Deadlock Conditions (Review)

- These 4 conditions are **necessary** and **sufficient** for deadlock to occur:
  - **Mutual exclusion** — if one process holds a resource, other processes requesting that resource must wait until the process releases it (only one can use it at a time)
  - **No preemption** — resources are released voluntarily; neither another process nor the OS can force a process to release a resource
  - **Hold and wait** — processes are allowed to *hold* one (or more) resource and be *waiting* to acquire additional resources that are being held by other processes
  - **Circular wait** — there must exist a set of waiting processes such that P0 is waiting for a resource held by P1, P1 is waiting for a resource held by P2, … Pn-1 is waiting for a resource held by Pn, and Pn is waiting for a resource held P0

Deadlock Prevention

- Basic idea: ensure that one of the 4 conditions for deadlock can not hold
- **Mutual exclusion** — if one process holds a resource, other processes requesting that resource must wait until the process releases it
  - Hard to avoid mutual exclusion for non-sharable resources
    - Printer & other I/O devices
    - Files
    - Network connections
  - However, many resources are sharable, so deadlock can be avoided for them
    - Read-only files (binaries, perhaps)
    - Most files in your account
  - For printer, avoid mutual exclusion through spooling — then process won't have to wait on physical printer

Deadlock Prevention (cont.)

- **Circular wait** — there must exist a set of waiting processes such that P0 is waiting for a resource held by P1, P1 is waiting for a resource held by P2, … Pn-1 is waiting for a resource held by Pn, and Pn is waiting for a resource held P0
  - To avoid, impose a total order on all resources, and require process to request resource in that order
    - Order: disk drive, printer, CDROM
    - Process A requests disk drive, then printer
    - Process B requests disk drive, then printer
    - Process B does <u>not</u> request printer, then disk drive, which could lead to deadlock
  - Order should be in the logical sequence that the resources are usually acquired
    - Allow process to release all resources, and start request sequence over
    - Or force process to request total number of each resource in a single request

Deadlock Prevention (cont.)

- **No preemption** — resources are released voluntarily; neither another process nor the OS can force a process to release a resource
  - To avoid, allow preemption
    - If process A requests resources that aren't available, see who holds those resources
      - If the holder (process B) is waiting on additional resources, preempt the resource requested by process A
      - Otherwise, process A has to wait
        - » While waiting, some of its current resources may be preempted
        - » Can only wake up when it acquires the new resources plus any preempted resources
    - If a process requests a resource that can not be allocated to it, **all** resources held by that process are preempted
      - Can only wake up when it can acquire all the requested resources
    - Only works for resources whose state can be saved/restored (memory, not printer)

Deadlock Prevention (cont.)

- **Hold and wait** — processes are allowed to *hold* one (or more) resource and be *waiting* to acquire additional resources that are being held by other processes
  - To avoid, ensure that whenever a process requests a resource, it doesn't hold any other resources
    - Request all resources (at once) at beginning of process execution
      - Process which loops forever?
    - Request all resources (at once) at any point in the program
    - To get a new resource, release all current resources, then try to acquire new one plus old ones all at once
  - Difficult to know what to request in advance
  - Wasteful; ties up resources and reduces resource utilization
  - Starvation is possible

Atomic Transactions

- A *transaction* (also called an *atomic transaction*) is a set of read, compute, and write operations that perform some logically complete task (from the field of databases)
  - Transactions must be prevented from interfering with one another
  - If a transaction terminates normally, its effects are permanent; otherwise it has no effect (I.e., there is failure recovery)
- Example transaction involving a client and three bank accounts A, B, and C:

  Withdraw(A, 100);
  Deposit(B, 100);
  Withdraw(C, 200);
  Deposit(B, 200);

  - Result is $100 transferred from A to B, and $200 transferred from C to

ACID Properties of a Transaction (Härder and Reuter, 1983)

- **A**tomicity — a transaction is either performed in its entirety or not at all; it appears to an outside observer as a single, instantaneous, indivisible action
- **C**onsistency — a transaction must take the database from one consistent state to another; invariants that should always hold will hold after the transaction
- **I**solated (Serializable) — if two transactions run at the same time, the result must look as if they ran sequentially in some arbitrary order; a transaction's updates must not be visible to other transactions until it commits
- **D**urable — once a transaction commits, its result is permanent (must never be lost)

Transaction Primitives

- Begin transaction — start a transaction
- Operations
  - Read — read data from a file or object
  - Write — write data to a file or object
  - Computation, or other operations appropriate to the type of transaction…
- Commit and end transaction — save updates and terminate the transaction
  - Changes are permanently recorded; all future transactions will see the results of the changes made during the transaction
- Abort and end transaction — restore system state and terminate the transaction
  - None of the changes are visible in future transactions

Other Properties and Implications of Atomic Transactions

- Recoverability — the changes due to all completed transactions must be available in permanent storage (write to permanent storage before reporting the transaction complete)
  - If a server halts unexpectedly, when it wakes up again it aborts any uncommitted transactions, and recovers data values committed by recent transactions
- Server is responsible for synchronizing operations to ensure that the isolation / serializability requirement is met
  - Simple but unacceptable — perform each transaction sequentially
  - Harder but generally required — interleave operations of various transactions, while ensuring that isolation holds

Implementing Transactions, and Recovery from an Aborted Transaction

- Can't just update objects
  - Doesn't enforce atomicity
  - State can't be restored on abort
  - Multiple transactions will not be isolated
- When a process begins a transaction, give it a **private workspace**
  - Contains copies of all files and objects it needs
  - Changes are made to private copies
  - Commit changes originals, abort leaves originals untouched
  - Optimizations:
    - Don't copy objects read but not written
    - Copy only the file index (location of blocks on disk) and blocks actually written

Implementing Transactions, Recovery (cont.)

- Record changes in a **writeahead log**
  - Record in the writeahead log ("ahead" of the change)
    - Which transaction is making the change
    - Which file and block is being changed
    - Old and new values
  - *Immediate* update:
    - Operations record in log as described above, then update the actual data
    - If transaction aborts, must use log to *rollback* — restore original state
  - *Deferred* update:
    - Operations update local workspace
    - Commit writes record to log as described above, then updates the actual data
    - If transaction aborts, data remains unchanged
  - Log can also be used to recover from a crash (compare log to actual values to determine state at crash)

Need for Concurrency Control

- *Concurrency control* — allow two or more transactions to proceed concurrently, while preserving serializability (isolation)
- Lost update problem:
  - Account A = $100, B = $200, C = $300
    - Transaction T transfers $4 from A to B
    - Transaction U transfers $3 from C to B
    - Should end A = $96, B = $207, C = $297
  - U's update of B is lost:

Transaction T		Transaction U	
bal=read(A)	$100		
write(A,bal–4)	$96		
		bal=read(C)	$300
		write(C,bal–3)	$297
bal=read(B)	$200		
		bal=read(B)	$200
		write(B,bal+3)	$203
write(B,bal+4)	$204		

Need for Concurrency Control (cont.)

- Inconsistent retrievals problem:
  - Account A = $200, B = $200
    - Transaction T transfers $100 from A to B
    - Transaction U computes sum of all accounts in the bank
    - Should end A = $100, B = $300, total = $400+
  - U's retrievals are inconsistent because T has not completed the transfer when the sum is calculated:

Transaction T		Transaction U (part)	
bal=read(A)	$200		
write(A,bal–100)	$100		
		bal=read(A)	$100
		bal+=read(B)	$300
bal=read(B)	$200		
write(B,bal+100)	$300		

Concurrency Control — Enforcing Serializability

- Lost update problem:
  - Not interleaving updates:

Transaction T		Transaction U	
bal=read(A)	$100		
write(A,bal–4)	$96		
		bal=read(C)	$300
		write(C,bal–3)	$297
bal=read(B)	$200		
write(B,bal+4)	$204		
		bal=read(B)	$204
		write(B,bal+3)	$207

- Inconsistent retrievals problem:
  - Not interleaving transfer retrieval:

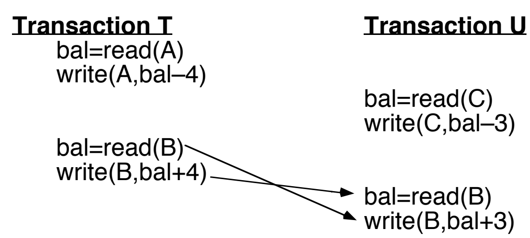
Transaction T		Transaction U (part)	
bal=read(A)	$200		
write(A,bal–100)	$100		
bal=read(B)	$200		
write(B,bal+100)	$300		
		bal=read(A)	$100
		bal+=read(B)	$400

Serializability

- A serializable schedule has the same result as one with no interleaving at all
  - Can we prove a schedule is serializable?
  - A *conflict* occurs when:
    - Both transactions access the same variable, and
    - At least one of those accesses is a write
  - When all conflicts happen in the same order (T before U or U before T), then the schedule is serializable; otherwise not.
- In general, with > 2 transactions, we can build a *conflict serializability graph*
  - Each transaction is a node of the graph
  - For each conflict, draw an arc from the earlier transaction to the later transaction.
  - If this graph has a cycle, then the schedule is *not serializable*

Serializability Testing

- Draw a downward (forward in time) arrow for each conflict. If all arrows point the same way, then the schedule is serializable



- If at least one arrow is pointing leftward and another arrow is pointing rightward, the schedule is *not serializable*