

# Minimal Spanning Trees

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- MST problem
- Generic algorithm
- Prim and Kruskal

- Given a weighted graph  $G = (V, E)$ 
  - ▶ with “weight” function  $w : E \rightarrow \mathbb{R}$

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- Find an *acyclic* subset  $T \subseteq E$ 
  - ▶ a ***tree***

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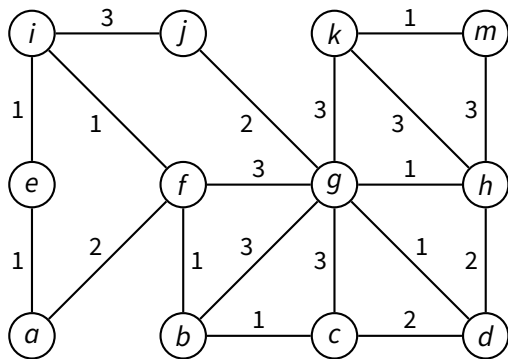
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- $T$ ’s total weight of the tree is minimal

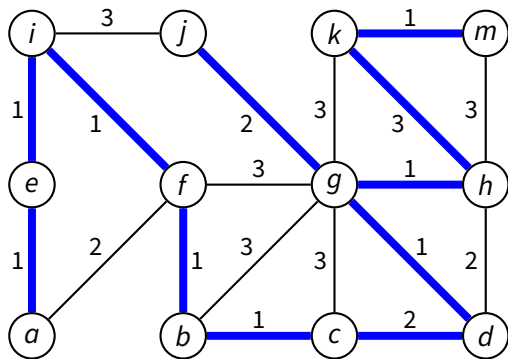
$$w(T) = \sum_{(u,v) \in T} w(u, v)$$

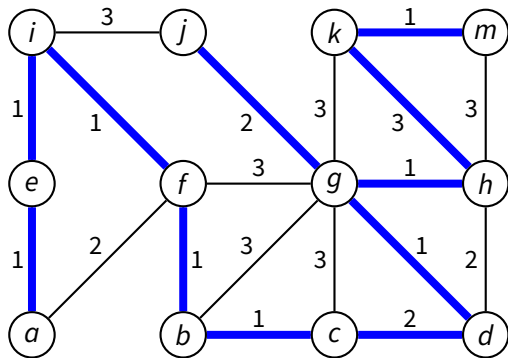
- ▶ a **minimum-weight spanning tree**, or “minimum spanning tree”

# Example

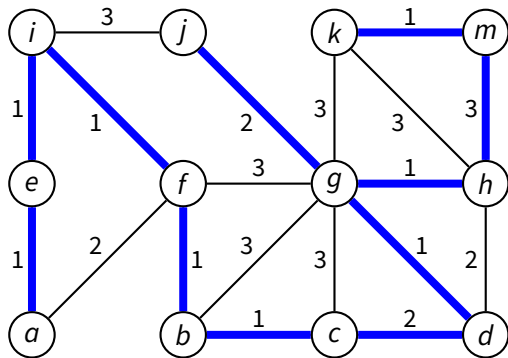


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- Does it work?

## GENERIC-MST( $G, w$ )

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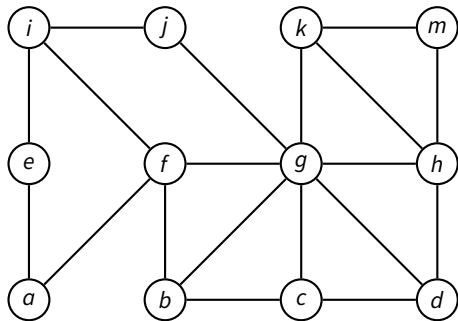
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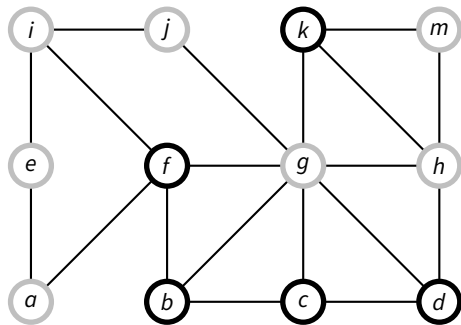
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  - ▶ more or less the *definition* of a greedy algorithm

- A **cut**  $(S, V - S)$  of an undirected graph  $G = (V, E)$  is a *partition* of  $V$

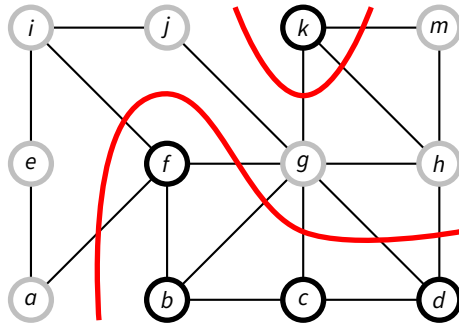
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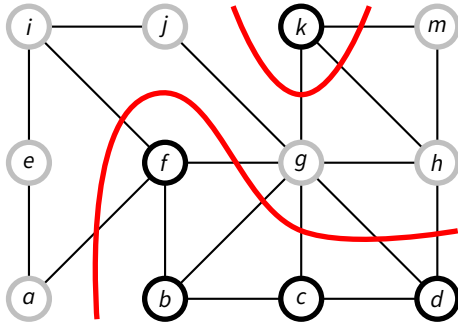
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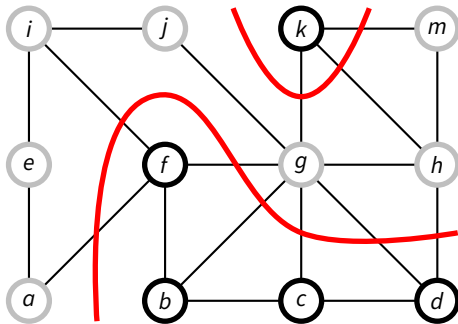
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# Preliminary Definitions

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- A cut  $(S, V - S)$  *respects* a set of edges  $A$  if no edge in  $A$  crosses the cut

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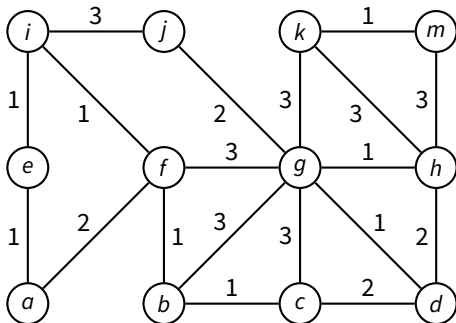
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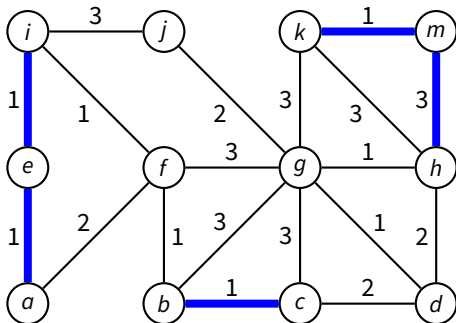
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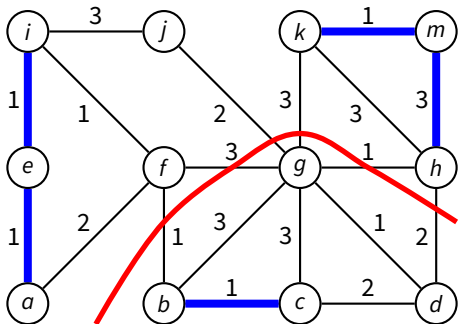


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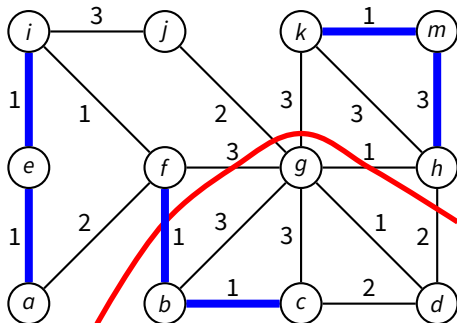
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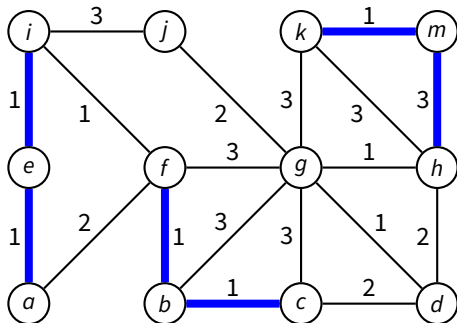
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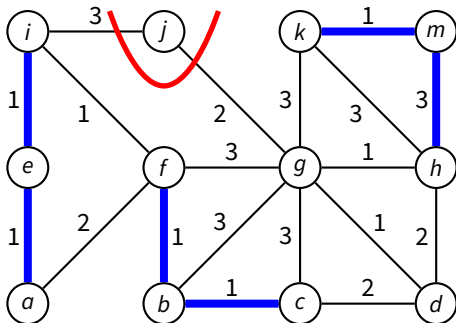
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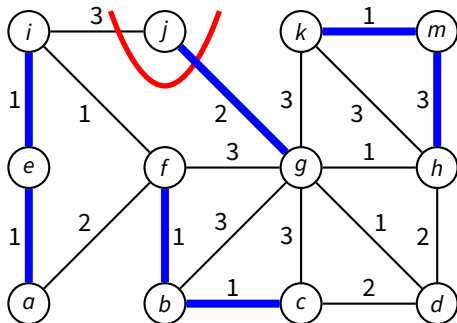
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## ■ Prim's algorithm (1957)

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- ▶ incrementally builds a **single tree**  $A$

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- *Union*( $x, y$ ) joins the sets containing  $x$  and  $y$

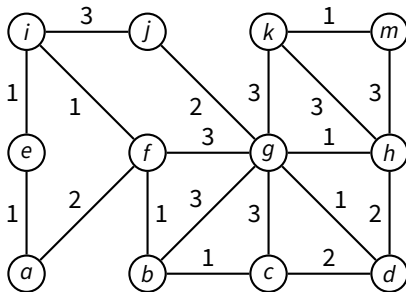
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2  for each vertex  $v \in V(G)$ 
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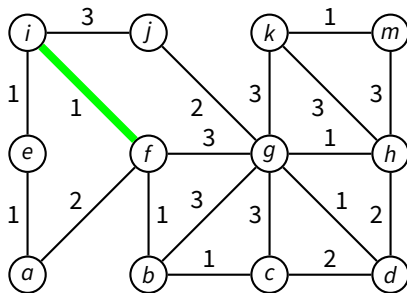
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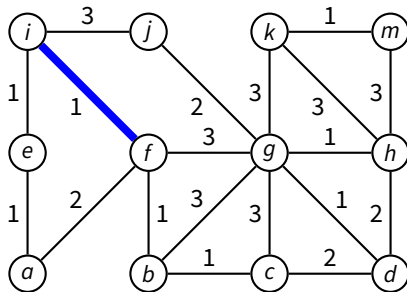
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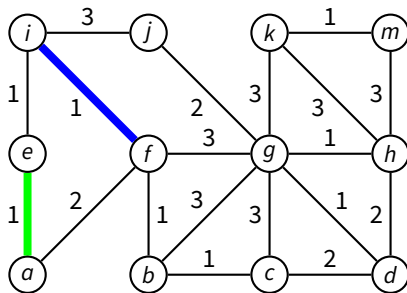
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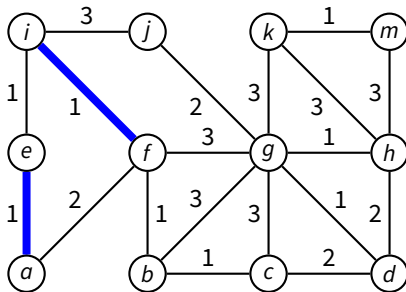
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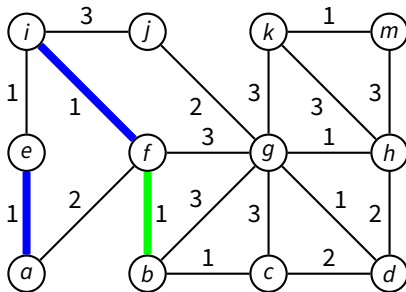
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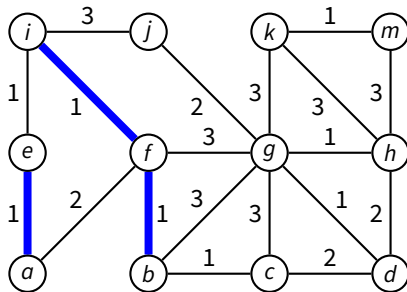
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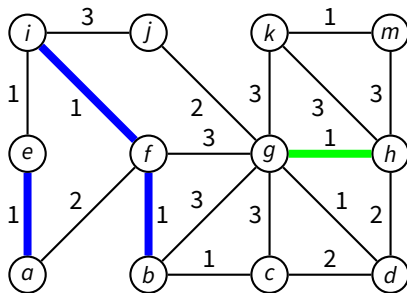
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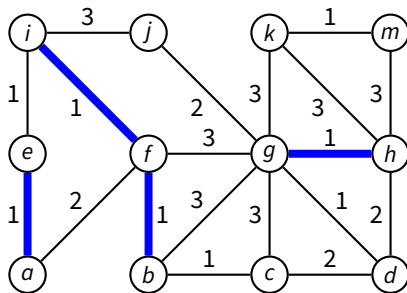
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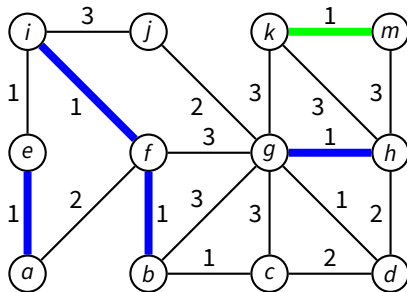
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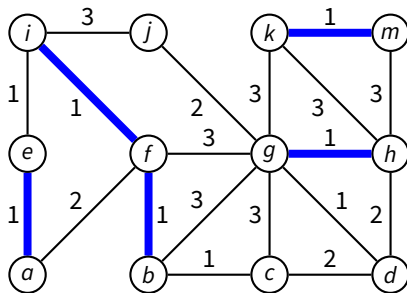
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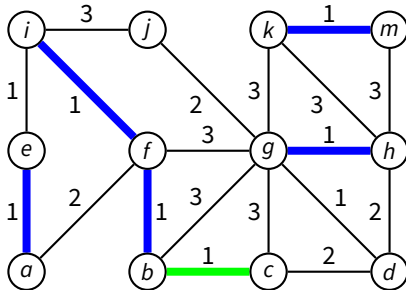
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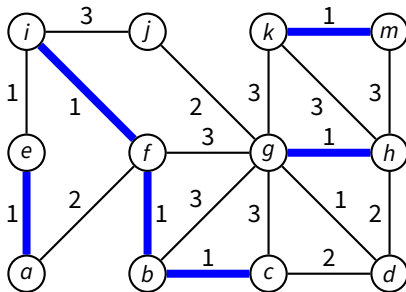
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# Kruskal's Algorithm

**MST-KRUSKAL**( $G, w$ )

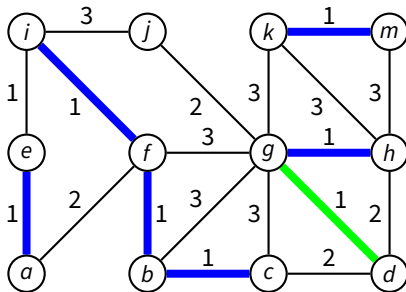
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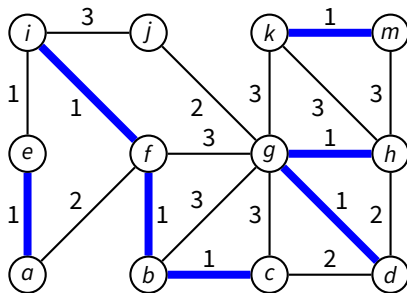
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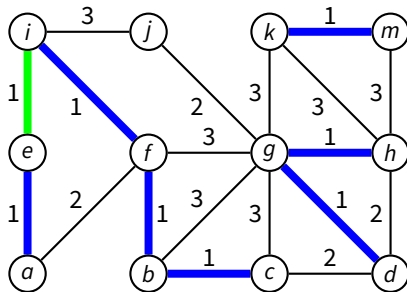
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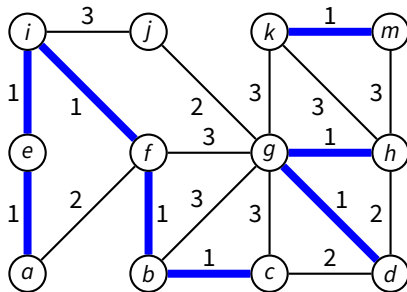
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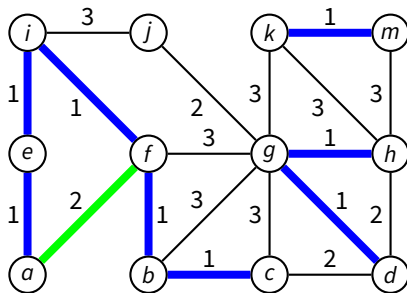
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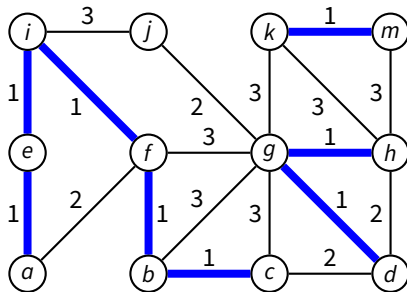
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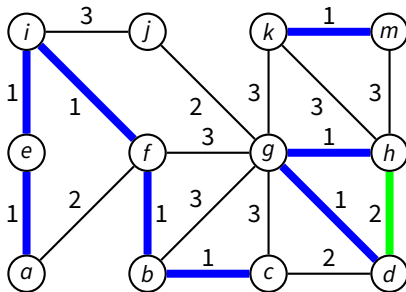
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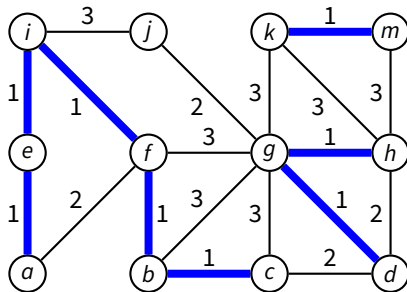
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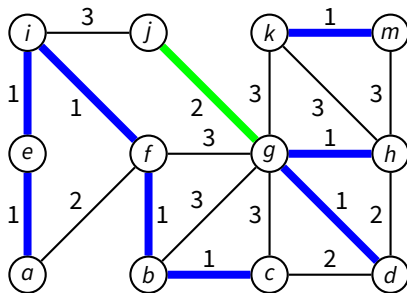
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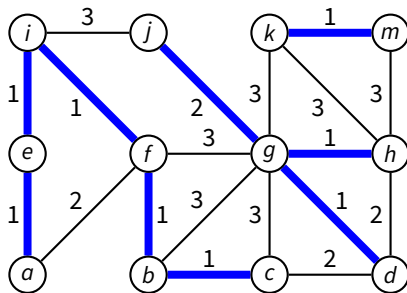
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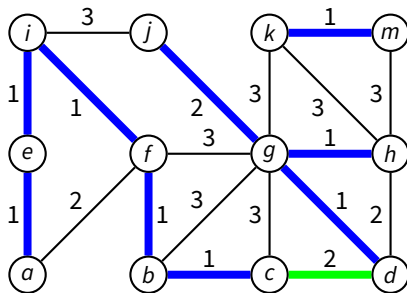
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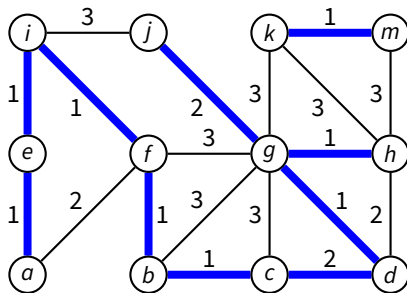
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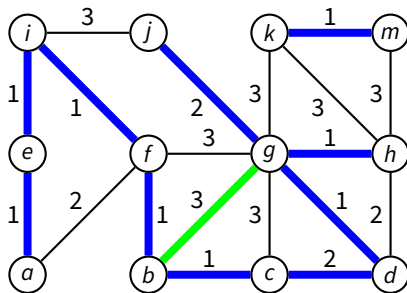
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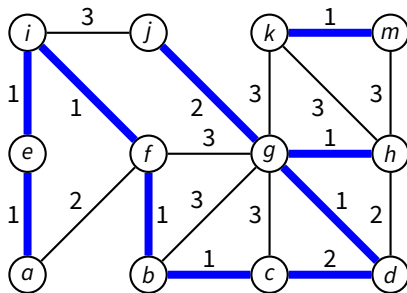
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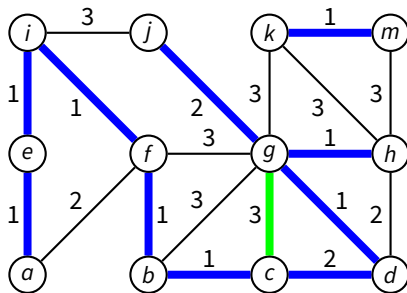
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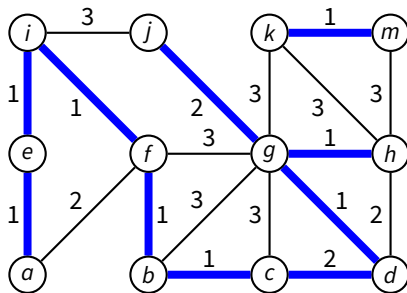
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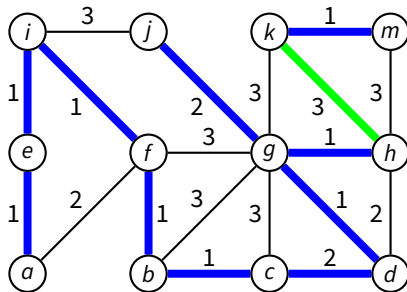
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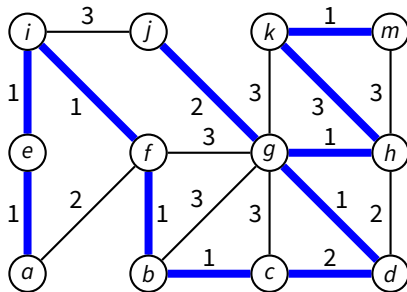
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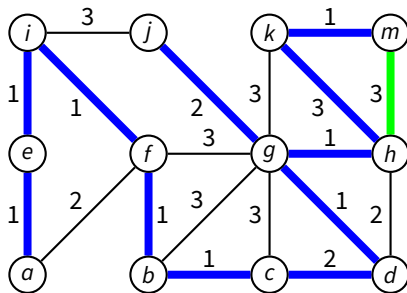
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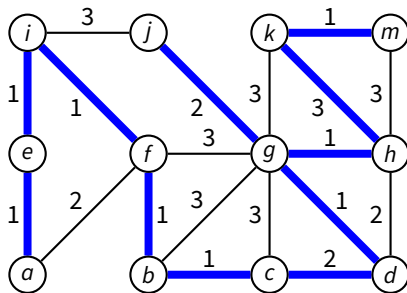
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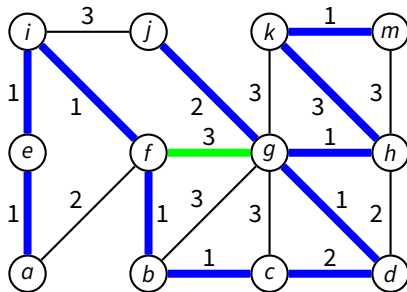
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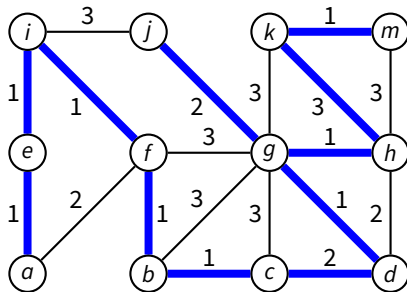
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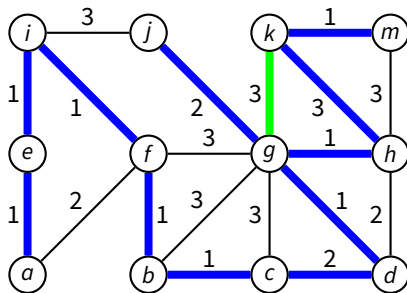
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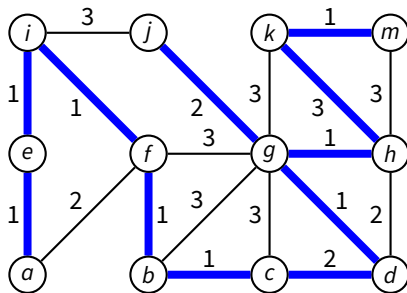
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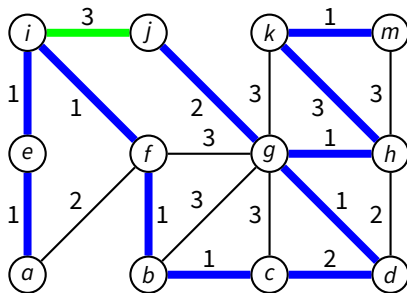
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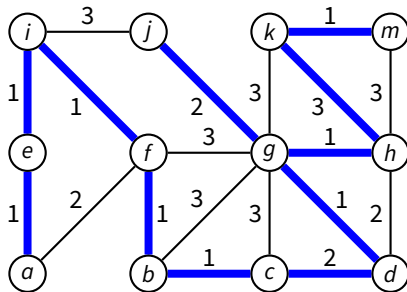
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- $O(|E| \log |E|)$  for sorting  $E$  (line 4)
- $2|E|$  times **FIND-SET**

# Complexity of MST-KRUSKAL

```
MST-KRUSKAL( $G, w$ )
1   $A = \emptyset$ 
2  for each vertex  $v \in V(G)$ 
3      MAKE-SET( $v$ )           // disjoint-set data structure
4  sort  $E$  in non-decreasing order by weight  $w$ 
5  for each edge  $(u, v) \in E$ , taken in non-decreasing order by  $w$ 
6      if FIND-SET( $u$ )  $\neq$  FIND-SET( $v$ )
7           $A = A \cup \{(u, v)\}$ 
8      UNION( $u, v$ )
```

- $|V|$  times **MAKE-SET** (loop of line 2–3)
- $O(|E| \log |E|)$  for sorting  $E$  (line 4)
- $2|E|$  times **FIND-SET**
- $O(|E|)$  times **UNION**

- Build builds  $T$  incrementally
  - ▶ in each iteration, add a node  $v$  to  $T$  through an edge that connects  $v$  with  $T$

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  - ▶  $T$ , tree being built
  - ▶  $W[v]$  best known cost/weight of connecting  $v$  with  $T$
  - ▶  $P[v]$ , node  $u \in T$  such that the edge  $(u, v)$  is the least-cost edge connecting  $v$  with  $T$

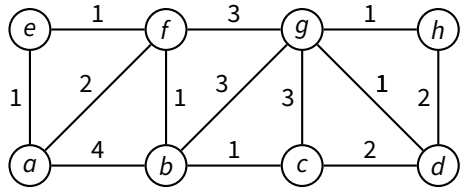
**MST-PRIM**( $G, u, w$ )

```
1   $T = (\emptyset, \emptyset)$ 
2  for each vertex  $v \in V(G)$ 
3       $W[v] = \infty$ 
4       $P[v] = \text{NIL}$ 
5   $W[u] = 0$ 
6  while  $V(T) \neq V(G)$ 
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8       $T = T \cup \{u\}$  // add  $u$  to  $T$ 
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# Prim's Algorithm

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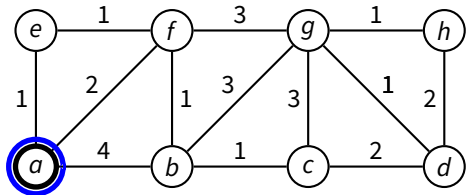


$v$	$W$	$P$	$T$
$a$	0		
$b$	$\infty$		
$c$	$\infty$		
$d$	$\infty$		
$e$	$\infty$		
$f$	$\infty$		
$g$	$\infty$		
$h$	$\infty$		

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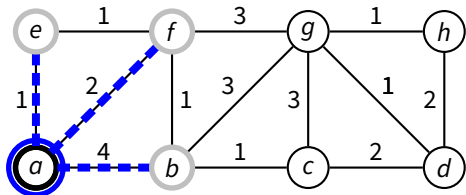


$v$	$W$	$P$	$T$
$a$	0		✓
$b$	$\infty$		
$c$	$\infty$		
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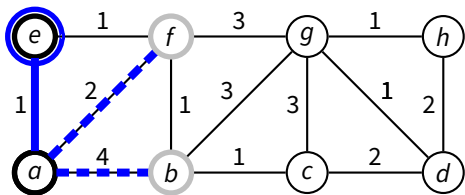


$v$	$W$	$P$	$T$
$a$	0		✓
$b$	4	$a$	
$c$	$\infty$		
$d$	$\infty$		
$e$	1	$a$	
$f$	2	$a$	
$g$	$\infty$		
$h$	$\infty$		

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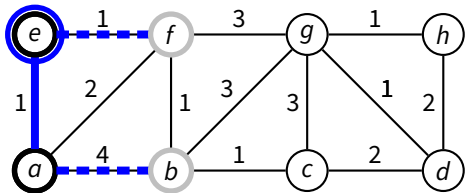


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$c$	$\infty$		
$d$	$\infty$		
$e$	1	$a$	✓
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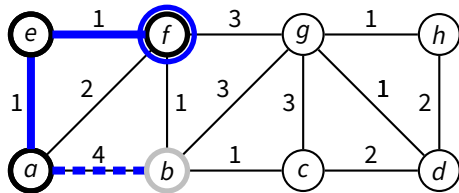


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$b$	4	$a$	
$c$	$\infty$		
$d$	$\infty$		
$e$	1	$a$	✓
$f$	1	$e$	
$g$	$\infty$		
$h$	$\infty$		

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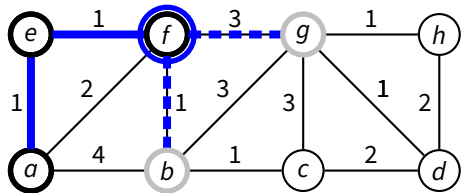


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$c$	$\infty$		
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$f$	1	$e$	✓
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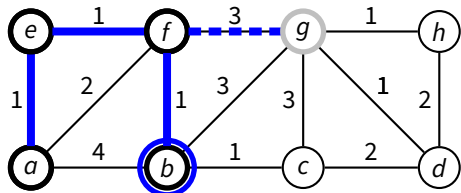


$v$	$W$	$P$	$T$
$a$	0		✓
$b$	1	$f$	
$c$	$\infty$		
$d$	$\infty$		
$e$	1	$a$	✓
$f$	1	$e$	✓
$g$	3	$f$	
$h$	$\infty$		

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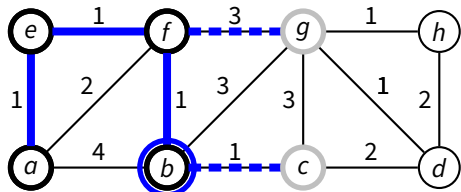


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$a$	0		✓
$b$	1	$f$	✓
$c$	$\infty$		
$d$	$\infty$		
$e$	1	$a$	✓
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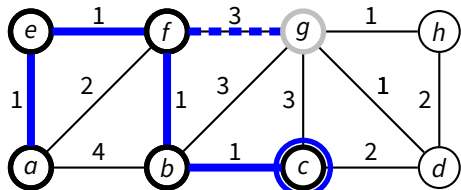


$v$	$W$	$P$	$T$
$a$	0		✓
$b$	1	$f$	✓
$c$	1	$b$	
$d$	$\infty$		
$e$	1	$a$	✓
$f$	1	$e$	✓
$g$	3	$f$	
$h$	$\infty$		

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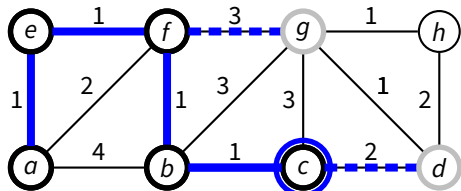


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$b$	1	$f$	✓
$c$	1	$b$	✓
$d$	$\infty$		
$e$	1	$a$	✓
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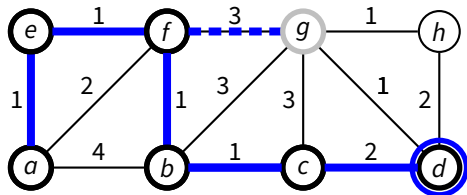


$v$	$W$	$P$	$T$
$a$	0		✓
$b$	1	$f$	✓
$c$	1	$b$	✓
$d$	2	$c$	
$e$	1	$a$	✓
$f$	1	$e$	✓
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$h$	$\infty$		

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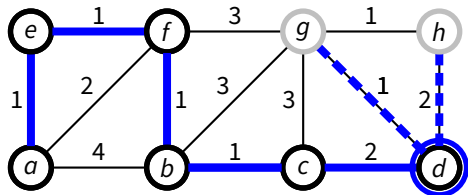
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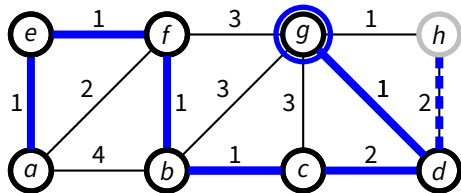


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$a$	0		✓
$b$	1	$f$	✓
$c$	1	$b$	✓
$d$	2	$c$	✓
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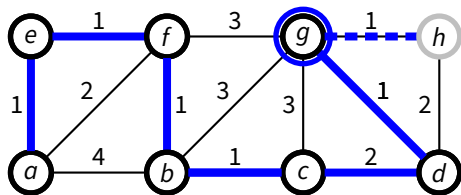


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$c$	1	$b$	✓
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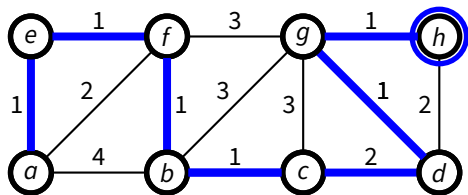


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$b$	1	$f$	✓
$c$	1	$b$	✓
$d$	2	$c$	✓
$e$	1	$a$	✓
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$h$	1	$g$	

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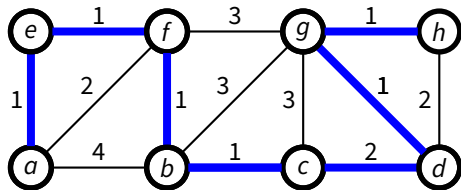


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5  $W[u] = 0$ 
6 while  $V(T) \neq V(G)$ 
7   find  $u \notin V(T)$  such that  $W[u]$  is minimal
8    $T = T \cup \{u\}$  // add  $u$  to  $T$ 
9   for all  $v \in \text{Adj}(u) \setminus V(T)$ 
10    if  $w(u, v) < W[v]$ 
11       $W[v] = w(u, v)$ 
12       $P[v] = u$ 
```

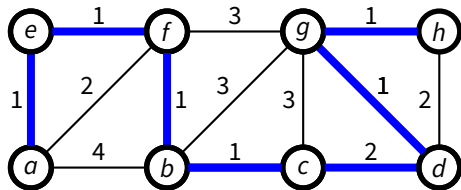


$v$	$W$	$P$	$T$
$a$	0		✓
$b$	1	$f$	✓
$c$	1	$b$	✓
$d$	2	$c$	✓
$e$	1	$a$	✓
$f$	1	$e$	✓
$g$	1	$d$	✓
$h$	1	$g$	✓

# Prim's Algorithm

## MST-PRIM( $G, u, w$ )

```
1  $T = (\emptyset, \emptyset)$ 
2 for each vertex  $v \in V(G)$ 
3    $W[v] = \infty$ 
4    $P[v] = \text{NIL}$ 
5  $W[u] = 0$ 
6 while  $V(T) \neq V(G)$ 
7   find  $u \notin V(T)$  such that  $W[u]$  is minimal
8    $T = T \cup \{u\}$  // add  $u$  to  $T$ 
9   for all  $v \in \text{Adj}(u) \setminus V(T)$ 
10    if  $w(u, v) < W[v]$ 
11       $W[v] = w(u, v)$ 
12       $P[v] = u$ 
```



$v$	$W$	$P$	$T$
$a$	0		✓
$b$	1	$f$	✓
$c$	1	$b$	✓
$d$	2	$c$	✓
$e$	1	$a$	✓
$f$	1	$e$	✓
$g$	1	$d$	✓
$h$	1	$g$	✓