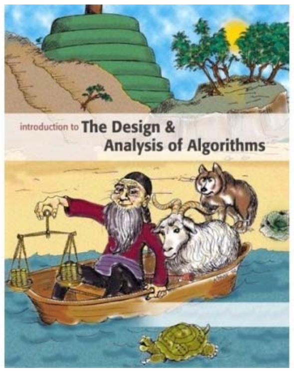
Introduction to

Algorithm Design and Analysis

[14] Minimum Spanning Tree



Yu Huang

http://cs.nju.edu.cn/yuhuang
Institute of Computer Software
Nanjing University

In the last class…

- **Undirected and Symmetric Digraph**
  - DFS skeleton
- **Biconnected Components**
  - Articulation point
  - Bridge
- **Other undirected graph problems**
  - Orientation for undirected graphs
  - MST based on graph traversal

当年我们学贪心算法

定义 7　一个图论算法的计算量$f(\nu,\varepsilon)=O(P(\nu,\varepsilon))$**时，则称此算法为有效算法或好算法，其中**$P(\nu,\varepsilon)$**是某个多项式，**$\nu$ **与** ε **分别是图的顶数与边数。**

Dijkstra **算法**（u,v 不相邻时，$w(uv)=\infty$）

（1）令$l(u_0)=0$；$l(v)=\infty$，$v\neq u_0$；$S_0=\{u_0\}$，$i=0$。

（2）对每一个$v\in\bar{S}_i$（$\bar{S}_i$ 指 S_i 以外的顶所成之集合），用$\min\{l(v),l(u_i)+w(u_iv)\}$代替$l(v)$；设$u_{i+1}$是使$l(v)$取最小值的$\bar{S}_i$中的顶，令$S_{i+1}=S_i\cup\{u_{i+1}\}$；

（3）若$i=\nu-1$，止；若$i<\nu-1$，用$i+1$代替 i，转（2）。

由上述算法知：

（1）S_i中各顶标$l(u)$即为u_0到 u 的距离。又因 $\nu<\infty$，故有限步之后，$V(G)$中每一顶都标志了与u_0的距离，从而可以找到各顶到u_0的最短轨。

（2）Dijkstra 算法的时间复杂度$f(\nu,\varepsilon)=O(\nu^2)$，所以是有效算法。

Greedy Strategy

- **Optimization Problem**
- **Greedy Strategy**

- **MST Problem**
  - Prim's Algorithm
  - Kruskal's Algorithm
- **Single-Source Shortest Path Problem**
  - Dijkstra's Algorithm

Greedy Strategy for Optimization Problems

- **Coin change Problem**
  - o [candidates] A finite set of coins, of 1, 5, 10 and 25 units, with enough number for each value
  - o [constraints] Pay an exact amount by a selected set of coins
  - o [optimization] a smallest possible number of coins in the selected set
- **Solution by greedy strategy**
  - o For each selection, choose the highest-valued coin as possible.

Greedy Fails Sometimes

We have to pay 15 in total

- **If the available types of coins are {1,5,12}**
  - The greedy choice is {12,1,1,1}
  - But the smallest set of coins is {5,5,5}

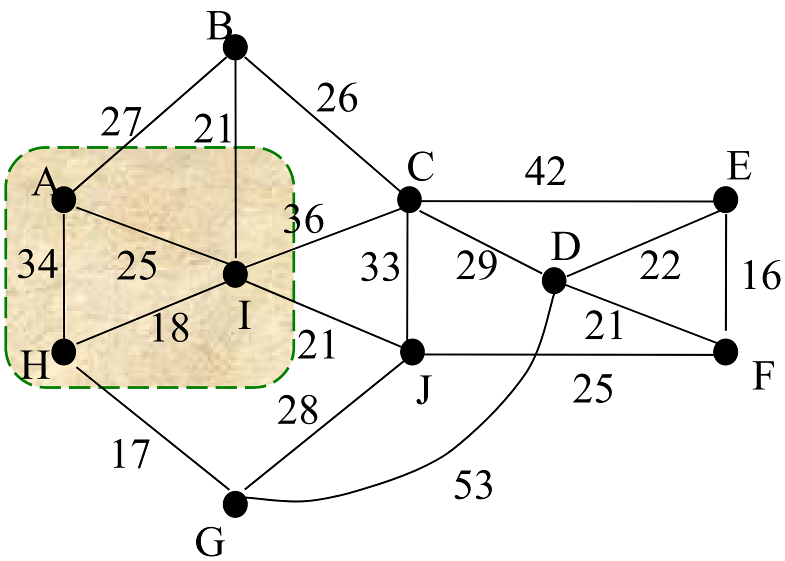
- **If the available types of coins are {1,5,10,25}**
  - The greedy choice is always correct

Greedy Strategy

- **Expanding the partial solution step by step.**
- **In each step, a selection is made from a set of candidates. The choice made must be:**
  - [Feasible] it has to satisfy the problem's constraints
  - [Locally optimal] it has to be the best local choice among all feasible choices on the step
  - [Irrevocable] the choice cannot be revoked in subsequent steps

```
set greedy(set candidate)
   set S=∅;
   while not solution(S) and   candidate≠∅
      select locally optimizing x from candidate;
      candidate=candidate-{x};
      if feasible(x) then S=S∪{x};
   if solution(S) then return S
        else return ("no solution")
```

Weighted Graph and MST

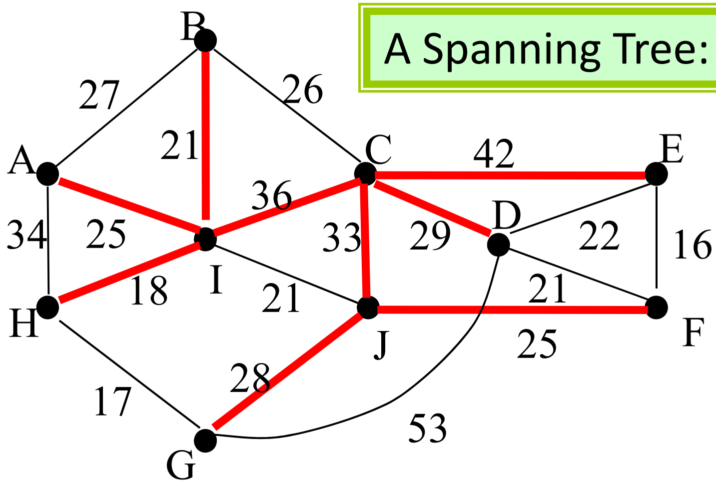


A weighted graph

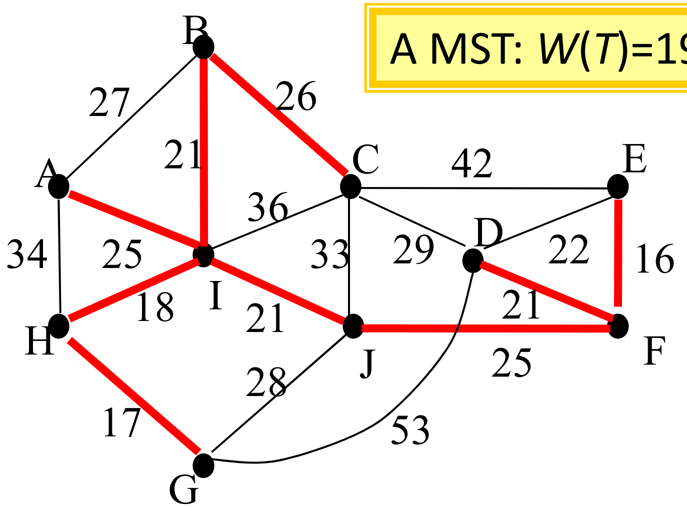
The nearest neighbor of vertex ***I*** is ***H***

The nearest neighbor of shaded

subset of vertex is ***G***



A Spanning Tree: $W(T)$=257

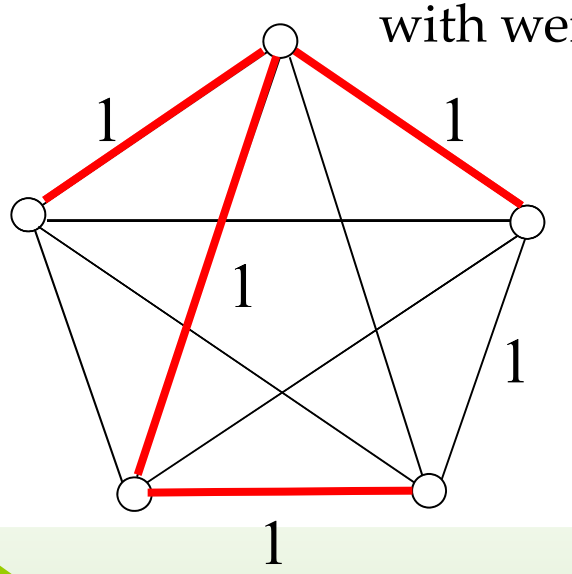


A MST: $W(T)$=190

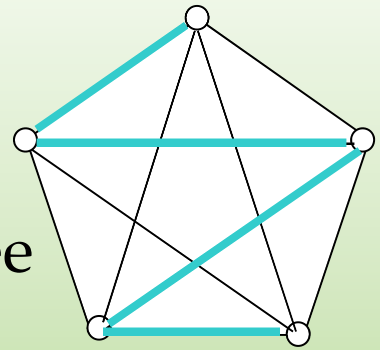
Graph Traversal and MST

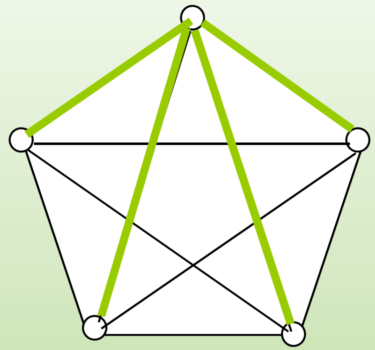
There are cases that graph traversal tree **cannot** be minimum spanning tree, with the vertices explored in any order.

All other edges with weight 5



DFS tree





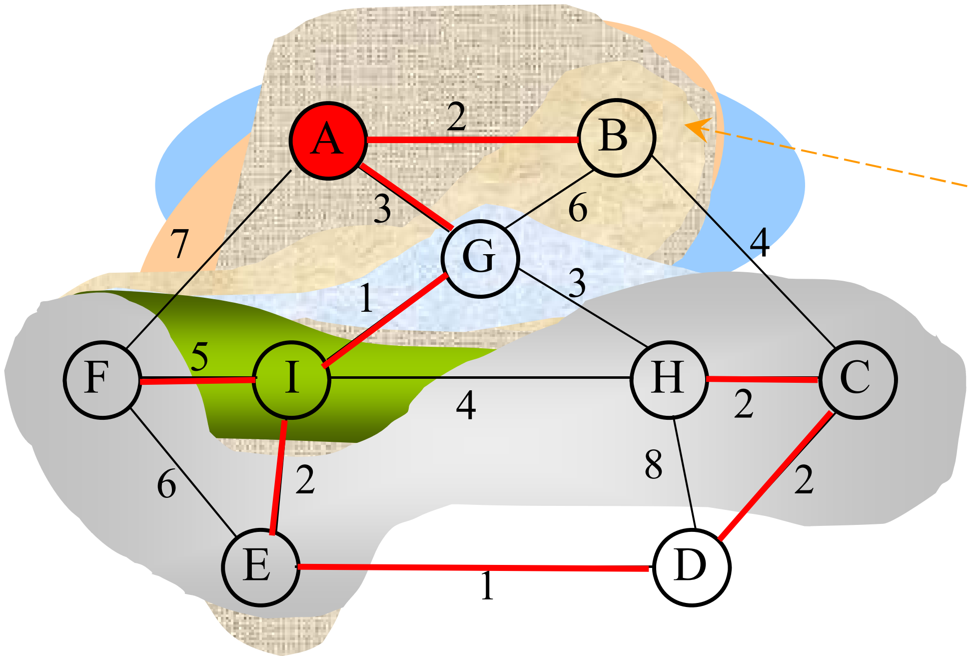
BFS tree

in any ordering of vertex

Greedy Algorithms for MST

- **Prim's algorithm:**
  - o Difficult selecting: "best local optimization means **no cycle and small weight under limitation**.
  - o Easy checking: doing nothing
- **Kruskal's algorithm:**
  - o Easy selecting: smallest in primitive meaning
  - o Difficult checking: **no cycle**

Prim's Algorithm



Greedy strategy:
For each set of fringe vertex, select the edge with the minimal weight, that is, local optimal.

edges included in the MST

Correctness: How to Prove

of nodes selected

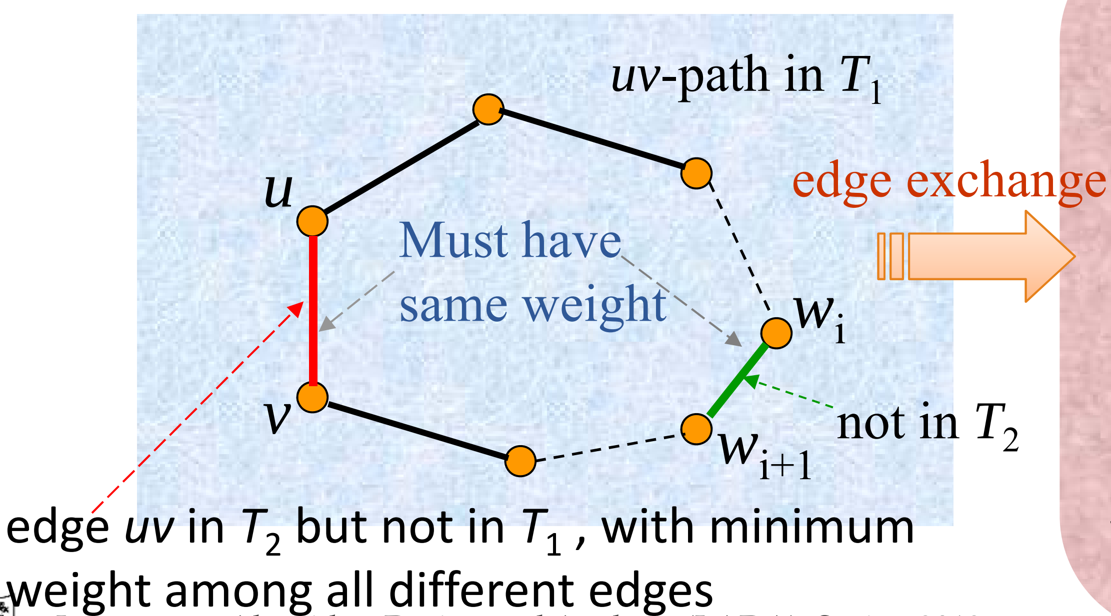
$T^{(1)} \quad T^{(2)} \quad \ldots \quad T^{(k\text{-}1)} \quad T^{(k)} \quad T^{(k+1)} \quad \ldots \quad T^{(n)}$

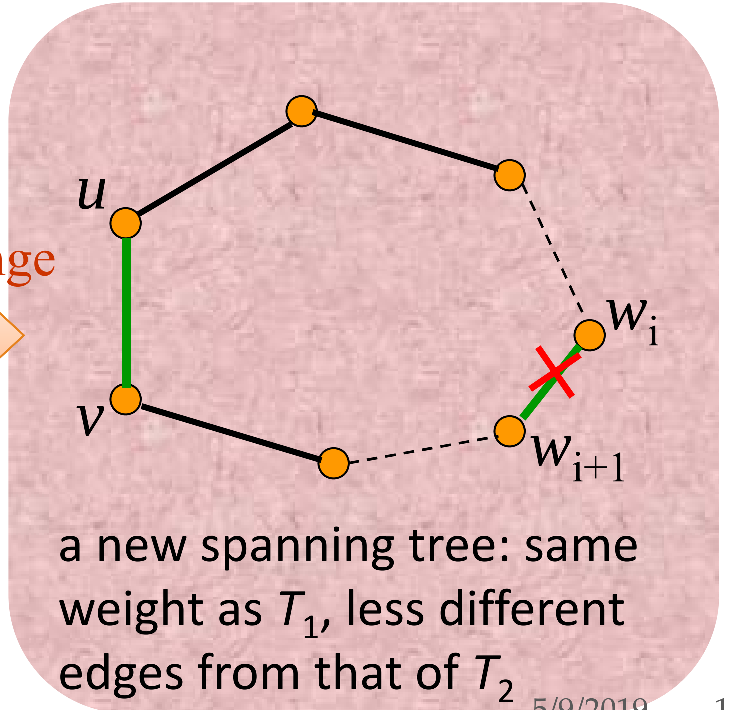
Invariance: MST
- Spanning tree
- Min weight

Definition transformation

Minimum Spanning Tree Property

- **A spanning tree *T* of a connected, weighted graph has MST property if and only if for any non-tree edge *uv*, $T \cup \{uv\}$ contain a cycle in which *uv* is one of the maximum-weight edge.**
- **All the spanning trees having MST property have the same weight.**



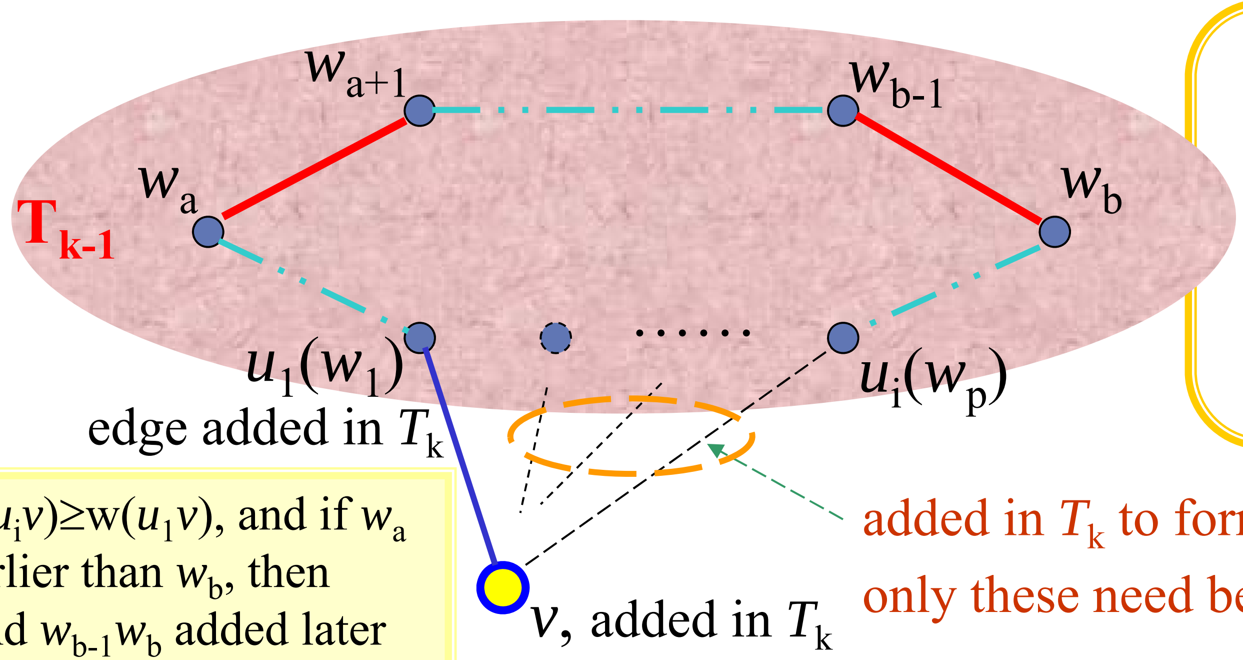


MST Property and Minimum Spanning Tree

- **In a connected, weighted graph G=(V,E,W), a tree T is a minimum spanning tree if and only if T has the MST property.**
- **Proof**
  - $\Rightarrow$ For a minimum spanning tree T, if it doesn't has MST property. So, there is a non-tree edge uv, and $T\cup\{uv\}$ contain an edge xy with weight larger than that of uv. Substituting uv for xy results a spanning tree with less weight than T. Contradiction.
  - $\Leftarrow$ As claimed above, any minimum spanning tree has the MST property. Since T has MST property, it has the same weight as any minimum spanning tree, i.e. T is a minimum spanning tree as well.

Correctness of Prim's Algorithm

- Let T_k be the tree constructed after the k^{th} step of Prim's algorithm is executed. Then T_k has the MST property in G_k, the subgraph of G induced by vertices of T_k.



added in T_k to form a cycle, only these need be considered

assumed first and last edges with larger weight than $w(u_i v)$, resulting contradictions.

Note: $w(u_i v) \geq w(u_1 v)$, and if w_a added earlier than w_b, then $w_a w_{a+1}$ and $w_{b-1} w_b$ added later than any edges in $u_1 w_a$-path, and v as well

Key Issue in Implementation

- **Maintaining the set of fringe vertices**
  - Create the set and update it after each vertex is "selected" (***deleting*** the vertex having been selected and ***inserting*** new fringe vertices)
  - Easy to decide the vertex with "highest priority"
  - Changing the priority of the vertices (***decreasing key***).
- **The choice: priority queue**

Implementation

Main Procedure

primMST(*G*,*n*)
  Initialize the priority queue *pq* as empty;
  Select vertex *s* to start the tree;
  Set its candidate edge to (-1,*s*,0);
  insert(*pq*,*s*,0);
  while (*pq* is not empty)
    v=getMin(*pq*); deleteMin(*pq*);
    add the candidate edge of *v* to the tree;
    updateFringe(*pq*,*G*,*v*);
  return

ADT operation executions:

insert, getMin, deleteMin: *n* times

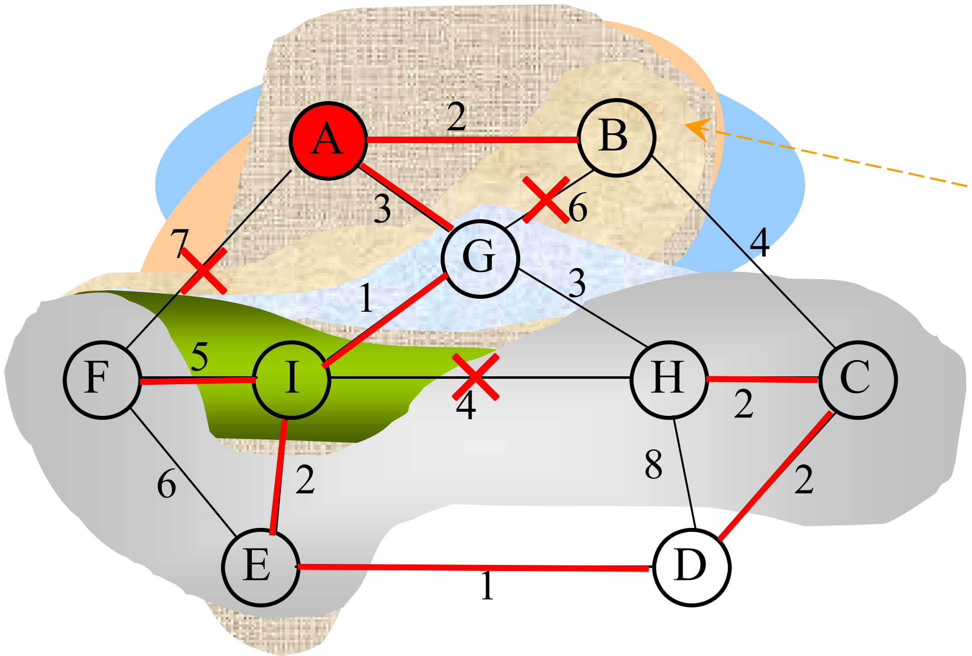
decreaseKey: *m* times

Updating the Queue

updateFringe(*pq*,*G*,*v*)
  For all vertices *w* adjcent to *v* //2*m* loops
    newWgt=w(*v*,*w*);
    if *w*.status is unseen **then**
      Set its candidate edge to (*v*,*w*,*newWgt*);
      insert(*pq*,*w*,*newWgt*)
    else
      if *newWgt*<getPriorty(*pq*,*w*)
        Revise its candidate edge to (*v*,*w*,newWgt);
        decreaseKey(*pq*,*w*,*newWgt*)
return

getMin(*pq*) always be the vertex with the smallest key in the fringe set.

Prim's Algorithm



Greedy strategy:
For each set of fringe vertex, select the edge with the minimal weight, that is, local optimal.

edges included in the MST

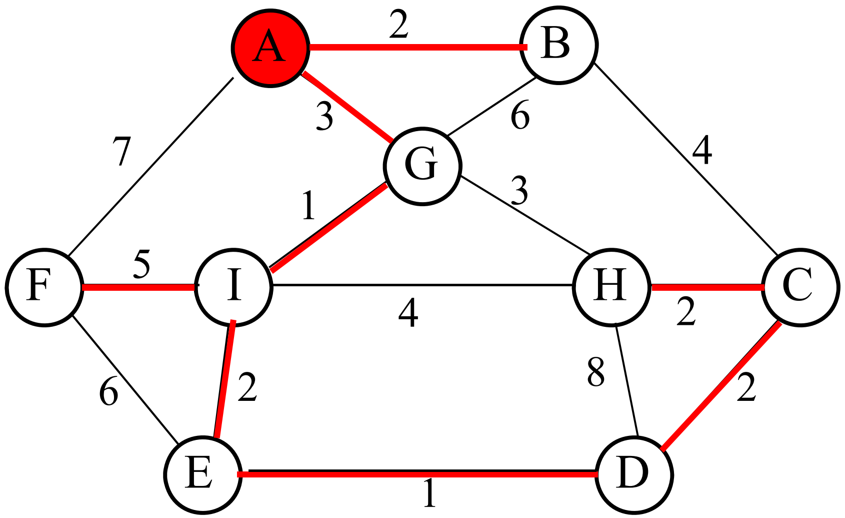
Complexity

- **Operations on ADT priority queue: (for a graph with n vertices and m edges)**
  - insert: n ;   getMin: n ;   deleteMin: n ;
  - decreasKey: m (appears in $2m$ loops, but execute at most m)
- **So,**

$$T(n,m) = O(nT(\text{getMin})+nT(\text{deleteMin+insert})+mT(\text{decreaseKey}))$$

- **Implementing priority queue using array, we can get $\Theta(n^2+m)$**

Kruskal's Algorithm



edges included in the MST

Also Greedy strategy:
From the set of edges not yet included in the partially built MST, select the edge with the minimal weight, that is, local optimal, in another sense.

Key Issue in Implementation

- How to know an insertion of edge will result in a cycle *efficiently*?
- For correctness: the two endpoints of the selected edge *can not* be in the same connected components.
- For the efficiency: connected components are implemented as dynamic equivalence classes using union-find.

Kruskal's Algorithm: the Procedure

- kruskalMST(G,n,F) //outline
- int count;
- Build a minimizing priority queue, pq, of edges of G, prioritized by weight.
- Initialize a Union-Find structure, sets, in which each vertex of G is in its own set.
-
- F=ϕ;
- while (isEmpty(pq) == false)
- vwEdge = getMin(pq);
- deleteMin(pq);
- int vSet = find(sets, vwEdge.from);
- int wSet = find(sets, vwEdge.to);
- if (vSet ≠ wSet)
- Add vwEdge to F;
- union(sets, vSet, wSet)
- return

Simply sorting, the cost will be $\Theta(m\log m)$

Prim vs. Kruskal

- **Lower bound for MST**
  - For a correct MST, each edge in the graph should be examined at least once.
  - So, the lower bound is $\Omega(m)$
- **$\Theta(n^2+m)$ and $\Theta(m\log m)$, which is better?**
  - Generally speaking, depends on the density of edge of the graph.

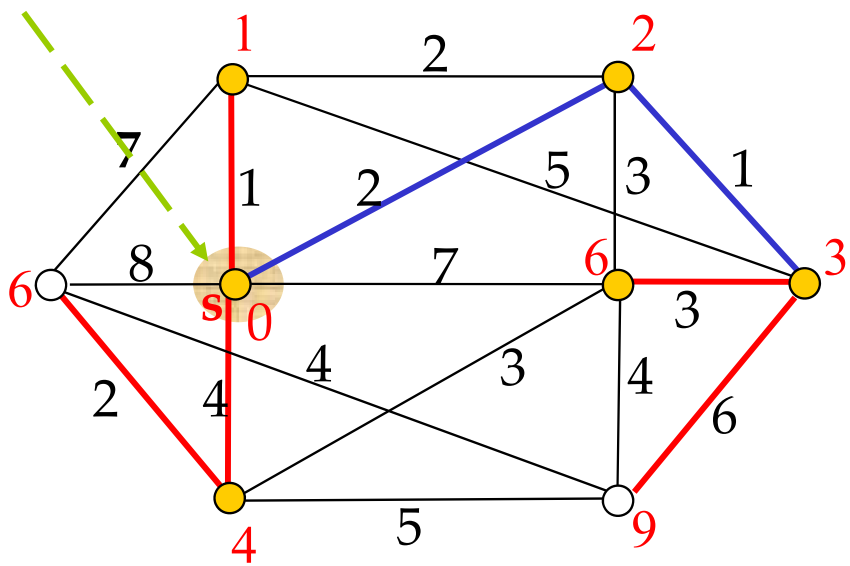
Single Source Shortest Paths

The single source

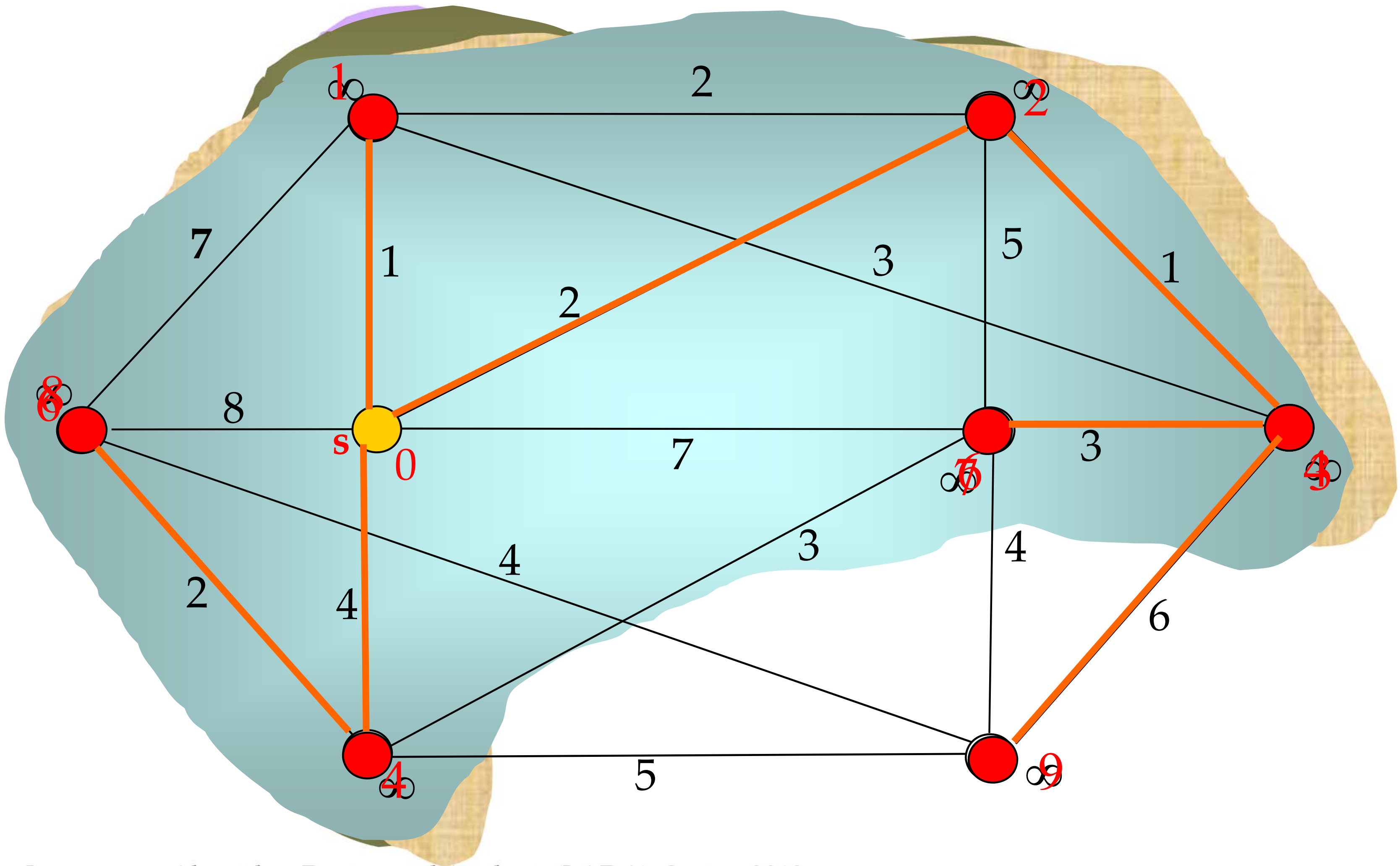
Red labels on each vertex is the length of the shortest path from s to the vertex.

Note:

The shortest [0, 3]-path doesn't contain the shortest edge leaving s, the edge [0,1]



Dijkstra's Algorithm



Thank you!

Q & A

Yu Huang
http://cs.nju.edu.cn/yuhuang