Operating Systems

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U of T

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 */
}
```

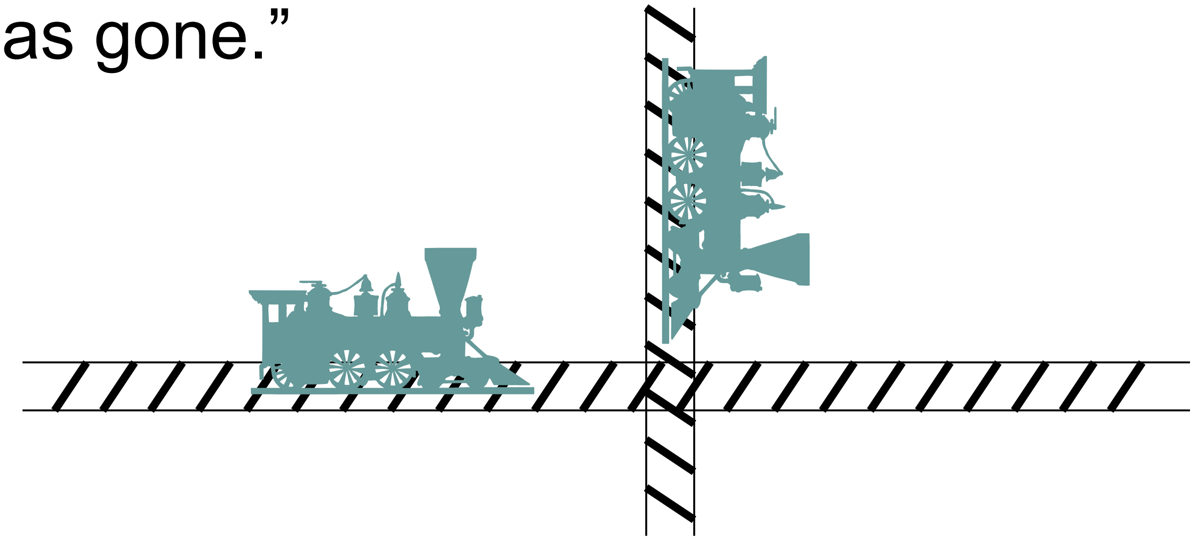
- What went wrong here?

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.”

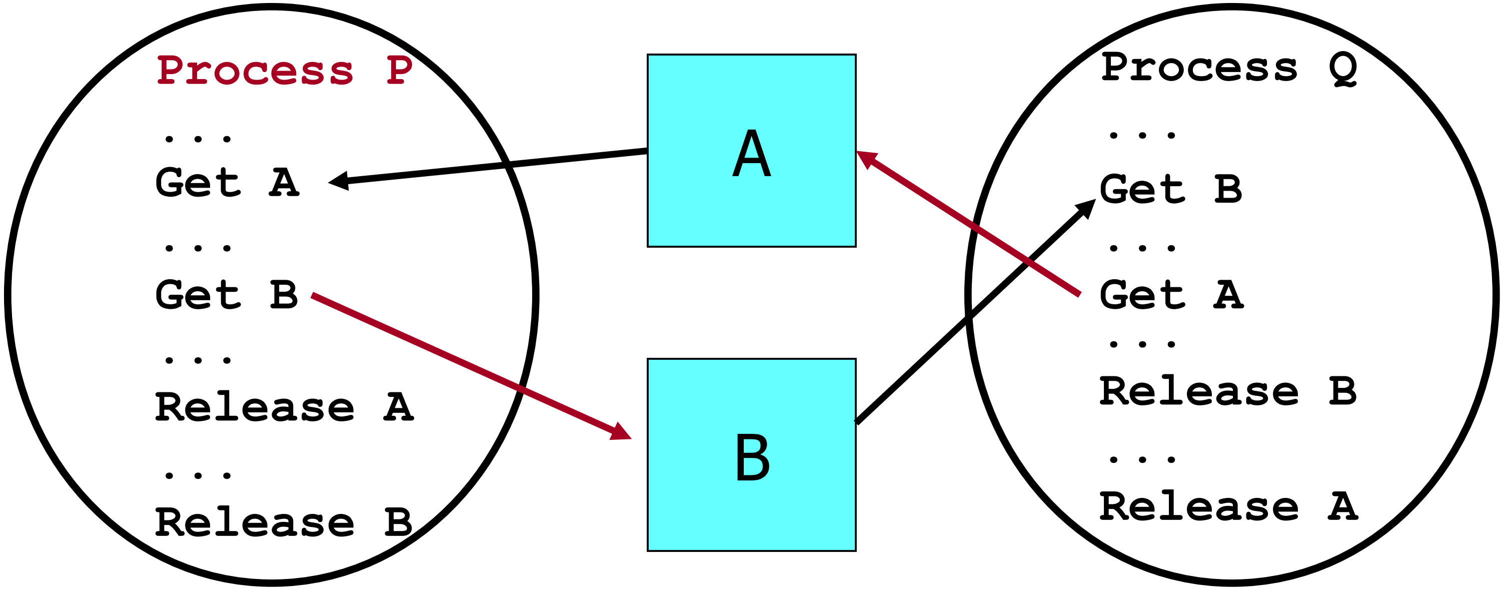


Deadlock Defined

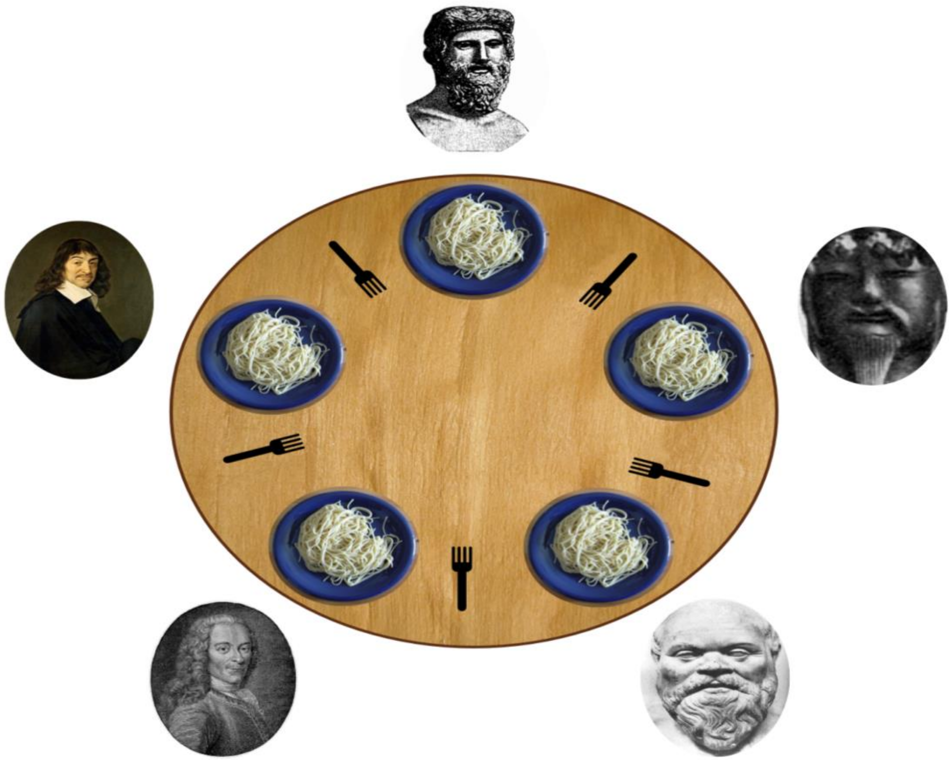
- The *permanent* blocking of a set of processes that either:
  - Compete for system resources, or
  - Communicate with each other
- Each process in the set is blocked, waiting for an event which can only be caused by another process in the set
  - Resources are *finite*
  - Processes wait if a resource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

Example of Deadlock

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



Example: dining philosophers:



- 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 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 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

- 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

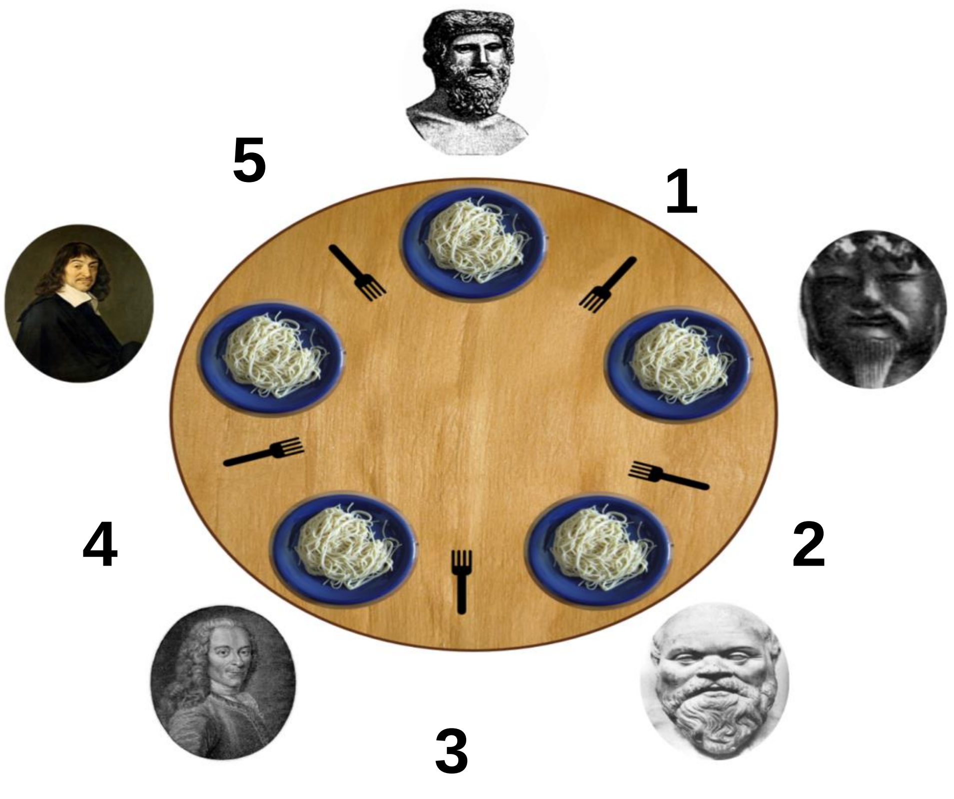
Preventing No-Preemption

- 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

  - 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



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

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

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

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

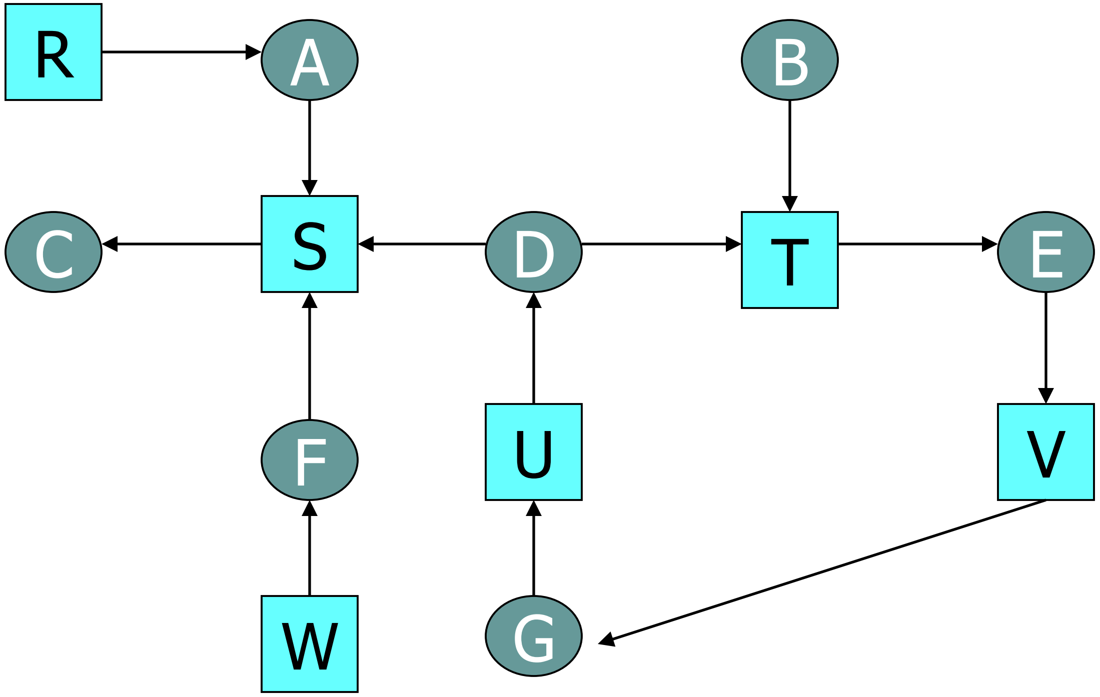
Deadlock Detection & Recovery

- 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

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?

- 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;
}
```

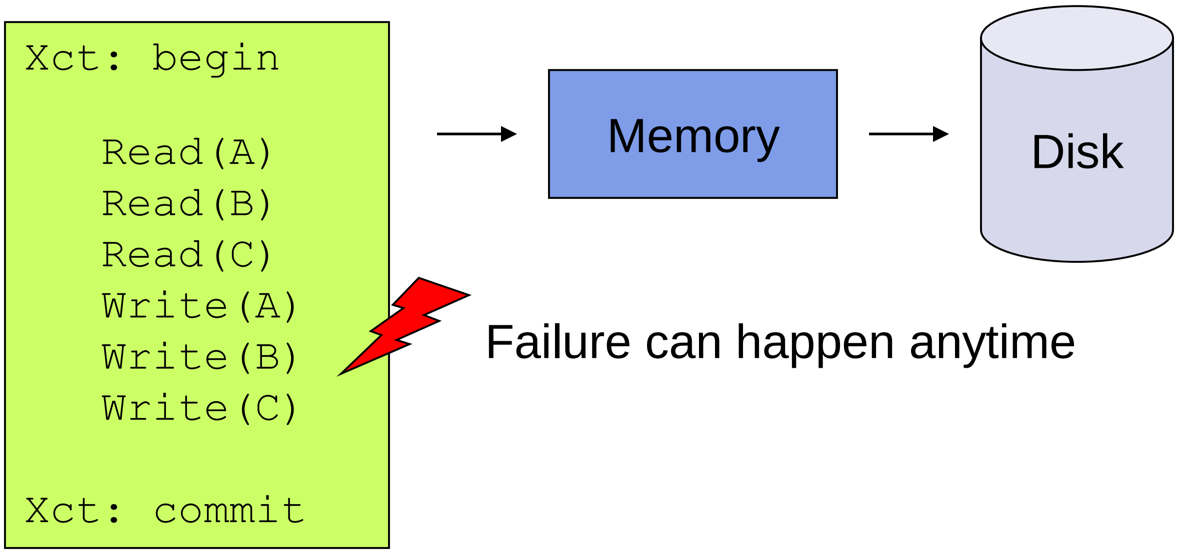
```
Transfer (acctA, acctB, amt) {

    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

How to ensure atomicity in the face of failures?



- 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.

Concurrent Transactions

- 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)

Conflict Serializabile?

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

- Two-phase locking
  - 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)

Read(B)

Lock(C)

Unlock(A)

Unlock(B)

Write(C)

Unlock(C)

Transaction_end

Growing: Lock(A) … Lock(C)

Shrinking: Unlock(A) … Unlock(C)

Timestamp Protocols

- Each transaction gets unique *timestamp* before it starts executing
  - 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

- Reads:
  - 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:
  - 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)

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