since that would create a cycle.<sup>94</sup>

# Keep the trees in a special data structure

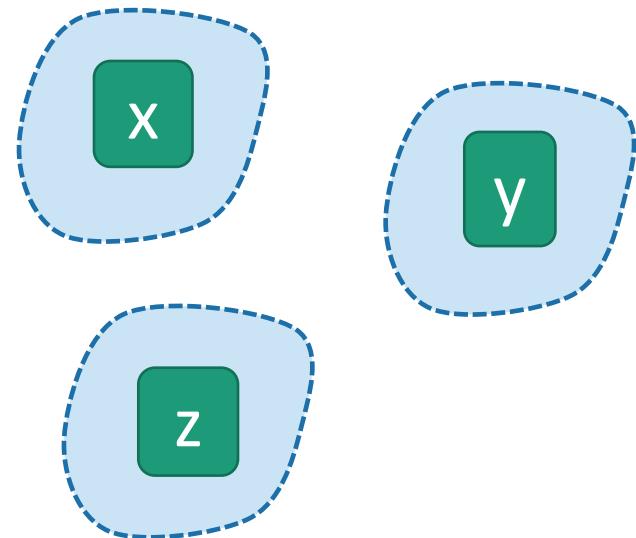


# Union-find data structure also called disjoint-set data structure

- Used for storing collections of sets
- Supports:
  - **makeSet(u)**: create a set  $\{u\}$
  - **find(u)**: return the set that  $u$  is in
  - **union(u,v)**: merge the set that  $u$  is in with the set that  $v$  is in.

```
makeSet(x)  
makeSet(y)  
makeSet(z)
```

```
union(x,y)
```

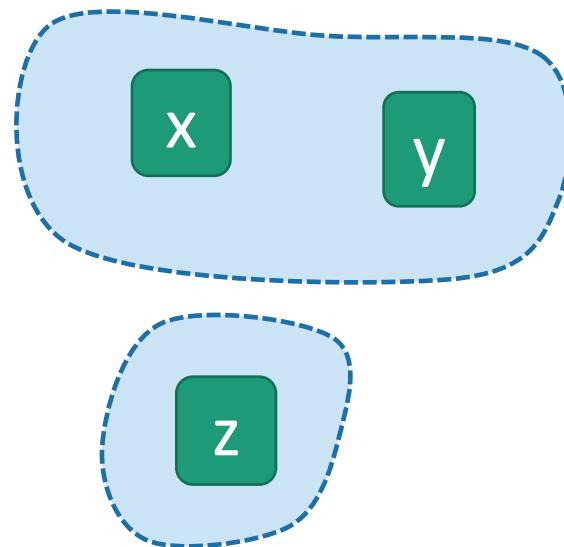


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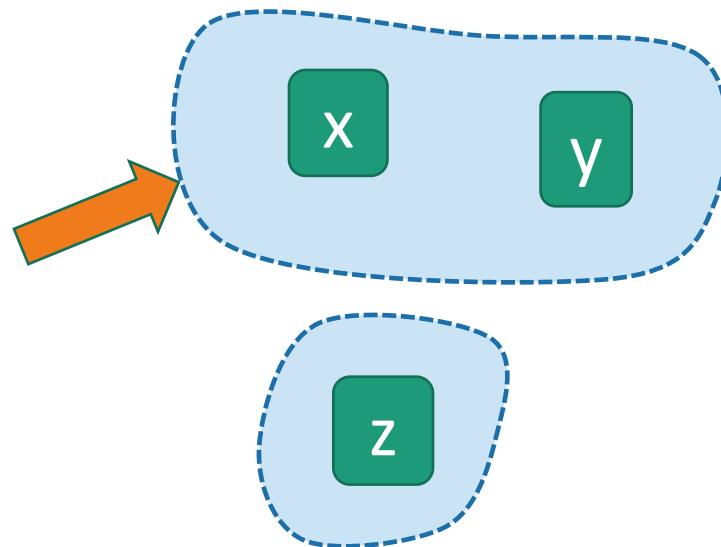
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makeSet(z)
```

```
union(x,y)
```

```
find(x)
```

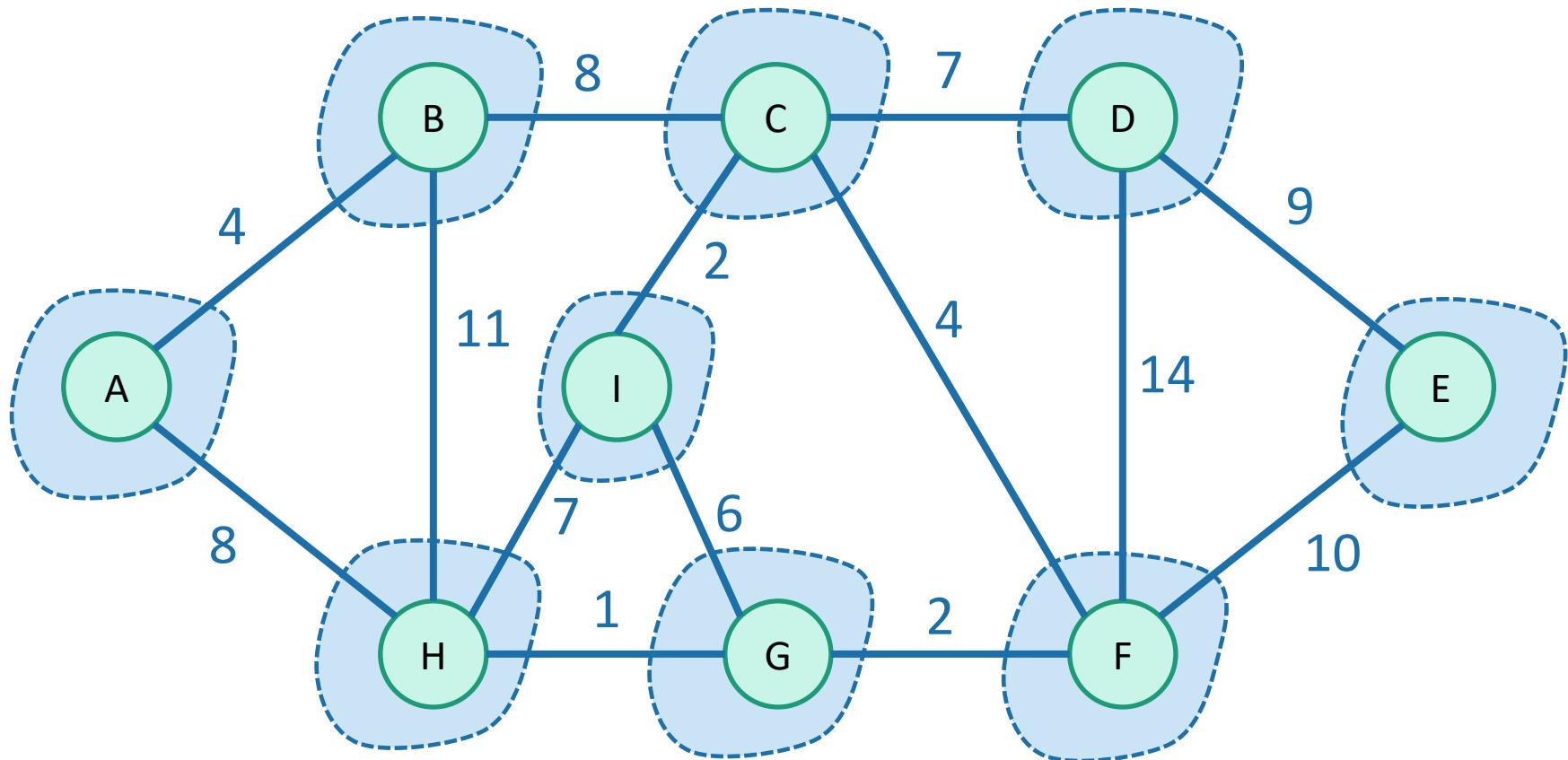


# Kruskal pseudo-code

- **kruskal(G = (V,E)):**
  - Sort E by weight in non-decreasing order
  - **MST = {}** // initialize an empty tree
  - **for** v in V:
    - **makeSet(v)** // put each vertex in its own tree in the forest
  - **for** (u,v) in E: // go through the edges in sorted order
    - **if find(u) != find(v):** // if u and v are not in the same tree
      - add (u,v) to MST
      - **union(u,v)** // merge u's tree with v's tree
  - **return** MST

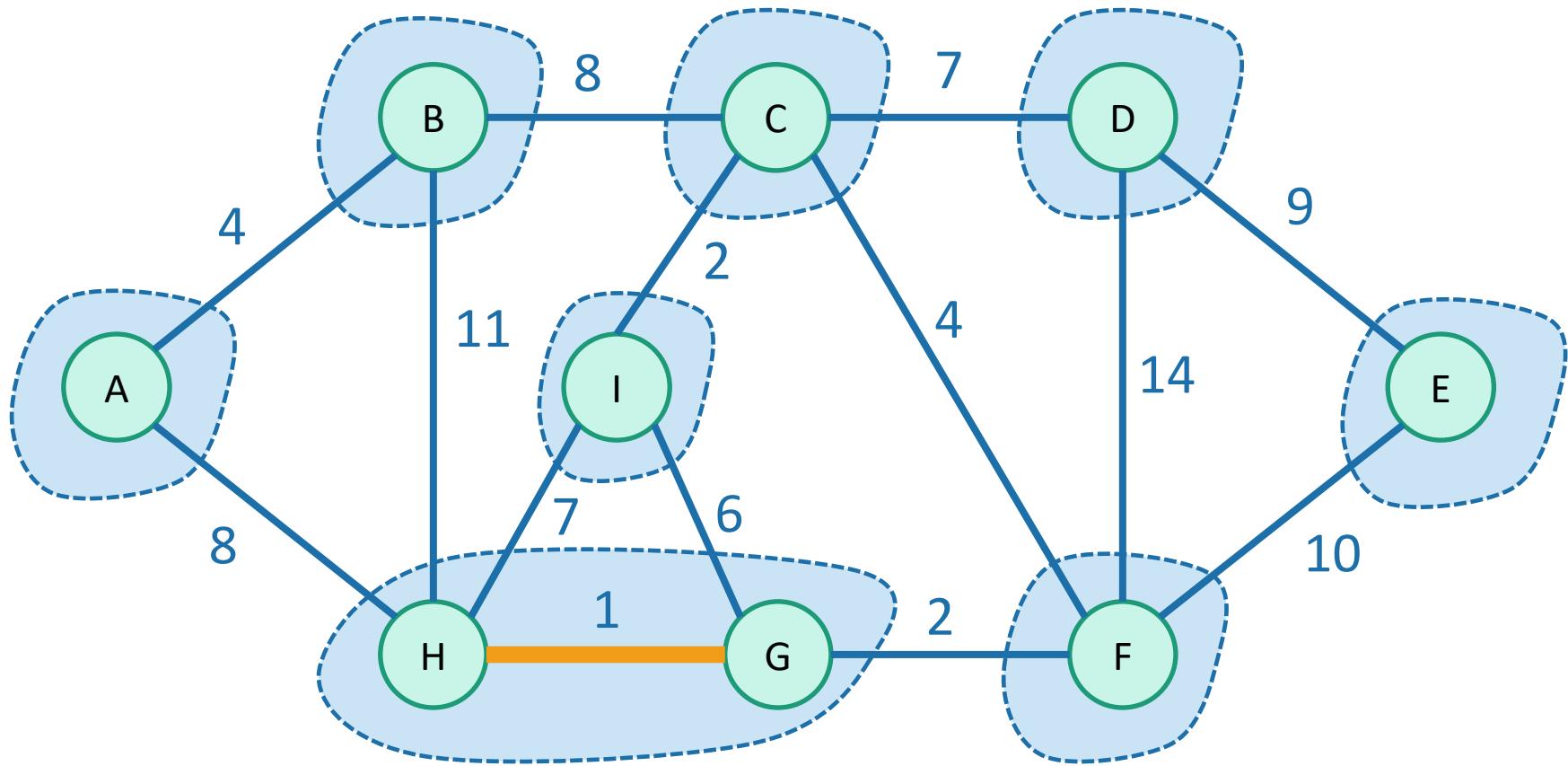
# Once more...

To start, every vertex is in its own tree.



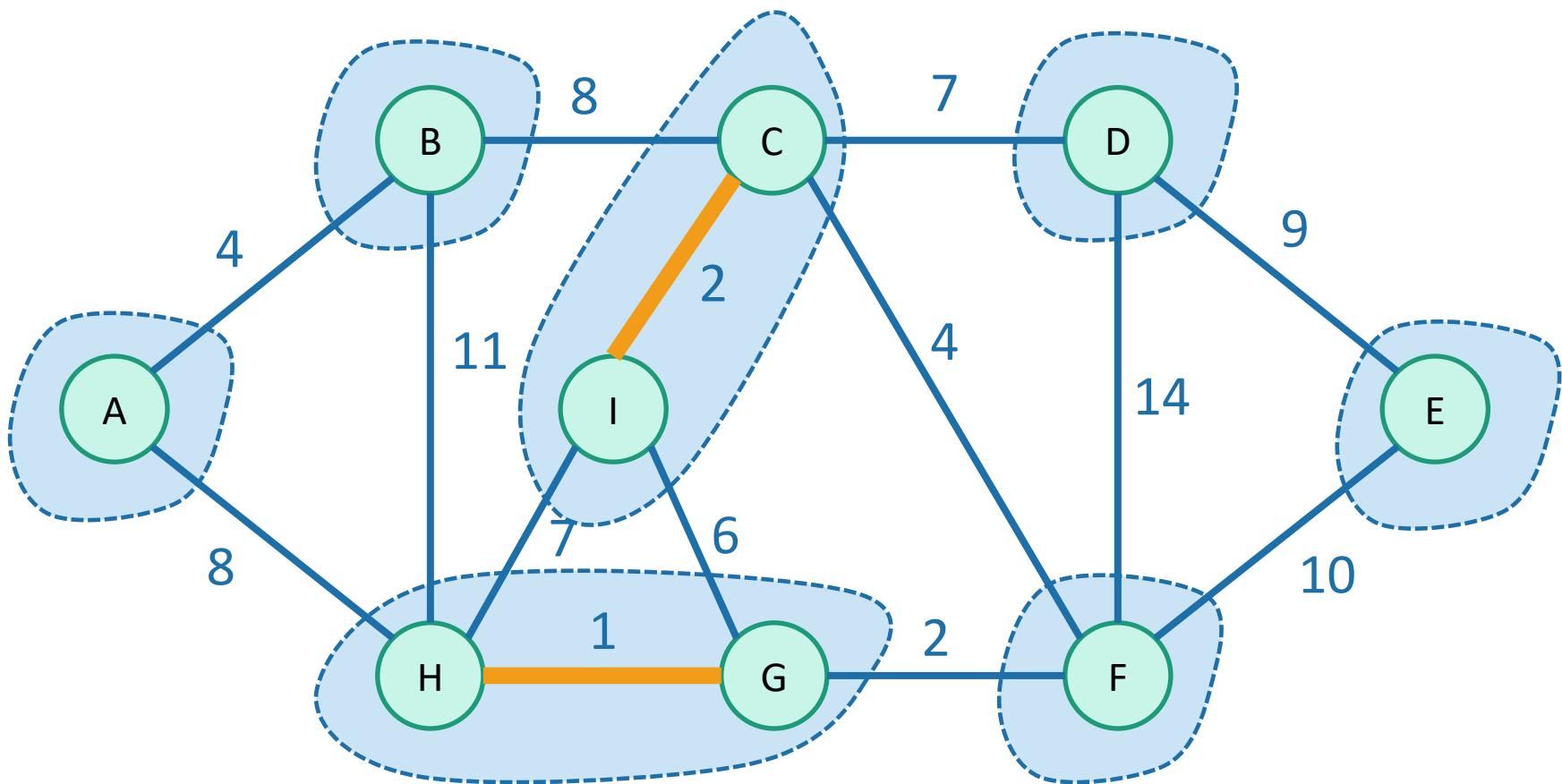
# Once more...

Then start merging.



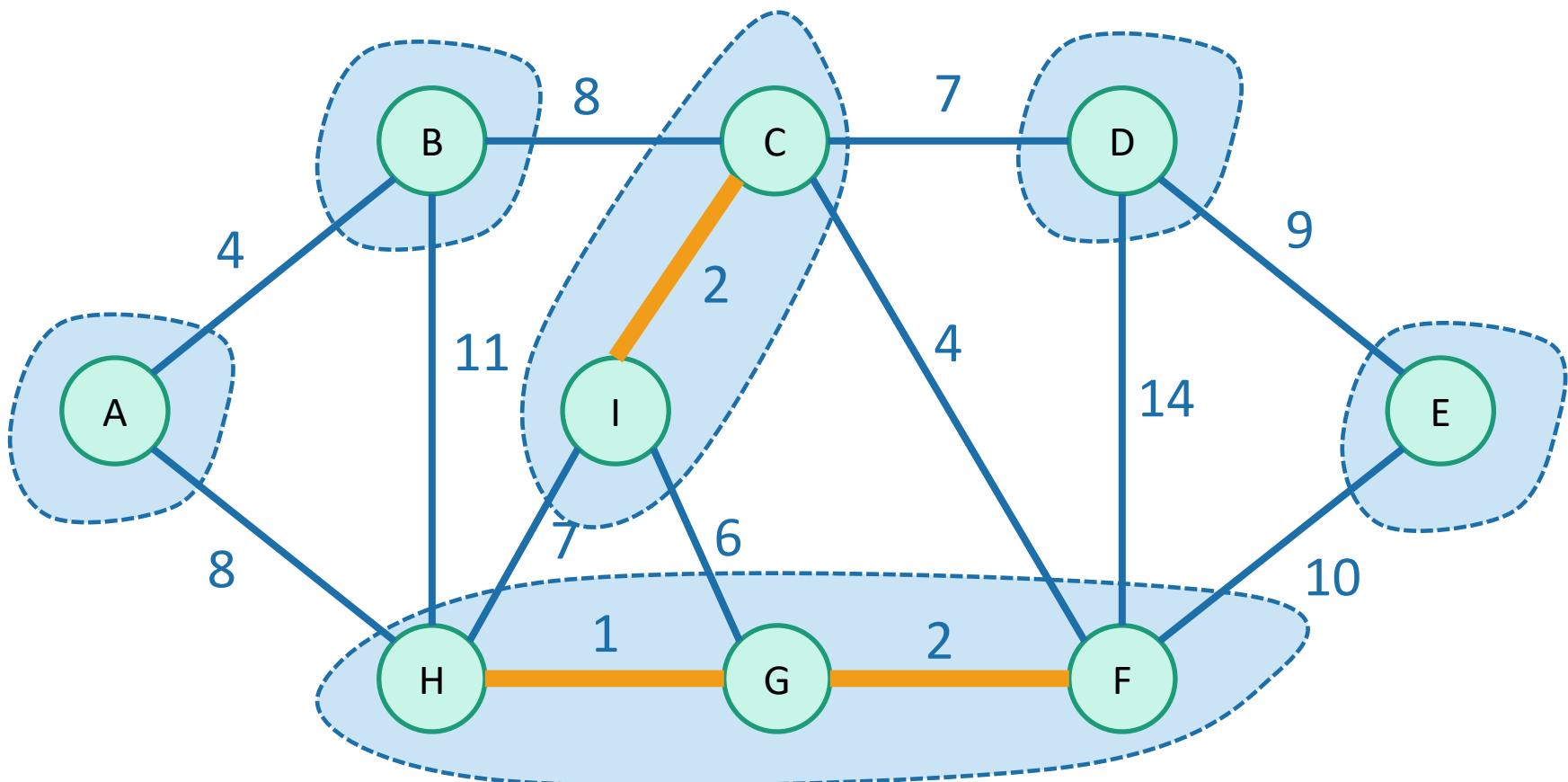
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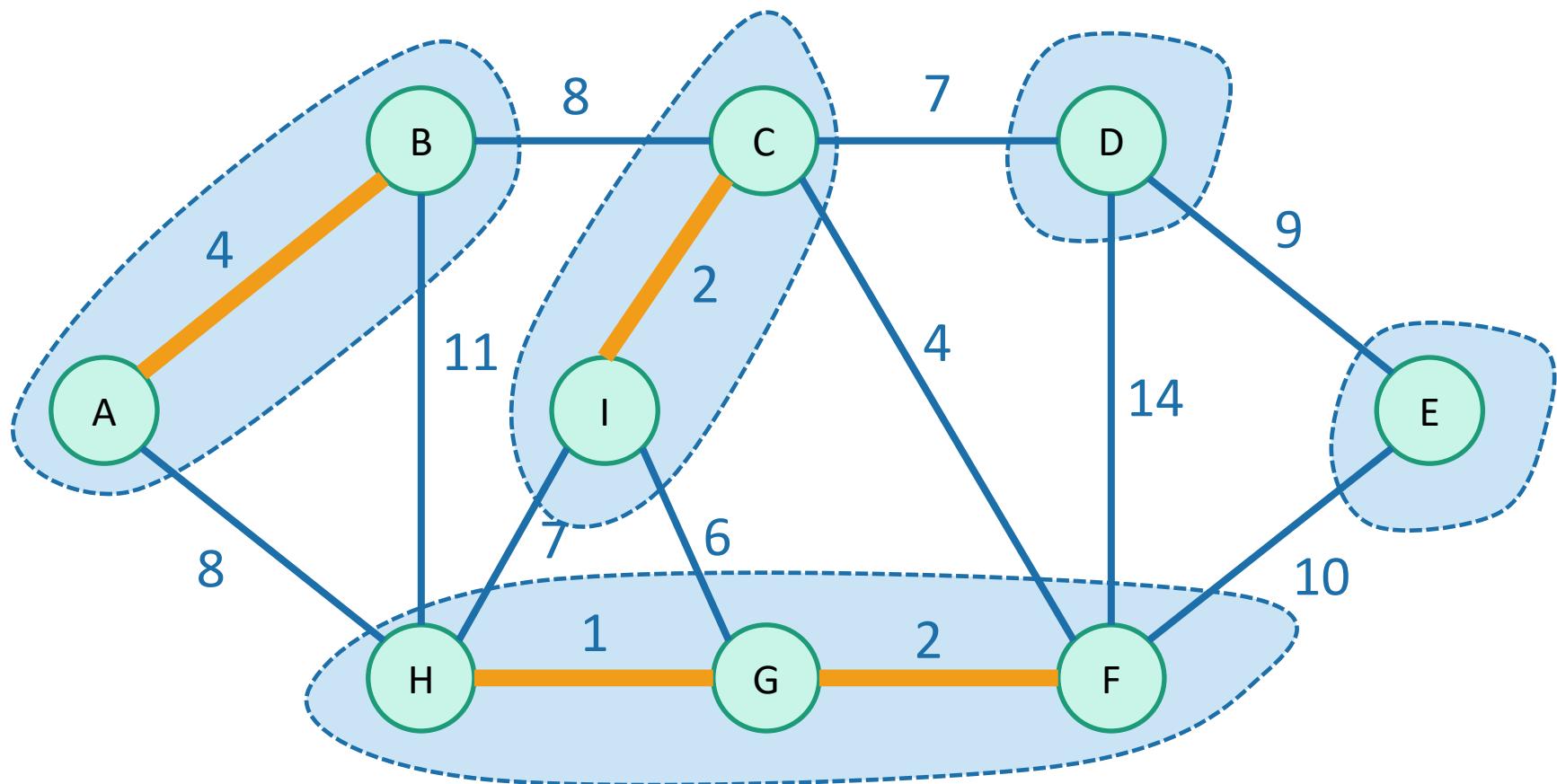
# Once more...

Then start merging.



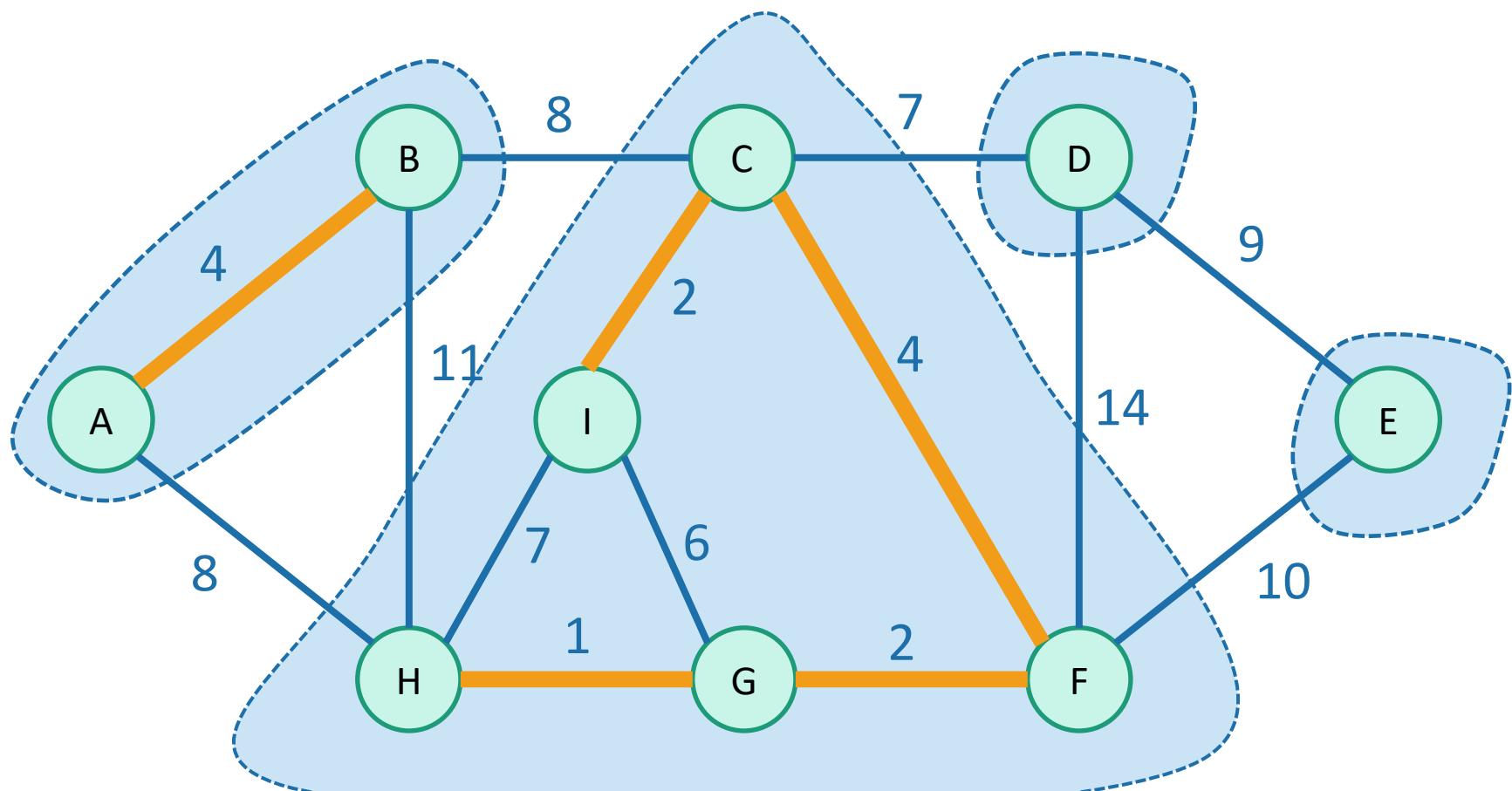
# Once more...

Then start merging.



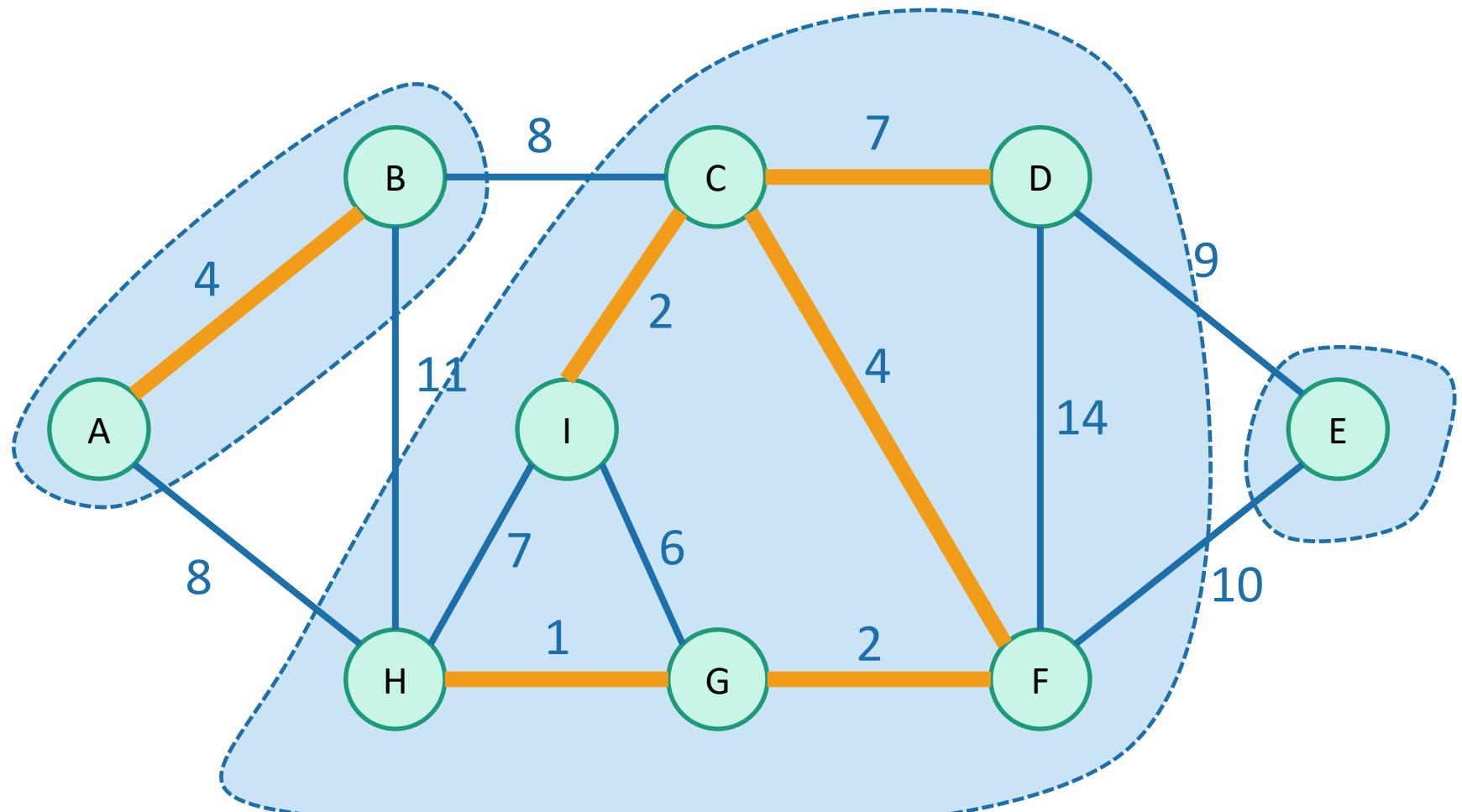
# Once more...

Then start merging.



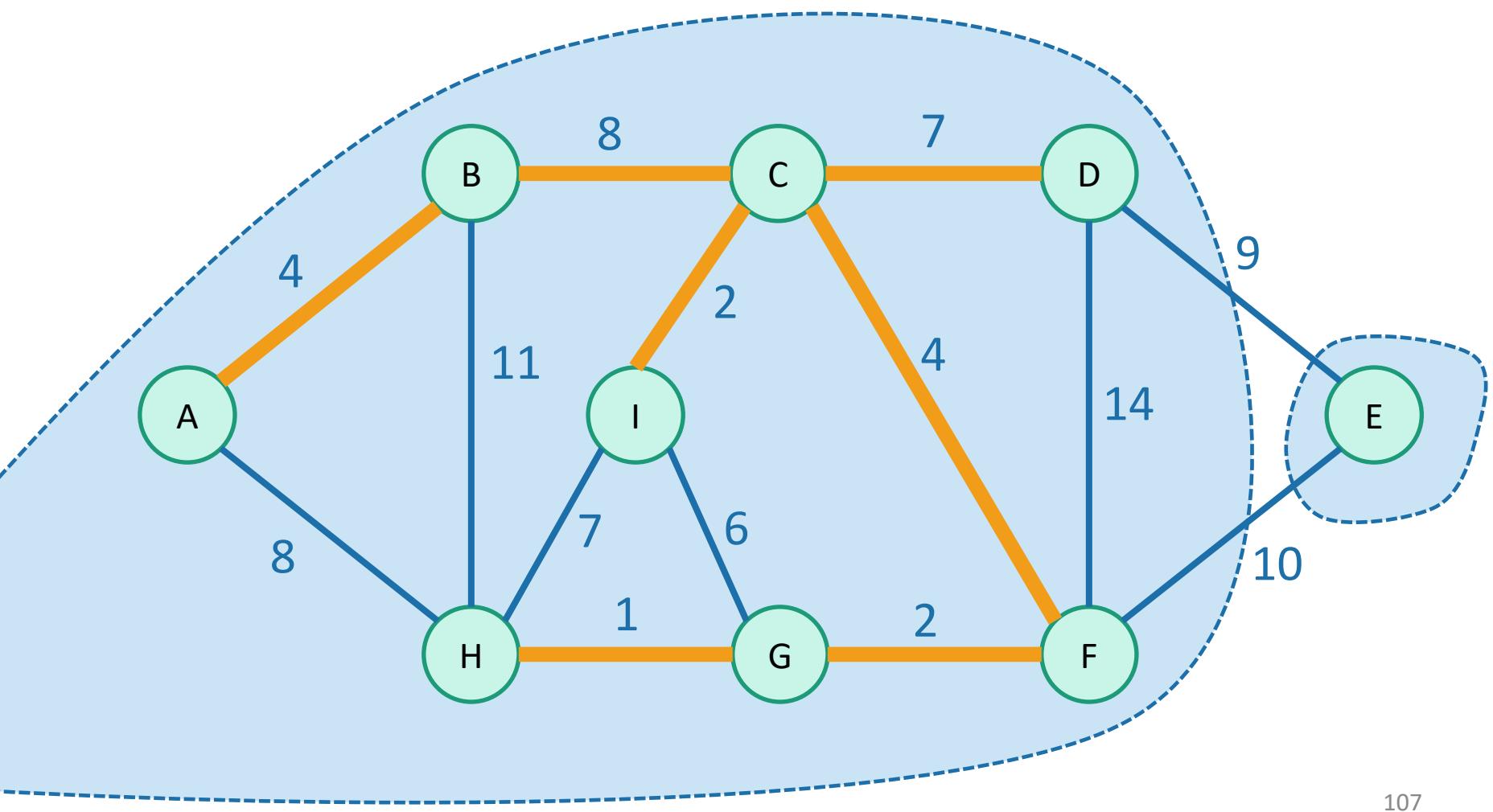
# Once more...

Then start merging.



# Once more...

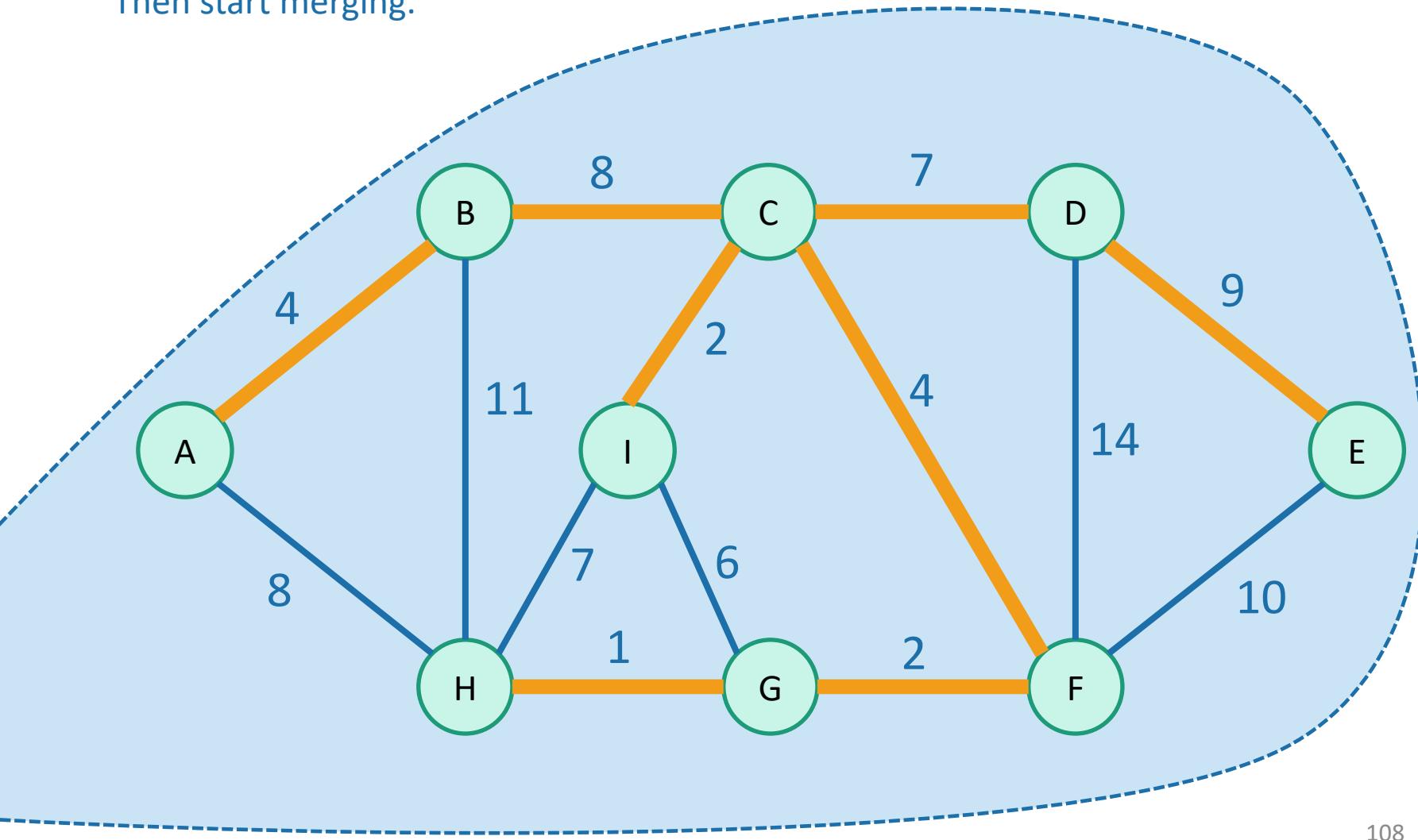
Then start merging.



Stop when we have one big tree!

# Once more...

Then start merging.



# Running time

- Sorting the edges takes  $O(m \log(n))$ 
  - In practice, if the weights are small integers we can use radixSort and take time  $O(m)$
- For the rest:
  - $n$  calls to **makeSet**
    - put each vertex in its own set
  - $2m$  calls to **find**
    - for each edge, **find** its endpoints
  - $n-1$  calls to **union**
    - we will never add more than  $n-1$  edges to the tree,
    - so we will never call **union** more than  $n-1$  times.
- Total running time:
  - Worst-case  $O(m\log(n))$ , just like Prim with an RBtree.
  - Closer to  $O(m)$  if you can do radixSort

In practice, each of makeSet, find, and union run in constant time\*  
(See book for a simpler way which does find and union in time  $O(\log n)$ ).

\*technically, they run in *amortized time*  $O(\alpha(n))$ , where  $\alpha(n)$  is the *inverse Ackerman function*.  $\alpha(n) \leq 4$  provided that  $n$  is smaller than the number of atoms in the universe.

# Two questions

1. Does it work?

- That is, does it actually return a MST?



Now that we understand this “tree-merging” view, let’s do this one.

2. How do we actually implement this?

- the pseudocode above says “slowKruskal”...

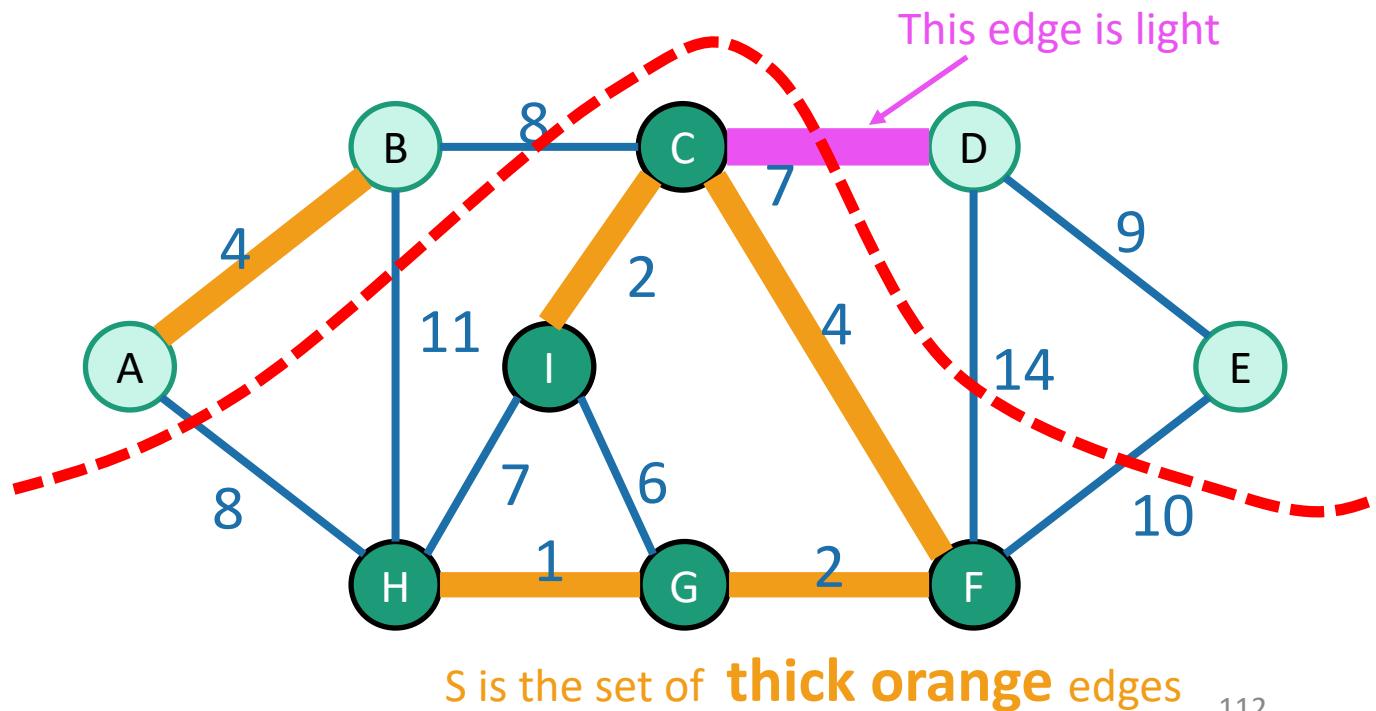
- **Worst-case running time  $O(m\log(n))$  using a union-find data structure.**

# Does it work?

- We need to show that our greedy choices **don't rule out success**.
- That is, at every step:
  - There exists an MST that contains all of the edges we have added so far.
- Now it is time to use our lemma!  
*again!*

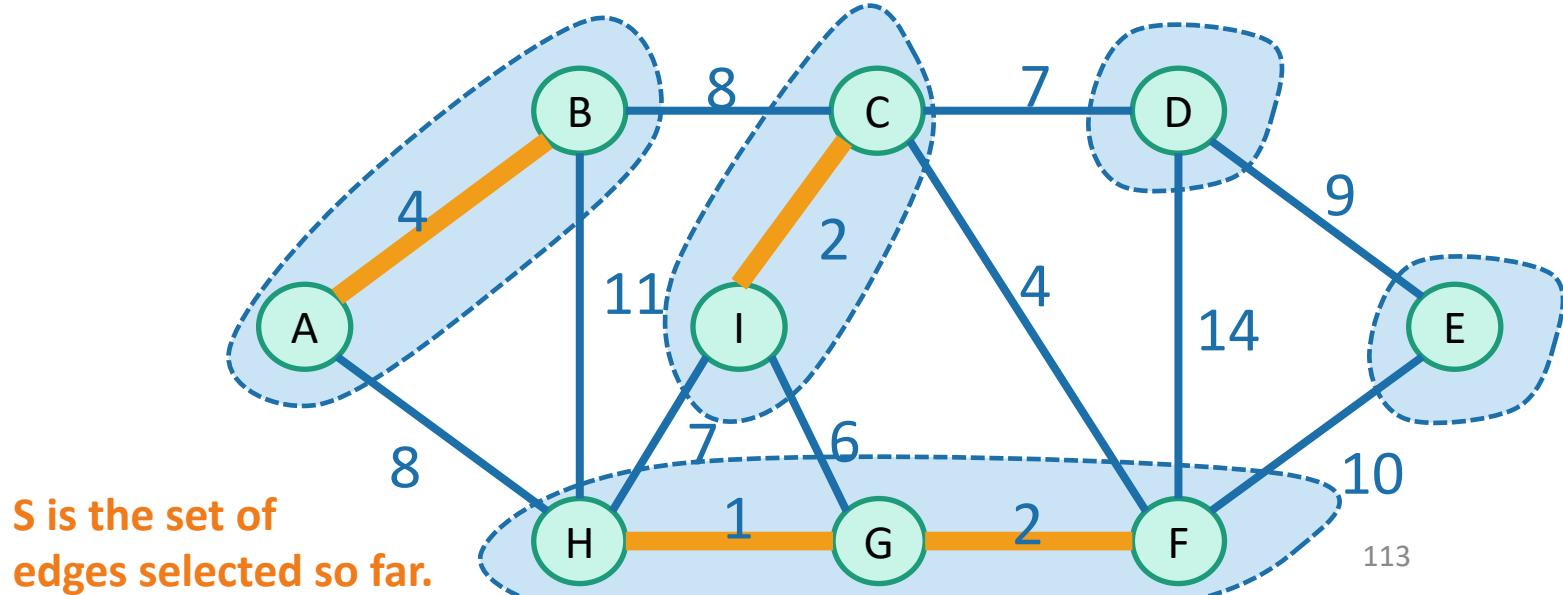
# Lemma

- Let  $S$  be a set of edges, and consider a cut that respects  $S$ .
- Suppose there is an MST containing  $S$ .
- Let  $\{u,v\}$  be a light edge.
- Then there is an MST containing  $S \cup \{\{u,v\}\}$



# Partway through Kruskal

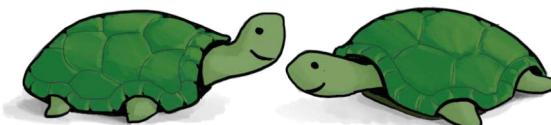
- Assume that our choices **S** so far don't rule out success.
  - There is an MST extending them
- The **next edge** we add will merge two trees, **T1, T2**



# Partway through Kruskal

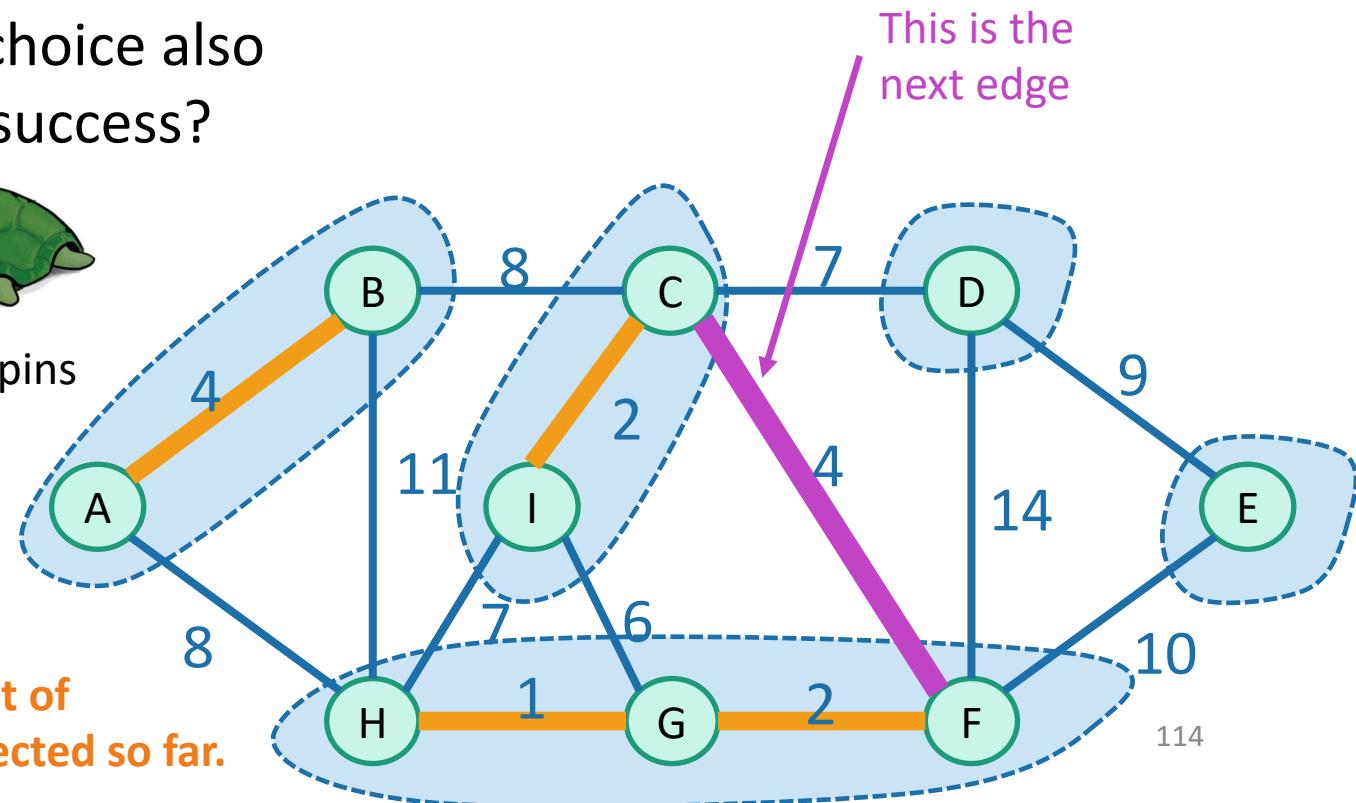
- Assume that our choices **S** so far don't rule out success.
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- The **next edge** we add will merge two trees, **T1, T2**

How can we use our lemma to show that our next choice also does not rule out success?



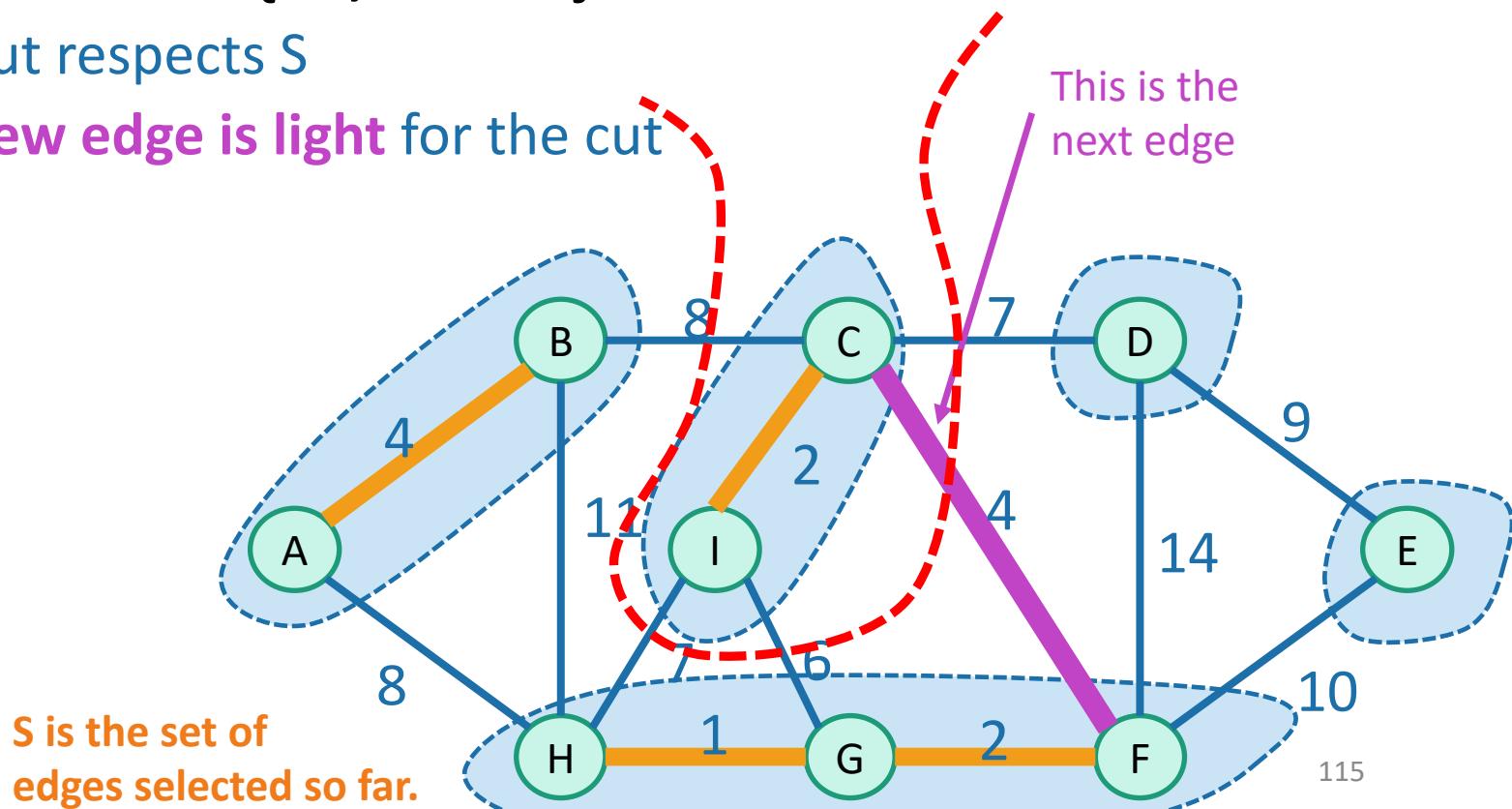
Think-Pair-Share Terrapins  
1 minute think  
1 minute pair+share

**S** is the set of edges selected so far.



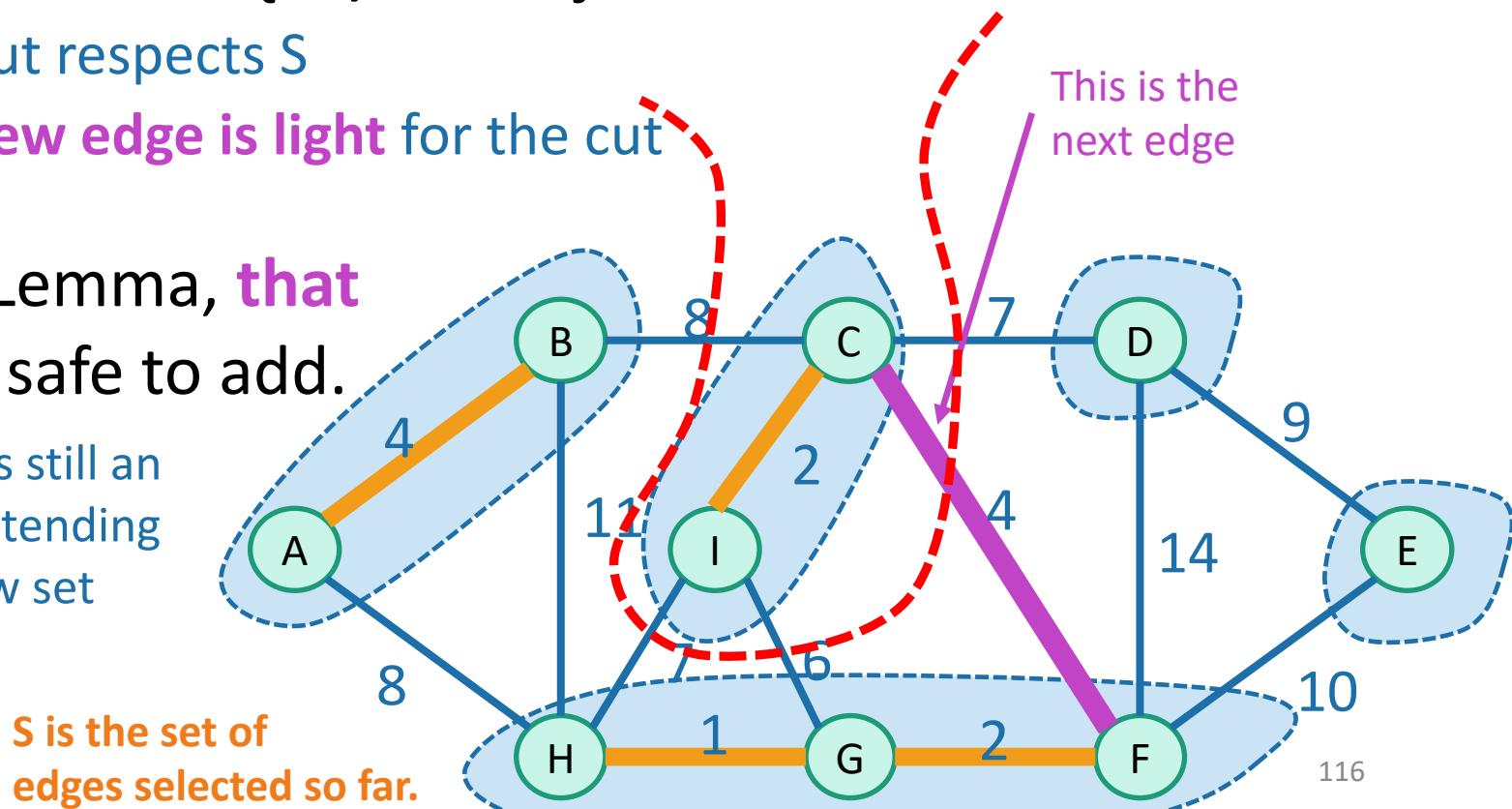
# Partway through Kruskal

- Assume that our choices  $S$  so far don't rule out success.
  - There is an MST extending them
- The **next edge** we add will merge two trees,  $T_1, T_2$
- Consider the cut  $\{T_1, V - T_1\}$ .
  - This cut respects  $S$
  - Our **new edge is light** for the cut



# Partway through Kruskal

- Assume that our choices  $S$  so far don't rule out success.
  - There is an MST extending them
- The **next edge** we add will merge two trees,  $T_1, T_2$
- Consider the cut  $\{T_1, V - T_1\}$ .
  - This cut respects  $S$
  - Our **new edge is light** for the cut
- By the Lemma, **that edge** is safe to add.
  - There is still an MST extending the new set



# Hooray!

- Our greedy choices **don't rule out success**.
- This is enough (along with an argument by induction) to guarantee correctness of Kruskal's algorithm.

# Two questions

1. Does it work?
  - That is, does it actually return a MST?
    - Yes
2. How do we actually implement this?
  - the pseudocode above says “slowKruskal”...
    - Using a union-find data structure!

# What have we learned?

- Kruskal's algorithm greedily grows a forest
- It finds a Minimum Spanning Tree in time  $O(m\log(n))$ 
  - if we implement it with a Union-Find data structure
  - if the edge weights are reasonably-sized integers and we ignore the inverse Ackerman function, basically  $O(m)$  in practice.
- To prove it worked, we followed the same recipe for greedy algorithms we saw last time.
  - Show that, at every step, we **don't rule out success**.

# Compare and contrast

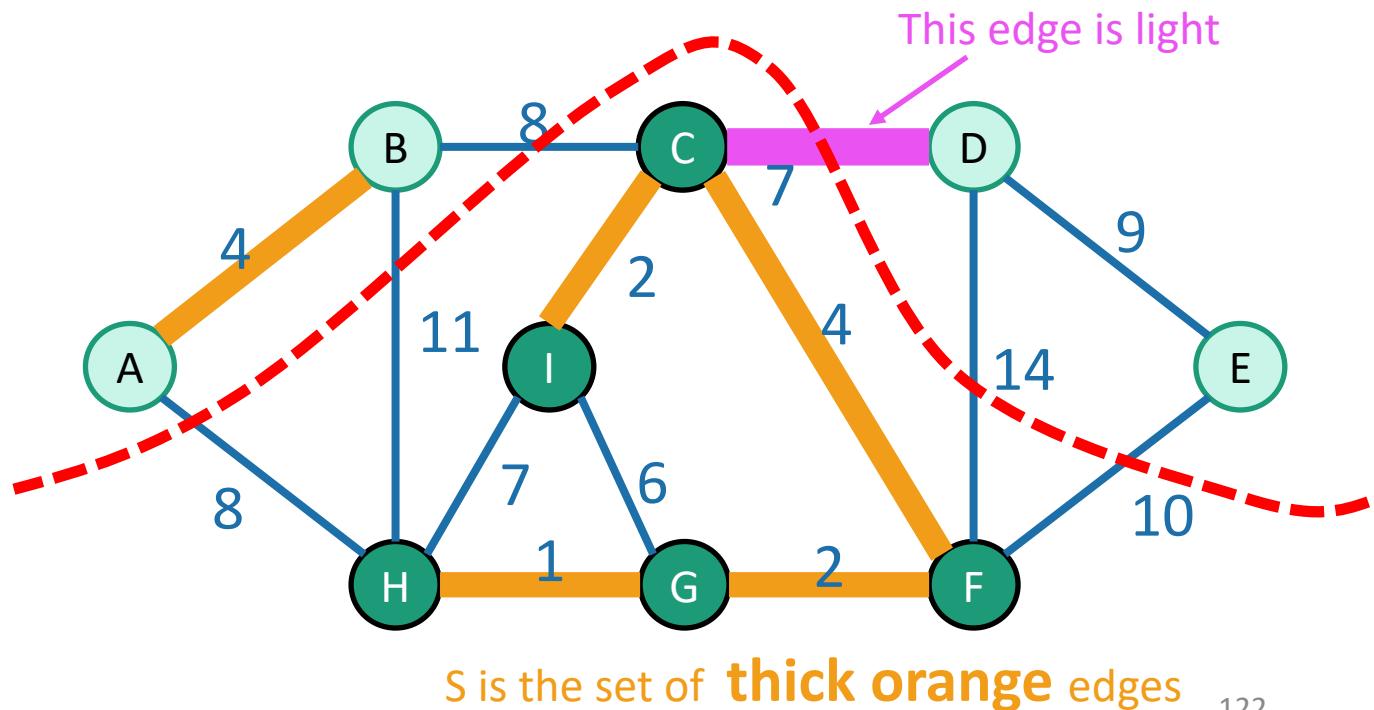
- Prim:
  - Grows a tree.
  - Time  $O(m\log(n))$  with a red-black tree
  - Time  $O(m + n\log(n))$  with a Fibonacci heap
- Kruskal:
  - Grows a forest.
  - Time  $O(m\log(n))$  with a union-find data structure
  - If you can do radixSort on the edge weights, morally  $O(m)$

Prim might be a better idea  
on dense graphs if you can't  
radixSort edge weights

Kruskal might be a better idea  
on sparse graphs if you can  
radixSort edge weights

# Both Prim and Kruskal

- Greedy algorithms for MST.
- Similar reasoning:
  - Optimal substructure: subgraphs generated by cuts.
  - The way to make safe choices is to choose light edges crossing the cut.



# Can we do better?

State-of-the-art MST on connected undirected graphs

- Karger-Klein-Tarjan 1995:
  - $O(m)$  time randomized algorithm
- Chazelle 2000:
  - $O(m \cdot \alpha(n))$  time deterministic algorithm
- Pettie-Ramachandran 2002:
  - $O\left(\text{The optimal number of comparisons you need to solve the problem, whatever that is...}\right)$  time deterministic algorithm

What is this number?

Do we need that silly  $\alpha(n)$ ?

Open questions!

# Recap

- Two algorithms for Minimum Spanning Tree
  - Prim's algorithm
  - Kruskal's algorithm
- Both are (more) examples of **greedy algorithms!**
  - Make a **series of choices.**
  - Show that at each step, your choice **does not rule out success.**
  - At the end of the day, you haven't ruled out success, so **you must be successful.**

# Next time

- Back to randomized algorithms
- Minimum cuts!

## Before next time

- Pre-lecture exercise: a probability thought experiment.