Operating Systems

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Remember example from third week?

```
My_work(id_t id) {   /* id can be 0 or 1 */
      ...
     flag[id] = true;      /* indicate entering CS */
      while (flag[1-id]) ;/* entry section */
      /* critical section, access protected resource */
      flag[id] = false;    /* exit section */
      ...                  /* remainder section */
}
```

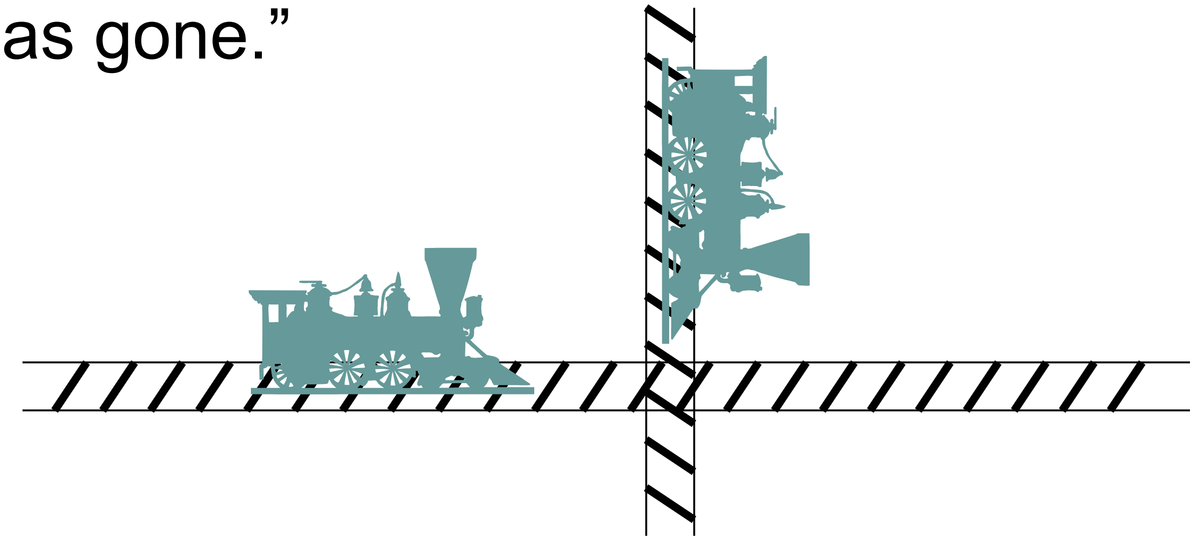
- What went wrong here?

Types of Resources

- Reusable
  - Can be used by one process at a time, released and used by another process
    - printers, memory, processors, files
    - Locks, semaphores, monitors
- Consumable
  - Dynamically created and destroyed
  - Can only be allocated once
    - e.g. interrupts, signals, messages

Not just an OS Problem!

- Law passed by Kansas Legislature in early 20th Century:
  - "When two trains approach each other at a crossing, both shall come to a full stop and neither shall start upon again until the other has gone."



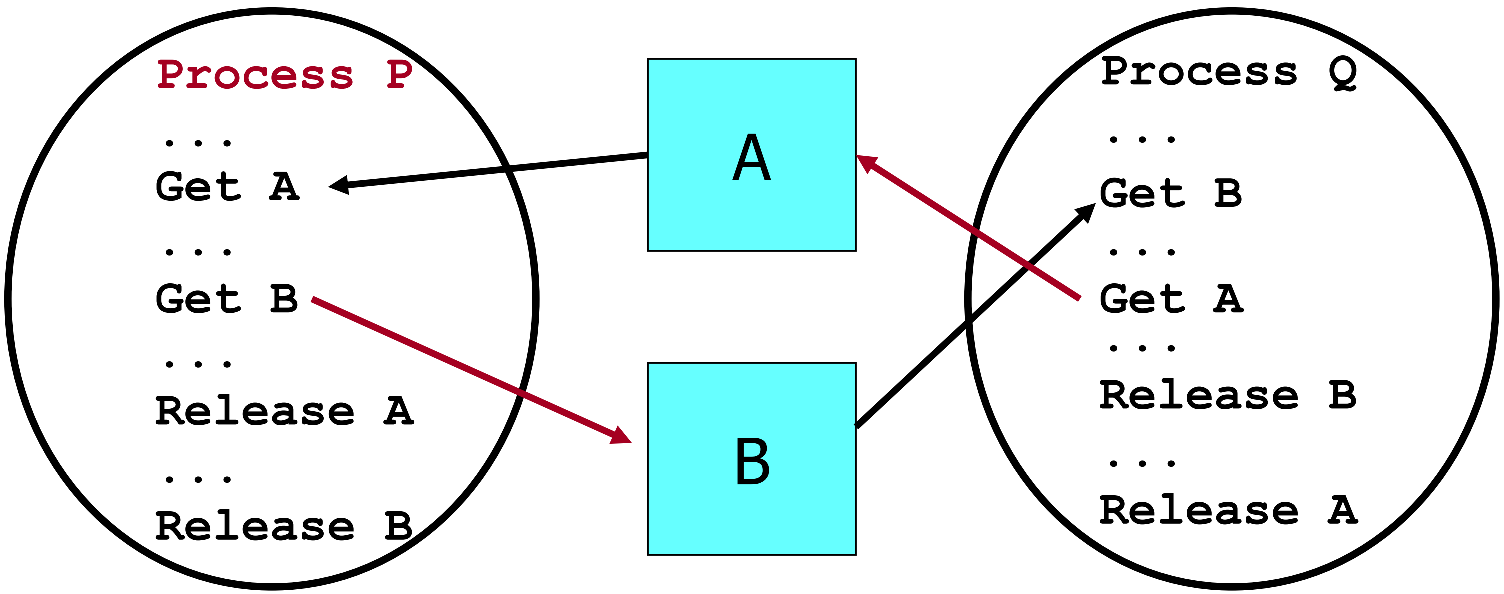
Deadlock Defined

- The *permanent* blocking of a set of processes that either:
  - Compete for system resources, or
  - Communicate with each other
- Each process in the set is blocked, waiting for an event which can only be caused by another process in the set
  - Resources are *finite*
  - Processes wait if a resource they need is unavailable
  - Resources may be held by other waiting processes

Example of Deadlock

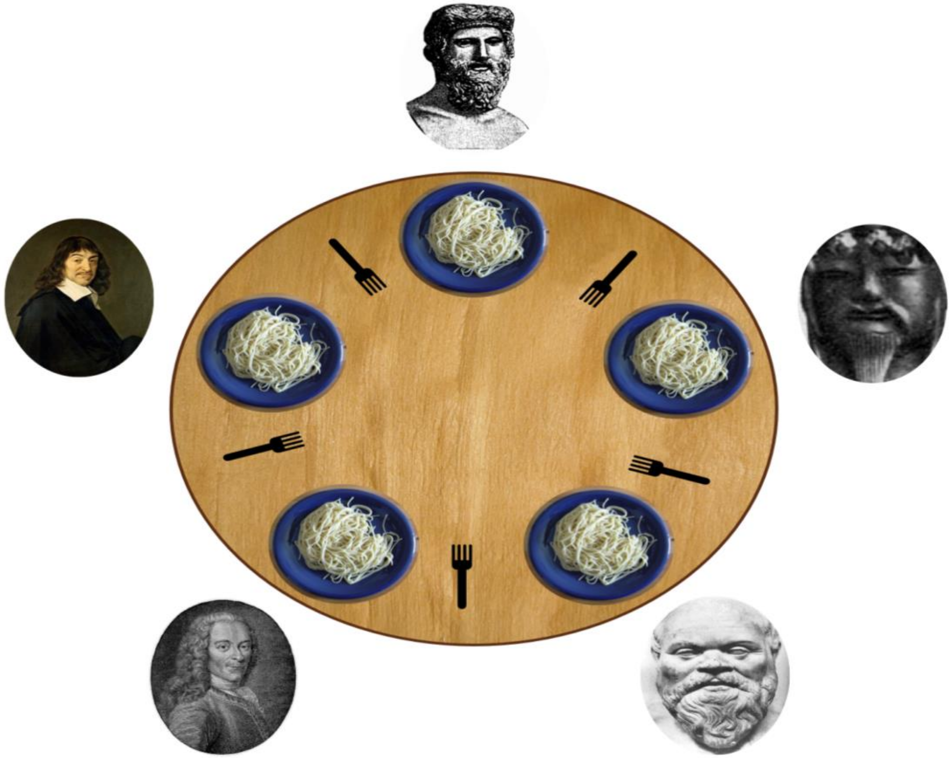
the process resource graph -> show if there is deadlock

- Suppose processes *P* and *Q* need (reusable) resources A and B:



red arrow -> waiting…
deadlock since both wait for resources that is acquired by the other process, …

Example: dining philosophers:



all grab left fork -> deadlock

- A philosopher needs two forks to eat.
- Idea for protocol:
  - When philosopher gets hungry grab right fork, then grab left fork.
- Is this a good solution?

Deadlock continued …

- What conditions must hold for a deadlock to occur?
  - Necessary conditions
  - Sufficient conditions

Conditions for Deadlock

1. Mutual Exclusion
   - Only one process may use a resource at a time
2. Hold and wait A processh holds a resource, and then await for a second resource
   - A process may hold allocated resources while awaiting assignment of others
3. No preemption
   - No resource can be forcibly removed from a process holding it

- These are *necessary* conditions

One more condition…

4. Circular wait — A cycle
   - A closed chain of processes exists, such that each process holds at least one resource needed by the next process in the chain

- Together, these four conditions are *necessary and sufficient* for deadlock

Solutions

- Prevention
- Avoidance
- Detection and Recovery
- Do Nothing!

Deadlock Prevention

- Ensure one of the four conditions doesn't occur
  - Break mutual exclusion - not much help here, as it is often required for correctness

Preventing Hold-and-Wait

1. hard to get all resources at once
2. do not know what resources required in dynamic systems

- Break “hold and wait” - processes must request all resources at once, and will block until entire request can be granted simultaneously
  - May wait a long time for all resources to be available at the same time
  - May hold resources for a long time without using them (blocking other processes)
  - May not know all resource requirements in advance
- An alternative is to release all currently-held resources when a new one is needed, then make a request for the entire set of resources

Preventing No-Preemption

need to maintain state to keep track of which resources assigned

- Break “no preemption” - forcibly remove a resource from one process and assign it to another
  - Need to save the state of the process losing the resource so it can recover later
  - May need to rollback to an earlier state

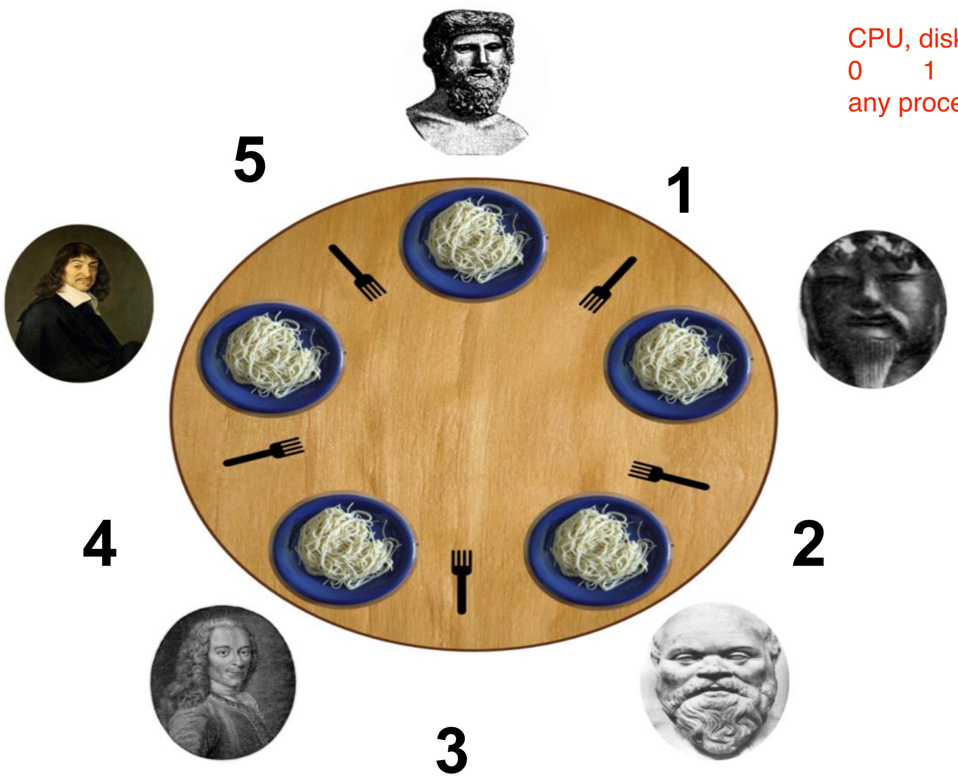
need space, time to store
for each operation, too expensive

  - Name some resources that this works for…
  - Name some resources for which this is hard…
  - Impossible for consumable resources

Preventing Circular-wait

- Break "circular wait" - assign a linear ordering to resource types and require that a process holding a resource of one type, *R*, can only request resources that follow *R* in the ordering

CPU, disk, memory, …
0 1 2, ….
any process has to acquire resources in some ordering



Preventing Circular-wait

- Break "circular wait" - assign a linear ordering to resource types and require that a process holding a resource of one type, *R,* can only request resources that follow *R* in the ordering
  - e.g. R_i precedes R_j if $i < j$
  - For deadlock to occur, need P to hold R_i and request R_j, while Q holds R_j and requests R_i
  - This implies that $i < j$ (for P's request order) and $j < i$ (for Q's request order), which is impossible.
- Hard to come up with total order when there are lots of resource types

Deadlock Avoidance

- All prevention strategies are unsatisfactory in some situations
- *Avoidance* allows the first three conditions, but orders events to ensure circular wait does not occur
  - How is this different from preventing circular wait?
- Requires knowledge of future resource requests to decide what order to choose
  - Amount and type of information varies by algorithm

need to know need of resources for all processes (regardless when they request it)
dont care about the order of resource request (unlike prevention)

Two Avoidance Strategies

1. Do not start a process if its maximum resource requirements, together with the maximum needs of all processes already running, exceed the total system resources
   - Pessimistic, assumes all processes will need all their resources at the same time
2. Do not grant an individual resource request if it might lead to deadlock

Safe States

- A state is *safe* if there is at least one sequence of process executions that does not lead to deadlock, *even if every process requests their maximum allocation immediately*
- Example: 3 processes, 1 resource type, 10 instances

resource count taken

T0: Available = 3
T1: Available = 1
T2: Available = 5
T3: Available = 0
T4: Available = 7

PID	Alloc	Max Claim
A	3	9
B	~~2~~ ~~4~~ 0	4
C	~~2~~ ~~7~~ 0	7

Unsafe States & Algorithm

- An unsafe state is one which is not safe
  - Is this the same as a deadlocked state?
- Deadlock avoidance algorithm
  - For every resource request
    - Update state assuming request is granted
    - Check if new state is safe
    - If so, continue
    - If not, restore the old state and block the process until it is safe to grant the request
- This is the banker's algorithm
  - Processes must declare maximum needs
  - See text for details of the algorithm

initially, state is safe,
then start from a safe state, look at all possible allocations to find a safe execution pattern, i.e. the next safe state

Restrictions on Avoidance

- Maximum resource requirements for each process must be known in advance
- Processes must be independent
  - If order of execution is constrained by synchronization requirements, system is not free to choose a safe sequence
- There must be a fixed number of resources to allocate

still have to maintain the state

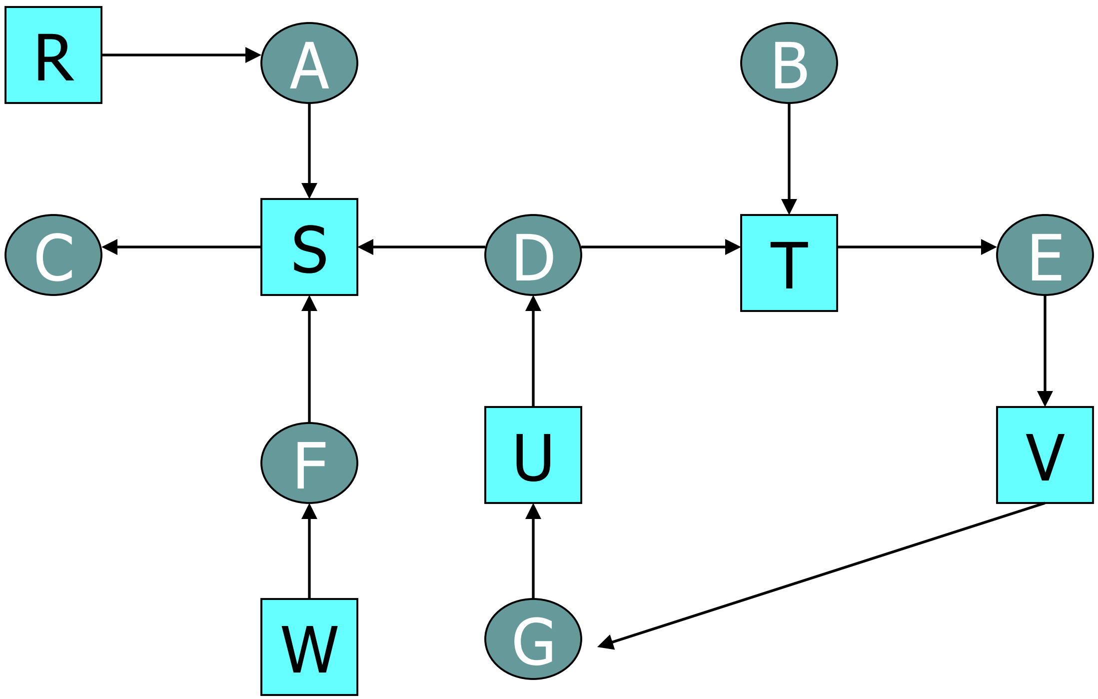
Deadlock Detection & Recovery

- Prevention and avoidance is awkward and costly
  - Need to be cautious, thus low utilization
- Instead, allow deadlocks to occur, but detect when this happens and find a way to break it
  - Check for circular wait condition periodically
- When should the system check for deadlocks?

Deadlock Detection & Recovery

- How can you detect a deadlock?

Draw resource alloc graph



- Check for cycles in resource allocation graph

Deadlock Detection

- Finding circular waits is equivalent to finding a cycle in the *resource allocation graph*
  - Nodes are processes (drawn as circles) and resources (drawn as squares)
  - Arcs from a resource to a process represent allocations
  - Arcs from a process to a resource represent ungranted requests
- Any algorithm for finding a cycle in a directed graph will do
  - note that with multiple instances of a type of resource, cycles may exist without deadlock

Deadlock Recovery

- Basic idea is to break the cycle
  - Drastic - kill all deadlocked processes
  - Painful - back up and restart deadlocked processes (hopefully, non-determinism will keep deadlock from repeating)
  - Better - selectively kill deadlocked processes until cycle is broken
    - Re-run detection alg. after each kill
  - Tricky - selectively preempt resources until cycle is broken
    - Processes must be rolled back

have to maintain state, and rollback to a previous state

Reality Check

- No single strategy for dealing with deadlock is appropriate for all resources in all situations
- All strategies are costly in terms of computation overhead, or restricting use of resources
- Most operating systems employ the “Ostrich Algorithm”
  - Ignore the problem and hope it doesn’t happen often

Why does the Ostrich Alg work?

virtualization (like paging) let the underlying OS manage allocation (evict page) and the user application assumes an infinite (large enough….) resource.

- Recall causes of deadlock:
  - Resources are *finite*
  - Processes wait if a resource they need is unavailable
  - Resources may be held by other waiting processes
- Prevention/Avoidance/Detection mostly deal with last 2 points
- Modern operating systems virtualize most physical resources, eliminating the first problem
  - Some logical resources can't be virtualized (there has to be exactly one), such as bank accounts or the process table
    - These are protected by synchronization objects, which are now the only resources that we can deadlock on

What is atomicity?

- Recall ATM banking example:
  - Concurrent deposit/withdrawal operation
  - Need to protect shared account balance
- What about transferring funds between accounts?
  - Withdraw funds from account A
  - Deposit funds into account B
- Should appear as a single **atomic** operation
  - Another process reading the account balances should see either both updates, or none
  - Either both operations complete, or neither does

Why would atomicity fail?

- Suppose fund transfer is implemented by our known withdraw and deposit functions using locks.

```
Withdraw(acct, amt) {
    acquire(lock);
    balance = get_balance(acct);
    balance = balance - amt;
    put_balance(acct,balance);
    release(lock);
    return balance;
}
```

```
Deposit(acct, amt) {
    acquire(lock);
    balance = get_balance(acct);
    balance = balance + amt;
    put_balance(acct,balance);
    release(lock);
    return balance;
}
```

```
Transfer (acctA, acctB, amt) {

    Withdraw (acctA,amt);
    Deposit (acctB,amt;
}
```

- What can go wrong?

Definitions for Transactions

- Defn: Transaction
  - A collection of operations that performs a single logical function and are executed **atomically**
  - Here: a sequence of **read** and **write** operations, terminated by a **commit** or **abort**
- Defn: Committed
  - A transaction that has completed successfully;
  - **All** operations took effect
  - Once committed, a transaction cannot be undone
- Defn: Aborted
  - A transaction that did not complete normally
  - **None** of the operations took effect

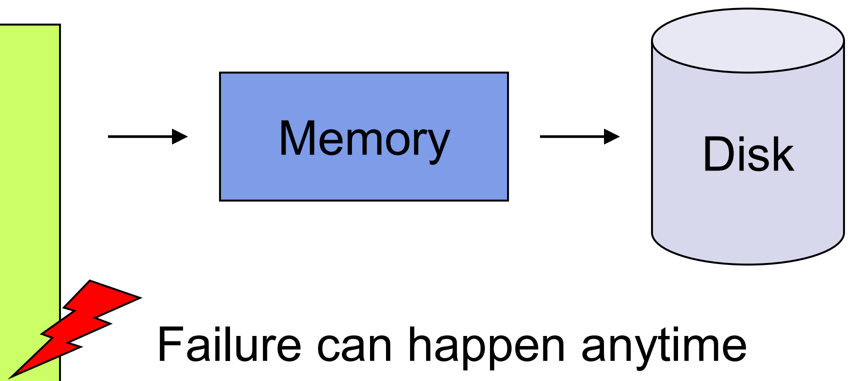
a no-op

How to ensure atomicity in the face of failures?

```
Xct: begin

    Read(A)
    Read(B)
    Read(C)
    Write(A)
    Write(B)
    Write(C)

Xct: commit
```



- Write intended operation to a *log* on **stable** storage
- Then execute the actual operation
- Log can be used to undo/redo any transaction, allowing recovery from arbitrary failures

Write-ahead log

<T_i begins>

<A_old, A_new>

<B_old, B_new>

<C_old, C_new>

<T_i commits>

Write-ahead logging

- Before performing any operations on the data, write the intended operations to a *log* on stable storage
- Log records identify the transaction, the data item, the old value, and the new value
- Special records indicate the *start* and *commit* (or *abort*) of a transaction
- Log can be used to undo/redo the effect of any transactions, allowing recovery from arbitrary failures

Problems with logging …

- Limitations of basic log strategy:
  - Time-consuming to process entire log after failure
  - Large amount of space required by log
  - Performance penalty – each write requires a log update before the data update
- **Checkpoints** help with first two problems
  - Periodically write all updates to log and data to stable storage; write a *checkpoint* entry to the log
  - Recovery only needs to look at log since last ckpt.

instead of log on every operation, do it once in a while

Concurrent Transactions

w

- Transactions must appear to execute in some arbitrary but serial order
  - Soln 1: All transactions execute in a critical section, with a single common lock (or mutex semaphore) to protect access to all shared data.
    - But most transactions will access different data
    - Limits concurrency unnecessarily
  - Soln 2: Allow operations from multiple transactions
    - To overlap, as long as they don't conflict
    - End result of a set of transactions must be indistinguishable from Solution 1

Conflicting Operations

- Operations in two different transactions conflict if both access the same data item and at least one is a write
  - Non-conflicting operations can be reordered (swapped with each other) without changing the outcome
  - If a serial schedule can be obtained by swapping non-conflicting operations, then the original schedule is conflict-serializable

Conflict Serializability

- Is there an equivalent serial execution of T0 and T1 ?

T_0	T_1
read(A)	
write(A)	
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)

Look for writes
+ A's final value determined by T_1
+ B's final value determined by T_1

the schedule is a concurrent schedule, and is conflict-serializable,

Conflict Serializabile?

a serial schedule, i.e. a transaction is made
to execute to finish all its operations

T_0	T_1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Yes

T_0	T_1
	read(A)
	write(A)
	read(B)
	write(B)
read(A)	
write(A)	
read(B)	
write(B)	

No

Ensuring serializability

pessimistic, before do anything, gets the lock

- Two-phase locking assumes conflict-serializable
  - Individual data items have their own locks
  - Each transaction has a growing phase and shrinking phase:
    - Growing: a transaction may obtain locks, but may not release any lock
    - Shrinking: a transaction may release locks, but may not acquire any new locks.
  - Does not guarantee deadlock-free

Example of 2 phase locking

Transaction_start

Lock(A)

Read(A)

Lock(B) Growing

Read(B)

Lock(C)

owns all locks required for this transaction

Unlock(A)

Unlock(B) Shrinking

Write(C)

Unlock(C)

Transaction_end

allows transaction run concurrently while enforcing serialization

Timestamp Protocols

- Each transaction gets unique *timestamp* before it starts executing
  the start time
  - Transaction with "earlier" timestamp must appear to complete before any later transactions
- Each data item has two timestamps
  - W-TS: the largest timestamp of any transaction that successfully wrote the item
  - R-TS: the largest timestamp of any transaction that successfully read the item

Timestamp Ordering

No locking

- Reads:

  a read transaction that comes earlier (smaller TS) should not read a data that was previously modified

  - If transaction has "earlier" timestamp than W-TS on data, then transaction needs to read a value that was already overwritten
    - Abort transaction, restart with new timestamp

- Writes:

  the conflicting transaction restart -> re-do all operation for that transaction operation in memory (so not a rollback in disk)

  - If transaction has "earlier" timestamp than R-TS (W-TS) on data, then the value produced by this write should have been read (overwritten) already!
    - Abort & restart
- Some transactions may "starve" (abort & restart repeatedly)

too many aborts

Deadlock and Starvation

- A set of threads is in a deadlocked state when every process in the set is waiting for a event that can be caused only by another process in the set
- A thread is suffering starvation (or indefinite postponement) if it is waiting indefinitely because other threads are in some way preferred

Communication Deadlocks

- Messages between communicating processes are a consumable resource
- Example:
  - Process B is waiting for a request
  - Process A sends a request to B, and waits for reply
  - The request message is lost in the network
  - B keeps waiting for a request, A keeps waiting for a reply, we have a deadlock
- Solution: Use timeouts and protocols to detect duplicate messages

Livelock

- Occurs when a set of processes continually retry some failed operation and prevent other processes in the set from making progress
- Functionally equivalent to deadlock
  - Ex 1: two processes each request the same two spinlocks in the opposite order
    - Each succeeds in first acquire, then spins
    - CPU utilization is high, but no progress
  - Ex 2: A set of processes retries a failed fork()
    - operation when the process table is full
    - No process exits, so fork() keeps failing