# Last Class

- Distributed Snapshots
  - Termination detection
- Election algorithms
  - Bully
  - Ring

# Today: Still More Canonical Problems

- Distributed synchronization and mutual exclusion
- Distributed transactions

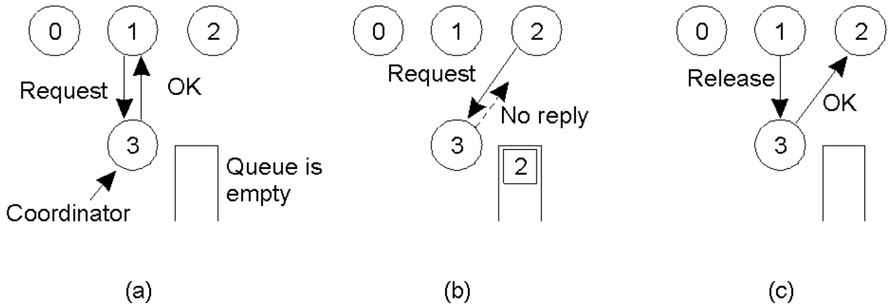
# Distributed Synchronization

- Distributed system with multiple processes may need to share data or access shared data structures
  - Use critical sections with mutual exclusion
- Single process with multiple threads
  - Semaphores, locks, monitors
- How do you do this for multiple processes in a distributed system?
  - Processes may be running on different machines
- Solution: lock mechanism for a distributed environment
  - Can be centralized or distributed

# Centralized Mutual Exclusion

- Assume processes are numbered
- One process is elected coordinator (highest ID process)
- Every process needs to check with coordinator before entering the critical section
- To obtain exclusive access: send request, await reply
- To release: send release message
- Coordinator:
  - Receive *request*: if available and queue empty, send grant; if not, queue request
  - Receive *release*: remove next request from queue and send grant

# Mutual Exclusion:
# A Centralized Algorithm



a) Process 1 asks the coordinator for permission to enter a critical region. Permission is granted

b) Process 2 then asks permission to enter the same critical region. The coordinator does not reply.

c) When process 1 exits the critical region, it tells the coordinator, when then replies to 2

# Properties

- Simulates centralized lock using blocking calls
- Fair: requests are granted the lock in the order they were received
- Simple: three messages per use of a critical section (request, grant, release)
- Shortcomings:
  - Single point of failure
  - How do you detect a dead coordinator?
    - A process can not distinguish between “lock in use” from a dead coordinator
      - No response from coordinator in either case
  - Performance bottleneck in large distributed systems

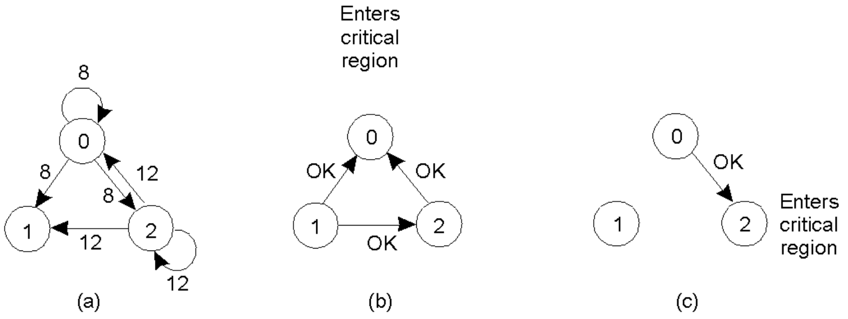
# Decentralized Algorithm

- Use voting
- Assume n replicas and a coordinator per replica
- To acquire lock, need majority vote $m > n/2$ coordinators
  - Non blocking: coordinators returns OK or “no”
- Coordinator crash => forgets previous votes
  - Probability that k coordinators crash $P(k) = {}^{m}C_{k}\, p^{k} (1-p)^{m-k}$
  - Atleast 2m-n need to reset to violate correctness
    - $\sum_{2m-n}^{n} P(k)$

# Distributed Algorithm

- [Ricart and Agrawala]: needs 2(n-1) messages
- Based on event ordering and time stamps
  - Assumes total ordering of events in the system (Lamport’s clock)
- Process *k* enters critical section as follows
  - Generate new time stamp $TS_k = TS_k+1$
  - Send *request*$(k,TS_k)$ all other *n-1* processes
  - Wait until *reply(j)* received from all other processes
  - Enter critical section
- Upon receiving a *request* message, process *j*
  - Sends *reply* if no contention
  - If already in critical section, does not reply, queue request
  - If wants to enter, compare $TS_j$ with $TS_k$ and send reply if $TS_k<TS_j$, else queue

# A Distributed Algorithm

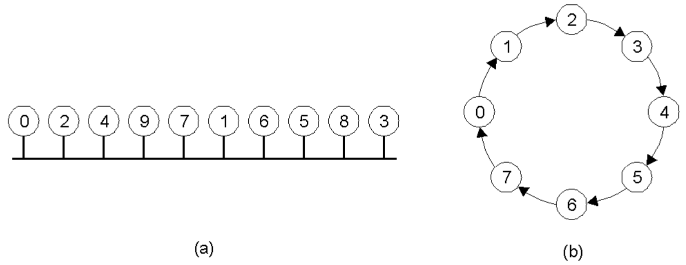


a) Two processes want to enter the same critical region at the same moment.
b) Process 0 has the lowest timestamp, so it wins.
c) When process 0 is done, it sends an OK also, so 2 can now enter the critical region.

# Properties

- Fully decentralized
- *N* points of failure!
- All processes are involved in all decisions
  - Any overloaded process can become a bottleneck

# A Token Ring Algorithm



a) An unordered group of processes on a network.
b) A logical ring constructed in software.

- Use a token to arbitrate access to critical section
- Must wait for token before entering CS
- Pass the token to neighbor once done or if not interested
- Detecting token loss in non-trivial

# Comparison

| Algorithm | Messages per entry/exit | Delay before entry (in message times) | Problems |
|---|---|---|---|
| Centralized | 3 | 2 | Coordinator crash |
| Decentralized | 3mk | 2m | starvation |
| Distributed | 2 ( n – 1 ) | 2 ( n – 1 ) | Crash of any process |
| Token ring | 1 to ∞ | 0 to n – 1 | Lost token, process crash |

- A comparison of four mutual exclusion algorithms.

# Transactions

- Transactions provide higher level mechanism for *atomicity* of processing in distributed systems
  - Have their origins in databases
- Banking example: Three accounts A:$100, B:$200, C:$300
  - Client 1: transfer $4 from A to B
  - Client 2: transfer $3 from C to B
- Result can be inconsistent unless certain properties are imposed on the accesses

| Client 1 | Client 2 |
|---|---|
| Read A: $100 | |
| Write A: $96 | |
| | Read C: $300 |
| | Write C:$297 |
| Read B: $200 | |
| | Read B: $200 |
| | Write B:$203 |
| Write B:$204 | |

# ACID Properties

- *Atomic:* all or nothing
- *Consistent*: transaction takes system from one consistent state to another
- *Isolated*: Immediate effects are not visible to other (serializable)
- *Durable:* Changes are permanent once transaction completes (commits)

| Client 1 | Client 2 |
|---|---|
| Read A: $100 | |
| Write A: $96 | |
| Read B: $200 | |
| Write B:$204 | |
| | Read C: $300 |
| | Write C:$297 |
| | Read B: $204 |
| | Write B:$207 |

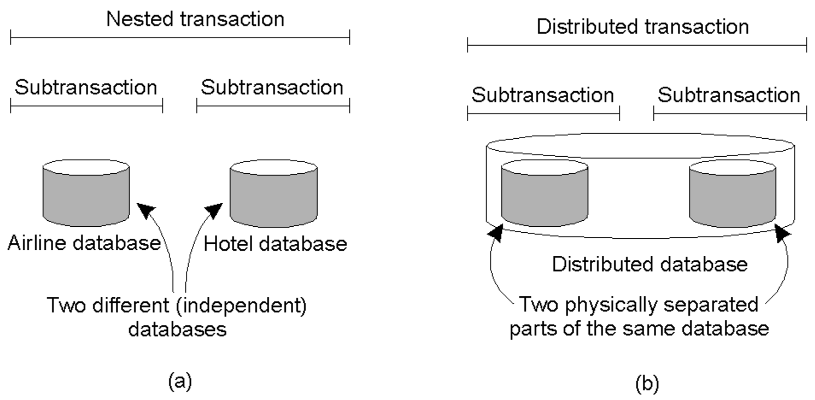
# Transaction Primitives

| **Primitive** | **Description** |
|---|---|
| BEGIN_TRANSACTION | Make the start of a transaction |
| END_TRANSACTION | Terminate the transaction and try to commit |
| ABORT_TRANSACTION | Kill the transaction and restore the old values |
| READ | Read data from a file, a table, or otherwise |
| WRITE | Write data to a file, a table, or otherwise |

Example: airline reservation

```
Begin_transaction
    if(reserve(NY,Paris)==full) Abort_transaction
    if(reserve(Paris,Athens)==full)Abort_transaction
    if(reserve(Athens,Delhi)==full) Abort_transaction
End_transaction
```

# Distributed Transactions

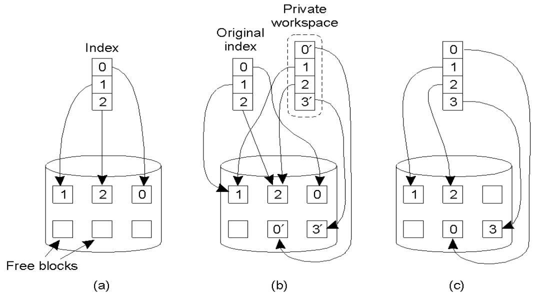


(a)

(b)

# Implementation: Private Workspace

- Each transaction get copies of all files, objects
- Can optimize for reads by not making copies
- Can optimize for writes by copying only what is required
- Commit requires making local workspace global



# Option 2: Write-ahead Logs

- *In-place updates*: transaction makes changes *directly* to all files/objects
- *Write-ahead log:* prior to making change, transaction writes to log on *stable storage*
  - Transaction ID, block number, original value, new value
- Force logs on commit
- If abort, read log records and undo changes [*rollback*]
- Log can be used to rerun transaction after failure

- Both workspaces and logs work for distributed transactions
- Commit needs to be *atomic* [will return to this issue in Ch. 7]

# Writeahead Log Example

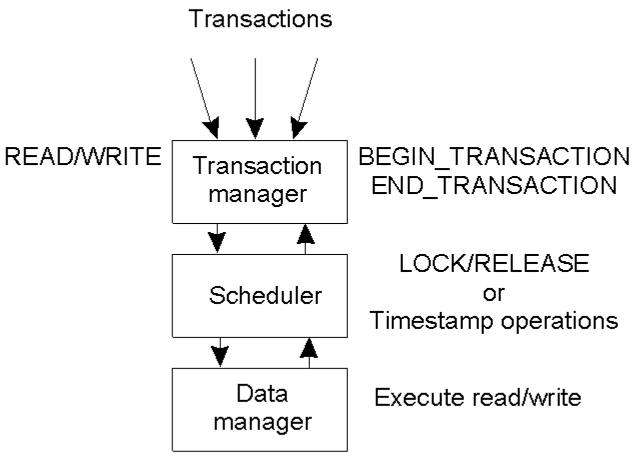
| x = 0; | Log | Log | Log |
|---|---|---|---|
| y = 0; | | | |
| BEGIN_TRANSACTION; | | | |
| x = x + 1; | [x = 0 / 1] | [x = 0 / 1] | [x = 0 / 1] |
| y = y + 2 | | [y = 0/2] | [y = 0/2] |
| x = y * y; | | | [x = 1/4] |
| END_TRANSACTION; | | | |
| (a) | (b) | (c) | (d) |

- a) A transaction
- b) – d) The log before each statement is executed

# Concurrency Control

- Goal: Allow several transactions to be executing simultaneously such that
  - Collection of manipulated data item is left in a consistent state
- Achieve consistency by ensuring data items are accessed in an specific order
  - Final result should be same as if each transaction ran sequentially
- Concurrency control can implemented in a *layered* fashion

# Concurrency Control Implementation



Transactions

READ/WRITE

Transaction manager

BEGIN_TRANSACTION
END_TRANSACTION

Scheduler

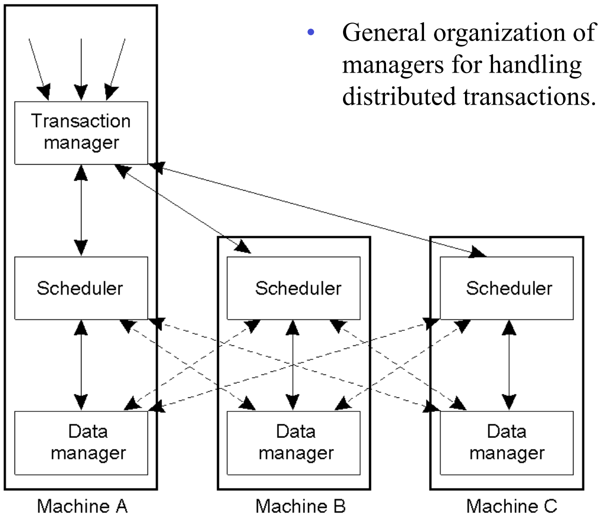
LOCK/RELEASE
or
Timestamp operations

Data manager

Execute read/write

- General organization of managers for handling transactions.

# Distributed Concurrency Control



- General organization of managers for handling distributed transactions.

# Serializability

```
BEGIN_TRANSACTION
  x = 0;
  x = x + 1;
END_TRANSACTION
```

(a)

```
BEGIN_TRANSACTION
  x = 0;
  x = x + 2;
END_TRANSACTION
```

(b)

```
BEGIN_TRANSACTION
  x = 0;
  x = x + 3;
END_TRANSACTION
```

(c)

| | | |
|---|---|---|
| Schedule 1 | x = 0; x = x + 1; x = 0; x = x + 2; x = 0; x = x + 3 | Legal |
| Schedule 2 | x = 0; x = 0; x = x + 1; x = x + 2; x = 0; x = x + 3; | Legal |
| Schedule 3 | x = 0; x = 0; x = x + 1; x = 0; x = x + 2; x = x + 3; | Illegal |

- Key idea: properly schedule conflicting operations
- Conflict possible if at least one operation is write
  - Read-write conflict
  - Write-write conflict

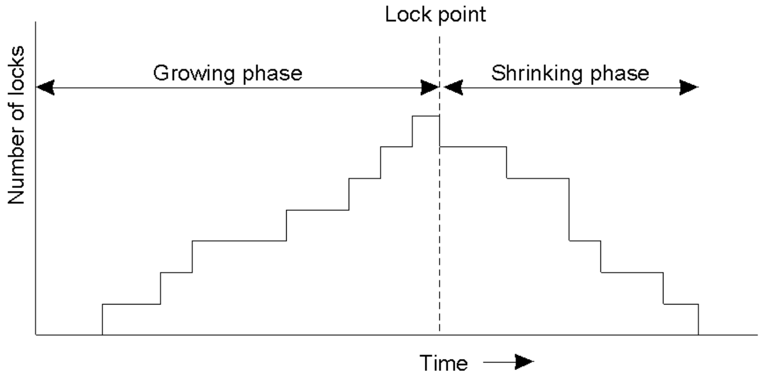
# Optimistic Concurrency Control

- Transaction does what it wants and *validates* changes prior to commit
  - Check if files/objects have been changed by committed transactions since they were opened
  - Insight: conflicts are rare, so works well most of the time
- Works well with private workspaces
- Advantage:
  - Deadlock free
  - Maximum parallelism
- Disadvantage:
  - Rerun transaction if aborts
  - Probability of conflict rises substantially at high loads
- Not used widely

# Two-phase Locking

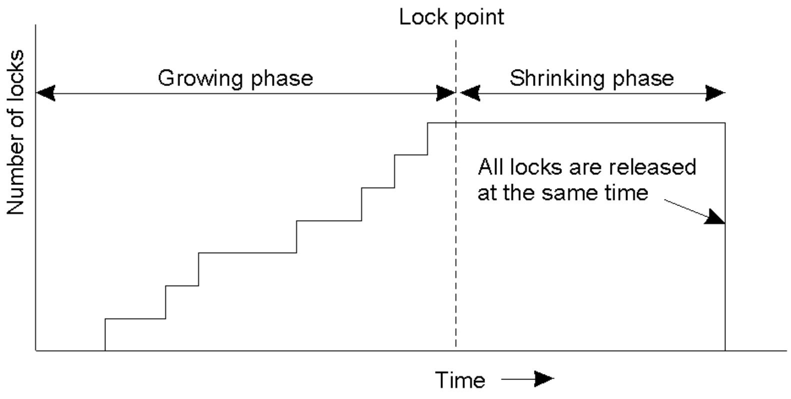
- Widely used concurrency control technique
- Scheduler acquires all necessary locks in growing phase, releases locks in shrinking phase
  - Check if operation on *data item x* conflicts with existing locks
    - If so, delay transaction. If not, grant a lock on *x*
  - Never release a lock until data manager finishes operation on *x*
  - One a lock is released, no further locks can be granted
- Problem: deadlock possible
  - Example: acquiring two locks in different order
- Distributed 2PL versus centralized 2PL

# Two-Phase Locking



- Two-phase locking.

# Strict Two-Phase Locking



- Strict two-phase locking.

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# Timestamp-based Concurrency Control

- Each transaction Ti is given timestamp ts(Ti)
- If Ti wants to do an operation that conflicts with Tj
  - Abort Ti if *ts(Ti) < ts(Tj)*
- When a transaction aborts, it must restart with a new (larger) time stamp
- Two values for each data item *x*
  - *Max-rts(x):* max time stamp of a transaction that read *x*
  - *Max-wts(x):* max time stamp of a transaction that wrote *x*

# Reads and Writes using Timestamps

- $Read_i(x)$
  - If $ts(T_i) < max\text{-}wts(x)$ then Abort $T_i$
  - Else
    - Perform $R_i(x)$
    - $Max\text{-}rts(x)$ = max($max\text{-}rts(x)$, $ts(T_i)$)
- $Write_i(x)$
  - If $ts(T_i) < max\text{-}rts(x)$ or $ts(T_i) < max\text{-}wts(x)$ then Abort $T_i$
  - Else
    - Perform $W_i(x)$
    - $Max\text{-}wts(x) = ts(T_i)$

# Pessimistic Timestamp Ordering