Introduction to Concurrency & Logical Time

COS 316: Principles of Computer System Design
Lecture 15

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Concurrency

• Multiple things happening at the same time

• Primary benefit is better performance
  • Do more work in the same amount of time
  • Complete fixed amount work in less time
  • Better utilize resources

• Primary cost is complexity
  • Hard to reason about
  • Hard to get right
  • (Systems deal with it, not applications, ... to some extent)
Concurrency Examples

- Run a computation on all cores in a machine

- Run a computation on all cores on 100K machines!
Concurrency Examples

Run a computation on all cores in a machine

Application with multiple outstanding writes to disk

Run a computation on all cores on 100K machines!

Many applications write to the disk
Distributed Systems

1) Multiple computers
2) Connected by a network
3) Doing something together

Concurrency is Inevitable!
Motivation: Multi-site database replication

• A New York-based bank wants to make its transaction ledger database resilient to whole-site failures

• Replicate the database, keep one copy in sf, one in nyc
The consequences of concurrent updates

- **Replicate** the database, keep one copy in sf, one in nyc
  - Client sends query to the nearest copy
  - Client sends update to both copies
The consequences of concurrent updates

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“Deposit $100”

“Pay 1% interest”

$1,000

$1,000

$1,100

$1,111

$1,110

$1,010

Inconsistent replicas!

Updates should have been performed in the same order at each copy
What to Do?

• Handle one client at a time?
  • Deposit $100 in both replicas, then pay 1% interest in both replicas
  • Pay 1% interest in both replicas, then deposit $100 in both replicas

• How to enforce a consistent order?
  • Based on wall-clock time?
RFC 677 “The Maintenance of Duplicate Databases” (1975)

“To the extent that the communication paths can be made reliable, and the clocks used by the processes kept close to synchrony, the probability of seemingly strange behavior can be made very small. However, the **distributed nature of the system dictates that this probability can never be zero.**”
Idea: Logical clocks

• Landmark 1978 paper by Leslie Lamport

• Insight: only the events themselves matter

Idea: Disregard the precise clock time
Instead, capture just a “happens before” relationship between a pair of events
Defining “happens-before” (→)

• Consider three processes: P1, P2, and P3

• Notation: Event a happens before event b (a → b)
Defining “happens-before” (→)

• Can observe event order at a single process
Defining “happens-before” (→)

1. If same process and a occurs before b, then a → b
Defining “happens-before” (→)

1. If **same process** and **a** occurs before **b**, then **a → b**

2. Can observe ordering when processes communicate

![Diagram](image)
Defining “happens-before” (\(\xrightarrow{}\))

1. If same process and a occurs before b, then \(a \xrightarrow{} b\)

2. If c is a message receipt of b, then \(b \xrightarrow{} c\)

![Diagram showing the order of events]

Physical time ↓
Defining “happens-before” (⇒)

1. If **same process** and a occurs before b, then a ⇒ b

2. If c is a message receipt of b, then b ⇒ c

3. Can observe ordering transitively

![Diagram](image-url)
Defining “happens-before” (→)

1. If same process and a occurs before b, then a → b

2. If c is a message receipt of b, then b → c

3. If a → b and b → c, then a → c
Concurrent events

• Not all events are related by $\rightarrow$

• $a, d$ not related by $\rightarrow$ so concurrent, written as $a \parallel d$

Physical time $\downarrow$
Lamport clocks: Objective

• We seek a clock time $C(a)$ for every event $a$

Plan: Tag events with clock times; use clock times to make distributed system correct

• Clock condition: If $a \rightarrow b$, then $C(a) < C(b)$
The Lamport Clock algorithm

• Each process $P_i$ maintains a local clock $C_i$

1. Before executing an event, $C_i \leftarrow C_i + 1$
The Lamport Clock algorithm

1. Before executing an event \(a\), \(C_i \leftarrow C_i + 1:\)
   - Set event time \(C(a) \leftarrow C_i\)

![Diagram of the Lamport Clock algorithm showing a sequence of events and the update of the Lamport clock.]
The Lamport Clock algorithm

1. Before executing an event b, $C_i \leftarrow C_i + 1$:

   - Set event time $C(b) \leftarrow C_i$

![Diagram showing the Lamport Clock algorithm with nodes P1, P2, and P3 and their respective event times C(a) = 1, C(b) = 2, and C(c) = 3.](image)
The Lamport Clock algorithm

1. Before executing an event b, $C_i \leftarrow C_i + 1$

2. Send the local clock in the message m

```
P1  $C_1=2$
  a
b

P2  $C_2=0$
  c

P3  $C_3=0$

C(a) = 1
C(b) = 2
C(m) = 2

Physical time ↓
```
3. On process $P_j$ receiving a message $m$:

- Set $C_j$ and receive event time $C(c) \leftarrow 1 + \max\{ C_j, C(m) \}$

The Lamport Clock algorithm

- $P_1$
  - $C_1 = 2$
  - $C(a) = 1$
  - $C(b) = 2$
  - $C(m) = 2$

- $P_2$
  - $C_2 = 3$
  - $C(c) = 3$

- $P_3$
  - $C_3 = 0$

Physical time ↓
Lamport Timestamps: Ordering all events

• **Break ties** by appending the process number to each event:

1. Process $P_i$ timestamps event $e$ with $C_i(e).i$

2. $C(a).i < C(b).j$ when:
   • $C(a) < C(b)$, or $C(a) = C(b)$ and $i < j$

• Now, for any two events $a$ and $b$, $C(a) < C(b)$ or $C(b) < C(a)$
  • This is called a total ordering of events
Lamport Timestamps: Ordering all events

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• Now, for any two events $a$ and $b$, $C(a) < C(b)$ or $C(b) < C(a)$
  • This is called a total ordering of events
Order all these events (with total ordering)

P1: $C_1 = 0$

P2: $C_2 = 0$

P3: $C_3 = 0$

P4: $C_4 = 0$

Physical time ↓

1.1 a

2.1 b
c
d 3.2
e
f
h
i
g

Physical time ↓
Order all these events (with total ordering)

1.1 a
2.1 b
c
d 3.2
e
f 4.3
h 5.4
i 6.4

Physical time ↓
Which events are concurrent with h?
How are c, d, e, f ordered (in the total order)?

Impose an order on concurrent events!

Is it d, f, c, e?

Instead, c, d, e, f

Physical time ↓
Totally-Ordered Multicast

Goal: All sites apply updates in (same) Lamport clock order

• Client sends update to one replica site $j$
  • Replica assigns it Lamport timestamp $C_j \cdot j$

• Key idea: Place events into a sorted local queue
  • Sorted by increasing Lamport timestamps

Example: P1’s local queue:
Totally-Ordered Multicast

Goal: All sites apply updates in (same) Lamport clock order

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- Key idea: Place events into a sorted local queue
  - Sorted by increasing Lamport timestamps

Example: P1’s local queue:

\[ \begin{array}{c}
  \text{Example: P1’s local queue:} \\
  \text{\$} \\
  \text{P1} \\
  \text{1.1} \\
  \text{1.2}
\end{array} \]
Totally-Ordered Multicast (Almost correct)

1. On receiving an update from client, broadcast to others (including yourself)

2. On receiving an update from replica:
   a) Add it to your local queue
   b) Broadcast an acknowledgement message to every replica (including yourself)

3. On receiving an acknowledgement:
   • Mark corresponding update acknowledged in your queue

4. Remove and process updates everyone has ack’ed from head of queue
1. On receiving an update from client, broadcast to others (including yourself)

2. On receiving an update from replica:
   a) Add it to your local queue
   b) Broadcast an acknowledgement message to every replica (including yourself)

3. On receiving an acknowledgement:
   • Mark corresponding update acknowledged in your queue

4. Remove and process updates everyone has ack’ed from head of queue
Totally-Ordered Multicast (Almost correct)

- P1 queues $, P2 queues %
- P1 queues and ack’s %
  - P1 marks % fully ack’ed
- P2 marks % fully ack’ed

X P2 processes %
1. On receiving an update from client, broadcast to others (including yourself)

2. On receiving or processing an update:
   a) Add it to your local queue, if received update
   b) Broadcast an acknowledgement message to every replica (including yourself) only from head of queue

3. On receiving an acknowledgement:
   • Mark corresponding update acknowledged in your queue

4. Remove and process updates everyone has ack’ed from head of queue
Totally-Ordered Multicast *(Correct version)*

- $1.1$
- $1.2$
- $1.1$

(P1)

- $1.1$
- %

(P2)

- $1.1$
- $%$

(Ack’s to self not shown here)
So, are we done?

• *Does totally-ordered multicast solve the problem of multi-site replication in general?*

• Not by a long shot!

1. Our protocol **assumed**:  
   • No node failures  
   • No message loss  
   • No message corruption

2. All to all communication **does not scale**

3. **Waits forever** for message delays (performance?)
Intro to Concurrency Conclusion

• Concurrency is great for performance, hard to reason about, and often unavoidable in systems

• Replicated DB example
  • Concurrent updates can lead to inconsistency between replicas
  • Lamport clocks can order events in a distributed system
  • Lamport clocks + careful protocol = correct replication

• What is “correct”? 