CS 555: DISTRIBUTED SYSTEMS [REPLICATION & CONSISTENCY]

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Frequently asked questions from the previous class survey

Topics covered in this lecture

- Replication
- Consistency Models
- Data centric consistency model
  - Continuous consistency models
  - Sequential consistency

REPLICATION & CONSISTENCY

What we will look at in our discussions

- Replication
- Consistency
  - Models
  - Client models
  - Protocols
- Eventual Consistency
- Brewer's CAP Theorem

Why are these inter-related topics important?

- Performance
- Correctness
- Failure to account for interactions between these issues?
  - Poor performance
  - Inaccurate results

The holy grail of demonstrable incompetency in systems development!

REPLICATION

Rationale for replication

- Reliability
- Availability
- Performance

Rationale for replication: Reliability

- Replication as a safeguard against **failures**
- Protection against data **corruptions**
- File System example:
  - **3** copies
  - If one fails, process can choose from the other two
  - Read/write performed on each copy
    - At least 2 of the reads must *concur*
    - Protects against a failing write

  } Data corruptions

Rationale for replication: Increased Availability

- Users require services to be **highly available**
  - Proportion of time when service is *accessible with reasonable response times* should be close to 100%
- Factors relevant to high-availability
  - Delays due to pessimistic concurrency control
  - Server failures
  - Network partitions and disconnected operations

Replication maintains availability despite server failures [1/2]

- Data is replicated at failure independent servers
- Client software should be able to access data at an alternative server if default server fails

Replication maintains availability despite server failures [2/2]

- If each of the n servers has an independent probability p of failing or becoming unreachable
- The availability of an object stored at each of these servers?
  - 1- *probability(all servers fail or are unreachable)*
  - $1 - p^n$

Replication maintains availability despite server failures: Example

- There is a 5% probability of independent server failures?
- There are two servers
  - Availability is $1 - p^n$
  - $1 - (0.05)^2 = 1 - 0.0025 = 99.75\%$

Rationale for replication: Performance

- Ability to scale with **numbers**
  - Processes access data managed by a server
  - Replicate server; distribute work
- Ability to scale with **geographical area**
  - Place copy of data in *proximity* of processes using it
  - Time to access service decreases
    - **Perceived performance** improves

But replication exacts a price …

- A client may perceive better performance but …
  - More *network bandwidth* needed
    - To keep replicas in sync
- **Consistency** problems
  - When a copy is modified, it becomes *different*
  - Modifications have to be made on **all** copies

Replication Costs: *When* and *how* modifications must be made to copies

- Fetching a page from a remote Web server
  - OBJECTIVE: Improving access times
- Web browsers locally **cache** a web page
  - If user requests the same page
    - Returned from cache
    - User is happy with the load times
  - What if user always wants the latest copy?

Simple solutions to the stale copy problem

1. **Don't cache** web page
   - If there is no nearby replica, performance is poor
   - Also, what if the page does not change that often?
2. Let server **invalidate/update** caches
   - Server must track all caches
   - Degrades server performance

Replication as a scaling technique

- Placing data copies close to processes
  - Improves access times
  - Distributes work
- Potential problems …

Replication for scaling: Network bandwidth

- Process **P** accesses a replica **N** times per second
- Replica is itself updated **M** times per second
- If **N** << **M** ?
  - Several updated versions of replica *never* accessed
  - *Network traffic* to install those versions: wasted!
  - Perhaps installing a replica was not a good idea?

Replication for scaling: Consistency issues

- Consistency might itself be subject to **scaling problems**
- Collection of copies is consistent when *all* copies are the same
  - Read on any copy returns the *same* result
  - Updates propagated to all copies before the next operation?
    - **Tight consistency**

Consistency issues in replication

- Update performed at all copies as an **atomic operation**
  - Transaction
- Implementing atomicity with large number of replicas is difficult
  - May be dispersed on a WAN
  - Operations *cannot* complete quickly

Other things that replicas need to agree on …

- Replicas must agree on ***when*** operation must be performed locally
- Replicas need to decide on **ordering**
  - Lamport timestamps
  - Coordinator assigned order

The Replication Dilemma

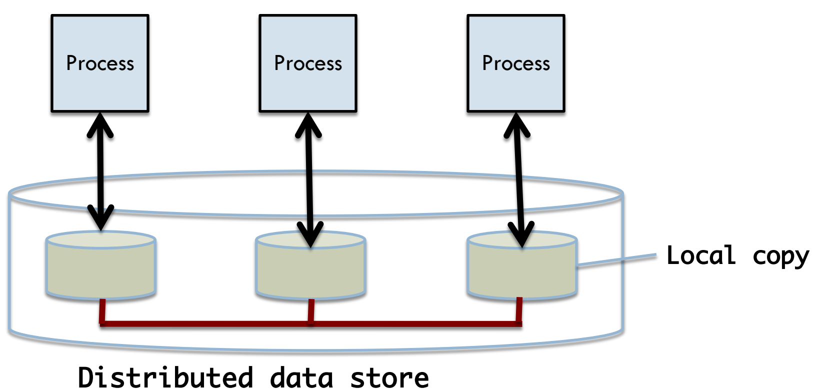
- Alleviating scalability issues
  - Replication and caching: Improves performance
- Keeping copies consistent?
  - Requires *global* synchronization
  - *Costly* in terms of performance
    - Time
    - Network bandwidth

Data centric consistency models

Data centric consistency models

- Consistency is in the context of read/write operation on **distributed**, **shared** data
  - Memory
  - Database
  - File systems
- The broader term **data store** is more commonly used

Distributed data store



Consistency model

- **Contract** between processes and the data store
- If processes agree to obey certain **rules**
  - Data store works correctly

Consistency that we intuitively expect

- Process performing a *read* on a data item
  - Expects value to show results of *last write* operation on that item
- Without a global clock?
  - Difficult to define *which* write was the last one

We thus need to provide other definitions … consistency models

- Each model **restricts values** that a **read** operation on a data item can return
- Models with the greatest restrictions
  - Easiest to use
- Models with minor restrictions
  - Difficult to use
- Easy-to-use models ***do not*** perform as well as difficult ones

Loosening of consistency

- Needed for efficiency and performance
- No *general rules* however
  - **Tolerance depends on the application**

CONTINUOUS CONSISTENCY MODELS

Continuous consistency

- **Three axes** for defining inconsistencies
- **Deviations** between replicas in terms of
  - Numerical values
  - Staleness between replicas
  - Ordering of update operations
- Deviations form **continuous consistency** ranges

Example of using continuous consistency models: Stock prices

- Two copies of a stock should not deviate by more than 2 cents.
  - **Absolute** *numerical deviation*
- Two copies do not deviate by more than 0.5%
  - **Relative** *numerical deviation*
- If stock goes up and one replica is updated
  - If change *does not* violate specified deviations?
    - Replicas are considered consistent

Numerical and Staleness deviations

- Numerical deviation can also be expressed in terms of number of **updates**
  - Applied at a replica, but not seen by other replicas
- **Staleness** deviations
  - Last time a replica was updated
  - Replica can provide *old data* as long as it is not too old
    - Weather reports

Ordering of updates may also be allowed to be different

- Within a certain **bound**
- Updates applied *tentatively* at local copy
  - Need global agreement with all replicas
- Before an update becomes *permanent* it
  - Might be rolled back
  - Applied in a different order

CONSISTENCY UNIT (CONIT)

Consistency Unit: conit

- Specifies *unit* over which consistency is to be **measured**
- Examples
  - Record representing a stock
  - Weather report

Looking at the conit a little closer: Example with 2 replicas

- Each replica maintains a 2D vector clock
- Operation carried out by replica i at (its) logical time t : $\langle t, i \rangle$
- Example conit contains data items x and y

Tracking consistency deviations: Conit items x and y are initialized to 0

Replica A

Conit: x=6, y=3

Operation		Result
<5, B>	x= x+2	[x = 2]
<8, A>	y= y+2	[y = 2]
<12, A>	y= y+1	[y = 3]
<14, A>	x= yx2	[x = 6]

Replica B

Conit: x=2, y=5

Operation		Result
<5, B>	x= x+2	[x = 2]
<10, B>	y= y+5	[y = 5]

Committed Operation: ▢

Tentative Operation: ▢

Vector Clocks at each replica

Replica A

Conit: x=6, y=3

Operation		Result
<5, B>	x= x+2	[x = 2]
<8, A>	y= y+2	[y = 2]
<12, A>	y= y+1	[y = 3]
<14, A>	x= yx2	[x = 6]

Replica B

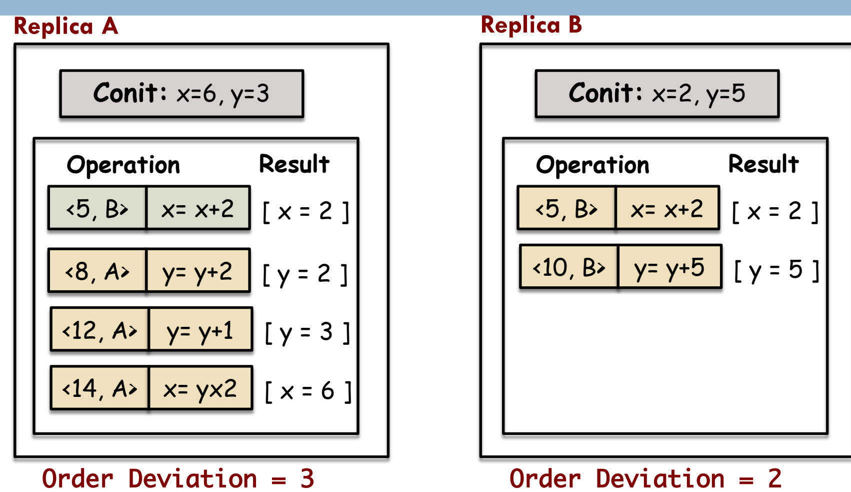
Conit: x=2, y=5

Operation		Result
<5, B>	x= x+2	[x = 2]
<10, B>	y= y+5	[y = 5]

`Vector clock A = (15, 5)`

`Vector clock B = (0, 11)`

Order deviations are the number of tentative operations at each replica



Numerical deviations in our example

- Numerical deviation here is the number of **unseen updates** from the other replica
- Weight of this deviation at replica **A** is the maximum **difference** between
  - Committed values of conit at **A**
  - Result from operations at **B** not seen by **A**

Quantifying the numerical deviations at each replica

Replica A

Conit: x=6, y=3

Operation		Result
<5, B>	x= x+2	[x = 2]
<8, A>	y= y+2	[y = 2]
<12, A>	y= y+1	[y = 3]
<14, A>	x= yx2	[x = 6]

```
Unseen Updates = 1
Weight = Max[diff(2,2), diff (0,5)]
       = 5
```

Replica B

Conit: x=2, y=5

Operation		Result
<5, B>	x= x+2	[x = 2]
<10, B>	y= y+5	[y = 5]

Note: B's committed value is (0,0)

```
Unseen updates = 3
Weight= Max[diff(0,6), diff(0,3)]
      = 6
```


Tradeoffs between fine grained and coarse grained conits

- If conit represents a **lot** of data
  - Updates aggregated for all data in conit
  - Replicas become *inconsistent sooner*
- If conit is smaller
  - Fewer updates needed
  - *Total number* of conits to be managed goes up

Before we put conits to practical use two things need to happen

- **Protocols** to enforce consistency
- Developers **specify** consistency requirements
  - Difficult!

Conits are declared alongside updates

```
AffectsConit(ConitQ, 1, 1)
  append message m to queue Q
```

- Appending message `m` to queue `Q` belongs to a conit named `ConitQ`

Conits are declared alongside reads

```
DependsOnConit(ConitQ, 4, 0, 60)
  read message m from the head of queue Q
```

- Numerical deviation: 4
  - At most 4 unseen updates at other replicas
- Ordering deviation: 0
  - No tentative local updates
- Staleness deviation: 60 seconds
  - Check Q for staleness periodically

Consistent Ordering of Operations

Consistent ordering of operations

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

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!

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

- *Distributed Systems: Concepts and Design. George Coulouris, Jean Dollimore, Tim Kindberg, Gordon Blair. 5th Edition. Addison Wesley. ISBN: 978-0132143011.* [Chapter 6, 7]
- *Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van Steen. 2nd Edition. Prentice Hall. ISBN: 0132392275/978-0132392273.* [Chapter 4, 18]