Distributed Systems
Consistency & Replication I

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Last Time

- Logical Clocks
- Vector Clocks
- Consistent Snapshots
- Passive Monitoring
- Active Monitoring

Active Monitoring

- Recall: we used vector clocks so we can construct consistent global states (or cuts) from processes' local histories via passive monitoring
- Remember, there is another type of monitoring – **active monitoring**
  - Active monitoring is also referred to as constructing a ***distributed snapshot***

Distributed Snapshot Protocol (Chandy and Lamport)

- Monitor p_0 sends “take snapshot” message to all processes p_i
- If p_i receives such “take snapshot” message for the first time, it:
  - Records its state
  - Stops doing any activity related to the distributed computation
  - Relays the “take snapshot” message on all of its outgoing channels
  - Starts recording a state of its incoming channels – records all messages that have been delivered after the receipt of the first “take snapshot” message

Distributed Snapshot Protocol (Chandy and Lamport)(cont.)

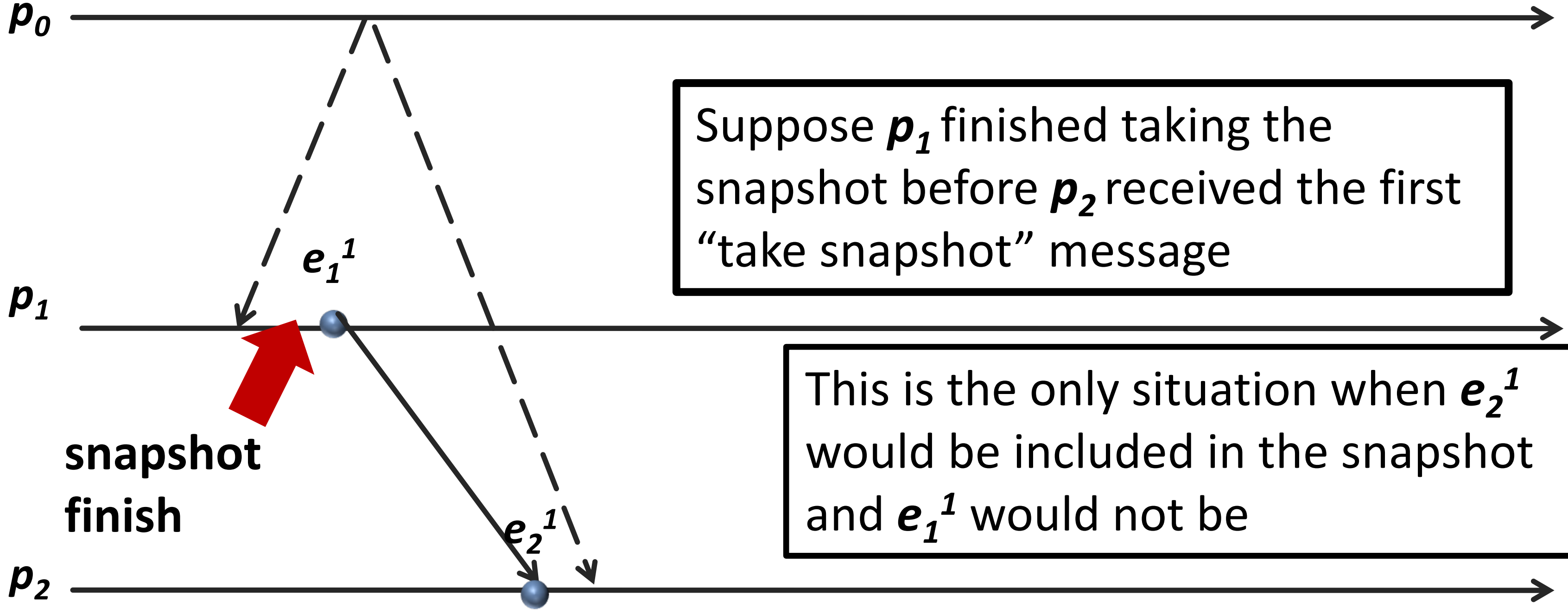
- When p_i receives a "take snapshot" message from process p_j, it stops recording the state of the channel between itself and p_j
- When p_i received "take snapshot" message from all processes and from p_o, it stops recording the snapshot and sends it to p_o

Properties of Chandy-Lamport Protocol

- Let’s see why this protocol constructs only consistent snapshots, provided that FIFO channels are used
- Recall the key property of a consistent snapshot (i.e., consistent cut):
  - If event ***(e → e”)*** and ***e”*** is included in the snapshot, then ***e*** must also be included in that snapshot
- Let’s see why this property holds if we use the Chandy-Lamport distributed snapshot protocol

Properties of Chandy-Lamport Protocol

Can it happen that e_2^1 is included in the snapshot and e_1^1 is not?



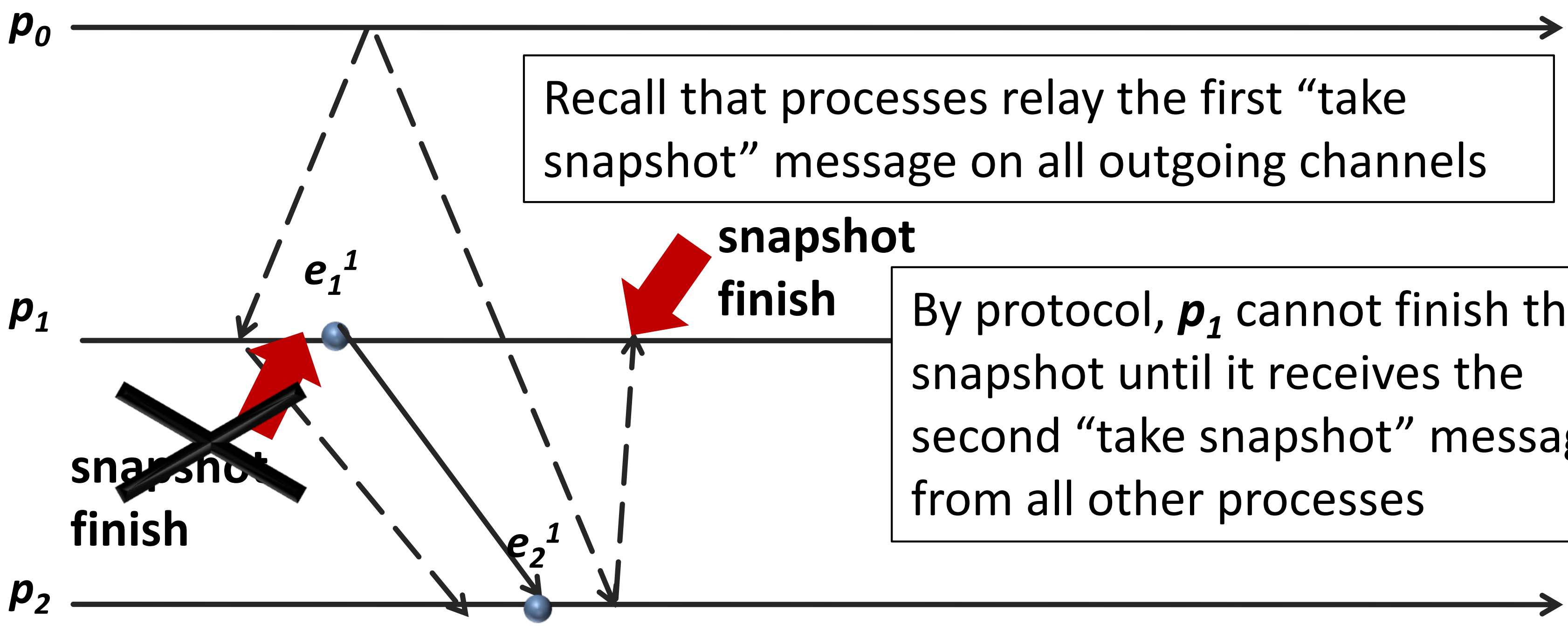
Suppose p_1 finished taking the snapshot before p_2 received the first "take snapshot" message

This is the only situation when e_2^1 would be included in the snapshot and e_1^1 would not be

"take snapshot" message

Let's see why this won't happen

Chandy-Lamport Protocol: Example 1



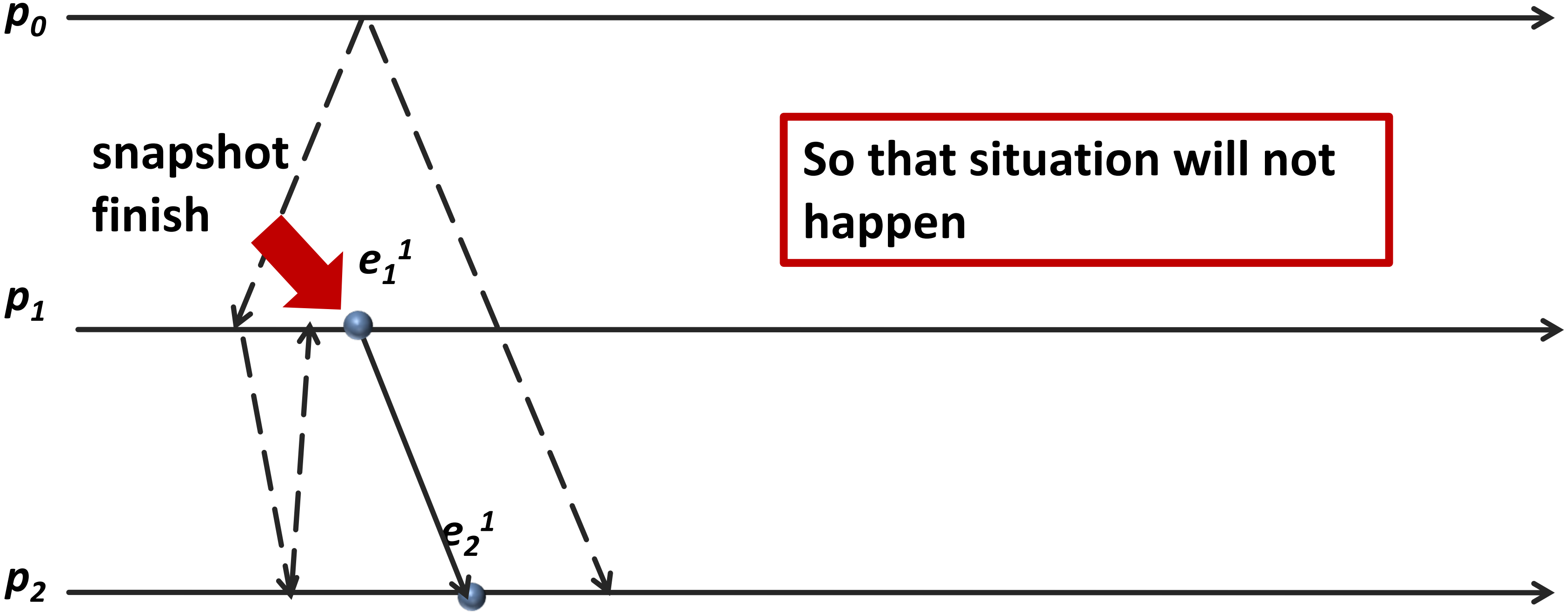
Recall that processes relay the first "take snapshot" message on all outgoing channels

By protocol, p_1 cannot finish the snapshot until it receives the second "take snapshot" message from all other processes

So p_1 cannot send e_1^1 and finish taking the snapshot before p_2 received the first "take snapshot" message.

So that situation will not happen

Chandy-Lamport Protocol: Example 2



So that situation will not happen

But p_2 must **stop recording events** from p_1 after it receives the “take snapshot” message from p_1.

Questions

- Active monitoring vs. passive monitoring?
  - Active monitoring: query the system
- Goal of Chandy and Lamport protocol?
  - Global snapshot

Summary

- Constructing a consistent global state is difficult in absence of global clocks
- Consistent global states can be constructed using
  - Active monitoring (distributed snapshots)
  - Passive monitoring (local event histories with vector clock timestamps)

Today…

- Consistency and Replication
  - Introduction
  - Data-centric Consistency Models

Why Replication?

- Replication is the process of maintaining the data at multiple computers

- Replication is necessary for:
  - **<u>Improving performance</u>**
    - A client can access the replicated copy of the data that is near to its location

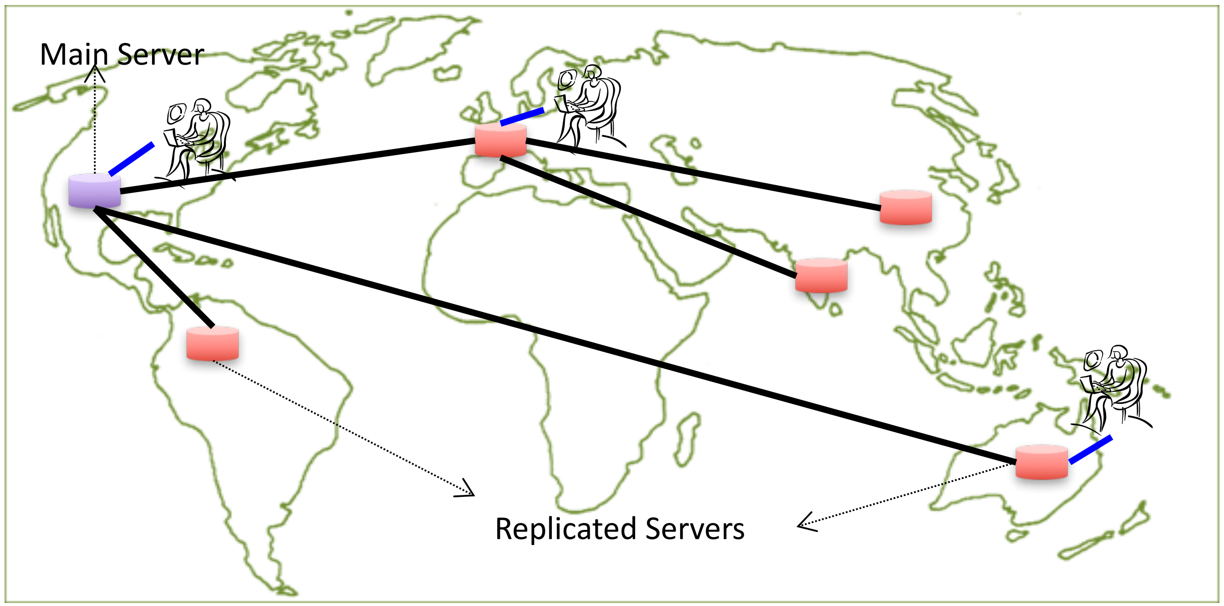
  - **<u>Increasing the availability of services</u>**
    - Replication can mask failures such as server crashes and network disconnection

  - **<u>Enhancing the scalability of the system</u>**
    - Requests to the data can be distributed to many servers which contain replicated copies of the data

  - **<u>Securing against malicious attacks</u>**
    - Even if some replicas are malicious, secure data can be guaranteed to the client by relying on the replicated copies at the non-compromised servers

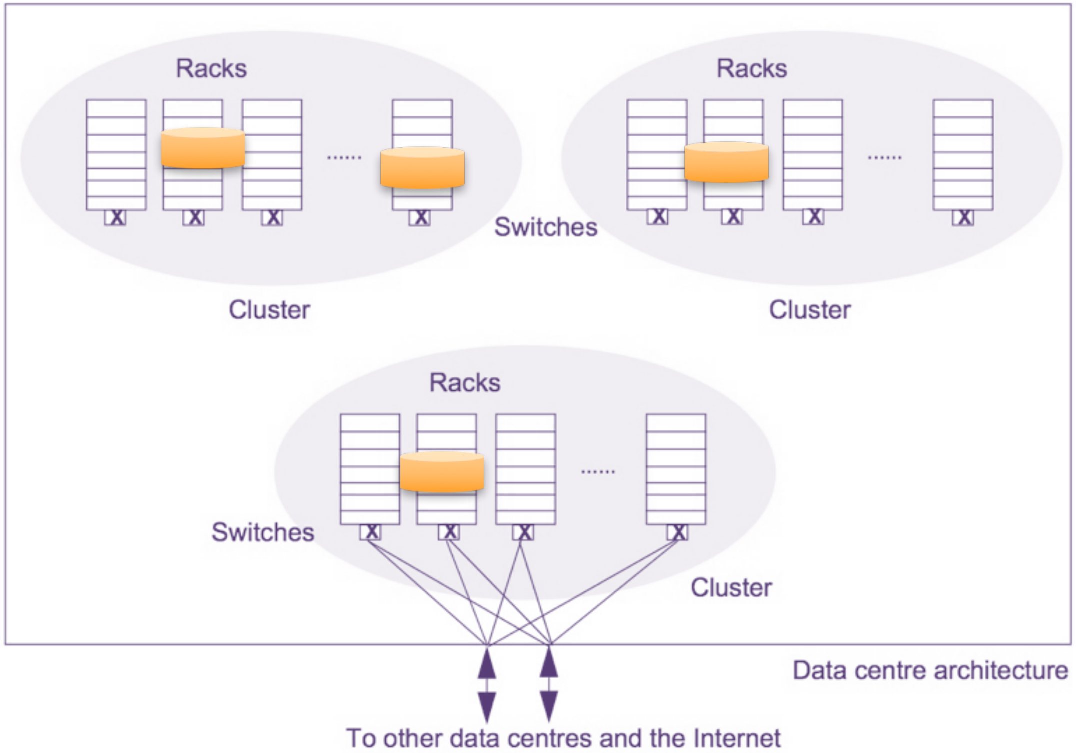
1. Replication for Improving Performance

- Example Applications
  - Caching webpages at the client browser
  - Caching IP addresses at clients and DNS Name Servers
  - Caching in Content Delivery Network (CDNs)
    - Commonly accessed contents, such as software and streaming media, are cached at various network locations



2. Replication for High-Availability

- Availability can be increased by storing the data at replicated locations (instead of storing one copy of the data at a server)

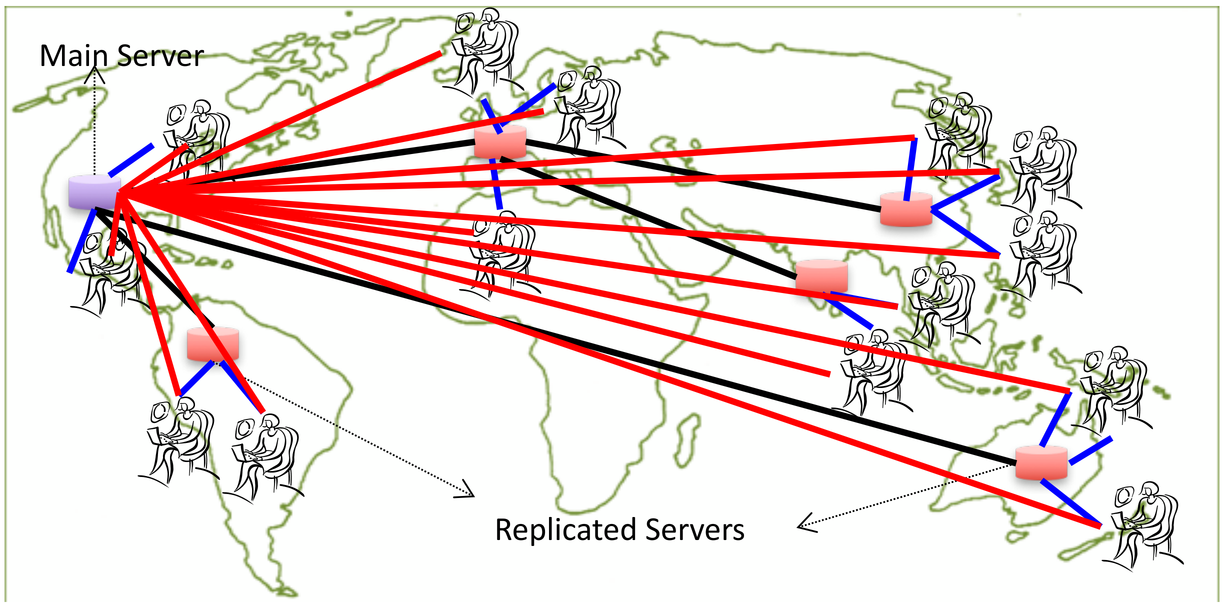


- Example:
  Google File-System and Chubby replicate the data at computers across different racks, clusters and data-centers
  - If one computer or a rack or a cluster crashes, then a replica of the data can still be accessed

3. Replication for Enhancing Scalability

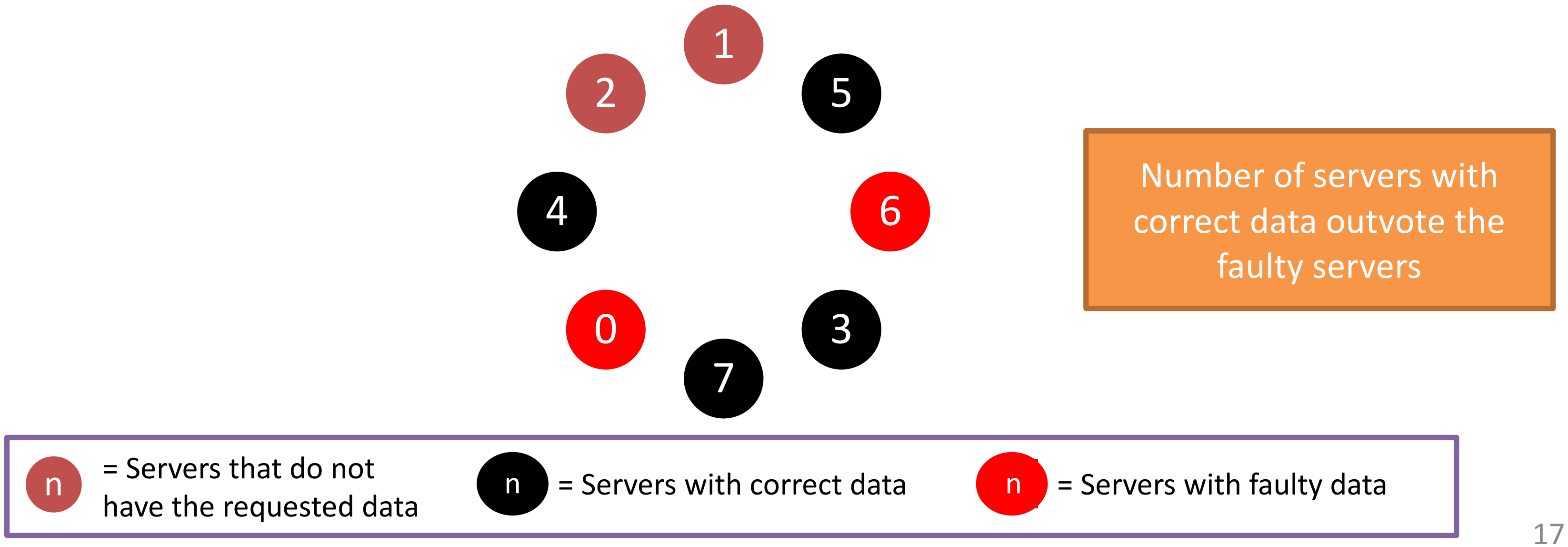
- Distributing the data across replicated servers helps in avoiding bottle-necks at the main server
  - It balances the load between the main and the replicated servers

- Example: Content Delivery Networks decrease the load on main servers of the website



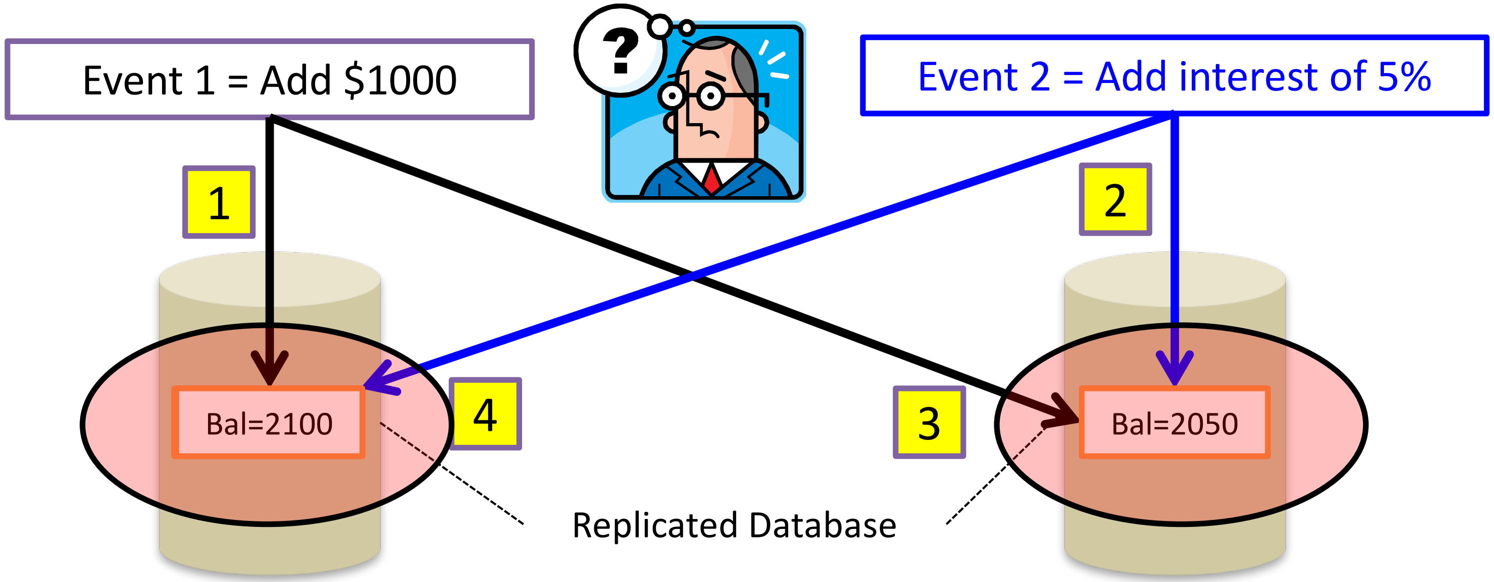
4. Replication for Securing Against Malicious Attacks

- If a minority of the servers that hold the data are malicious, the non-malicious servers can outvote the malicious servers, thus providing security.
- The technique can also be used to provide fault-tolerance against non-malicious but faulty servers



Why Consistency?

- In a DS with replicated data, one of the main problems is keeping the data consistent
- An example:
  - In an e-commerce application, the bank database has been replicated across two servers
  - Maintaining consistency of replicated data is a challenge



Overview of Consistency and Replication

Today's lecture

- Consistency Models
  - Data-Centric Consistency Models
  - Client-Centric Consistency Models
- Replica Management
  - When, where and by whom replicas should be placed?
  - Which consistency model to use for keeping replicas consistent?
- Consistency Protocols
  - We study various implementations of consistency models

Next lectures

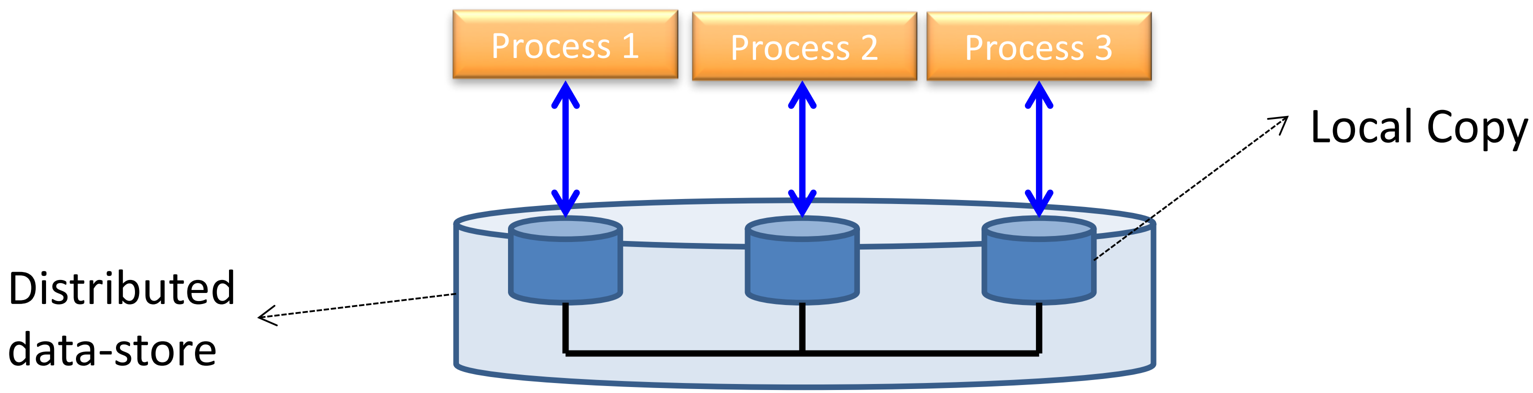
Overview

- Consistency Models
  - Data-Centric Consistency Models
  - Client-Centric Consistency Models
- Replica Management
- Consistency Protocols

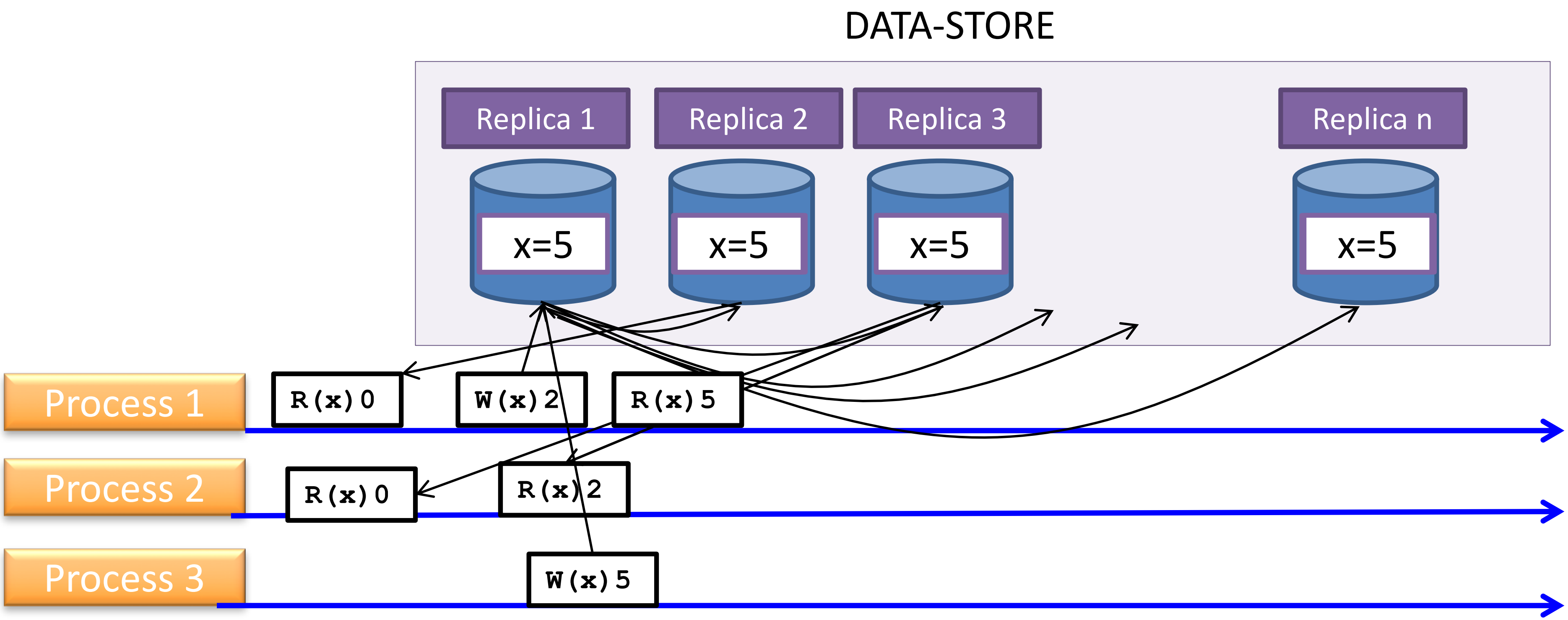
Introduction to Consistency and Replication

- In a distributed system, shared data is typically stored in distributed shared memory, distributed databases or distributed file systems.
  - The storage can be distributed across multiple computers
  - Simply, we refer to a series of such data storage units as data-stores

- Multiple processes can access shared data by accessing any replica on the data-store
  - Processes generally perform read and write operations on the replicas

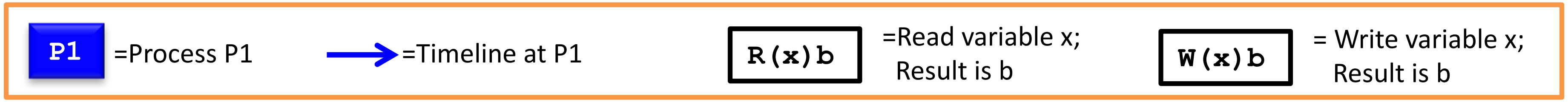


Maintaining Consistency of Replicated Data

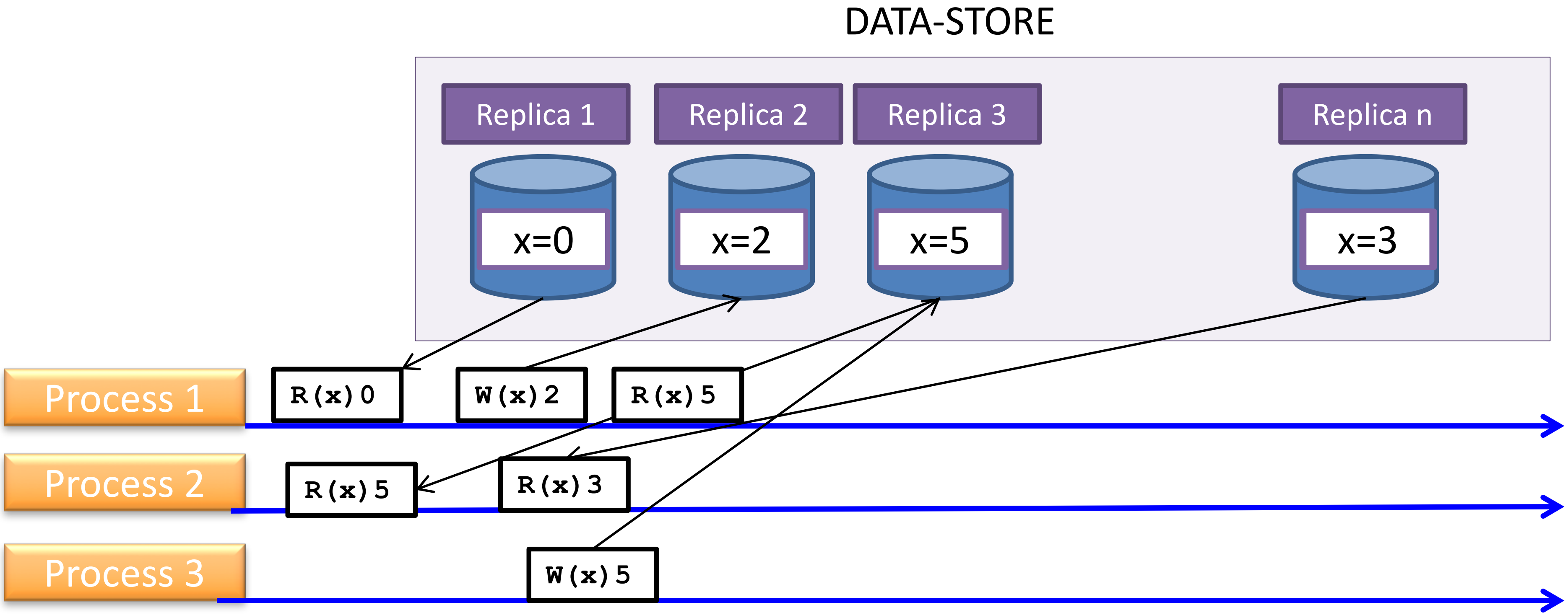


<u>Strict Consistency</u>

- Data is always fresh
  - After a write operation, the update is propagated to all the replicas
  - A read operation will result in reading the most recent write
- If there are many writes, this leads to large overheads

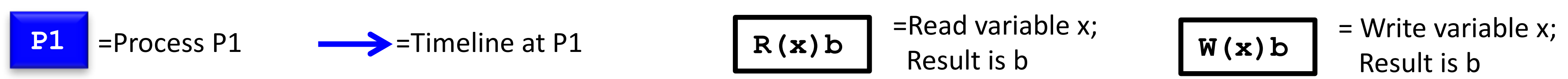


Maintaining Consistency of Replicated Data (cont'd)



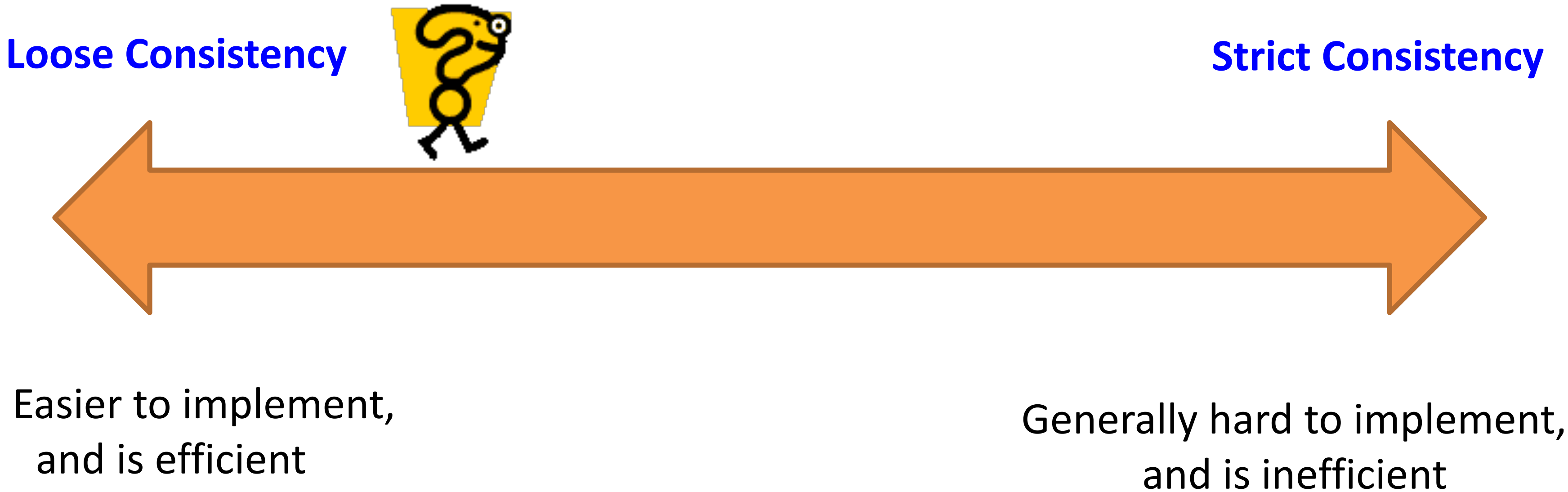
<u>Loose Consistency</u>

- Data might be stale
  - A read operation may result in reading a value that was written long back
  - Replicas are generally out-of-sync
- The replicas may sync at coarse grained time, thus reducing the overhead



Trade-offs in Maintaining Consistency

- Maintaining consistency should balance between the strictness of consistency versus efficiency
  - How much consistency to we need?
  - Good-enough consistency depends on your application



Questions

- Strict consistency vs. loose consistency?
  - Strict consistency: data is always up-to-date
  - Loose consistency: data maybe be outdated
- Which one to implement for
  - a Bank?
  - Facebook?

Consistency Model

- A consistency model is a contract between
  - the process that wants to use the data, and
  - the replicated data repository (or data-store)

- A consistency model states the level of consistency provided by the data-store to the processes while reading and writing the data

Types of Consistency Models

- Consistency models can be divided into two types:
  - Data-Centric Consistency Models
    - These models define how the data updates are propagated across the replicas to keep them consistent
  - Client-Centric Consistency Models
    - These models assume that clients connect to different replicas at each time
    - The models ensure that whenever a client connects to a replica, the replica is bought up to date with the replica that the client accessed previously

Overview

- Consistency Models
  - Data-Centric Consistency Models
  - Client-Centric Consistency Models
- Replica Management
- Consistency Protocols

Data-Centric Consistency Models

- Data-centric Consistency Models describe how the replicated data is kept consistent, and what the process can expect

- Under Data-centric Consistency Models, we study two types of models:
  - Consistency Specification Models:
    - These models enable specifying the consistency levels that are tolerable to the application
  - Models for Consistent Ordering of Operations:
    - These models specify the order in which the data updates are propagated to different replicas

Overview

- Consistency Models
  - Data-Centric Consistency Models
    - Consistency Specification Models
    - Models for Consistent Ordering of Operations
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Consistency Specification Models

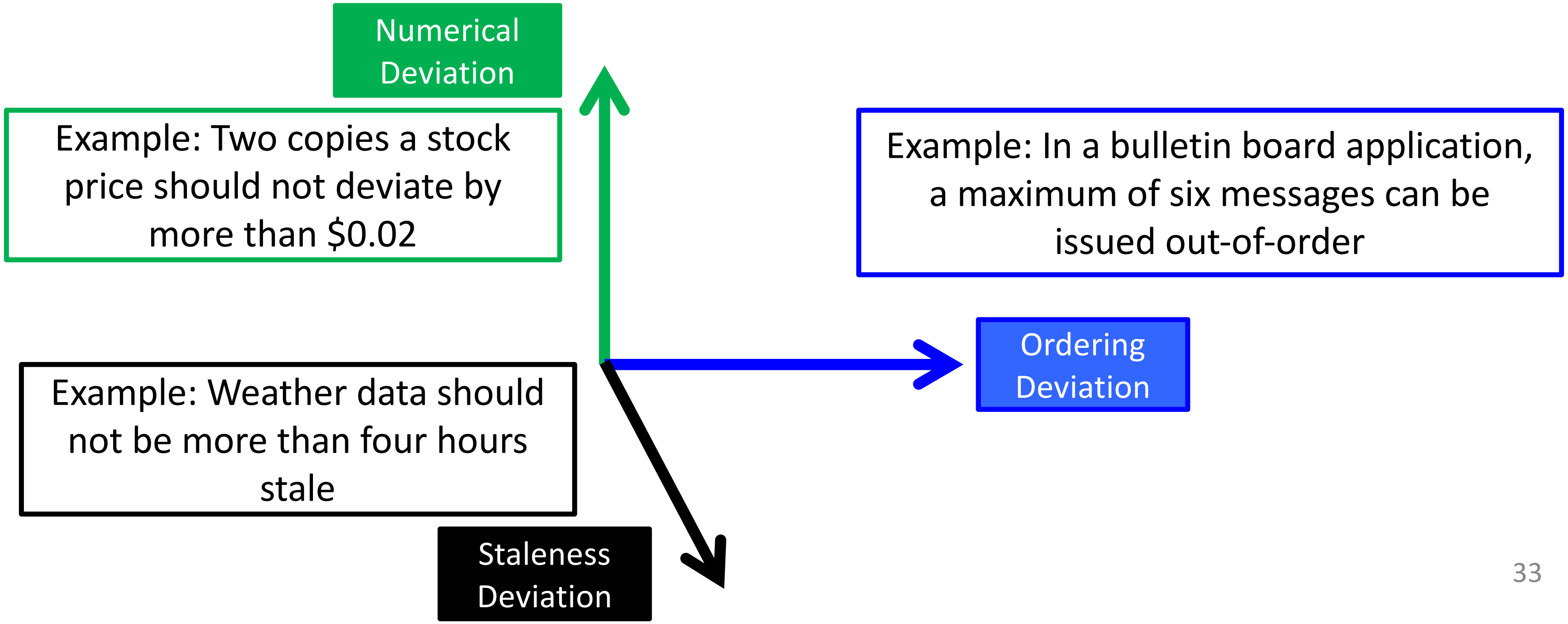
- In replicated data-stores, there should be a mechanism to:
  - Measure how inconsistent the data might be on different replicas
  - How replicas and applications can specify the tolerable inconsistency levels
- Consistency Specification Models enable measuring and specifying the level of inconsistency in a replicated data-store
- We study a Consistency Specification Model called Continuous Consistency Model

Continuous Consistency Model

- Continuous Consistency Model
  - is used to measure inconsistencies and
  - express what inconsistencies can be expected in the system

Continuous Consistency Ranges

- Level of consistency is defined over three independent axes:
  - Numerical Deviation: Deviation in the numerical values between replicas
  - Order Deviation: Deviation with respect to the ordering of update operations
  - Staleness Deviation: Deviation in the staleness between replicas



Consistency Unit (Conit)

- Consistency unit (Conit) specifies the data unit over which consistency is measured
  - For example, conit can be defined as a record representing a single stock
- Level of consistency is measured by each replica along the three dimensions
  - Numerical Deviation
    - For a given replica R, how many updates at other replicas are not yet seen at R? What is the effect of the non-propagated updates on local Conit values?
  - Order Deviation
    - For a given replica R, how many local updates are not propagated to other replicas?
  - Staleness Deviation
    - For a given replica R, how long has it been since updates were propagated?

Conit and Consisten…

Assume … table of operations and measures

Order De… number of operations in R that are not prese…

… at r… R is defin…

… oth… plicas that…

…iatio…

…unt f… ll variables

There is one operation at B which is not yet pushed to A with a value difference of x=2,y=0

There are no operations at A which are not yet pushed to B

No operations at A are not yet pushed to B

One operation at B was not yet pushed to A

…A					Repl…				
x	y		Ord	n(w)	x	y	VC	Ord	n(w)
0	0	(0,0)	0	0(0,0)	0	0	(0,0)	0	0(0,0)
0	0	(0,0)	0	1(2,0)	2	0	(0,5)	1	0(0,0)
2	0	(1,5)	0	0(0,0)	2	0	(0,5)	0	0(0,0)
2	1	(10,5)	1	0(0,0)	2	0	(0,5)	0	1(0,1)
2	1	(10,5)	1	1(0,1)	2	1	(0,16)	1	1(0,1)
3	1	(14,5)	2	1(0,1)	2	1	(0,16)	1	2(1,1)
3	4	(23,5)	3	1(0,1)	2	1	(0,16)	1	3(1,4)

Replica A

x; y

Operation		Result
<5,B>	x+=2	x=2
<10,A>	y+=1	y=1
<14,A>	x+=1	x=3
<23,A>	y+=3	y=4

Replica B

x; y

Operation		Result
<5,B>	x+=2	x=2
<16,B>	y+=1	y=1

<5,B> = Operation performed at **B** when the vector clock was **5**

<m,n> = Uncommitted operation

<m,n> = Committed operation

x;y = A Conit

FOR PRINTING – WITHOUT BUBBLES

Assume a **global observer keeps a table of operations and measures**

Order Deviation at a replica R is the number of operations in R that are not present at the other replicas

Numerical Deviation at replica R is defined as n(w), where
n = # of operations at other replicas that are not yet seen by R,
w = weight of the deviation
= list of update amount for all variables in a Conit

Replica A					Replica B				
x	y	VC	Ord	n(w)	x	y	VC	Ord	n(w)
0	0	(0,0)	0	0(0,0)	0	0	(0,0)	0	0(0,0)
0	0	(0,0)	0	1(2,0)	2	0	(0,5)	1	0(0,0)
2	0	(1,5)	0	0(0,0)	2	0	(0,5)	0	0(0,0)
2	1	(10,5)	1	0(0,0)	2	0	(0,5)	0	1(0,1)
2	1	(10,5)	1	1(0,1)	2	1	(0,16)	1	1(0,1)
3	1	(14,5)	2	1(0,1)	2	1	(0,16)	1	2(1,1)
3	4	(23,5)	3	1(0,1)	2	1	(0,16)	1	3(1,4)

Replica A

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Replica B

x; y

Operation		Result
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Overview

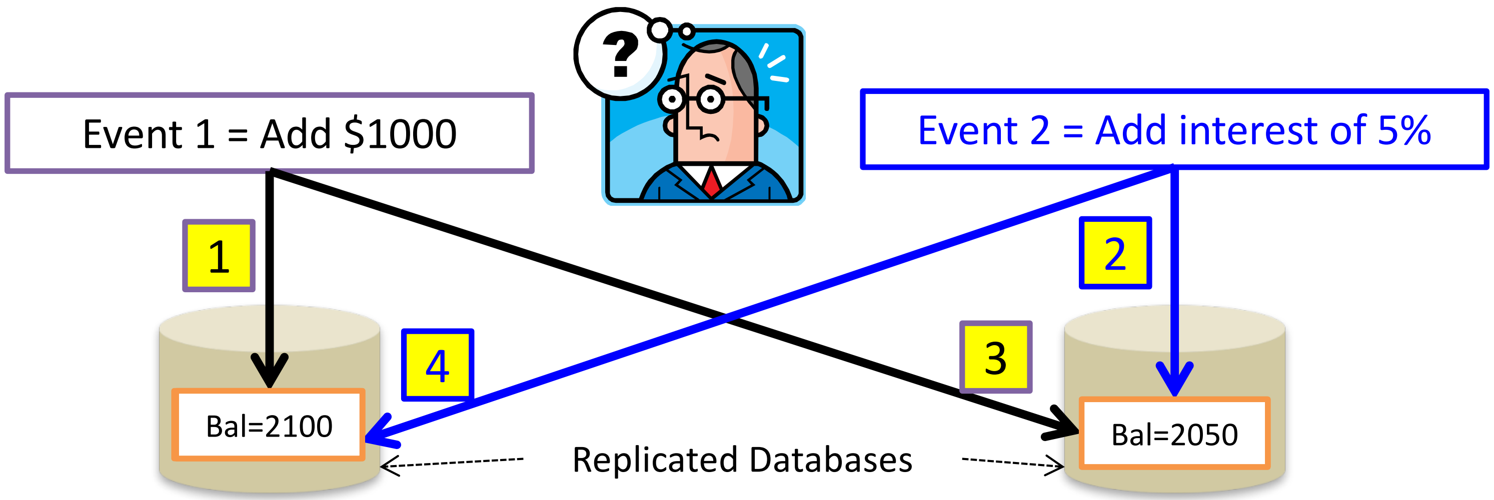
- Consistency Models
  - Data-Centric Consistency Models
    - Continuous Specification Models
    - Models for Consistent Ordering of Operations
  - Client-Centric Consistency Models

- Replica Management

- Consistency Protocols

Why is Consistent Ordering Required in Replication?

- In several applications, the order or the sequence in which the replicas commit to the data store is critical
- Example:



- Continuous Specification Models defined how inconsistency is measured
  - However, the models did not enforce any order in which the data is committed

Consistent Ordering of Operations (cont'd)

- Whenever a replica is updated, it propagates the updates to other replicas at some point in time
- Updating different replicas is carried out by passing messages between the replica data-stores
- We will study different types of ordering and consistency models arising from these orderings

Types of Ordering

- We will study three types of ordering of messages that meet the needs of different applications:
  - Total Ordering
  - Sequential Ordering
    - Sequential Consistency Model
  - Causal Ordering
    - Causal Consistency Model

Questions

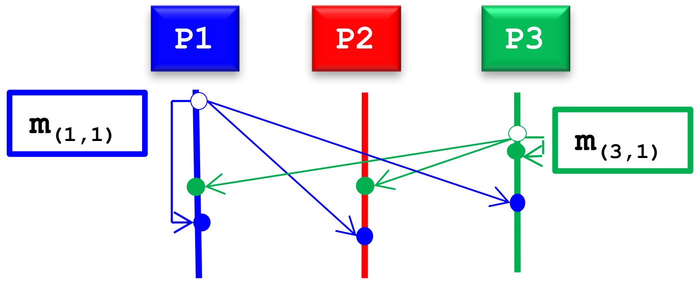
- How do we measure consistency?
  – Global observer
- Metrics to measure consistency?
  – Numerical Deviation: Deviation in the numerical values between replicas
  – Order Deviation: Deviation with respect to the ordering of update operations
  – Staleness Deviation: Deviation in the staleness between replicas

Types of Ordering

- Total Ordering
- Sequential Ordering
- Causal Ordering

Total Ordering

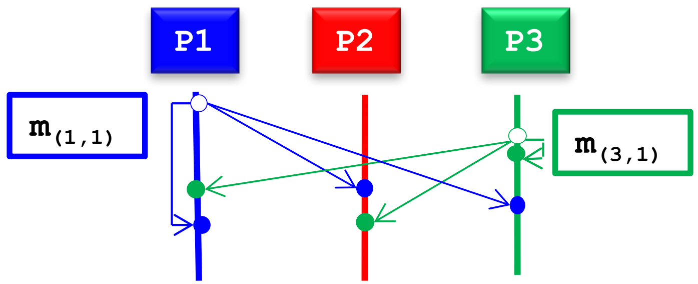
- Total Order
  - If process $\mathbf{P_i}$ sends a message $\mathbf{m_i}$ and $\mathbf{P_j}$ sends $\mathbf{m_j}$, and if one correct process delivers $\mathbf{m_i}$ before $\mathbf{m_j}$ then every correct process delivers $\mathbf{m_i}$ before $\mathbf{m_j}$



Ex1: Total Order

- Messages can contain replica updates, such as passing the read or write operation that needs to be performed at each replica, example:
  - if $\mathbf{P_1}$ issues the operation $\mathbf{m_{(1,1)}}$: **x=x+1;** and
  - If $\mathbf{P_3}$ issues $\mathbf{m_{(3,1)}}$: **print(x);**
  - Then, at all replicas $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_3}$ execute in the same order, for example:

```
print(x);
x=x+1;
```



Ex2: Not in Total Order

Types of Ordering

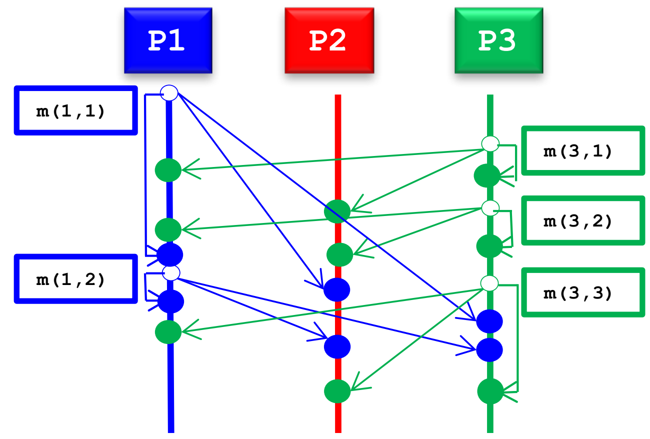
– Total Ordering

– Sequential Ordering

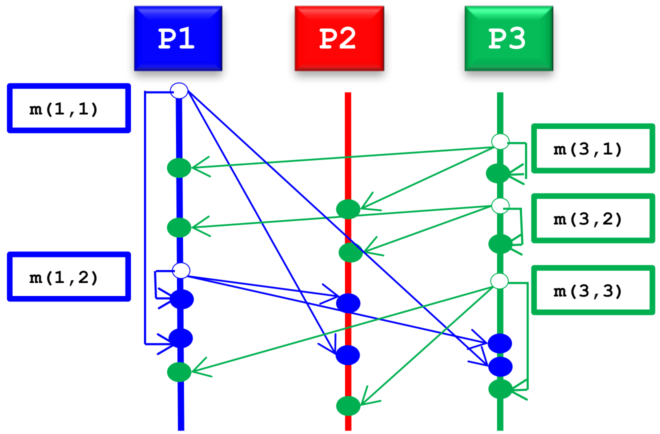
– Causal Ordering

Sequential Ordering

- If a process **Pi** sends a sequence of messages $\mathbf{m}_{(i,1)},\ldots,\mathbf{m}_{(i,ni)}$, and
- Process **Pj** sends a sequence of messages $\mathbf{m}_{(j,1)},\ldots,\mathbf{m}_{(j,nj)}$,
- Then, :
  - At any process, the set of messages received are in the same sequential order
  - Messages from each individual process appear in this sequence in the order sent by the sender
    - At every process, $\mathbf{m}_{i,1}$ should be delivered before $\mathbf{m}_{i,2}$, which is delivered before $\mathbf{m}_{i,3}$ and so on...
    - At every process, $\mathbf{m}_{j,1}$ should be delivered before $\mathbf{m}_{j,2}$, which is delivered before $\mathbf{m}_{j,3}$ and so on...



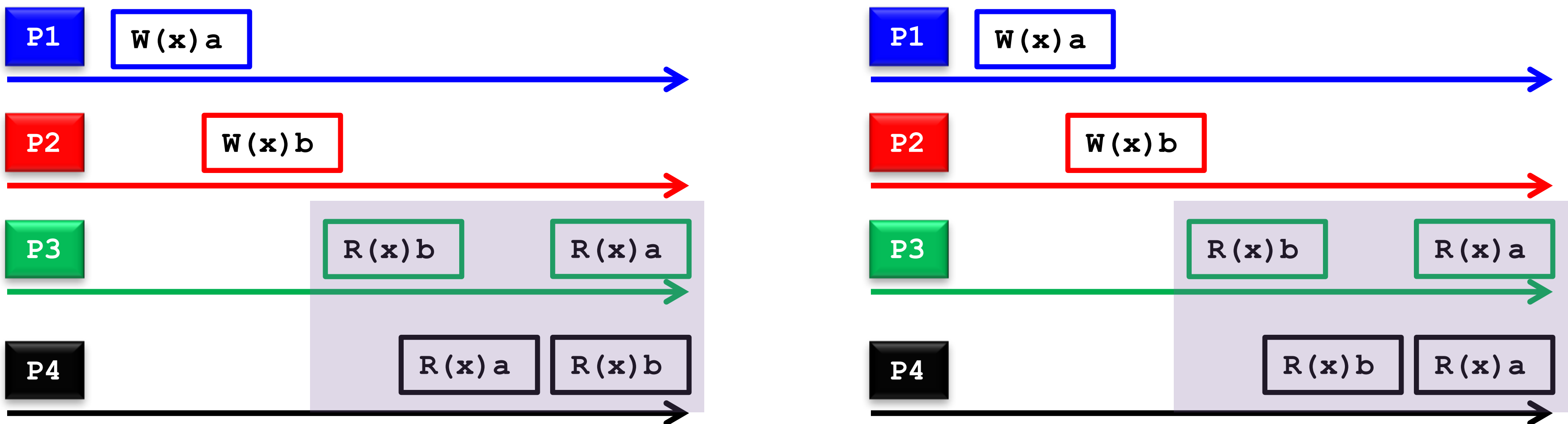
Valid Sequential Orders



Invalid Sequential Orders, but Valid Total Order

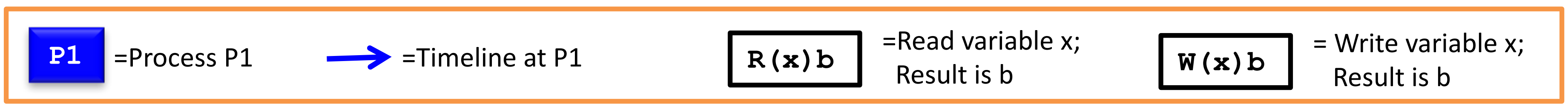
Sequential Consistency Model

- Sequential Consistency Model enforces that all the update operations are executed at the replicas in a sequential order
  - "all read operations should see writes in the same order"
- Consider a data-store with variable **x** (Initialized to **NULL**)
  - In the two data-stores below, identify the sequentially consistent data-store



Results while operating on DATA-STORE-1

Results while operating on DATA-STORE-2



Sequential Consistency (cont'd)

- Consider three processes **P**$_1$, **P**$_2$ and **P**$_3$ executing multiple instructions on three shared variables **x**, **y** and **z**
  - Assume that **x**, **y** and **z** are set to zero at start

P1
```
x = 1
print (y,z)
```

P2
```
y = 1
print (x,z)
```

P3
```
z = 1
print (x,y)
```

- There are many valid sequences in which operations can be executed at the replica respecting sequential consistency
  - Identify the output?

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

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

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

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

Output	001011	101011	000111	010111

Sequential Con

http://olafland.polldaddy.com/s/seqcons

- Consider three processes $\mathbf{P}_1$, $\mathbf{P}_2$ ar three shared variables **x**, **y** and **z**
  - Assume that **x**, **y** and **z** are set to

P1
```
x = 1
print (y,z)
```

P2
```
y = 1
print (x,z)
```

P3
```
z = 1
print (x,y)
```

- There are many valid sequences in the replica respecting sequential cc
  - Identify the output?
  - Which ones brakes the seq. order?

	x = 1 print (y,z) y = 1 print (x,z) z = 1 print (x,y)	x = 1 y = 1 print (x,z) print (y,z) z = 1 print (x,y)	z = 1 print (x,y) print (x,z) y = 1 x = 1 print (y,z)	y = 1 z = 1 print (x,y) print (x,z) x = 1 print (y,z)
Output	001011	101011	000111	010111

http://olafland.polldaddy.com/s/seqcons

Sequential Consistency (cont'd)

- Consider three processes $\mathbf{P_1}$, $\mathbf{P_2}$ and $\mathbf{P_3}$ executing multiple instructions on three shared variables **x**, **y** and **z**
  - Assume that **x**, **y** and **z** are set to zero at start

P1	P2	P3
`x = 1` `print (y,z)`	`y = 1` `print (x,z)`	`z = 1` `print (x,y)`

- There are many valid sequences in which operations can be executed at the replica respecting sequential consistency
  - Identify the output?
  - Which ones brakes the seq. order?

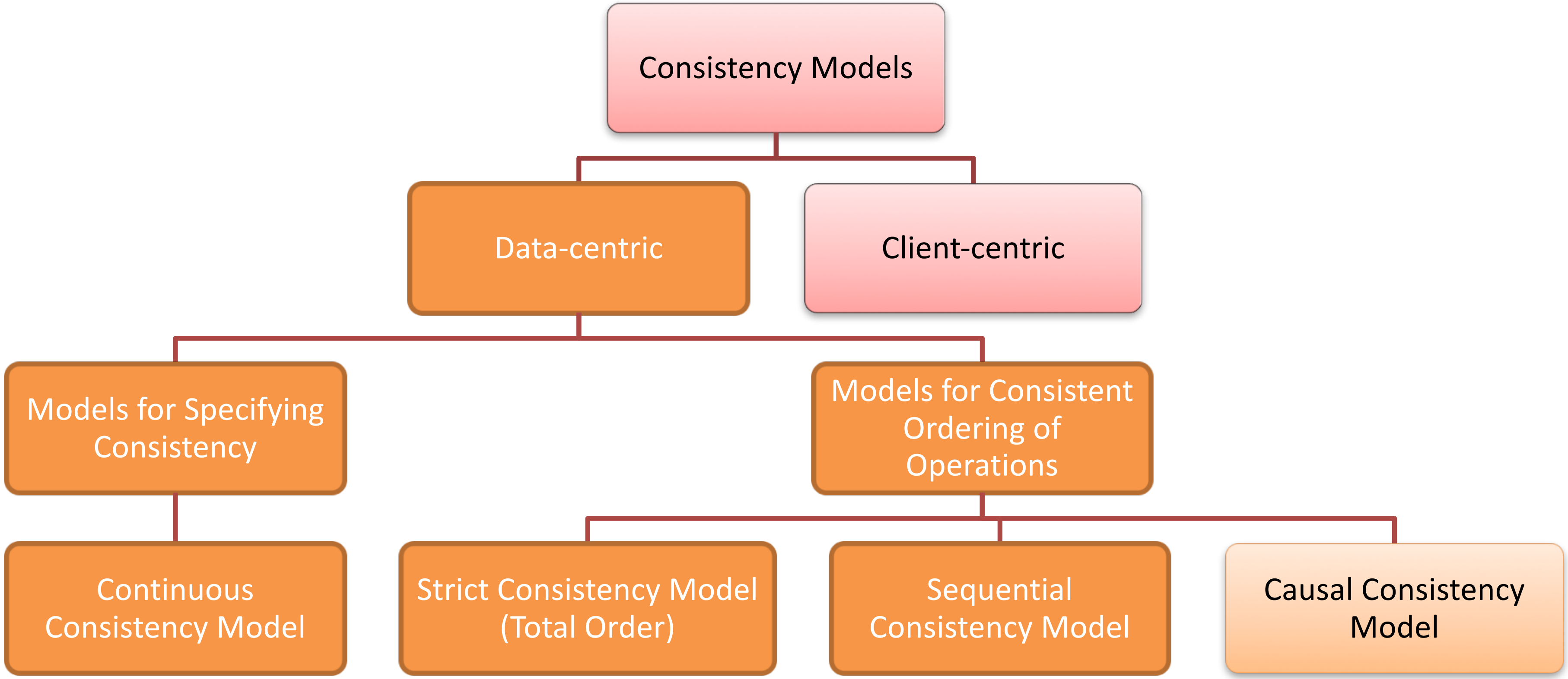
	`x = 1` `print (y,z)` `y = 1` `print (x,z)` `z = 1` `print (x,y)`	`x = 1` `y = 1` `print (x,z)` `print (y,z)` `z = 1` `print (x,y)`	`z = 1` `print (x,y)` `print (x,z)` `y = 1` `x = 1` `print (y,z)`	`y = 1` `z = 1` `print (x,y)` `print (x,z)` `x = 1` `print (y,z)`
Output	001011	101011	000111	010111

Implications of Adopting Sequential Consistency Model for Applications

- There might be several different sequentially consistent combinations of ordering
  - Number of combinations for a total of n instructions = $O(n!)$
- The contract between the process and the distributed data-store is that the process must accept all of the sequential orderings as valid results
  - A process that works for some of the sequential orderings and does not work correctly for others is INCORRECT

Recap: Consistency Models

- A consistency model states the level of consistency provided by the *data-store* to the processes while reading and writing the data



Questions

- Total Order?
  - Same order on all nodes
- Sequential Ordering?
  - At any process, the set of messages received are in the same sequential order
  - Messages from each individual process appear in this sequence in the order sent by the sender

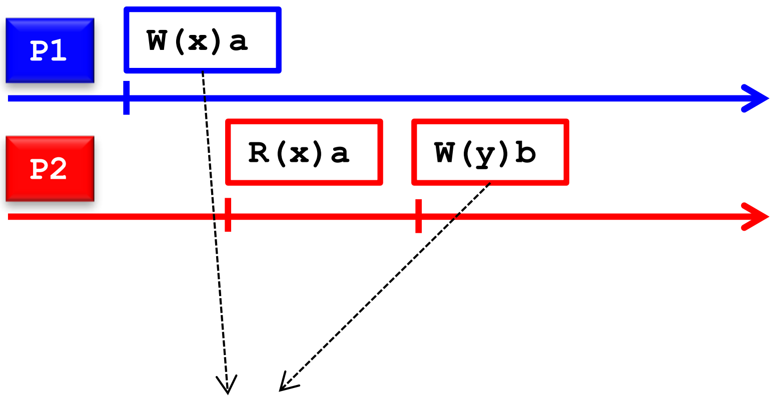
Causality (Recap)

- Causal relation between two events
  - If **a** and **b** are two events such that **a happened-before b** or **a→b**, and
  - If the (logical) time when event **a** and **b** is received at a process $\mathbf{P_i}$ is denoted by $\mathbf{C_i(a)}$ and $\mathbf{C_i(b)}$
  - Then, if we can infer that **a→b** by observing that $\mathbf{C_i(a) < C_i(b)}$, then **a** and **b** are causally related

- How can we implement causality?
  - Logical Clocks or Vector Clocks (see prev. lectures)

Causal vs. Concurrent events

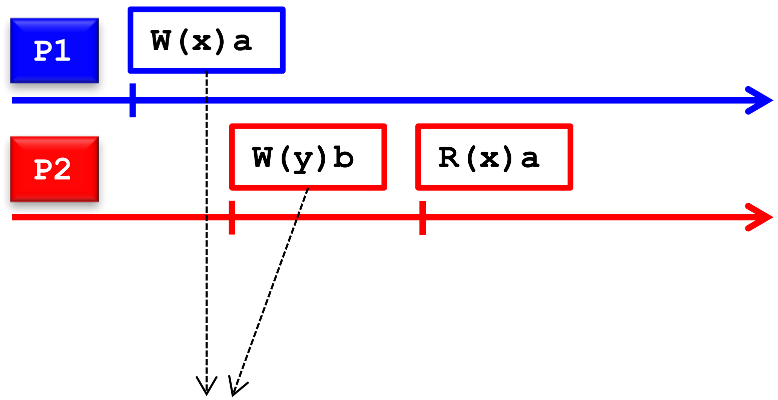
- Consider an interaction between processes $\mathbf{P}_1$ and $\mathbf{P}_2$ operating on replicated data **x** and **y**



Events are causally related

Events are not concurrent

- Computation of **y** at $\mathbf{P}_2$ may have depended on value of **x** written by $\mathbf{P}_1$ (As $\mathbf{P}_2$ reads **x** before writing **y**)



Events are not causally related

Events are concurrent

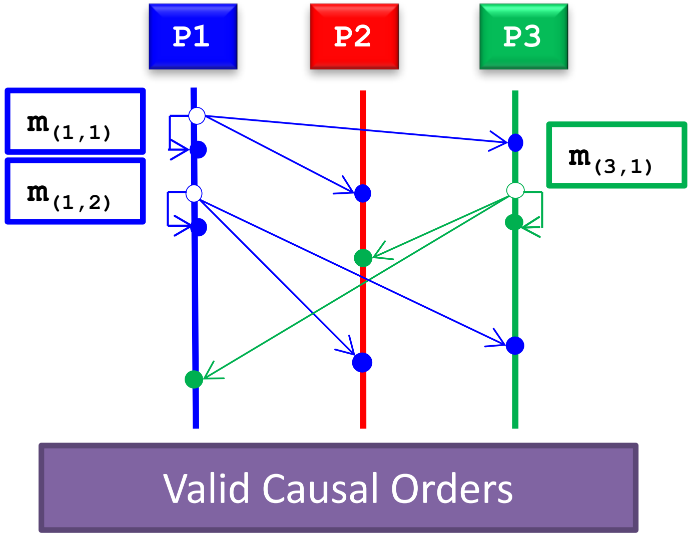
- Computation of **y** at $\mathbf{P}_2$ does not depend on value of **x** written by $\mathbf{P}_1$

P1 =Process P1 | → =Timeline at P1 | `R(x)b` =Read variable x; Result is b | `W(x)b` = Write variable x; Result is b

Causal Ordering

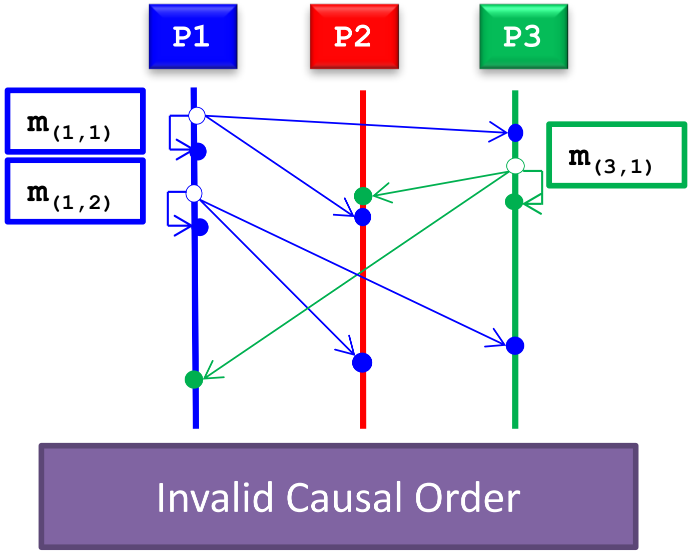
Causal Order

- If process $\mathbf{P_i}$ sends a message $\mathbf{m_i}$ and $\mathbf{P_j}$ sends $\mathbf{m_j}$, and if $\mathbf{m_i} \rightarrow \mathbf{m_j}$ (operator '$\rightarrow$' is **`happened-before`** relation) then any correct process that delivers $\mathbf{m_j}$ will deliver $\mathbf{m_i}$ before $\mathbf{m_j}$



Drawback:

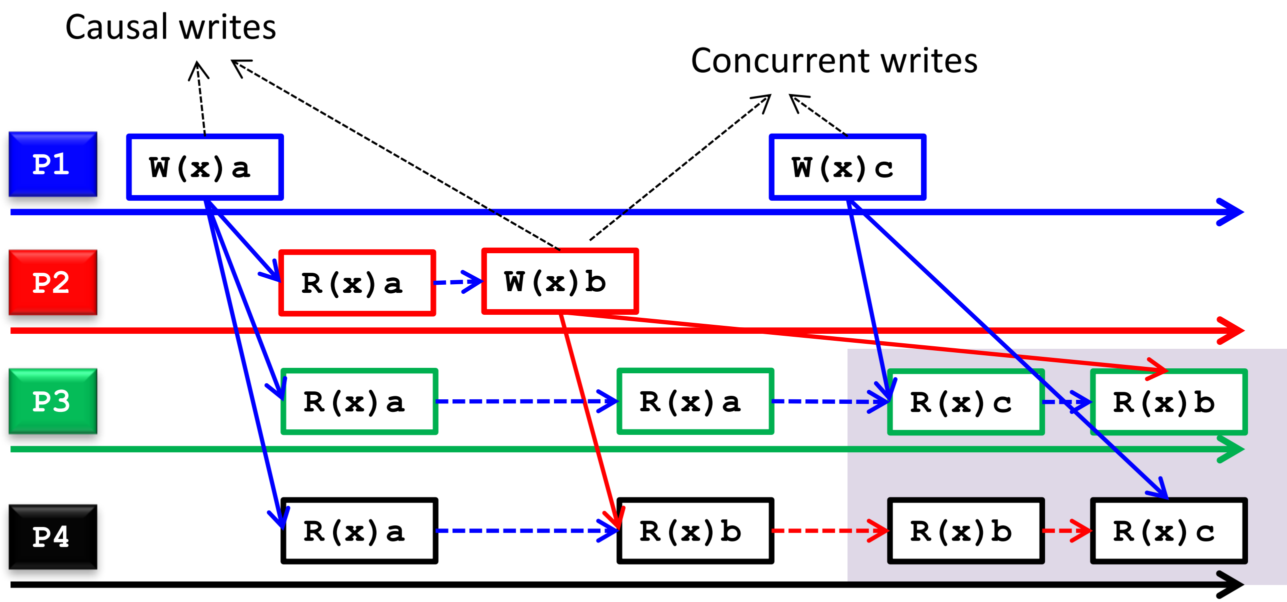
– The **`happened-before`** relation between $\mathbf{m_i}$ and $\mathbf{m_j}$ should be induced before communication



Causal Consistency Model

- A data-store is causally consistent if:
  - Writes that are potentially causally related must be seen by all the processes in the same order
  - Concurrent writes may be seen in a different order on different machines

Example of a Causally Consistent Data-store



A Causally Consistent Data-Store

But not a Sequentially Consistent Data-Store

P1 =Process P1

=Timeline at P1

R(x)b =Read variable x; Result is b

W(x)b = Write variable x; Result is b

Causally Consistent Data-Store?

http://olafland.polldaddy.com/s/causcons

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

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

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

http://olafland.polldaddy.com/s/causcons

Causally Consistent Data-Store?

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

This sequence is allowed with a causally-consistent store, but not with sequentially consistent store.

Note: $W_1(x)a \rightarrow W_2(x)b$, but not $W_2\,(x)b \rightarrow W_1(x)c$

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

A violation of a causally-consistent store.

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

A correct sequence of events in a causally consistent store.

Implications of adopting a Causally Consistent Data-store for Applications

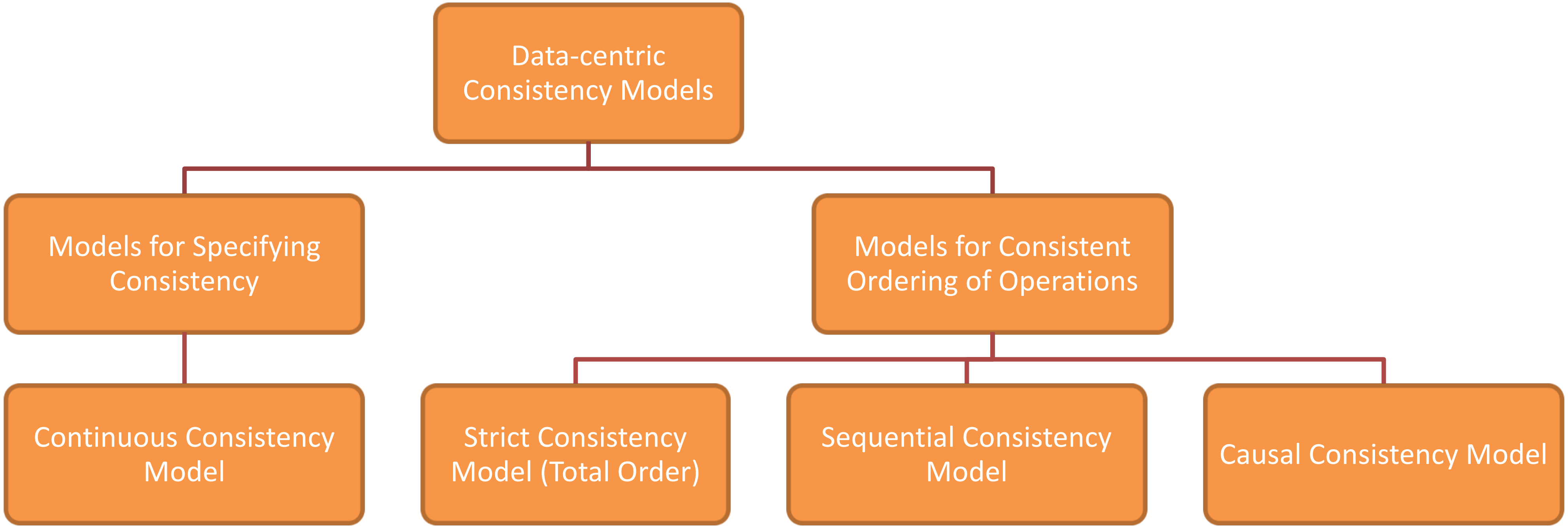
- Processes have to keep track of which processes have seen which writes

- This requires maintaining a dependency graph between write and read operations
  - Vector clocks provide a way to maintain causal consistentcy

Summary

- Total Order?
  - Same order on all nodes
- Sequential Ordering?
  - Same order as sent by the sender
- Causal Order
  - Same order on all nodes only for causally related msg.

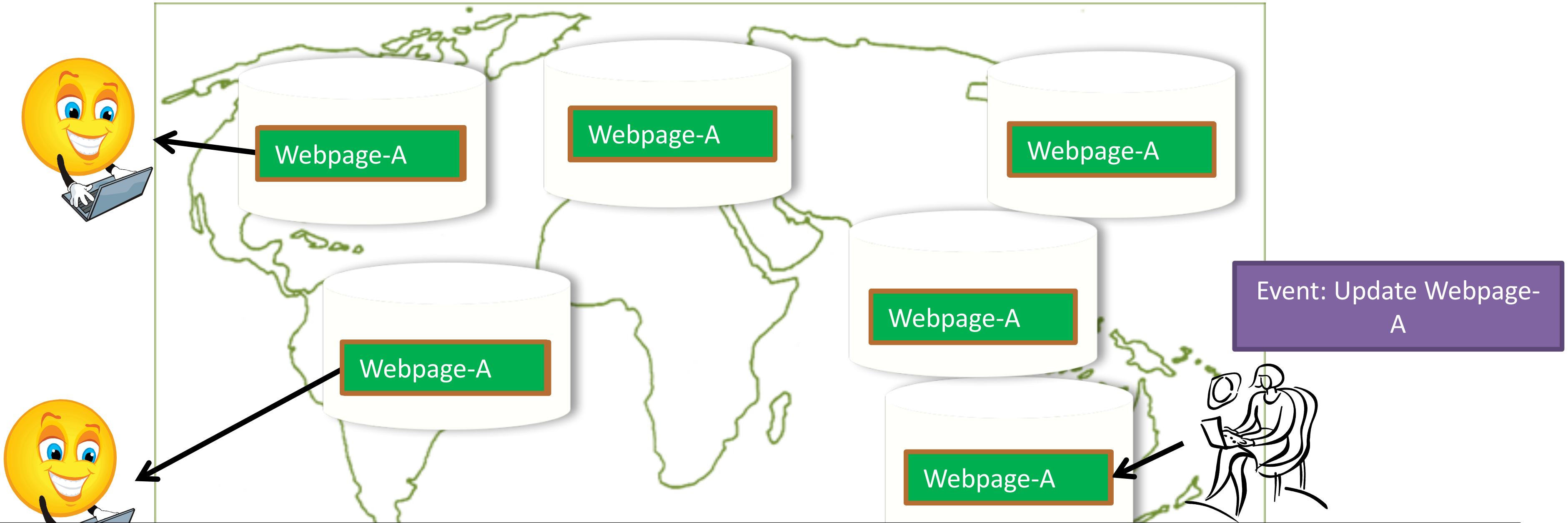
Topics Covered in Data-centric Consistency Models



But, is Data-centric Consistency Model good for all applications?

Applications that can use Data-centric Models

- Data-centric models are applicable when many processes are concurrently updating the data-store
- But, do all applications need all replicas to be consistent?



Data-Centric Consistency Model is too strict when

- One client process updates the data
- Other processes read the data, and are OK with reasonably stale data

Summary of Data-Centric Consistency Models

Data-centric consistency models describe how the replicated data is kept consistent across different data-stores, and what the process can expect from the data-store

These models allow measuring and specifying the consistency levels that are tolerable to the application

These models specify what ordering of operations are ensured at the replicas

- Data-centric Consistency Models
  - Models for Specifying Consistency
    - Continuous Consistency Model
  - Models for Consistent Ordering of Operations
    - Strict Consistency Model (Total Order)
    - Sequential Consistency Model
    - Causal Consistency Model

Data-centric models are too strict when:

- most operations are read operations
- updates are generally triggered from one client process

Summary

- Replication is necessary for improving performance, scalability and availability, and for providing fault-tolerance
- Replicated data-stores should be designed after carefully evaluating the trade-off between tolerable data inconsistency and efficiency
- Consistency Models describe the contract between the data-store and process about what form of consistency to expect from the system
- Data-centric consistency models:
  - Continuous Consistency Models provide mechanisms to measure and specify inconsistencies
  - Consistency Models can be defined based on the type of ordering of operations that the replica guarantees the application

Next Classes

- Consistency Models
  - Client-Centric Consistency Models
- Replica Management
  - Replica management studies:
    - when, where and by whom replicas should be placed
    - which consistency model to use for keeping replicas consistent
- Consistency Protocols
  - We study selected implementations of consistency models

Questions?

In part, inspired from / based on slides from

- Vinay Kolar
- A. S. Tanenbaum, M. v. Steen