CSE 332 Autumn 2023 Lecture 26: Wisdom and Deadlock

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Back Account Using Synchronize (Final)

```
class BankAccount {
	private int balance = 0;
	synchronized int getBalance() { return balance; }
	synchronized void setBalance(int x) { balance = x; }
	synchronized void withdraw(int amount) {
		int b = getBalance();
		if (amount > b)
			throw new WithdrawTooLargeException();
		setBalance(b – amount); }
	// other operations like deposit (which would use synchronized)
}
```

How to fix this?

Make a bigger critical section

```
class Stack {
        private E[] array = (E[])new Object[SIZE];
        private int index = -1;
        synchronized boolean isEmpty() { … }
        synchronized void push(E val) { … }
        synchronized E pop() { … }
        E peek(){
                E ans = pop();
                push(ans);
                return ans;
        }
}
```

bad state

How to fix this?

Make a bigger critical section

```
class Stack {
	private E[] array = (E[])new Object[SIZE];
	private int index = -1;
	synchronized boolean isEmpty() { … }
	synchronized void push(E val) { … }
	synchronized E pop() { … }
	synchronized E peek(){
		E ans = pop();
		push(ans);
		return ans;
	}
}
```

Parallel Code Conventional Wisdom

Memory Categories

All memory must fit one of three categories:

1. Thread Local: Each thread has its own copy
2. Shared and Immutable: There is just one copy, but nothing will ever write to it
3. Shared and Mutable: There is just one copy, it may change
   - Requires Synchronization!

Thread Local Memory

- **Guidance: Whenever possible, avoid sharing resources**
- Dodges all race conditions, since no other threads can touch it!
  - No synchronization necessary! (Remember Ahmdal's law)
- Use whenever threads do not need to communicate using the resource
  - E.g., each thread should have its on Random object
- In most cases, most objects should be in this category

Immutable Objects

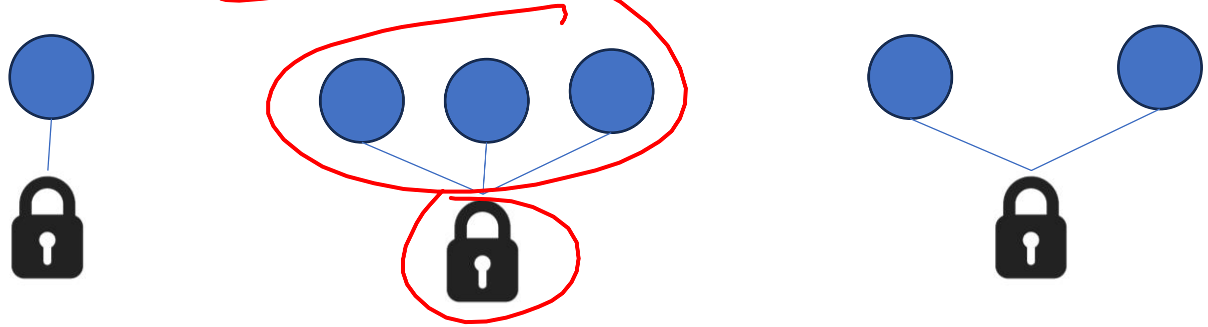
- **Guidance: Whenever possible, avoid changing objects**
  - Make new objects instead
- Parallel reads are not data races
  - If an object is never written to, no synchronization necessary!
- Many programmers over-use mutation, minimize it

Shared and Mutable Objects

- **Guidance: For everything else, use locks**
- Avoid all data races
  - Every read and write should be projected with a lock, even if it “seems safe”
  - Almost every Java/C program with a data race is wrong
- Even without data races, it still may be incorrect
  - Watch for bad interleavings as well!
  - Use locks whenever there is an incomplete intermediate state!

Consistent Locking

- For each location needing synchronization, have a lock that is always held when reading or writing the location
- The same lock can (and often should) "guard" multiple fields/objects
  - Clearly document what each lock guards!
  - In Java, the lock should usually be the object itself (i.e. "this")
- **Guidance: Have a mapping between memory locations and lock objects and stick to it!**

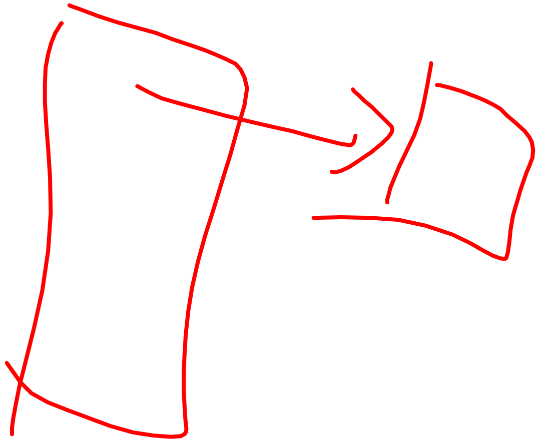


Lock Granularity

- Coarse Grained: Fewer locks guarding more things each
  - One lock for an entire data structure
  - One lock shared by multiple objects (e.g. one lock for all bank accounts)
- Fine Grained: More locks guarding fewer things each
  - One lock per data structure location (e.g. array index)
  - One lock per object or per field in one object (e.g. one lock for each account)
- Note: there’s really a continuum between them…

Example: Separate Chaining Hashtable

- Coarse-grained: One lock for the entire hashtable
- Fine-grained: One lock for each bucket
- Which supports more parallelism in insert and find?
- Which makes rehashing easier?
- What happens if you want to have a size field?



Tradeoffs

- Coarse-Grained Locking:
  - Simpler to implement and avoid race conditions
  - Faster/easier to implement operations that access multiple locations (because all guarded by the same lock)
  - Much easier for operations that modify data-structure shape
- Fine-Grained Locking:
  - More simultaneous access (performance when coarse grained would lead to unnecessary blocking)
  - Can make multi-location operations more difficult: say, rotations in an AVL tree
- **Guidance: Start with coarse-grained, make finer only as necessary to improve performance**

Similar But Separate Issue: Critical Section Granularity

- Coarse-grained
  - For every method that needs a lock, put the entire method body in a lock
- Fine-grained
  - Keep the lock only for the sections of code where it's necessary
- **Guidance:**
  - **Try to structure code so that expensive operations (like I/O) can be done outside of your critical section**
  - E.g., if you're trying to print all the values in a tree, maybe copy items into an array inside your critical section, then print the array's contents outside.

Atomicity

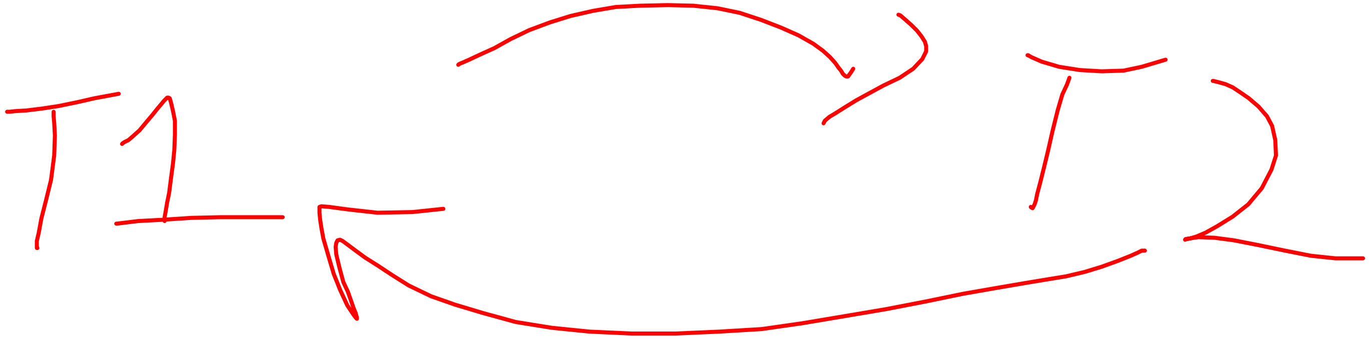
- Atomic: indivisible
- Atomic operation: one that should be thought of as a single step
- Some sequences of operations should behave as if they are one unit
  - Between two operations you may need to avoid exposing an intermediate state
  - Usually ADT operations should be atomic
    - You don’t want another thread trying to do an insert while another thread is rotating the AVL tree
- **Guidance: Think first in terms of what operations need to be atomic**
  - **Design critical sections and locking granularity based on these decisions**

Use Pre-Tested Code

- **Guidance: Whenever possible, use built-in libraries!**
- Other people have already invested tons of effort into making things both efficient and correct, use their work when you can!
  - Especially true for concurrent data structures
  - Use thread-safe data structures when available
    - E.g. Java as ConcurrentHashMap

Deadlock

- Occurs when two or more threads are mutually blocking each other
- T1 is blocked by T2, which is blocked by T3, …, Tn is blocked by T1
  - A cycle of blocking



Bank Account

```
class BankAccount {
        …
        synchronized void withdraw(int amt) {…}
        synchronized void deposit(int amt) {…}
        synchronized void transferTo(int amt, BankAccount a) {
                this.withdraw(amt);
                a.deposit(amt);
        }
}
```

The Deadlock

Expected Behavior:
Thread 2 items from a stack are popped in LIFO order

Thread 1:

```
x.transferTo(1,y);
```

Thread 2:

```
y.transferTo(1,x);
```

Thread 1	Thread 2
acquire lock for account x b/c transferTo is synchronized **acquire lock for account y** b/c deposit is synchronized **release lock for account y** after depost **release lock for account x** at end of transferTo	**acquire lock for account y** b/c transferTo is synchronized **acquire lock for account x** b/c deposit is synchronized **release lock for account x** after deposit **release lock for account y** at end of transferTo

The Deadlock

Expected Behavior:
Thread 2 items from a stack are popped in LIFO order

Thread 1:	Thread 2:
x.transferTo(1,y);	y.transferTo(1,x);

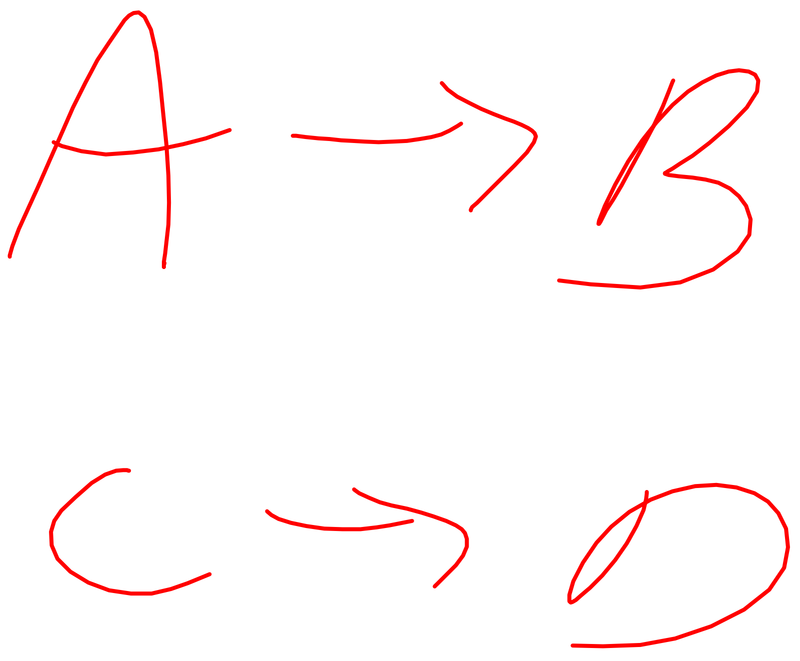
acquire lock for account x b/c transferTo is synchronized	**acquire lock for account y** b/c transferTo is synchronized
acquire lock for account y b/c deposit is synchronized	**acquire lock for account x** b/c deposit is synchronized
release lock for account y after depost	**release lock for account x** after deposit
release lock for account x at end of transferTo	**release lock for account y** at end of transferTo

Resolving Deadlocks

- Deadlocks occur when there are multiple locks necessary to complete a task and different threads may obtain them in a different order
- Option 1:
  - Have a coarser lock granularity
  - E.g. one lock for ALL bank accounts
- Option 2:
  - Have a finer critical section so that only one lock is needed at a time
  - E.g. instead of a synchronized transferTo, have the withdraw and deposit steps locked separately
- Option 3:
  - Force the threads to always acquire the locks in the same order
  - E.g. make transferTo acquire both locks before doing either the withdraw or deposit, make sure both threads agree on the order to aquire

Option 1: Coarser Locking

```
static final Object BANK = new Object();
class BankAccount {
        ...
        synchronized void withdraw(int amt) {...}
        synchronized void deposit(int amt) {...}
        void transferTo(int amt, BankAccount a) {
                synchronized(BANK){
                        this.withdraw(amt);
                        a.deposit(amt);
                }
        }
}
```



Option 2: Finer Critical Section

```
class BankAccount {
        …
        synchronized void withdraw(int amt) {…}
        synchronized void deposit(int amt) {…}
        void transferTo(int amt, BankAccount a) {
                synchronized(this){
                        this.withdraw(amt);
                }
                synchronized(a){
                        a.deposit(amt);
                }
        }
}
```

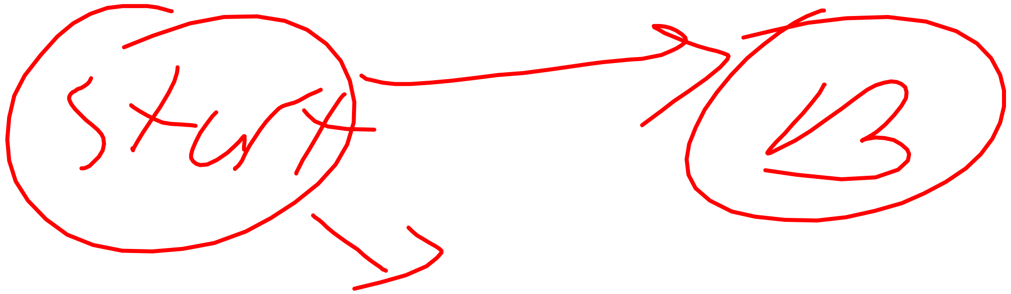
Option 3: First Get All Locks In A Fixed Order

```
class BankAccount {
        …
        synchronized void withdraw(int amt) {…}
        synchronized void deposit(int amt) {…}
        void transferTo(int amt, BankAccount a) {
                if (this.acctNum < a.acctNum){
                        synchronized(this){
                                synchronized(a){
                                        this.withdraw(amt);
                                        a.deposit(amt);

                } } }
                else {
                        synchronized(a){
                                synchronized(this){
                                        this.withdraw(amt);
                                        a.deposit(amt);

                } } }
        }
}
```

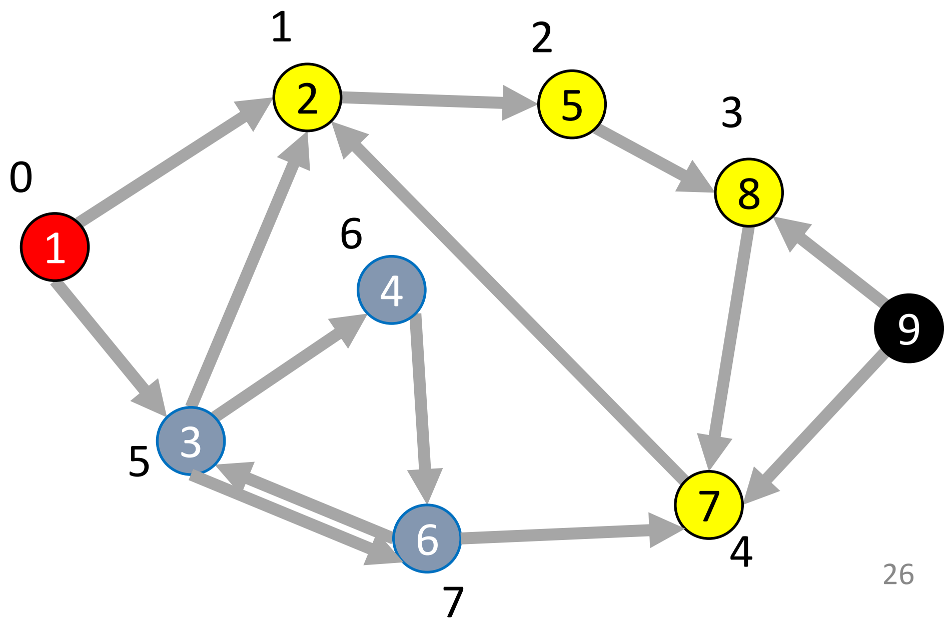
Depth-First Search



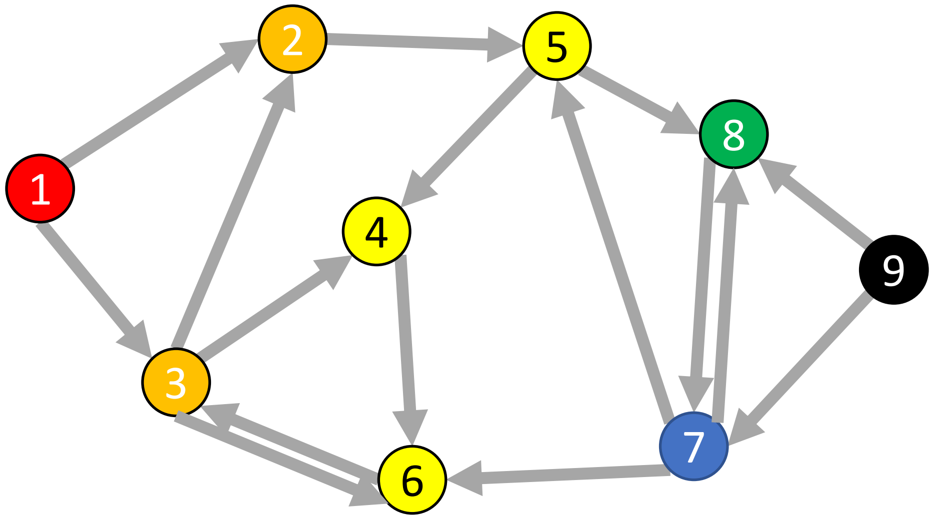
from node A, visit B, then visit everything reachable before moving on to C

Depth-First Search

- Input: a node s
- Behavior: Start with node s, visit one neighbor of s, then all nodes reachable from that neighbor of s, then another neighbor of s,…
- Output:
  - Does the graph have a cycle?
  - A **topological sort** of the graph.



DFS (non-recursive)

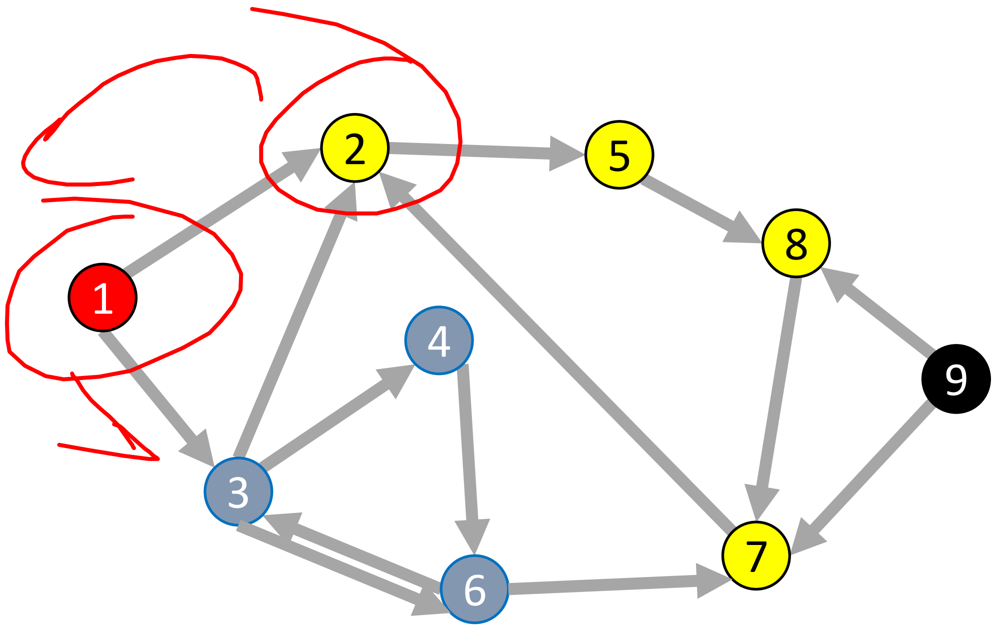



```
void dfs(graph, s){
        found = new Stack();
        found.pop(s);
        mark s as "visited";
        While (!found.isEmpty()){
                current = found.pop();
                for (v : neighbors(current)){
                        if (! v marked "visited"){
                                mark v as "visited";
                                found.push(v);
                        }
                }
        }
}
```

Running time: $\Theta(|V| + |E|)$

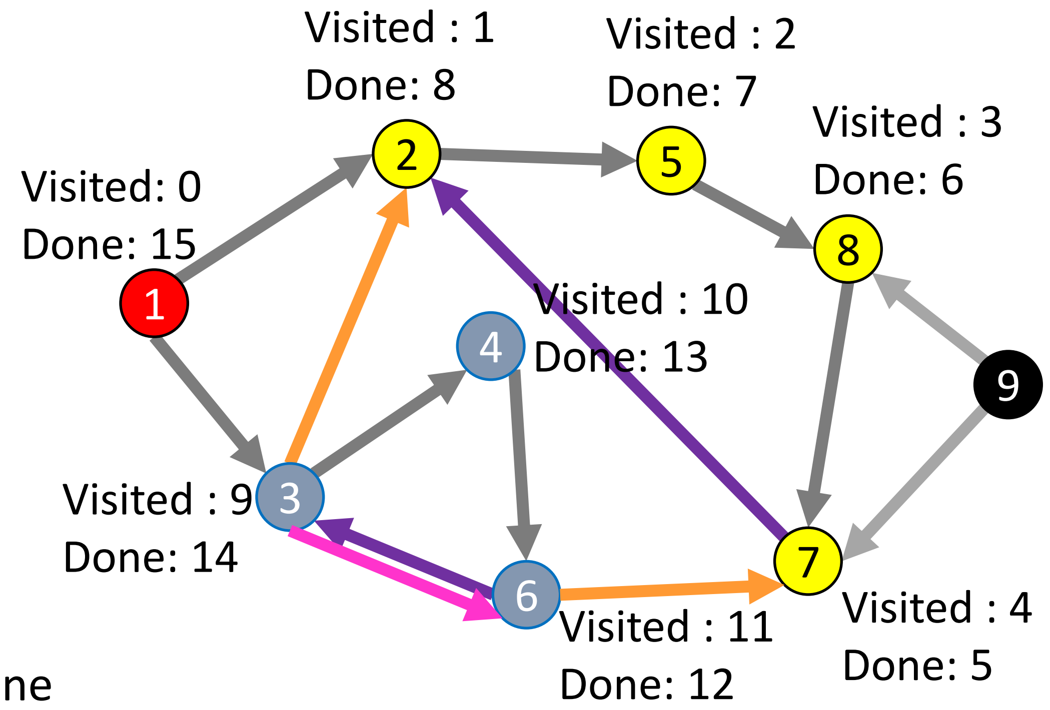
DFS Recursively (more common)

```
void dfs(graph, curr){
        mark curr as "visited";
        for (v : neighbors(current)){
                if (! v marked "visited"){
                        dfs(graph, v);
                }
        }
        mark curr as "done";
}
```



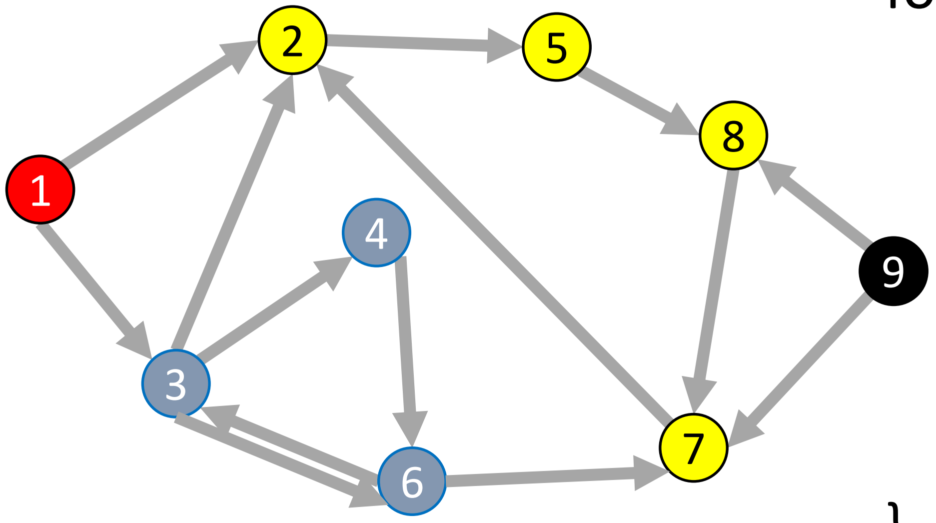
Using DFS

- Consider the "visited times" and "done times"
- Edges can be categorized:
  - Tree Edge
    - (a, b) was followed when pushing
    - (a, b) when b was unvisited when we were at a
  - Back Edge
    - (a, b) goes to an "ancestor"
    - a and b visited but not done when we saw (a, b)
    - $t_{visited}(b) < t_{visited}(a) < t_{done}(a) < t_{done}(b)$
  - Forward Edge
    - (a, b) goes to a "descendent"
    - b was visited and done between when a was visited and done
    - $t_{visited}(a) < t_{visited}(b) < t_{done}(b) < t_{done}(a)$
  - Cross Edge
    - (a, b) goes to a node that doesn't connect to a
    - b was seen and done before a was ever visited
    - $t_{done}(b) < t_{visited}(a)$



Cycle Detection

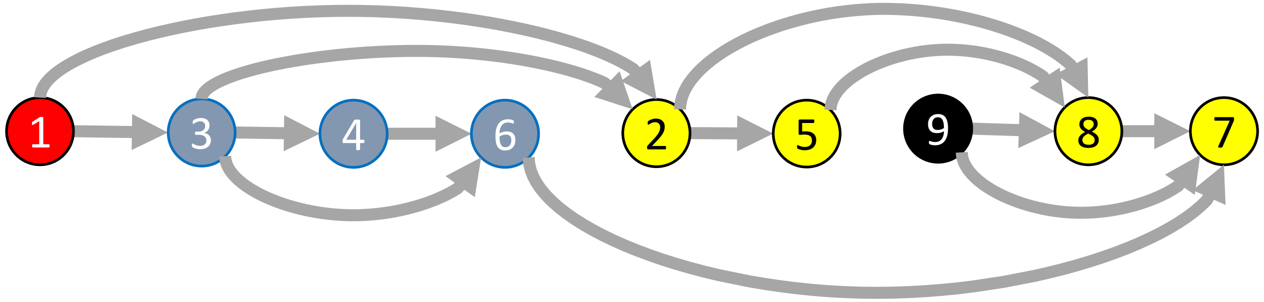
Idea: Look for a back edge!

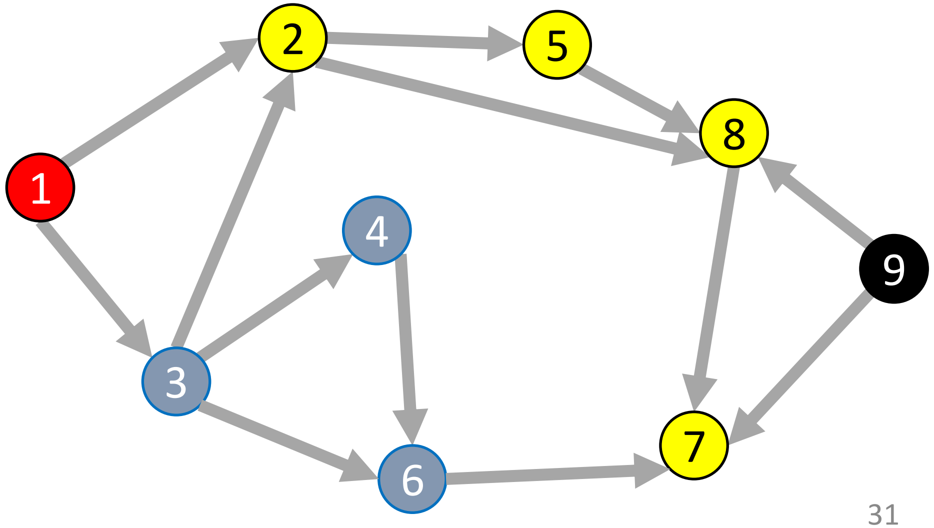



```
boolean hasCycle(graph, curr){
        mark curr as “visited”;
        cycleFound = false;
        for (v : neighbors(current)){
                if (v marked “visited” && ! v marked “done”){
                        cycleFound=true;
                }
                if (! v marked “visited” && !cycleFound){
                        cycleFound = hasCycle(graph, v);
                }
        }
        mark curr as “done”;
        return cycleFound;
}
```

Topological Sort

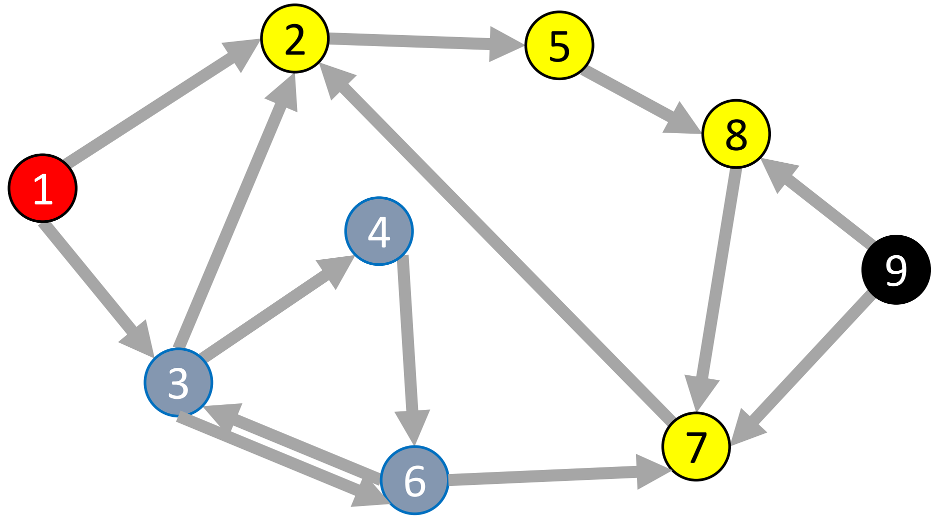
- A Topological Sort of a **directed acyclic graph** $\boldsymbol{G = (V, E)}$ is a permutation of V such that if $(u, v) \in E$ then u is before v in the permutation





DFS Recursively

```
void dfs(graph, curr){
        mark curr as "visited";
        for (v : neighbors(current)){
                if (! v marked "visited"){
                        dfs(graph, v);
                }
        }
        mark curr as "done";
}
```

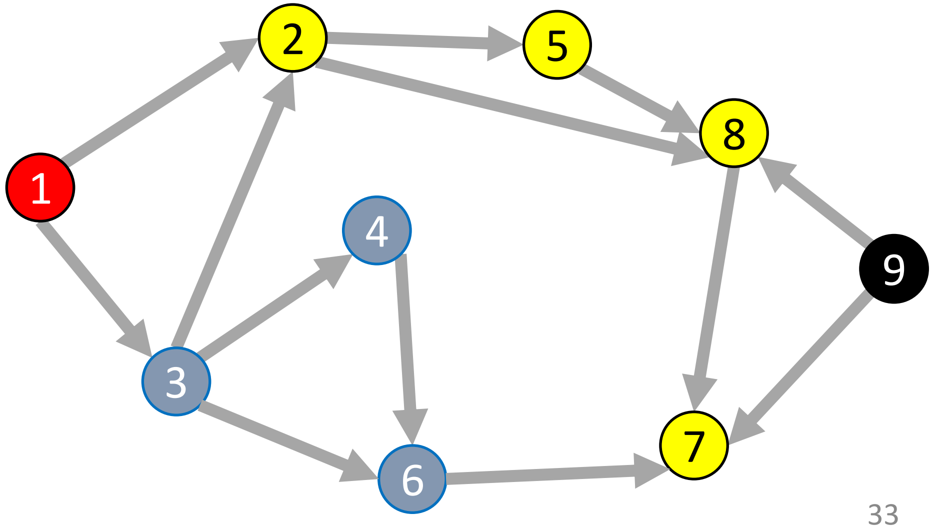


DFS: Topological sort

```
def dfs(graph, s):
        seen = [False, False, False, …] # length matches |V|
        done = [False, False, False, …] # length matches |V|
        dfs_rec(graph, s, seen, done)

def dfs_rec(graph, curr, seen, done):
        mark curr as seen
        for v in neighbors(current):
                if v not seen:
                        dfs_rec(graph, v, seen, done)
        mark curr as done
```

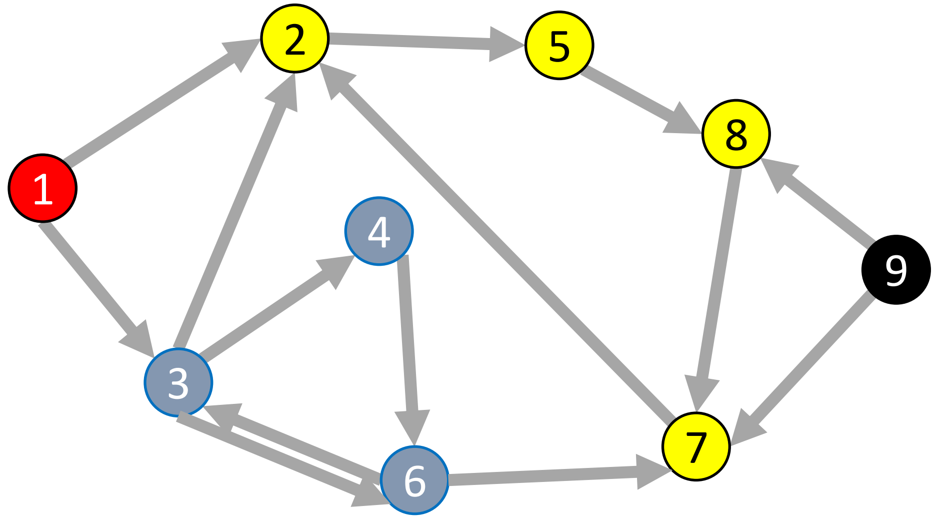
Idea: List in reverse order by finish time



DFS Recursively

```
void dfs(graph, curr){
        mark curr as "visited";
        for (v : neighbors(current)){
                if (! v marked "visited"){
                        dfs(graph, v);
                }
        }
        mark curr as "done";
}
```

Idea: List in reverse order by finish time



DFS: Topological sort

```
List topSort(graph){
        List<Nodes> finished = new List<>();
        for (Node v : graph.vertices){
                if (!v.visited){
                        finishTime(graph, v, finished);
                }
        }
        finished.reverse();
        return finished;
}

void finishTime(graph, curr, finished){
        curr.visited = true;
        for (Node v : curr.neighbors){
                if (!v.visited){
                        finishTime(graph, v, finished);
                }
        }
        finished.add(curr)
}
```

Idea: List in reverse order by finish time

finished: