CS 425 / ECE 428
Distributed Systems
Fall 2022

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Lecture 19-20: RPCs and Concurrency Control

Why RPCs

- RPC = Remote Procedure Call
- Proposed by Birrell and Nelson in 1984
- Important abstraction for processes to call functions in other processes
- Allows code reuse
- Implemented and used in most distributed systems, including cloud computing systems
- Counterpart in Object-based settings is called RMI (Remote Method Invocation)

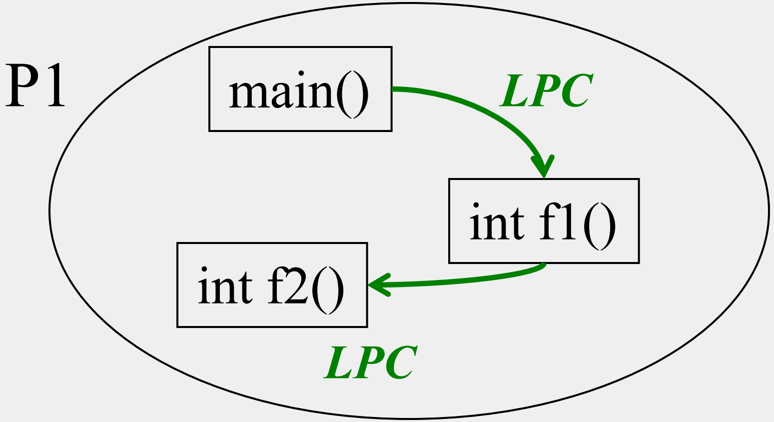
Local Procedure Call (LPC)

- Call from one function to another function within the same process
  - Uses stack to pass arguments and return values
  - Accesses objects via pointers (e.g., C) or by reference (e.g., Java)
- LPC has ***exactly-once*** semantics
  - If process is alive, called function executed exactly once

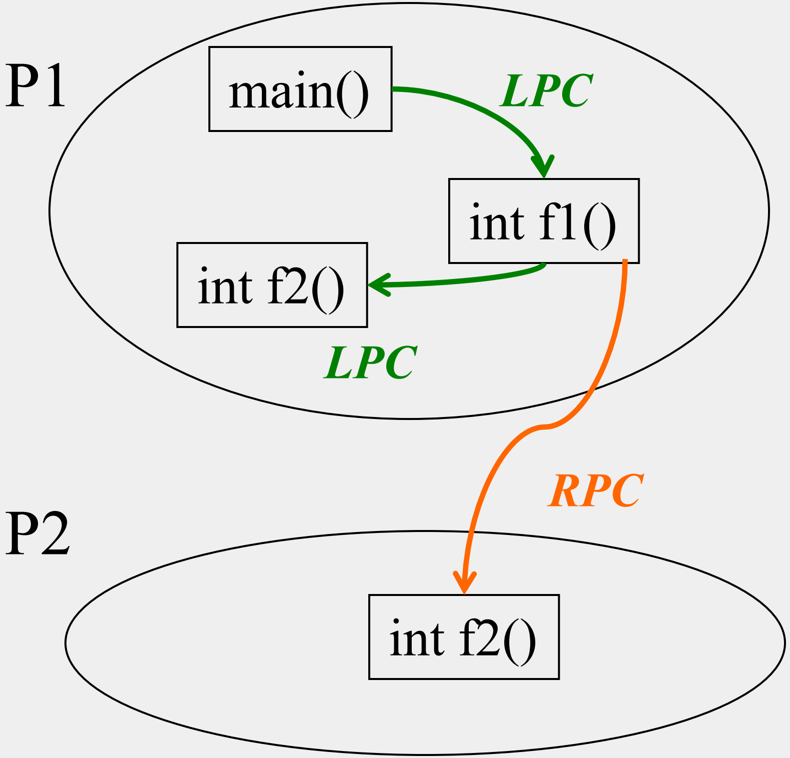
Remote Procedure Call

- Call from one function to another function, where caller and callee function reside in different processes
  - Function call crosses a process boundary
  - Accesses procedures via global references
    - Can't use pointers across processes since a reference address in process P1 may point to a different object in another process P2
    - E.g., Procedure address = IP + port + procedure number
- Similarly, RMI (Remote Method Invocation) in Object-based settings

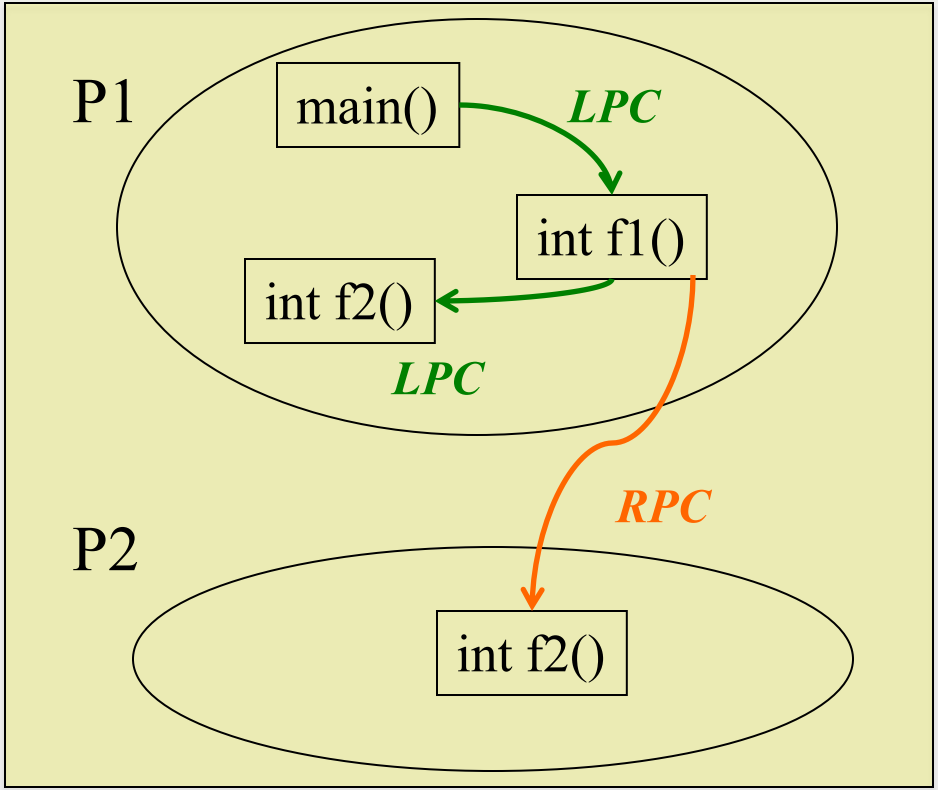
LPCs



RPCs

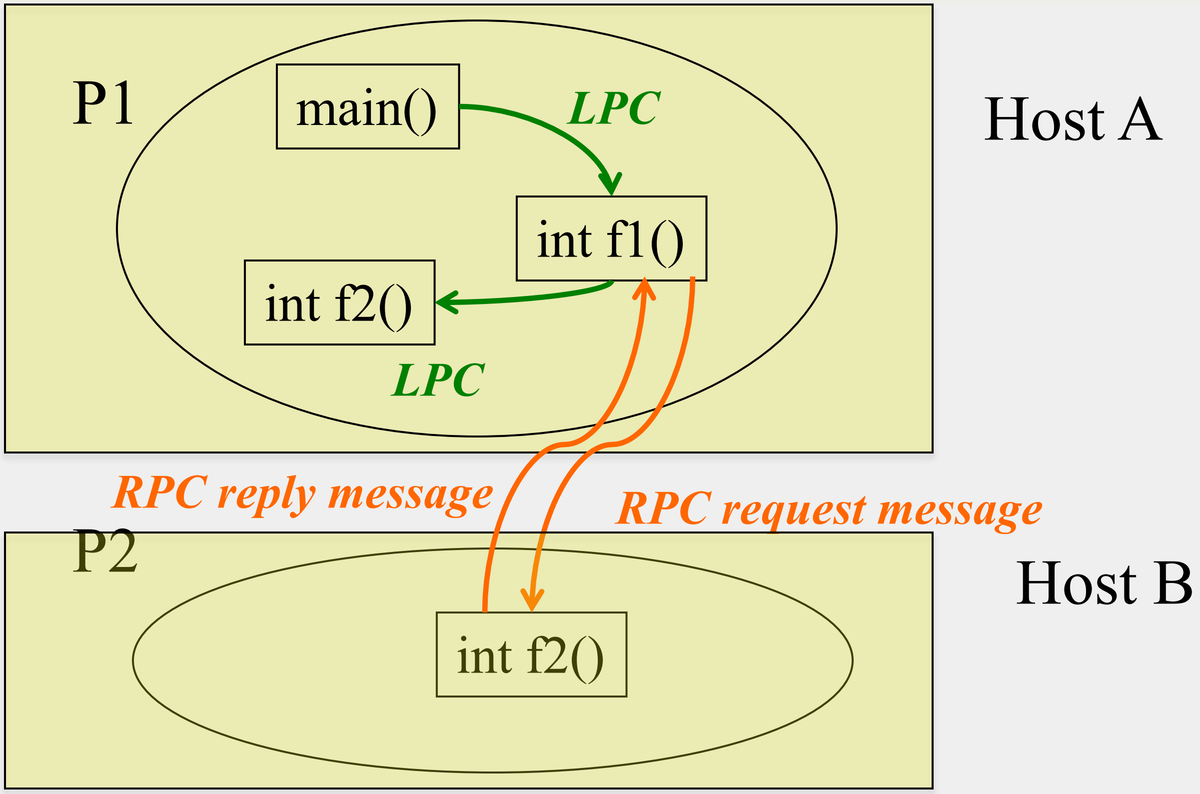


RPCs



Host A

RPCs


P1
main()
LPC
int f1()
int f2()
LPC
Host A
RPC reply message
RPC request message
P2
int f2()
Host B

RPC Call Semantics

- Under failures, hard to guarantee exactly-once semantics
- Function may not be executed if
  - Request (call) message is dropped
  - Reply (return) message is dropped
  - Called process fails before executing called function
  - Called process fails after executing called function
  - Hard for caller to distinguish these cases
- Function may be executed multiple times if
  - Request (call) message is duplicated

Implementing RPC Call Semantics

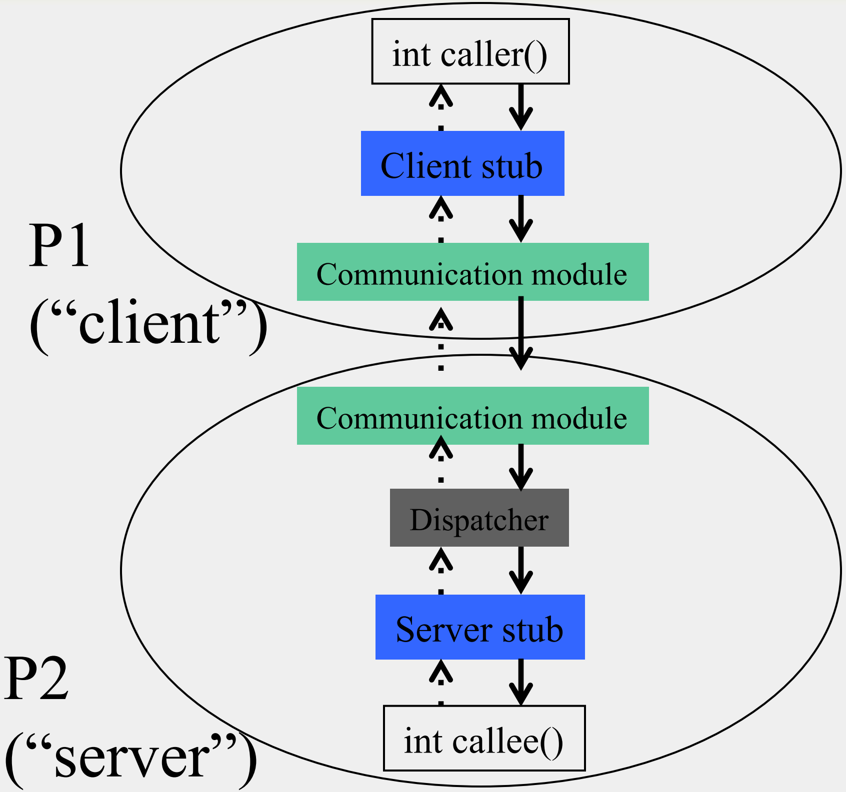
- Possible semantics
  - At most once semantics (e.g., Java RMI)
  - At least once semantics (e.g., Sun RPC)
  - Maybe, i.e., best-effort (e.g., CORBA)

Retransmit request	**Filter duplicate requests**	**Re-execute function or retransmit reply**	**RPC Semantics**
Yes	No	Re-execute	At least once
Yes	Yes	Retransmit	At most once
No	NA	NA	Maybe

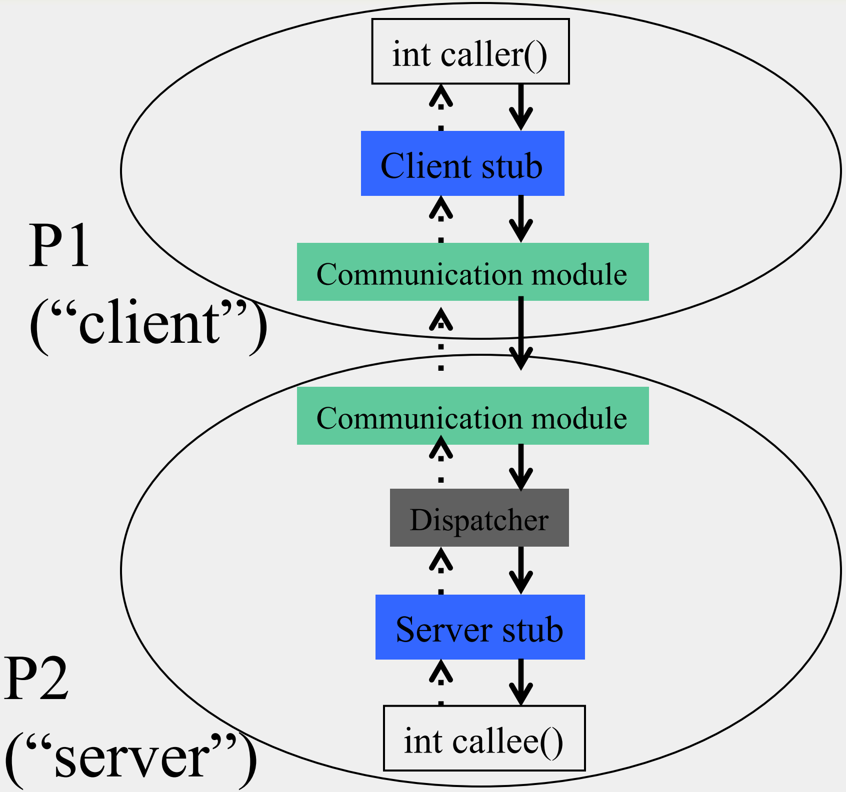
Idempotent Operations

- Idempotent operations are those that can be repeated multiple times, without any side effects
- Examples (x is server-side variable)
  - x=1;
  - x=(argument) y;
- Non-examples
  - x=x+1;
  - x=x*2
- Idempotent operations can be used with at-least-once semantics

Implementing RPCs



RPC Components



Client

- **Client stub**: has same function signature as callee()
  - Allows same caller() code to be used for LPC and RPC
- **Communication Module**: Forwards requests and replies to appropriate hosts

Server

- **Dispatcher**: Selects which server stub to forward request to
- **Server stub**: calls callee(), allows it to return a value

Generating Code

- Programmer only writes code for caller function and callee function
- Code for remaining components all **generated automatically** from function signatures (or object interfaces in Object-based languages)
  - E.g., Sun RPC system: Sun XDR interface representation fed into rpcgen compiler
- These components together part of a Middleware system
  - E.g., CORBA (Common Object Request Brokerage Architecture)
  - E.g., Sun RPC
  - E.g., Java RMI

Marshalling

- Different architectures use different ways of representing data
  - **Big endian**: Hex 12-AC-33 stored with 12 in lowest address, then AC in next higher address, then 33 in highest address
    - IBM z, System 360
  - **Little endian**: Hex 12-AC-33 stored with 33 in lowest address, then AC in next higher address, then 12
    - Intel
- Caller (and callee) process uses its own *platform-dependent* way of storing data
- Middleware has a common data representation (CDR)
  - *Platform-independent*

Marshalling (2)

- Middleware has a common data representation (CDR)
  - Platform-independent
- Caller process converts arguments into CDR format
  - Called “Marshalling”
- Callee process extracts arguments from message into its own platform-dependent format
  - Called “Unmarshalling”
- Return values are marshalled on callee process and unmarshalled at caller process

Next

- Now that we know RPCs, we can use them as a building block to understand transactions

Transaction

- Series of operations executed by client
- Each operation is an RPC to a server
- Transaction either
  – completes and *commits* all its operations at server
    - Commit = reflect updates on server-side objects
  – Or *aborts* and has no effect on server

Example: Transaction

Client code:

```
int transaction_id = openTransaction();
x = server.getFlightAvailability(ABC, 123, date);
if (x > 0)
    y = server.bookTicket(ABC, 123, date);
server.putSeat(y, “aisle”);
// commit entire transaction or abort
closeTransaction(transaction_id);
```

RPCs

Example: Transaction

Client code:

RPCs

```
int transaction_id = openTransaction();
x = server.getFlightAvailability(ABC, 123, date);   // read(ABC, 123, date)
if (x > 0)
    y = server.bookTicket(ABC, 123, date);          // write(ABC, 123, date)
server.putSeat(y, "aisle");                         // write(ABC, 123, date)
// commit entire transaction or abort
closeTransaction(transaction_id);
```

Atomicity and Isolation

- Atomicity: All or nothing principle: a transaction should either i) complete successfully, so its effects are recorded in the server objects; or ii) the transaction has no effect at all.
- Isolation: Need a transaction to be indivisible (atomic) from the point of view of other transactions
  - No access to intermediate results/states of other transactions
  - Free from interference by operations of other transactions
- But…
- Clients and/or servers might crash
- Transactions could run concurrently, i.e., with multiple clients
- Transactions may be distributed, i.e., across multiple servers

ACID Properties for Transactions

- **A**tomicity: All or nothing
- **C**onsistency: if the server starts in a consistent state, the transaction ends the server in a consistent state.
- **I**solation: Each transaction must be performed without interference from other transactions, i.e., non-final effects of a transaction must not be visible to other transactions.
- **D**urability: After a transaction has completed successfully, all its effects are saved in permanent storage.

Multiple Clients, One Server

- What could go wrong?

1. Lost Update Problem

Transaction T1	Transaction T2	
		At Server: seats = 10
x = getSeats(ABC123); // **x = 10**		
	x = getSeats(ABC123);	**T1's or T2's update was lost!**
if(x > 1)	if(x > 1) // **x = 10**	
x = x – 1;		
write(x, ABC123);		seats = 9
	x = x – 1;	
	write(x, ABC123);	seats = 9
commit		
	commit	

2. Inconsistent Retrieval Problem

<u>Transaction T1</u>

```
x = getSeats(ABC123);
y = getSeats(ABC789);
write(x-5, ABC123);
    // ABC123 = 5 now

write(y+5, ABC789);

commit
```

<u>Transaction T2</u>

```
x = getSeats(ABC123);
y = getSeats(ABC789);
    // x = 5, y = 15
print("Total:" x+y);
    // Prints "Total: 20"
commit
```

At Server:
ABC123 = 10
ABC789 = 15

T2's sum is the wrong value!
Should have been "Total: 25"

Next

- How to prevent transactions from affecting each other

Concurrent Transactions

- To prevent transactions from affecting each other
  - Could execute them one at a time at server
  - But reduces number of concurrent transactions
  - *Transactions per second* directly related to revenue of companies
    - This metric needs to be maximized
- Goal: increase concurrency while maintaining correctness (ACID)

Serial Equivalence

- An interleaving (say O) of transaction operations is serially equivalent iff (if and only if):
  - There is some ordering (O') of those transactions, one at a time, which
  - Gives the same end-result (for all objects and transactions) as the original interleaving O
  - Where the operations of each transaction occur consecutively (in a batch)
- Says: Cannot distinguish end-result of real operation O from (fake) serial transaction order O'

Checking for Serial Equivalence

- An operation has an effect on
  - The server object if it is a write
  - The client (returned value) if it is a read
- Two <u>operations</u> are said to be <u>conflicting operations</u>, if their *combined effect* depends on the <u>order</u> they are executed
  - read(x) and write(x)
  - write(x) and read(x)
  - write(x) and write(x)
  - NOT read(x) and read(x): swapping them doesn't change their effects
  - NOT read/write(x) and read/write(y): swapping them ok

Checking for Serial Equivalence (2)

- *Two transactions are serially equivalent if and only if all pairs of conflicting operations (pair containing one operation from each transaction) are executed in the same order (transaction order) for all objects (data) they both access.*
  - Take all pairs of conflict operations, one from T1 and one from T2
  - If the T1 operation was reflected first on the server, mark the pair as "(T1, T2)", otherwise mark it as "(T2, T1)"
  - All pairs should be marked as either "(T1, T2)" or all pairs should be marked as "(T2, T1)".

1. Lost Update Problem – Caught!

At Server: seats = 10

Transaction T1	Transaction T2	
x = getSeats(ABC123);		
// **x = 10**	x = getSeats(ABC123);	**T1's or T2's update was lost!**
if(x > 1)	if(x > 1) // **x = 10**	
x = x – 1;		
write(x, ABC123);		seats = 9
	x = x – 1;	
	write(x, ABC123);	seats = 9
commit		
	commit	

(T2, T1)

(T1, T2)

(T1, T2)

2. Inconsistent Retrieval Problem – Caught!

Transaction T1		**Transaction T2**
x = getSeats(ABC123);		
y = getSeats(ABC789);		
write(x-5, ABC123);	(T1, T2)	
		x = getSeats(ABC123);
		y = getSeats(ABC789);
write(y+5, ABC789);	(T2, T1)	**// x = 5, y = 15**
		print("Total:" x+y);
		// Prints "Total: 20"
commit		
		commit

At Server:
ABC123 = 10
ABC789 = 15

T2's sum is the wrong value!
Should have been "Total: 25"

What’s Our Response?

- At commit point of a transaction T, check for serial equivalence with all other transactions
  – Can limit to transactions that overlapped in time with T
- If not serially equivalent
  – Abort T
  – Roll back (undo) any writes that T did to server objects

Can We do better?

- Aborting => wasted work
- Can you prevent violations from occurring?

Two Approaches

- Preventing isolation from being violated can be done in two ways
  1. Pessimistic concurrency control
  2. Optimistic concurrency control

Pessimistic vs. Optimistic

- Pessimistic: assume the worst, prevent transactions from accessing the same object
  - E.g., Locking
- Optimistic: assume the best, allow transactions to write, but check later
  - E.g., Check at commit time, multi-version approaches

Pessimistic: Exclusive Locking

- Each object has a lock
- At most one transaction can be inside lock
- Before reading or writing object O, transaction T must call lock(O)
  - Blocks if another transaction already inside lock
- After entering lock T can read and write O multiple times
- When done (or at commit point), T calls unlock(O)
  - If other transactions waiting at lock(O), allows one of them in
- Sound familiar? (This is Mutual Exclusion!)

Can we improve concurrency?

- More concurrency => more transactions per second => more revenue ($$$)
- Real-life workloads have a lot of read-only or read-mostly transactions
  - Exclusive locking reduces concurrency
  - Hint: Ok to allow two transactions to concurrently read an object, since read-read is not a conflicting pair

Another Approach: Read-Write Locks

- Each object has a lock that can be held in one of two modes
  - Read mode: multiple transactions allowed in
  - Write mode: exclusive lock
- Before first reading O, transaction T calls read_lock(O)
  - T allowed in only if *all* transactions inside lock for O all entered via read mode
  - Not allowed if *any* transaction inside lock for O entered via write mode

Read-Write Locks (2)

- Before first writing O, call write_lock(O)
  - Allowed in only if no other transaction inside lock
- If T already holds read_lock(O), and wants to write, call write_lock(O) to *promote* lock from read to write mode
  - Succeeds only if no other transactions in write mode or read mode
  - Otherwise, T blocks
- Unlock(O) called by transaction T releases any lock on O by T

Guaranteeing Serial Equivalence With Locks

- Two-phase locking
  - A transaction cannot acquire (or promote) any locks after it has started releasing locks
  - Transaction has two phases
    1. Growing phase: only acquires or promotes locks
    2. Shrinking phase: only releases locks
       - Strict two phase locking: releases locks only at commit point

Why Two-phase Locking => Serial Equivalence?

- Proof by contradiction
- Assume two phase locking system where serial equivalence is violated for some two transactions T1, T2
- Two facts must then be true:
  - (*A*) For some object O1, there were conflicting operations in T1 and T2 such that the time ordering pair is (T1, T2)
  - (*B*) For some object O2, the conflicting operation pair is (T2, T1)
  - (*A*) => T1 released O1's lock and T2 acquired it after that

    => T1's shrinking phase is before or overlaps with T2's growing phase
- Similarly, *(B)* => T2's shrinking phase is before or overlaps with T1's growing phase
- But both these cannot be true!

Downside of Locking

- Deadlocks!

Downside of Locking – Deadlocks!

Transaction T1

Lock(ABC123);

x = write(10, ABC123);

Lock(ABC789);

// Blocks waiting for T2

…

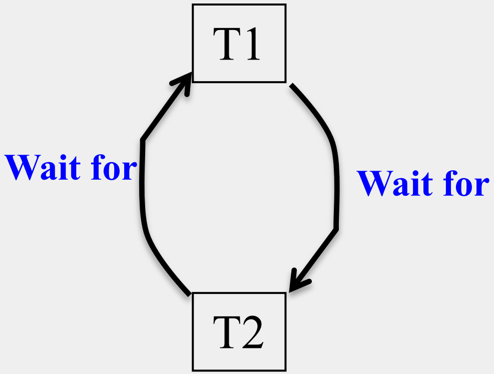
Transaction T2

Lock(ABC789);

y = write(15, ABC789);

Lock(ABC123);

… **// Blocks waiting for T1**



When do Deadlocks Occur?

- 3 necessary conditions for a deadlock to occur
  1. Some objects are accessed in exclusive lock modes
  2. Transactions holding locks cannot be preempted
  3. There is a circular wait (cycle) in the Wait-for graph
- "Necessary" = if there's a deadlock, these conditions are all definitely true
- (Conditions not sufficient: if they're present, it doesn't imply a deadlock is present.)

Combating Deadlocks

1. Lock timeout: abort transaction if lock cannot be acquired within timeout

   ☹ Expensive; leads to wasted work

2. Deadlock Detection:

   –keep track of Wait-for graph (e.g., via Global Snapshot algorithm), and

   –find cycles in it (e.g., periodically)

   –If find cycle, there’s a deadlock => Abort one or more transactions to break cycle

   ☹ Still allows deadlocks to occur

Combating Deadlocks (2)

3. Deadlock Prevention

- Set up the system so one of the *necessary conditions* is violated
  1. *Some objects are accessed in exclusive lock modes*
     - Fix: Allow read-only access to objects
  2. *Transactions holding locks cannot be preempted*
     - Fix: Allow preemption of some transactions
  3. *There is a circular wait (cycle) in the Wait-for graph*
     - Fix: Lock all objects in the beginning; if fail any, abort transaction => No cycles in Wait-for graph

Next

- Can we allow more concurrency?
- Optimistic Concurrency Control

Optimistic Concurrency Control

- Increases concurrency more than pessimistic concurrency control
- Increases transactions per second
- For non-transaction systems, increases operations per second and lowers latency
- Used in Dropbox, Google apps, Wikipedia, key-value stores like Cassandra, Riak, and Amazon's Dynamo
- Preferable than pessimistic when conflicts are *expected to be* rare
  - But still need to ensure conflicts are caught!

First-cut Approach

- Most basic approach
  - Write and read objects at will
  - Check for serial equivalence at commit time
  - If abort, roll back updates made
  - An abort may result in other transactions that read dirty data, also being aborted
    - Any transactions that read from *those* transactions also now need to be aborted

    ☹ *Cascading aborts*

Second approach: Timestamp Ordering

- Assign each transaction an id
- Transaction id determines its position in serialization order
- Ensure that for a transaction T, both are true:
    1. T's write to object O allowed only if transactions that have read or written O had lower ids than T.
    2. T's read to object O is allowed only if O was last written by a transaction with a lower id than T.
- Implemented by maintaining read and write timestamps for the object
- If rule violated, abort!
    - Can we do better?

Third Approach: Multi-version Concurrency Control

- For each object
  - A per-transaction version of the object is maintained
    - Marked as *tentative* versions
  - And a committed version
- Each tentative version has a timestamp
  - Some systems maintain both a read timestamp and a write timestamp
- On a read or write, find the "correct" tentative version to read or write from
  - "Correct" based on transaction id, and tries to make transactions only read from "immediately previous" transactions

Eventual Consistency…

- …in key-value stores…
- … is a form of optimistic concurrency control
  - In Cassandra key-value store
  - In DynamoDB key-value store
  - In Riak key-value store
- But since non-transaction systems, the optimistic approach looks different

Eventual Consistency in Cassandra and DynamoDB

- Only one version of each data item (key-value pair)
- Last-write-wins (LWW)
  - Timestamp, typically based on *physical time*, used to determine whether to overwrite

```
if(new write's timestamp > current object's timestamp)
    overwrite;
else
    do nothing;
```

- With unsynchronized clocks
  - If two writes are close by in time, older write might have a newer timestamp, and might win

Eventual Consistency in Riak Key-value Store

- An older version of Riak uses vector clocks! (Should sound familiar to you!)
- Implements causal ordering
- Uses vector clocks to detect whether
  1. New write is strictly newer than current value, or
  2. If new write conflicts with existing value
- In case (2), a *sibling value* is created
  - Resolvable by user, or automatically by application (but not by Riak)
- To prevent vector clocks from getting too many entries
  - Size-based pruning
- To prevent vector clocks from having entries updated a long-time ago
  - Time-based pruning

Summary

- RPCs and RMIs
- Transactions
- Serial Equivalence
  - Detecting it via conflicting operations
- Pessimistic Concurrency Control: locking
- Optimistic Concurrency Control

Announcements

- Next week
  - MP3 due 11/6 Sunday, demos next Monday 11/7
  - HW3 due 10/28 2 pm
- Midterm Regrade Requests: Please collect them now from me! (in class 10/26 or 10/28)
  - After that they will not be available to you (grades have been uploaded on Canvas)