Dealing with Deadlock
(Review)

- The Ostrich Approach — stick your head in the sand and ignore the problem
- Deadlock avoidance — consider resources and requests, and only fulfill requests that will not lead to deadlock
  - Too hard for centralized systems, even harder in distributed systems!!
- Deadlock prevention — eliminate one of the 4 deadlock conditions
- Deadlock detection and recovery — detect, then break the deadlock
  - More difficult when state is distributed
    - Must avoid reporting false deadlock
  - In distributed systems, we typically assume single resource instances

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)
  - 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
  - No preemption — resources are released voluntarily; neither another process nor the OS can force a process to release a resource
  - 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 those resources
    - Read-only files
  - 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 not 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)

- **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 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

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)

- **Atomicity** — a transaction is either performed in its entirety or not at all; it appears to an outside observer as a single, instantaneous, indivisible action
- **Consistency** — a transaction must take the database from one consistent state to another; invariants that should always hold will hold after the transaction
- **Isolated** (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
- **Durable** — once a transaction commits, its result is permanent (must never be lost)
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

Transaction Primitives

- Begin transaction — start a transaction
- Operations
  - Read — read data from a file or object
  - Write — write data to a file or object
  - Others 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

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:

<table>
<thead>
<tr>
<th>Transaction T</th>
<th>Transaction U</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal=read(A) $100</td>
<td>bal=read(A) $200</td>
</tr>
<tr>
<td>write(A,bal–4) $96</td>
<td>write(A,bal–100) $100</td>
</tr>
<tr>
<td>bal=read(C) $300</td>
<td>bal+=read(A) $100</td>
</tr>
<tr>
<td>write(C,bal–3) $297</td>
<td>bal+=read(B) $300</td>
</tr>
<tr>
<td>bal=read(B) $200</td>
<td>bal=read(B) $200</td>
</tr>
<tr>
<td>write(B,bal+4) $204</td>
<td>write(B,bal+3) $207</td>
</tr>
</tbody>
</table>

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:

<table>
<thead>
<tr>
<th>Transaction T</th>
<th>Transaction U (part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal=read(A) $200</td>
<td>bal=read(A) $100</td>
</tr>
<tr>
<td>write(A,bal–100) $100</td>
<td>bal+=read(A) $100</td>
</tr>
<tr>
<td>bal=read(B) $200</td>
<td>bal=read(B) $300</td>
</tr>
<tr>
<td>write(B,bal+100) $300</td>
<td>bal=read(B) $200</td>
</tr>
<tr>
<td>bal=read(A) $100</td>
<td>bal+=read(B) $400</td>
</tr>
</tbody>
</table>

Concurrency Control — Enforcing Serializability

- Lost update problem:
  - Not interleaving updates:

<table>
<thead>
<tr>
<th>Transaction T</th>
<th>Transaction U</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal=read(A) $100</td>
<td>bal=read(A) $200</td>
</tr>
<tr>
<td>write(A,bal–4) $96</td>
<td>write(A,bal–100) $100</td>
</tr>
<tr>
<td>bal=read(C) $300</td>
<td>bal+=read(A) $100</td>
</tr>
<tr>
<td>write(C,bal–3) $297</td>
<td>bal+=read(B) $300</td>
</tr>
<tr>
<td>bal=read(B) $200</td>
<td>bal=read(B) $200</td>
</tr>
<tr>
<td>write(B,bal+4) $204</td>
<td>write(B,bal+3) $207</td>
</tr>
</tbody>
</table>

- Inconsistent retrievals problem:
  - Not interleaving transfer retrieval:

<table>
<thead>
<tr>
<th>Transaction T</th>
<th>Transaction U (part)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bal=read(A) $200</td>
<td>bal=read(A) $100</td>
</tr>
<tr>
<td>write(A,bal–100) $100</td>
<td>bal+=read(A) $100</td>
</tr>
<tr>
<td>bal=read(B) $200</td>
<td>bal=read(B) $300</td>
</tr>
<tr>
<td>write(B,bal+100) $300</td>
<td>bal=read(B) $200</td>
</tr>
<tr>
<td>bal=read(A) $100</td>
<td>bal+=read(B) $400</td>
</tr>
</tbody>
</table>