CS x55: Distributed Systems [Consistency]

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Topics covered in this lecture

- Consistent Ordering of Operations
  - Sequential consistency
  - Causal consistency
- Client-centric consistency models

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CONSISTENT ORDERING OF OPERATIONS

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Consistent ordering of operations

- Class of models from **concurrent programming**
- We will look at
  - Sequential consistency
  - Causal consistency

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Sequential consistency: Notations

- Operations of processes depicted along time axis
- Write by a process P_i to data item x with value a
  - $W_i(x)a$
- Read by a process P_i of data item x that returns the value b
  - $R_i(x)b$
- All items are initially NIL

Two processes operating on the same data item

Time →

```
P1:        W(x)a
P2:               R(x)NIL   R(x)a
```

Time to propagate update of x to P2 is acceptable ☺

Sequential consistency

- Defined by Lamport
  - Context: Shared memory in multiprocessor setting
- When processes run concurrently
  - Any valid interleaving of read/write is acceptable
  - But all processes ***must see the same interleaving***

Sequential consistency example

Time →

P1: W(x)a				
P2:	W(x)b			
P3:		R(x)b		R(x)a
P4:			R(x)b	R(x)a

☺

Write operation of P2 appears to be before P1
This is acceptable

Sequential consistency: Example

Time →

```
P1: W(x)a
P2:         W(x)b
P3:                 R(x)b       R(x)a
P4:                     R(x)a   R(x)b
```

P3 concludes final value is a
P4 concludes final value is b

Unacceptable

Sequential Consistency: Another example

```
Process 1      Process 2      Process 3
---------      ---------      ---------
x = 1          y = 1          z = 1
print(y,z)     Print(x,z)     Print(x,y)
```

Multiple interleaved sequences are possible

- With 6 statements there are
  - 6! possibilities = 720
  - Some of these **violate program order**
- 120 (5!) sequences begin with `x=1`
  - Half `print(x,z)` before `y=1`
    - Half `print(x,y)` before `z=1`
      - Only ¼ or 30 are valid
- Similarly, there are 30 that start with `y=1`, `z=1`
  - Total of 90 valid execution sequences

Different, but valid interleaving of the statements

Signature is the concatenation of the outputs of P1, P2 and P3

```
x = 1           x = 1           y = 1           y = 1
print(y,z)      y = 1           z = 1           x = 1
y = 1           print(x,z)      print(x,y)      z = 1
print(x,z)      print(y,z)      print(x,z)      print(x,z)
z = 1           z = 1           x = 1           print(y,z)
print(x,y)      print(x,y)      print(y,z)      print(x,y)
```

Prints: 001011	**Prints:** 101011	**Prints:** 010111	**Prints:** 111111
Signature: 001011	**Signature:** 101011	**Signature:** 110101	**Signature:** 111111

Contract between processes and shared data store

- Processes must accept **all valid results**
- Must work if any of them occurs

Invalid sequences in signature patterns

- 000000?
  - Print statements ran before assignments
  - **Violates** program order
- 001001?
  - {00} y and z were 0 when **P1** did its printing
    - **P1** executes its statements *before* **P2** and **P3** start
  - {10} **P2** ran after **P1** started, but before **P3** started
  - {01} **P3** must complete *before* **P1** starts
    - Not possible!

```
Process 1
---------
x = 1
print(y,z)
```

```
Process 2
---------
y = 1
Print(x,z)
```

```
Process 3
---------
z = 1
Print(x,y)
```

CAUSAL CONSISTENCY

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Causal consistency

- **Weakens** sequential consistency
- Makes **distinction** between events that are *causally* related
  - If event *b* caused/is-influenced by event *a*
    - Everyone must see *a* before *b*
- Operations not causally related: **concurrent**

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Causal consistency example
Example 1

Time →

P1: W(x)a   W(x)c

P2:   R(x)a W(x)b

P3:   R(x)a   R(x)c R(x)b

P4:   R(x)a   R(x)b R(x)c ☺

Writes $W_2(x)b$ and $W_1(x)c$ are considered concurrent
Acceptable

Note: This is NOT ALLOWED in sequential consistency

Causal consistency example:
Example 2

Time →

P1: W(x)a

P2:   R(x)a W(x)b

P3:   R(x)b R(x)a

P4:   R(x)a R(x)b ☹

Writes $W_1(x)a$ and $W_2(x)b$ are causally related
Process must see them in the same order

Causal consistency example: Example 3

Time →

P1: W(x)a

P2: W(x)b

P3: R(x)b R(x)a

P4: R(x)a R(x)b ☺

Writes $W_1(x)a$ and $W_2(x)b$ are concurrent writes
Process can see them in different orders

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Grouping operations

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Concurrency using synchronization operations

- Operations bracketed by
  - `ENTER_CS`
  - `LEAVE_CS`
  - `CS`: Critical Section
- Semantics enforced using shared **synchronization** variables

Critical sections and synchronization variables

- Each synchronization variable has an **owner**
- Owner may repeatedly enter or exit critical section
- Process that does not own a synchronization variable
  - Must own it before it can enter critical section
  - **Acquire** by sending a message to the owner

Rules for critical sections

- Acquire cannot complete until all guarded shared data is up to date
- Before *updating* a shared item
  - Enter critical section in **exclusive mode**
- If a process enters a critical region in non-exclusive mode
  - **Fetch recent copies** of the shared guarded data from owner

Entry consistency example

Time →

```
P1: Acq(Lx) W(x)a Acq(Ly) W(y)b Rel(Lx) Rel(Ly)
P2:                          Acq(Lx) R(x)a    R(y)NIL
P3:                                  Acq(Ly) R(y)b
```

P2 does an acquire for x, but not y: MAY read NIL

CLIENT CENTRIC CONSISTENCY MODELS

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Applications have different requirements about:

- Concurrency
- Consistency

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Often only one or a few processes can perform updates

- How **fast** should these be propagated to processes that only read?
- DNS: Different domains managed by naming authority
  - Owner of that domain
  - **Write-write conflicts** never occur
    - Write-write conflicts result in overwriting uncommitted data (lost updates)
  - Read-write conflicts may occur
    - But it is still OK to do **lazy updates**
    - Read-write conflicts are also known as unrepeatable reads

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Often only one or a few processes can perform updates

- Web pages updated by authors
  - Write-write conflicts *never* occur
  - Read-write conflicts *may* occur
    - Browsers or proxies cache these pages
    - Several users find this inconsistency acceptable

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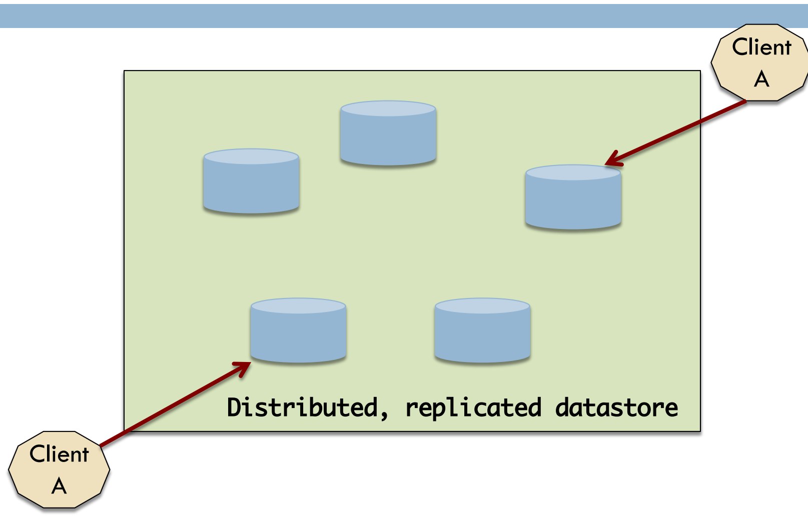
The DNS and Web page examples can be viewed as large (distributed) databases

- That tolerate a high degree of inconsistency
- If no updates take place for a long time
  - All replicas *gradually* become consistent
  - **Eventual consistency**

The caveat for eventual consistency

- Works fine as long as clients access the **same replica**
- **Problems** when you access *different replicas* within a short interval

An example of a mobile user accessing different replicas



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CLIENT-CENTRIC CONSISTENCY MODELS

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Client-centric consistency models

- Provides guarantees for a **single** client accessing the store
- No guarantees for *concurrent* accesses of store by *different* clients

Client-centric consistency models

- Monotonic read
- Monotonic write
- Read-your-writes
- Writes-follow-read

Notations for client-centric consistency

- Version of data item x at local copy L_i at time t
  - $x_i[t]$
- $x_i[t]$ is the **result** of a *series* of operations at L_i since initialization
  - This set of operations: $WS(x_i[t])$
  - Operation at L_i at t_1 and at L_j at time t_2
    - $WS(x_i[t_1]; x_j[t_2])$

Monotonic read consistency

- If a process reads a value of x, any successive read on x by that process returns either:
  - *Same* value

    OR
  - **More recent** value
- If process sees a value of x at time t
  - It *never* sees an older version

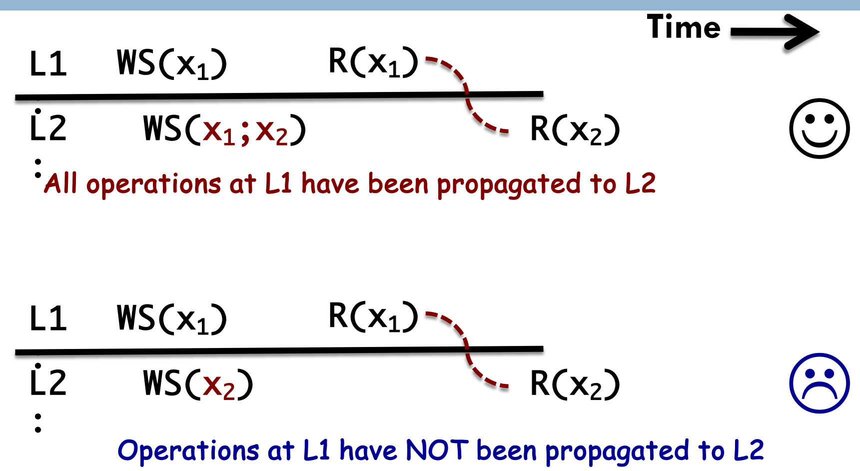
A mailbox example of monotonic read consistency

- Each user's mailbox is replicated & distributed
- **Lazy/on-demand** updates
  - When copies need data for consistency the updates are propagated
- User reads mail in San Francisco … goes to NYC
- Monotonic consistency
  - Messages in mailbox in SF are also there in NYC

Representing client-centric consistency

- Time is along horizontal axis
- Different copies of a replica on the vertical axis
- Operations are carried out by a **single process**

Monotonic Read Consistency: Operations by a single process P



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Monotonic Writes [1/2]

- Write operation on data item x is completed
  - *Before any successive* write operation on x by the **same** process
- Copy on which write is performed
  - Reflects affect of a *previous* write
  - Irrespective of *where* it was initiated

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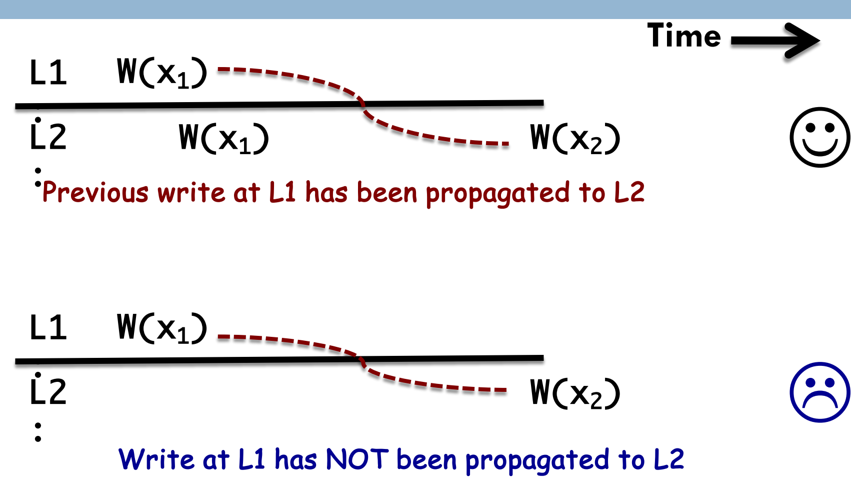
Monotonic Writes [2/2]

- When each write **completely overwrites** x
  - Getting things up to date is easier
- In most cases we perform **partial updates**; for e.g. x could be software library
  - We update functions etc. to get to the next version
  - If an update is performed to library
    - All preceding updates must *first* be performed

Monotonic Write Consistency: Operations by a single process P



Read your writes

- Effect of a write operation on data item x
  - **Seen** by successive reads on x by the same process
- Write operation is always **completed before** a successive read operation
  - By same process
  - No matter *where* operations are performed

Example of inability to enforce read-your-write consistency

- Web designer creates a web page
- Tries to view it
- But browser/proxy has cached the older version
- With a read-your-write consistent browser
  - Cache is invalidated when page is updated
- Other example: Updating passwords

Read-your-Writes Consistency: Operations by a single process P

Time →

L1 W(x_1)

L2 WS(x_1;x_2) R(x_2)

Previous write at L1 has been propagated to L2

L1 W(x_1)

L2 WS(x_2) R(x_2)

Write at L1 has NOT been propagated to L2

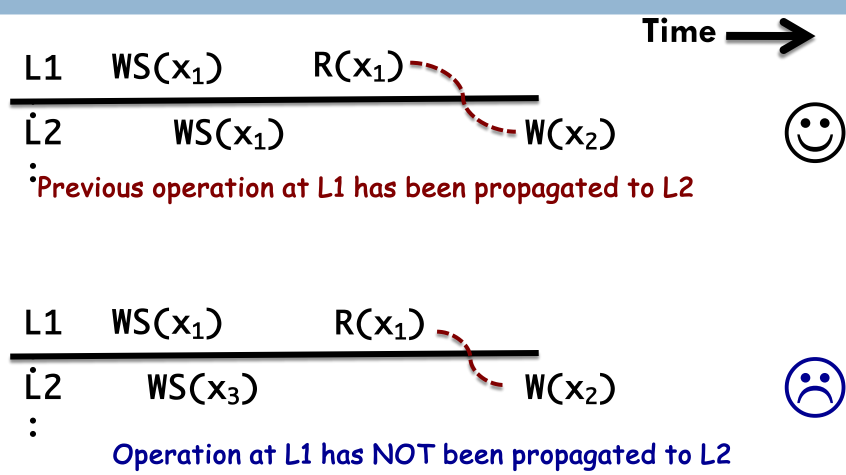
Write Follow Reads

- Write operation by process on data item x
  - Following a previous read on x by the *same* process
    - Will take place on the **same (or more recent)** value of x
- Write operation on item x will be performed on a copy that is up to date
  - With value (most) recently read by process

Write-follows-reads

- User reads an article **A**
- Reacts by posting article **B**
- Write follows reads consistency
  - **B** will be posted to a copy of the newsgroup
    - Only after **A** has been written

Writes-Follow-Reads Consistency: Operations by a single process P



The contents of this slide-set are based on the following references

- *Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van der Steen. 2nd Edition. Prentice Hall. ISBN: 0132392275/978-0132392273.* [Chapter 7]