Unit-7
Consistency and Replication

Compiled by Prashant Gautam

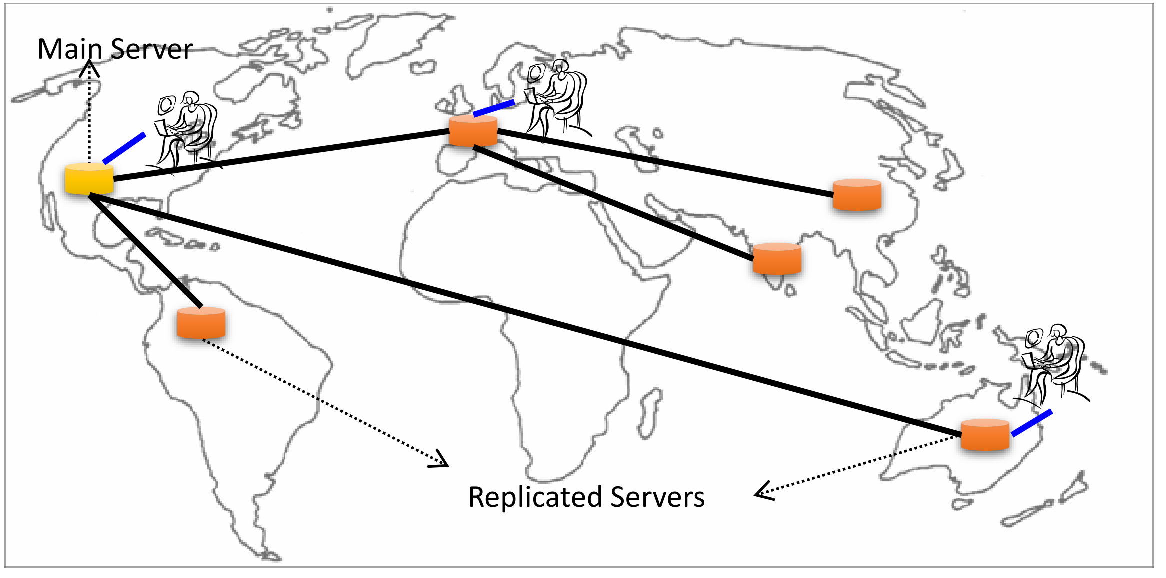
Why Replication?

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

- Replication is necessary for:
  1. Improving performance
     - A client can access the replicated copy of the data that is near to its location
  2. Increasing the availability of services
     - Replication can mask failures such as server crashes and network disconnection
  3. Enhancing the scalability of the system
     - Requests to the data can be distributed to many servers which contain replicated copies of the data
  4. Securing against malicious attacks
     - 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

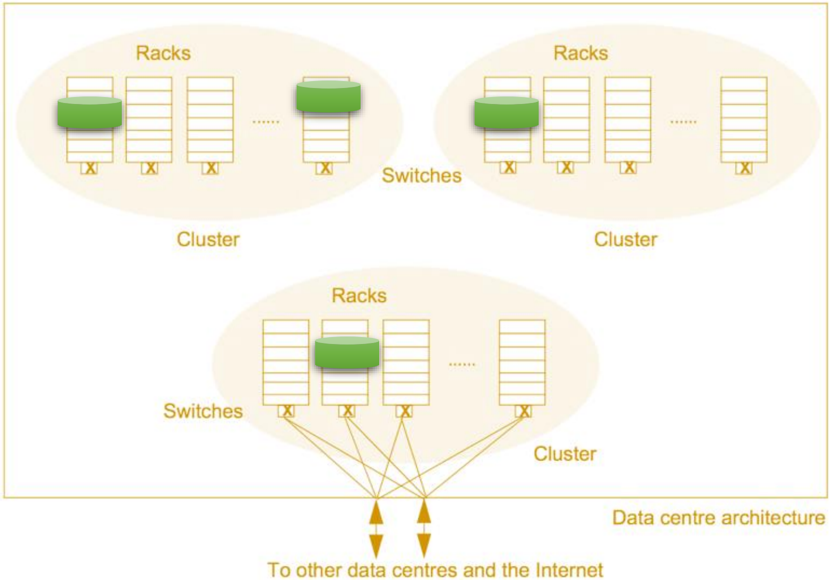
- Example Applications
  - Caching webpages at the client browser
  - Caching IP addresses at clients and DNS Name Servers
  - Caching in Content Delivery Network (CDNs)
    - Commonly accessed contents, such as software and streaming media, are cached at various network locations



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)

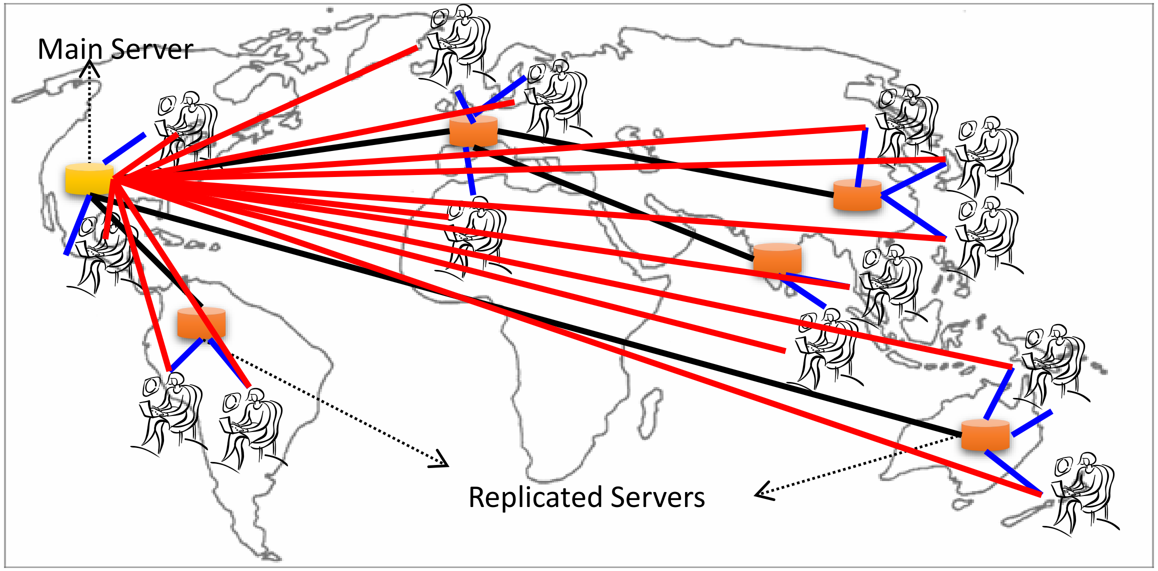
- Example: Google File-System and Chubby replicate the data at computers across different racks, clusters and data-centers
  - If one computer or a rack or a cluster crashes, then the data can still be accessed from another source



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

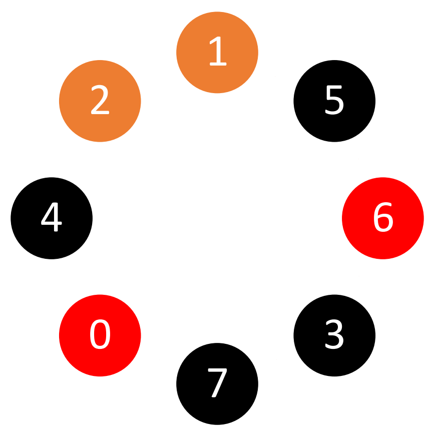
- Example: Content Delivery Networks decrease the load on main servers of the website



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

- Example: In a peer-to-peer system, peers can coordinate to prevent delivering faulty data to the requester



Number of servers with correct data outvote the faulty servers

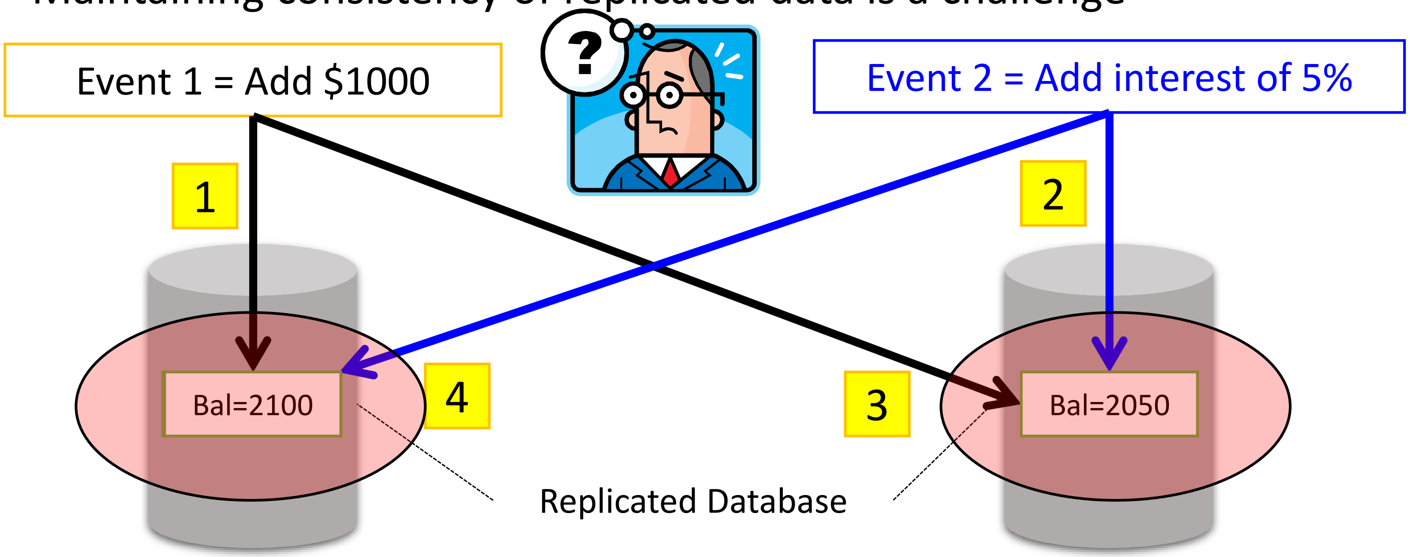
n = Servers that do not have the requested data

n = Servers with correct data

n = Servers with faulty data

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

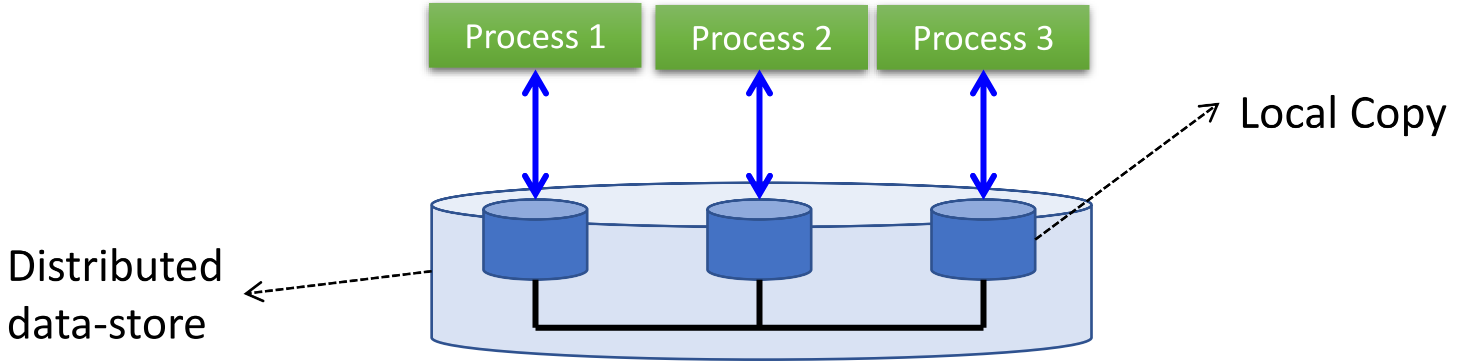
Overview

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

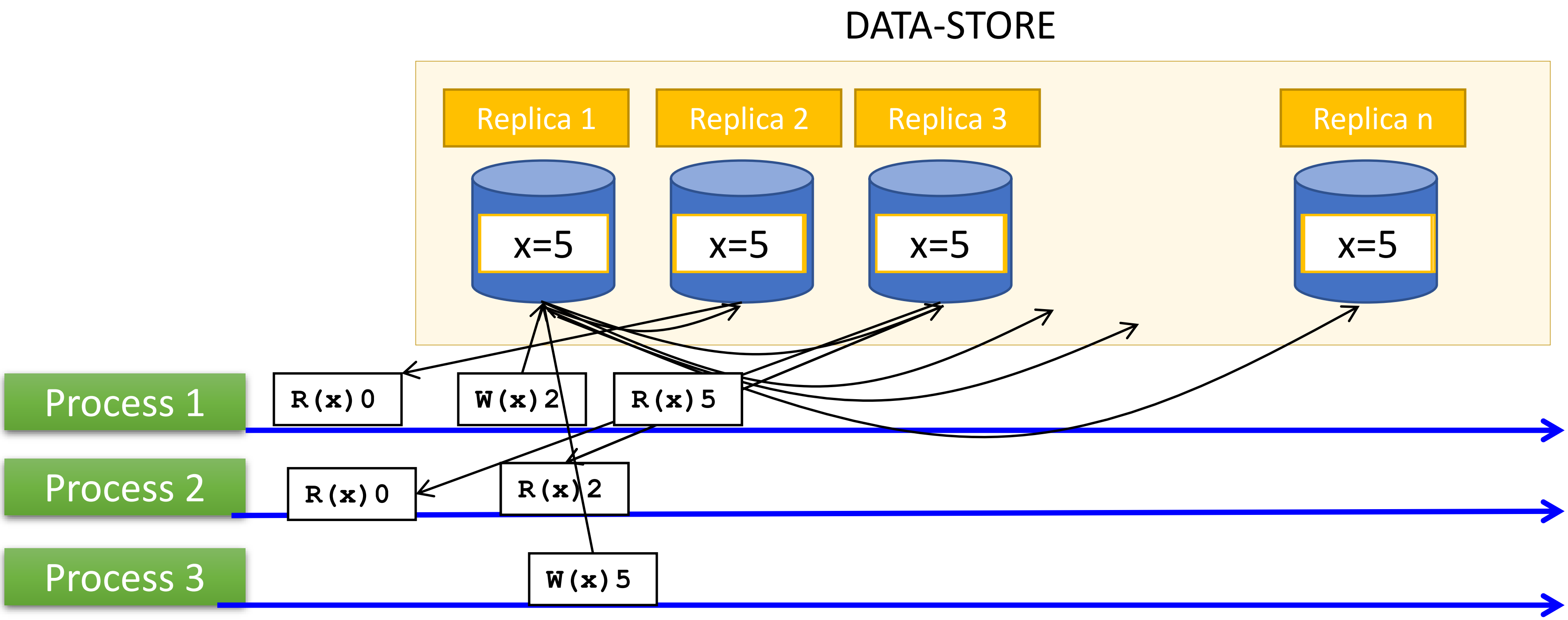
Introduction to Consistency and Replication

- 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

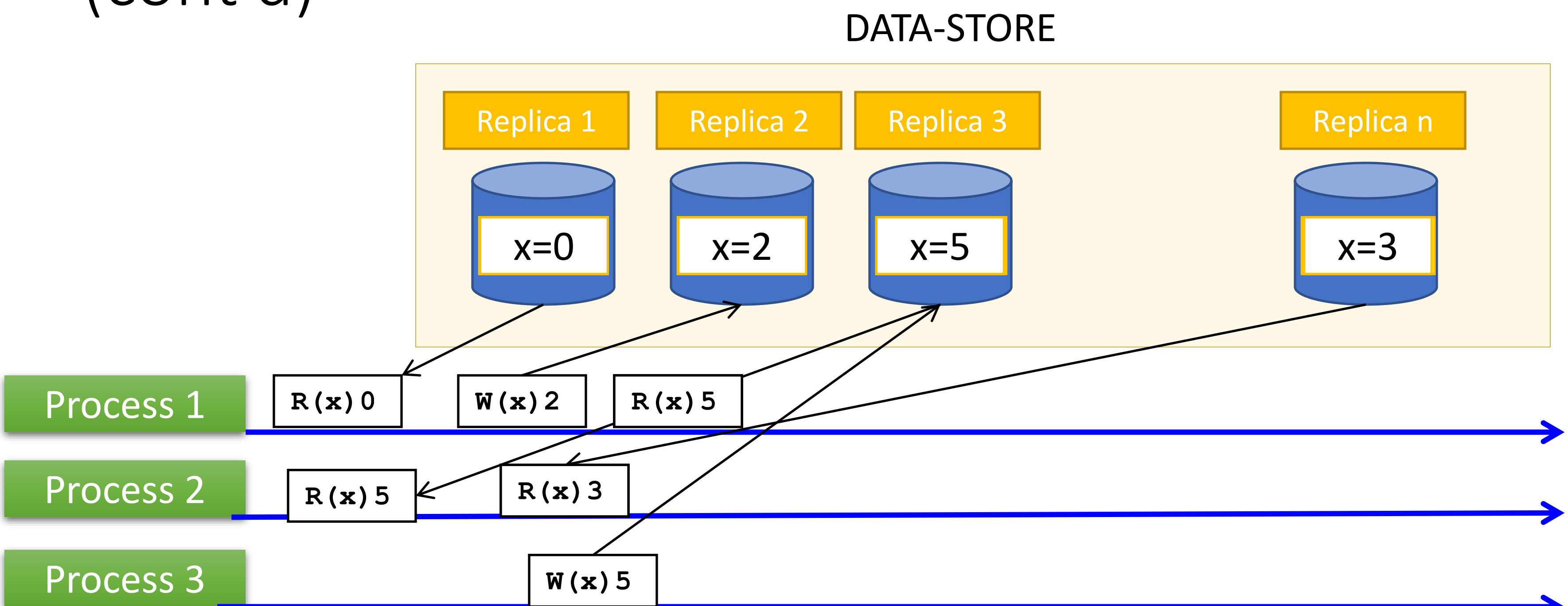


Strict Consistency

- 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 occassional writes and reads, this leads to large overheads

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

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

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

Trade-offs in Maintaining Consistency

- Maintaining consistency should balance between the strictness of consistency versus efficiency
  - Good-enough consistency depends on your application

Loose Consistency

Strict Consistency

Easier to implement,
and is efficient

Generally hard to implement,
and is inefficient

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

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*

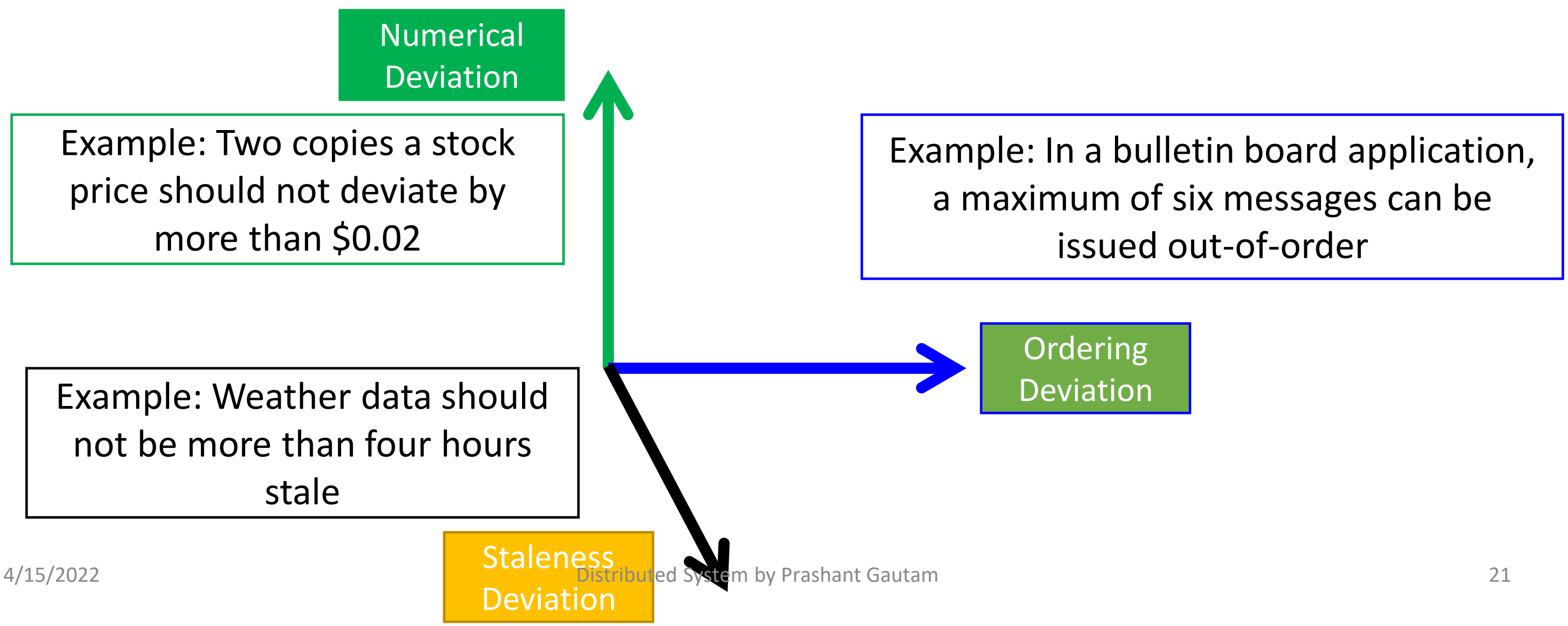
Continuous Consistency Model

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

- Yu and Vahdat [1] provided a framework for measuring and expressing consistency in replicated data-stores

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?

Example of Conit and Consistency 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
= max(update amount of all variables in a Conit)

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

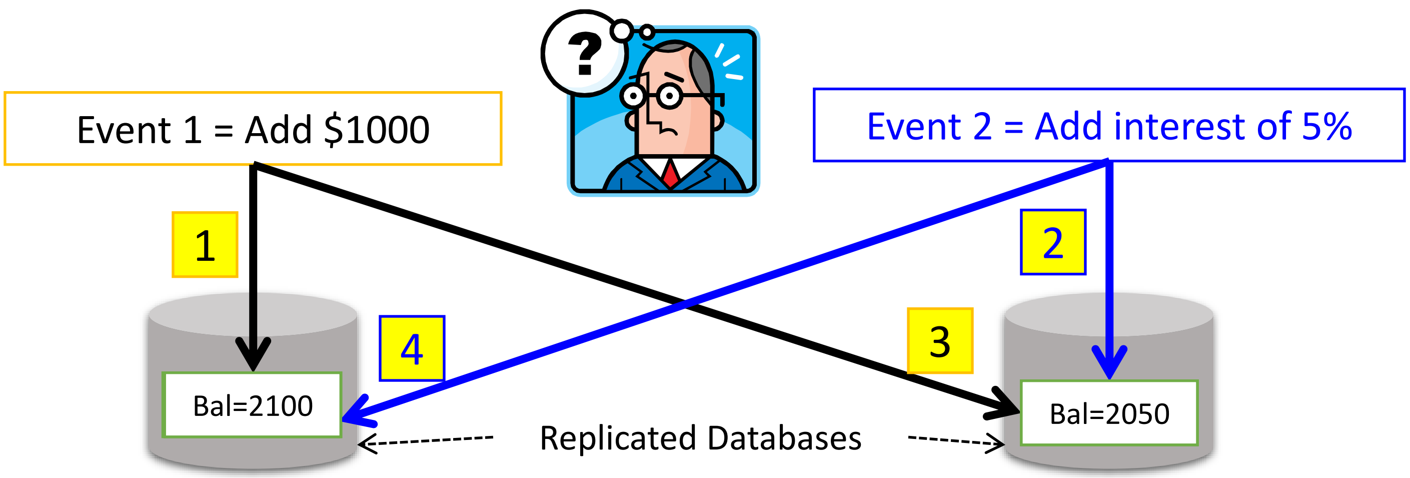
<5,B> =	Operation performed at **B** when the vector clock was **5**	<m,n>	= Uncommitted operation	<m,n>	= Committed operation	x;y	= A Conit

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

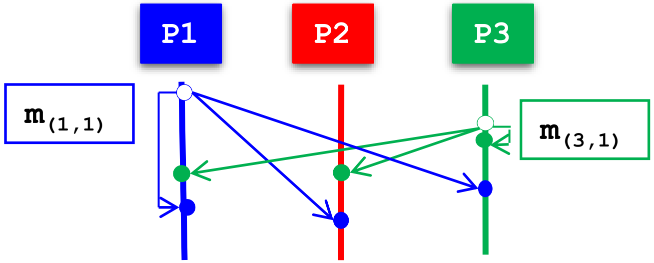
- We will study three types of ordering of messages that meet the needs of different applications:
  1. Total Ordering
  2. Sequential Ordering
     i. Sequential Consistency Model
  3. Causal Ordering
     i. Causal Consistency Model

Types of Ordering

1. Total Ordering
2. Sequential Ordering
3. Causal Ordering

Total Ordering

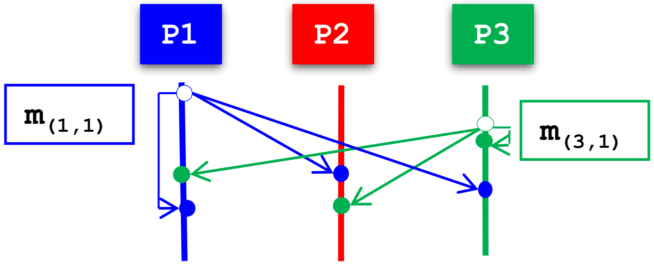
- Total Order
  - If process $\mathbf{P_i}$ sends a message $\mathbf{m_i}$ and $\mathbf{P_j}$ sends $\mathbf{m_j}$, and if one correct process delivers $\mathbf{m_i}$ before $\mathbf{m_j}$ then every correct process delivers $\mathbf{m_i}$ before $\mathbf{m_j}$



Ex1: Total Order

- Messages can contain replica updates, such as passing the read or write operation that needs to be performed at each replica
  - In the example Ex1, if $\mathbf{P_1}$ issues the operation `m(1,1): x=x+1;` and
  - If $\mathbf{P_3}$ issues `m(3,1): print(x);`
  - Then, at all replicas $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_3}$ the following order of operations are executed

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



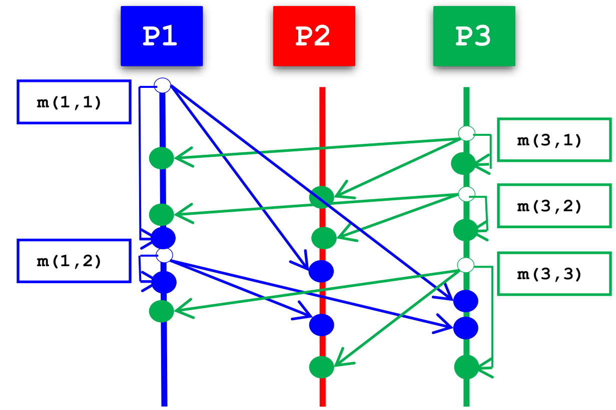
Ex2: Not in Total Order

Types of Ordering

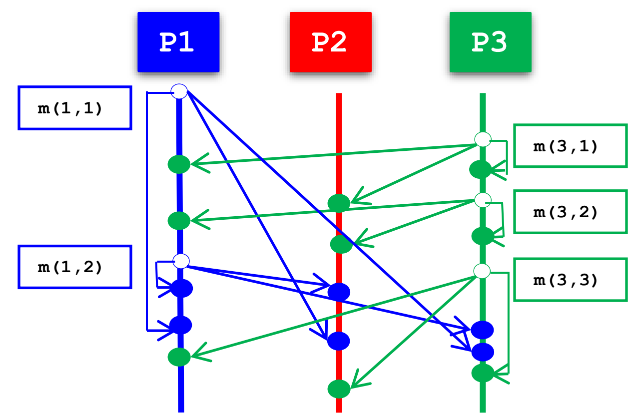
1. Total Ordering
2. Sequential Ordering
3. Causal Ordering

Sequential Ordering

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



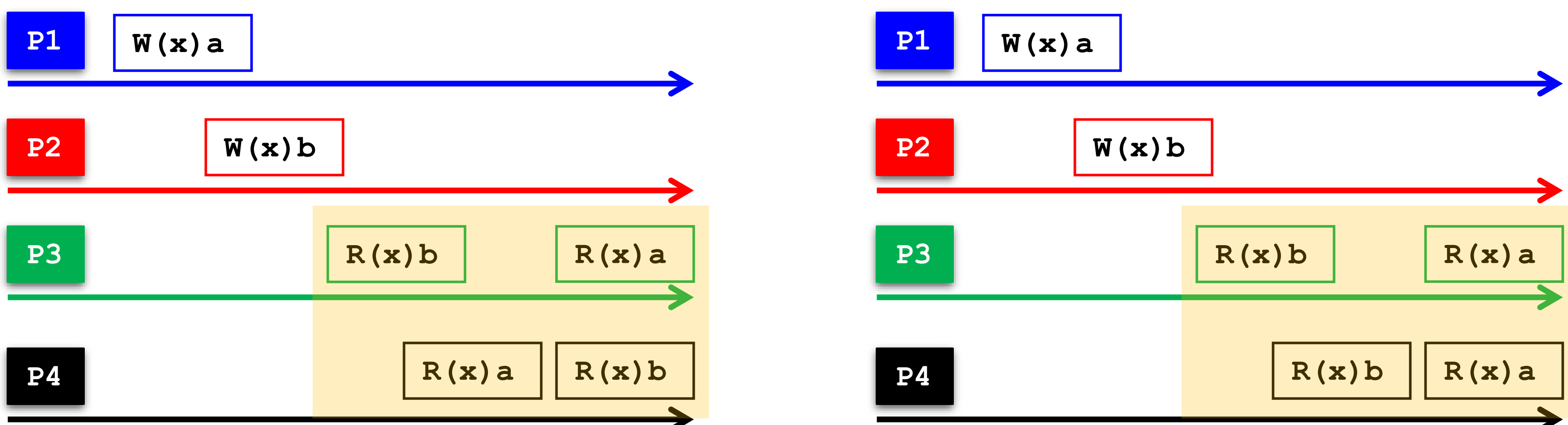
Valid Sequential Orders



Invalid Sequential Orders, but Valid Total Order

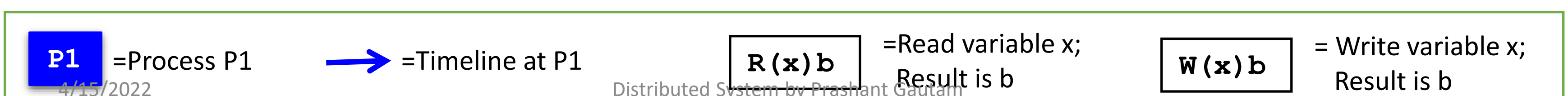
Sequential Consistency Model

- Sequential Consistency Model enforces that all the update operations are executed at the replicas in a sequential order
- 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 $\mathbf{P}_1$, $\mathbf{P}_2$ 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
```
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

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: Trade-offs in Maintaining Consistency

- Maintaining consistency should balance between the strictness of consistency versus efficiency
  - How much consistency is “good-enough” depends on the application

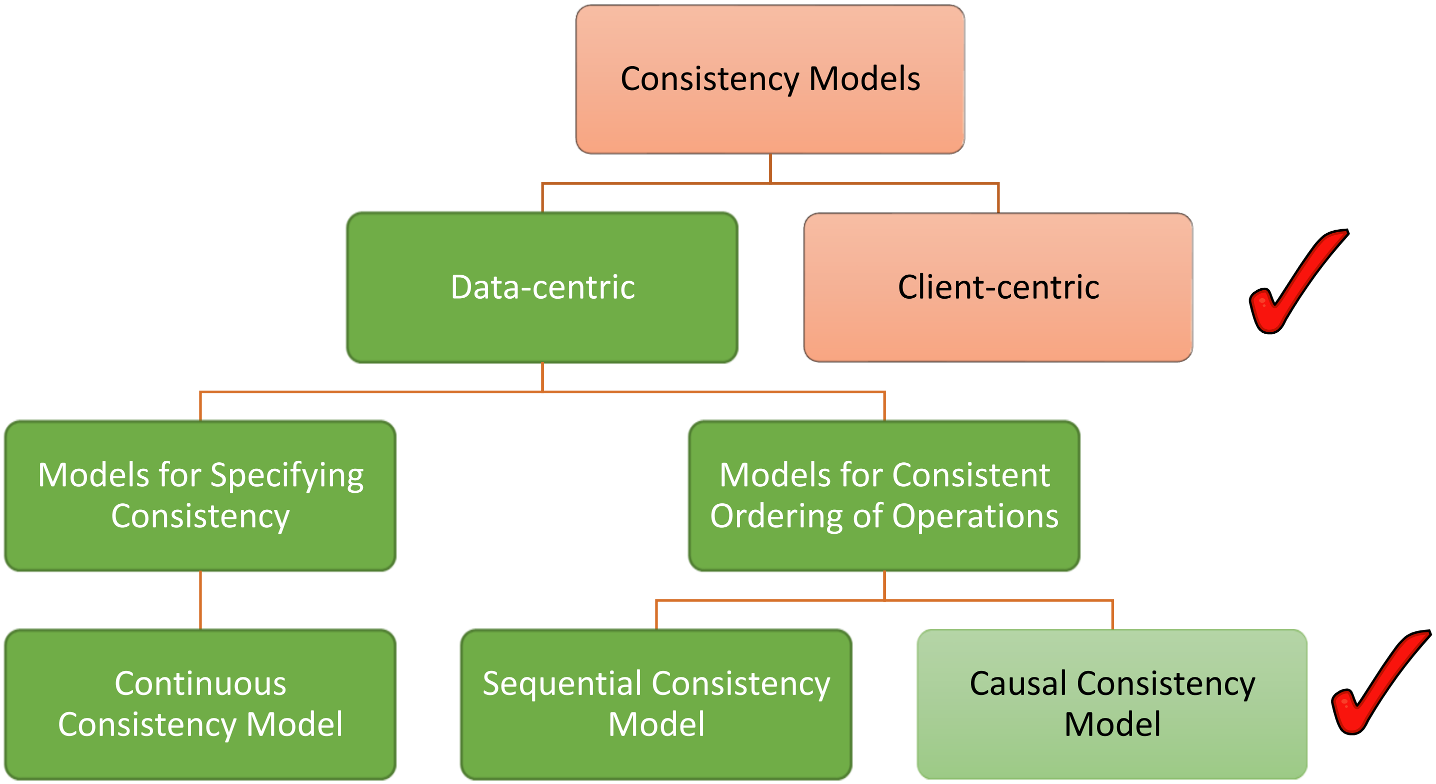
Loose Consistency **Strict Consistency**

Easier to implement, and is efficient

Generally hard to implement, and is inefficient

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



Types of Ordering

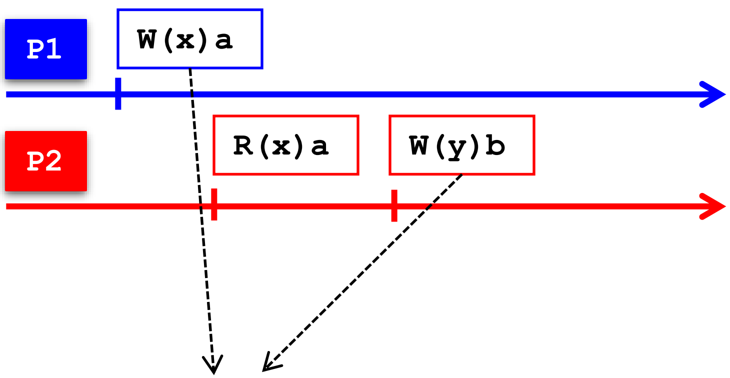
1. Total Ordering
2. Sequential Ordering
3. Causal Ordering

Causality (Recap)

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

Causal vs. Concurrent events

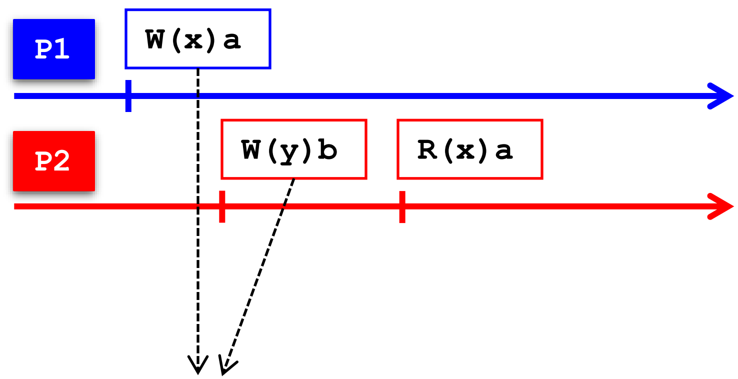
- Consider an interaction between processes $\mathbf{P_1}$ and $\mathbf{P_2}$ operating on replicated data $\mathbf{x}$ and $\mathbf{y}$



Events are causally related

Events are not concurrent

- Computation of $\mathbf{y}$ at $\mathbf{P_2}$ may have depended on value of $\mathbf{x}$ written by $\mathbf{P_1}$



Events are not causally related

Events are concurrent

- Computation of $\mathbf{y}$ at $\mathbf{P_2}$ does not depend on value of $\mathbf{x}$ written by $\mathbf{P_1}$

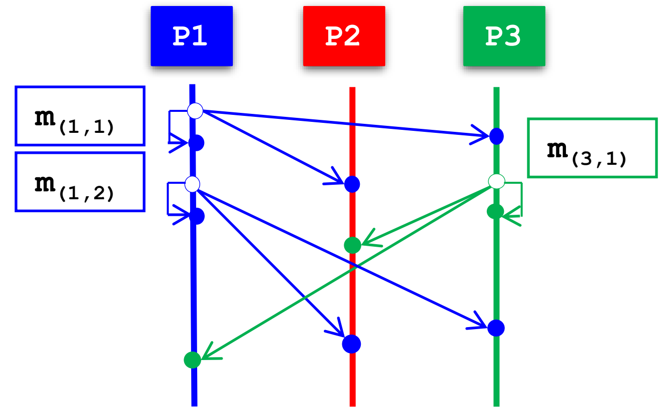
P1 =Process P1 | =Timeline at P1 | R(x)b =Read variable x; Result is b | W(x)b = Write variable x; Result is b

Causal Ordering

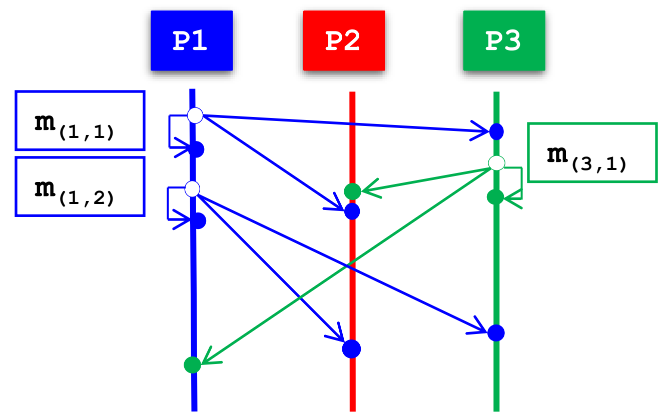
- Causal Order
  - If process $\mathbf{P_i}$ sends a message $\mathbf{m_i}$ and $\mathbf{P_j}$ sends $\mathbf{m_j}$, and if $\mathbf{m_i} \rightarrow \mathbf{m_j}$ (operator '$\rightarrow$' is Lamport's **happened-before** relation) then any correct process that delivers $\mathbf{m_j}$ will deliver $\mathbf{m_i}$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

- In the example, $\mathbf{m}_{(1,1)}$ and $\mathbf{m}_{(3,1)}$ are in Causal Order

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



Valid Causal Orders

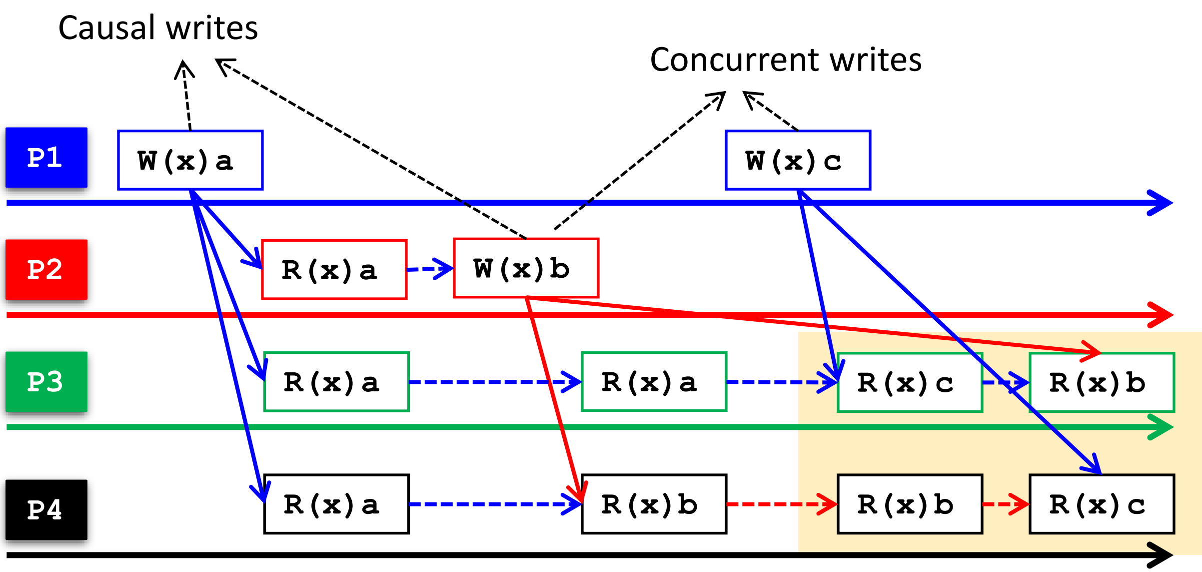


Invalid Causal Order

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

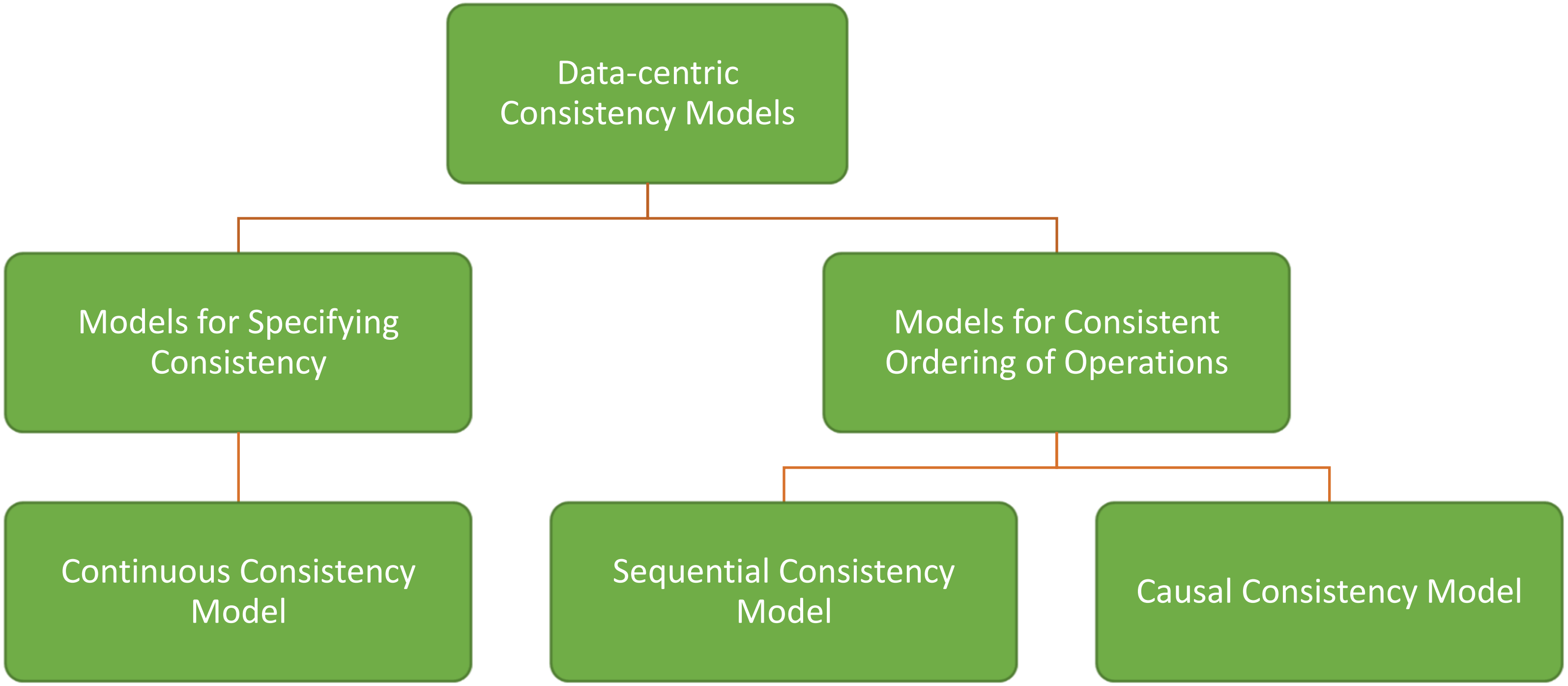
P1 =Process P1 | =Timeline at P1 | R(x)b =Read variable x; Result is b | W(x)b = Write variable x; Result is b

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 provides a way to maintain causally consistent data-base

Topics Covered in Data-centric Consistency Models

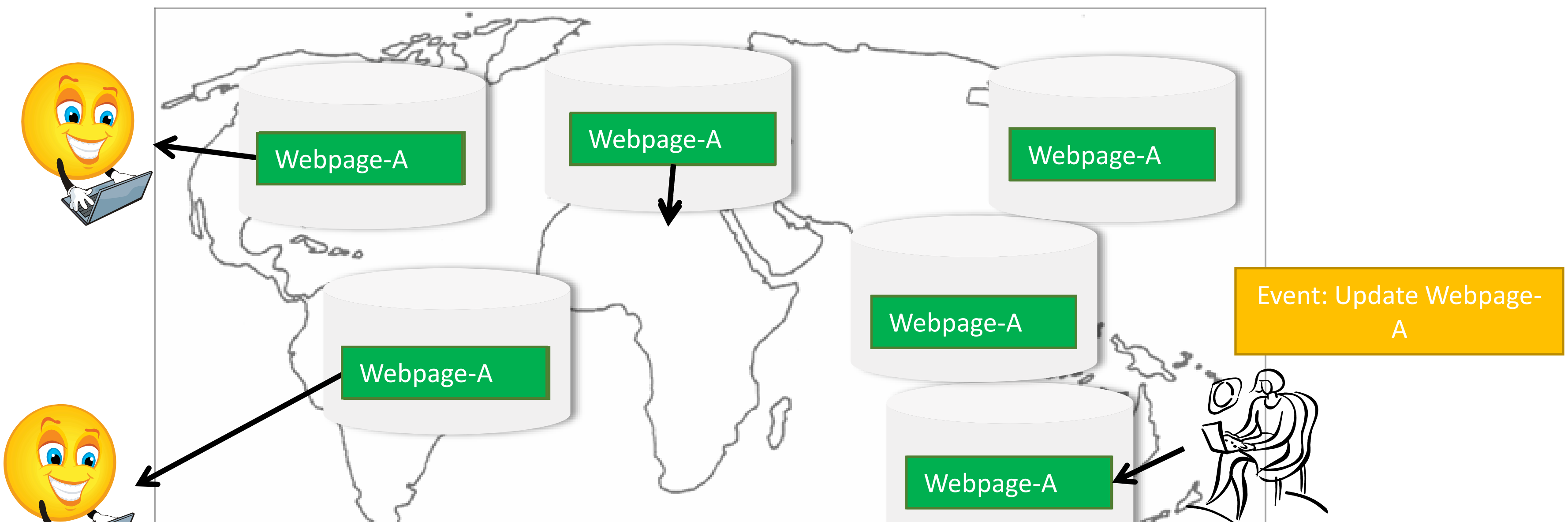


But, is Data-centric Consistency Model good for all applications?

Applications that can use Data-centric Models

- Data-centric models are applicable when many processes are concurrently updating the data-store

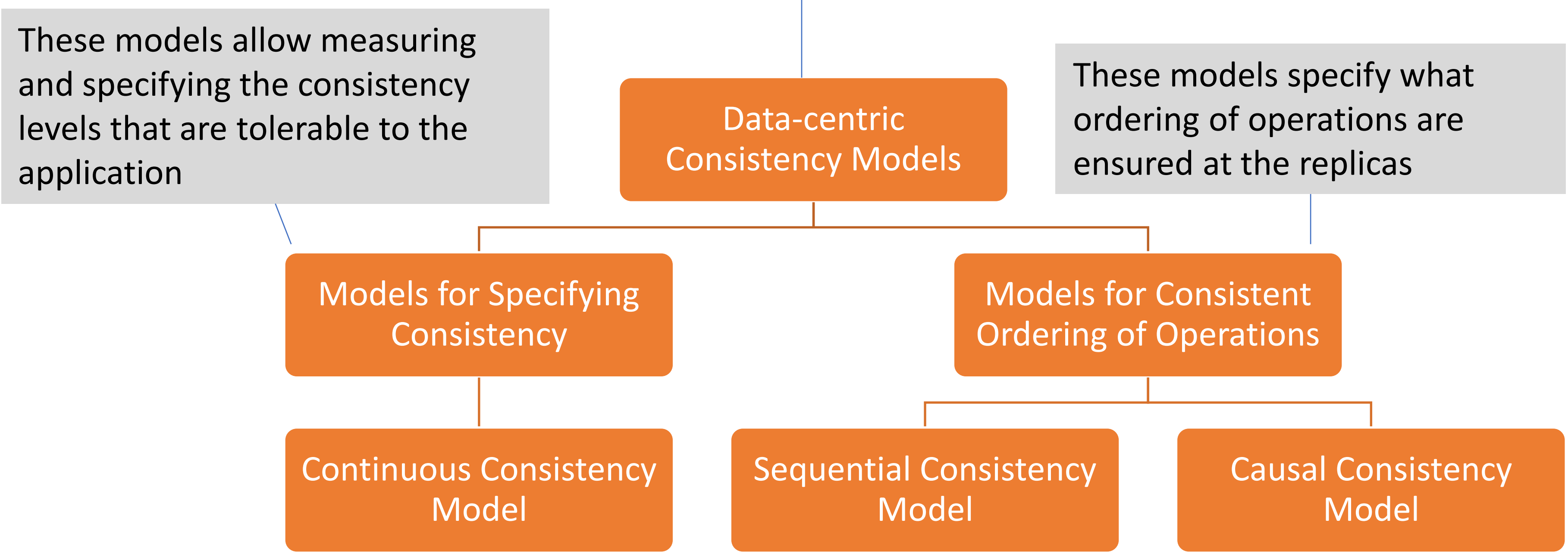
- But, do all applications need all replicas to be consistent?



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

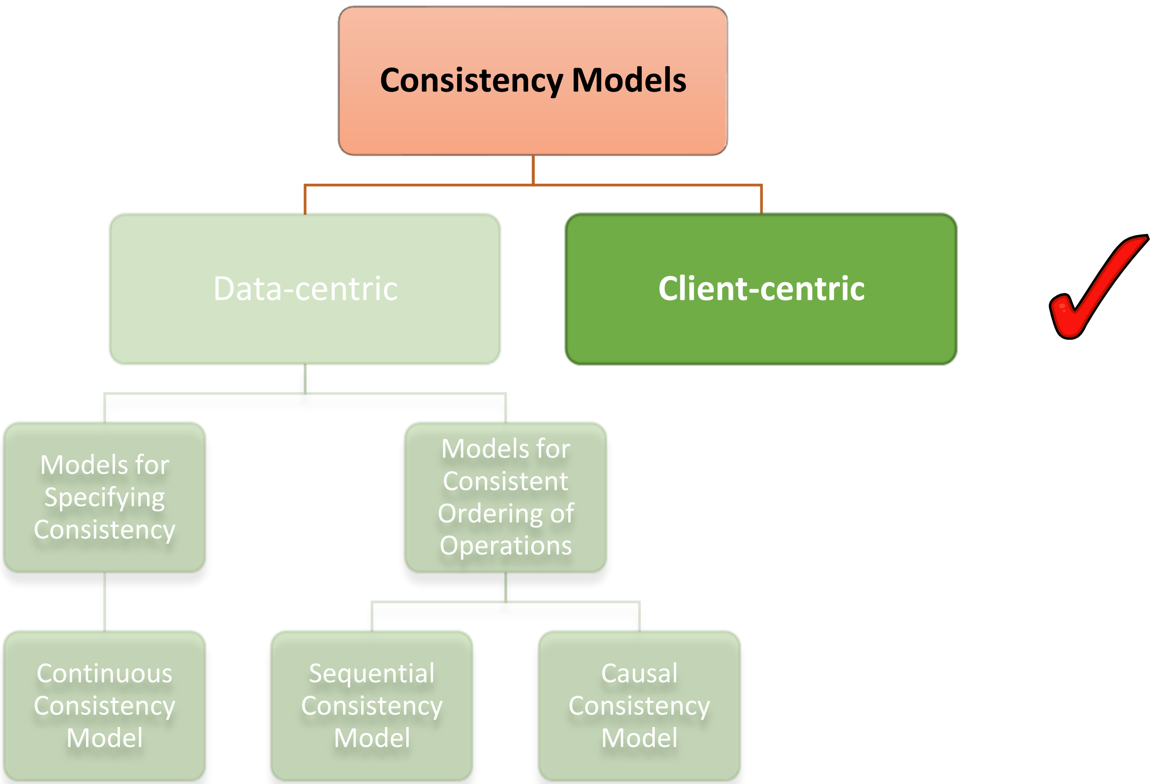
Data-centric consistency models describe how the replicated data is kept consistent across different data-stores, and what the process can expect from the data-store



Data-centric models are too strict when:

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

Overview


Consistency Models
Data-centric
Client-centric
Models for Specifying Consistency
Models for Consistent Ordering of Operations
Continuous Consistency Model
Sequential Consistency Model
Causal Consistency Model

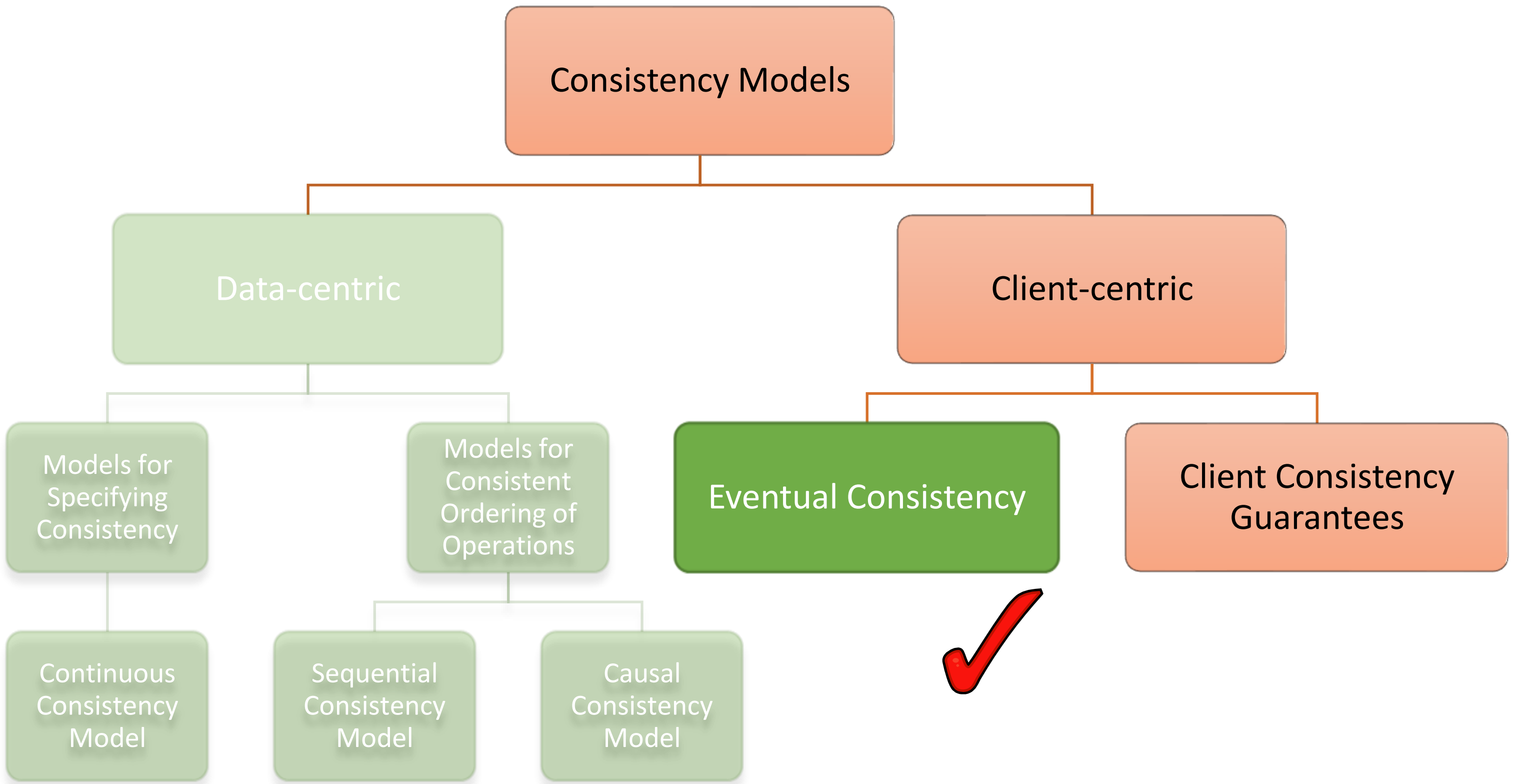
Client-Centric Consistency Models

- Data-centric models lead to excessive overheads in applications where:
  - a majority operations are reads, and
  - updates occur frequently, and are often from one client process

- For such applications, a weaker form of consistency called *Client-centric Consistency* is employed for improving efficiency

- Client-centric consistency models specify two requirements:
  1. Eventual Consistency
     - All the replicas should *eventually* converge on a final value
  2. Client Consistency Guarantees
     - Each client processes should be guaranteed some level of consistency while accessing the data value from different replicas

Overview


Consistency Models
Data-centric
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Models for Specifying Consistency
Models for Consistent Ordering of Operations
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Client Consistency Guarantees
Continuous Consistency Model
Sequential Consistency Model
Causal Consistency Model

Eventual Consistency

- Many applications can tolerate a inconsistency for a long time
  - Webpage updates, Web Search – Crawling, indexing and ranking, Updates to DNS Server

- In such applications, it is acceptable and efficient if replicas in the data-store rarely exchange updates

- A data-store is termed as *Eventually Consistent* if:
  - All replicas will gradually become consistent in the absence of updates

- Typically, updates are propagated infrequently in eventually consistent data-stores

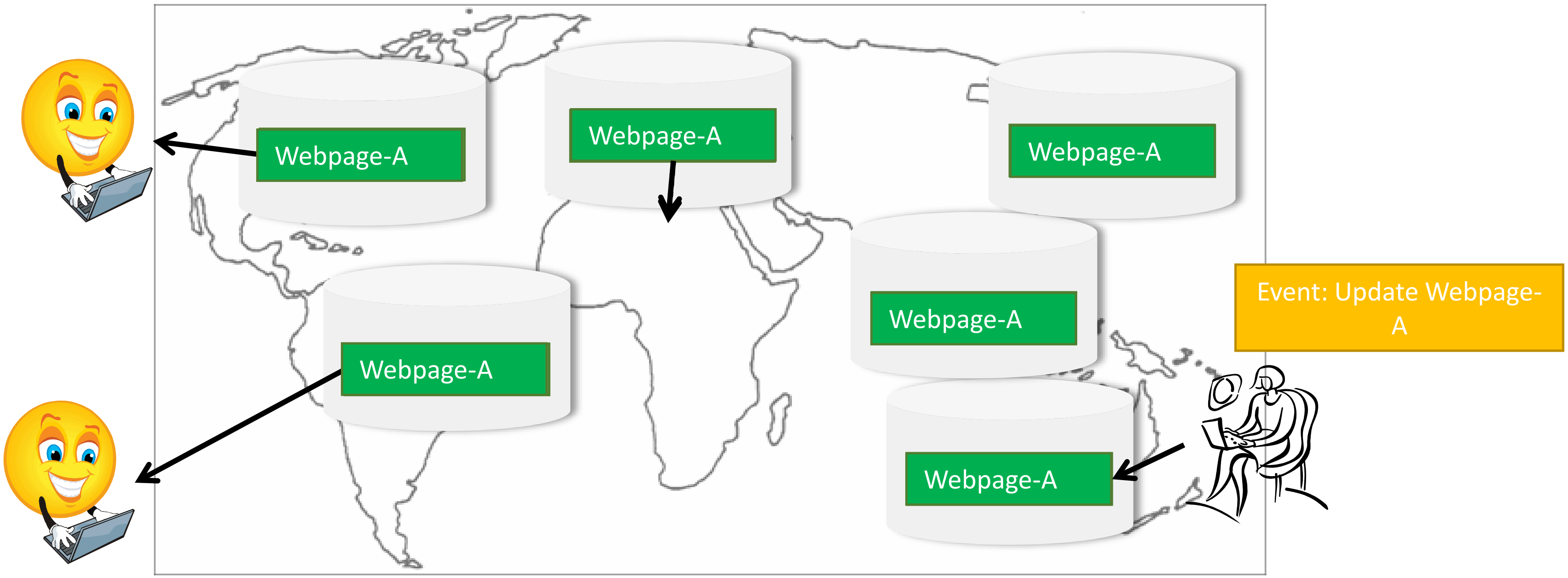
Designing Eventual Consistency

- In eventually consistent data-stores,
  - *Write-write conflicts* are rare
    - Two processes that write the same value are rare
    - Generally, one client updates the data value
      - e.g., One DNS server updates the name to IP mapping
    - Such rare conflicts can be handled through simple mechanisms, such as mutual exclusion

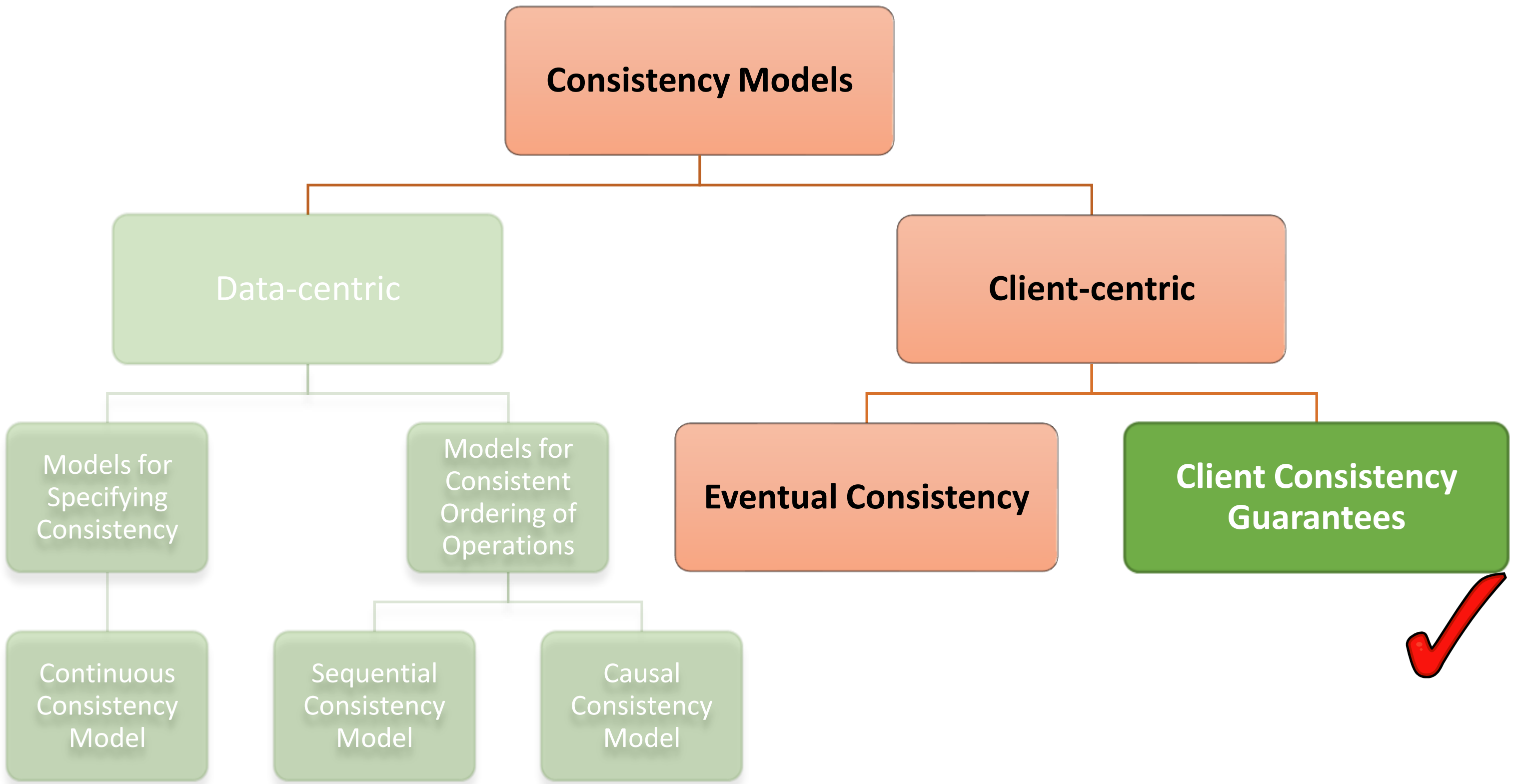
  - R*ead-write conflict* are more frequent
    - Conflicts where one process is reading a value, while another process is writing a value to the same variable
    - Eventual Consistency Design has to focus on efficiently resolving such conflicts

Challenges in Eventual Consistency

- Eventual Consistency is not good-enough when the client process accesses data from different replicas
  - We need consistency guarantees for a single client while accessing the data-store



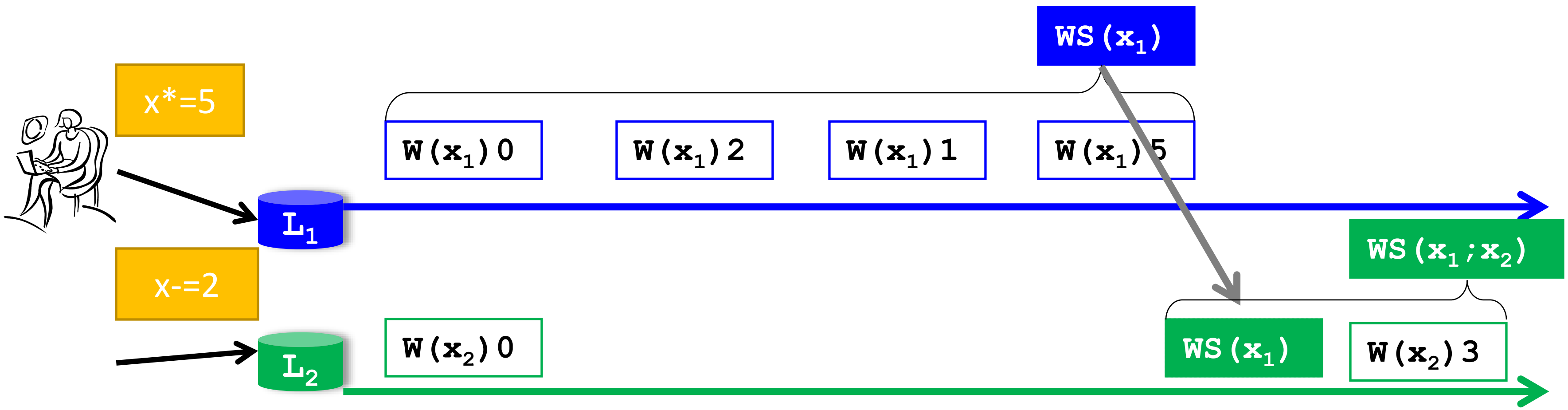
Overview


Consistency Models
Data-centric
Client-centric
Models for Specifying Consistency
Models for Consistent Ordering of Operations
Eventual Consistency
Client Consistency Guarantees
Continuous Consistency Model
Sequential Consistency Model
Causal Consistency Model

Client Consistency Guarantees

- Client-centric consistency provides guarantees for a single client for its accesses to a data-store

- Example: Providing consistency guarantee to a client process for data **x** replicated on two replicas. Let $\mathbf{x_i}$ be the local copy of a data **x** at replica $\mathbf{L_i}$.



WS(x_1) = **Write Set for $\mathbf{x_1}$** = Series of ops being done at some replica that reflects how $\mathbf{L_1}$ updated $\mathbf{x_1}$ till this time

WS(x_1;x_2) = **Write Set for $\mathbf{x_1}$ and $\mathbf{x_2}$** = Series of ops being done at some replica that reflects how $\mathbf{L_1}$ updated $\mathbf{x_1}$ and, later on, how $\mathbf{x_2}$ is updated on $\mathbf{L_2}$

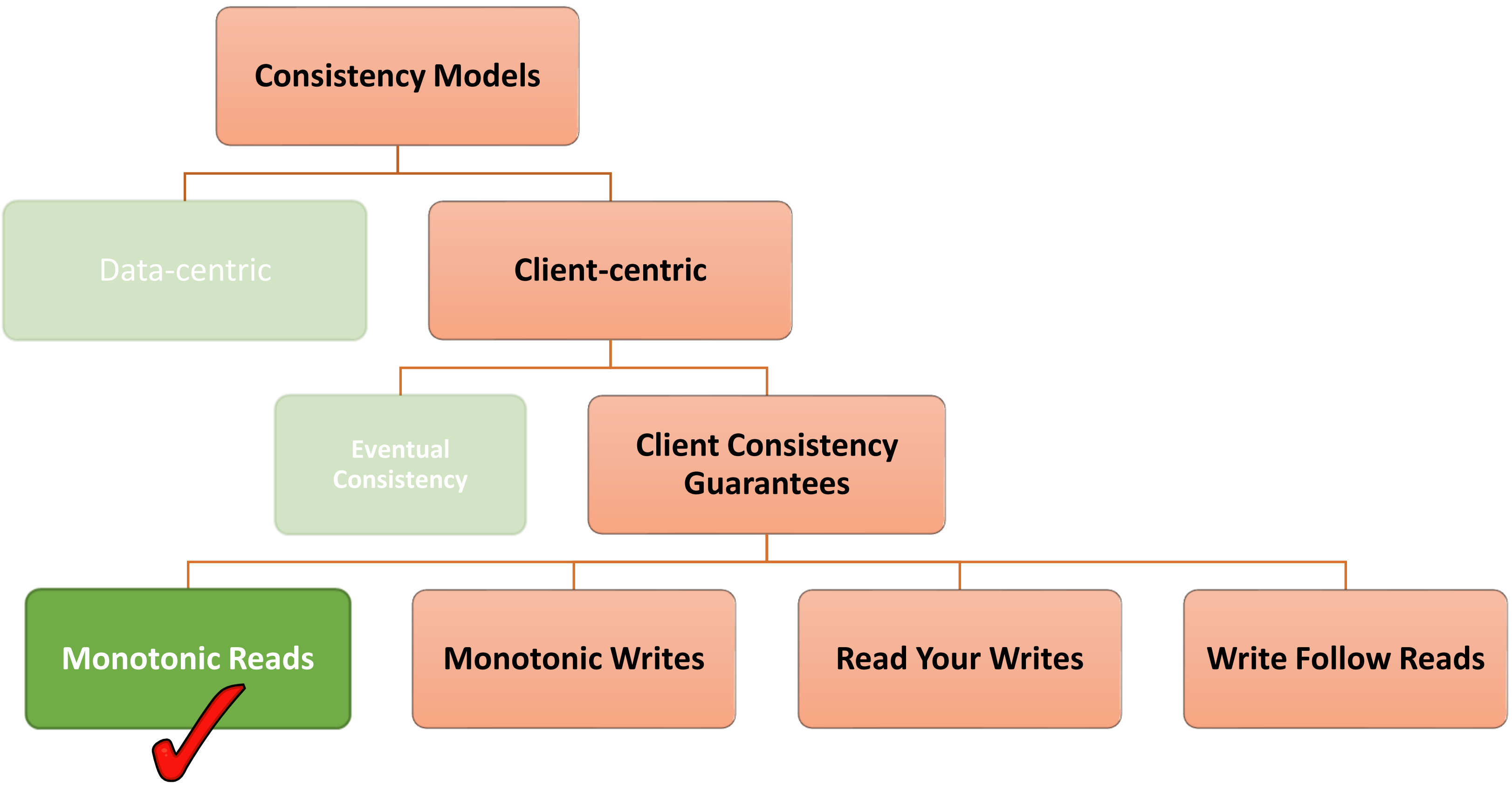
L_i = Replica i | R(x_i)b = Read variable x at replica i; Result is b | W(x_i)b = Write variable x at replica i; Result is b | WS(x_i) = Write Set

Client Consistency Guarantees

- We will study four types of client-centric consistency models[1]
    1. Monotonic Reads
    2. Monotonic Writes
    3. Read Your Writes
    4. Write Follow Reads

1. The work is based on the distributed database system built by Terry et al. [1]

Overview


Consistency Models
Data-centric
Client-centric
Eventual Consistency
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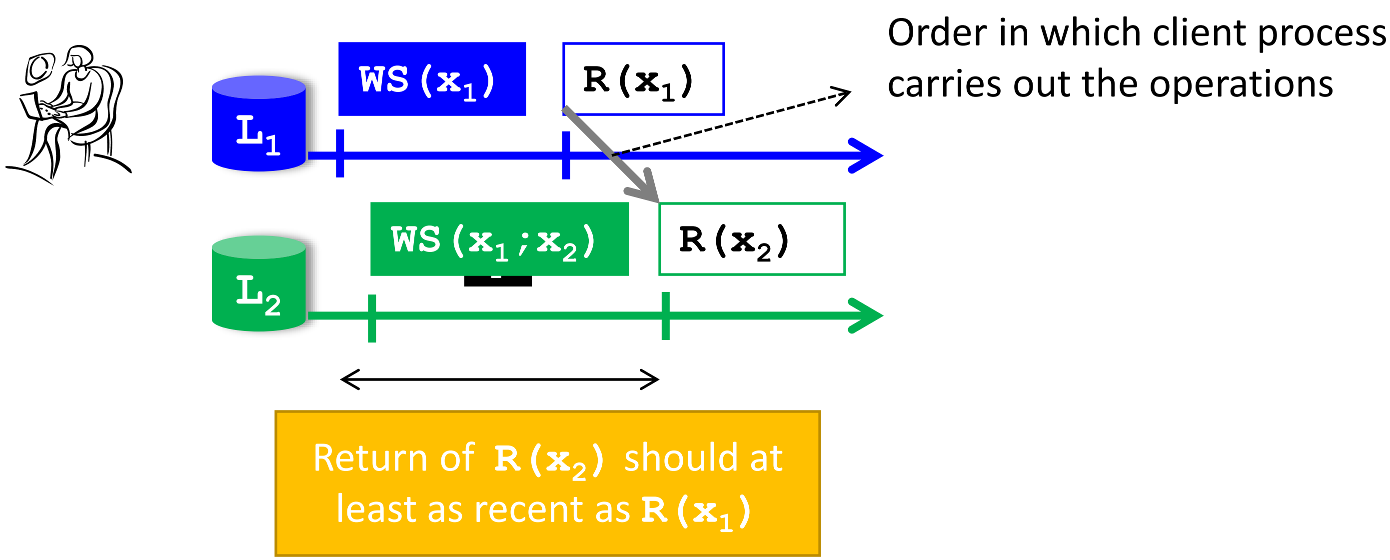
Monotonic Reads
Monotonic Writes
Read Your Writes
Write Follow Reads

Monotonic Reads

- The model provides guarantees on successive reads
- If a client process reads the value of data item **x**, then any successive read operation by that process should return the same or a more recent value for **x**



Monotonic Reads – Puzzle

Recognize data-stores that provide monotonic read guarantees

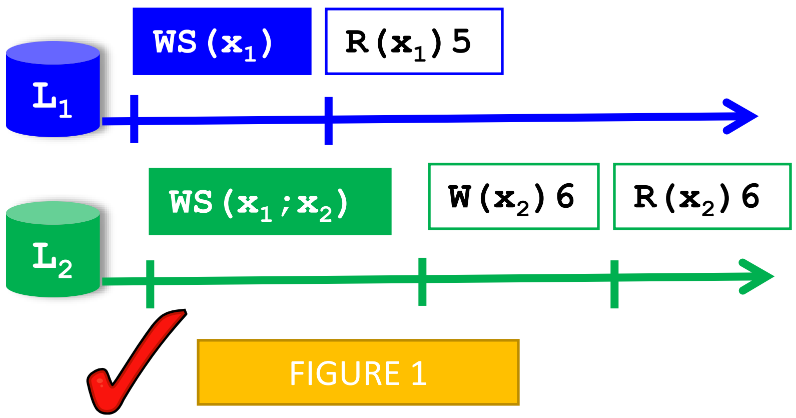


FIGURE 1

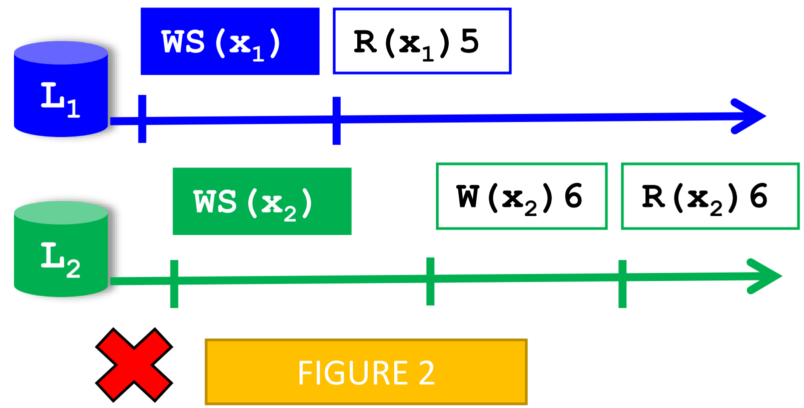


FIGURE 2

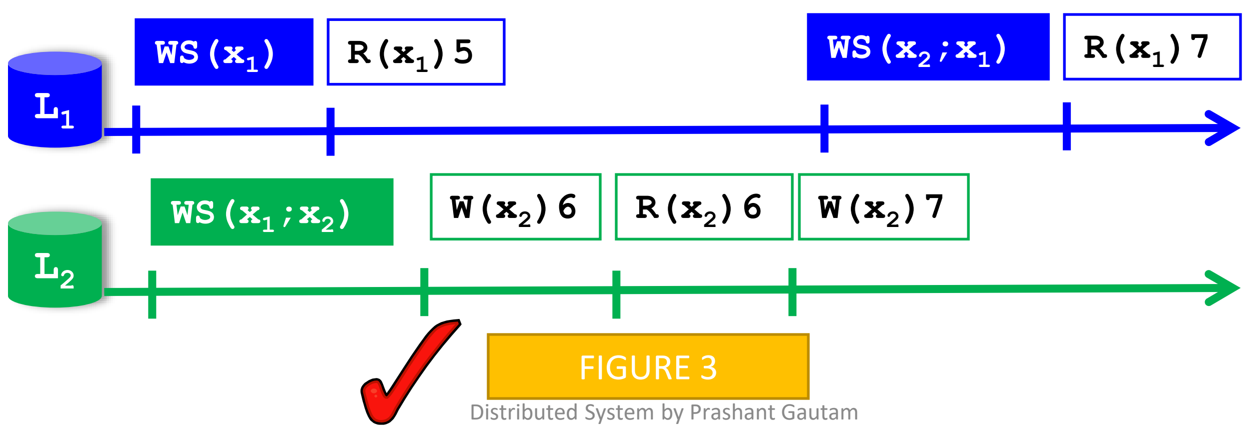
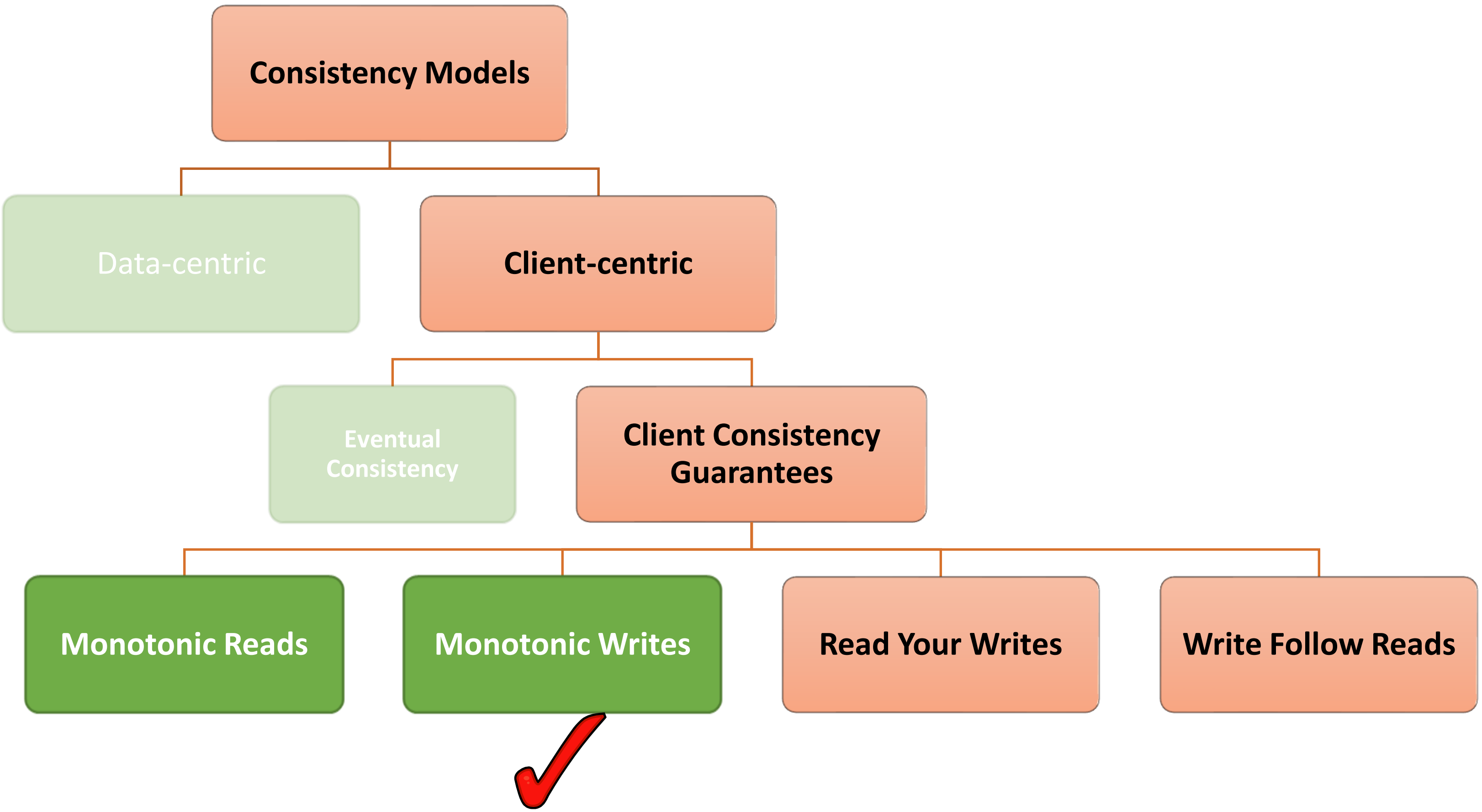


FIGURE 3

Overview



Consistency Models
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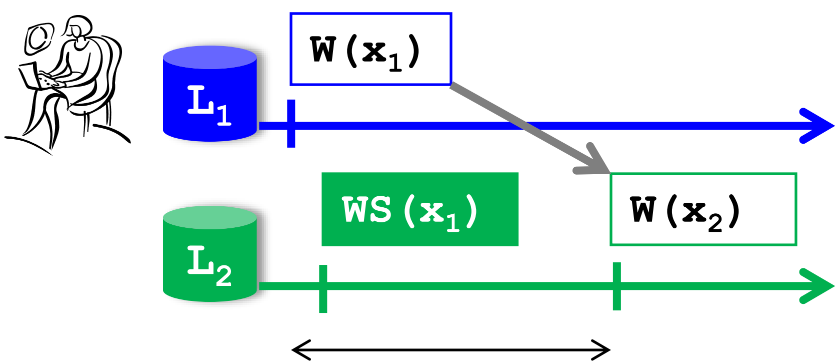
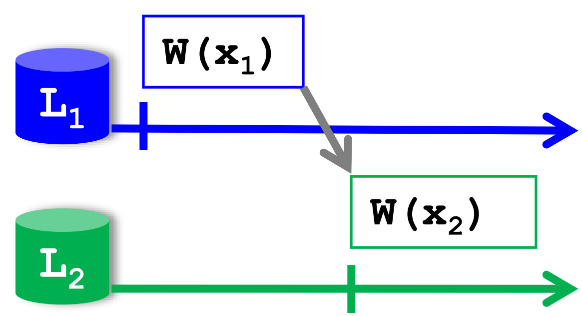
Monotonic Writes

- This consistency model assures that writes are monotonic
- A write operation by a client process on a data item $\mathbf{x}$ is completed <u>before any successive write</u> operation on $\mathbf{x}$ by the <u>same process</u>
  - A new write on a replica should wait for all old writes on any replica



$W(x_2)$ operation should be performed only after the result of $W(x_1)$ has been updated at L_2

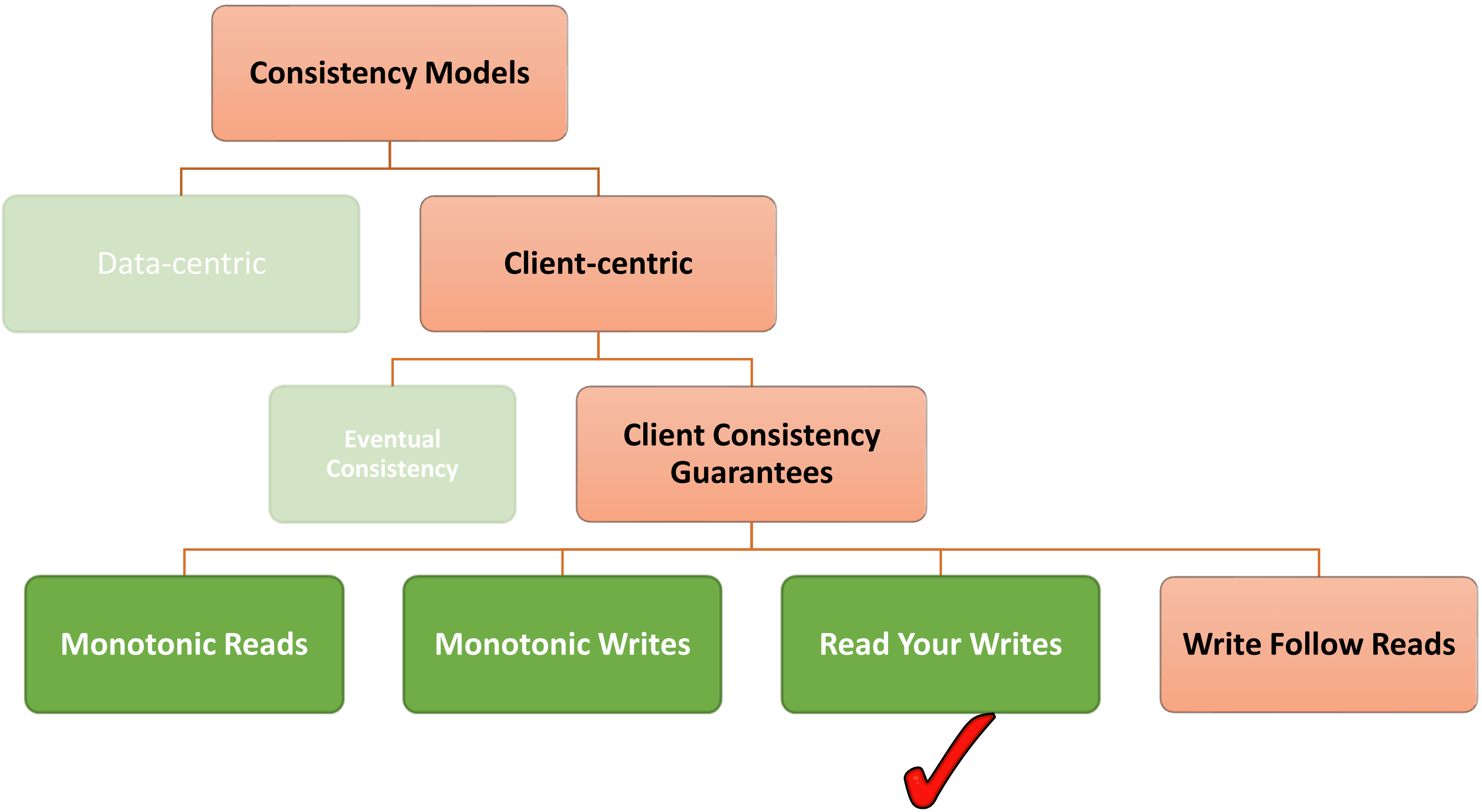


The data-store does not provide monotonic write consistency

Monotonic Writes – An Example

- Example: Updating individual libraries in a large software source code which is replicated
  - Updates can be propagated in a lazy fashion
  - Updates are performed on a part of the data item
    - Some functions in an individual library is often modified and updated
  - Monotonic writes: If an update is performed on a library, then all preceding updates on the same library are first updated
- Question: If the update overwrites the complete software source code, is it necessary to update all the previous updates?

Overview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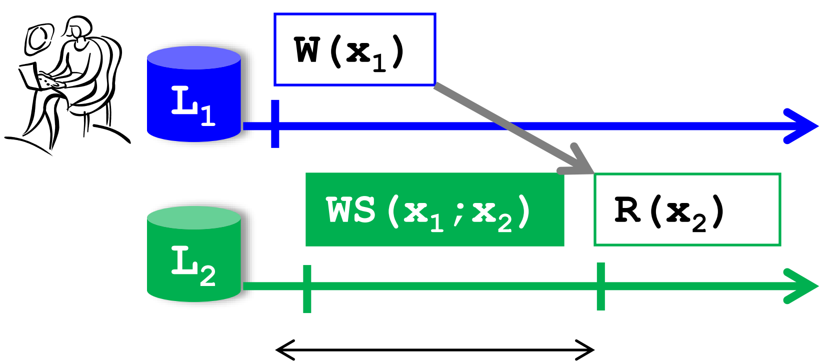
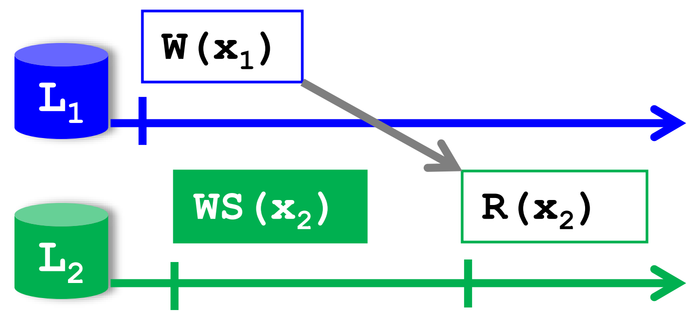
Read Your Writes

- The <u>effect of a write</u> operation on a data item **x** by a process will <u>always be seen by a successive read</u> operation on **x** by the same process
- Example scenario:
  - In systems where password is stored in a replicated data-base, the password change should be seen immediately

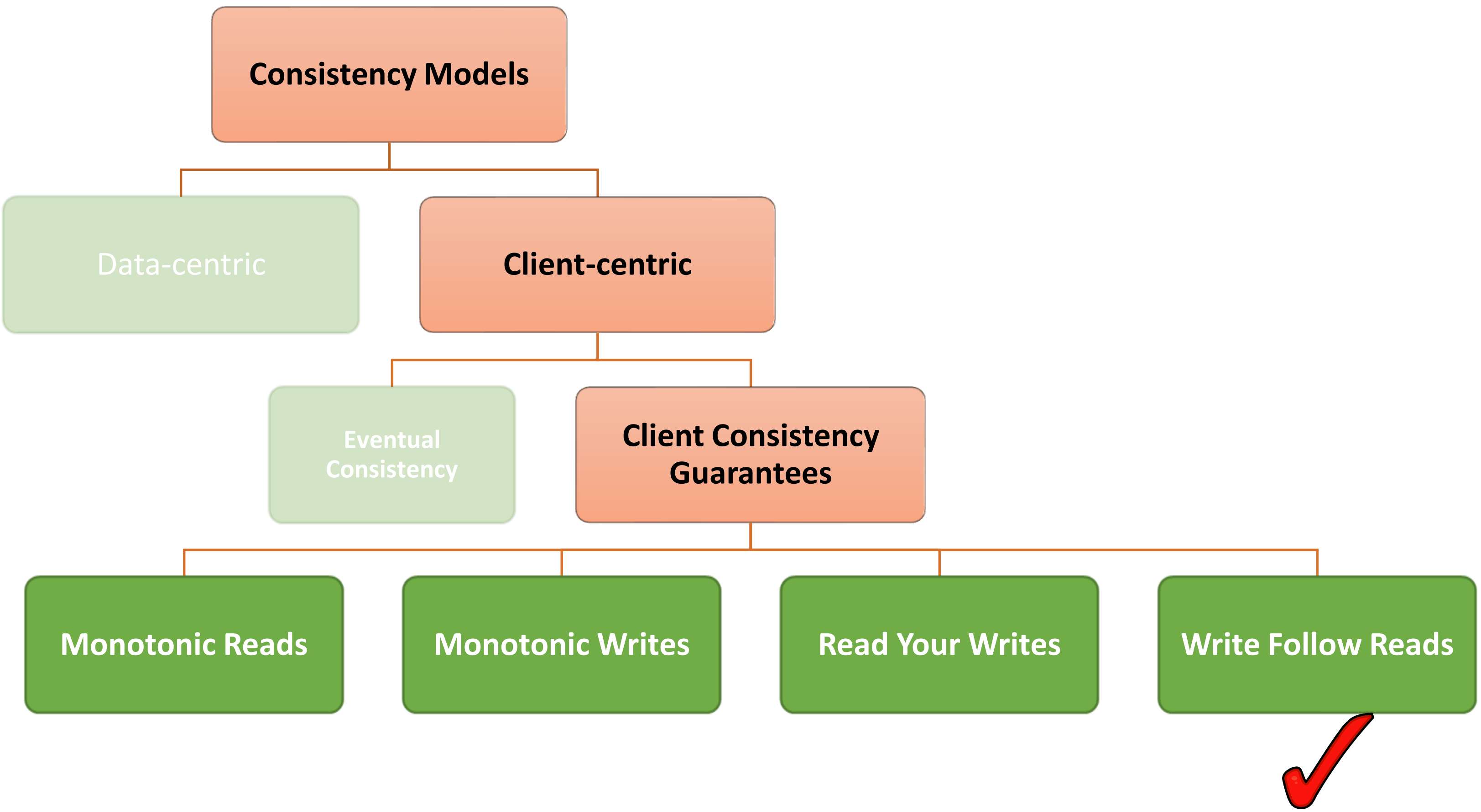




R(x_2) operation should be performed only after the updating the Write Set **WS(x_1)** at **L_2**

A data-store that does not provide *Read Your Write* consistency

Overview



Consistency Models
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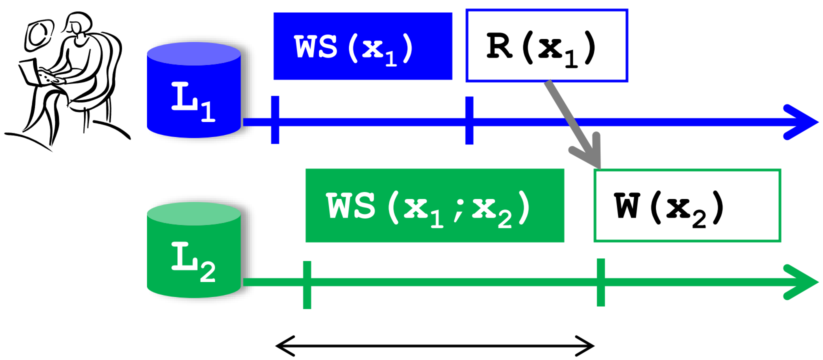
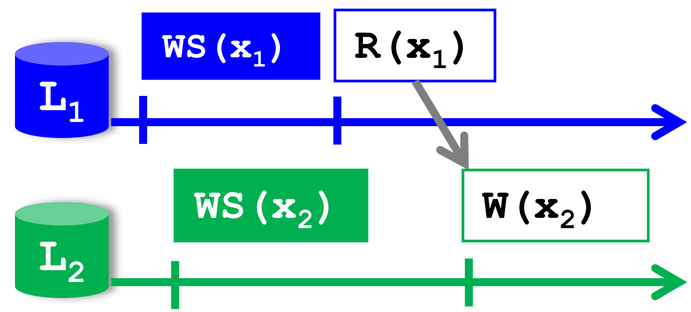
Write Follow Reads

- A write operation by a process on a data item **x** following a previous read operation on **x** by the same process is guaranteed to take place on the same or a more recent value of **x** that was read
- Example scenario:
  - Users of a newsgroup should post their comments only after they have read all previous comments



W(x_2) operation should be performed only after the all previous writes have been seen

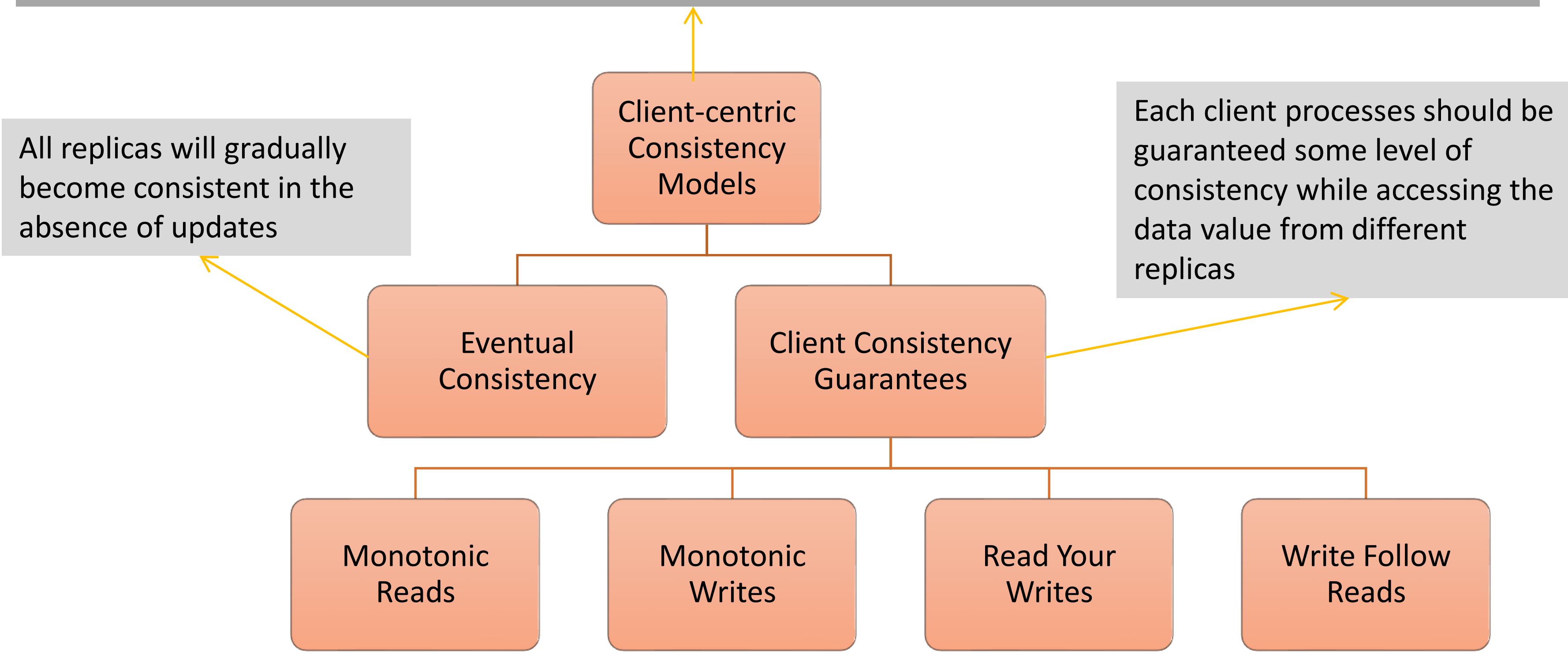


A data-store that does not guarantee Write Follow Read Consistency Model

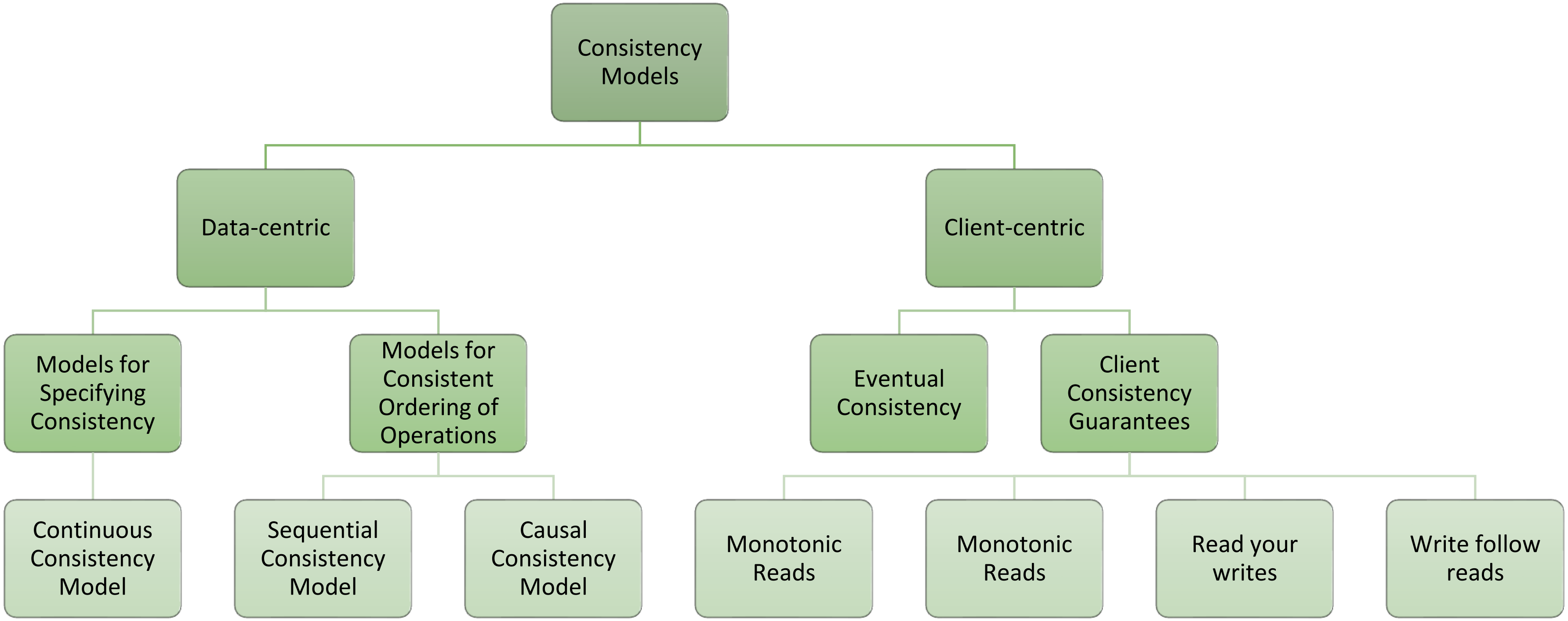
Summary of Client-centric Consistency Models

Client-centric Consistency Model defines how a data-store presents the data value to an individual client when the client process accesses the data value across different replicas.
It is generally useful in applications where:

- one client always updates the data-store.
- read-to-write ratio is high



Topics covered in Consistency Models



Overview

- Consistency Models
- Replica Management
- Consistency Protocols

Replica Management

- Replica management describes where, when and by whom replicas should be placed

- We will study two problems under replica management
  1. Replica-Server Placement
     - Decides the best locations to place the replica server that can host data-stores
  2. Content Replication and Placement
     - Finds the best server for placing the contents

Overview

- Consistency Models
- Replica Management
  - Replica Server Placement
  - Content Replication and Placement
- Consistency Protocols

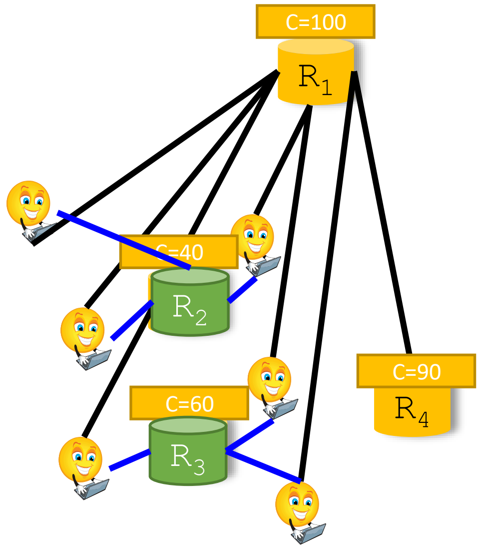
Replica Server Placement

- Factors that affect placement of replica servers:
  - What are the possible locations where servers can be placed?
    - Should we place replica servers close-by or distribute it uniformly?
  - How many replica servers can be placed?
    - What are the trade-offs between placing many replica servers vs. few?
  - How many clients are accessing the data from a location?
    - More replicas at locations where most clients access improves performance and fault-tolerance
- If **K** replicas have to be placed out of **N** possible locations, find the *best **K** out of **N*** locations **(K<N)**

Replica Server Placement – An Example Approach

- Problem: **K** replica servers should be placed on some of the **N** possible replica sites such that
  - Clients have low-latency/high-bandwidth connections
- Qiu *et al.* [2] suggested a Greedy Approach

1. Evaluate the cost of placing a replica on each of the **N** potential sites
   + Examining the *cost* of **C** clients connecting to the replica
   + Cost of a link can be **1/bandwidth** or **latency**
2. Choose the lowest-cost site
3. In the second iteration, search for a second replica site which, in conjunction with the already selected site, yields the lowest cost
4. Iterate steps 2,3 and 4 until **K** replicas are chosen

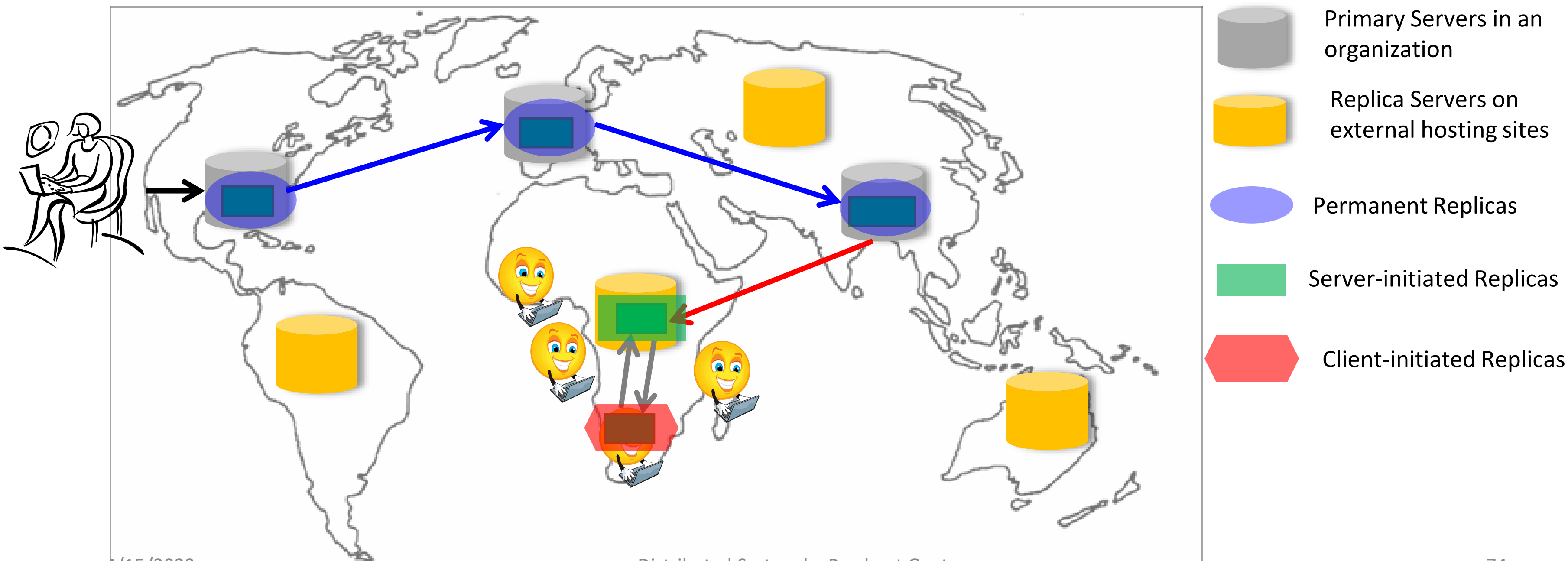


Overview

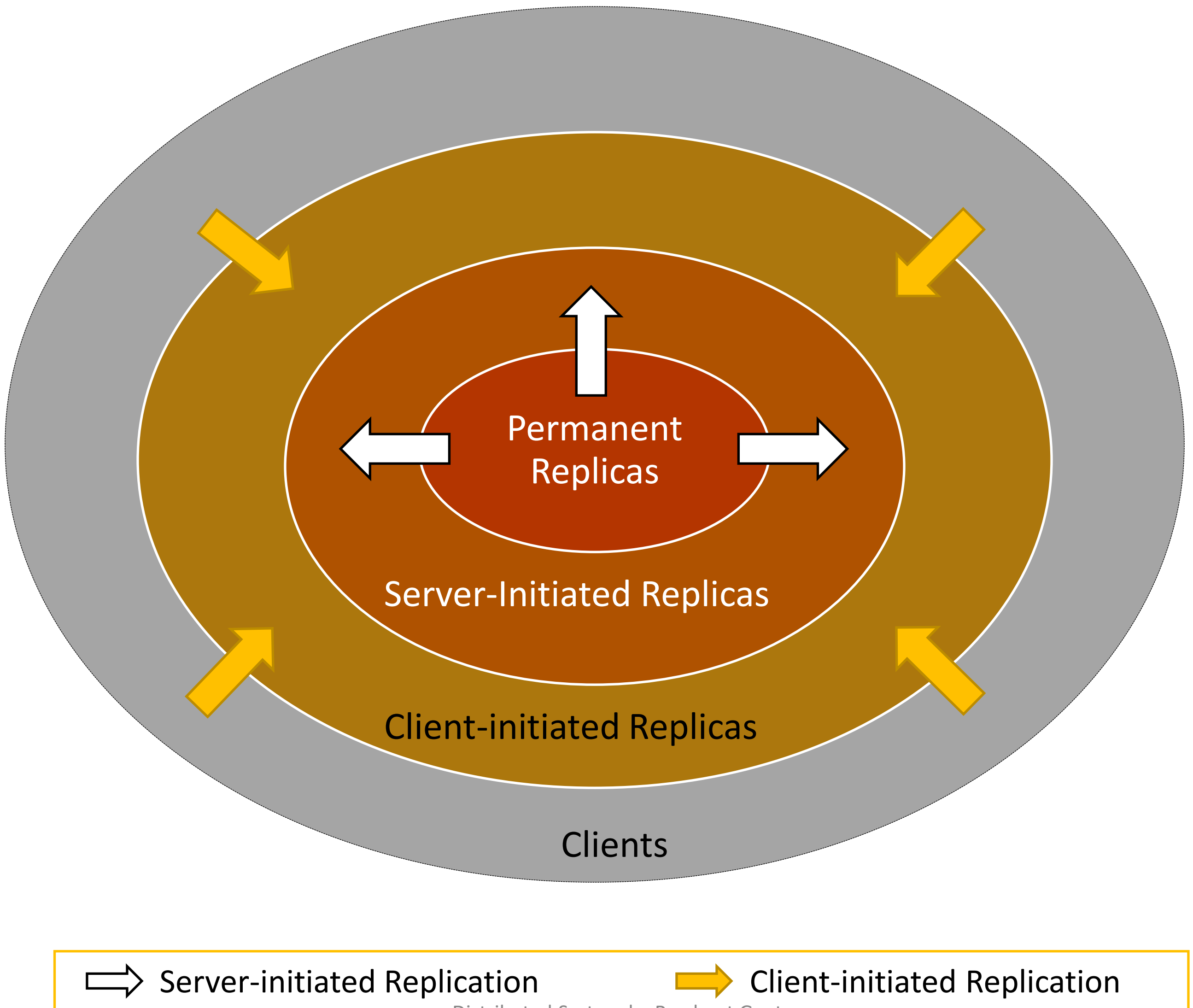
- Consistency Models
- Replica Management
  - Replica Server Placement
  - Content Replication and Placement
- Consistency Protocols

Content Replication and Placement

- In addition to the server placement, it is important:
  - how, when and by whom different data items (contents) are placed on possible replica servers
- Identify how webpage replicas are replicated:



Logical Organization of Replicas



1. Permanent Replicas

- Permanent replicas are the initial set of replicas that constitute a distributed data-store
- Typically, small in number
- There can be two types of permanent replicas:
  - Primary servers
    - One or more servers in an organization
    - Whenever a request arrives, it is forwarded into one of the primary servers
  - Mirror sites
    - Geographically spread, and replicas are generally statically configured
    - Clients pick one of the mirror sites to download the data

2. Server-initiated Replicas

- A third party (*provider*) owns the *secondary replica servers*, and they provide *hosting service*
  - The provider has a collection of servers across the Internet
  - The hosting service dynamically replicates files on different servers
    - Based on the popularity of the file in a region

- The permanent server chooses to host the data item on different *secondary replica servers*

- The scheme is efficient when updates are rare

- Examples of Server-initiated Replicas
  - Replicas in Content Delivery Networks (CDNs)

Dynamic Replication in Server-initiated Replicas

- Dynamic replication at secondary servers:
  - Helps to reduce the server load and improve client performance
  - But, replicas have to dynamically push the updates to other replicas

+ Rabinovich et al. [3] proposed a distributed scheme for replication:
  + Each server keeps track of:
    i. which is the closest server to the requesting client
    ii. number of requests per file per closest server
    + For example, each server **Q** keeps track of $\mathtt{cnt_Q(P,F)}$ which denotes how many requests arrived at **Q** which are closer to server **P** (for a file **F**)
  + If $\mathtt{cnt_Q(P,F) > 0.5 * cnt_Q(Q,F)}$
    + Request **P** to replicate a copy of file **F**
  + If $\mathtt{cnt_P(P,F) < LOWER\_BOUND}$
    + Delete the file at replica Q

If some other replica is nearer to the clients, request replication over that server

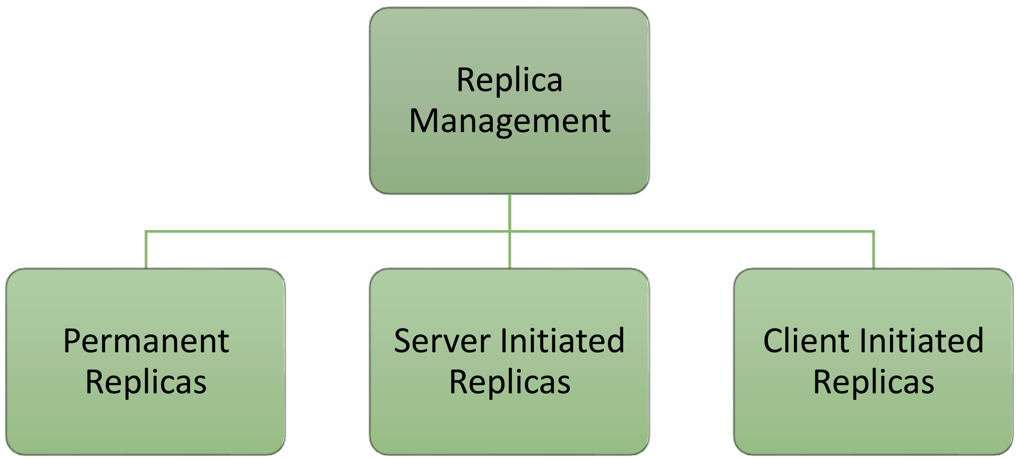
If the replication is not popular, delete the replica

3. Client-initiated Replicas

- Client-initiated replicas are known as *client caches*
- Client caches are used only to reduce the access latency of data
  - e.g., Browser caching a web-page locally
- Typically, managing a cache is entirely the responsibility of a client
  - Occasionally, data-store may inform client when the replica has become stale

Summary of Replica Management

- Replica management deals with placement of servers and content for improving performance and fault-tolerance



Till now, we know:

- how to place replica servers and content
- the required consistency models for applications

What else do we need to provide consistency in a distributed system?

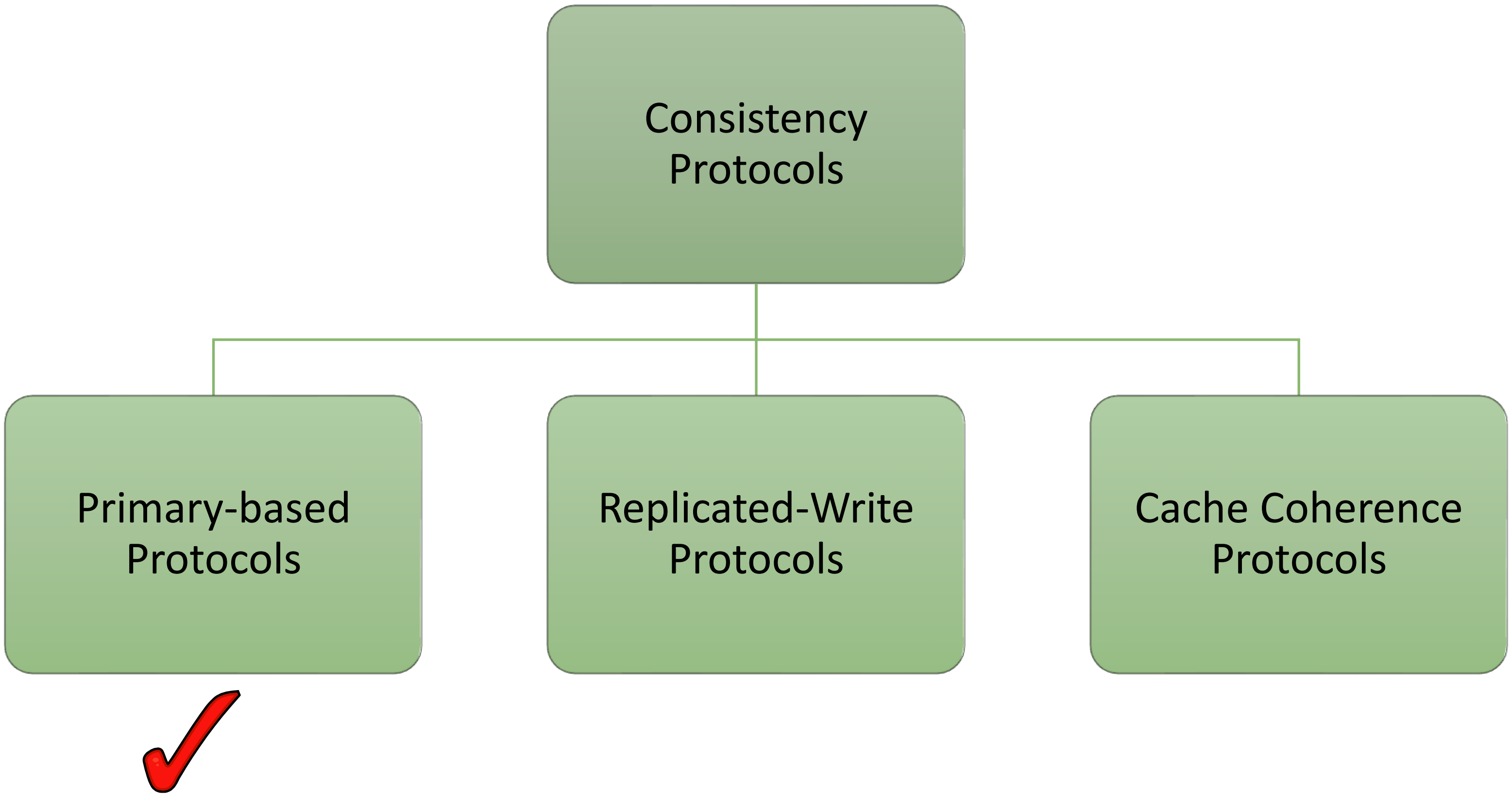
Overview

- Consistency Models
- Replica Management
- Consistency Protocols

Consistency Protocols

- A consistency protocol describes the implementation of a specific consistency model
- We are going to study three consistency protocols:
  - Primary-based protocols
    - One primary coordinator is elected to control replication across multiple replicas
  - Replicated-write protocols
    - Multiple replicas coordinate to provide consistency guarantees
  - Cache-coherence protocols
    - A special case of client-controlled replication

Overview of Consistency Protocols



Primary-based protocols

- In Primary-based protocols, a simple centralized design is used to implement consistency models
  - Each data-item **x** has an associated "*Primary Replica*"
  - Primary replica is responsible for coordinating write operations

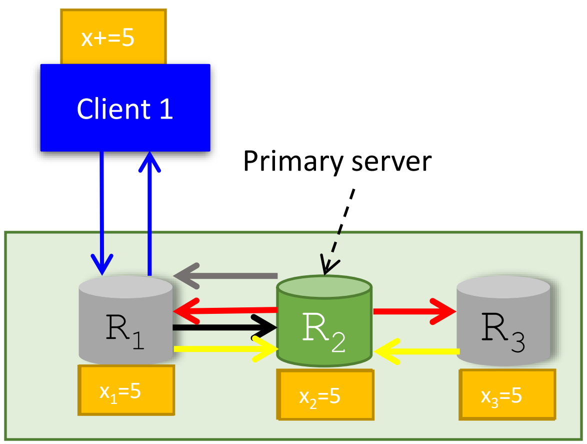
- We will study one example of Primary-based protocols that implement Sequential Consistency Model
  - Remote-Write Protocol

Remote-Write Protocol

- Rules:
  - All write operations are forwarded to the primary replica
  - Read operations are carried out locally at each replica

- Approach for write ops: (Budhiraja *et al.* [4])

  + Client connects to some replica R_C
  + If the client issues write operation to R_C:
    + R_C forwards the request to the primary replica R_P
    + R_P updates its local value
    + R_P forwards the update to other replicas R_i
    + Other replicas R_i update, and send an ACK back to R_P
  + After R_P receives all ACKs, it informs the R_C that write operation is successful
  + R_C acknowledges to the client that write operation was successful

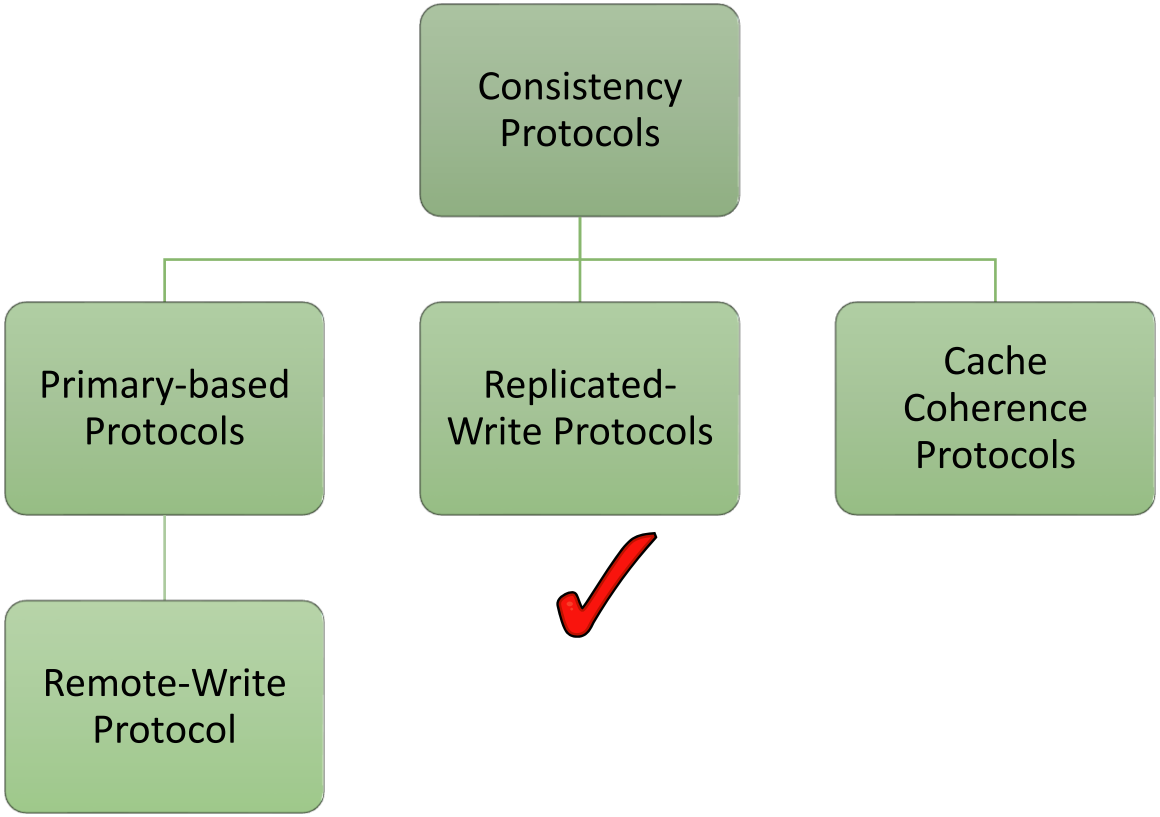


Data-store

Remote-Write Protocol – Discussion

- Remote-Write provides
  - A simple way to implement sequential consistency
  - Guarantees that client see the most recent write operations
- However, latency is high in Remote-Write Protocols
  - Client blocks until all the replicas are updated
  - In what scenarios would you use remote-write protocols?
- Remote-Write Protocols are applied to distributed databases and file systems that require fault-tolerance
  - Replicas are placed on the same LAN to reduce latency

Overview of Consistency Protocols



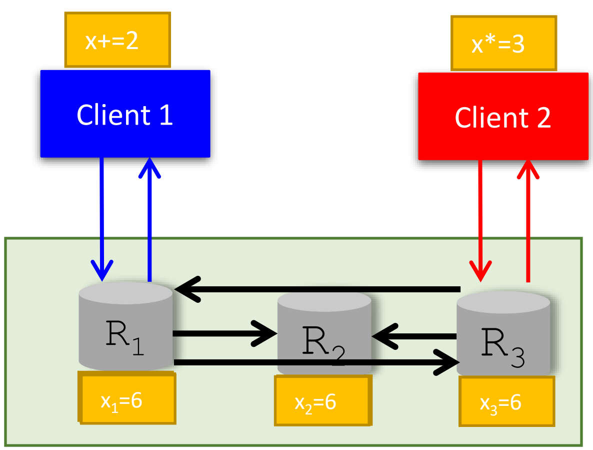
Replicated-Write Protocol

- In a replicated-write protocol, updates can be carried out at multiple replicas
- We will study one example replicated-write protocol called Active Replication Protocol
  - Here, clients write at any replica
  - The replica will propagate updates to other replicas

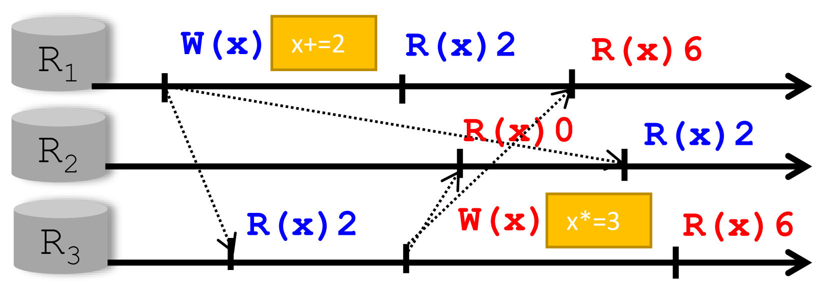
Active Replication Protocol

- When a client writes at a replica, the replica will send the write operation updates to all other replicas

- Challenges with Active Replication
  - Ordering of operations cannot be guaranteed across the replicas

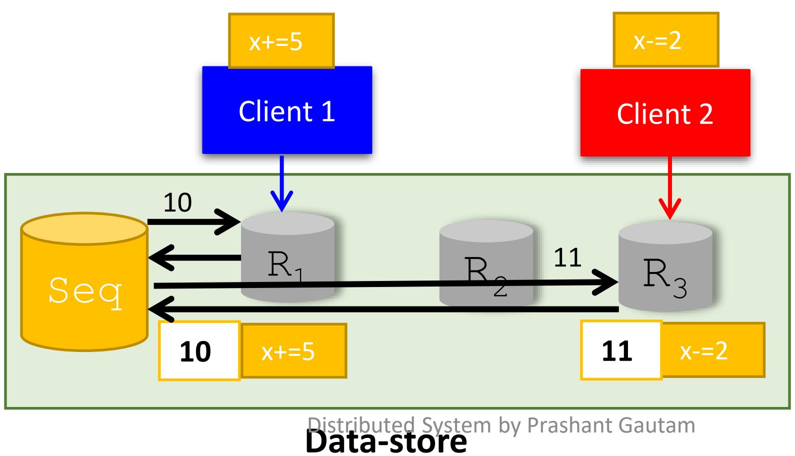


Data-store

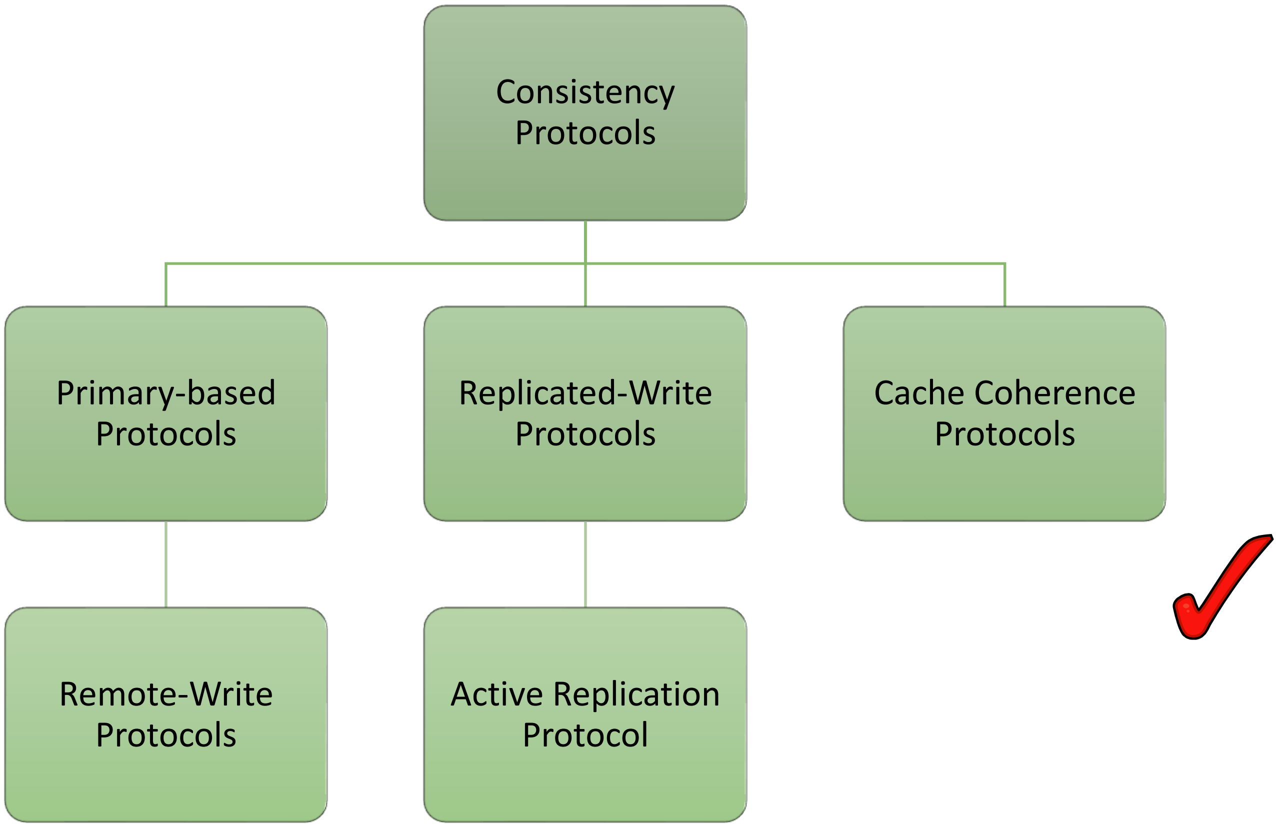


Centralized Active Replication Protocol

- Approach
  - There is a centralized coordinator called *sequencer* (**Seq**)
  - When a client connects to a replica $\mathbf{R_C}$ and issues a write operation
    - $\mathbf{R_C}$ forwards the update to the **Seq**
    - **Seq** assigns a sequence number to the update operation
    - $\mathbf{R_C}$ propagates the sequence number and the operation to other replicas
  - Operations are carried out at all the replicas in the order of the sequence number



Overview of Consistency Protocols



Cache Coherence Protocols

- Caches are special types of replicas
  - Typically, caches are client-controlled replicas
- Cache coherence refers to the consistency of data stored in caches
- How are the cache coherence protocols in shared-memory multiprocessor (SMP) systems different from those in Distributed Systems?
  - Coherence protocols in SMP assume cache states can be broadcasted efficiently
  - In DS, this is not possible because caches may reside on different machines

Cache Coherence Protocols (cont'd)

- Cache Coherence protocols determine <u>how</u> caches are kept consistent

- Caches may become inconsistent when data item is modified:
    1. at the server replicas, or
    2. at the cache

1. When Data is Modified at the Server

- Two approaches for enforcing coherence:
  1. Server-initiated invalidation
     - Here, server sends all caches an invalidation message when data item is modified
  2. Server updates the cache
     - Server will propagate the update to the cache

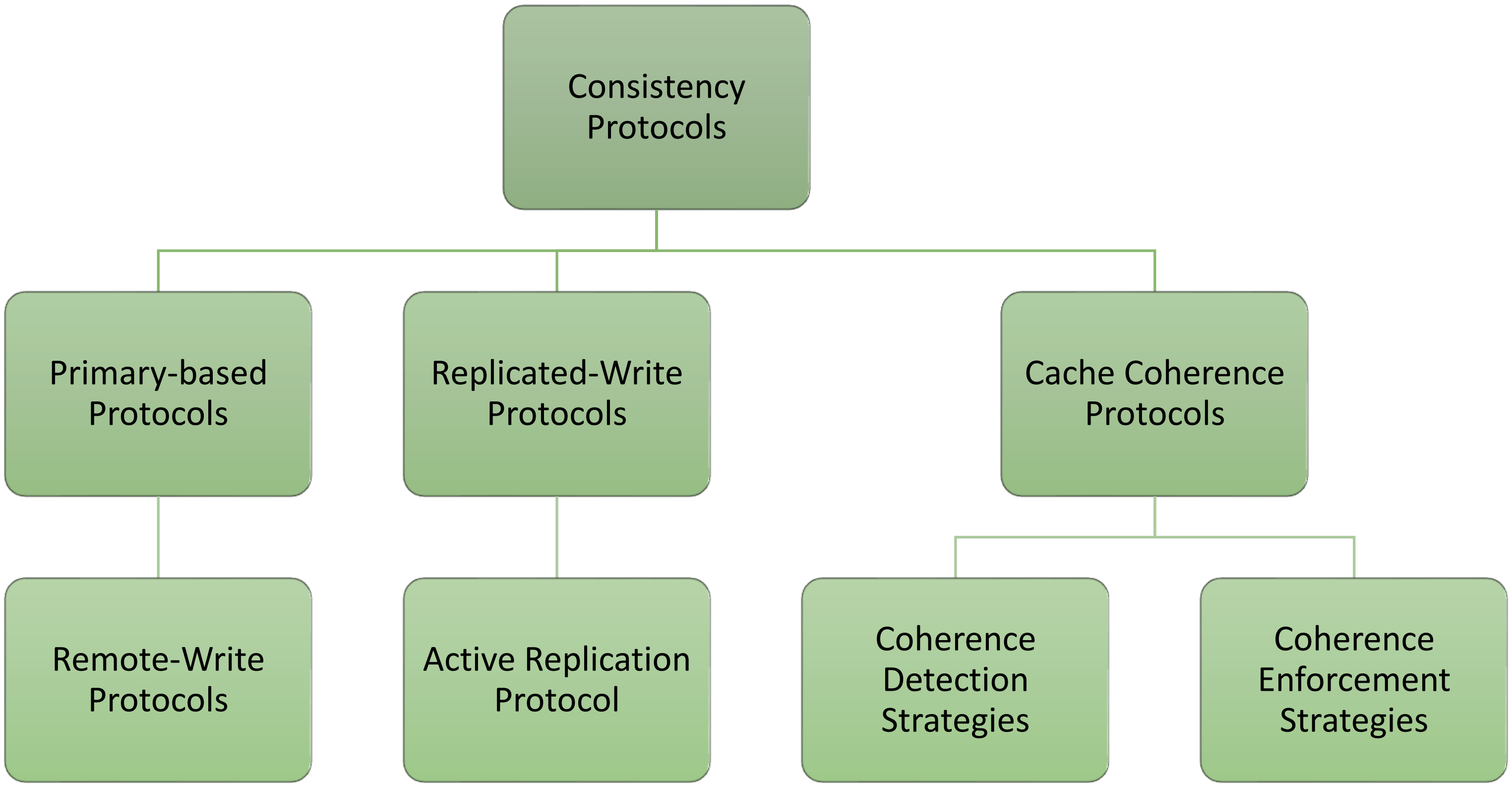
2. When Data is Modified at the Cache

- The enforcement protocol may use one of three techniques:
  i. Read-only cache
     - The cache does not modify the data in the cache
     - The update is propagated to the server replica

  ii. Write-through cache
     - Directly modify the cache, and forward the update to the server

  iii. Write-back cache
     - The client allows multiple writes to take place at the cache
     - The client batches a set of writes, and will send the batched write updates to the server replica

Summary of Consistency Protocols



Consistency and Replication – Brief Summary

- Replication improves performance and fault-tolerance
- However, replicas have to be kept reasonably consistent

Consistency Models

- A contract between the data-store and process
- Types: Data-centric and Client-centric

Replication Management

- Describes where, when and by whom replicas should be placed
- Types: Replica Server Placement, Content Replication and Placement

Consistency Protocols

- Implement Consistency Models
- Types: Primary-based, Replicated-Write, Cache Coherence

Next Classes

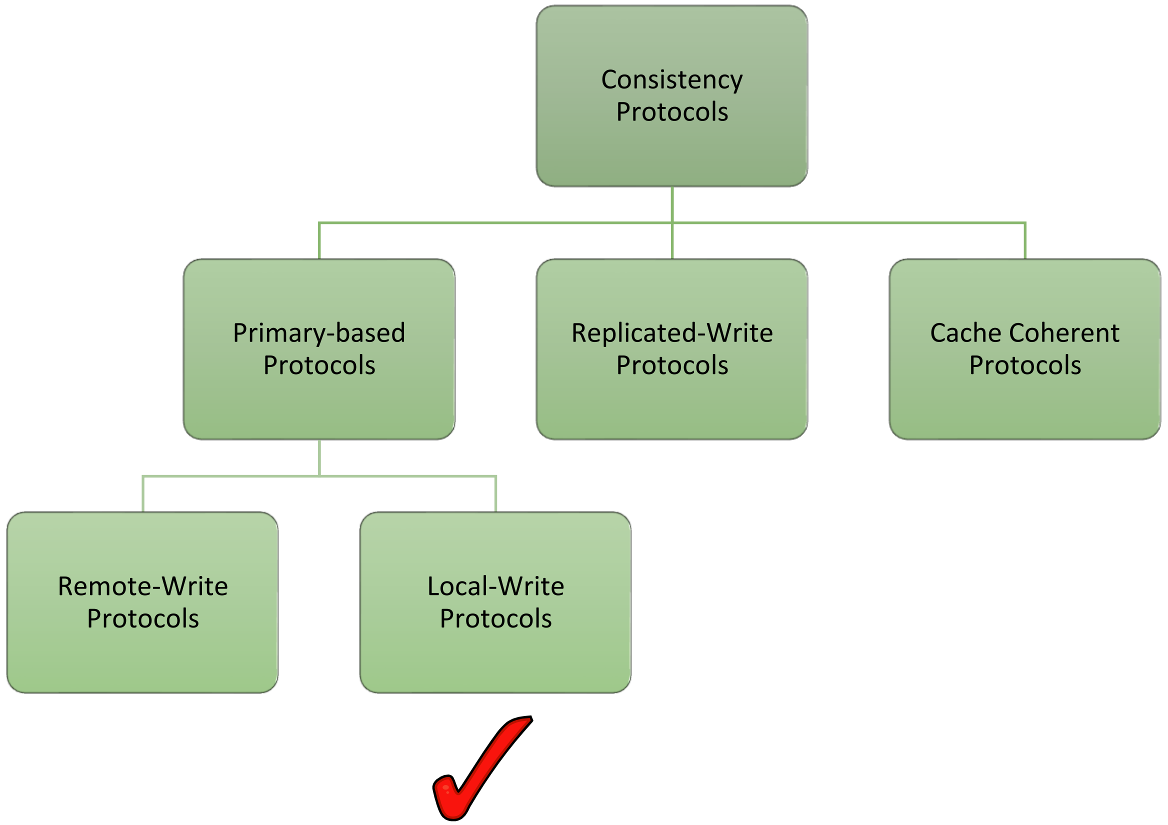
- Fault-tolerance
  - How to detect and deal with failures in Distributed Systems?

References

- [1] Terry, D.B., Demers, A.J., Petersen, K., Spreitzer, M.J., Theimer, M.M., Welch, B.B., "Session guarantees for weakly consistent replicated data", Proceedings of the Third International Conference on Parallel and Distributed Information Systems, 1994
- [2] Lili Qiu, Padmanabhan, V.N., Voelker, G.M., "On the placement of Web server replicas", Proceedings of IEEE INFOCOM 2001.
- [3] Rabinovich, M., Rabinovich, I., Rajaraman, R., Aggarwal, A., "A dynamic object replication and migration protocol for an Internet hosting service", Proceedings of IEEE International Conference on Distributed Computing Systems (ICDCS), 1999
- [4] Navin Budhiraja, Keith Marzullo. Fred B. Schneider. Sam Toueg, "The primary-backup approach", Distributed systems (2nd Ed.), ACM Press/Addison-Wesley Publishing Co., 1993
- [5] http://www.cdk5.net
- [6] http://en.wikipedia.org/wiki/Cache_coherence

Back-up Slides

Overview of Consistency Protocols

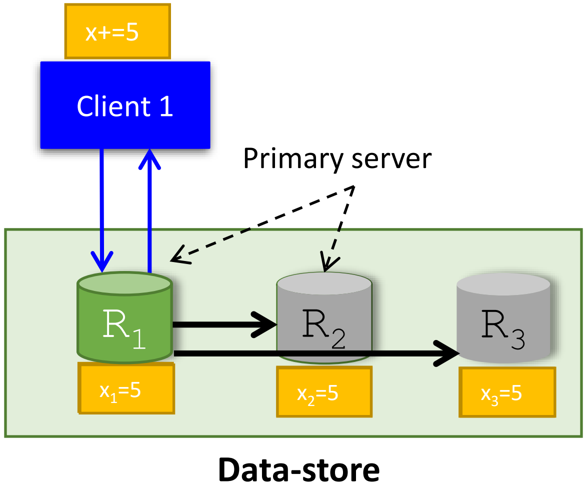


Local-Write Protocols

- Can we make Remote-Write better for applications that require client-centric consistency model?
  - Single client process issues write operations
  - Reasonably stale value of data is OK when other processes read

- Approach:

  + Client connects to some replica $\mathbf{R_C}$
  + If the client issues write op to $\mathbf{R_C}$:
    + $\mathbf{R_C}$ becomes the primary replica $\mathbf{R_P}$
    + Rest of the protocol is similar to Remote-Write



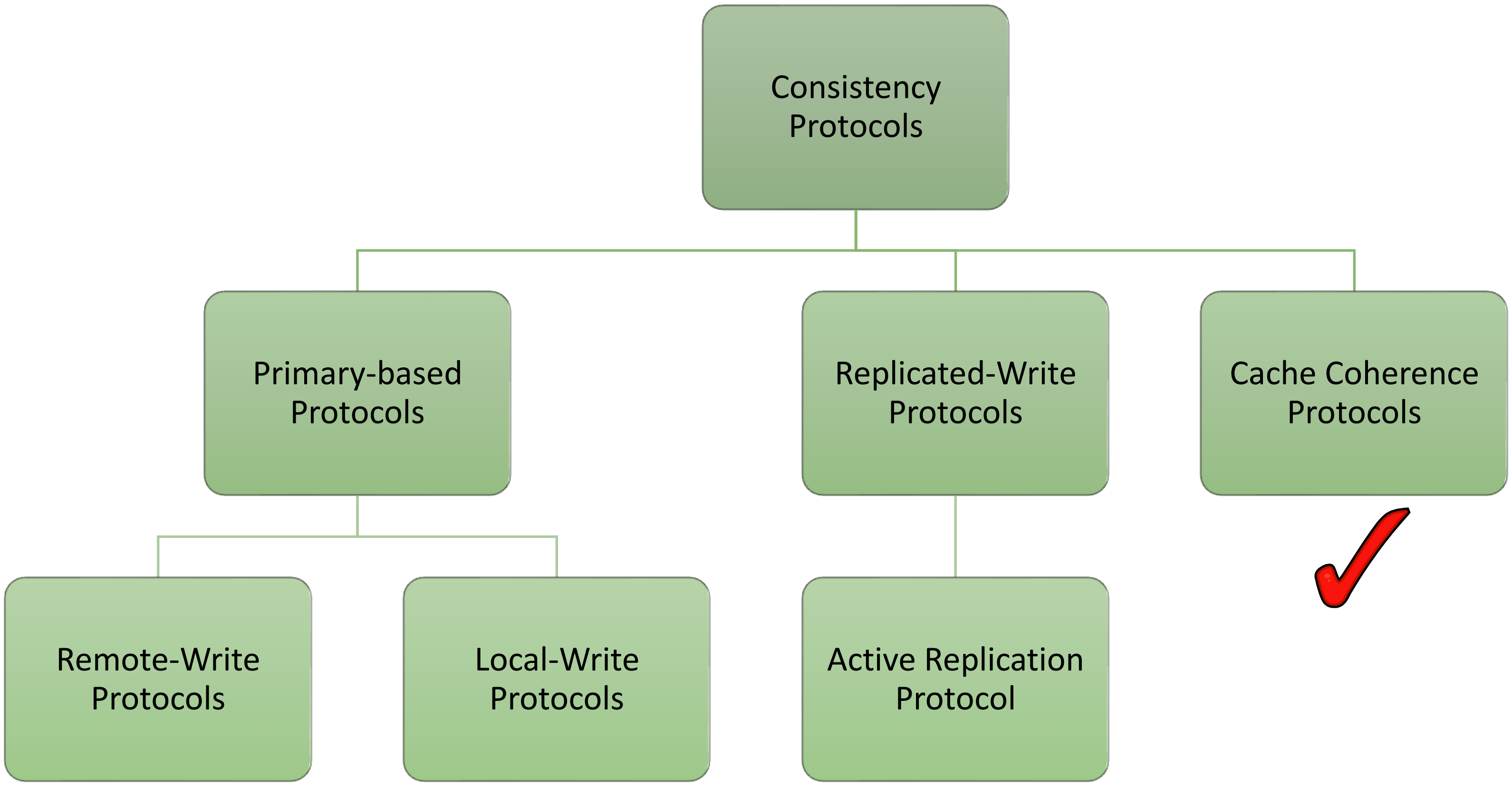
Local-Write Protocol

- Advantages
  - Primary replica can propagate a batch of write updates instead of an individual update

- Scenarios where Local-Write is applicable:
  - To provide client-centric consistency at mobile computers, which are often disconnected from the network
    - The primary replica is cached at the client

- Scenarios where Local-Write is inappropriate:
  - When (multiple) clients are writing at multiple replicas
    - Overhead of reassigning primary replica is high

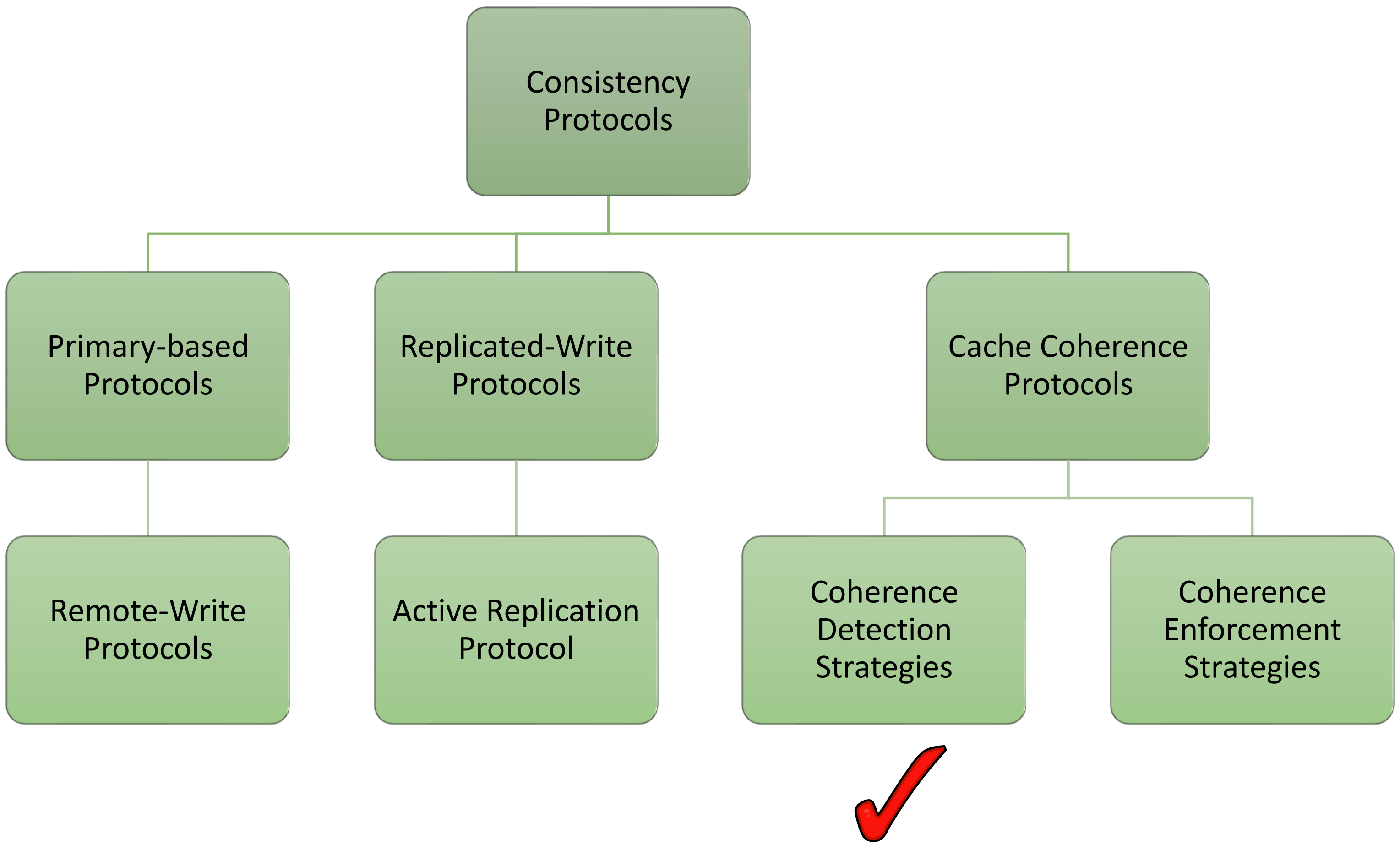
Overview of Consistency Protocols



Two aspects of Cache Coherence Protocols

- In order to maintain consistent caches, we need to perform two operations:
  - Coherence detection strategies
    - Detect inconsistent caches
  - Coherence enforcement strategies
    - Update caches

Overview of Consistency Protocols



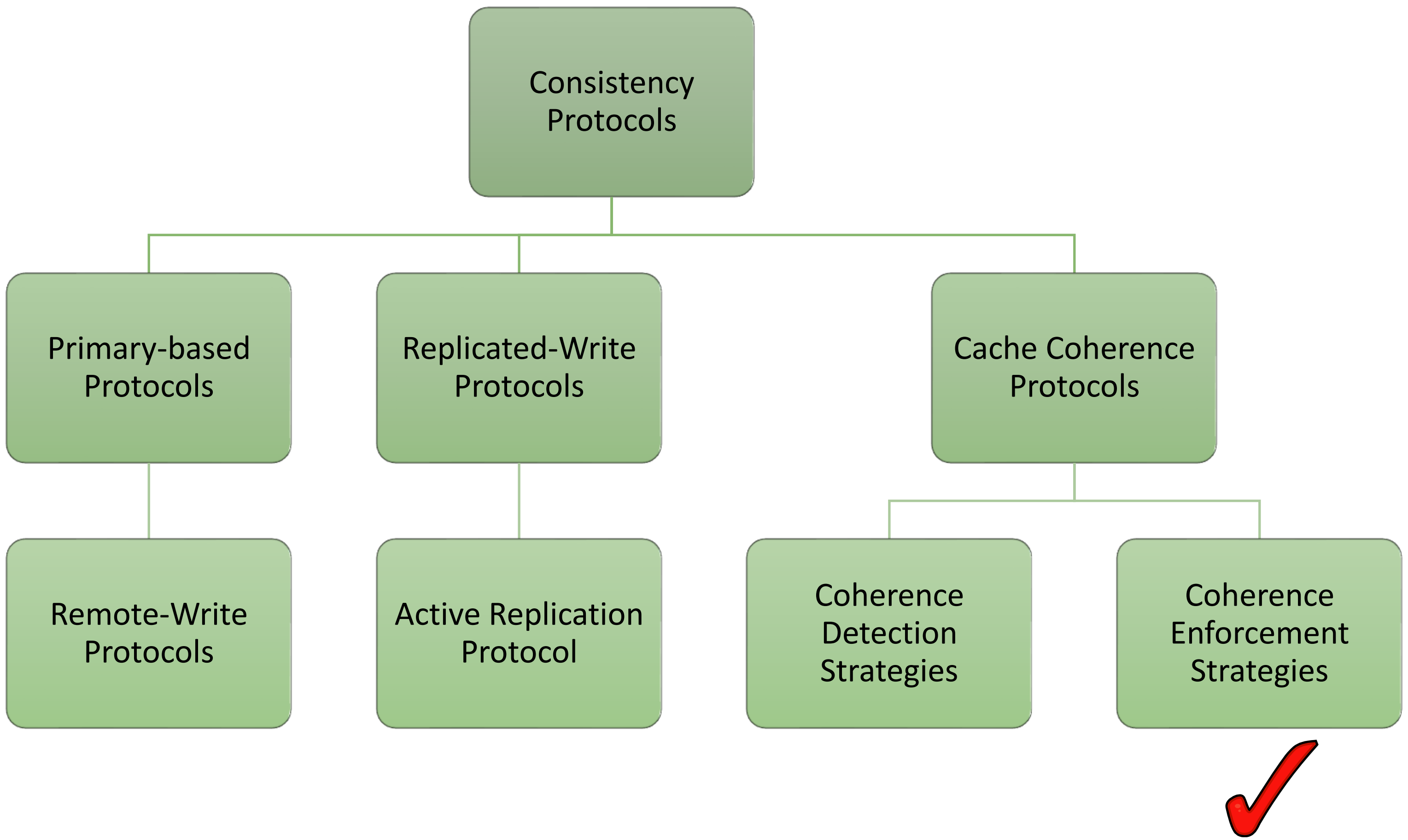
Coherence Detection Strategies

- Detection strategies deal with predicting <u>when</u> caches are inconsistent
- Since different replicas may be written by client processes, the protocol has to dynamically detect cache inconsistency

Coherence Detection Strategies

- In a distributed system, cache inconsistencies can be typically detected at three stages:
  1. Verify coherence before every access
     - Before every read or write operation
  2. Verify coherence before a write access
     - Cache coherence is checked before every write operation
  3. Verify coherence after a write access
     - First, an update is performed, and later cache consistency is verified
     - If cache was inconsistent
       - The write operation is rolled-back, and re-performed

Overview of Consistency Protocols



Coherence Enforcement Strategies

- Enforcement strategies determine how caches are kept consistent
- Caches may become inconsistent when data item is modified:
    1. at the server replicas, or
    2. at the cache

1. When Data is Modified at the Server

- Two approaches for enforcing coherence:
  1. Server-initiated invalidation
     - Here, server sends all caches an invalidation message when data item is modified
  2. Server updates the cache
     - Server will propagate the update to the cache

2. When Data is Modified at the Cache

- The enforcement protocol may use one of three techniques:
  i. Read-only cache
    - The cache does not modify the data in the cache
    - The update is propagated to the server replica

  ii. Write-through cache
    - Directly modify the cache, and forward the update to the server

  iii. Write-back cache
    - The client allows multiple writes to take place at the cache
    - The client batches a set of writes, and will send the batched write updates to the server replica