Fault-Tolerant State Machine Replication

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Slides borrowed from Hakim Weatherspoon and Drew Zagieboylo

Authors

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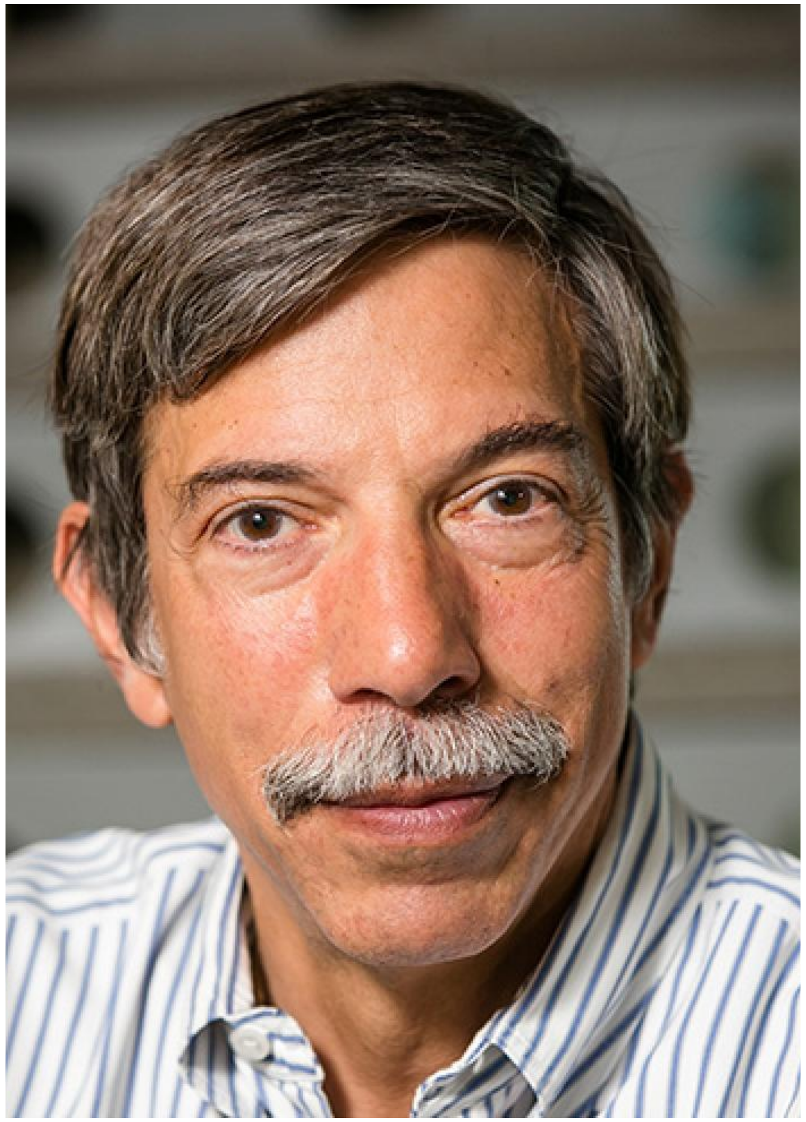
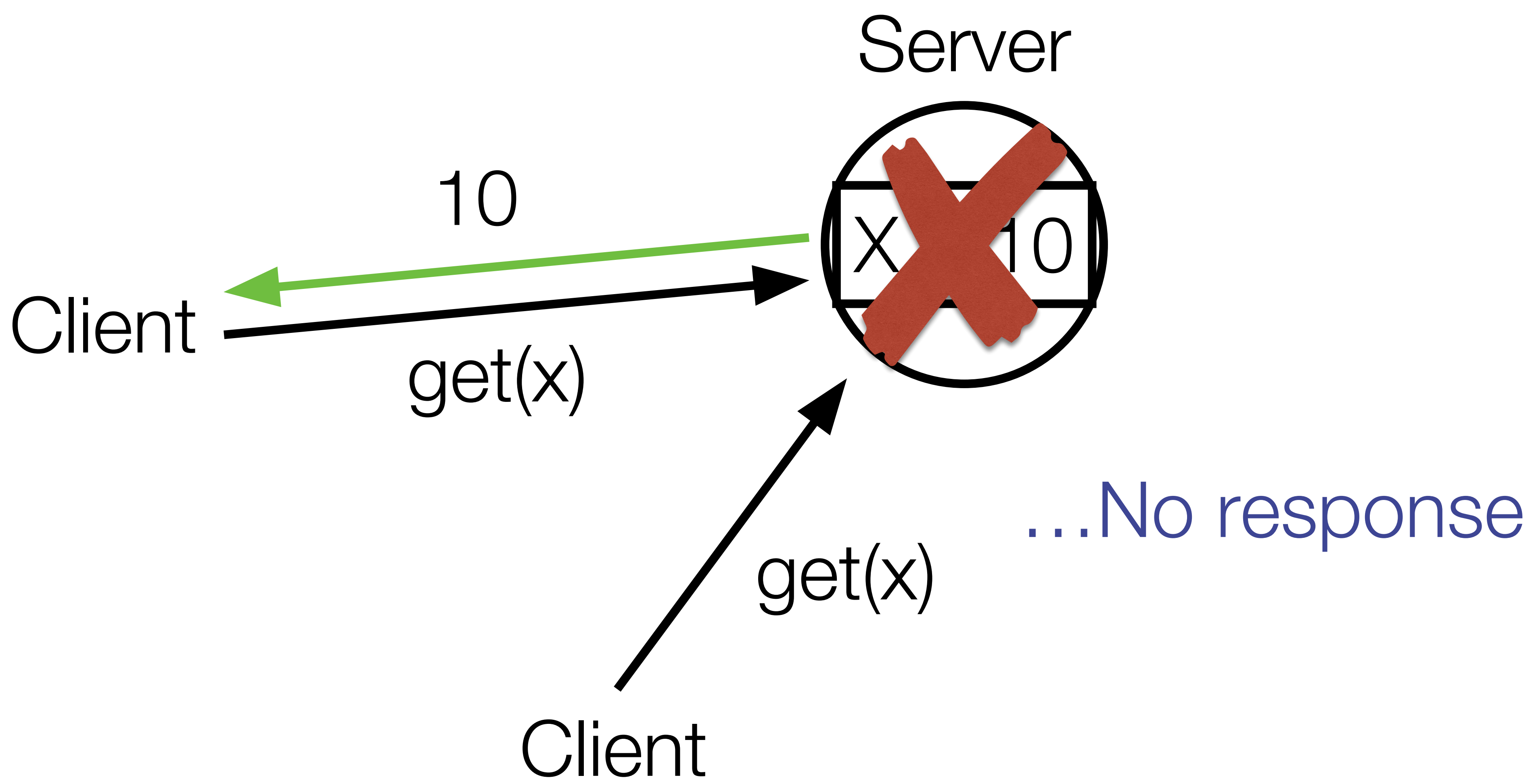


Outline

- Motivation
- State Machine Replication Approach
- Implementation
- Fault Tolerance
- Chain Replication
- Conclusions

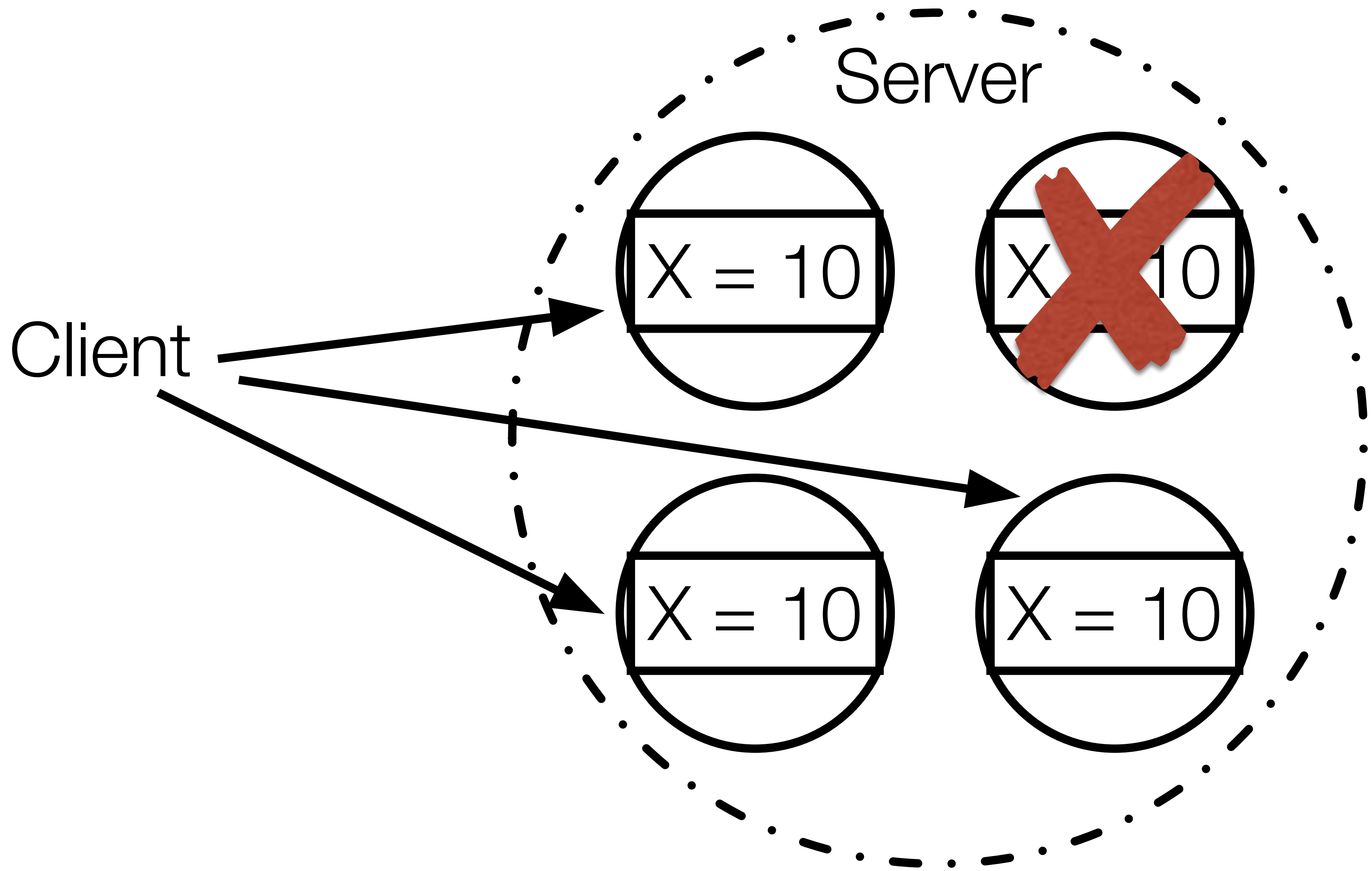
Motivation



Motivation

- Need replication for fault tolerance
- **What happens in scenarios without replication?**
  - Storage - Disk Failure
  - Web service - Network failure
- **Be able to reason about failure tolerance**
  - How badly can things go wrong and have our system continue to function?

Motivation



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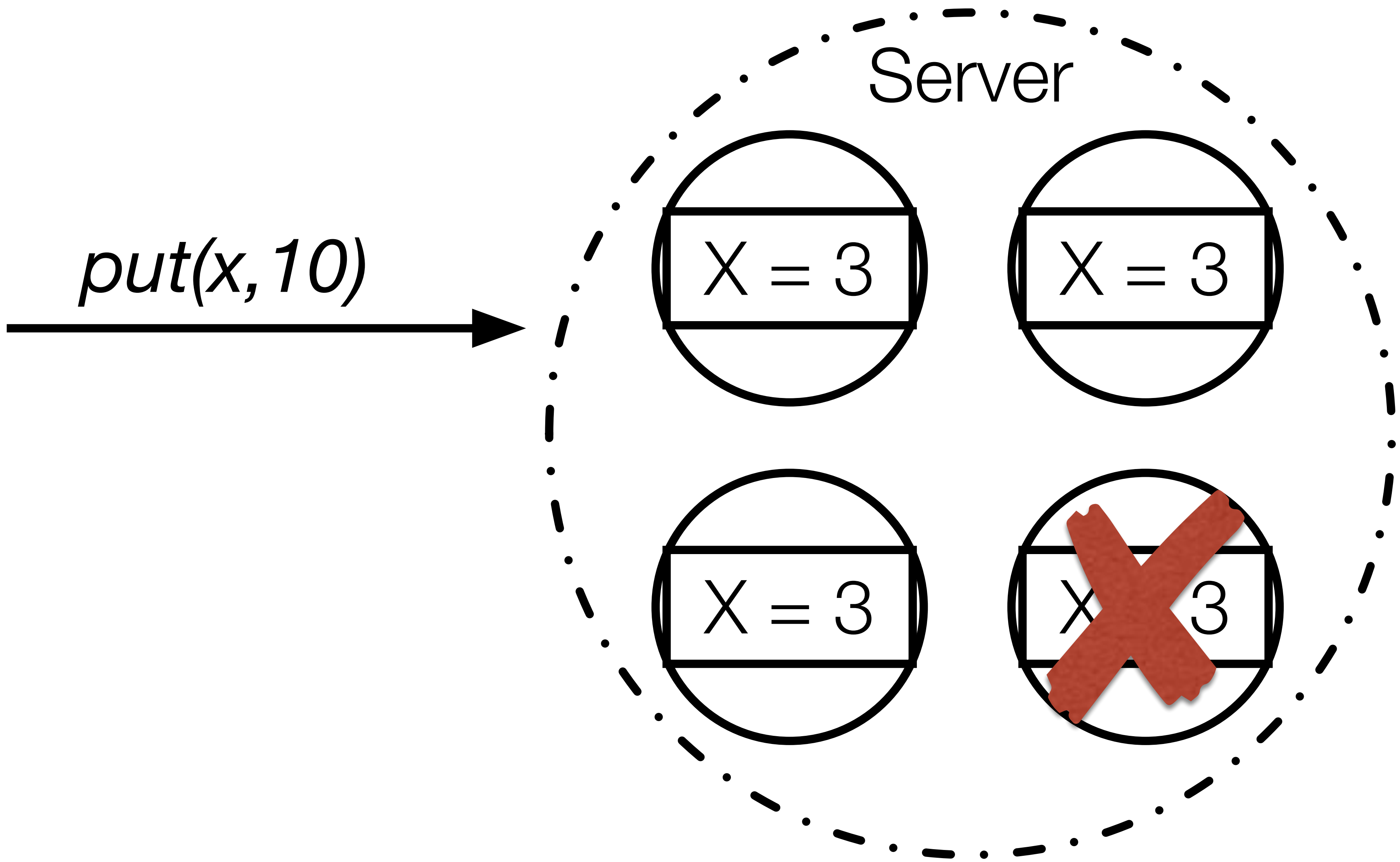
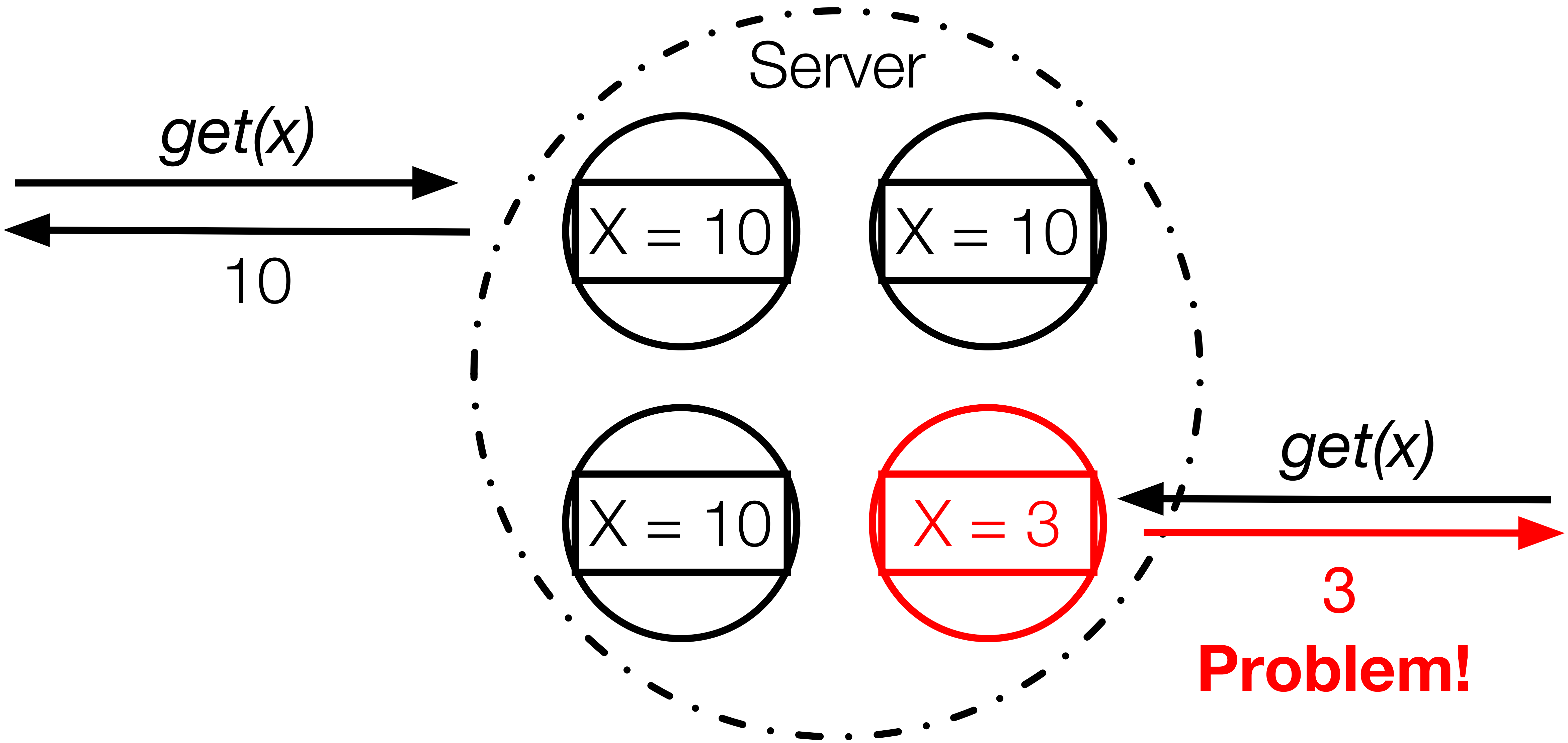


Motivation



Problem

How can we ensure that all replicas are in the same state all of the time?

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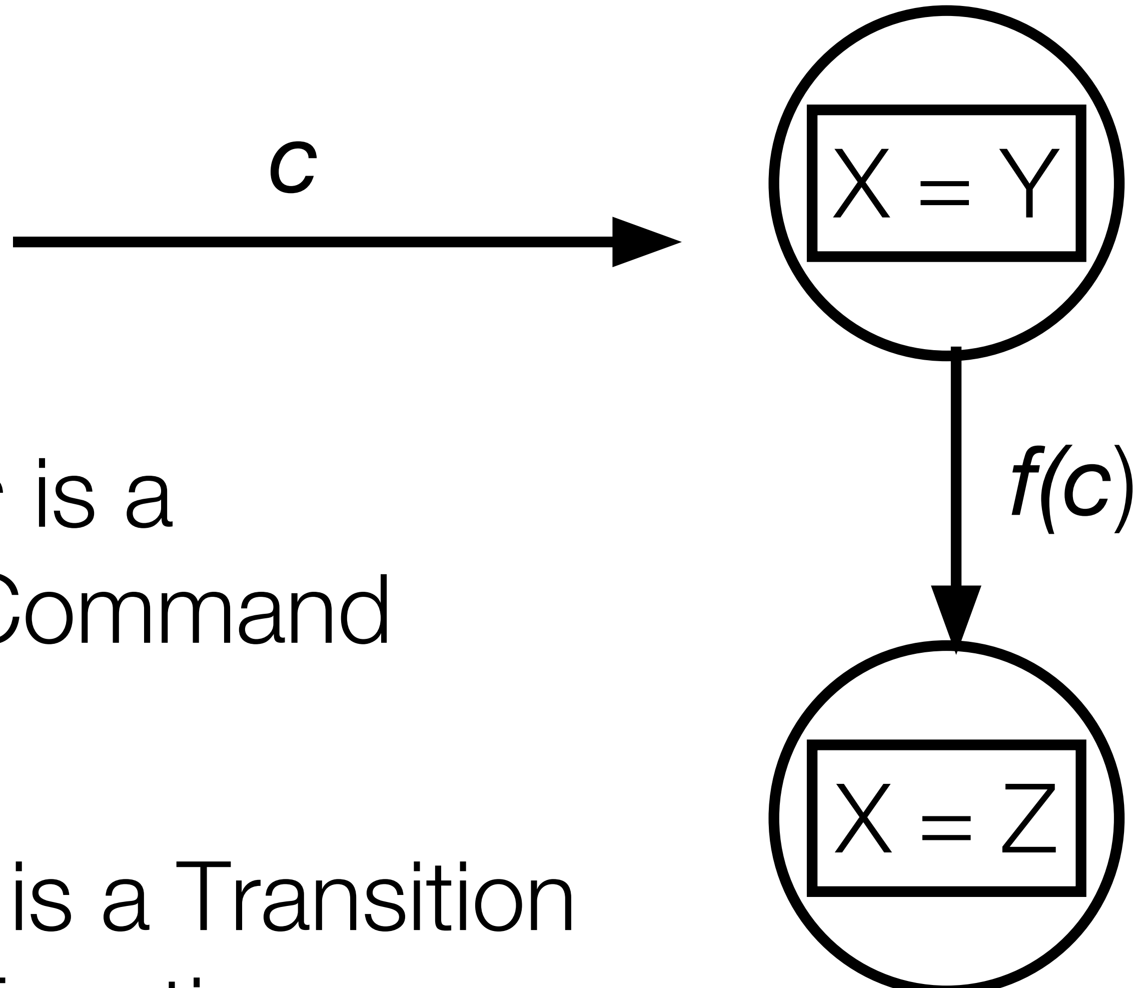
State Machines



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

State Machine Coding

- State machines are procedures
- Client calls procedure
- Avoid loops
- Flexible structure

State Machine Replication

- Each starts in the same initial state
- Executes the same requests
- Requires <u>consensus</u> to execute in same order
- Deterministic, each will do the exact same thing
- Produce the same output

State Machine Replication

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

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Implementation

Agreement

- Transmitter proposes a request; if it is non-faulty all servers will accept that request
- Transmitter can be client or server
- Client or Server can propose the request

Implementation

Agreement

- IC1: All non-faulty processors agree on the same value
- IC2: If transmitter is non-faulty, agree on its value

Ordering

"The Order requirement can be satisfied by assigning unique identifiers to requests and having state machine replicas process requests according to a total ordering relation on these unique identifiers."

Implementation

- **Order**
  - Assign unique ids to requests and process them in ascending order.
  - How do we assign unique ids in a distributed system?

Implementation
Client Generated IDs

Ordering via clocks

- Logical Clocks
- Synchronized Clocks

- Ideas from last class! [Lamport 1978]

Can the replicas generate unique identifiers?

Of course!

Implementation
Replica Generated IDs

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

Implementation
Replica Generated IDs

- When do we know a candidate is ***stable?***
  - A candidate is ***accepted***
  - No other pending requests with smaller candidate ids

Stability Testing

- Stability tests for logical and synchronized clocks?
- **Disadvantages**
  - Stability tests require all nodes to communicate
    - Logical: stabilizing requests
    - Synchronized: clock synchronization

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When does behavior become faulty?

When it's no longer consistent with specification!

Fault Tolerance

- **Fail-Stop**
  - A faulty server can be detected as faulty
- **Crash Failures**
  - Server can stop responding without notification (subset of Byzantine)
- **Byzantine**
  - Faulty servers can do arbitrary, perhaps malicious things

Fault Tolerance

- **Fail-Stop Tolerance**
  - To tolerate *t* failures, need *t+1* servers.
  - As long as 1 server remains, we're OK!
  - Only need to participate in protocols with other *live* servers

Fault Tolerance

Byzantine Failures

To tolerate *t* failures, need *2t + 1* servers

- Protocols now involve votes
  - Can only trust server response if the majority of servers say the same thing
- *t + 1* servers need to participate in replication protocols

Takeaways

- Can represent ***deterministic*** distributed system as *Replicated State Machine*
- Each replica reaches the same conclusion about the system ***independently***
- Formalizes notions of fault-tolerance in *SMR*

Discussion

- Why is State Machine Replication so important?
- What is the best case scenario in terms of replications for fault tolerance?
- Is the state machine approach still feasible?

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Chain Replication

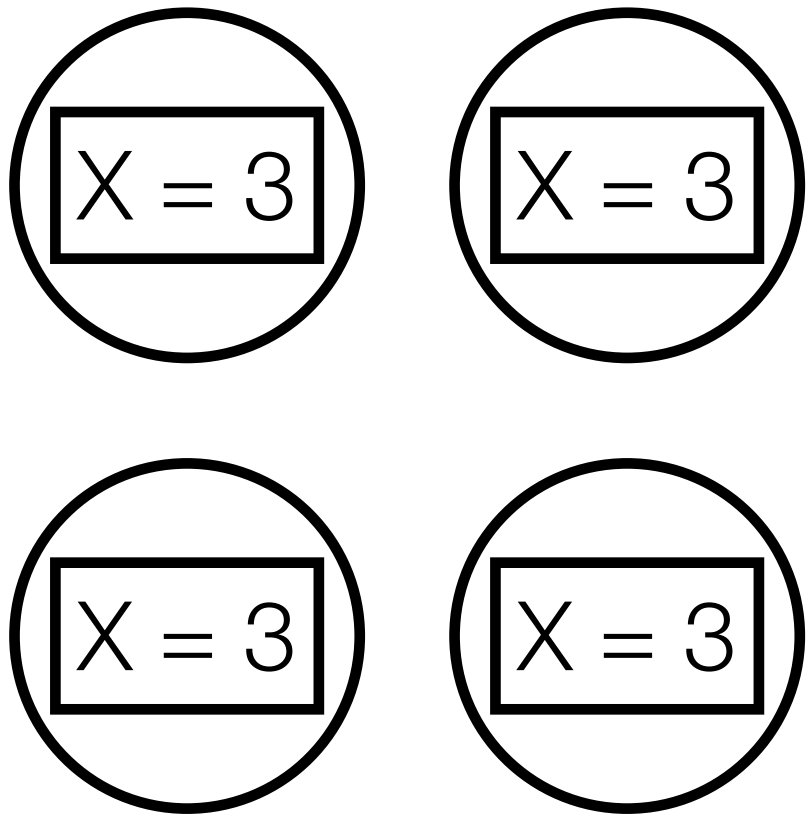
Authors

- Robert Van Renesse
  - Senior Researcher at Cornell
  - ACM Fellow and Ukelele enthusiast
  - Systems and Networking
- Fred Schneider

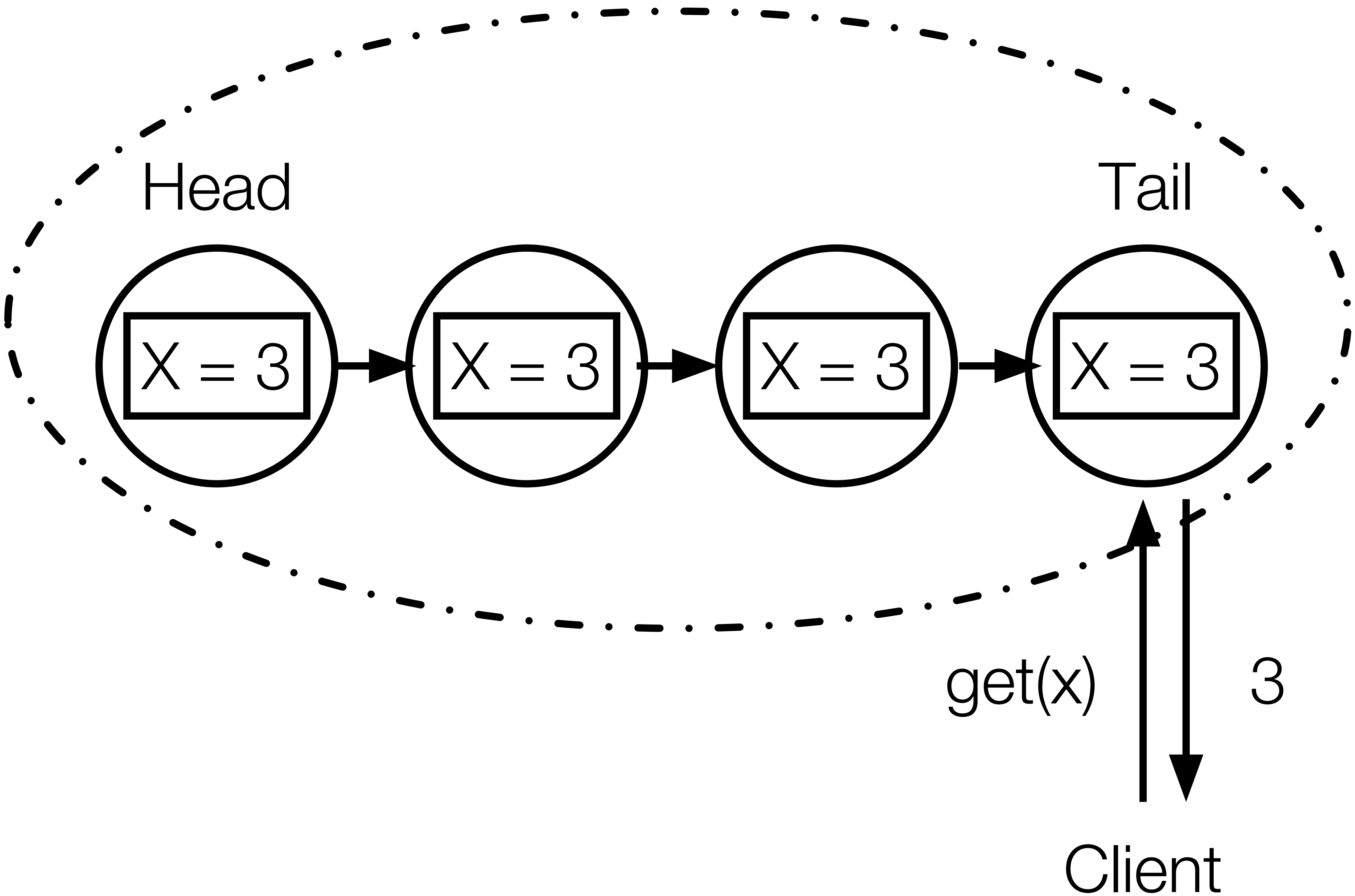
Chain Replication

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

Chain Replication



Chain Replication



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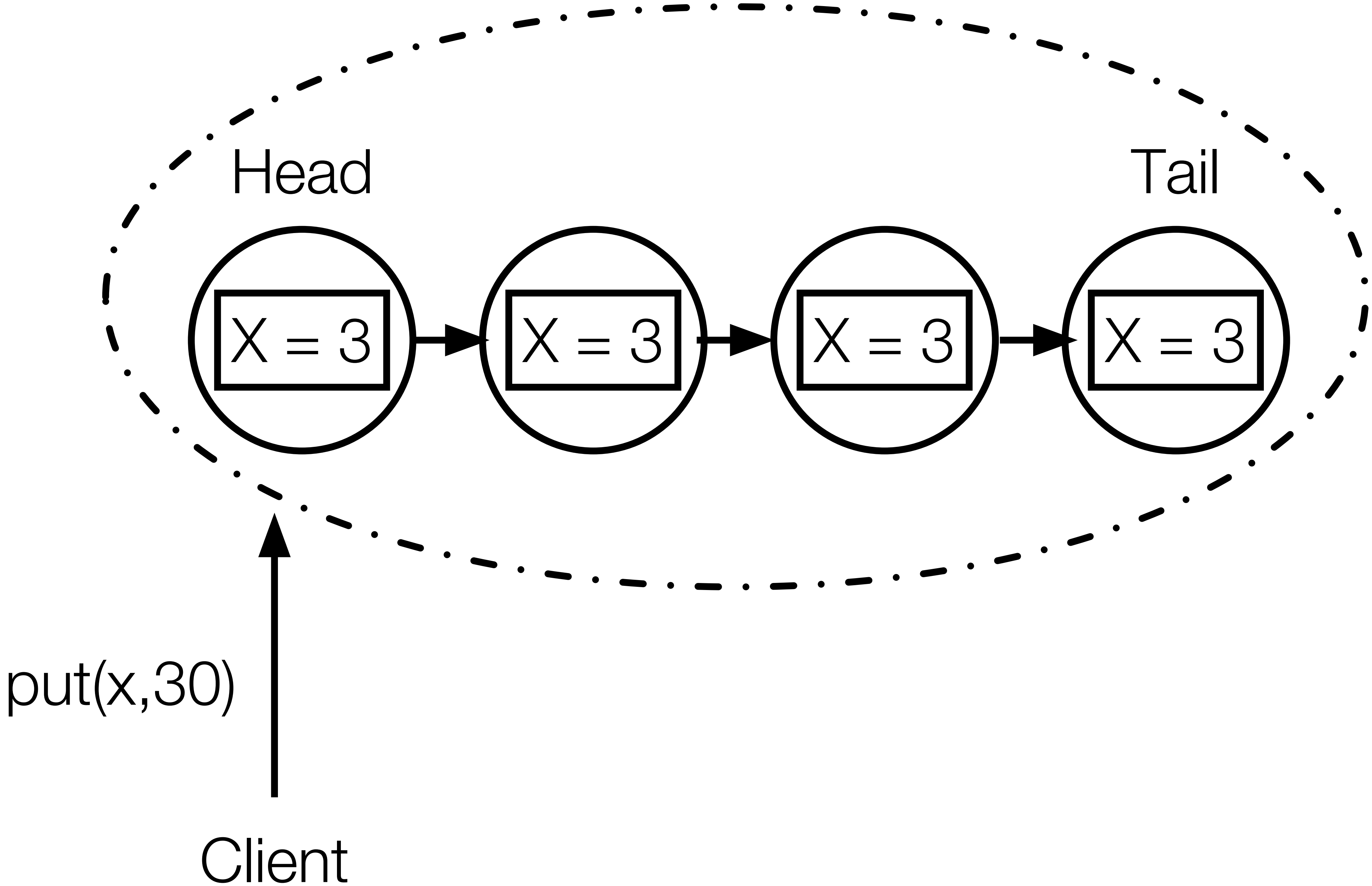
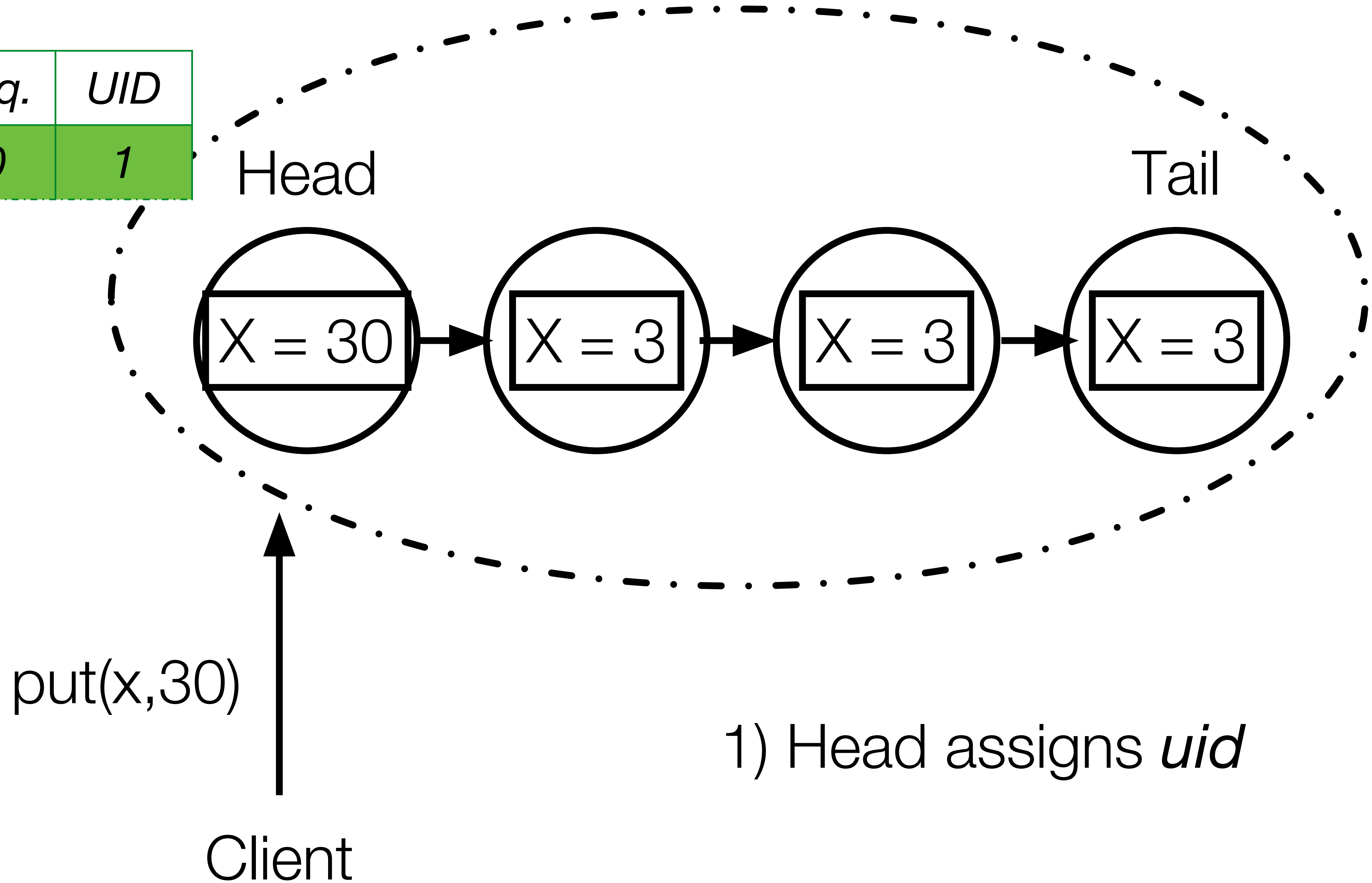


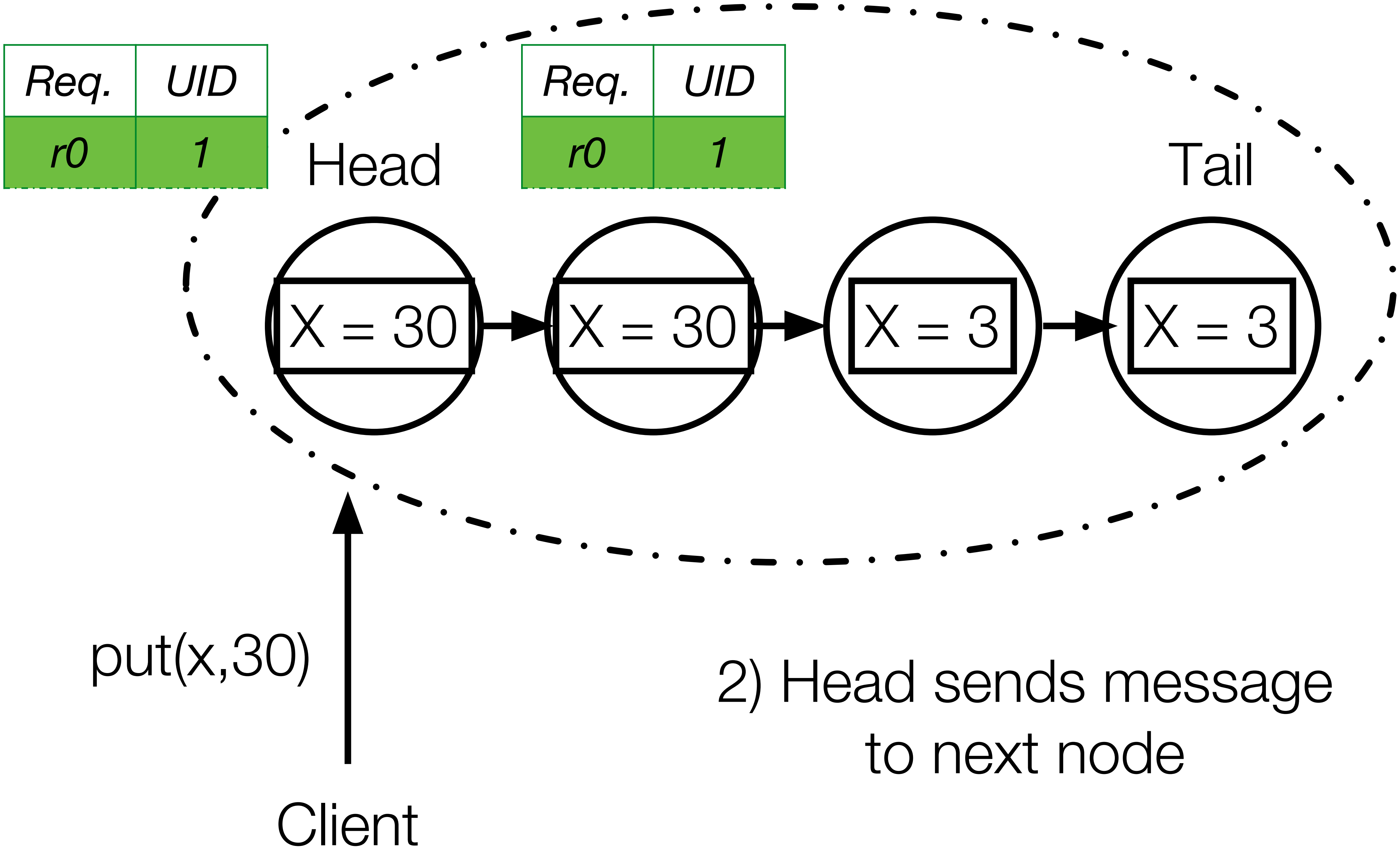
Chain Replication

Req.	UID
r0	*1*



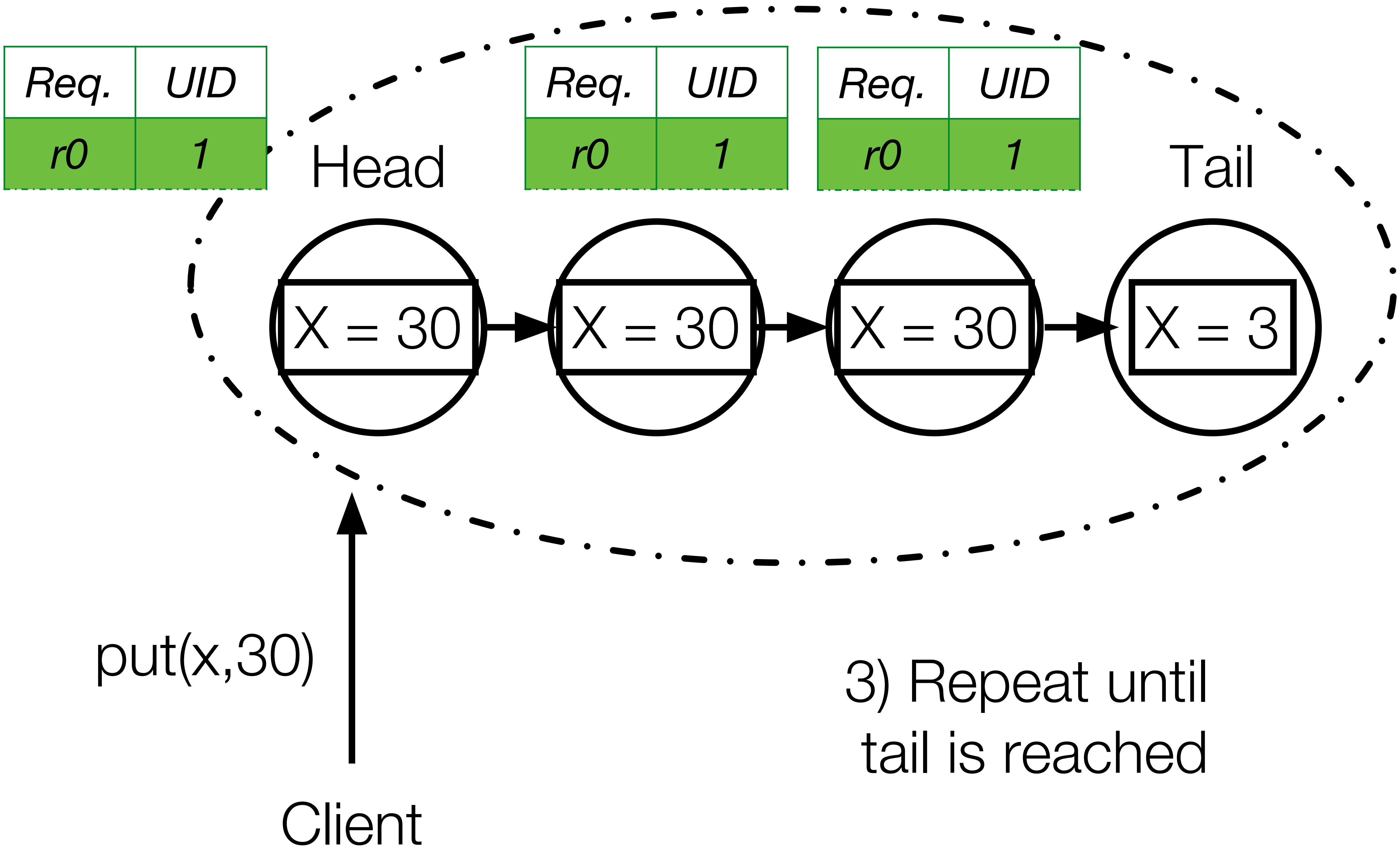
1) Head assigns *uid*

Chain Replication



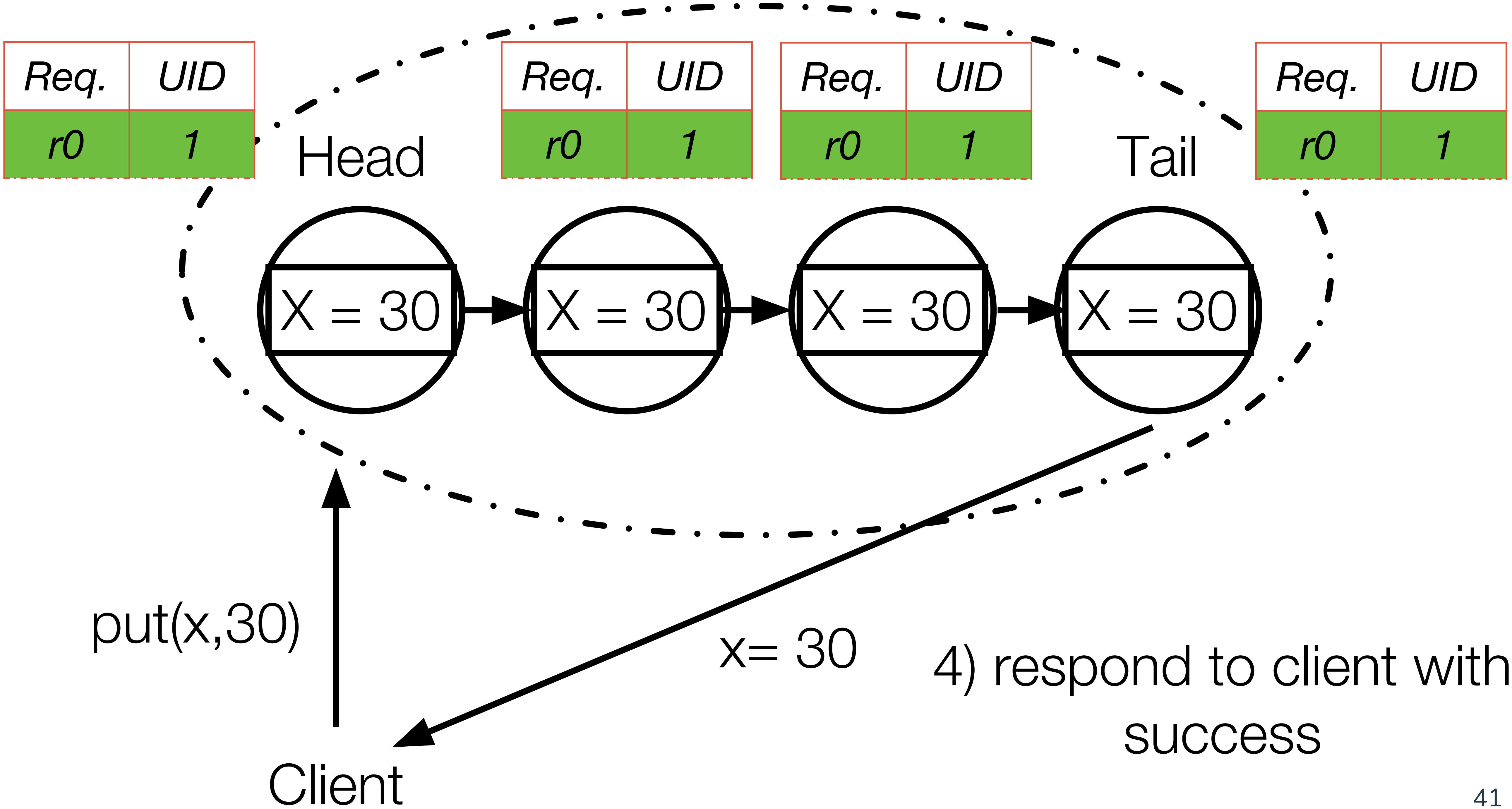
2) Head sends message to next node

Chain Replication



3) Repeat until tail is reached

Chain Replication



4) respond to client with success

Chain Replication Assumptions

- No partition tolerance
- High throughput
- Fail-stop processors
- A universally accessible, failure resistant or replicated Master

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

Chain Replication Fault Tolerance

- Trusted Master
  - *Fault-tolerant state machine*
  - Trusted by all replicas
  - Monitors all replicas & issues commands

Chain Replication Fault Tolerance

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

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Conclusions

- Implements the “exercise left to the reader” hinted at by Lamport’s paper
- Provides ***some*** of the concrete details needed to actually implement this idea
  - But still a fair number of details in real implementations that would need to be considered
  - Chain replication illustrates a “simple” example with fully concrete details
- A key contribution that bridges the gap between academia and practicality for SMR

Chain Replication Discussion

- Comparison to other primary/backup protocols?
- What are the tradeoffs of Chain Replication?
  - Latency
  - Consistency
- Any thoughts on the Trusted Master system?