A Quorum-Based Replication Framework for Distributed Software Transactional Memory

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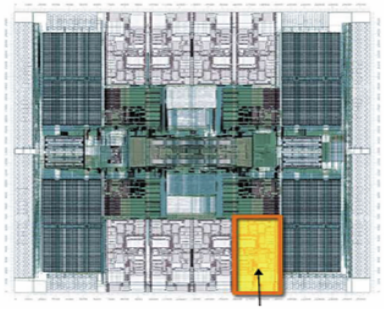
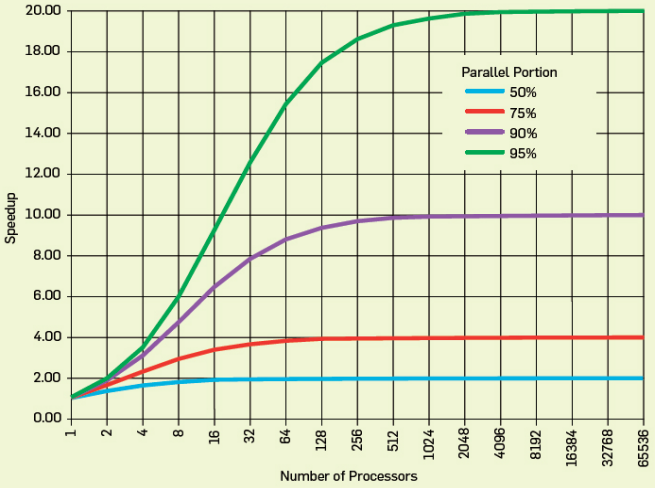
December 13, 2011

CONCURRENCY CONTROL ON CHIP MULTIPROCESSORS SIGNIFICANT AFFECTS PERFORMANCE (AND PROGRAMMABILITY)

- **Chip multiprocessors (CMPs/Multicore) are here**
  - Improve performance by exposing greater concurrency in software
- **Difficult: last *x*% involve significant coordination and synchronization**
  - *Amdahl's law: relationship between sequential execution time and speedup reduction is not linear*

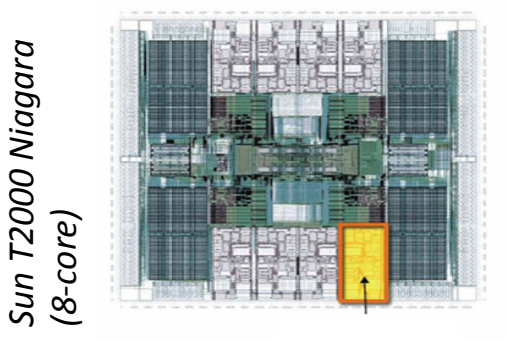
Sun T2000 Niagara (8-core)

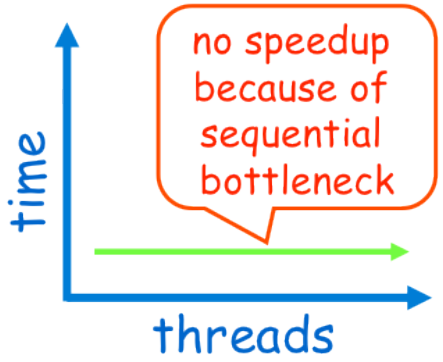




LOCK-BASED CONCURRENCY CONTROL IS CHALLENGING

- **Coarse-grained locking is simple, but permits little concurrency**





- **Fine-grained locking allows greater concurrency, but error-prone**
  - Must acquire only necessary and sufficient locks
  - Must avoid deadlocks
  - Livelocks, lock convoying, priority inversion,….

- **Challenges exacerbate in distributed systems**

TRANSACTIONAL MEMORY (TM): AN ALTERNATIVE TO LOCKS

- **Organize code that access shared memory as transactions that (appear to) execute *atomically* and in *isolation***

```
atomic{
   x = x + y;
}
```

- **Transactions optimistically execute, logging all changes**
- **Two transactions conflict if they access same object and one access is a write**
  - A conflict resolution policy is used: one is allowed to commit; other is aborted, changes rolled-back, retried
- **Gaining traction; implementations in software and hardware; but no silver bullet**

M. Herlihy and J. B. Moss (1993). Transactional memory: Architectural support for lock-free data structures. *ISCA*. pp. 289–300.
N. Shavit and D. Touitou (1995). Software Transactional Memory. *PODC*. pp. 204—213.

DISTRIBUTED SOFTWARE TRANSACTIONAL MEMORY (D-STM)

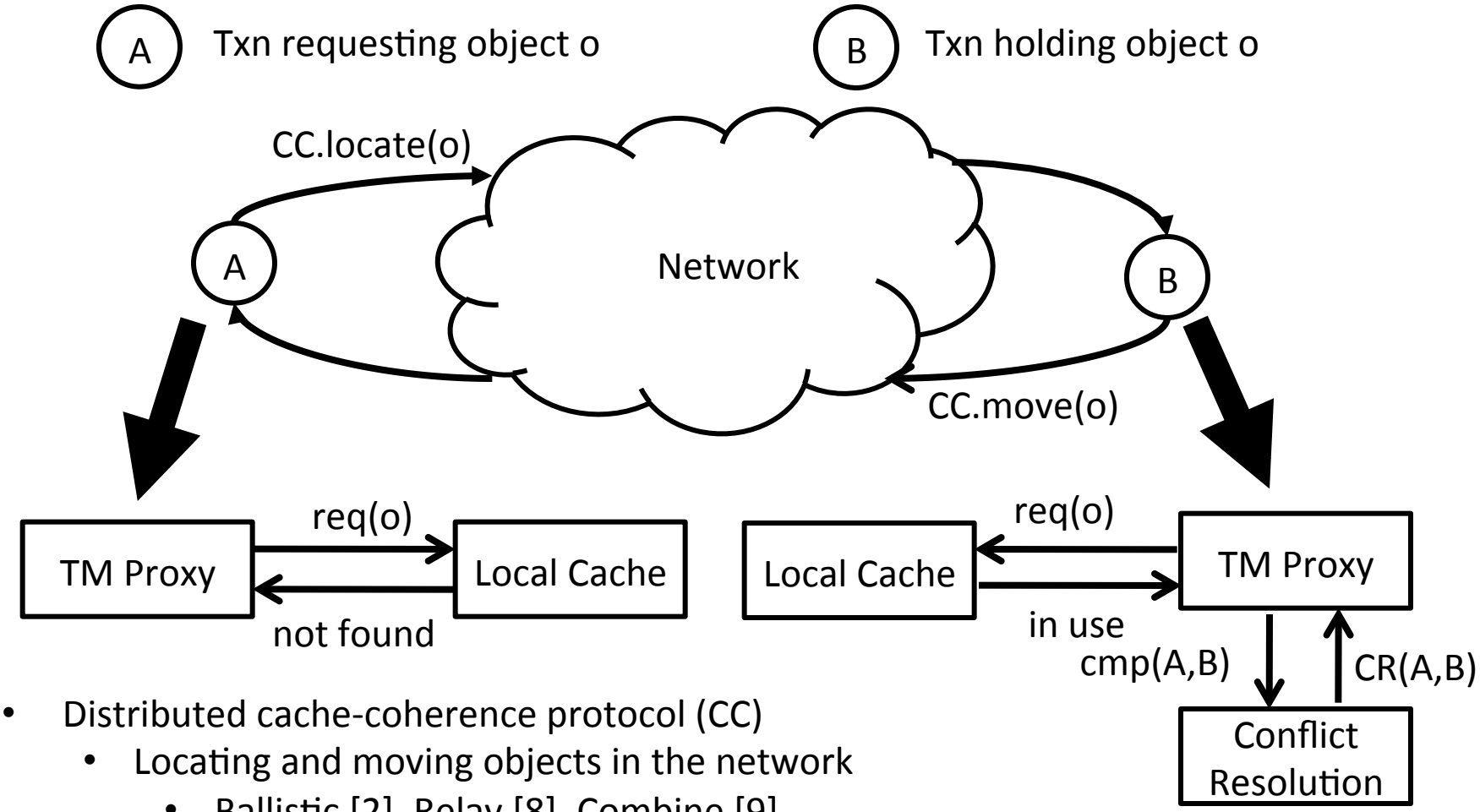
- **D-STM**
  - Support STM in distributed systems
  - Nodes communicate by message passing links

- **Control flow**
  - Transactions move, objects held locally
  - Inherited from database transactional synchronization
  - Consistency using distributed commit (e.g., two-phase commit)

- **Data flow**
  - Objects move, transactions run locally
  - Cache coherence, conflict resolution
  - No distributed commit
  - Easier to exploit locality

(paper's focus)

SINGLE COPY (SC) D-STM MODEL



- Distributed cache-coherence protocol (CC)
  - Locating and moving objects in the network
    - Ballistic [2], Relay [8], Combine [9]
  - Only one (writable) copy exists for each object
- Conflict resolution module (CR)
  - Resolve conflicts among transactions
  - Ensure progress and enhance concurrency

LIMITATIONS OF SC D-STM MODEL

- **No fault-tolerance property**
  - When node fails, held objects are lost
- **Limited support of concurrent reads**
  - CC protocol needs to maintain the consistency over read-only replicas while some transaction is writing the object
  - High communication cost to detect read/write conflict
  - Typical directory-based CC protocols often do not differentiate between read and write operations
- **Limited locality**
  - One major goal of directory-based CC protocols is to exploit locality
  - Directory-based CC protocols often keep track of the single writable copy
  - In practice, not all transactional requests are routed efficiently
  - Possible locality is often overlooked

QUORUM-BASED REPLICATION (QR) D-STM MODEL

- **Fault-tolerance guarantee**
  - Tolerate certain level of node failures

- **Inherent support of concurrent reads**
  - Multiple (writable) replicas of each object
  - Concurrent read transactions never serialized
  - (Conflicts resolved at commit)

- **Best-effort locality exploration under node failures**
  - Transactions need to find latest copy of requested object
  - Send request to a certain set of nodes
  - In case of node failures, do best effort to find the closest possible set of nodes which hold latest copy

SYSTEM MODEL

- **Failure-prone distributed system**
  - Nodes communicate by message passing links
  - Metric-space network of diameter *D*
  - Fail-stop node failures

- **Distributed transactions**
  - A set of transactions invoked by different nodes
  - Share a set of objects
  - R->W, W->R, W->W conflicts

- **A fixed contention manager**
  - Located at every node
  - Resolve conflicts based on a consistent policy

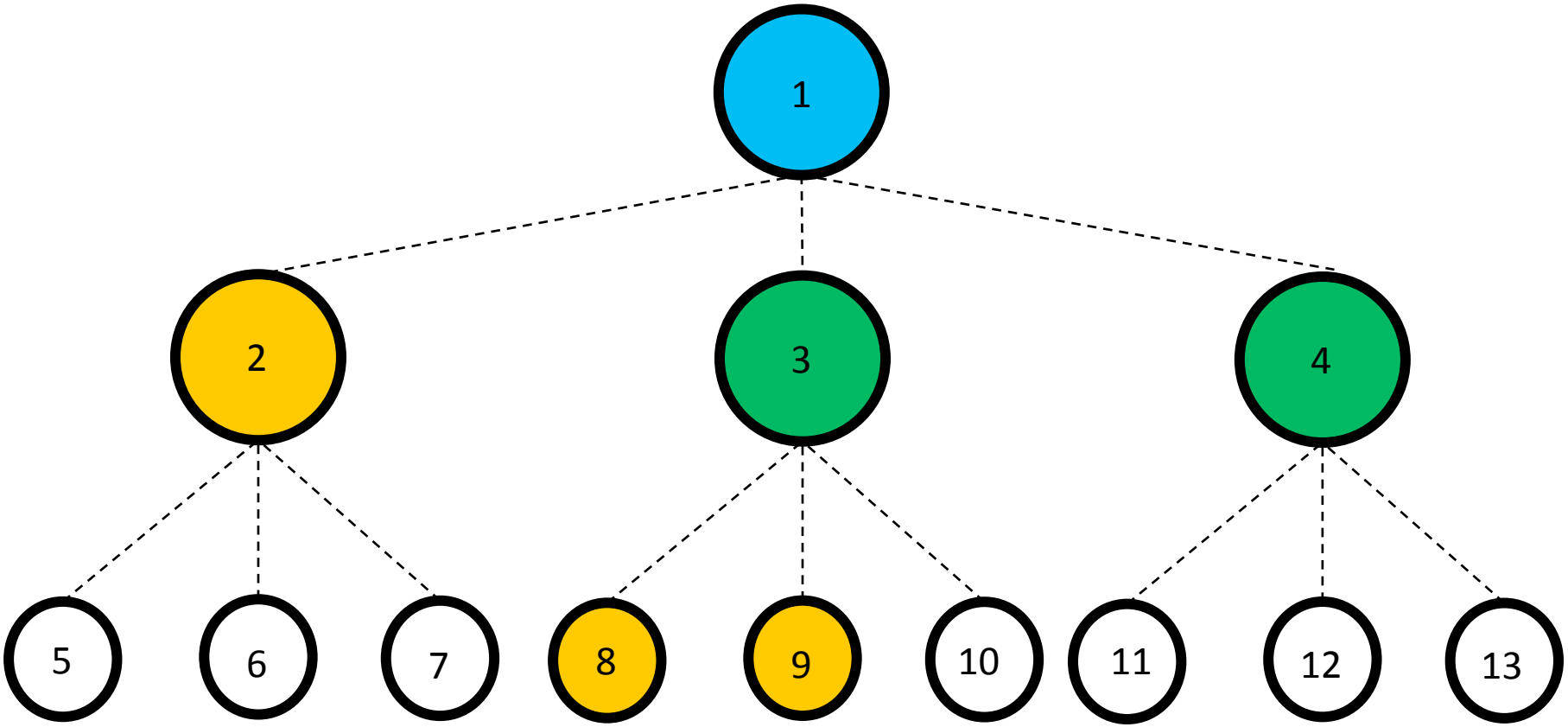
QR MODEL: PRELIMINARIES

- **Objects are replicated based on quorums**
  - A quorum system is constructed

- **Quorum: a collection of nodes**
  - Read quorum and write quorum
  - Two quorums *intersect* if one of them is a write quorum

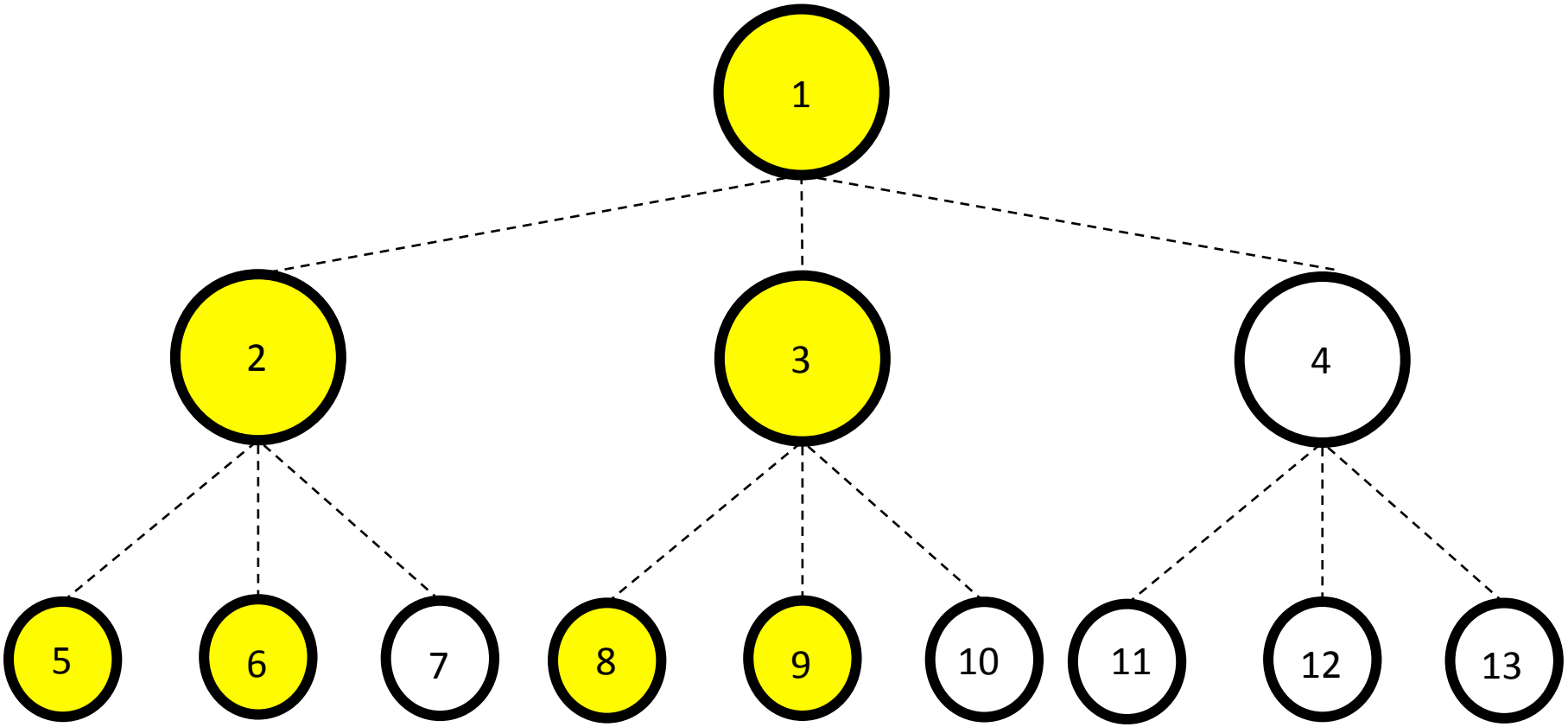
- **Five operations provided**
  - Read and write: regular operations
  - Request-commit: validate transaction after regular operations
  - Commit and abort: complete a transaction by the result of request-commit operation

EXAMPLE: TREE QUORUM SYSTEM



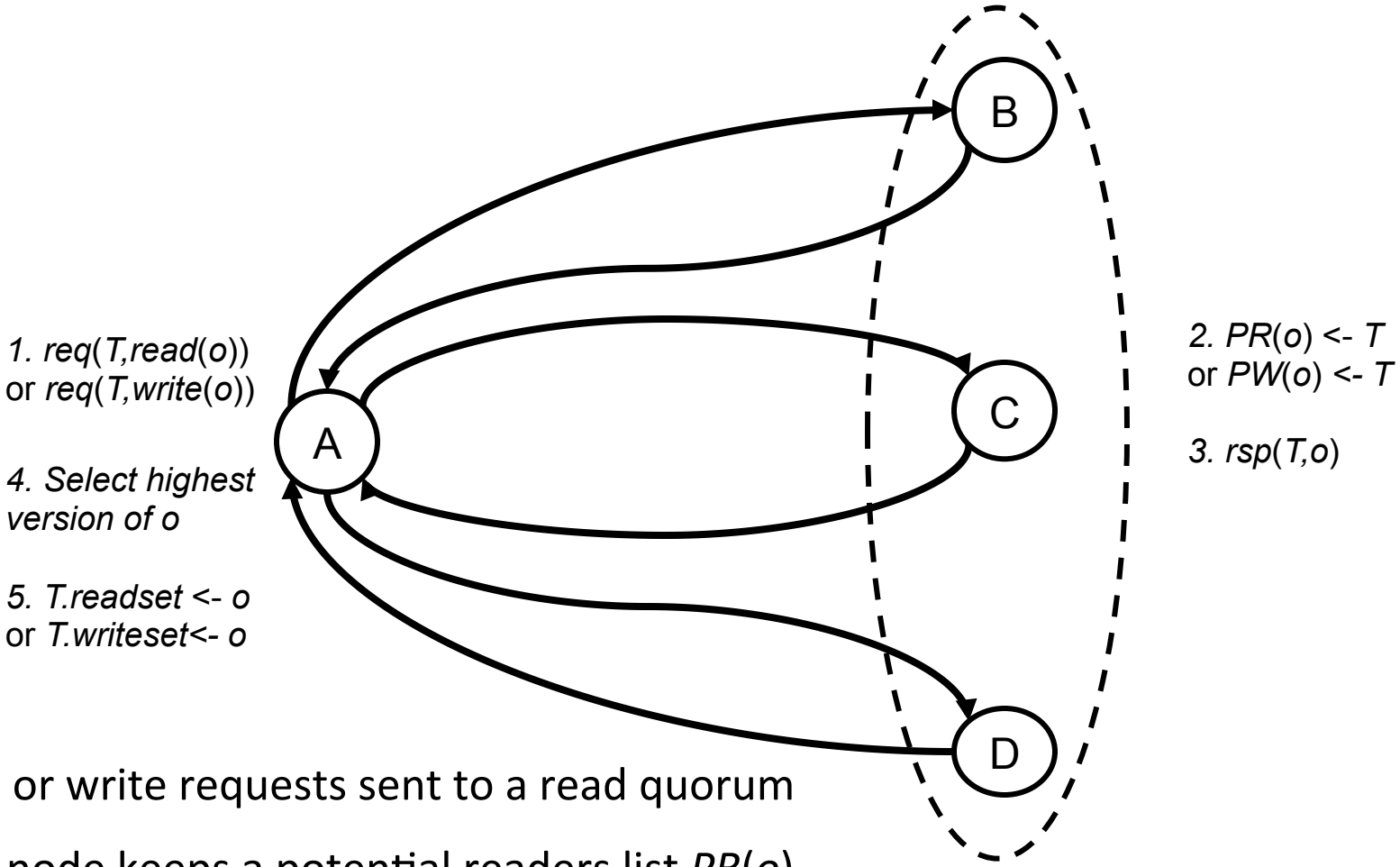
- Tree quorum system: Agrawal and Abbadi ‘90 [11]
  - Read quorum: the root, **or** replaced by its majority of children recursively
  - Three read quorums are shaded

EXAMPLE: TREE QUORUM SYSTEM



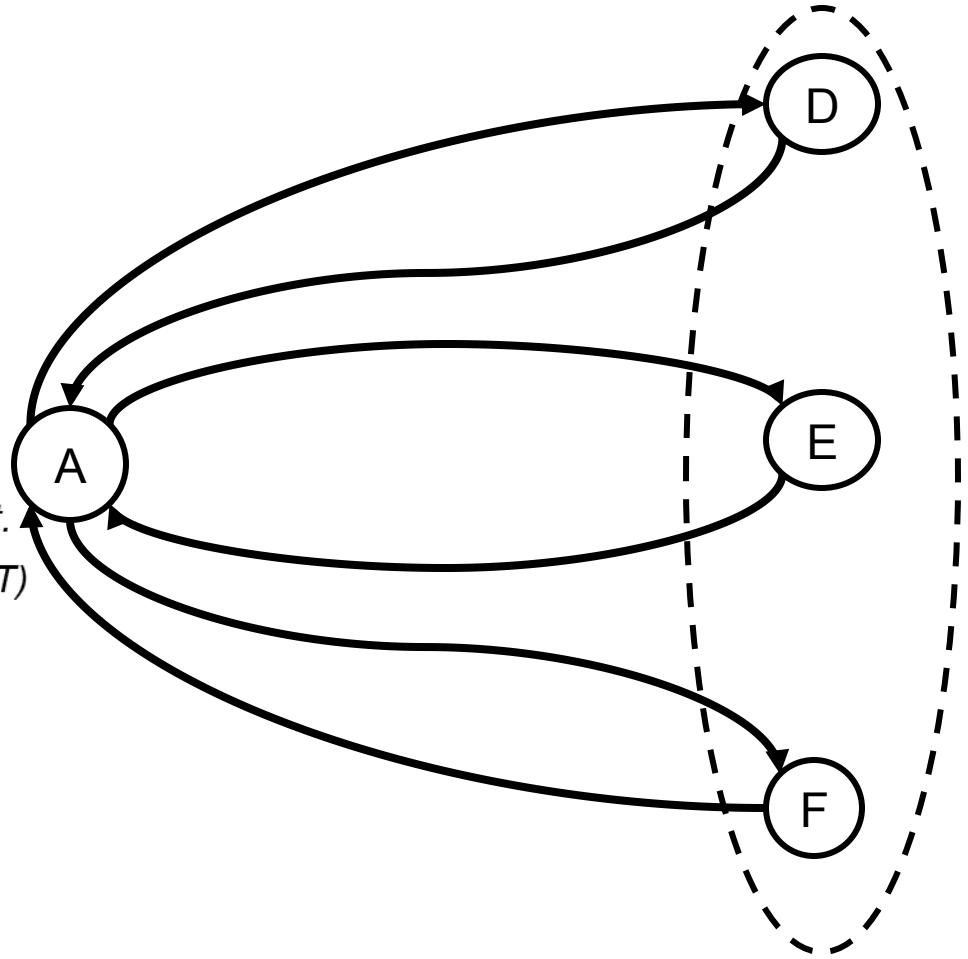
- Tree quorum system: Agrawal and Abbadi ‘90 [11]
  - Write quorum: the root **and** its majority of children recursively selected
  - One write quorum is shaded

QR MODEL: READ AND WRITE OPERATIONS



- Read or write requests sent to a read quorum
- Each node keeps a potential readers list *PR*(*o*) and a potential writers list *PW*(*o*) for each object *o*
- The highest version copy is selected when multiple copies received
- Each transaction keeps a readset and a writeset

QR MODEL: REQUEST-COMMIT OPERATION



1. req_cmt(T)

6. Abort if any rsp(T,abort) received

7. Else, commit.

AT(T) <- ∪CT(T)

2. Conflict-Detect(A,T) and update CT(T)

3. CM(T,CT(T))

4. If T aborts, rsp(T,abort); If not, rsp(T,cmt,CT(T)) and o.protected <- true for all o requested by T

5. Remove T from PR(o) and PW(o) for all o

QR MODEL: REQUEST-COMMIT OPERATION

- Request-commit after all regular operations
  - Request sent to a write quorum

- Remote: conflict detection and contention management
  - Conflicting transaction list: *CT*(*T*)
  - Conflicts are detected for each object requested by *T*, based on object's version number and potential reader and writer lists
  - *CM*(*T, CT*(*T*)): contention management for *T* and every transaction in *CT*(*T*)
  - *o.protected:* field to protect *o* from being overwritten after request-commit

- Local: determine commit or abort based on responses
  - If commit, update an abort transactions list *AT*(*T*) by including all received *CT*(*T*) from remote nodes

QR MODEL: COMMIT AND ABORT OPERATIONS

- Request sent to a write quorum

- Commit operation
  - Invoked immediately after request-commit operation
  - Local & remote: overwrite the object value, increase version number by 1, and set *o.protected* to *false* for every *o* requested by *T*
  - Local: send abort message to every transaction in *AT*(*T*)

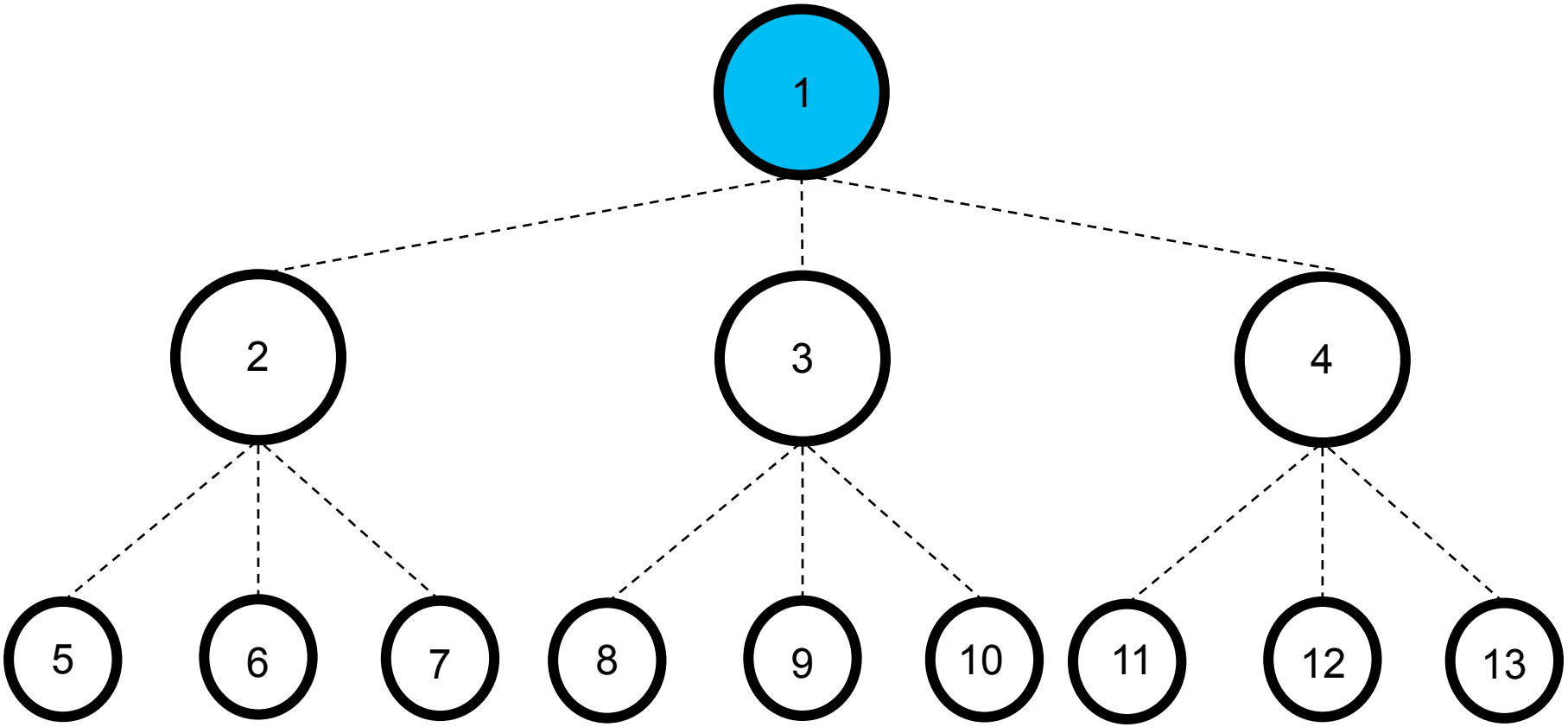
- Abort operation
  - Invoked immediately after any abort message received
  - Local: discard any changes made to objects
  - Remote: set *o.protected* to *false* for every *o* requested by *T* and remove *T* from all potential readers and writers list

QUORUM CONSTRUCTION

- A quorum construction is needed
  - Correctly define read and write quorums in the system
  - Determine which quorum should be selected for any operation invoked by any node
  - Find replacement of failed nodes

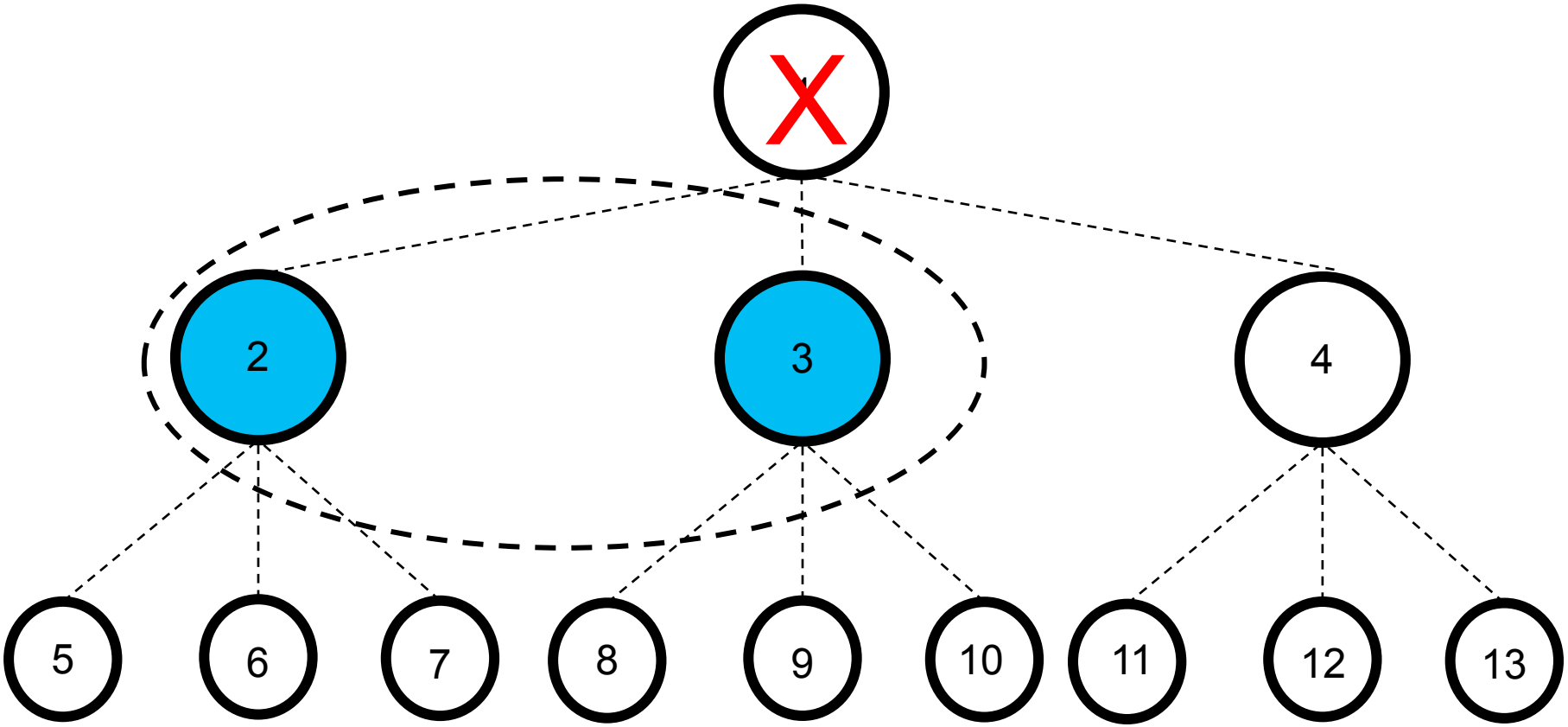
- FLOODING protocol
  - Motivated by tree quorum system by Agrawal and Abbadi [11]
  - An overlay tree constructed on Herlihy and Sun [2]'s hierarchical clustering structure
  - For each node, a basic read quorum and a basic write quorum is always selected when no node fails
  - When some node fails, a replacement is dynamically found

FLOODING PROTOCOL: EXAMPLE OF READ QUORUM



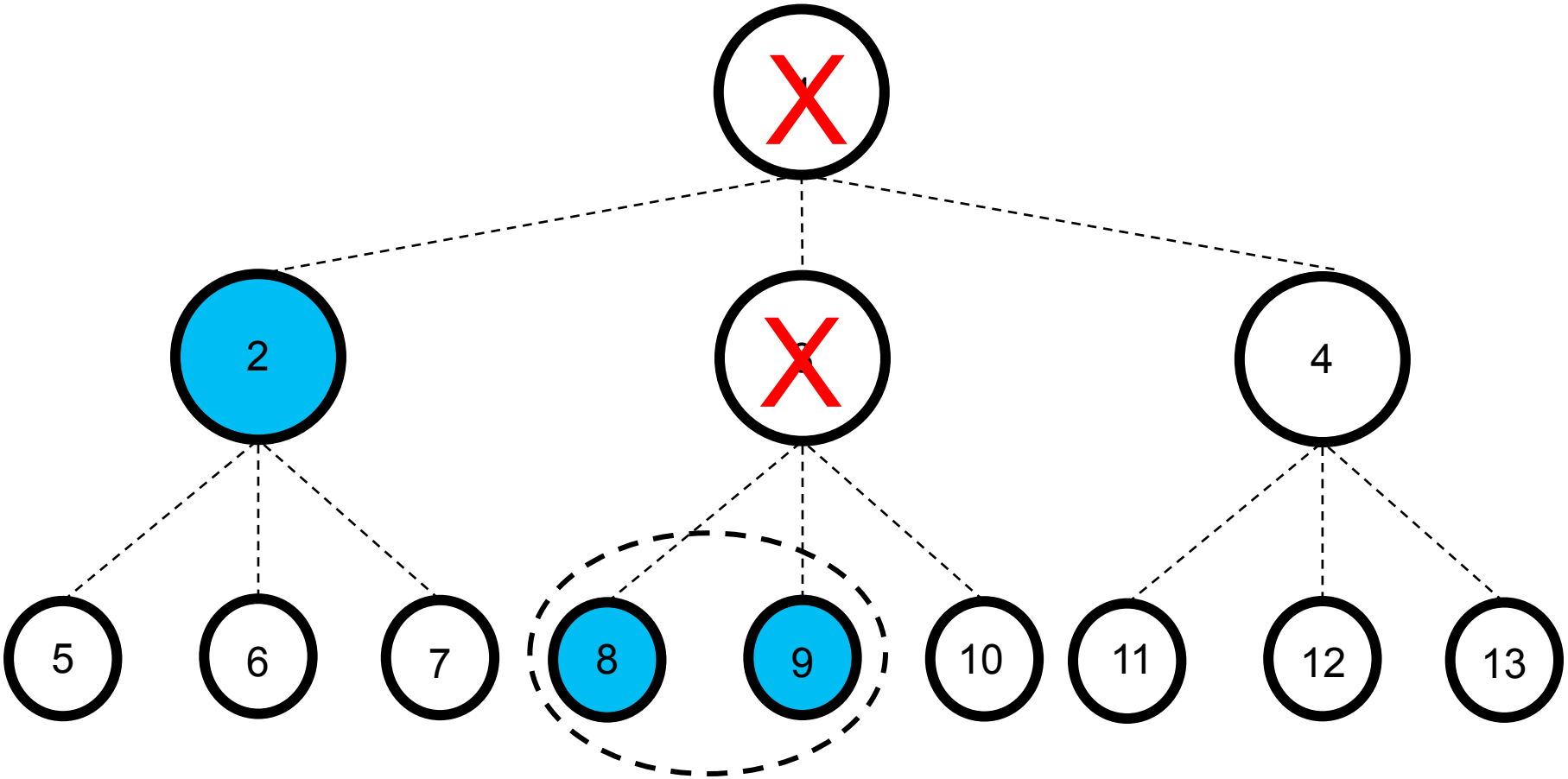
- Basic read quorum: root node

FLOODING PROTOCOL: EXAMPLE OF READ QUORUM



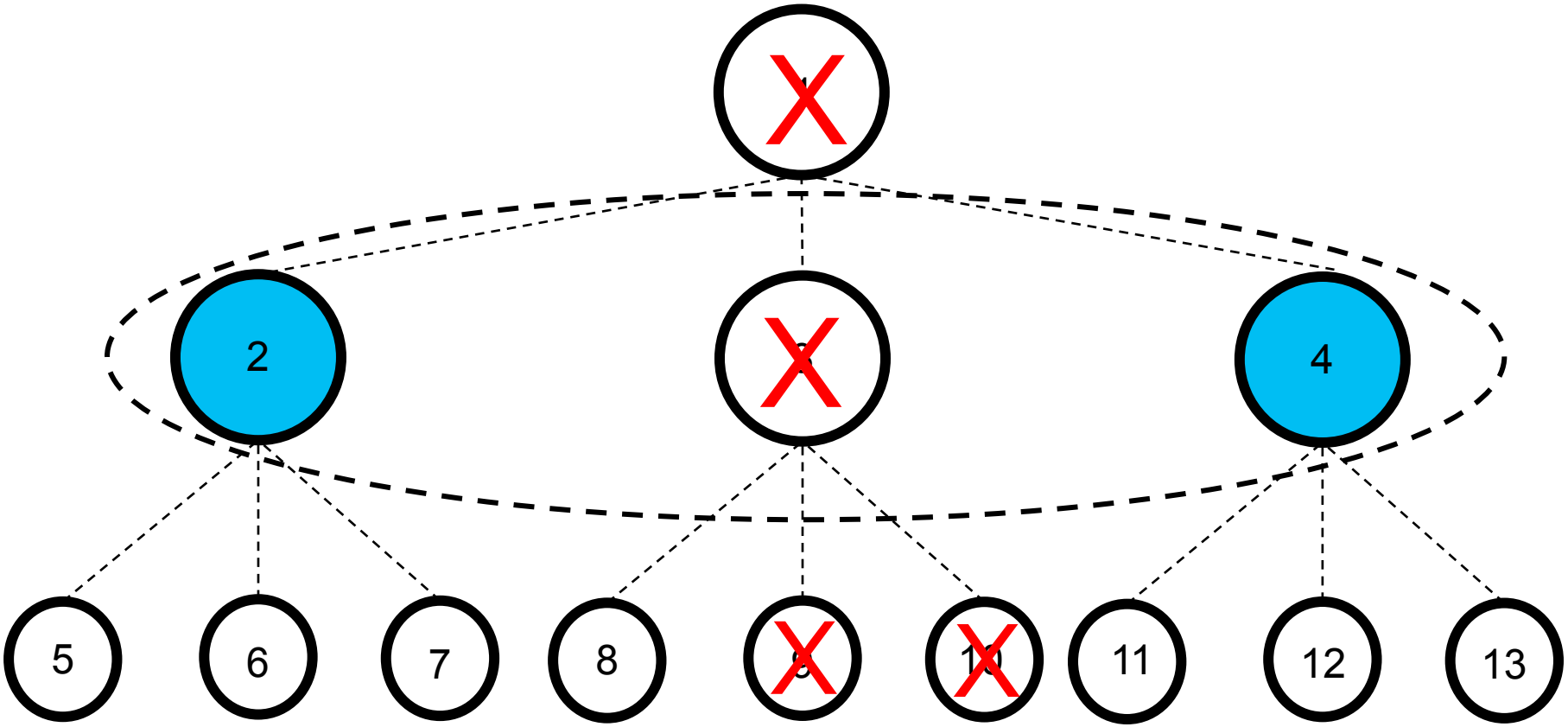
- If root node fails, the closest majority set is selected for replacement
- A new read quorum selected

FLOODING PROTOCOL: EXAMPLE OF READ QUORUM



- Closest majority set of nodes is selected recursively

FLOODING PROTOCOL: EXAMPLE OF READ QUORUM



- No available read quorum when reach the bottom
- Go up one level, find closest majority set
- A read quorum will finally be probed if at least one read quorum lives

QR MODEL: ANALYSIS

- Correctness: 1-copy serializability

- Communication cost when k nodes fails
  - Read and write: $O(k \cdot d(v, q{\downarrow}r(v)))$, where $q{\downarrow}r(v)$ is a live read quorum
  - Request-commit, commit and abort: $O(k \cdot d(v, q{\downarrow}w(v)))$, where $q{\downarrow}w(v)$ is a live write quorum

- Availability: similar to the classic tree quorum system
  - Can afford a certain level of node failures when at least one read and one write quorums live in the system

CONCLUSIONS

- Fast read/write operations, resolve conflicts at commit phase
- When no node fails, provide competitive communication cost as SC model
- When nodes fail, communication cost increases linearly as the number of failed nodes increases
- Provide similar availability as classic tree quorum system

❑ Future…

- Implementation
- Nested transactions?
- Other quorum systems to balance load?
- Reduce communication/improve concurrency?