Replicated State Machines Primary-Backup

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Primary-Backup Replication

- Widely used
- Reasonably simple to implement
- Hard to get desired consistency and performance
- Will revisit this and consider other approaches later in the class

Fault Tolerance

- we'd like a service that continues despite failures!
- available: still useable despite *some class of* failures
- strong consistency: act just like a single server to clients
- very useful!
- very hard!

Failure Model

- What do we want to cope with?
  - Independent fail-stop computer failure
  - Site-wide power failure (and eventual reboot)
  - Network partition
  - No bugs, no malice

Core Idea: replication

- Two servers (or more)
- Each replica keeps state needed for the service
- If one replica fails, others can continue

Key Questions

- What state to replicate?
- How does replica get state?
- When to cut over to backup?
- Are anomalies visible at cut-over?
- How to repair/re-integrate?

Two Main Approaches

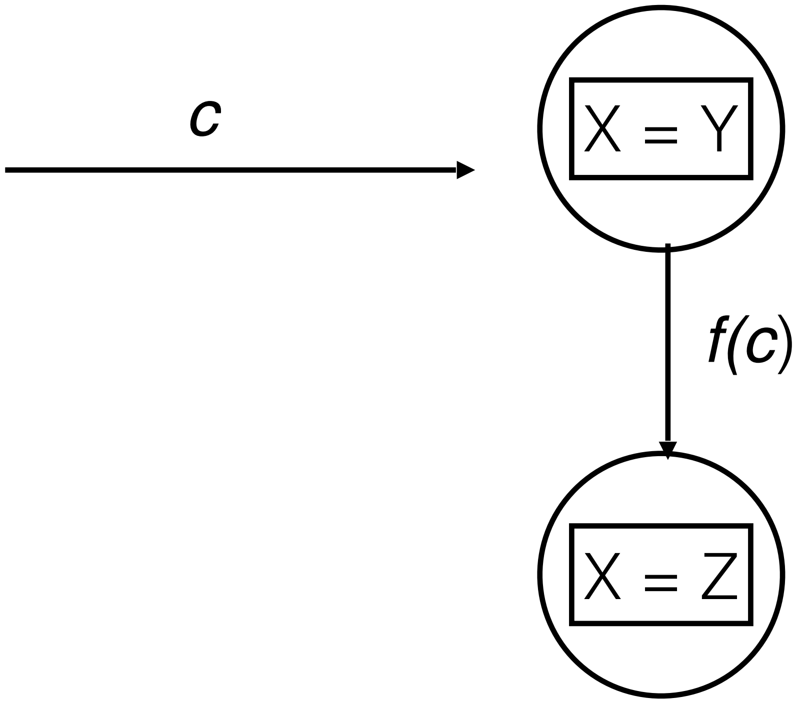
- State transfer
  - "Primary" replica executes the service
  - Primary sends [new] state to backups
- Replicated state machine
  - All replicas execute all operations
  - If same start state, same operations, same order, deterministic → then same end state

- There are tradeoffs: complexity, costs, consistency

Design Space

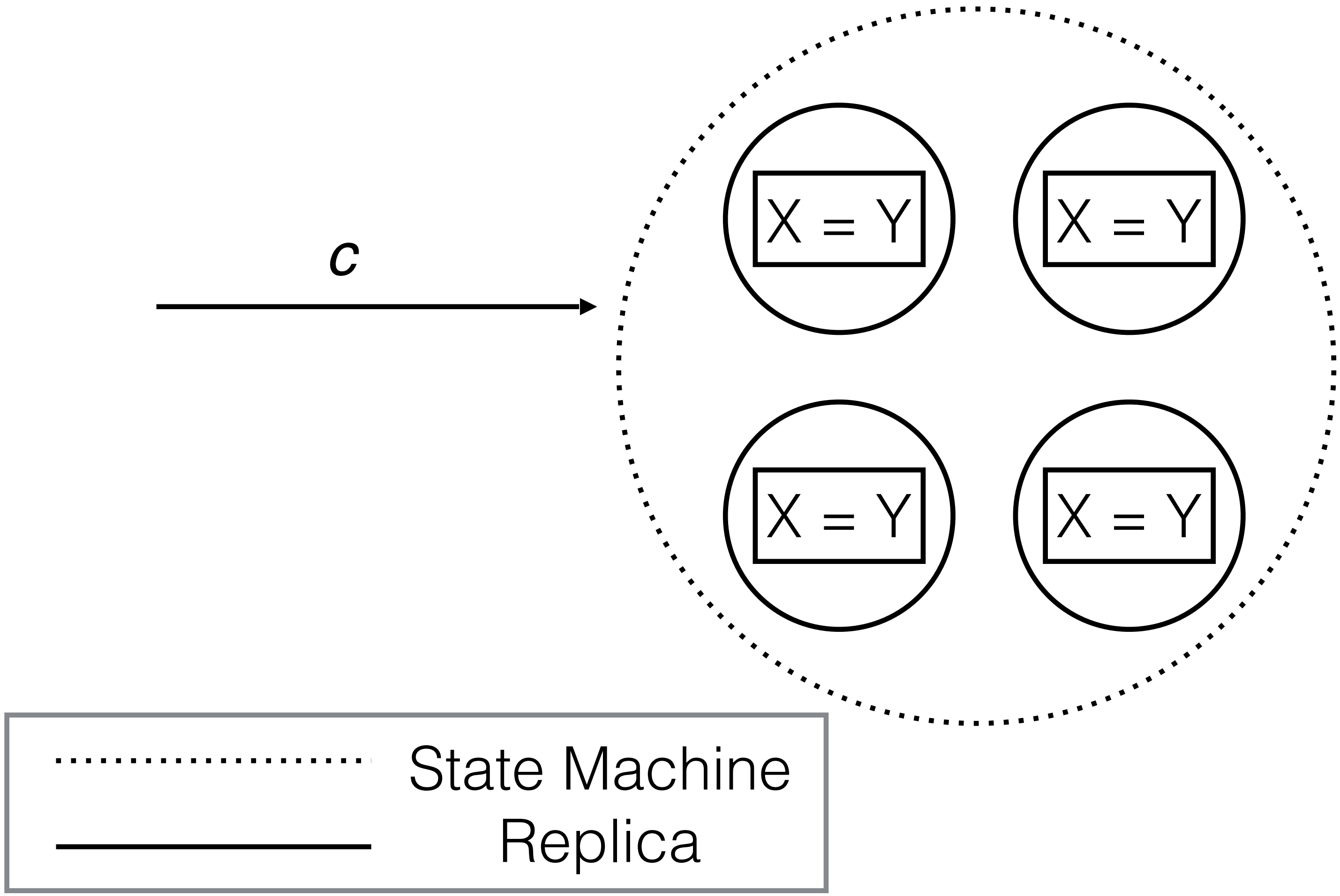
- Active or passive replicas
- Symmetric replicas or primary-backup
- Replicate commands or low-level inputs

State Machines



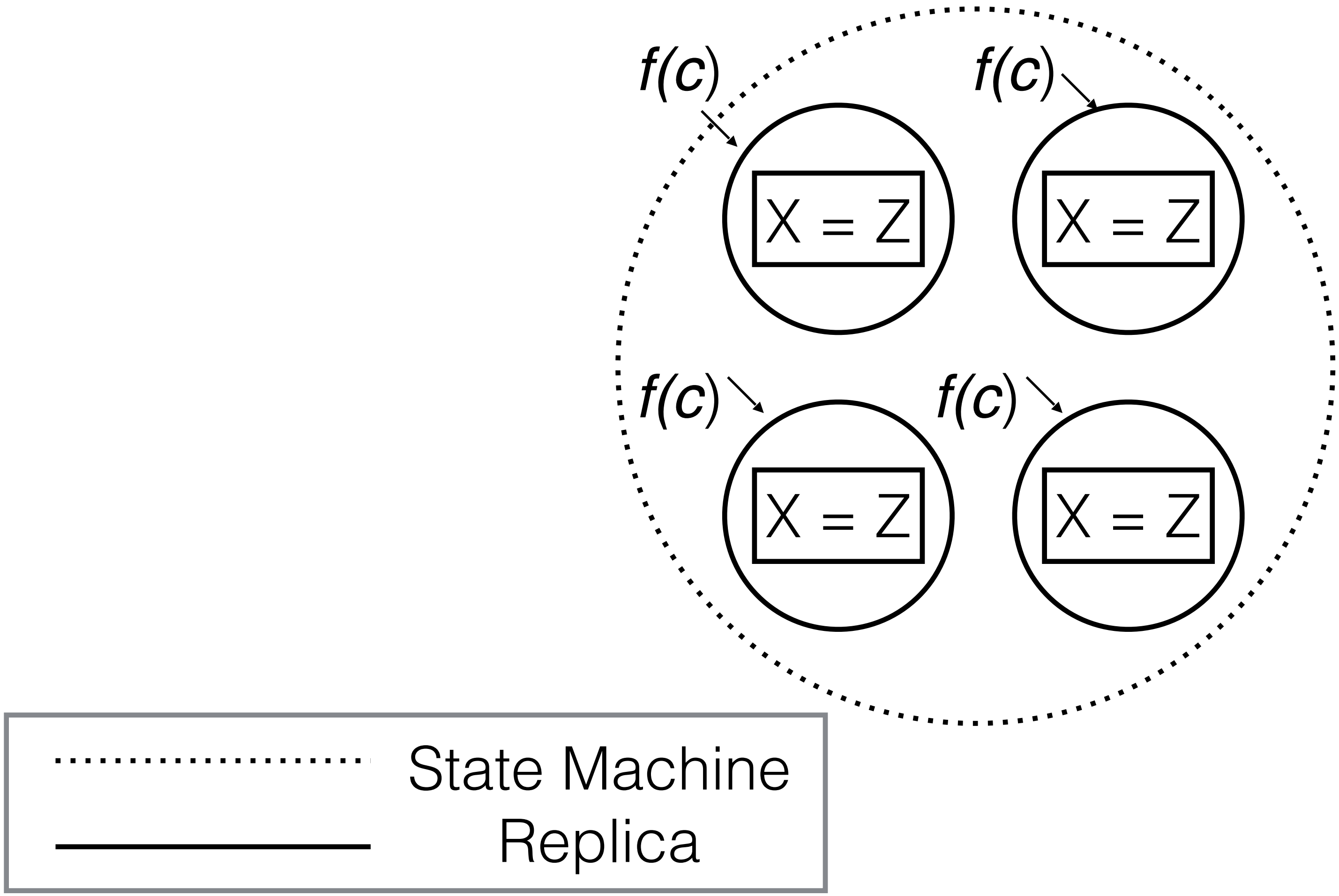
- ***c*** is a Command
- ***f*** is a Transition Function

State Machine Replication (SMR)



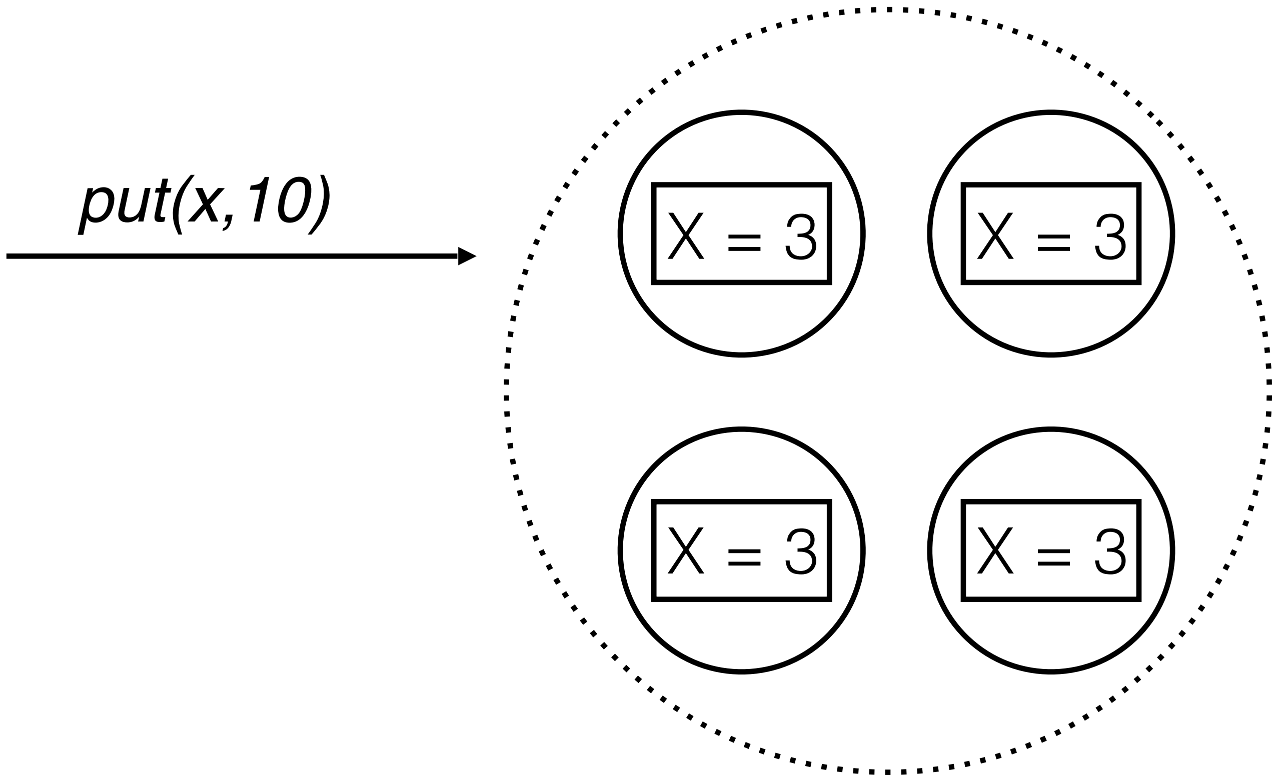
- The *State Machine Approach* to a fault tolerant distributed system
- Keep around *N* copies of the state machine

State Machine Replication (SMR)

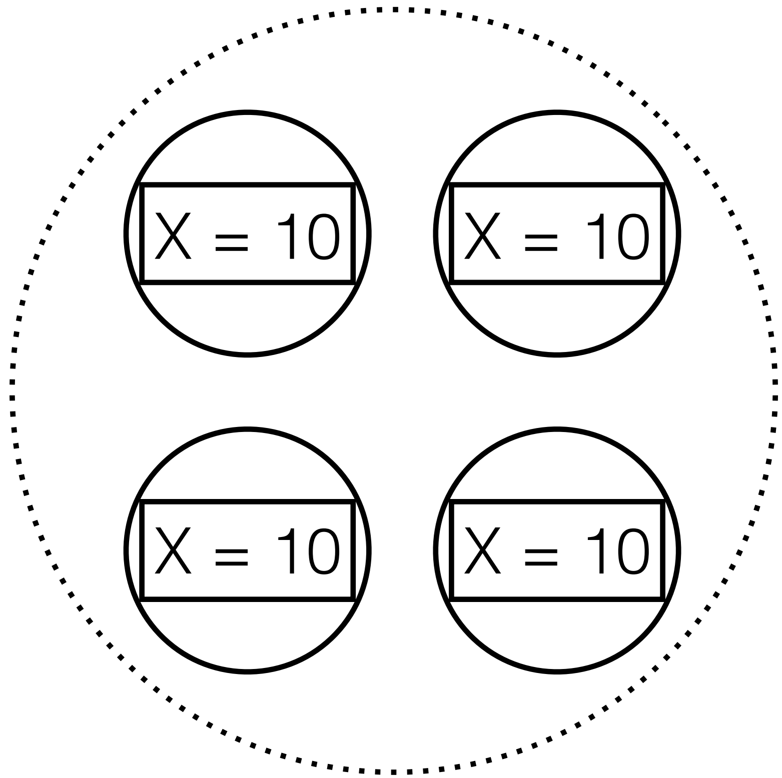


- The *State Machine Approach* to a fault tolerant distributed system
- Keep around *N* copies of the state machine

SMR Requirements

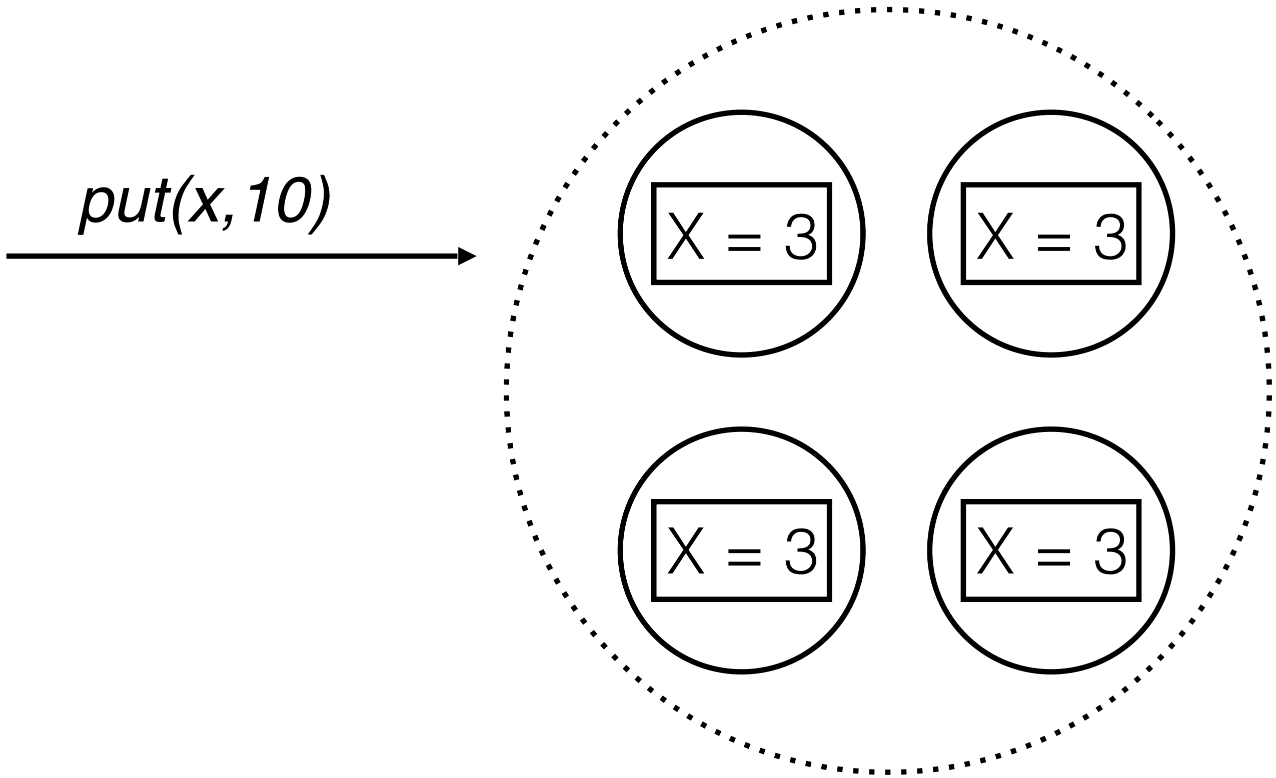


SMR Requirements

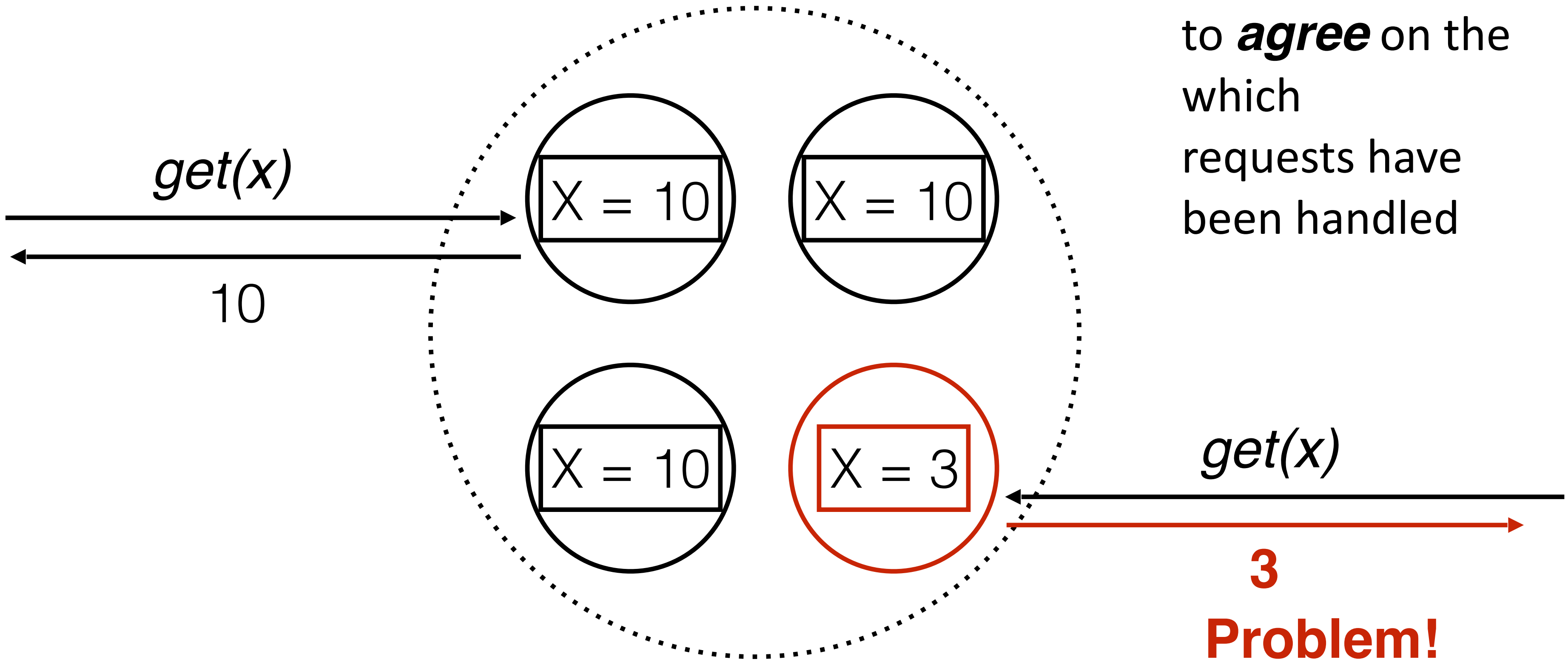


Great!

SMR Requirements

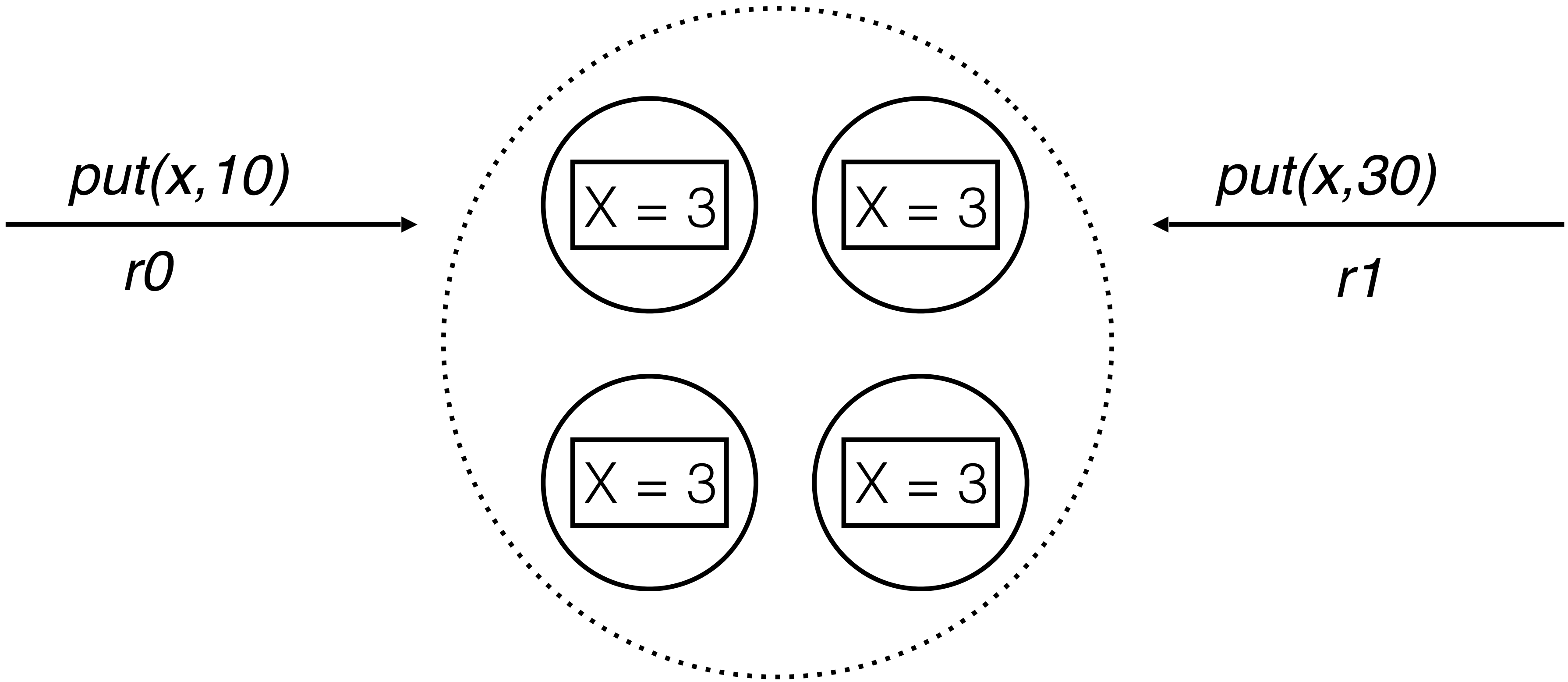


SMR Requirements

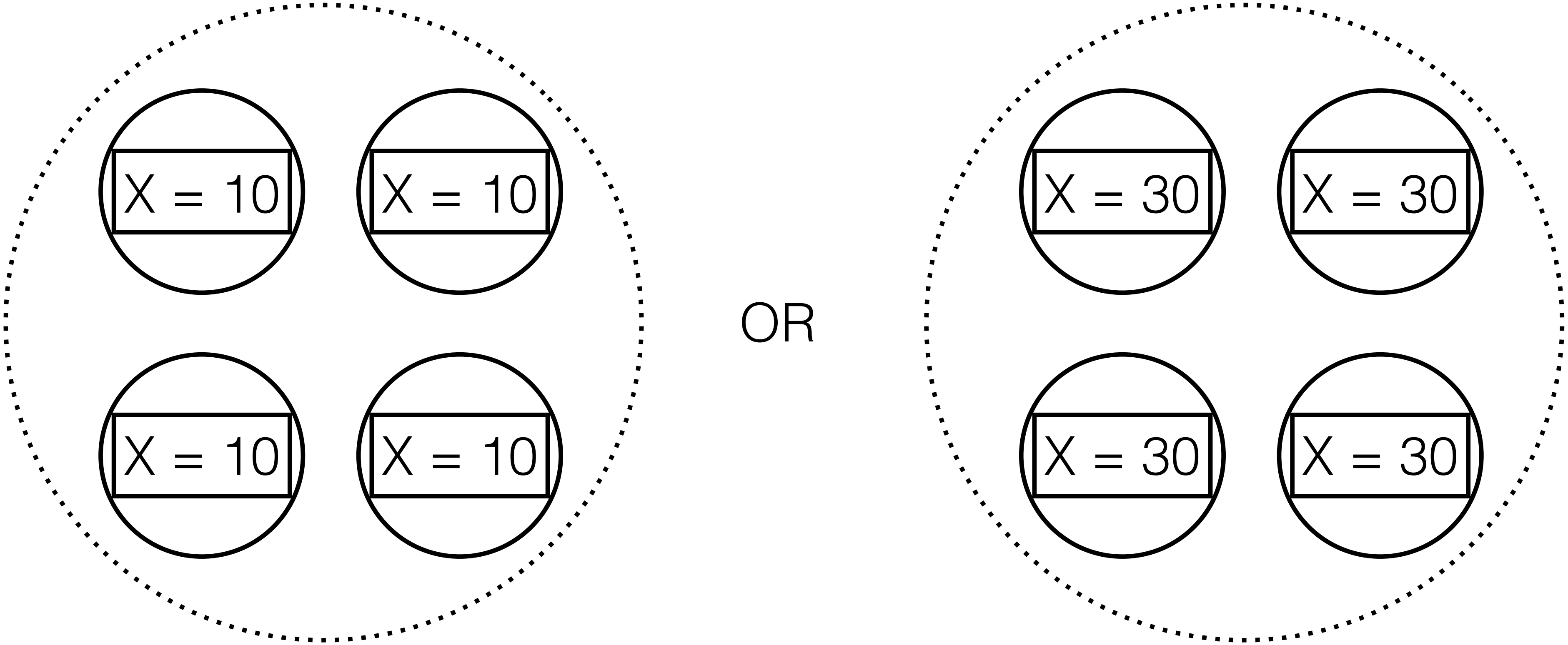


- Replicas need to ***agree*** on the which requests have been handled

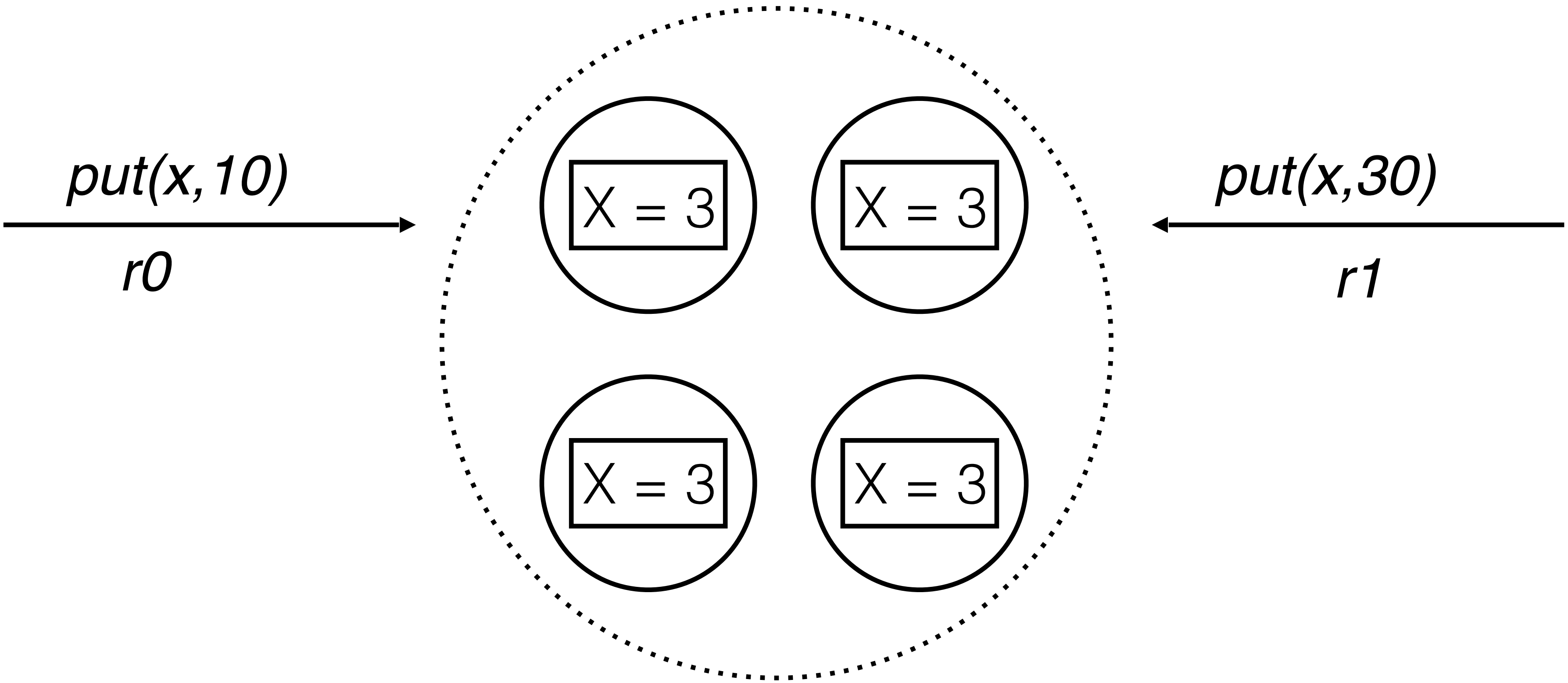
SMR Requirements



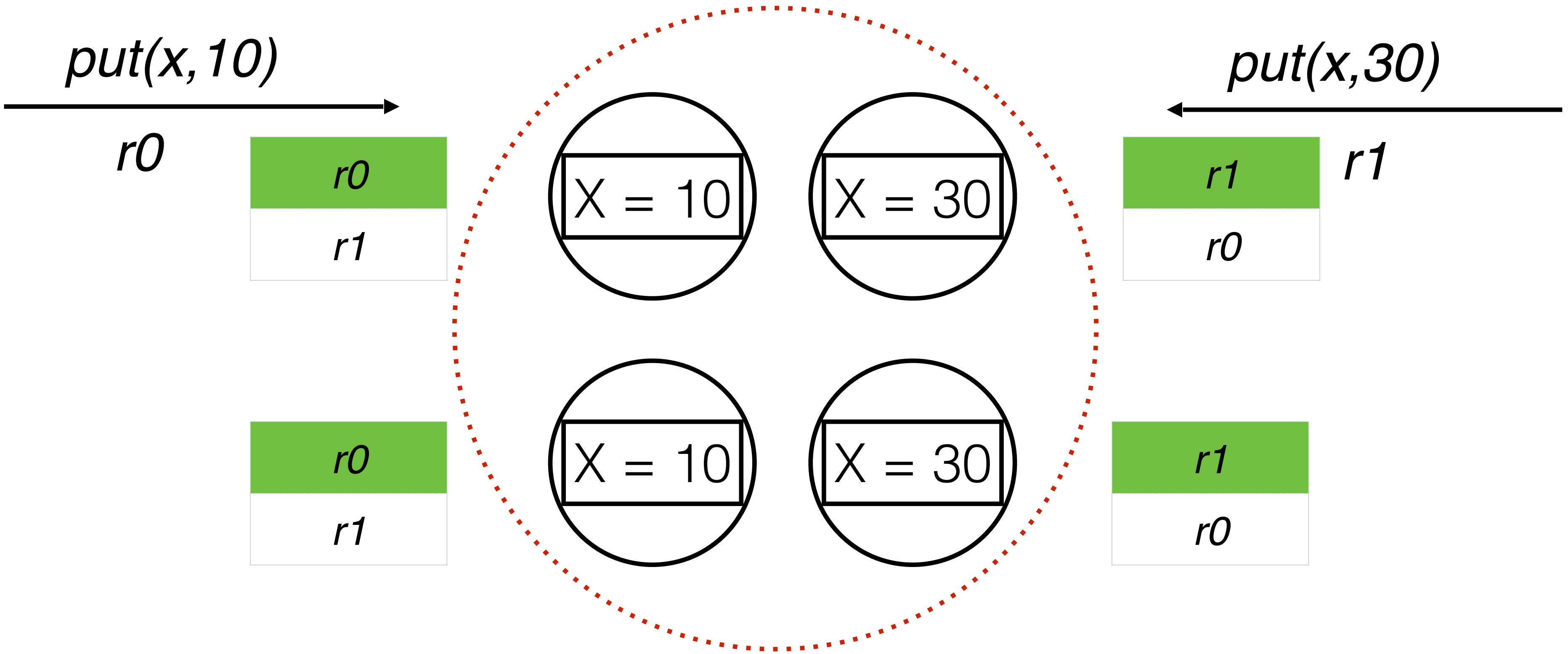
SMR Requirements



SMR Requirements

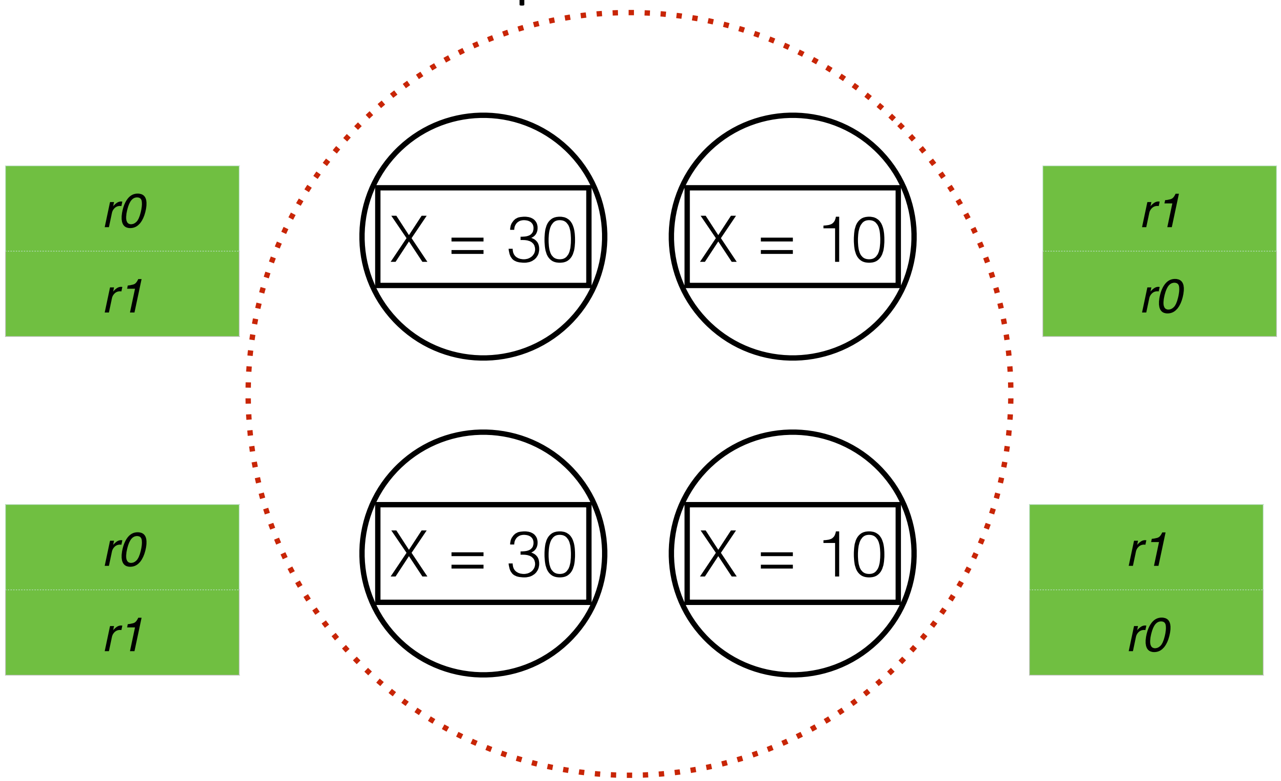


SMR Requirements



SMR Requirements

- Replicas need to handle requests in the same ***order***



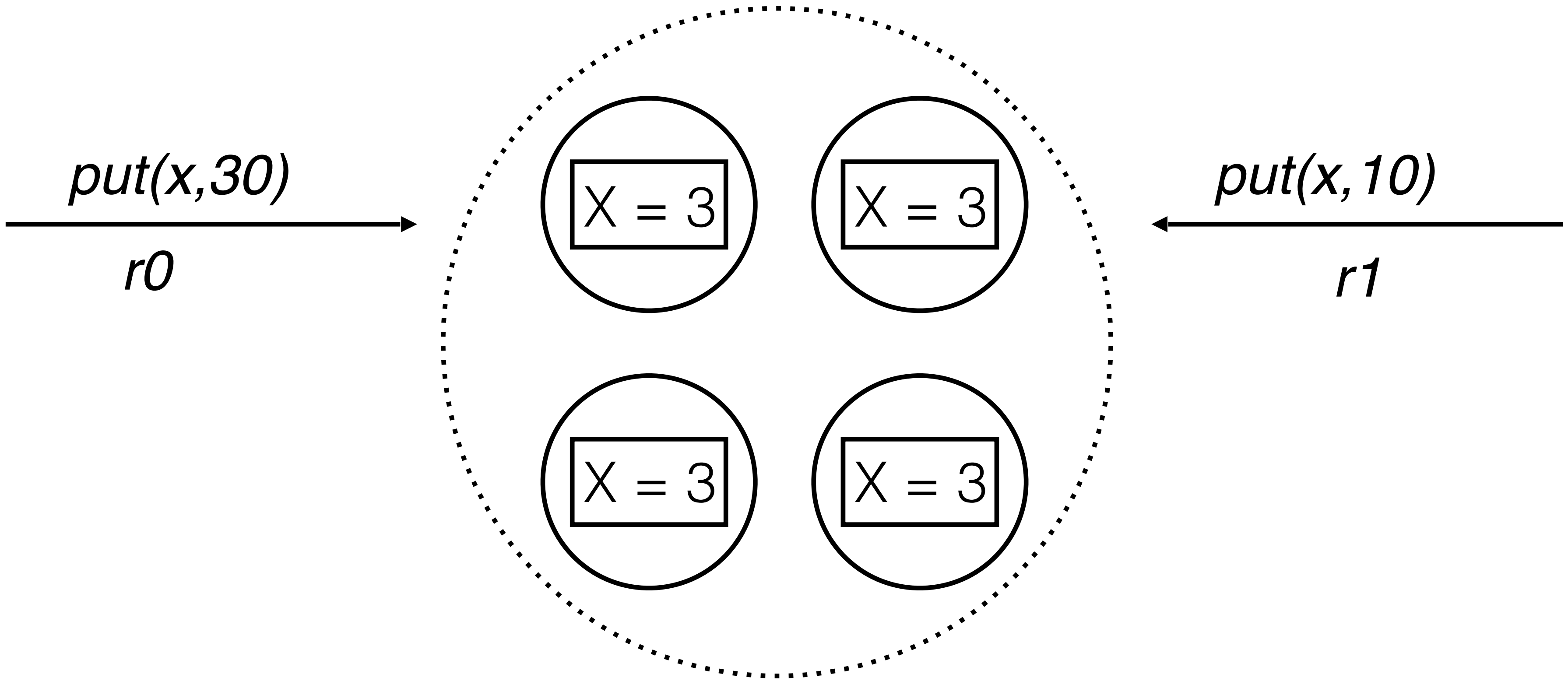
SMR

- All non faulty servers need:
  - Agreement
    - Every replica needs to accept the same set of requests
  - Order
    - All replicas process requests in the same relative order

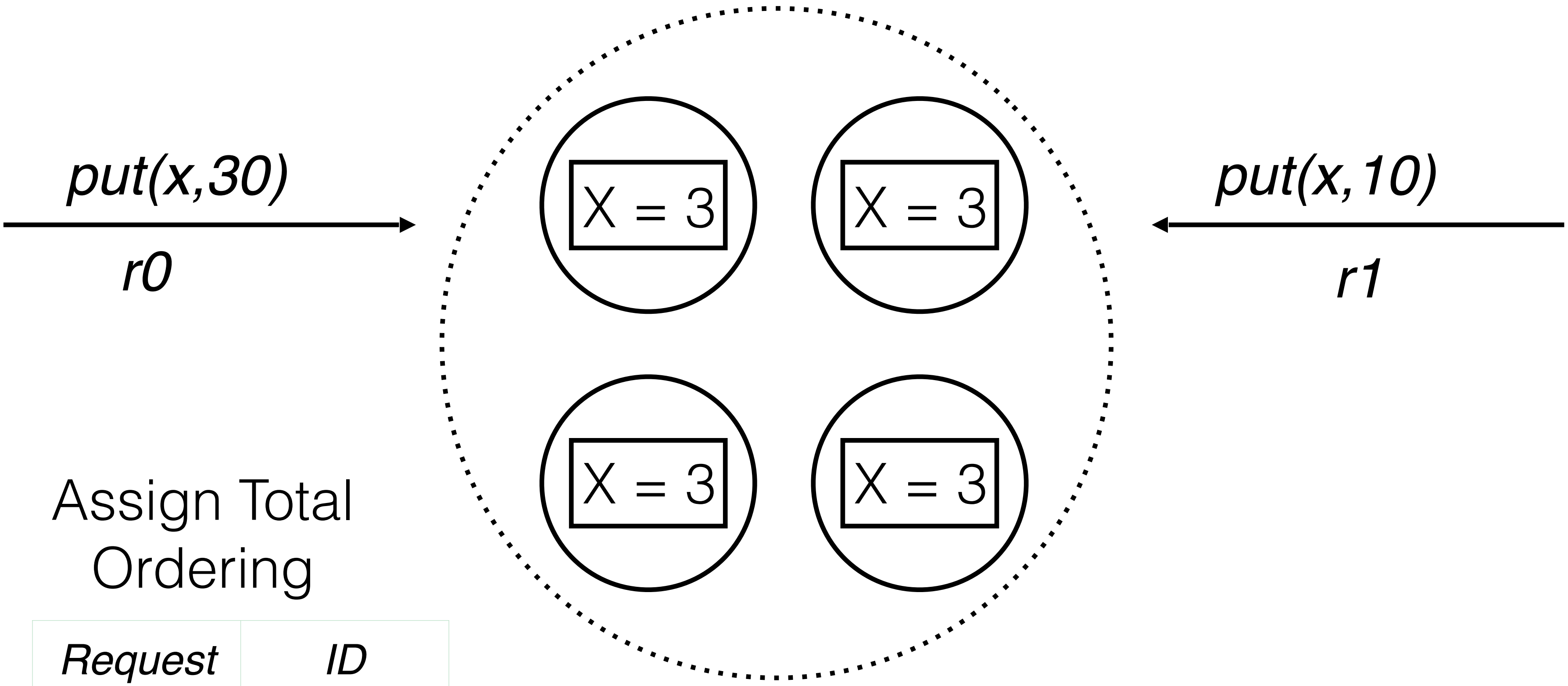
Implementation

- Order
  - Assign unique ids to requests, process them in ascending order.
  - How do we assign unique ids in a distributed system?
  - How do we know when every replica has processed a given request?

SMR Requirements



SMR Requirements



Assign Total Ordering

Request	*ID*
r0	*1*
r1	*2*

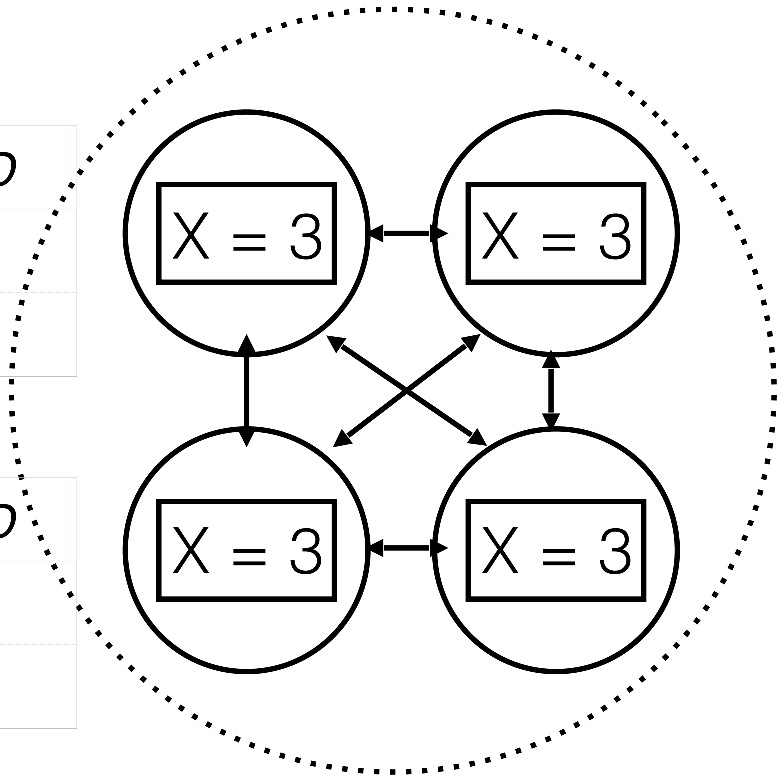
Replica Generated IDs

- 2 Phase ID generation
  - Every Replica proposes a ***candidate***
  - One candidate is chosen and agreed upon by all replicas

Replica ID Generation

Req.	CUID	UID
r0	1.1	
r1	2.1	

Req.	CUID	UID
r0	1.2	
r1	2.2	



Req.	CUID	UID
r1	1.3	
r0	2.3	

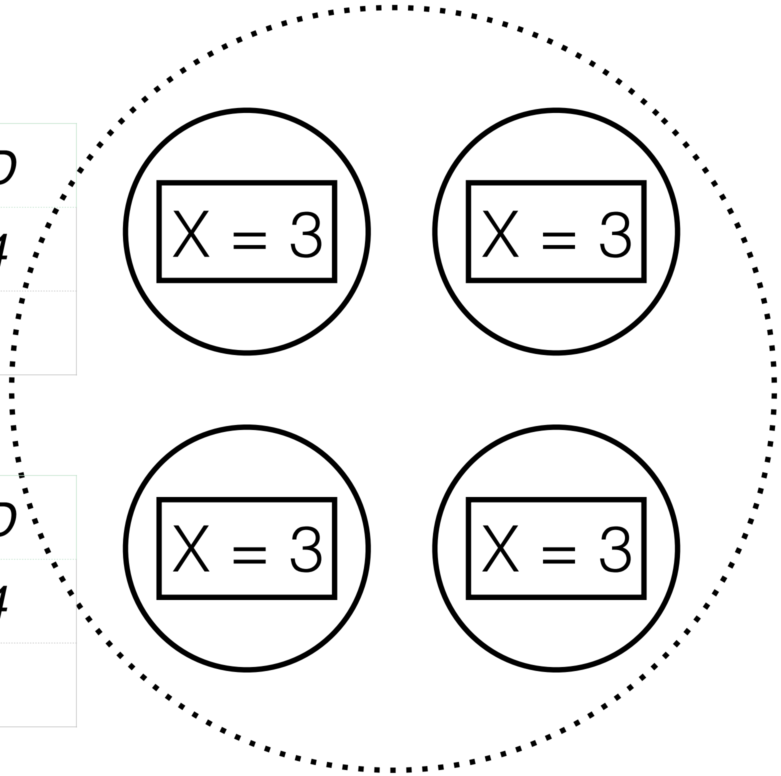
Req.	CUID	UID
r1	1.4	
r0	2.4	

1) Propose Candidates

Replica ID Generation

Req.	CUID	UID
r0	1.1	2.4
r1	2.1	

Req.	CUID	UID
r0	1.2	2.4
r1	2.2	



Req.	CUID	UID
r1	1.3	
r0	2.3	2.4

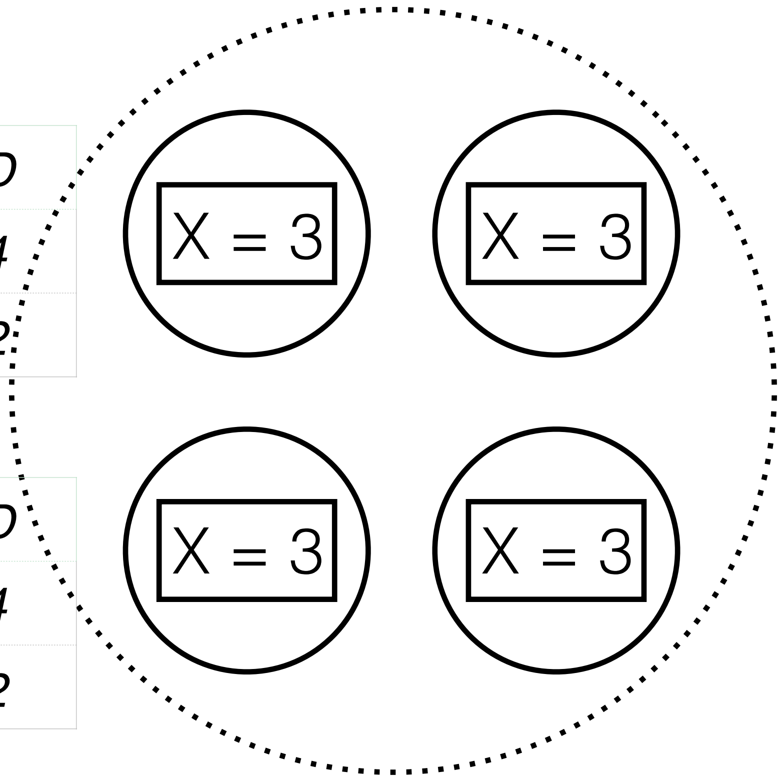
Req.	CUID	UID
r1	1.4	
r0	2.4	2.4

2) Accept ***r0***

Replica ID Generation

Req.	*CUID*	*UID*
r0	*1.1*	*2.4*
r1	*2.1*	*2.2*

Req.	*CUID*	*UID*
r1	*1.3*	*2.2*
r0	*2.3*	*2.4*



Req.	*CUID*	*UID*
r0	*1.2*	*2.4*
r1	*2.2*	*2.2*

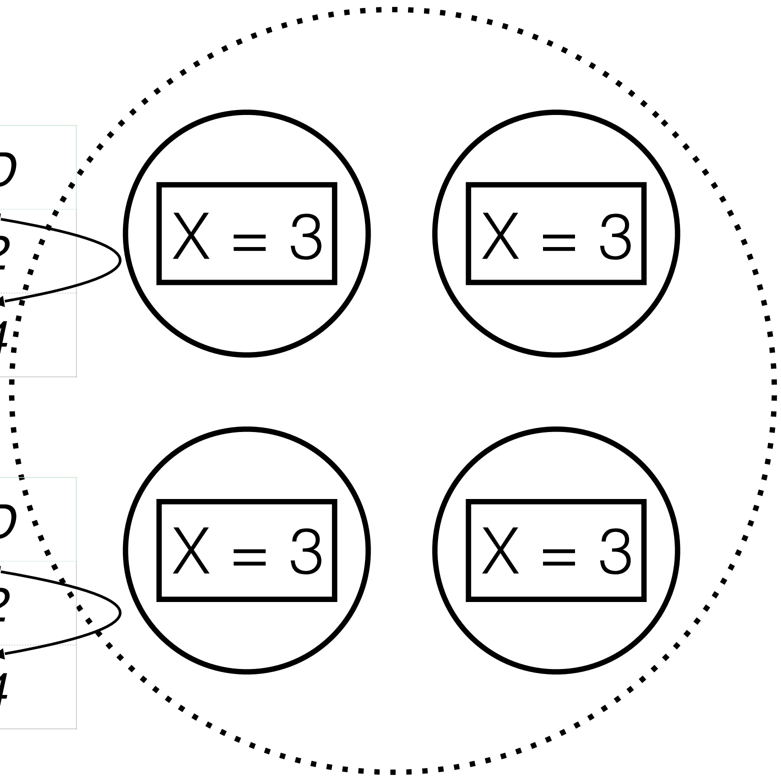
Req.	*CUID*	*UID*
r1	*1.4*	*2.2*
r0	*2.4*	*2.4*

3) Accept ***r1***

Replica ID Generation

Req.	*CUID*	*UID*
r1	*2.1*	*2.2*
r0	*1.1*	*2.4*

Req.	*CUID*	*UID*
r1	*2.2*	*2.2*
r0	*1.2*	*2.4*



Req.	*CUID*	*UID*
r1	*1.3*	*2.2*
r0	*2.3*	*2.4*

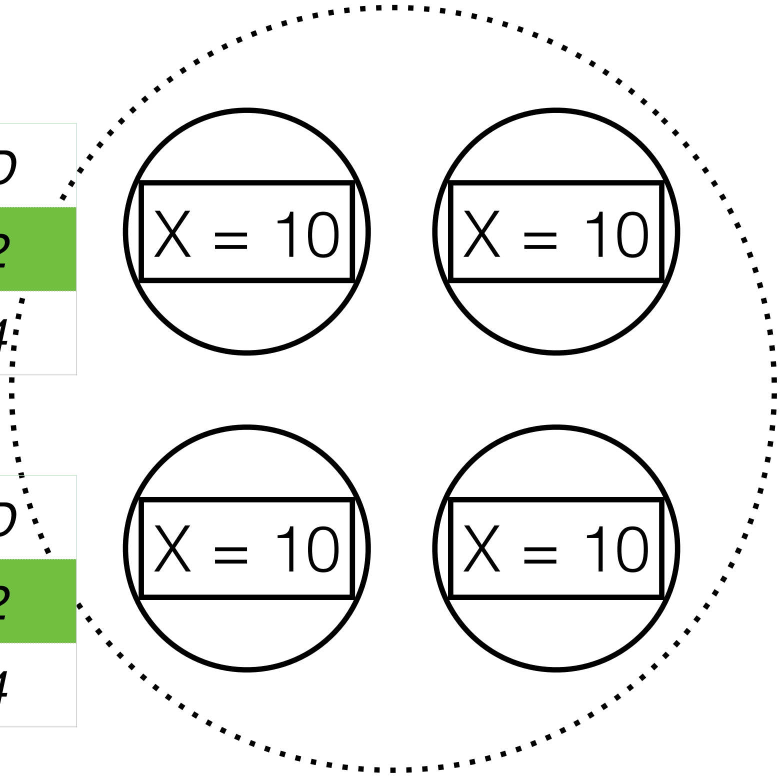
Req.	*CUID*	*UID*
r1	*1.4*	*2.2*
r0	*2.4*	*2.4*

r1 is now stable

Replica ID Generation

Req.	*CUID*	*UID*
r1	*2.1*	*2.2*
r0	*1.1*	*2.4*

Req.	*CUID*	*UID*
r1	*1.3*	*2.2*
r0	*2.3*	*2.4*



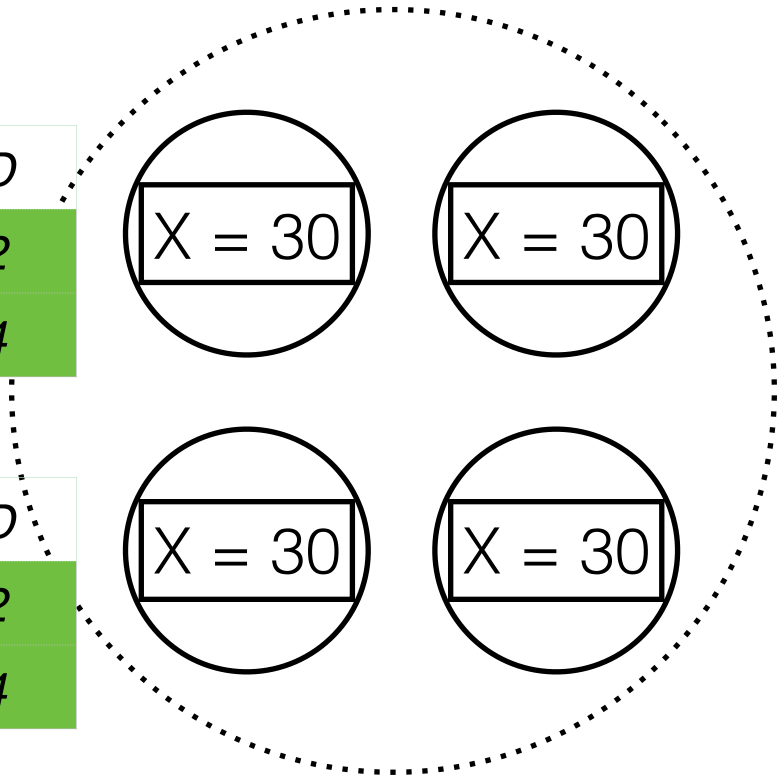
Req.	*CUID*	*UID*
r1	*2.2*	*2.2*
r0	*1.2*	*2.4*

Req.	*CUID*	*UID*
r1	*1.4*	*2.2*
r0	*2.4*	*2.4*

4) Apply ***r1***

Replica ID Generation

Req.	*CUID*	*UID*
r1	*2.1*	*2.2*
r0	*1.1*	*2.4*



Req.	*CUID*	*UID*
r1	*1.3*	*2.2*
r0	*2.3*	*2.4*

Req.	*CUID*	*UID*
r1	*2.2*	*2.2*
r0	*1.2*	*2.4*

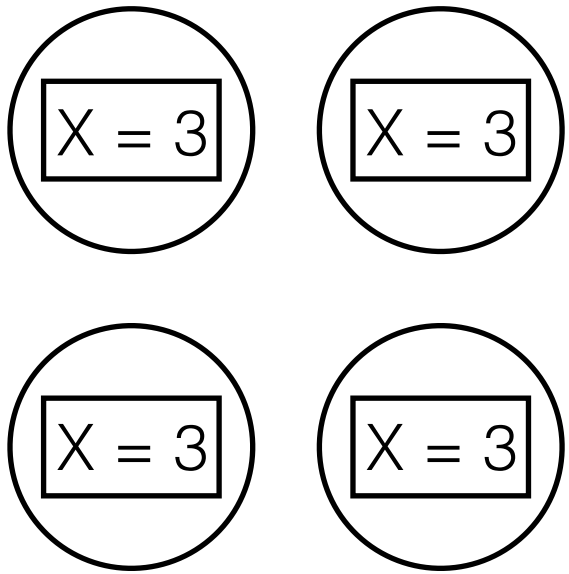
Req.	*CUID*	*UID*
r1	*1.4*	*2.2*
r0	*2.4*	*2.4*

5) Apply ***r0***

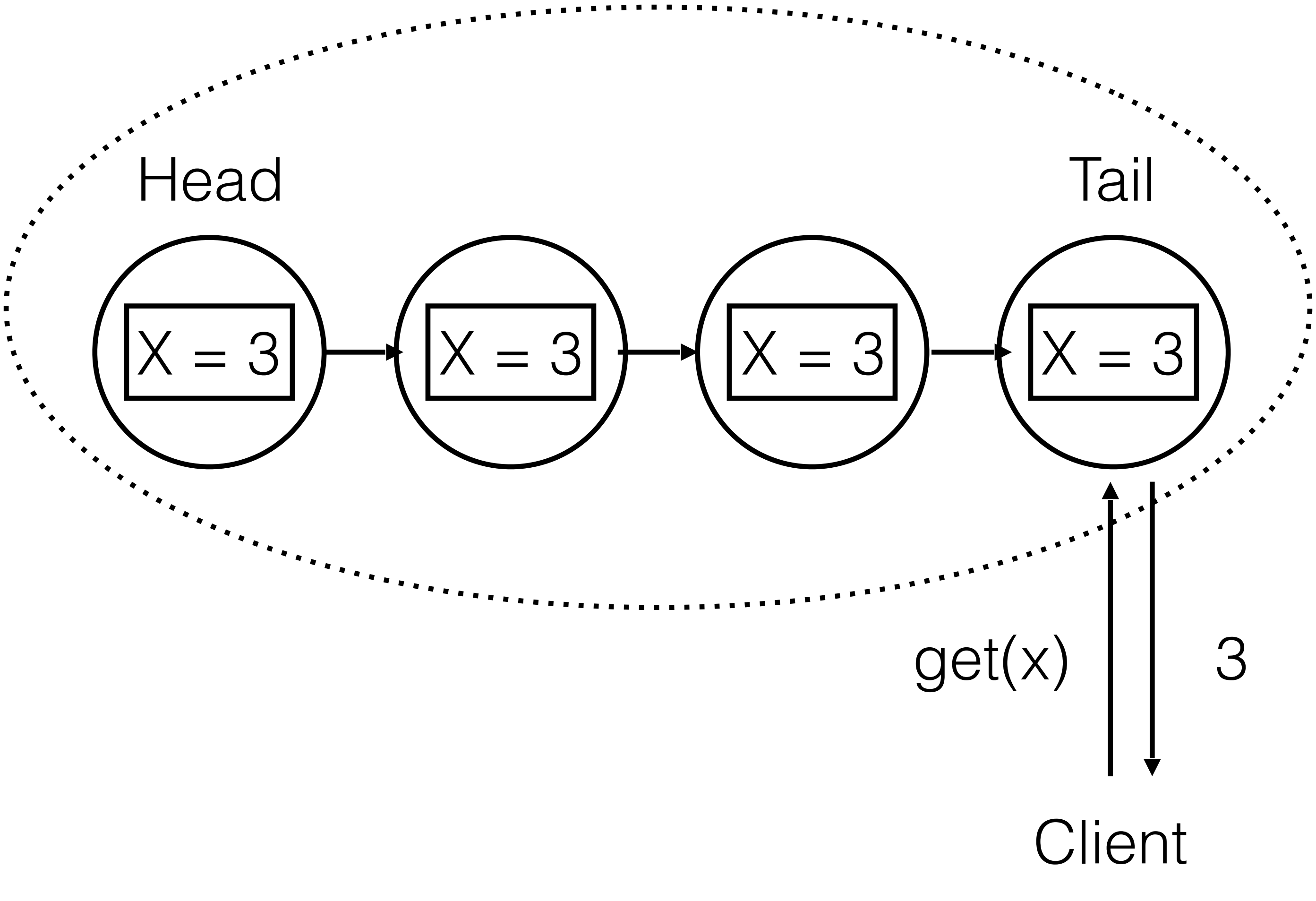
Chain Replication

- Fault Tolerant Storage Service (Fail-Stop)
- Requests:
  - Update(x, y) => set object ***x*** to value ***y***
  - Query(x) => read value of object ***x***

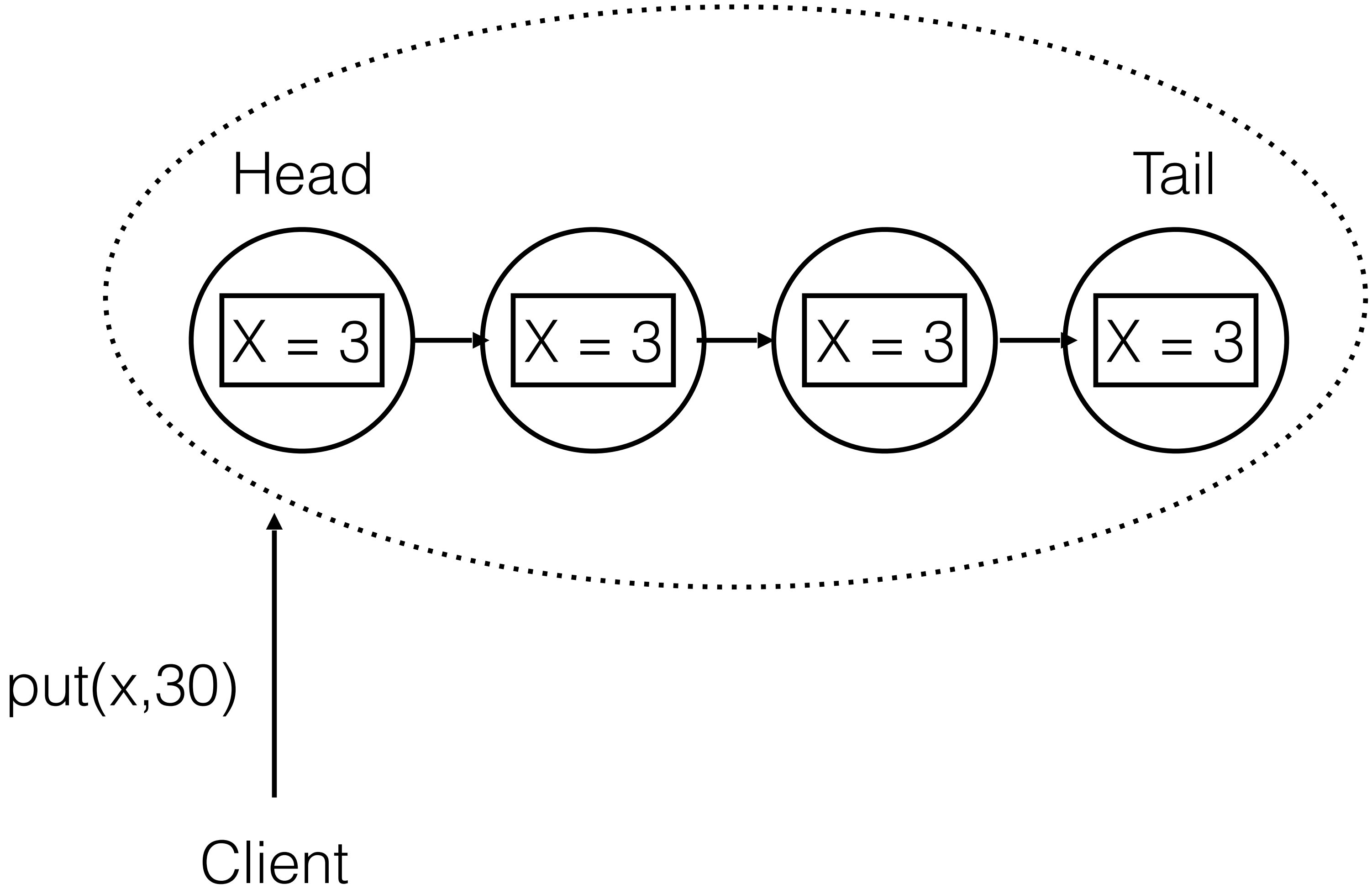
Chain Replication



Chain Replication

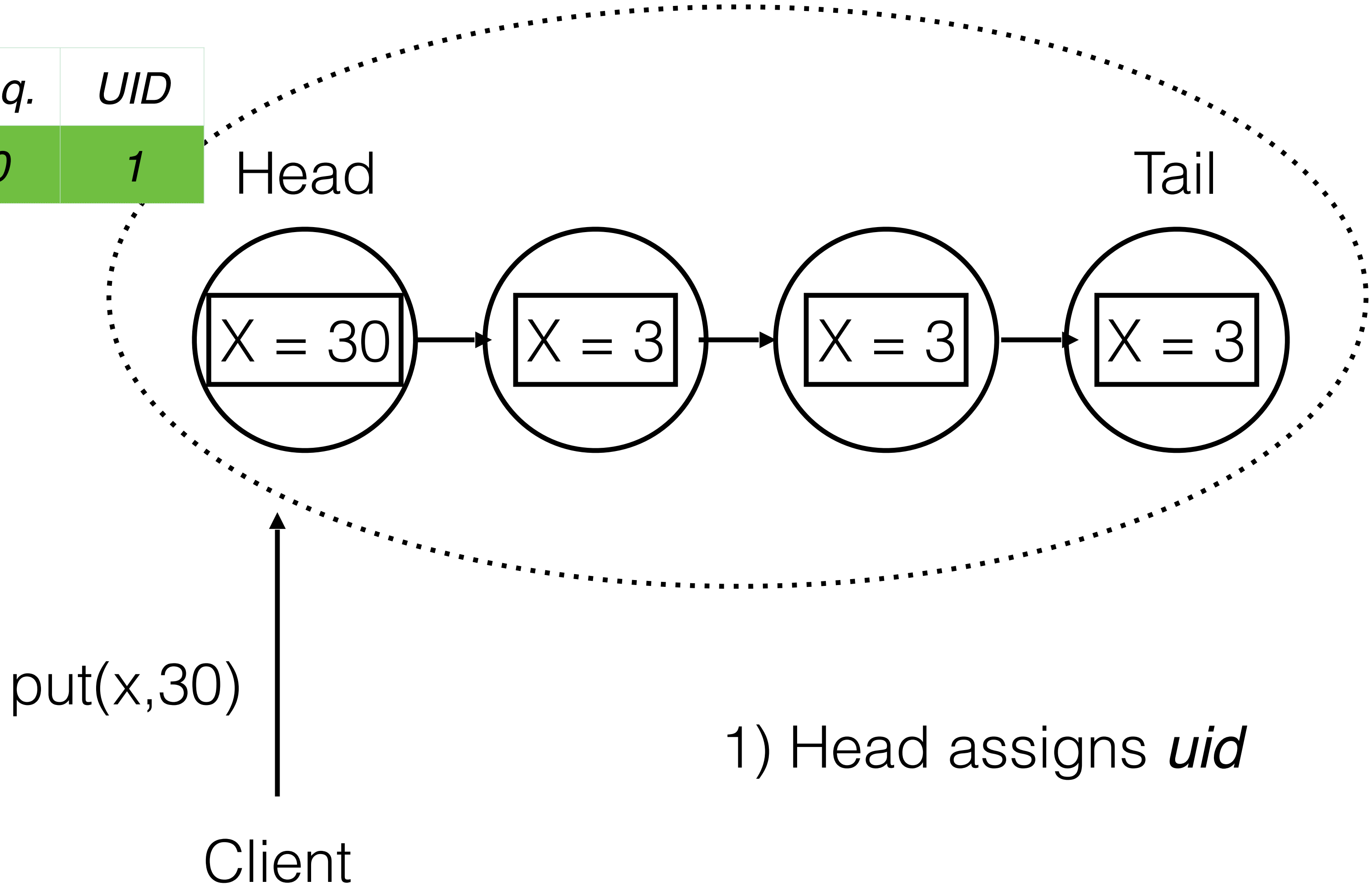


Chain Replication



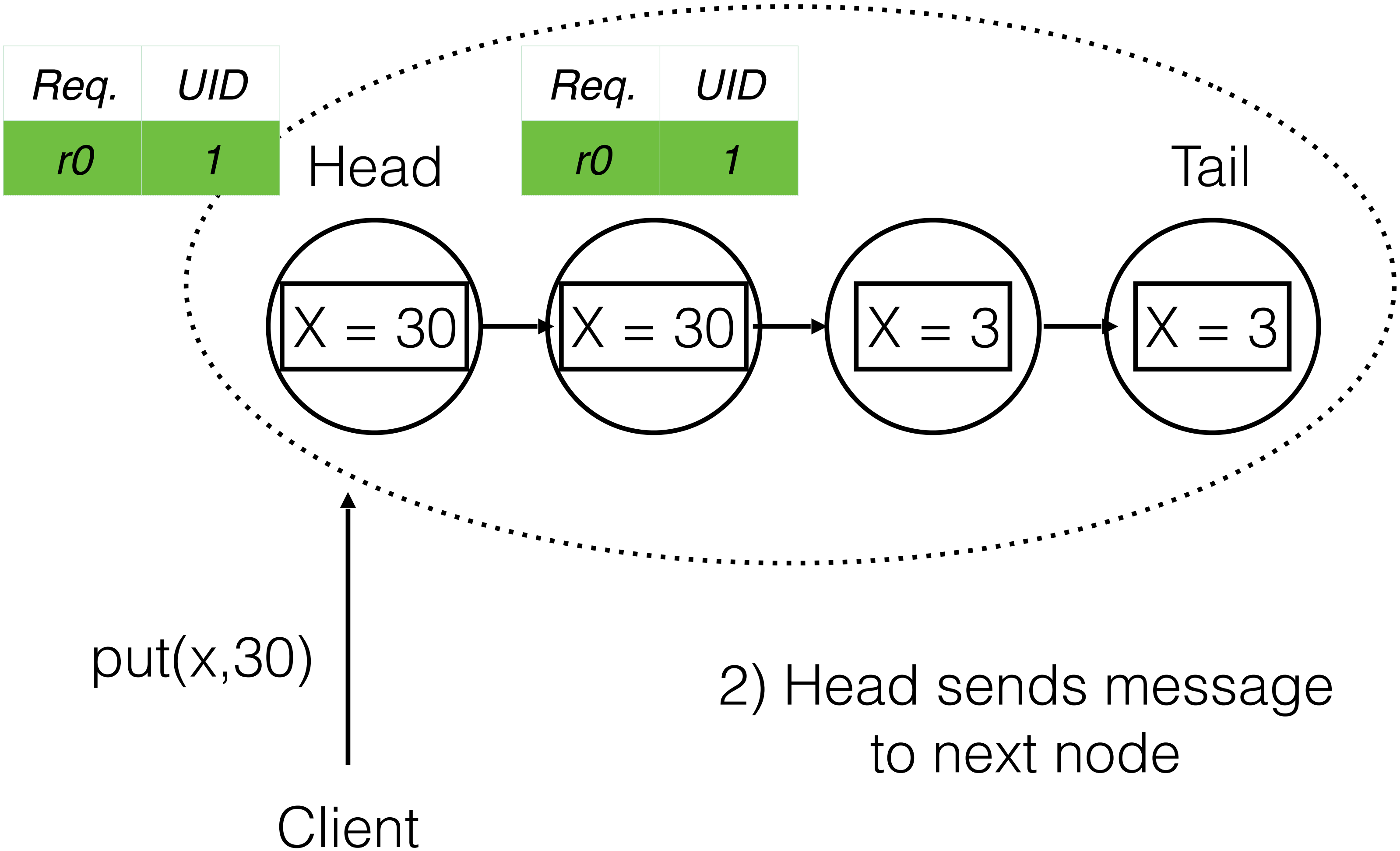
Chain Replication

Req.	*UID*
r0	*1*



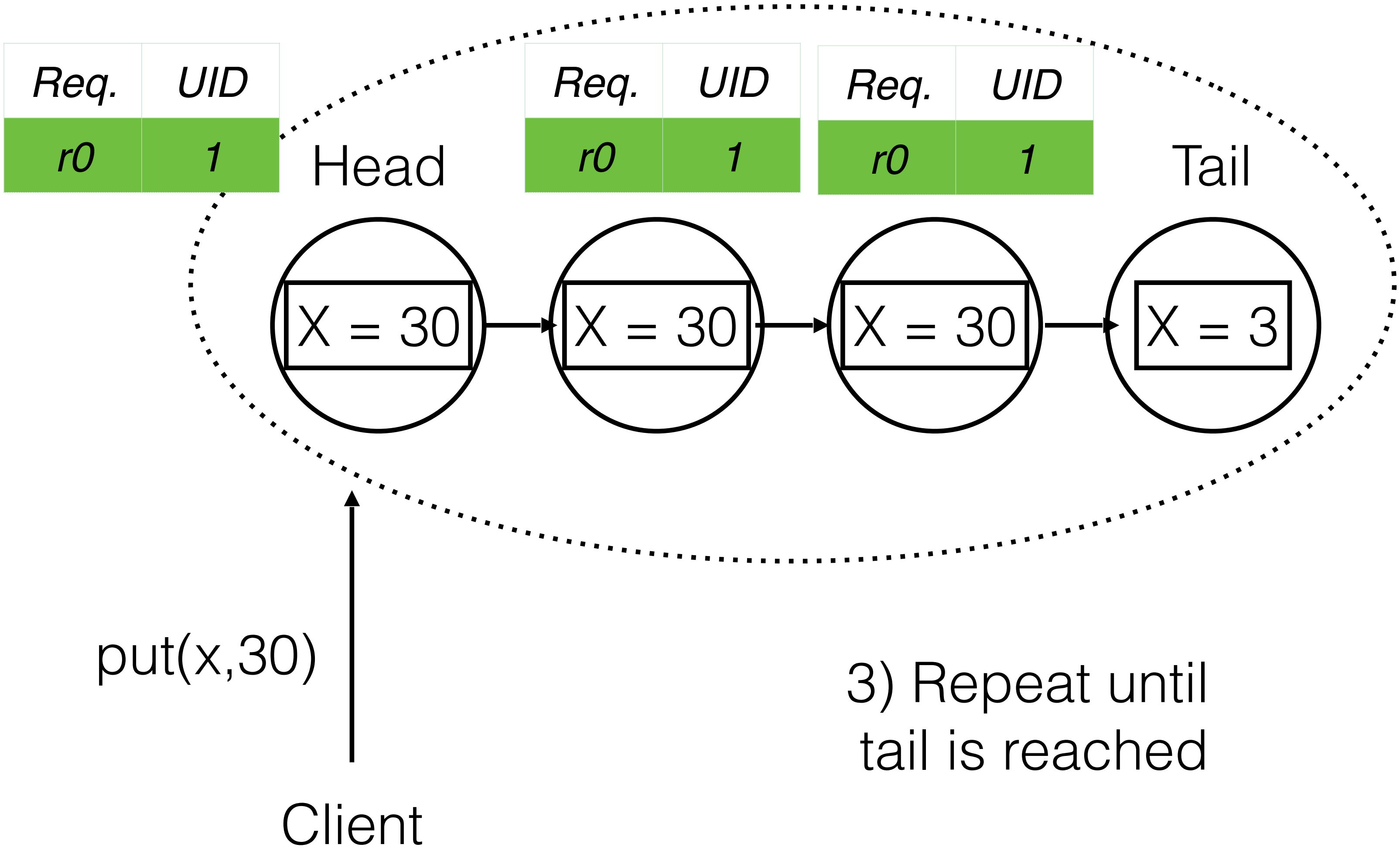
1) Head assigns ***uid***

Chain Replication

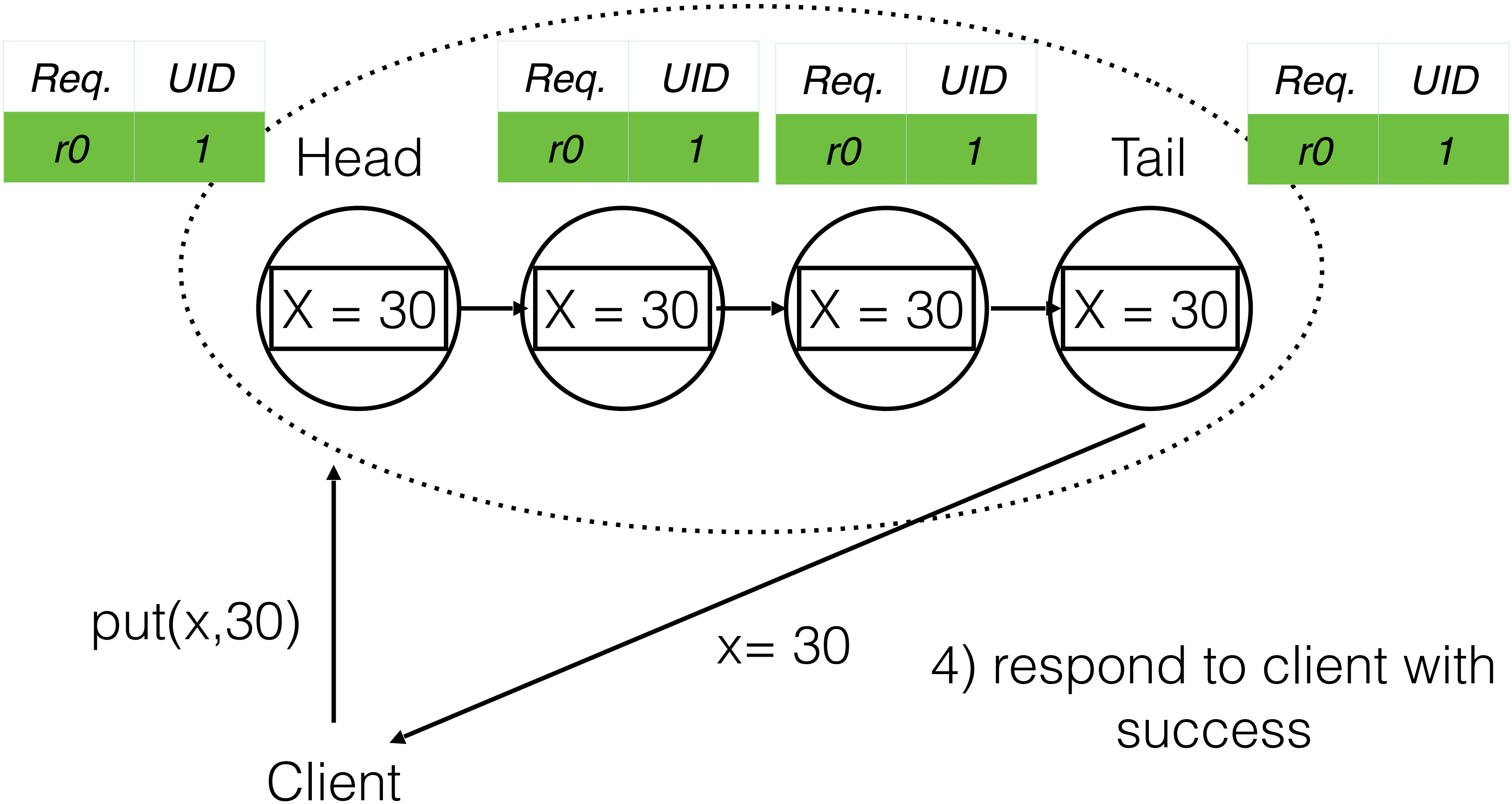


2) Head sends message to next node

Chain Replication



Chain Replication



Chain Replication

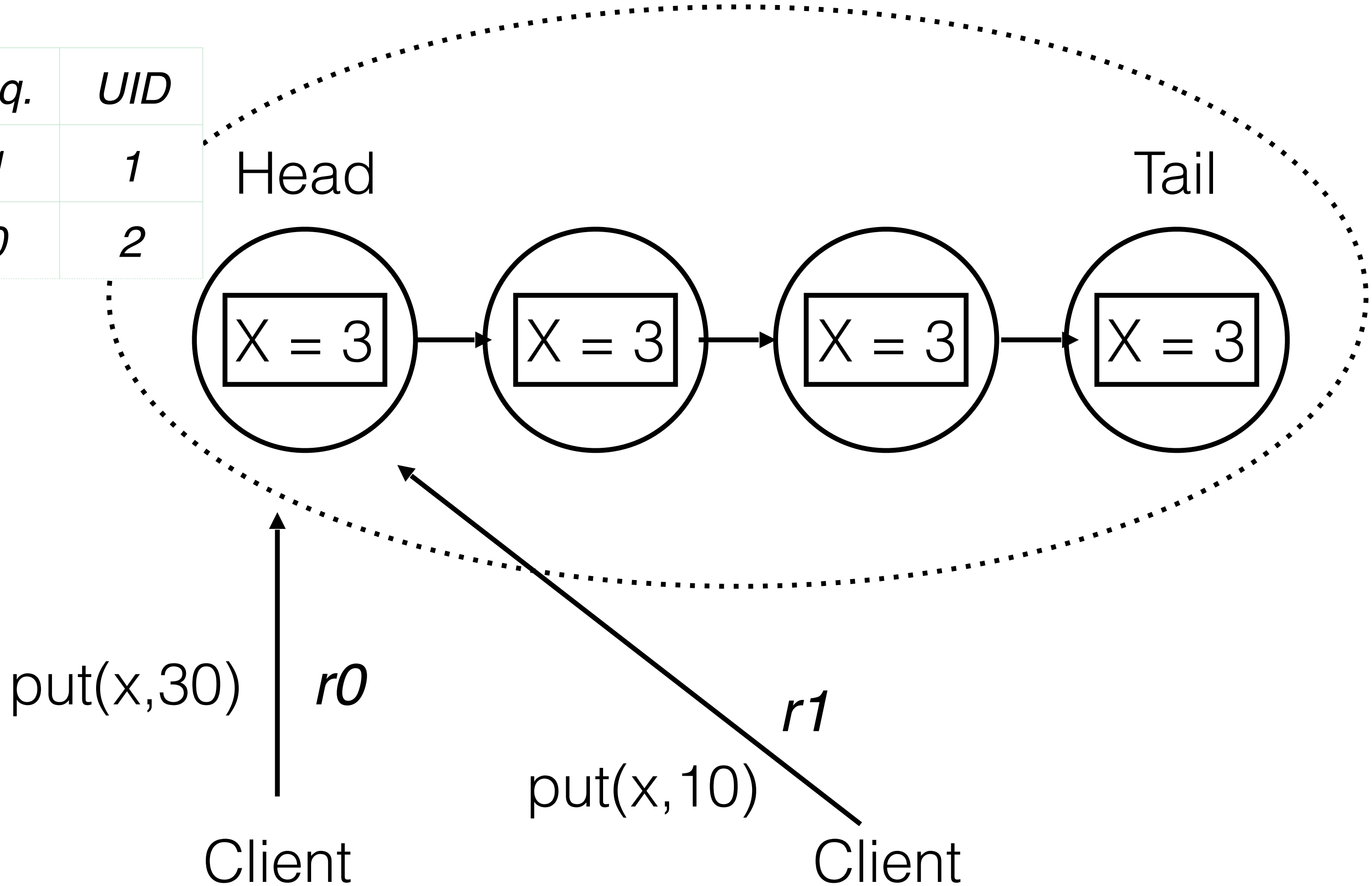
- How does Chain Replication implement State Machine Replication?
- Agreement
  - Only *Update* modifies state, can ignore *Query*
  - Client always sends *update* to *Head*. *Head* propagates request down chain to *Tail*.
  - Everyone accepts the request!

Chain Replication

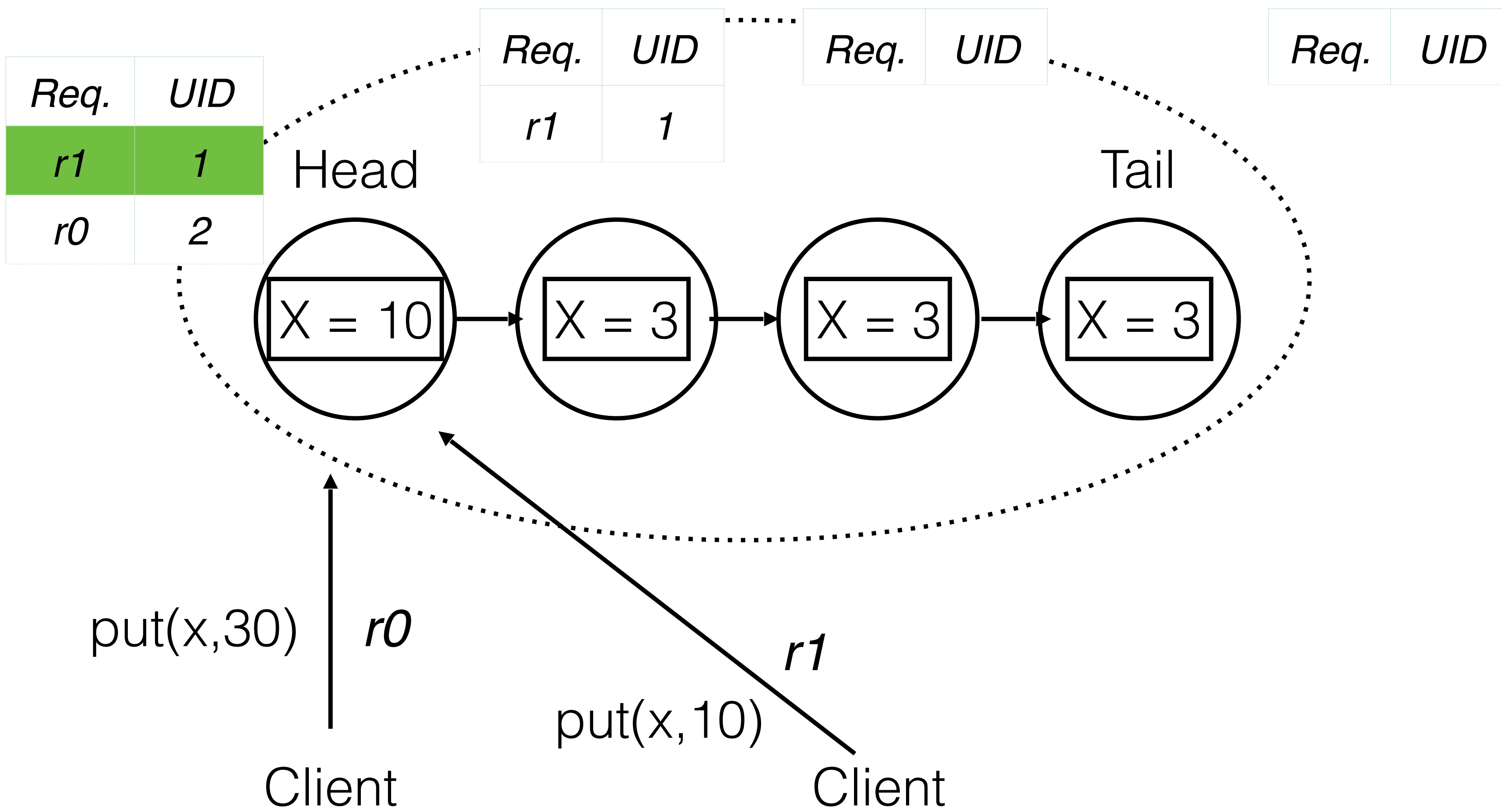
- How does Chain Replication implement State Machine Replication?
- Order
  - Unique IDs generated implicitly by ***Head***'s ordering
  - FIFO order preserved down the chain
  - Tail interleaves ***Query*** requests
  - How can clients tell when their ***Updates*** have been handled?

Chain Replication

Req.	*UID*
r1	*1*
r0	*2*



Chain Replication



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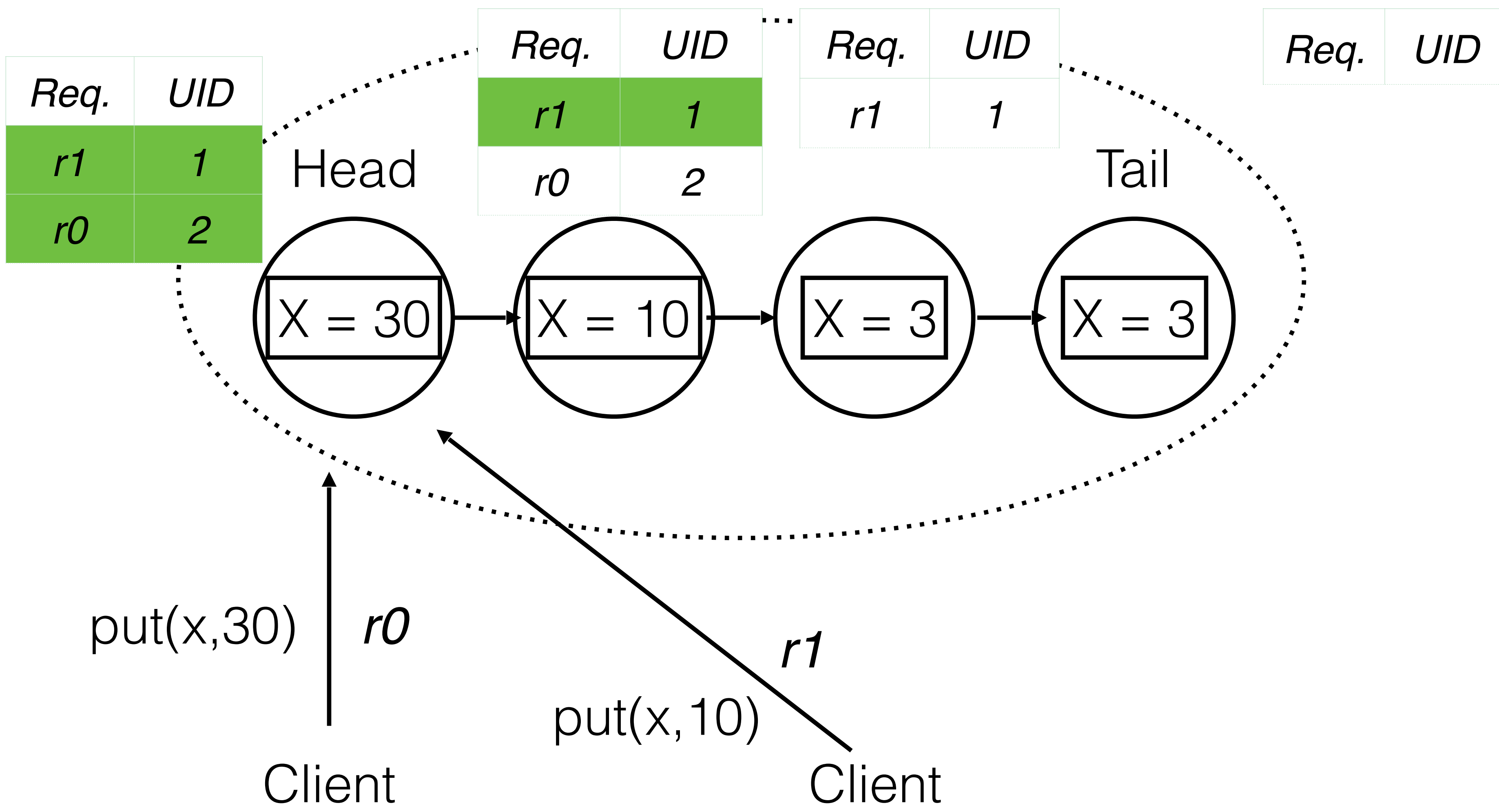
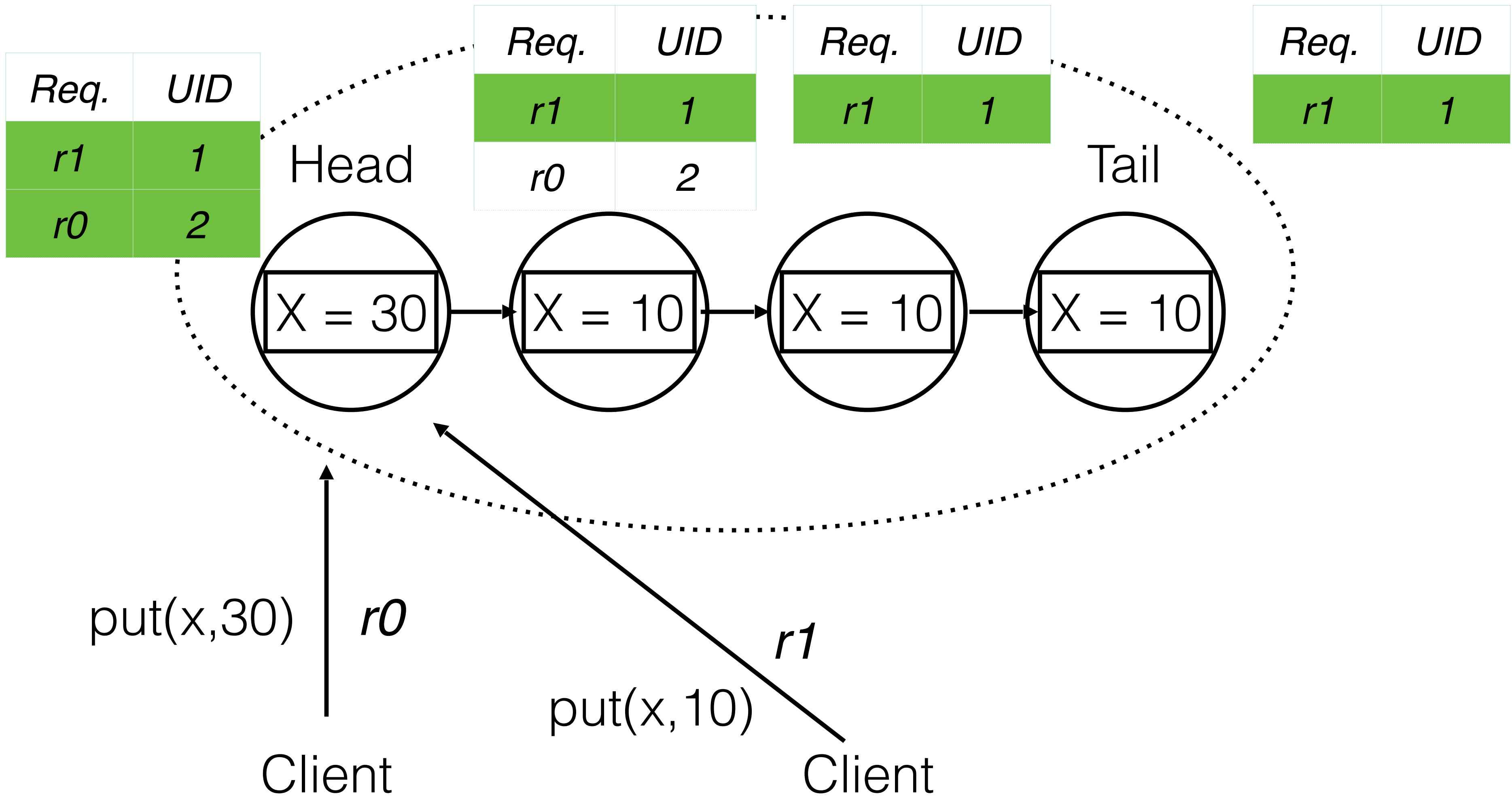


Chain Replication



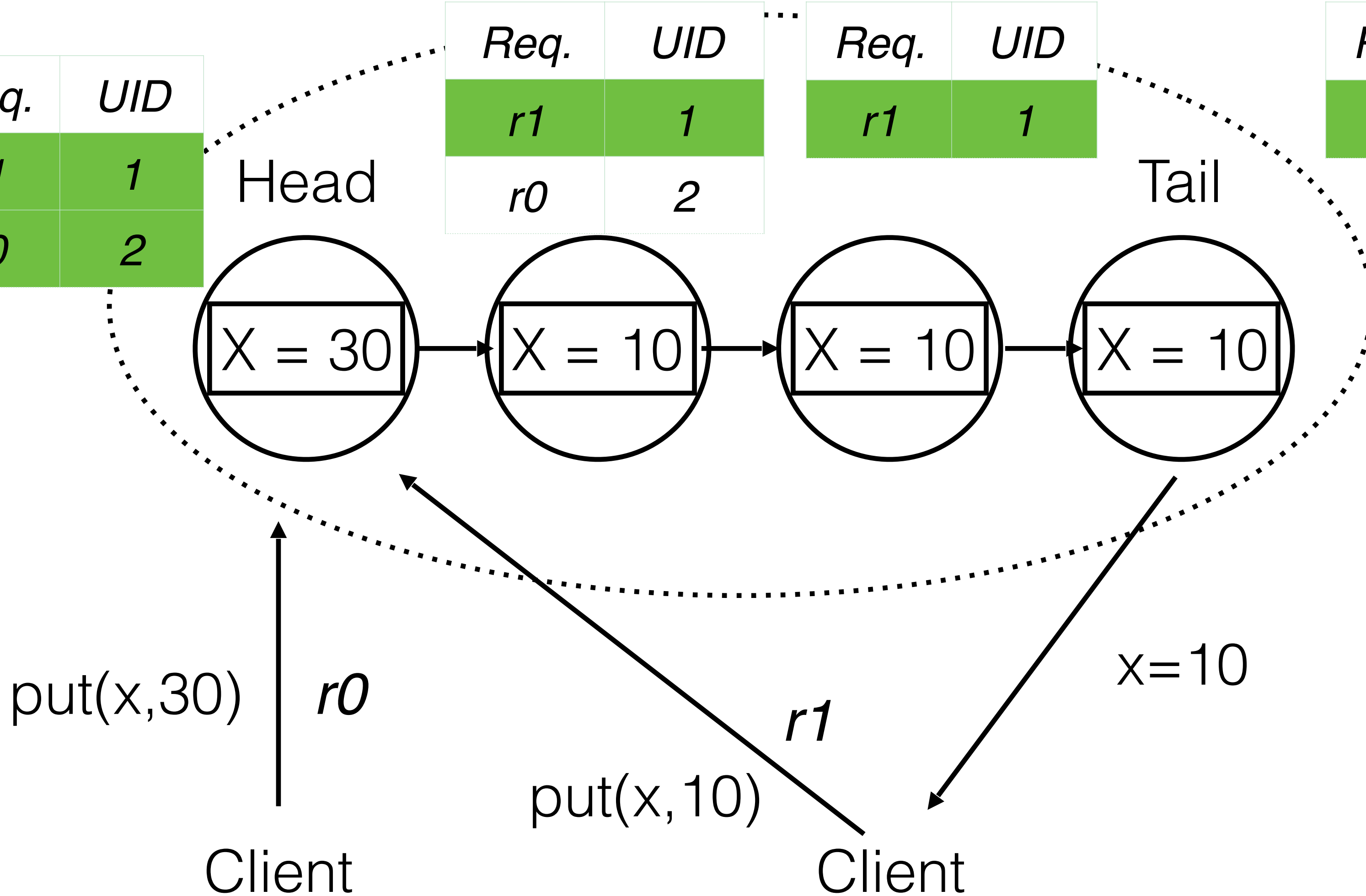
Chain Replication

Req.	*UID*
r1	*1*
r0	*2*

Req.	*UID*
r1	*1*
r0	*2*

Req.	*UID*
r1	*1*

Req.	*UID*
r1	*1*



Fault Tolerance

- Trusted Master
  - Fault-tolerant state machine
  - Trusted by all replicas
  - Monitors all replicas & issues commands
- How can you rely on this trusted master?

Fault Tolerance

- Failure cases:
  - Head Fails
    - *Master* assigns 2nd node as Head
  - Tail Fails
    - *Master* assigns 2nd to last node as Tail
  - Intermediate Node Fails
    - *Master* coordinates chain link-up

Chain Replication Evaluation

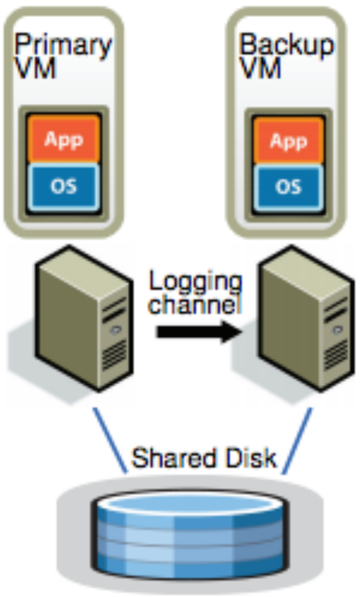
- Compare to other primary/backup protocols
- Tradeoffs?
  - Latency
  - Consistency
- *Trusted Master*

VMware's FT Virtual Machines

- Whole-system replication
- Completely transparent to applications and clients
- High availability for any existing software
- Failure model:
  - independent hardware faults
  - site-wide power failure
- Limited to uniprocessor VMs

Overview

- two machines, primary and backup
- shared-disk for persistent storage
- back-up in "lock step" with primary
    - primary sends all inputs to backup
    - outputs of backup are dropped
- heart beats between primary and backup
    - if primary fails, start backup executing!



Challenges

- Making it look like a single reliable server
- How to avoid two primaries? (“split-brain syndrome")
- How to make backup an exact replica of primary
- What inputs must be sent to backup?
- How to deal with non-determinism?

Technique 1: Deterministic Replay

- Goal: make x86 platform deterministic
  - idea: use hypervisor to make virtual x86 platform deterministic
- Log all hardware events into a log
  - clock interrupts, network interrupts, i/o interrupts, etc.
  - for non-deterministic instructions, record additional info
    - e.g., log the value of the time stamp register
    - on replay: return the value from the log instead of the actual register

Deterministic Replay

- Replay: deliver inputs in the same order, at the same instructions
  - if during recording delivered clock interrupt at nth instr.
  - during replay also deliver the interrupt at the nth instr.
- Given an event log, deterministic replay recreates VM
  - hypervisor delivers first event
  - lets the machine execute to the next event
  - using special hardware registers to stop the processor at the right instruction
  - OS runs identical, applications runs identical
- Limitation: cannot handle multicore processors and interleaving

Applying Deterministic Replay to VM-FT

- Hypervisor at primary records
  - Sends log entries to backup over logging channel
- Hypervisor at backup replays log entries
  - We need to stop virtual x86 at instruction of next event
  - We need to know what is the next event
  - backup lags behind one event

Example

- Primary receives network interrupt
  - hypervisor forwards interrupt plus data to backup
  - hypervisor delivers network interrupt to OS kernel
  - OS kernel runs, kernel delivers packet to server
  - server/kernel write response to network card
  - hypervisor gets control and puts response on the wire
- Backup receives log entries
  - backup delivers network interrupt
  - …
  - hypervisor does *not* put response on the wire
  - hypervisor ignores local clock interrupts

Technique 2: FT Protocol

- Primary delays any output until the backup acks
  - Log entry for each output operation
  - Primary sends output after backup acked receiving output operation
- Performance optimization:
  - primary keeps executing past output operations
  - buffers output until backup acknowledges

Questions

- Why send output events to backup and delay output until backup has acked?
- What happens when primary fails after receiving network input but before sending a corresponding log entry to backup?