

Introduction to

Algorithm Design and Analysis

[11] Graph Traversal

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[https://cs.nju.edu.cn/ics/people/jingweixu/
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Course Contents

optimization problems

greedy

DP

BFS
DFS

DFS
(directed)

DFS
(undirect
ed)

MST

Path
(single
source)

Path
(all-pair)

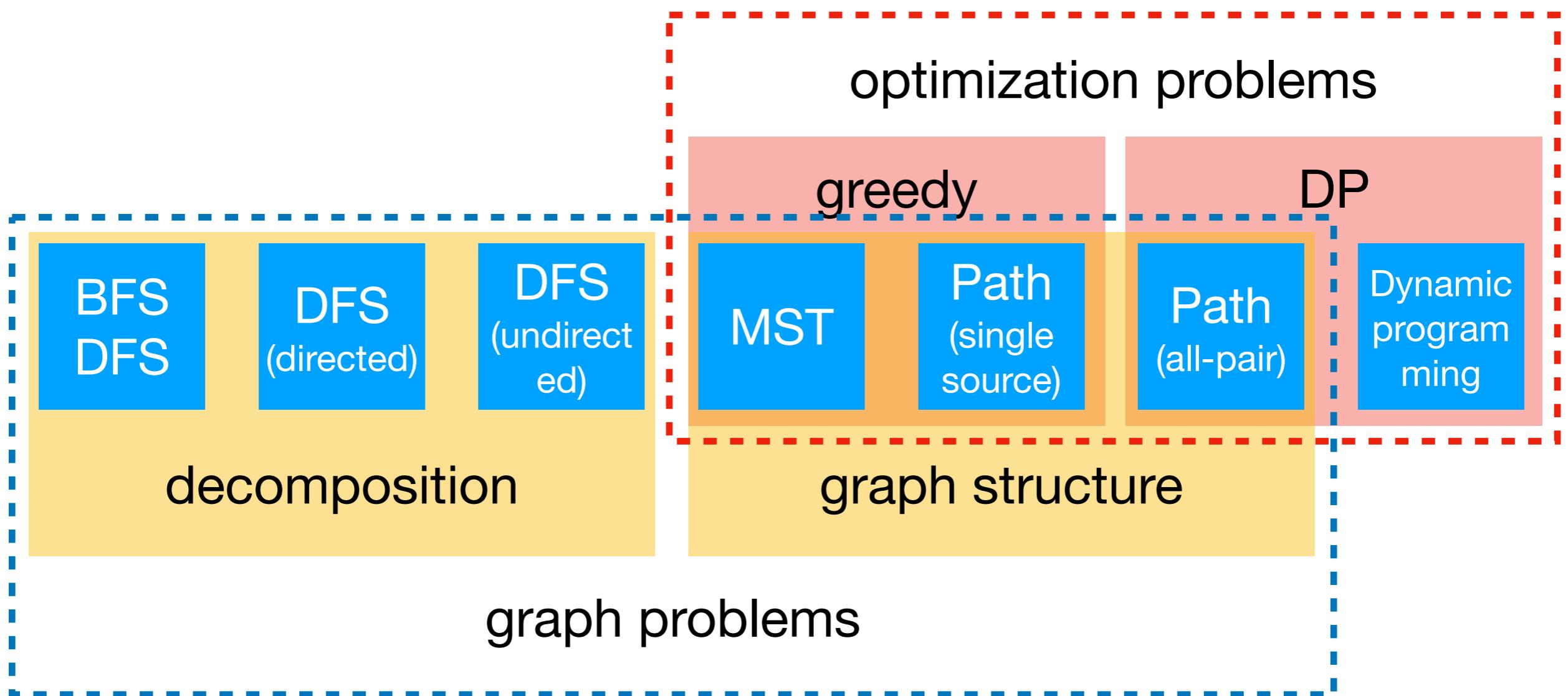
Dynamic
program
ming

decomposition

graph structure

graph problems

Course Contents



In the last class . . .

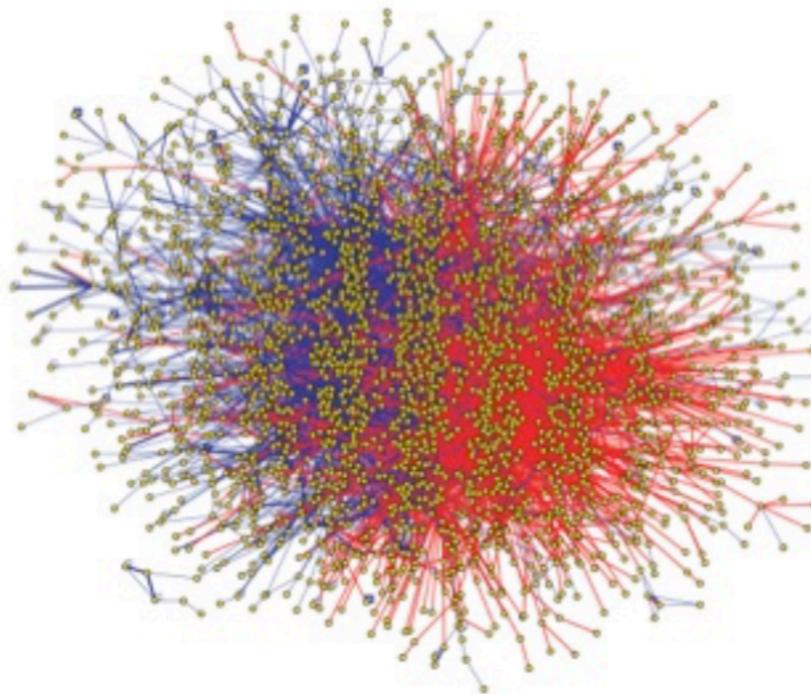
- Dynamic Equivalence Relation
- Implementing disjoint set by Union-Find
 - Straight Union-Find
 - Making Shorter Tree by **Weighted** Union
 - Compressing Path by **Compressing** Find
 - Amortized analysis of wUnion-cFind

Graph Everywhere



Graph Everywhere

Protein-protein interaction network



Graph Basics

- **Node**

- Entities of interest
- $V(G)$

- **Edge**

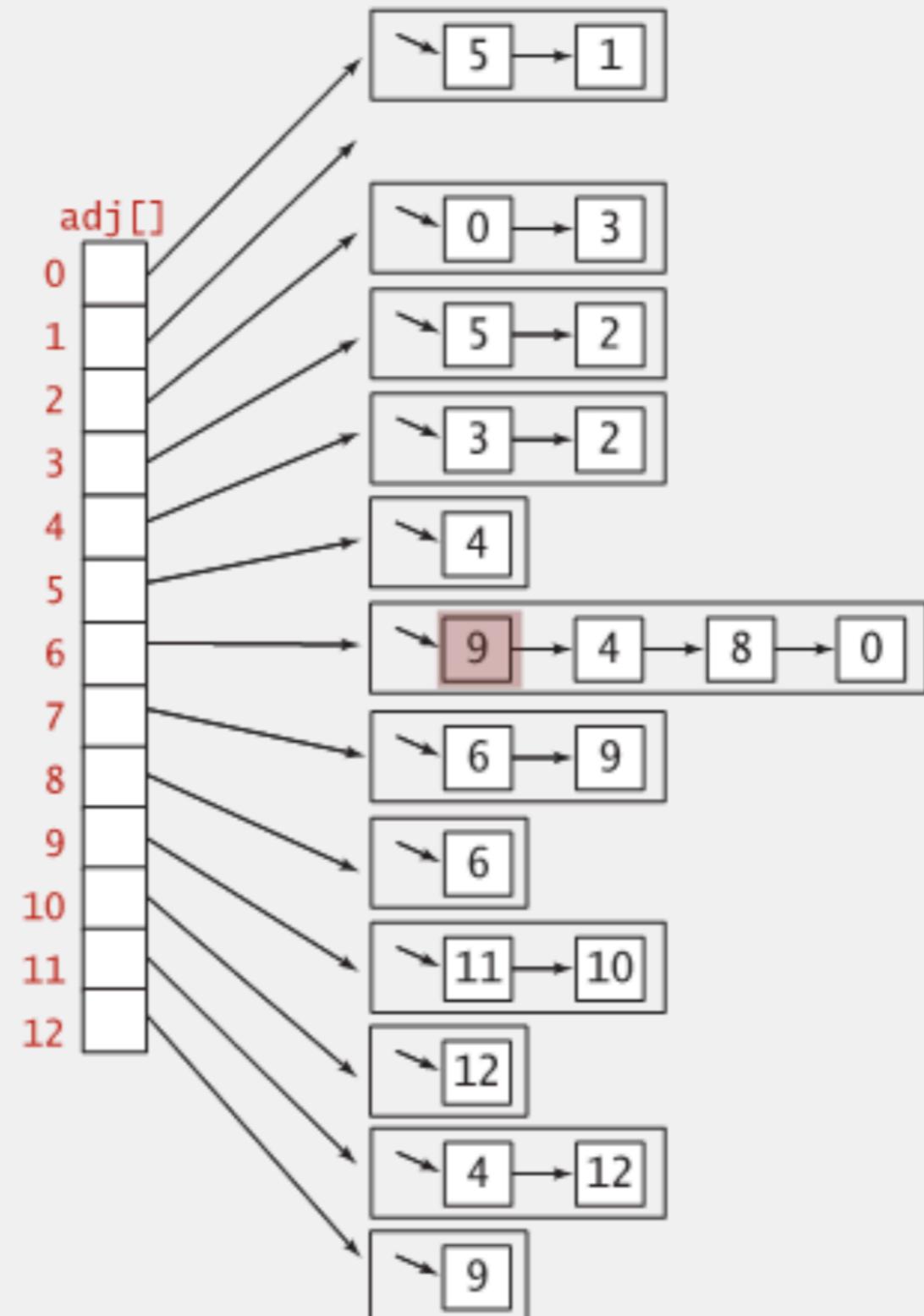
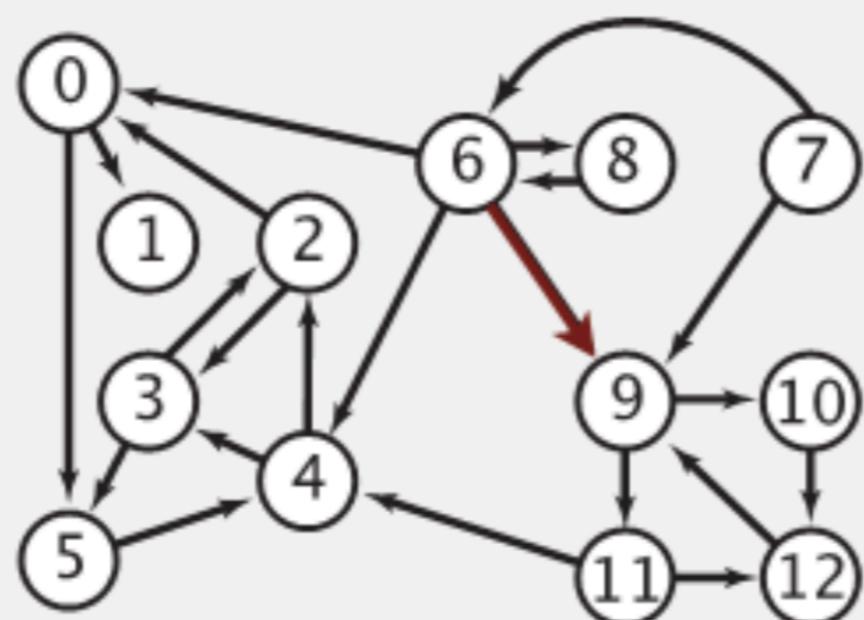
- Relations of interest
- $E(G) \in V \times V$

Graph Traversals

- Depth-First and Breadth-First Search
- Finding Connected Components
- General DFS/BFS Skeleton
- Depth-First Search Trace

Adjacency-lists digraph representation

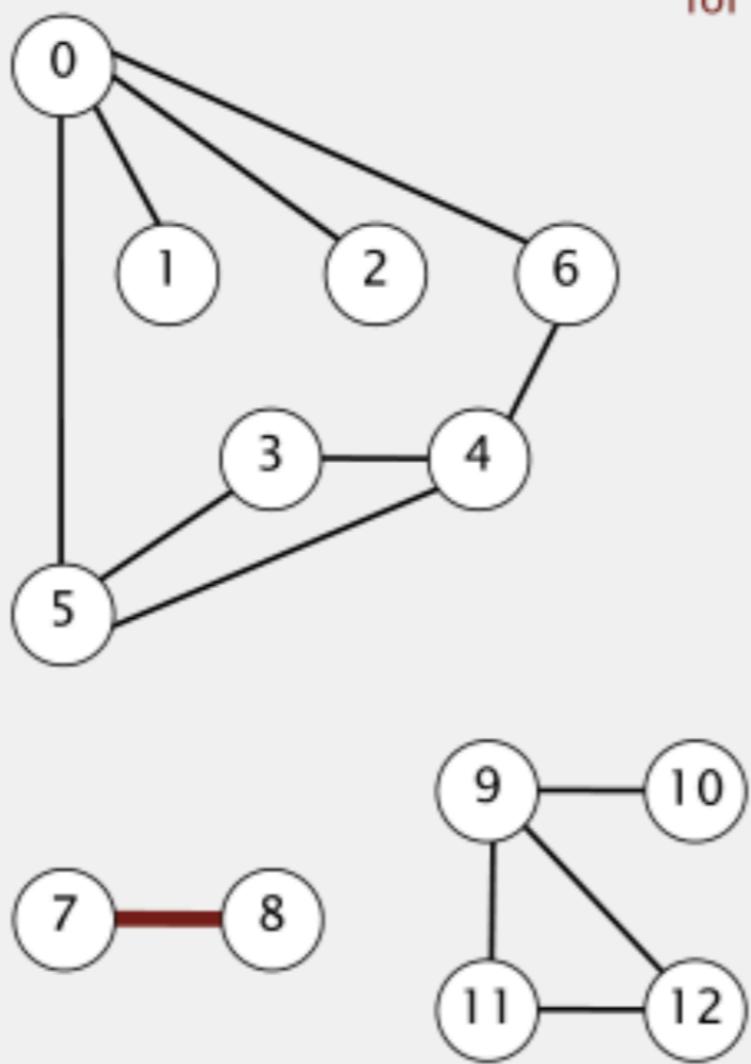
Maintain vertex-indexed array of lists.



Directed vs. **Undirected** graphs

Adjacency-matrix graph representation

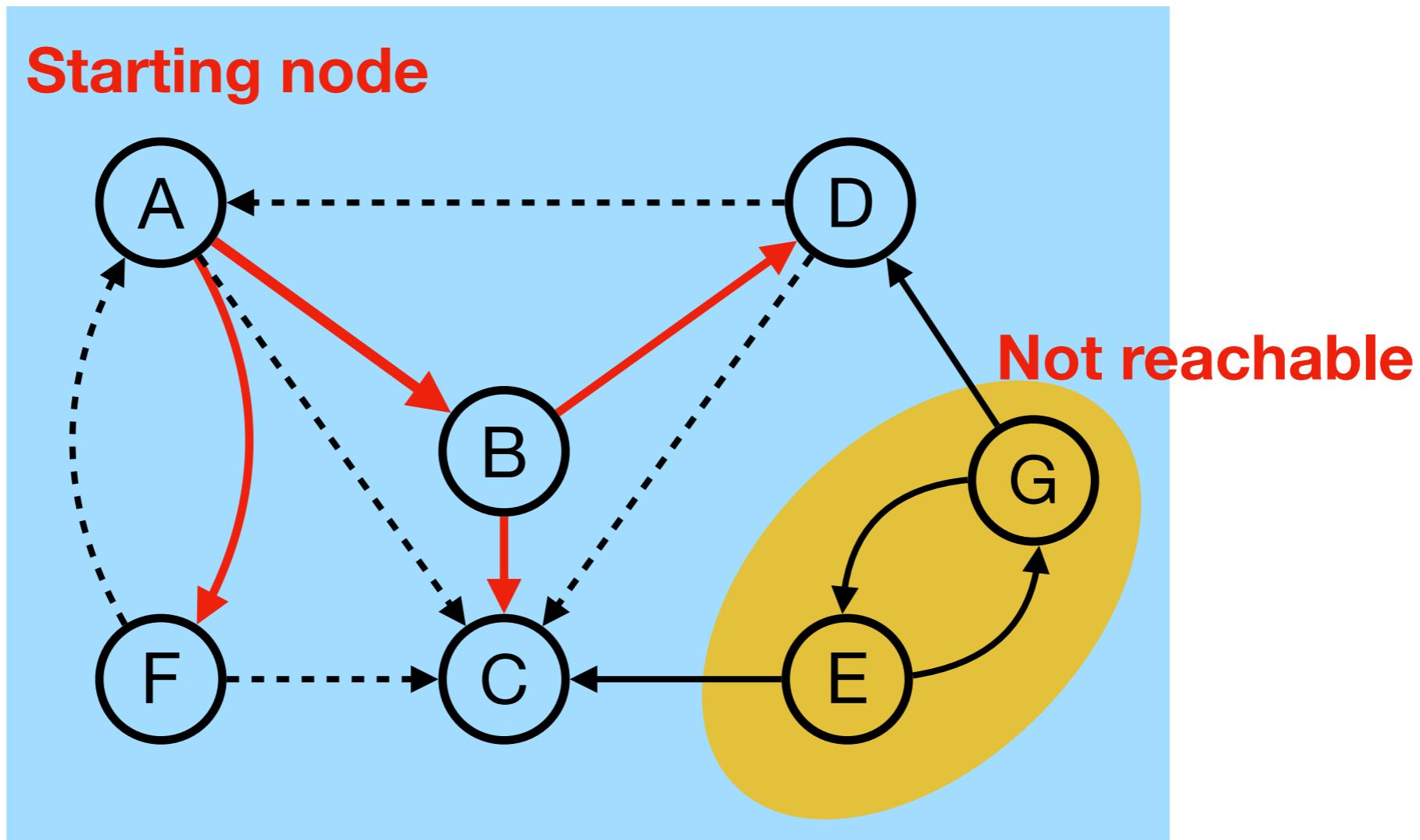
Maintain a two-dimensional V -by- V boolean array;
for each edge $v-w$ in graph: $\text{adj}[v][w] = \text{adj}[w][v] = \text{true}$.



two entries
for each edge

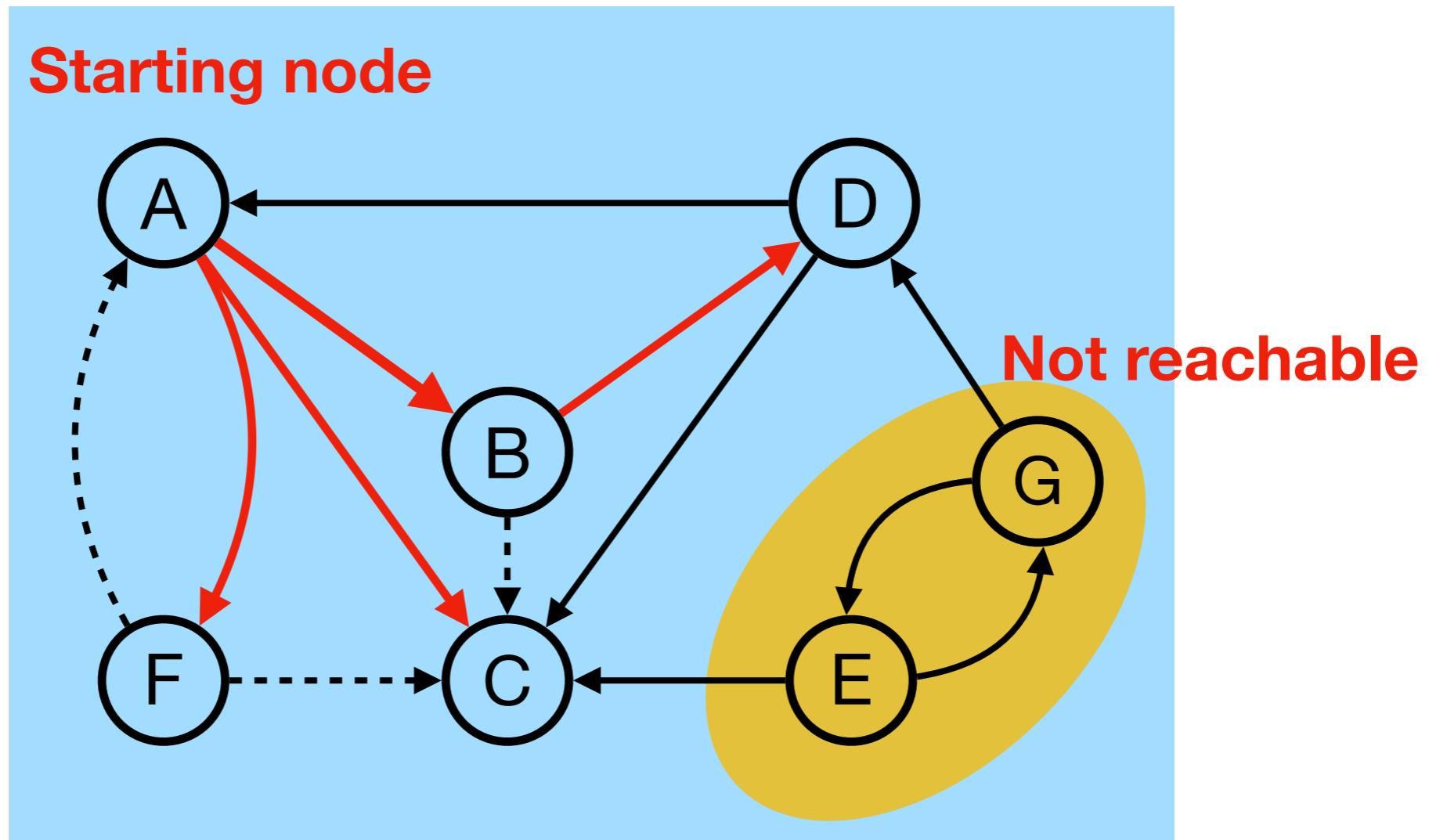
	0	1	2	3	4	5	6	7	8	9	10	11	12
0	0	1	1	0	0	1	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	1	0	0	0	0	0	0	0
4	0	0	0	1	0	1	1	0	0	0	0	0	0
5	1	0	0	1	1	0	0	0	0	0	0	0	0
6	1	0	0	0	1	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	0	1	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	1	1	1
10	0	0	0	0	0	0	0	0	0	1	0	0	0
11	0	0	0	0	0	0	0	0	1	0	0	0	1
12	0	0	0	0	0	0	0	0	0	1	0	1	0

Graph Traversal

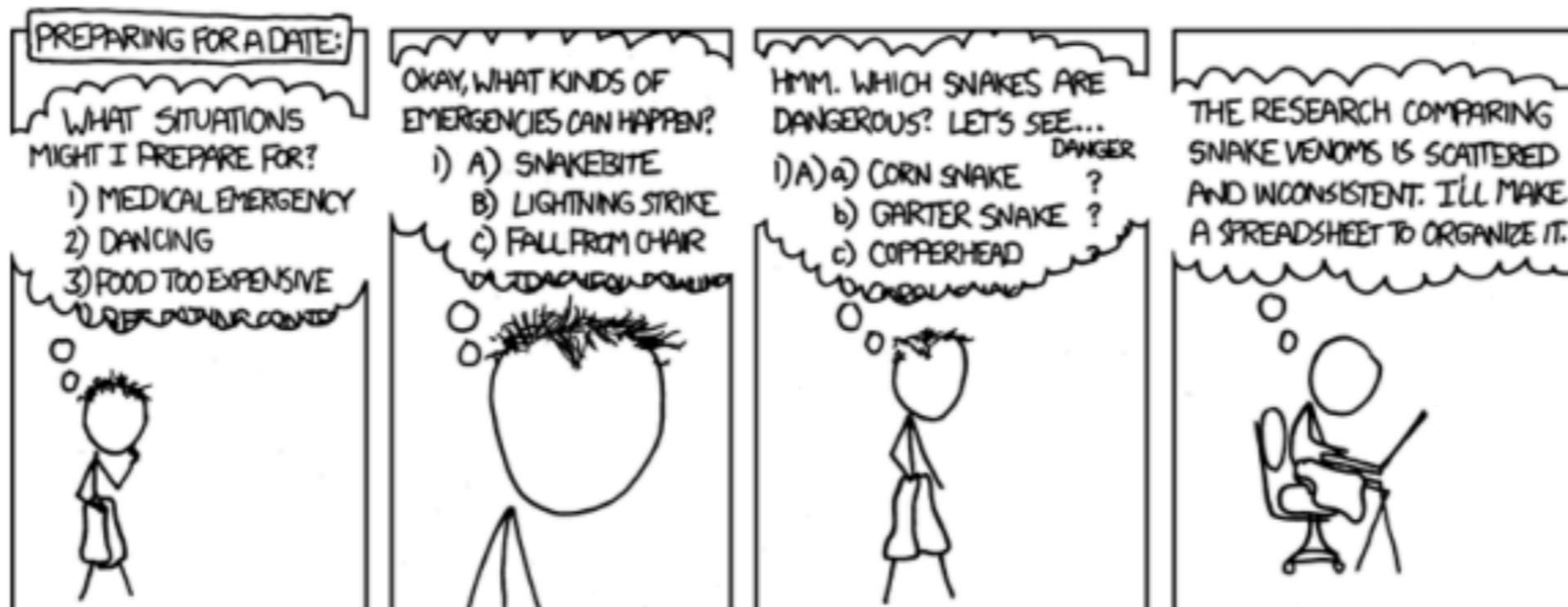


Depth-First Search

Graph Traversal



Depth-first search application: preparing for a date



I REALLY NEED TO STOP USING DEPTH-FIRST SEARCHES.

xkcd

<http://xkcd.com/761/>

Outline of Depth-First Search

- $\text{dfs}(G, v)$
- Mark v as “discovered”.
- For each vertex w that edge vw is in G :
- If w is undiscovered:
 - $\text{dfs}(G, w)$
- Otherwise:
 - “check” vw without visiting w .
- Mark v as “finished”.

A vertex must be exact one of three different status:

- Undiscovered
- Discovered but not finished
- Finished

That is: exploring vw , visiting w , exploring from there as much as possible, and backtrack from w to v .

Outline of Breadth-First Search

- $\text{bfs}(G, v)$
- Mark s as “discovered”;
- **enqueue**(pending, s);
- **while** (pending is nonempty)
 - **dequeue**(pending, v);
 - For each vertex w that edge vw is in G :
 - If w is “undiscovered”
 - Mark w as “discovered” and **enqueue**(pending, w)
- Mark v as “finished”;

Finding Connected Components

- Input: a symmetric digraph G, with n nodes and 2m edges (interpreted as undirected graph), implemented as a array adjVertices[1,...n] of adjacency lists.
- Output: an array cc[1..n] of component number for each node v_i .
- void connectedComponents(intlist[] adjVertices, int n, int[] cc)//
This is a wrapper procedure

```
● int[] color=new int[n+1];  
● int v;  
● <initialize color array to white for all vertices>  
● for(v=1; v≤n; v++)  
●   if(color[v]==white)  
●     ccDFS(adjVertices, color, v, v, cc);  
● return
```

Depth-first search



ccDFS: the procedure

- void ccDFS(intList[] adjVertices, int[] color, int v, int ccNum, int[] cc) // **v as the code of current connected component**

- int w;
- intList remAdj;
- color[v]=gray;
- cc[v]=ccNum;
- remAdj=adjVertices[v];
- while(remAdj != nil)
- w=first(remAdj);
- if(color[w]==white)
- ccDFS(adjVertices, color, w, ccNum, cc);
- remAdj=rest(remAdj);
- color[v]=black;
- return

The elements
of *remAdj* are
neighbors of *v*

Processing the next neighbor,
if existing, another depth-first
search to be incurred

v finished

Analysis of CC Algorithm

- `connectedComponents`, the wrapper
 - Linear in n (color array initialization+for loop on adjVertices)
- `ccDFS`, the depth-first searcher
 - In one execution of `ccDFS` on v , the number of instructions(`rest(remAdj)`) executed is proportional to the size of $\text{adjVertices}[v]$.
 - Note: \sum (size of $\text{adjVertices}[v]$) is $2m$, and the adjacency lists are traversed **only once**.
- So, the **time complexity is in $\Theta(m+n)$**
 - Extra space requirements:
 - Color array
 - Activation frame stack for recursion

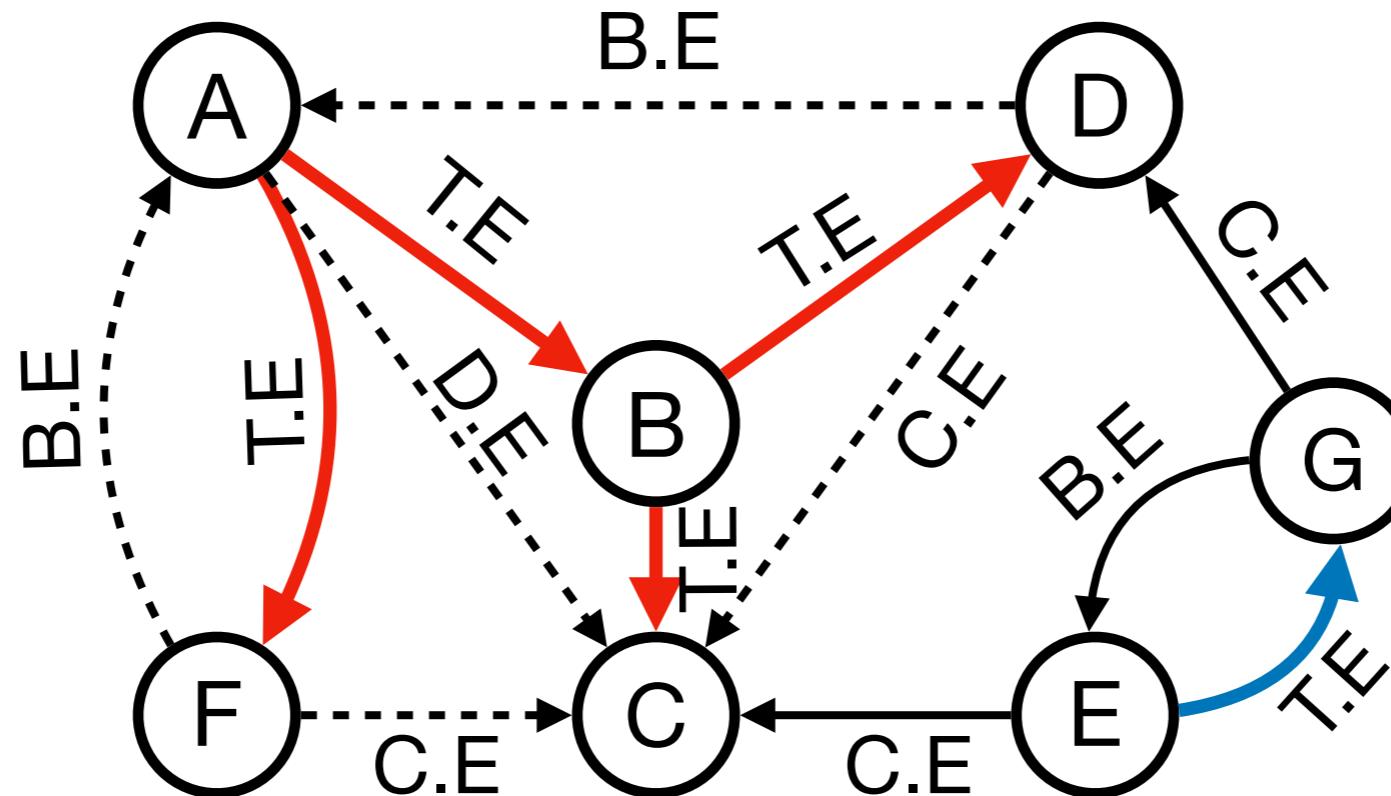
Visits On a Vertex

- Classification for visits on a vertex
 - First visit (exploring): status: white->gray
 - (Possibly) multi-visits by backtracking to: status keeps gray
 - Last visit (no more branch-finished): status: gray->black
- Different operations can be done, during the different visits on a specific vertex
 - On the vertex
 - On (selected) incident edges

Depth-first Search Trees

DFS forest={ (DFS tree1), (DFS tree2) }

Root of tree 1



Root of tree 2

T.E: tree edge

B.E: back edge

D.E: descendant edge

C.E: cross edge

A finished vertex is never revisited, such as C.

Depth-First Search – Generalized Skeleton

- Input: Array adjVertices for graph G
- Output: Return value depends on application
- int dfsSweep(intList[], adjVertices, int n, ...)
 - int ans;
 - <Allocate color array and initialize to white>
 - for each vertex v of G, in some order
 - if(color[v]==white)
 - int vAns=dfs(adjVertices, color, v, ...);
 - <Process vAns>
 - // continue loop
 - return ans;

Depth-First Search — Generalized Skeleton

- int dfs(intList[] adjVertices, int[] color, int v, ...)
- int w;
- intList remAdj;
- int ans;
- color[v]=gray;
- <Preorder processing of vertex v>
- remAdj=adjVertices[v];
- while(remAdj != nil)
 - w=first(remAdj);
 - if(color[w]==white)
 - <Exploratory processing for tree edge vw>
 - int wAns=dfs(adjVertices, color, w, ...)
 - <Backtrack processing for tree edge vw, using wAns>
 - else
 - <Checking for nontree edge vw>
 - remAdj=rest(remAdj);
- <Postorder processing of vertex v, including final computation of ans>
- color[v]=black;
- return ans;

If partial search is used for a application, tests for termination may be inserted here.

Specialized for connected components:
Parameter added
Preorder processing inserted - cc[v] =ccNum

Breadth-First Search – Skeleton

- Input: Array adjVertices for graph G
- Output: Return value depends on application
- void bfsSweep(intList[], adjVertices, int n, ...)
 - int ans;
 - <Allocate color array and initialize to white>
 - for each vertex v of G, in some order
 - if(color[v]==white)
 - void **bfs(adjVertices, color, v, ...);**
 - // continue loop
 - return;

Breadth-First Search – Skeleton

- void bfs(intList[] adjVertices, int[] color, int v, ...)
- int w; intList remAdj; Queue pending;
- color[v]=gray; enqueue(pending, v);
- while(pending is nonempty) 
 - w=dequeue(pending); remAdj=adjVertices[w];
 - while(remAdj!=nil)
 - x=first(remAdj);
 - if(color[x]==white)
 - color[x]=gray; enqueue(pending, x);
 - remAdj=rest(remAdj);
 - <processing of vertex w>
 - color[w]=black;
 - return

Can be further generalized

DFS v.s. BFS Search

- Processing opportunities for a node
 - Depth-first: 2
 - At discovering
 - At finishing
 - Breadth-first: only 1, when de-queued
 - At the second processing opportunity for the DFS, the algorithm can make use of information about the descendants of the current node.

Time Relation on Changing Color

- Keeping the order in which vertices are encountered for the first or last time
 - A global integer **time**: 0 as the initial value, incremented with each color changing for *any* vertex, and the final value is $2n$
 - **Array *discoverTime***: the i th element records the time vertex v_i turns into gray
 - **Array *finishTime***: the i th element records the time vertex v_i turns into black
 - The active interval for vertex v , denoted as $active(v)$, is the duration while v is gray, that is:
 - $discoverTime[v], \dots, finishTime[v]$

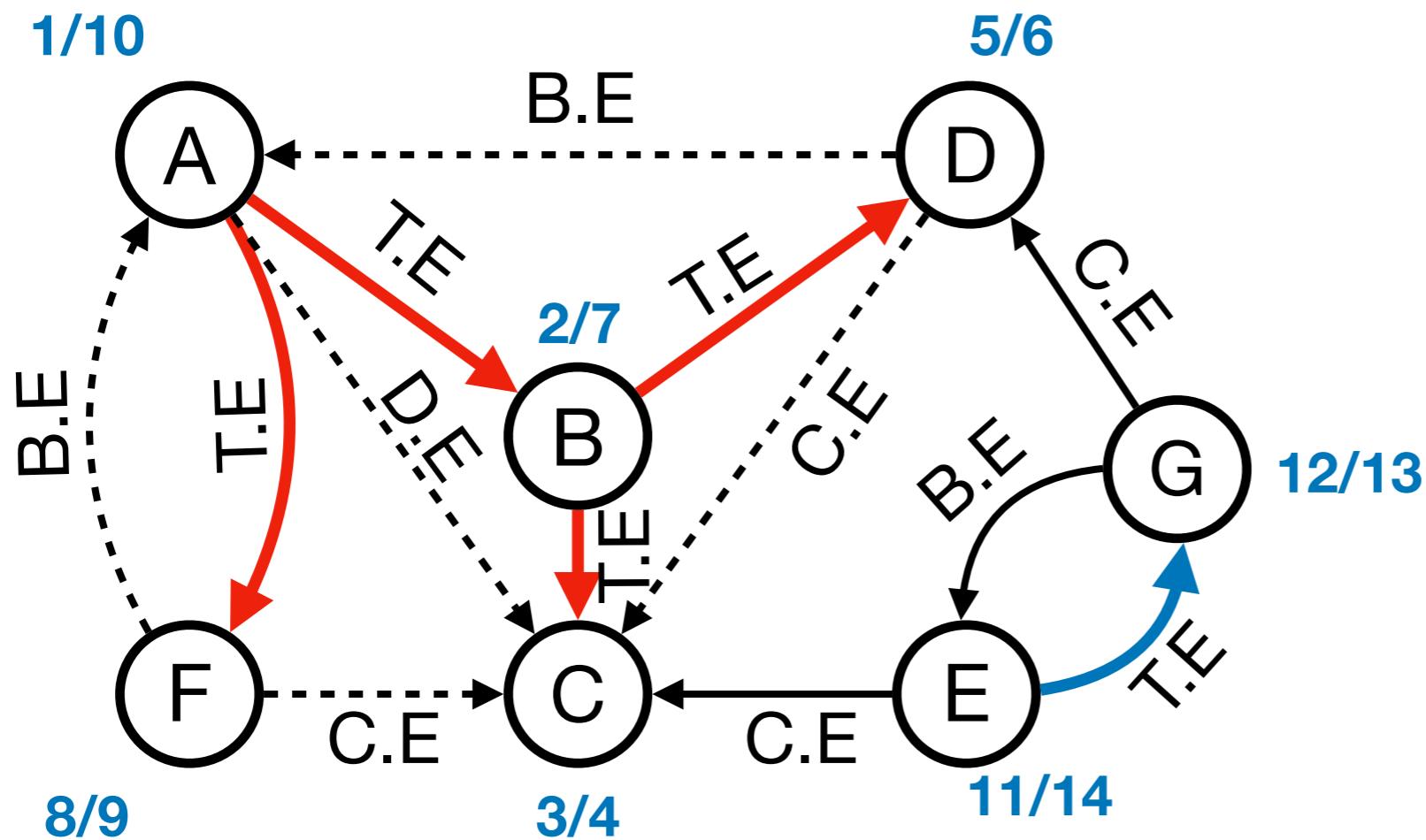
Depth-First Search Trace

- General DFS skeleton modified to compute discovery and finishing times and “construct” the depth-first search forest.
- `int dfsTraceSweep(intList[] adjVertices, int n, int[] discoverTime, int[] finishTime, int[] parent)`
- `int ans; int time=0;`
- `<Allocate color array and initialize to white>`
- `for each vertex v of G, in some order`
- `if(color[v]==white)`
- `parent[v]=-1`
- `int vAns=dfsTrace(adjVertices, color, v, discoverTime, finishTime, parent, time);`
- `//continue loop`
- `return ans;`

Depth-First Search Trace

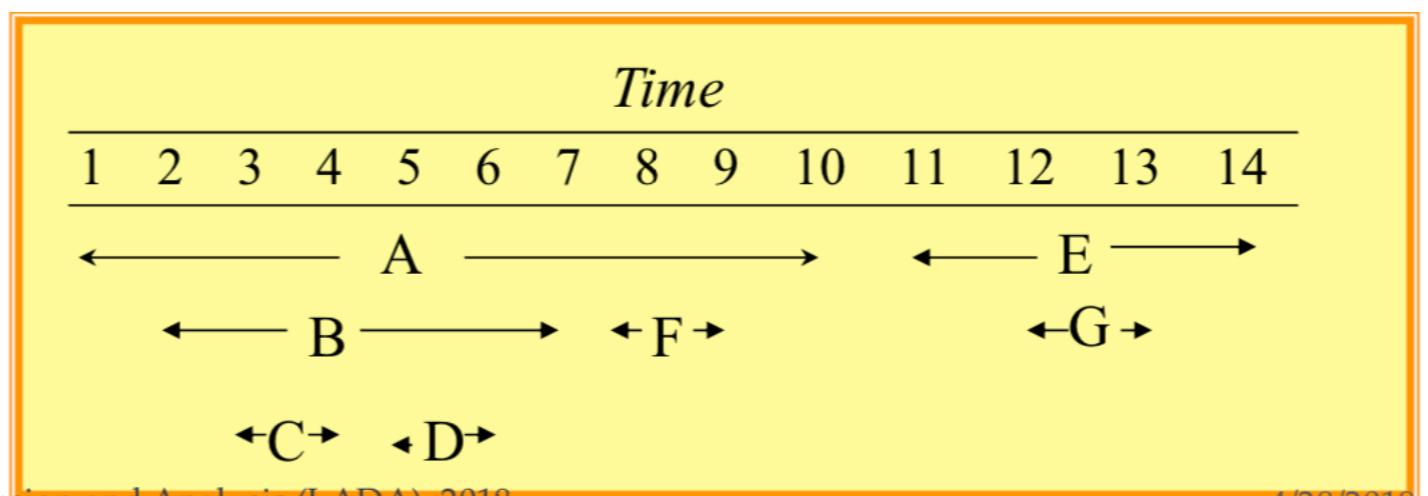
- int dfsTrace(intList[] adjVertices, int[] color, int v, int[] discoverTime, int[] finishTime, int[] parent, int time)
 - int w; intList remAdj; int ans;
 - color[v]=gray; **time++**; **discoverTime[v]=time**;
 - remAdj=adjVertices[v];
 - while(remAdj != nil)
 - w=**first**(remAdj);
 - if(color[w]==white)
 - **parent[w]=v**;
 - Int wAns=**dfs**(adjVertices, color, w, **discoverTime**, **finishTime**, **parent**, **time**);
 - else <Checking for nontree edge vw>
 - remAdj=**rest**(remAdj);
 - **time++**; **finishTime[v]=time**;
 - color[v]=black;
 - Return ans;

Active Interval



The relations are summarized in the next frame

T.E: tree edge
 B.E: back edge
 D.E: descendant edge
 C.E: cross edge



Properties of Active Intervals(1)

- If w is a descendant of v in the DFS forest, then $\text{active}(w) \subseteq \text{active}(v)$, and the inclusion is proper if $w \neq v$.
- Proof:
 - Define a partial order $<$: $w < v$ iff. w is a proper descendants of v in its DFS tree. The proof is by induction on $<$.
 - If v is minimal. The only descendant of v is itself. Trivial.
 - Assume that for all $x < v$, if w is a descendant of x , then $\text{active}(w) \subseteq \text{active}(x)$.
 - Let w be any proper descendant of v in the DFS tree, there must be some x such that vx is a tree edge on the tree path to w , so w is a descendant of x . According to `dfsTrace`, we have $\text{active}(x) \subset \text{active}(v)$, by inductive hypothesis, $\text{active}(w) \subset \text{active}(v)$.

Properties of Active Intervals(2)

- If $\text{active}(w) \subseteq \text{active}(v)$, then w is a descendant of v . And if $\text{active}(w) \subset \text{active}(v)$, then w is a proper descendant of v .
- That is: w is discovered while v is active.
- Proof:
 - If w is not a descendant of v , there are two cases:
 - v is a proper descendant of w , then $\text{active}(v) \subset \text{active}(w)$, so, it is impossible that $\text{active}(w) \subseteq \text{active}(v)$, contradiction.
 - There is no ancestor/descendant relationship between v and w , then $\text{active}(w)$ and $\text{active}(v)$ are disjoint, contradiction.

Properties of Active Intervals(3)

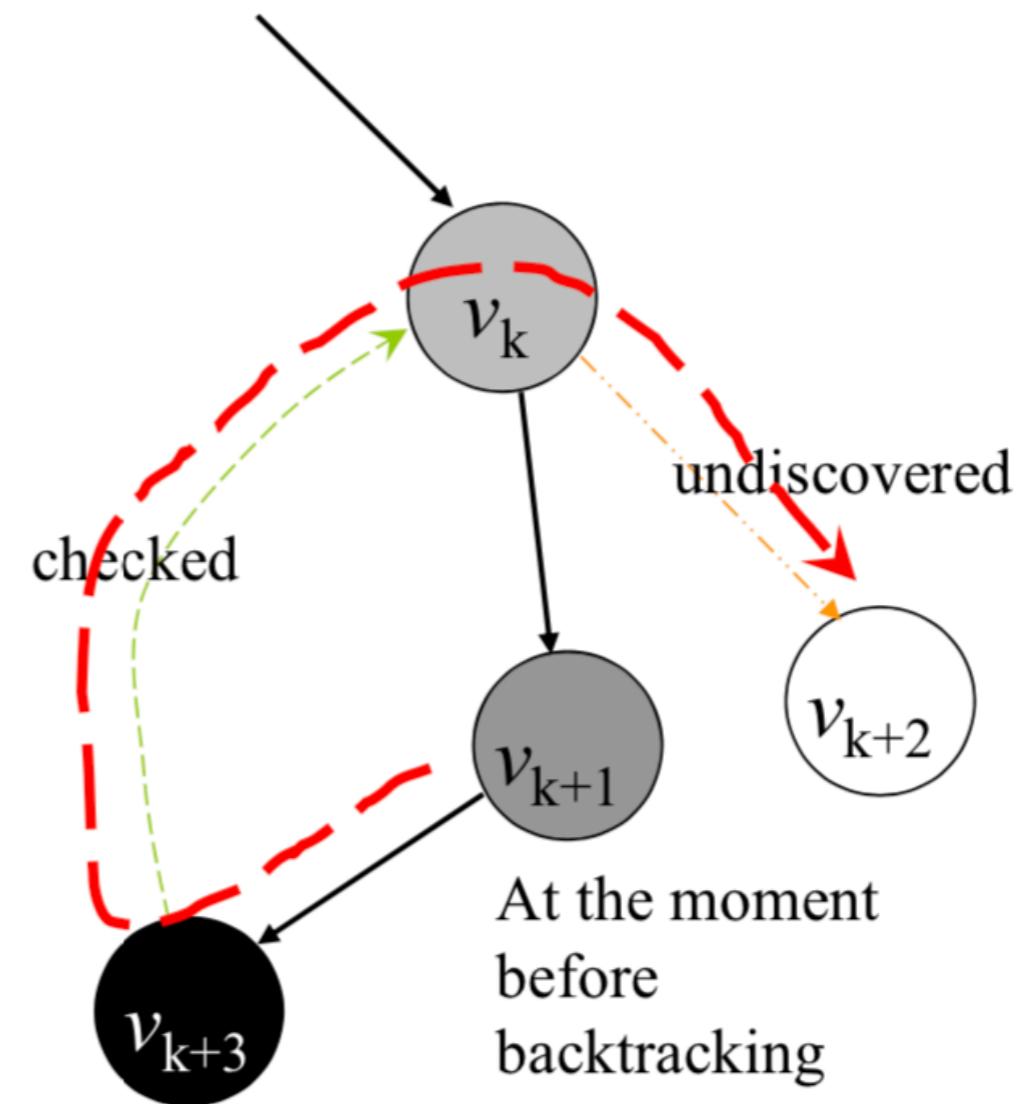
- If v and w have no ancestor/descendant relationship in the DFS forest, then their **active intervals** are disjoint.
- Proof:
 - If v and w are in different DFS tree, it is trivially true, since the trees are processed one by one.
 - Otherwise, there must be a vertex c , satisfying that there are tree paths c to v , and c to w , without edges in common. Let the leading edges of the two tree path are cy , cz , respectively. According to **dfsTrace**, $active(y)$ and $active(z)$ are disjoint.
 - We have $active(v) \in active(y)$, $active(w) \in active(z)$. So, $active(v)$ and $active(w)$ are disjoint.

Properties of Active Intervals(4)

- If edge $vw \in E_G$, then
 - vw is a **cross edge** iff. $active(w)$ entirely precedes $active(v)$.
 - vw is a **descendant edge** iff. there is some third vertex x , such that $active(w) \subset active(x) \subset active(v)$,
 - vw is a **tree edge** iff. $active(w) \subset active(v)$, and there is no third vertex x , such that $active(w) \subset active(x) \subset active(v)$,
 - vw is a **back edge** iff. $active(v) \subset active(w)$,

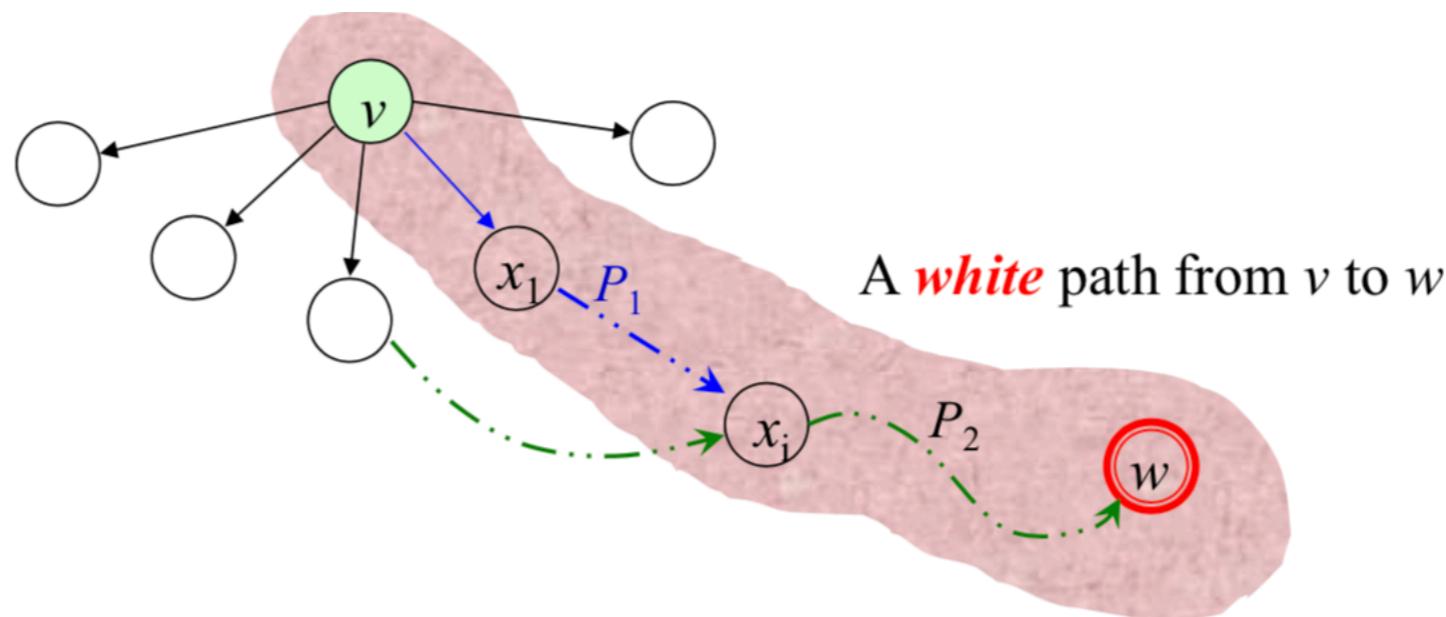
Ancestor and Descendant

- That w is a descendant of v in the DFS forest means that there is a direct path from v to w in some DFS tree.
- The path is also a path in G .
- However, if there is a direct path from v to w in G , is w necessarily a descendant of v in *the* DFS forest?



DFS Tree Path

- [White Path Theorem] w is a descendant of v in a DFS tree iff. At the time v is discovered(just to be changing color into gray), there is a path in G from v to w consisting entirely of white vertices.



Proof of White Path Theorem

● Proof

- \Rightarrow all the vertices in the path are descendants of v .
- \Leftarrow by induction on the length k of a white path from v to w .
 - When $k=0$, $v=w$.
 - For $k>0$, let $P=(v, x_1, x_2 \dots x_k=w)$. There must be some vertex on P which is discovered during the active interval of v , e.g. x_1 . Let x_i is earliest discovered among them. Divide P into P_1 from v to x_i , and P_2 from x_i to w . P_2 is a white path with length less than k , so, by inductive hypothesis, w is a descendant of x_i . Note: $active(x_i) \subseteq active(v)$, so x_i is a descendant of v . By transitivity, w is a descendant of v .

Thank you!
Q & A