ECS636U/ECS796P Distributed Systems

What this lecture is about

- Joining/Leaving in DHTs
- Key-Value store
- Memcached

(thanks to prof. Stoica)

What have we s[redacted]far?

- P2P networks introduct[redacted]

- Three basic architectures for locating and distributing content
  - Centralized directory (Napster, early BitTorrent)
  - Query flooding (Gnutella)
  - Hierarchical and non-hierarchical overlay designs (Kazaa, BT DHT)

- We finished looking at DHTs and how to locate content

This was the last slide: Chord (finger tables) analysis on look

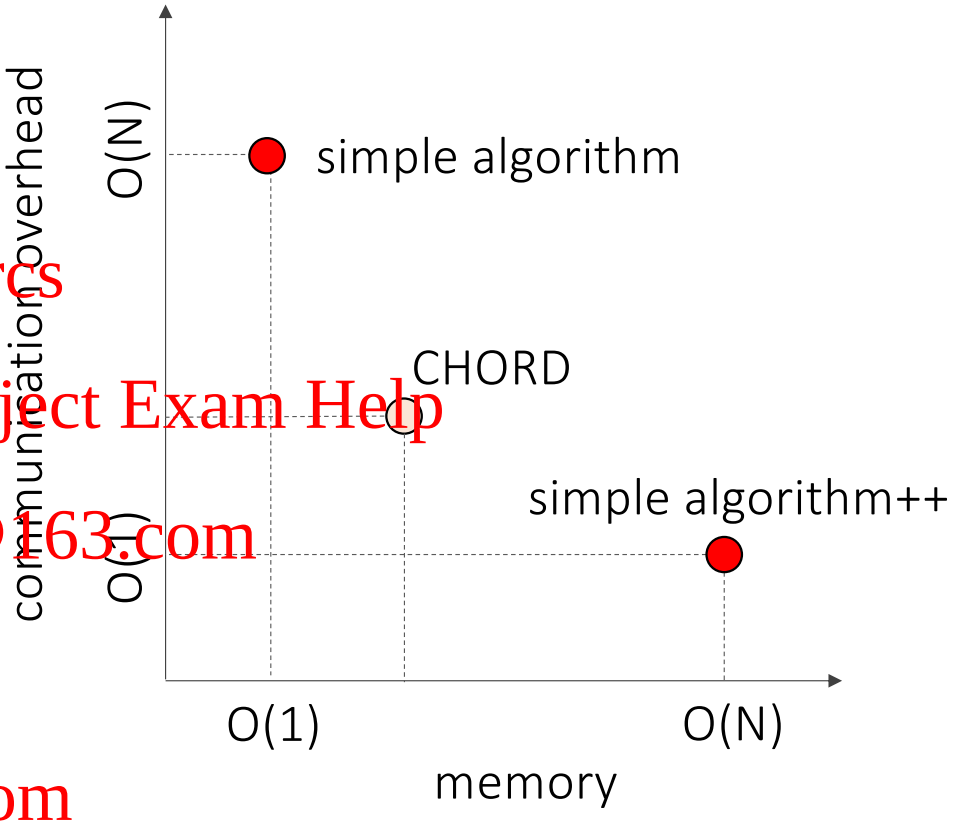
Each node stores a subset (ors:

- O(log N) memory

The search space is halved at each hop:

- O(log N) communicatio

More robust: unless the authority peer of the key ID fails, lookup operations work correctly

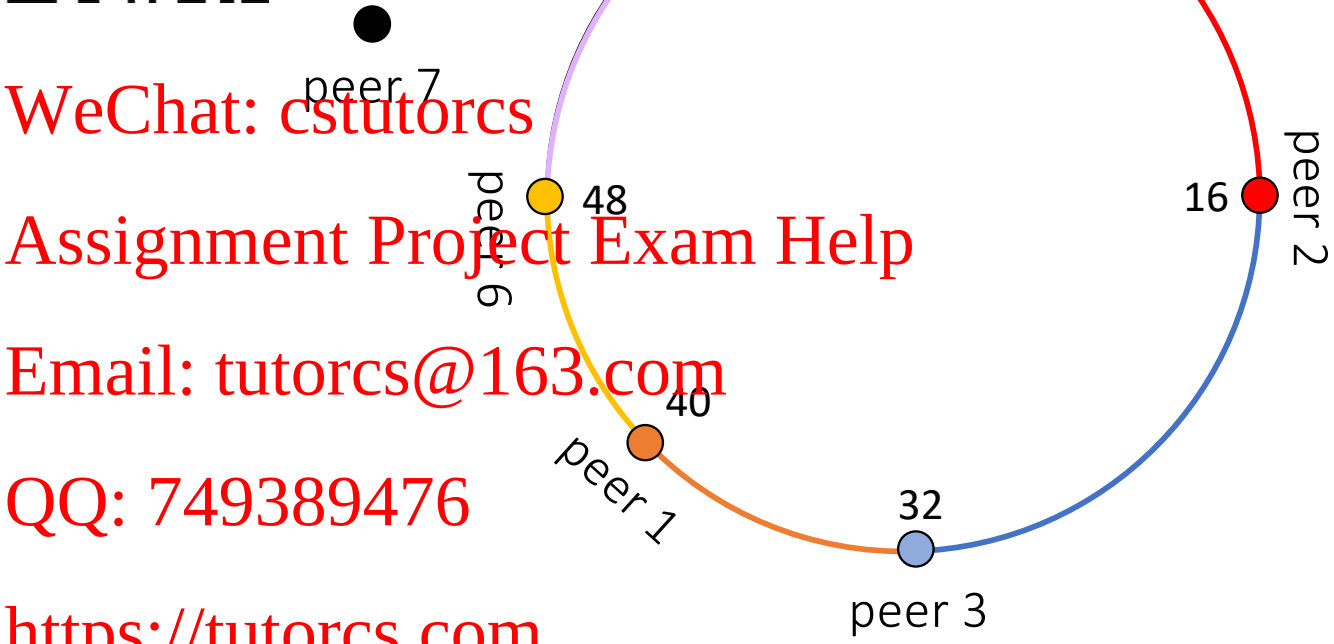


The fundamentals of P2P: the Chord example

static	localization	distribution
	how to find a resource?	*how to distribute resources?*
dynamic	joining	leaving
	how to enter a P2P network?	*how to leave a P2P network?*

Chord: joining the network

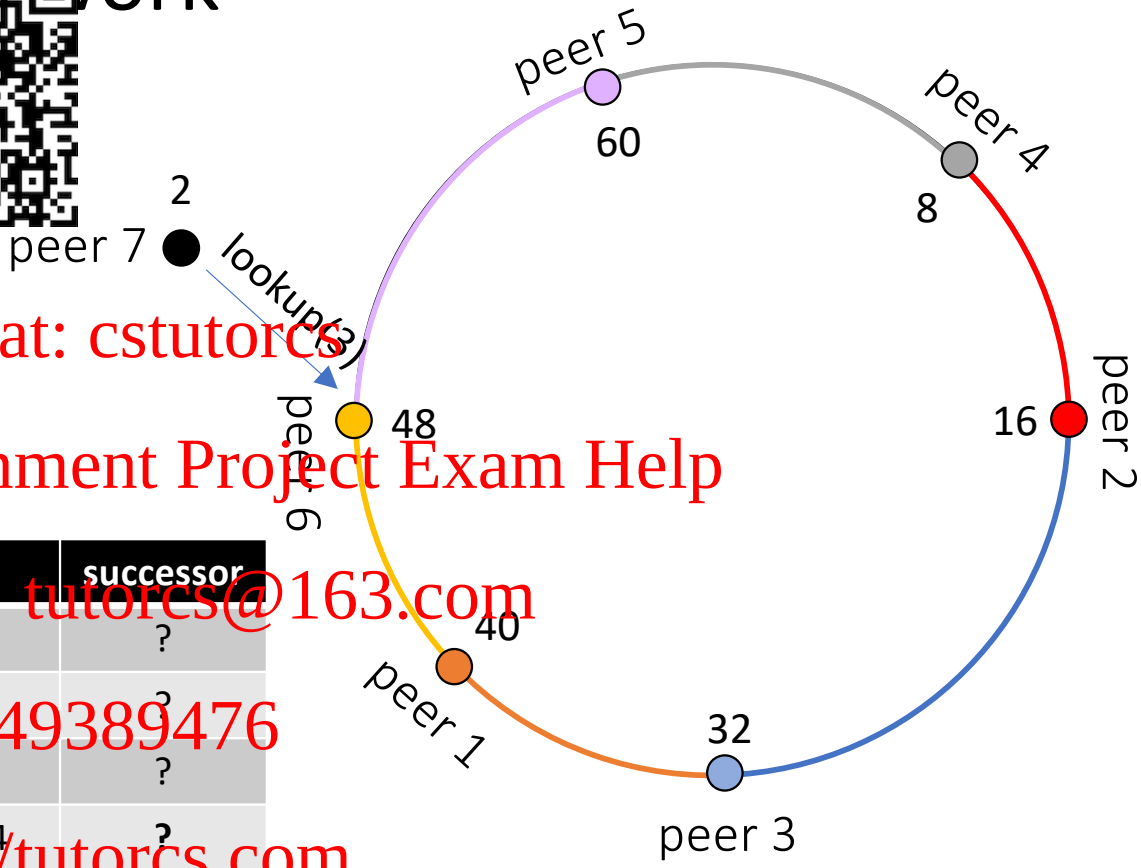
A peer that wants to joint th



Chord: joining the network

A peer that wants to joint the network

- computes its own *id*
- computes its own finger table



i	key id	successor
0	$2 + 2^0 \bmod 64 = 3$	?
1	$2 + 2^1 \bmod 64 = 4$	?
2	$2 + 2^2 \bmod 64 = 6$	?
3	$2 + 2^3 \bmod 64 = 14$	**?**
4	$2 + 2^4 \bmod 64 = 30$	?
5	$2 + 2^5 \bmod 64 = 46$	?

Chord: joining th[redacted]work

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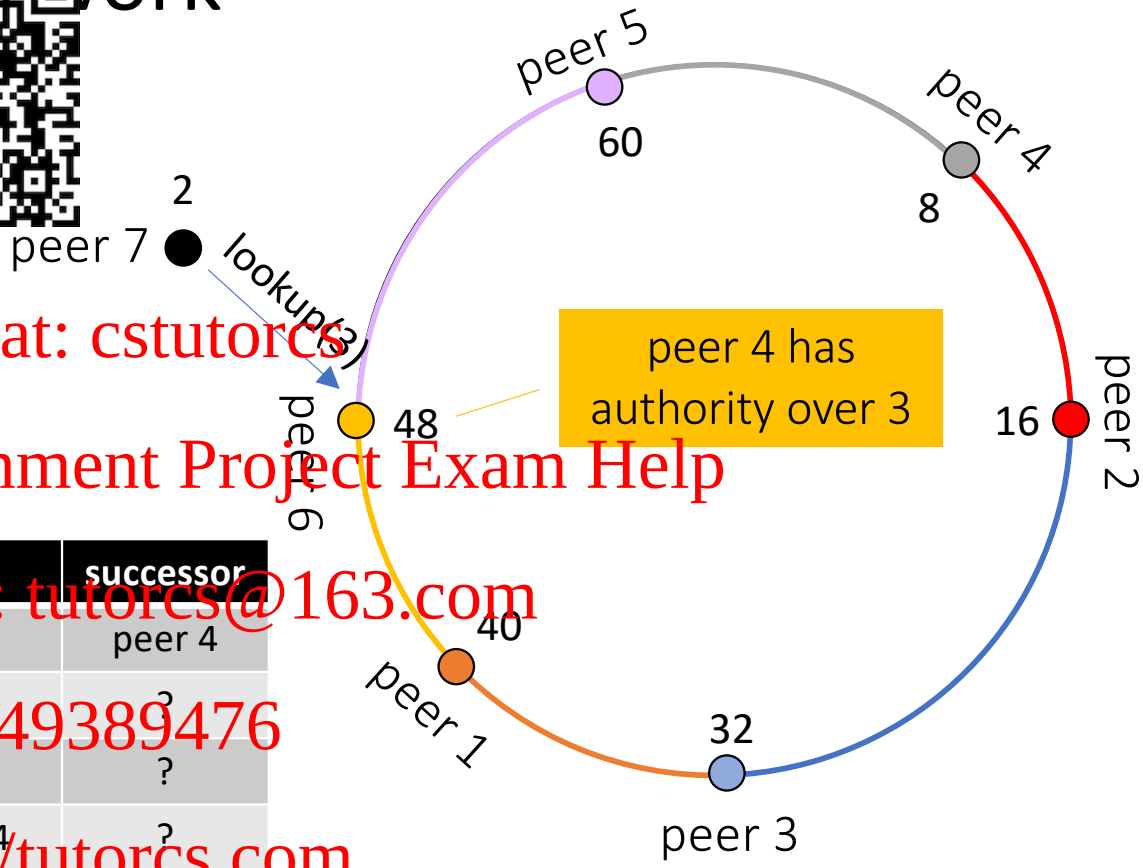

i	key id	successor
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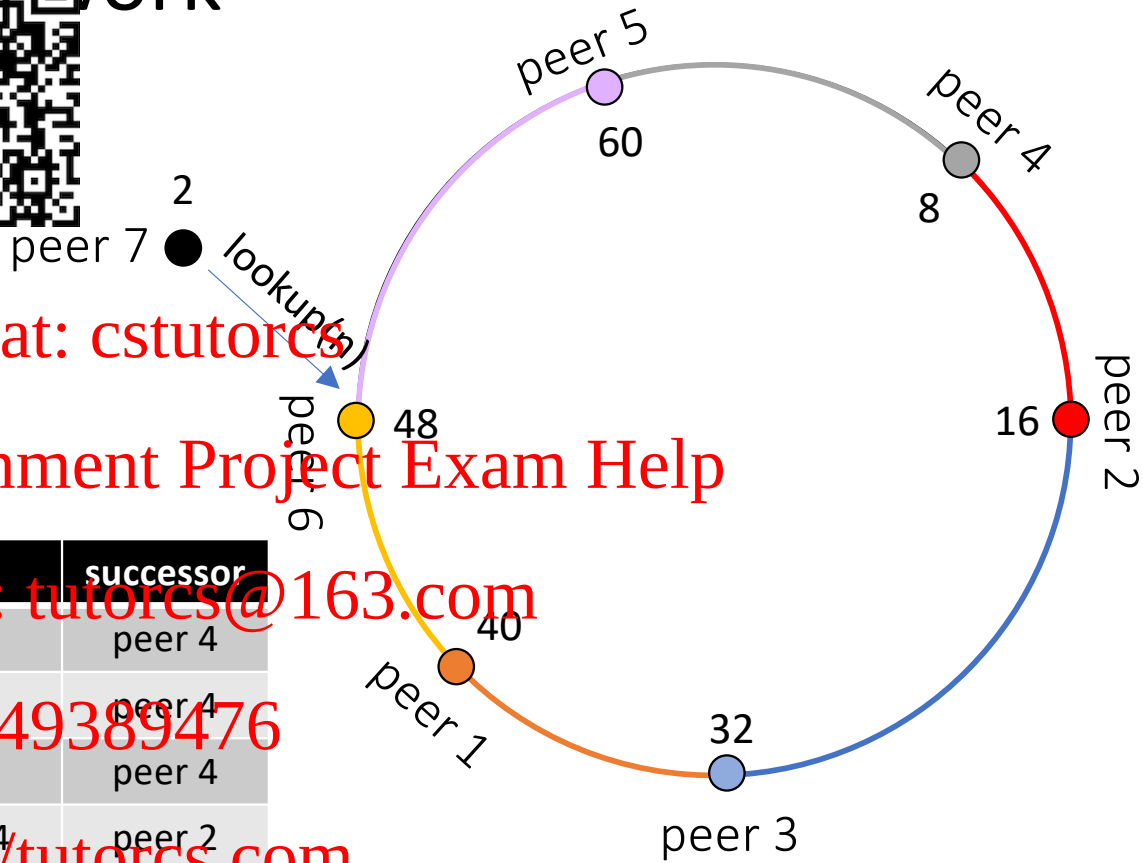

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4	$2 + 2^4 \bmod 64 = 30$	peer 3
5	$2 + 2^5 \bmod 64 = 46$	peer 6

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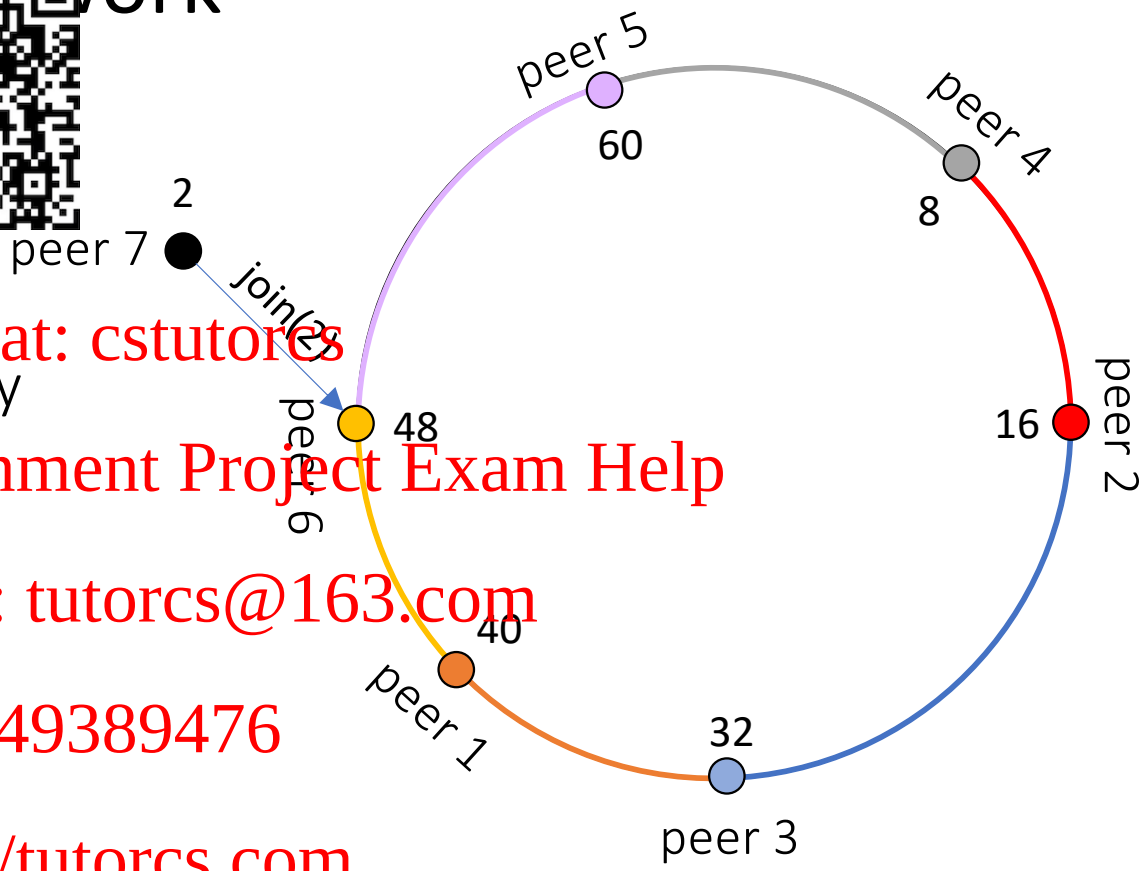

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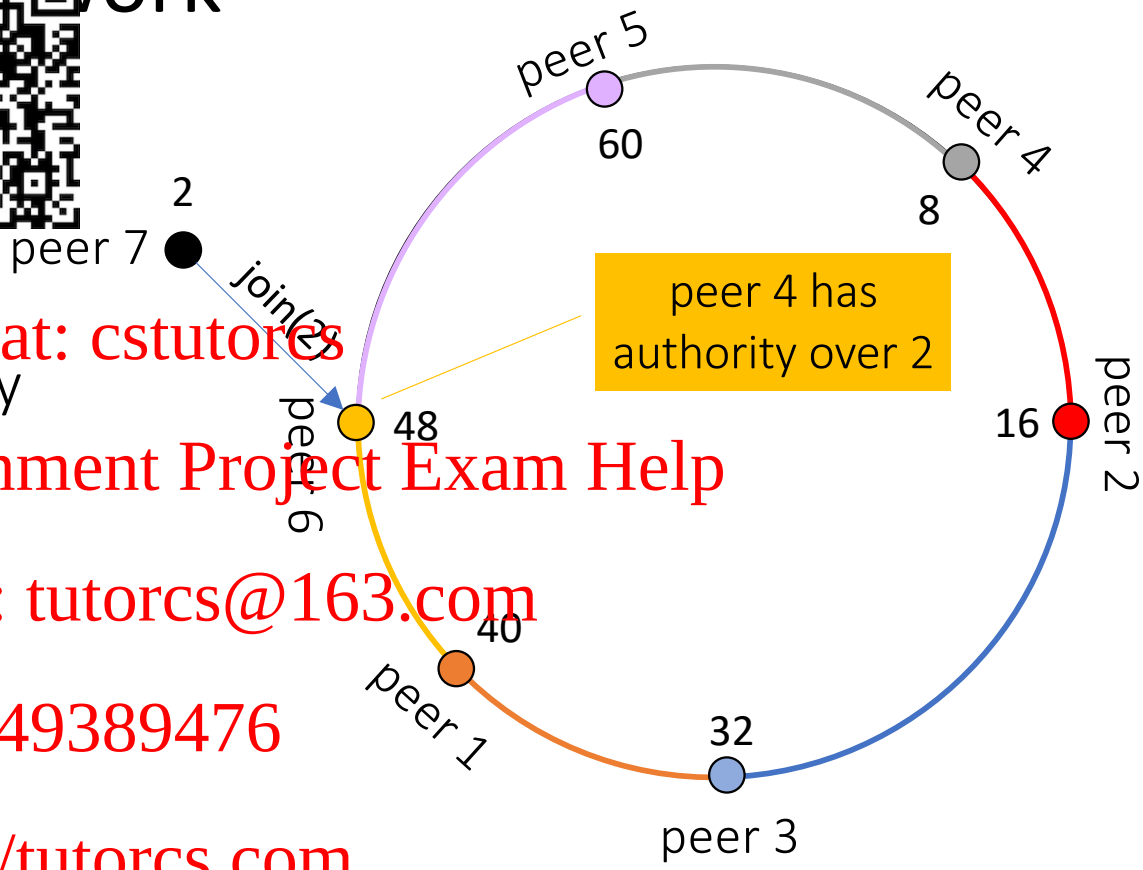
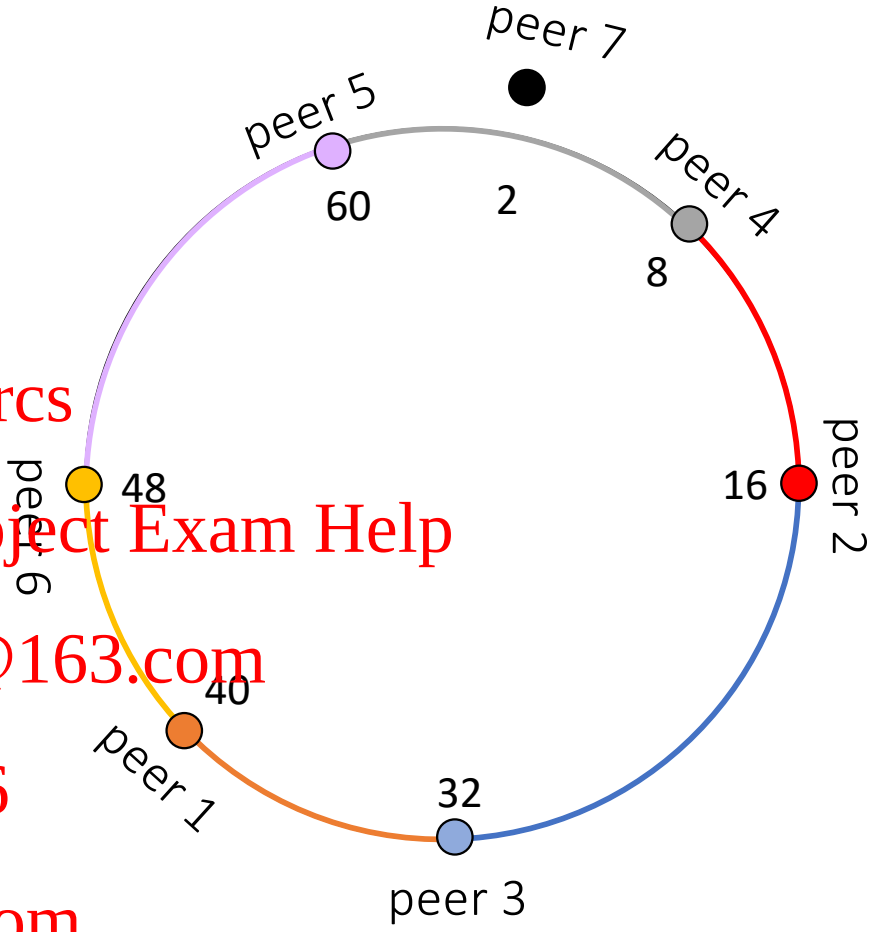


Chord: joining the network

A peer that wants to joint the network:

- computes its own *id*
- computes its own finger table
- ask any peer who has authority over *id*
- Trigger updates of the others' tables without creating anomalities!



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Steps to trigger update:

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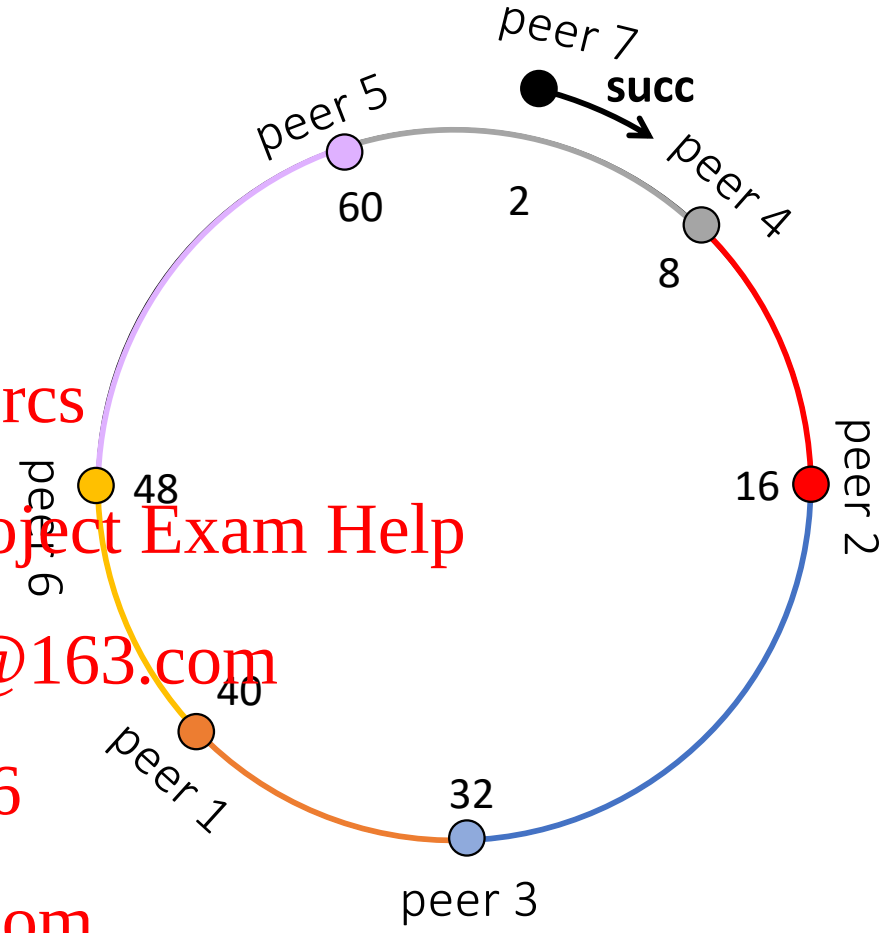

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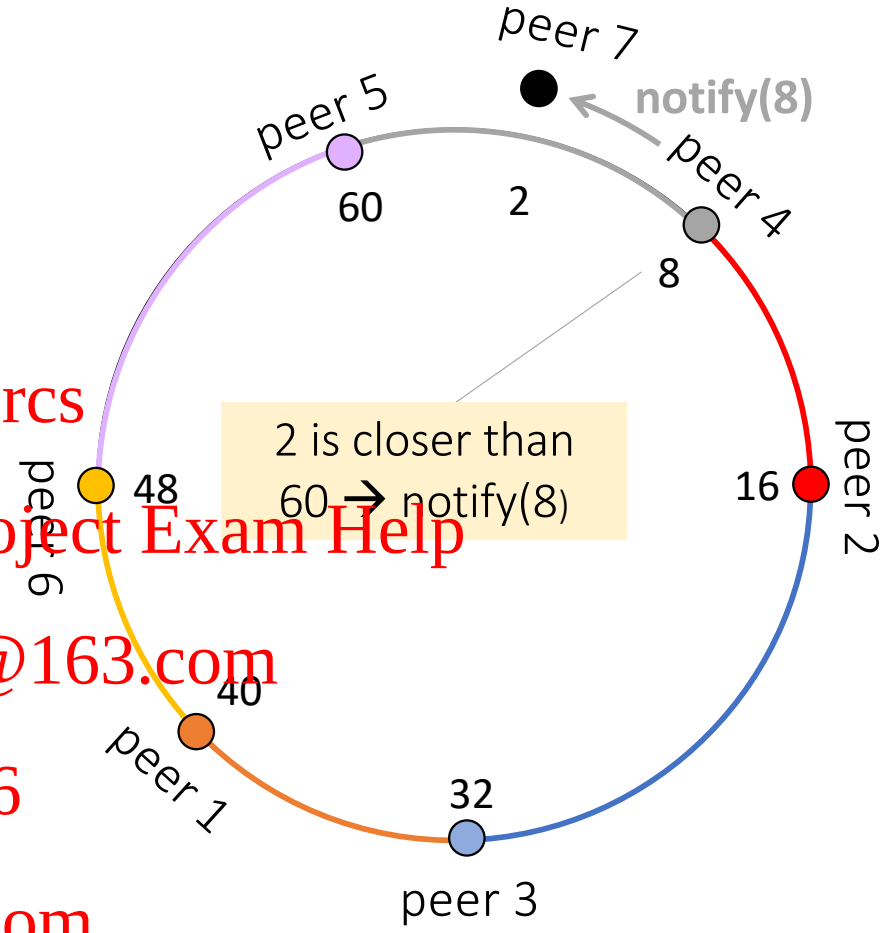

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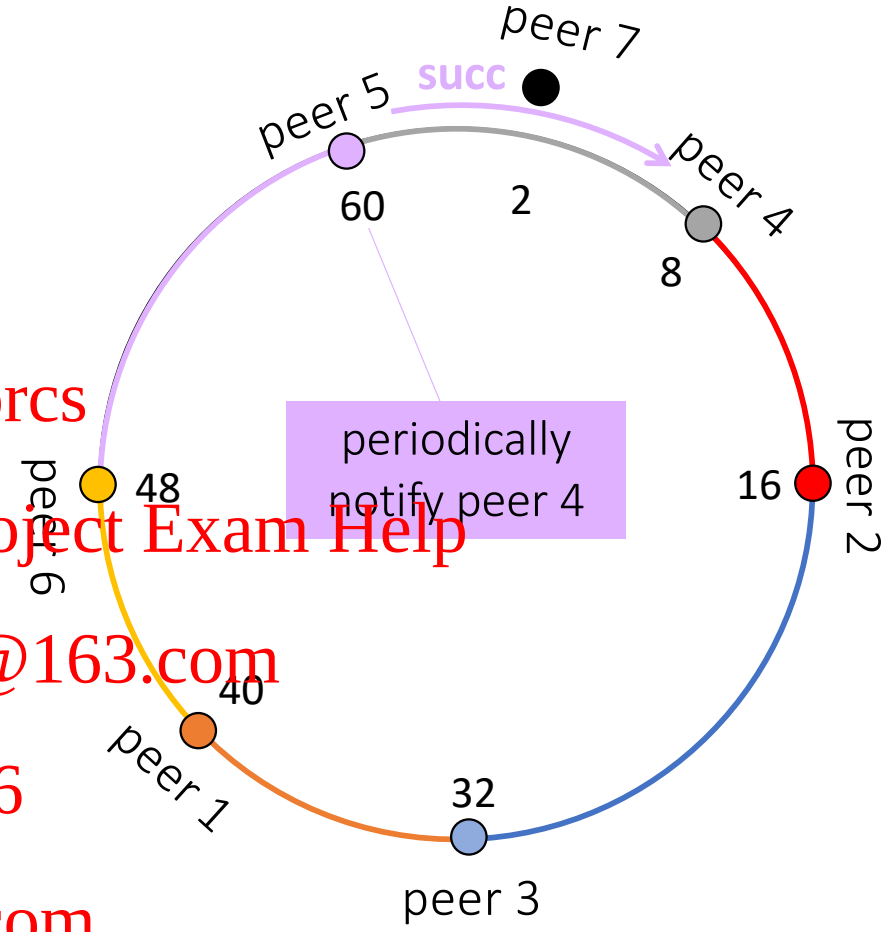

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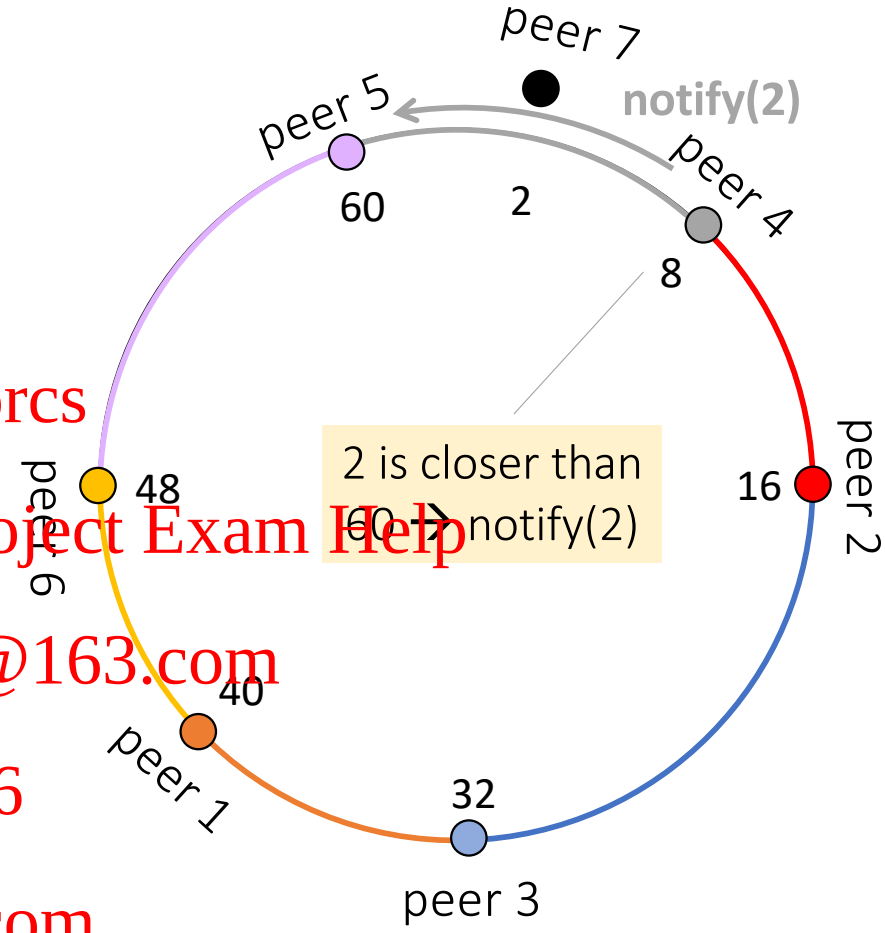

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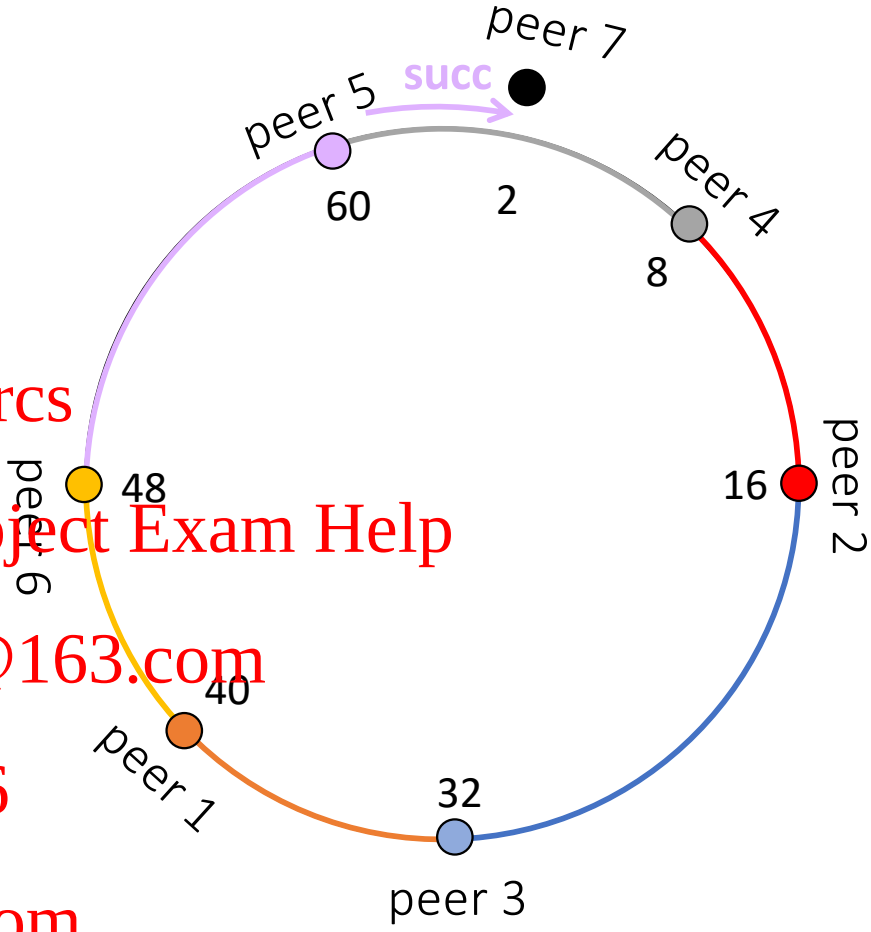

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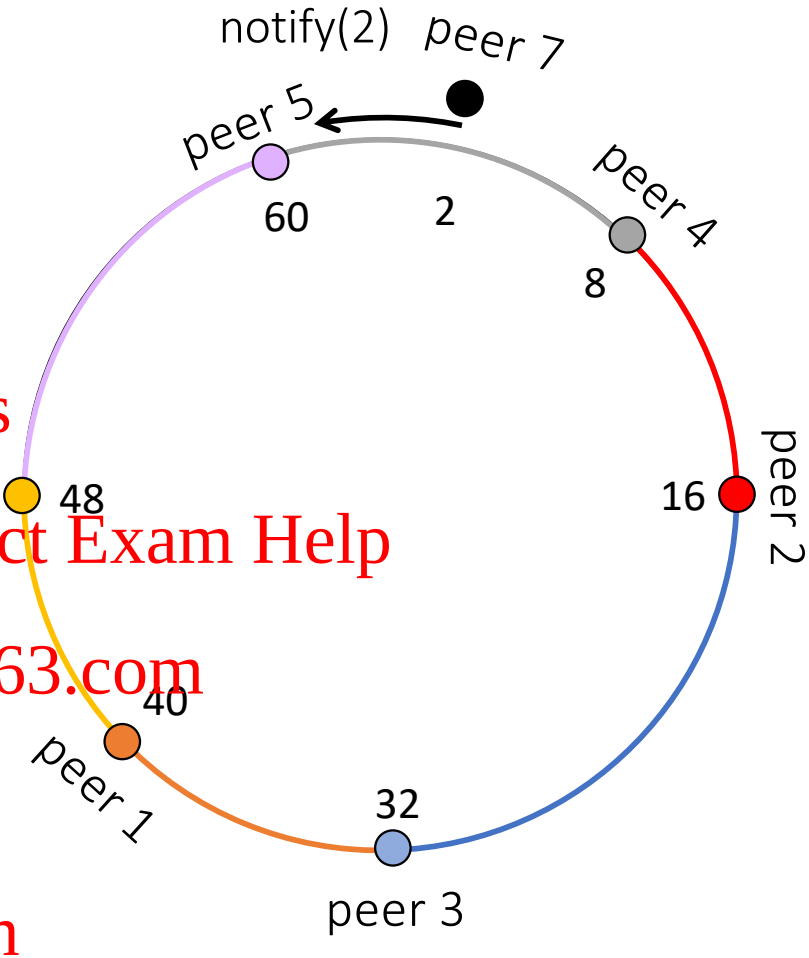
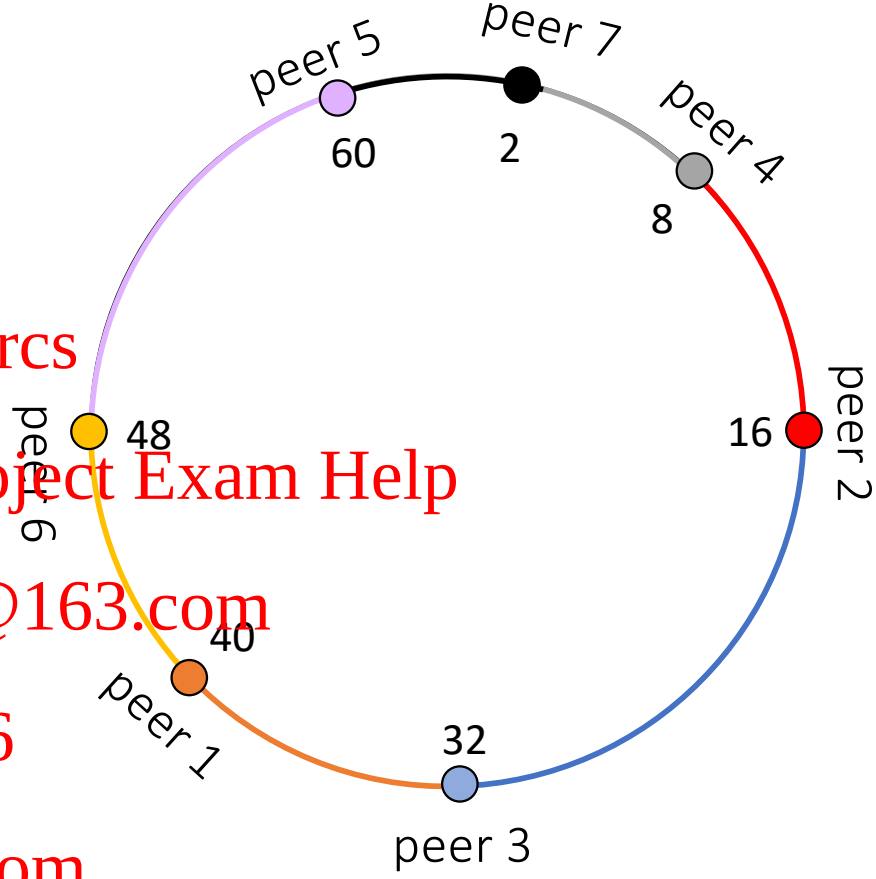


Chord: joining the network

Steps to trigger update:

- Notify succ/pred pointers
- Safe to move resource mapping



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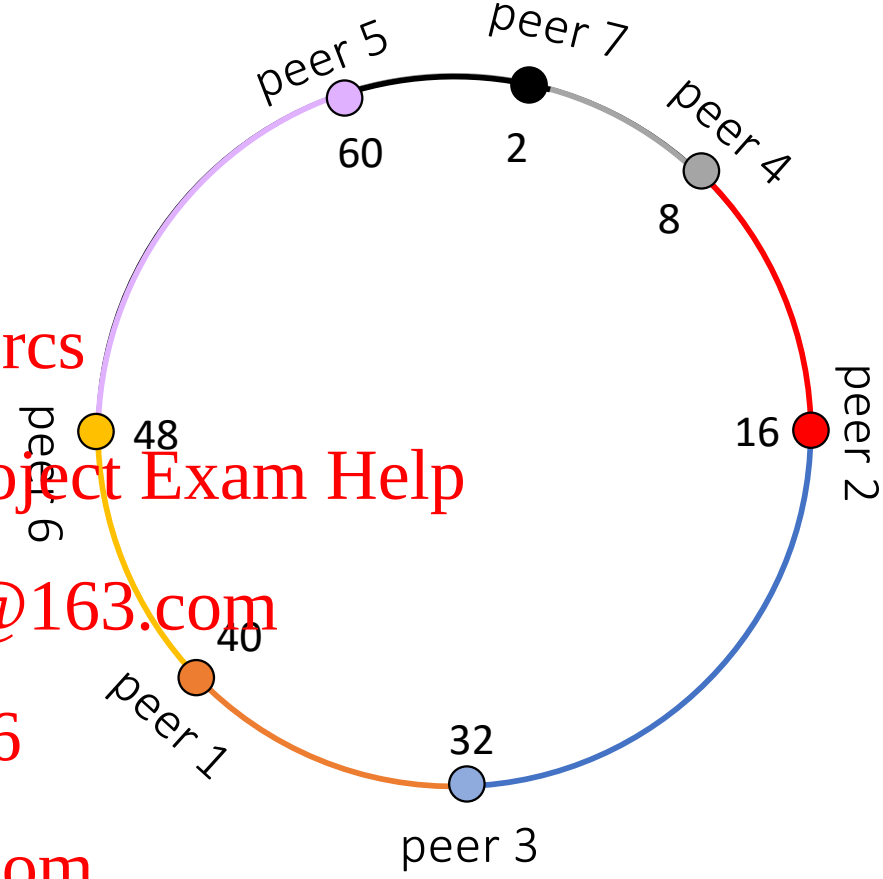

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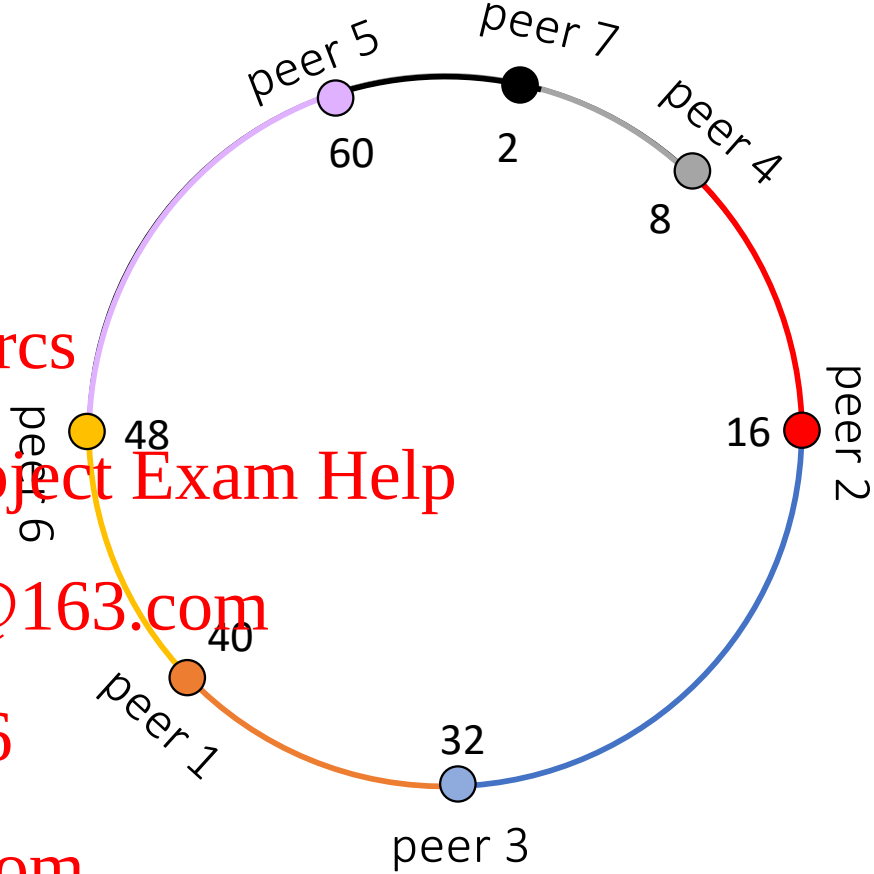

Notes:

- Peer 7 has authority over [61, 2]
- Finger table has 6 entries ($0 < i < 5$)
- $i = 5$ means $Peer_{ID} + 2^5 = Peer_{ID} + 32$
- Who are the Peers that might fall in Peer 7 authority field for $i = 5$?

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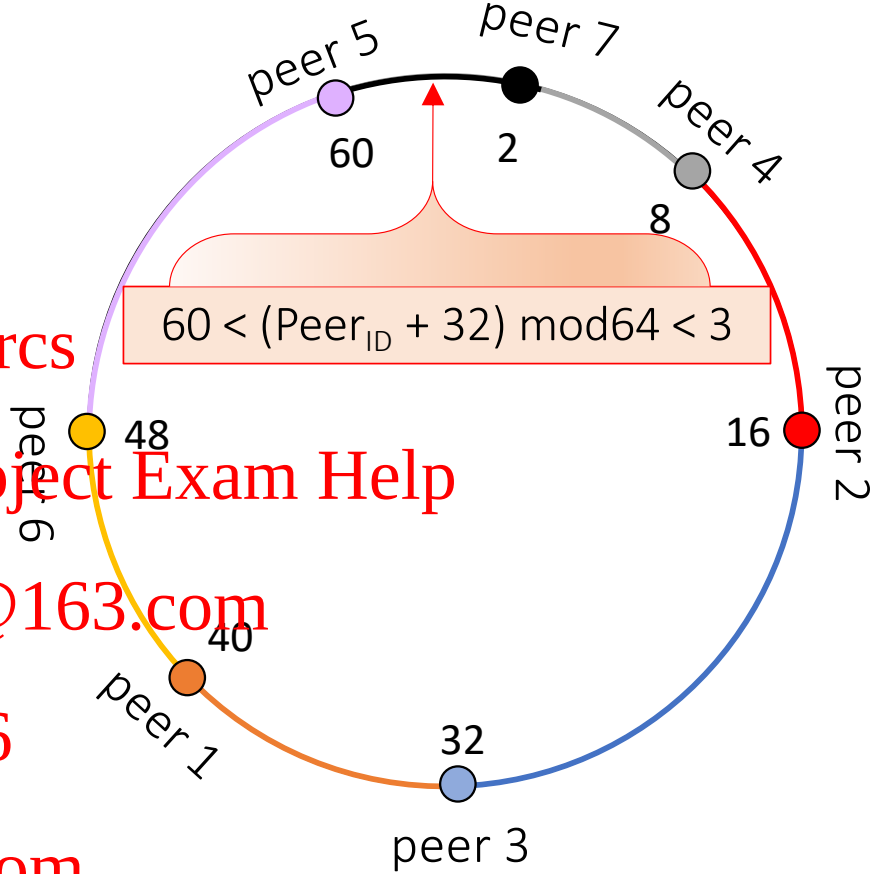

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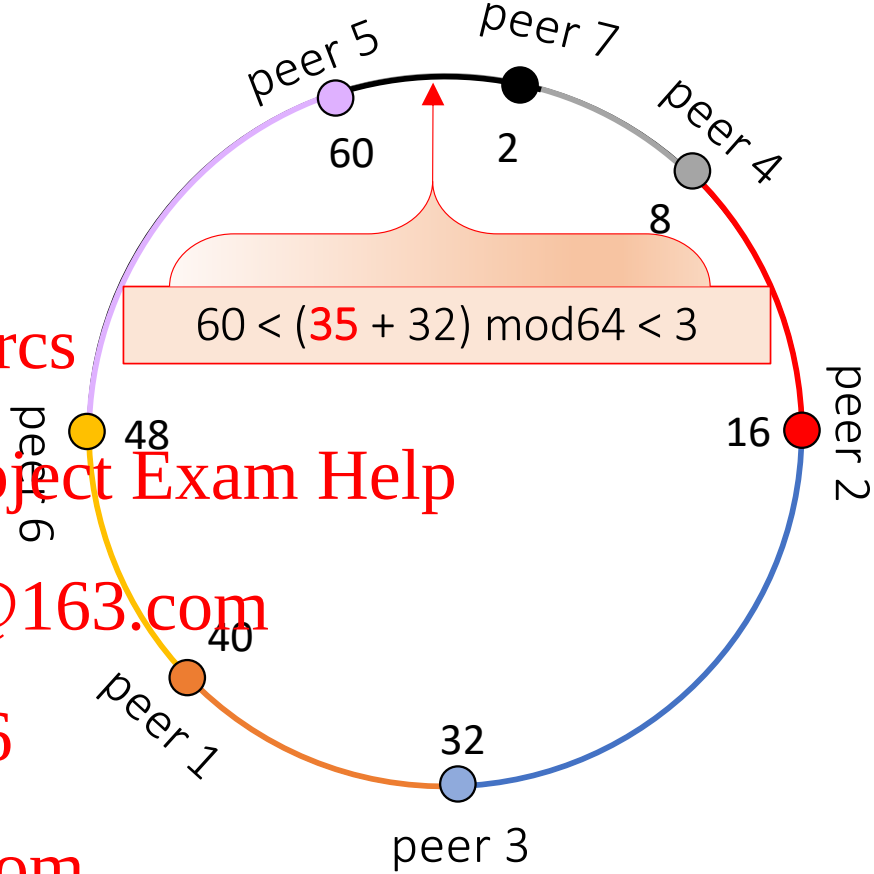

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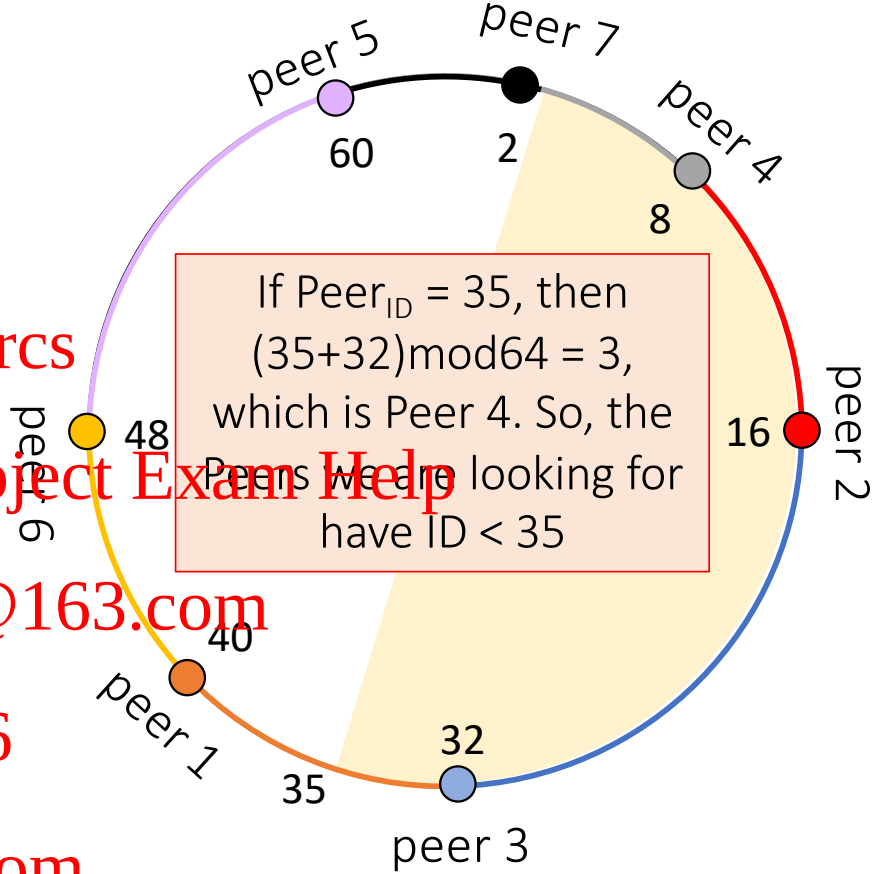

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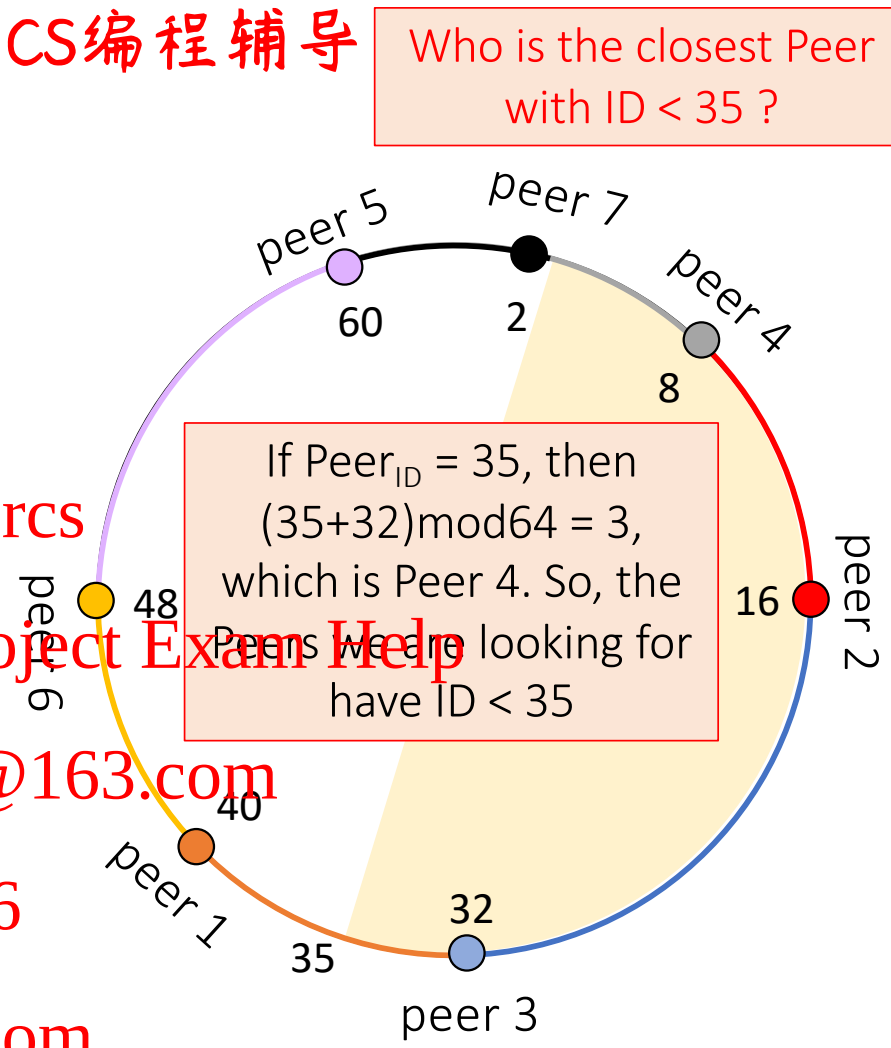

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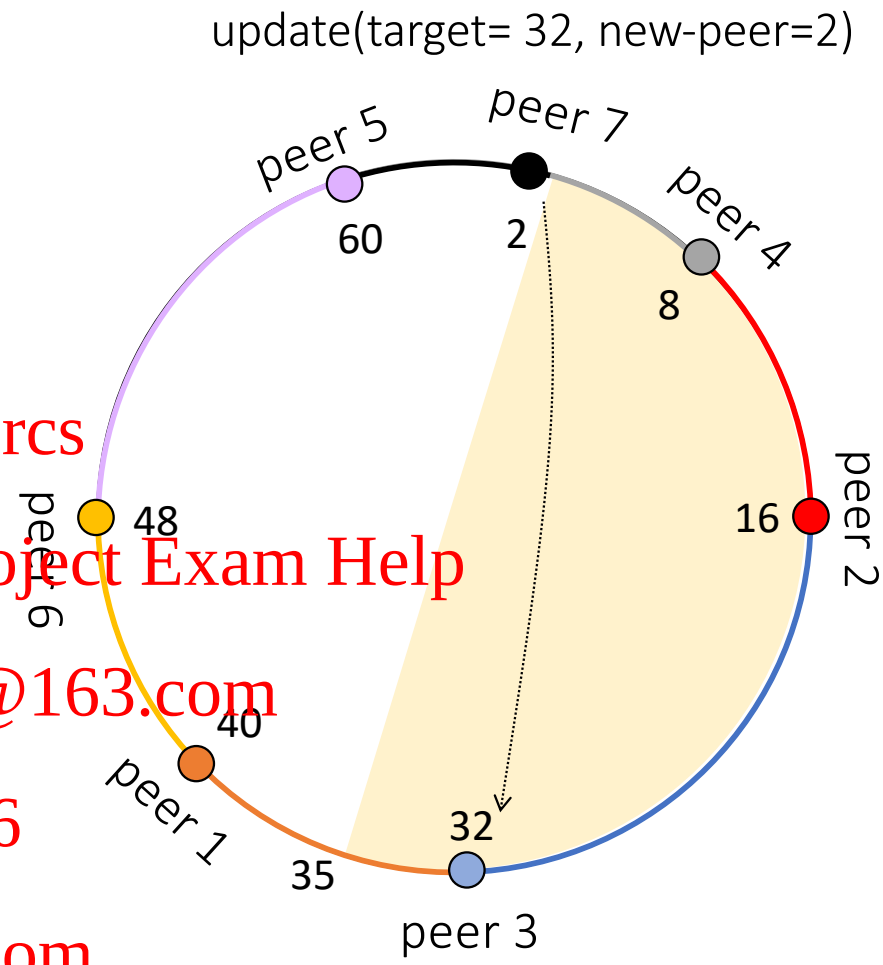

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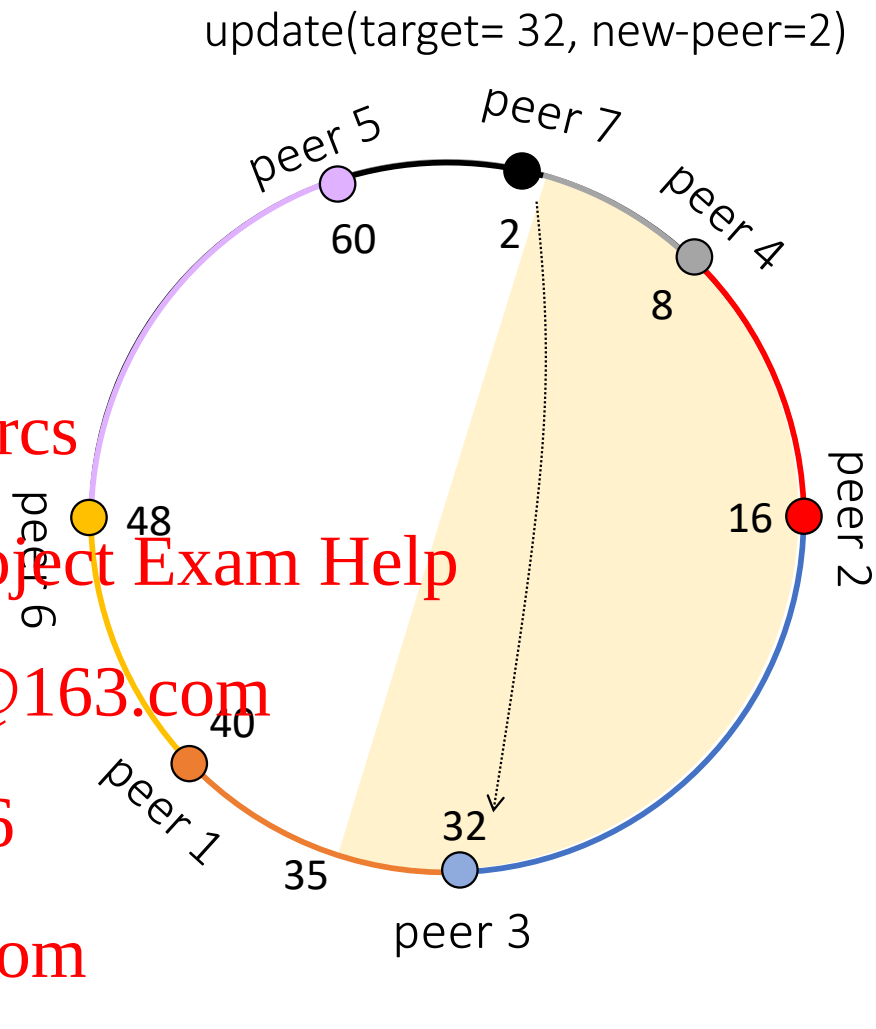
peer 3

i	key id	successor
0	$32 + 2^0 \bmod 64 = 33$	peer 1
1	$32 + 2^1 \bmod 64 = 34$	peer 1
2	$32 + 2^2 \bmod 64 = 36$	peer 1
3	$32 + 2^3 \bmod 64 = 40$	peer 1
4	$32 + 2^4 \bmod 64 = 48$	peer 6
5	$32 + 2^5 \bmod 64 = 0$	peer 4



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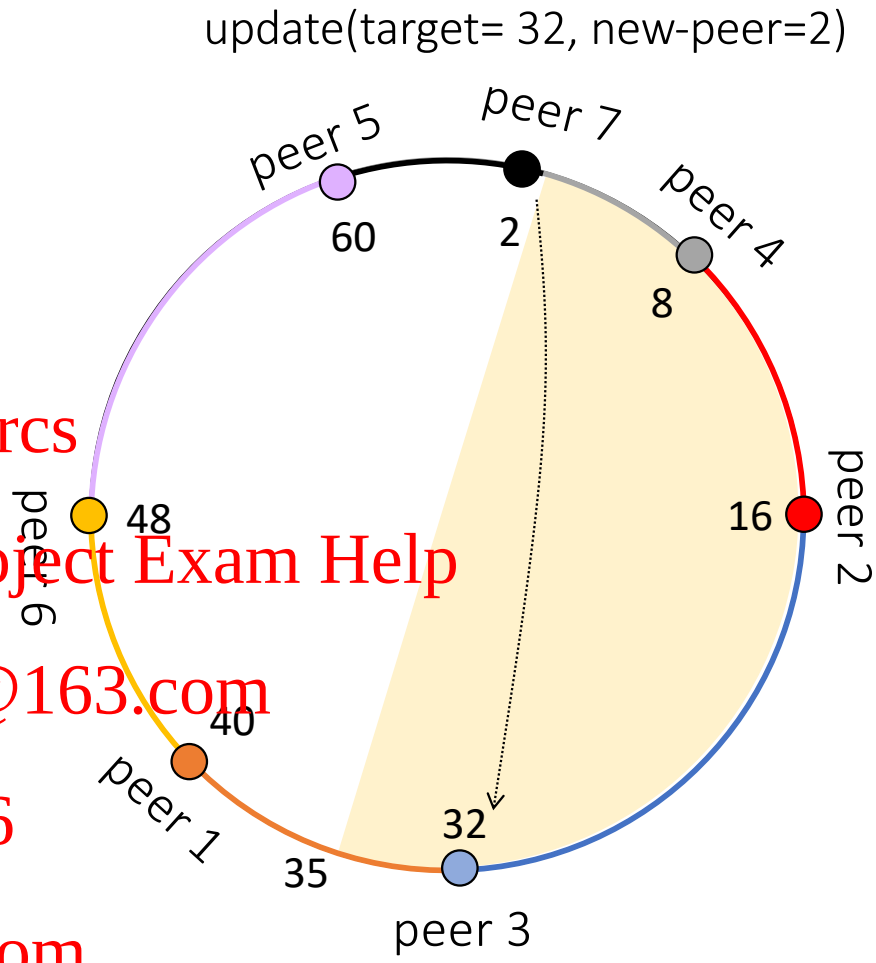
2	$32 + 2^2 \bmod 64 = 36$	peer 1
3	$32 + 2^3 \bmod 64 = 40$	peer 1
4	$32 + 2^4 \bmod 64 = 48$	peer 6
5	$32 + 2^5 \bmod 64 = 0$	**peer 7**



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Steps to trigger update:

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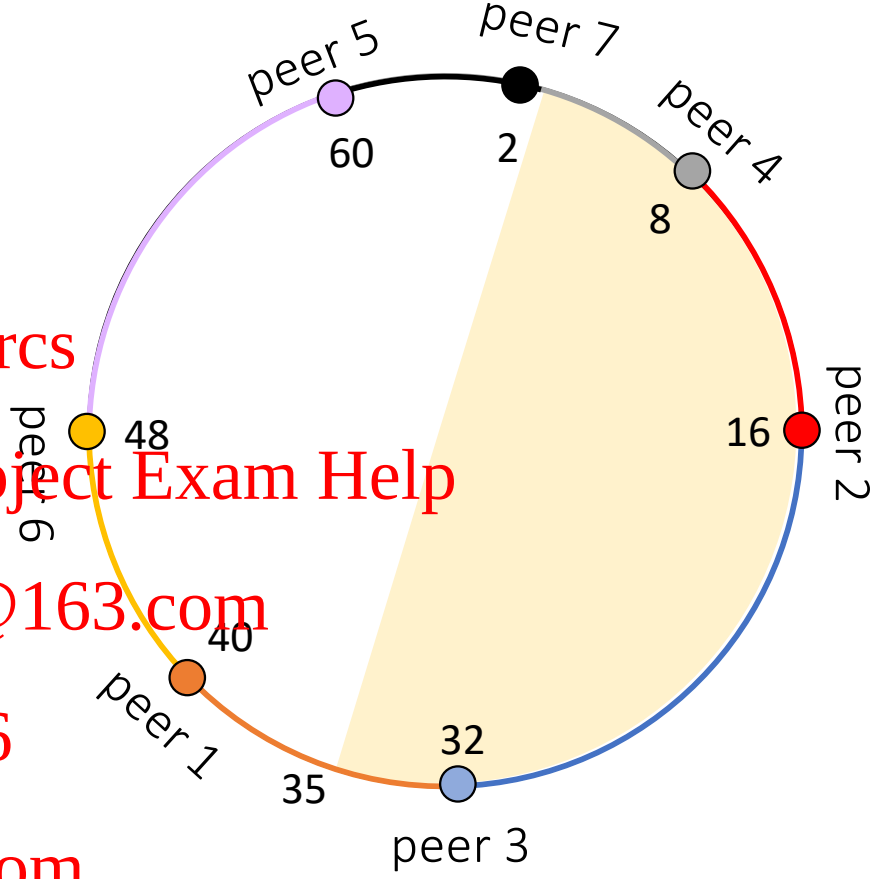
Notes:

- Now Peer 3 is fine!
- But, Peer 2 might not be!



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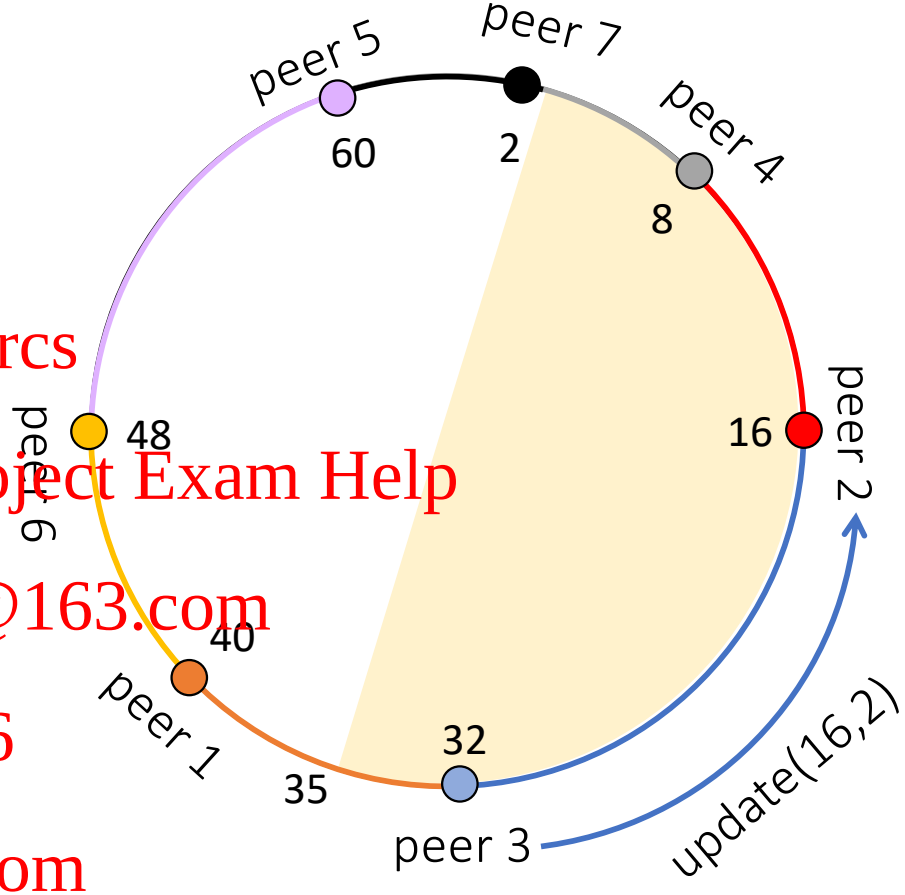
- Now Peer 3 is fine!
- But, Peer 2 might not be!
- Peer 3 sends a message to Peer 2 to warn a potential Finger table update!



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Steps to trigger update:

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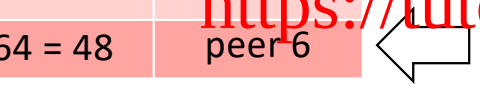
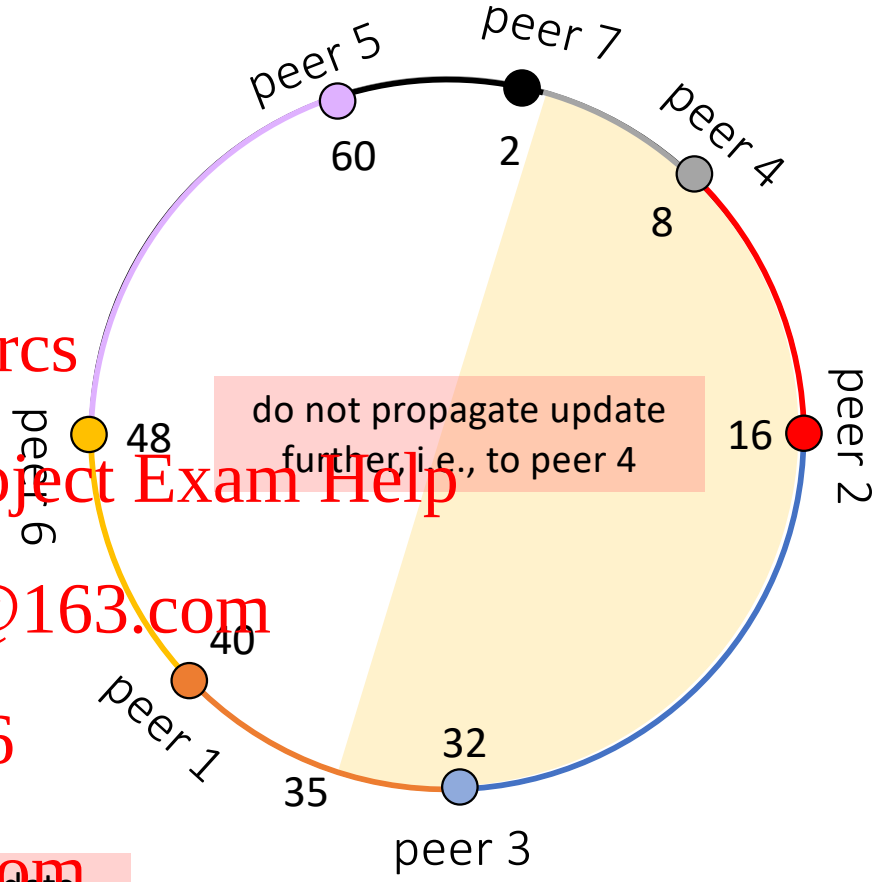
peer 2

i	key id	successor
0	$16 + 2^0 \bmod 64 = 17$	peer 3
1	$16 + 2^1 \bmod 64 = 18$	peer 3
2	$16 + 2^2 \bmod 64 = 20$	peer 3
3	$16 + 2^3 \bmod 64 = 24$	peer 3
4	$16 + 2^4 \bmod 64 = \mathbf{32}$	peer 3
5	$16 + 2^5 \bmod 64 = 48$	peer 6





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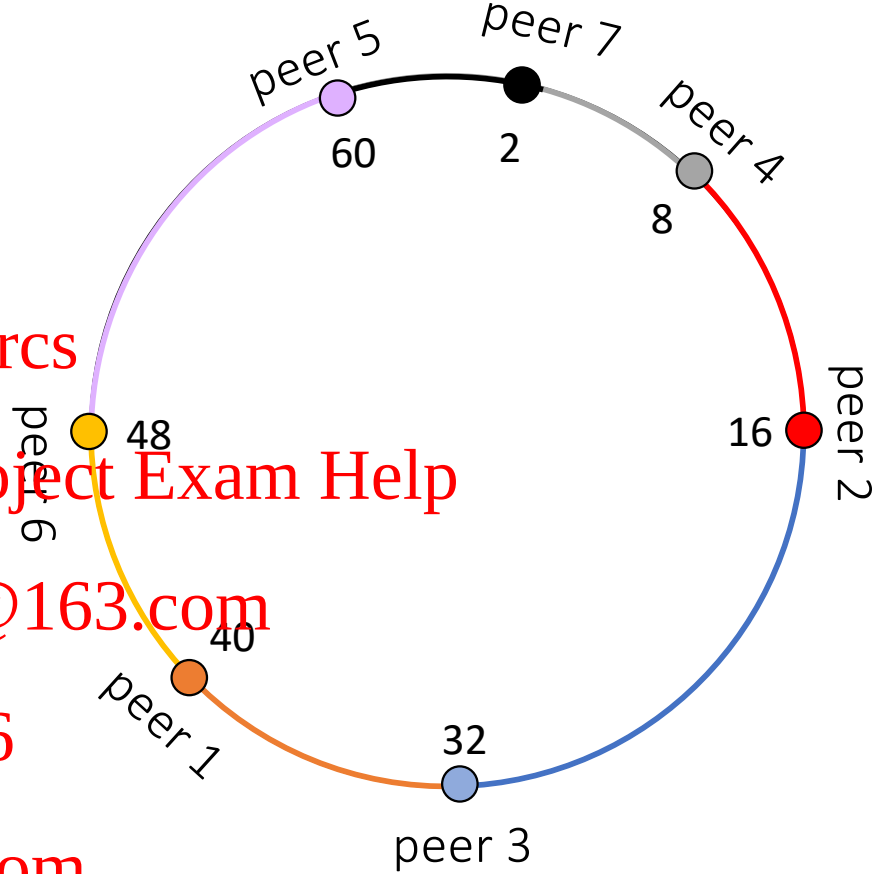

Notes:

- The case i = 5 now completed!!!
- What about i = 4 now?
- i = 4 means $Peer_{ID} + 2^4 = Peer_{ID} + 16$
- Who are the Peers that might fall in Peer 7 authority field for i= 4 ?

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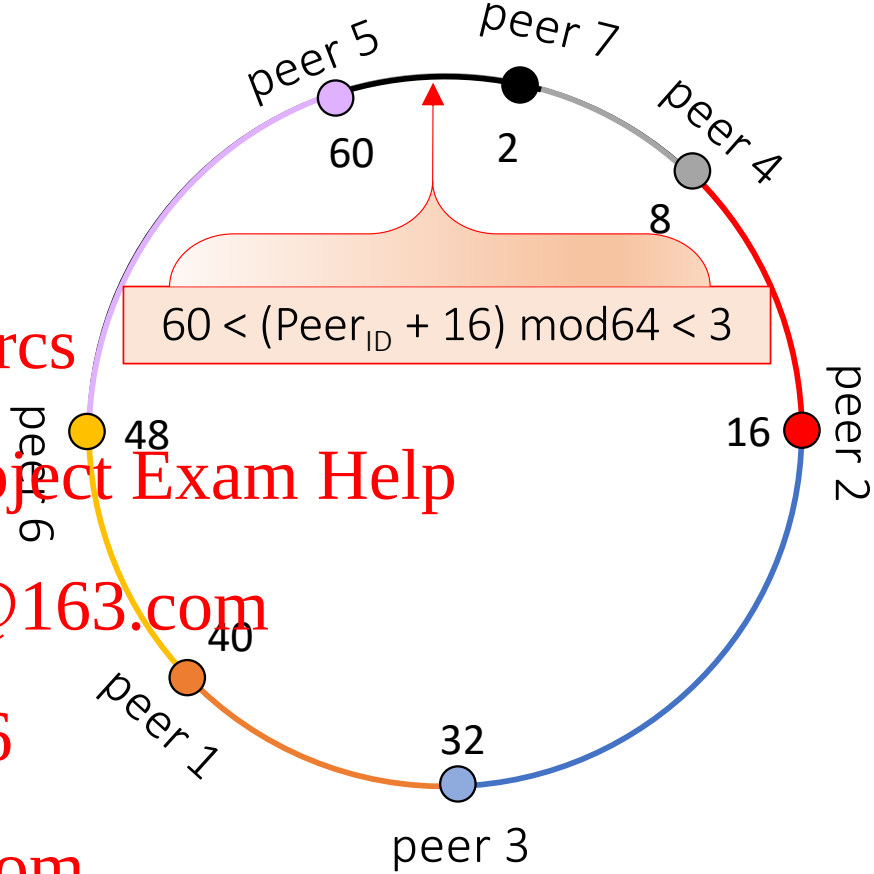

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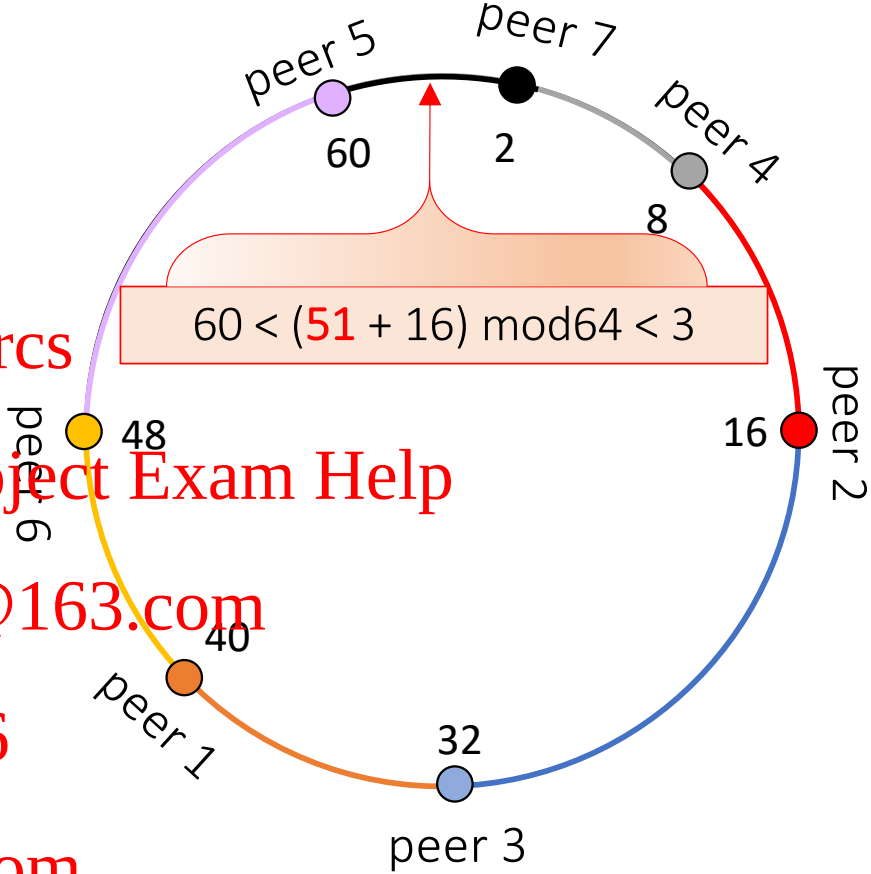

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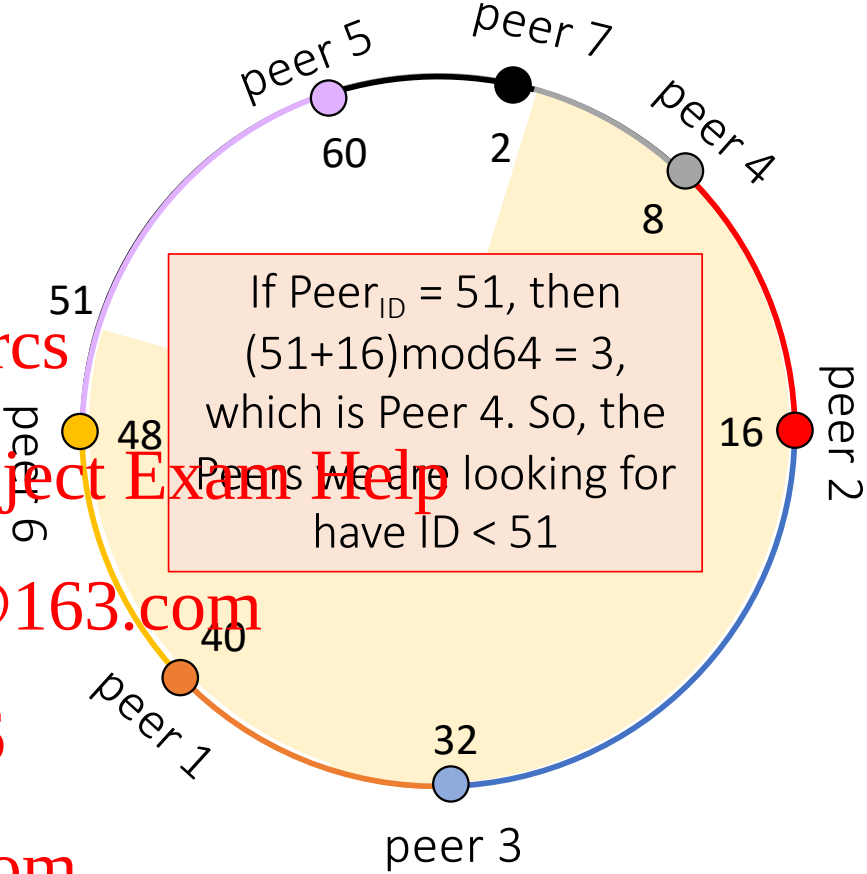

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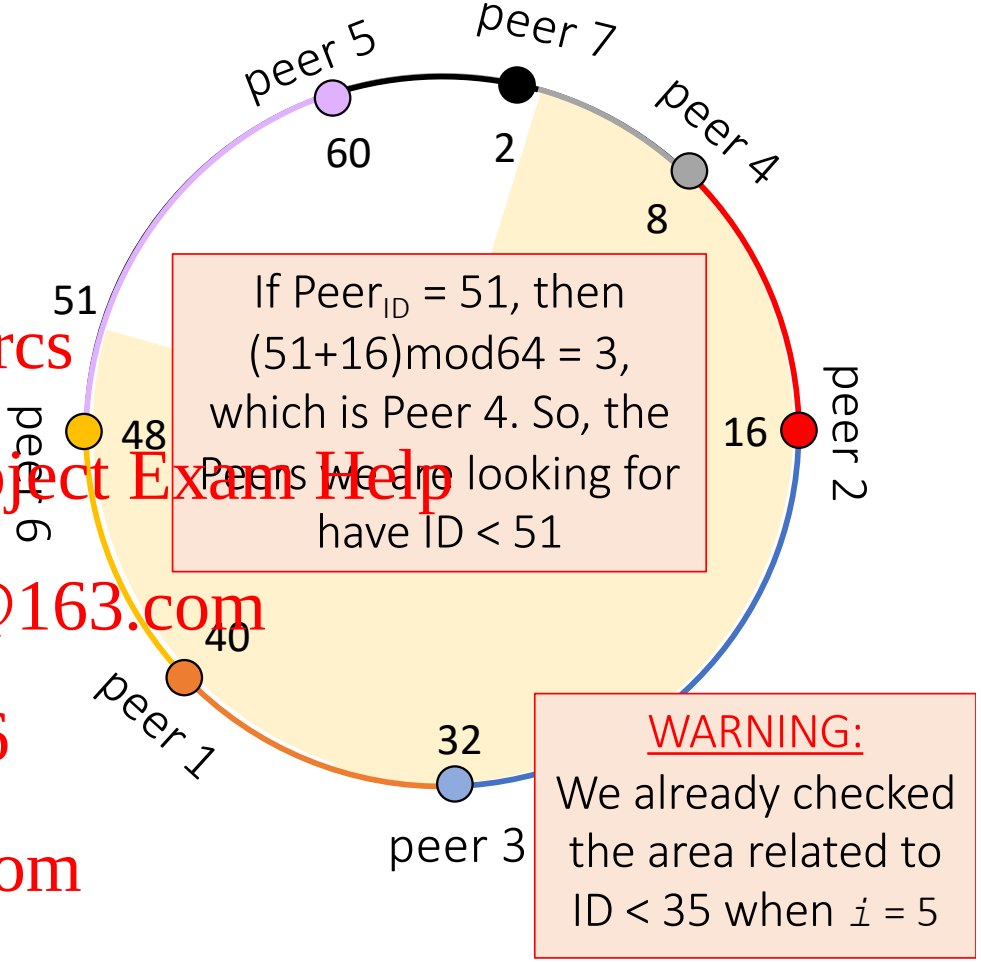

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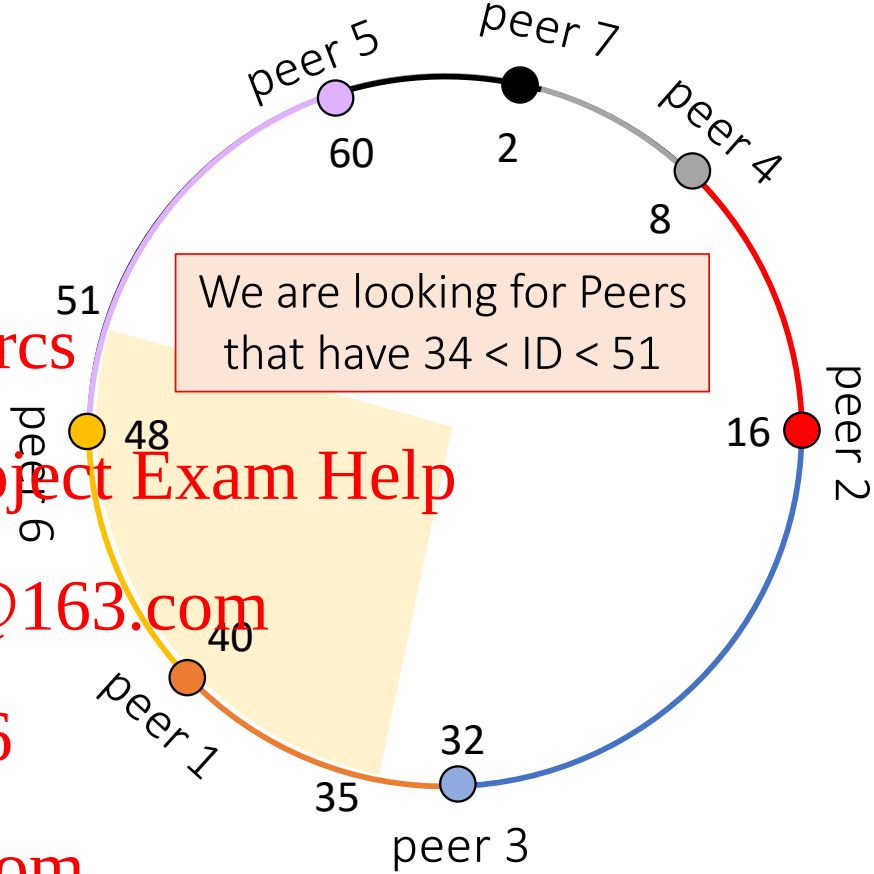

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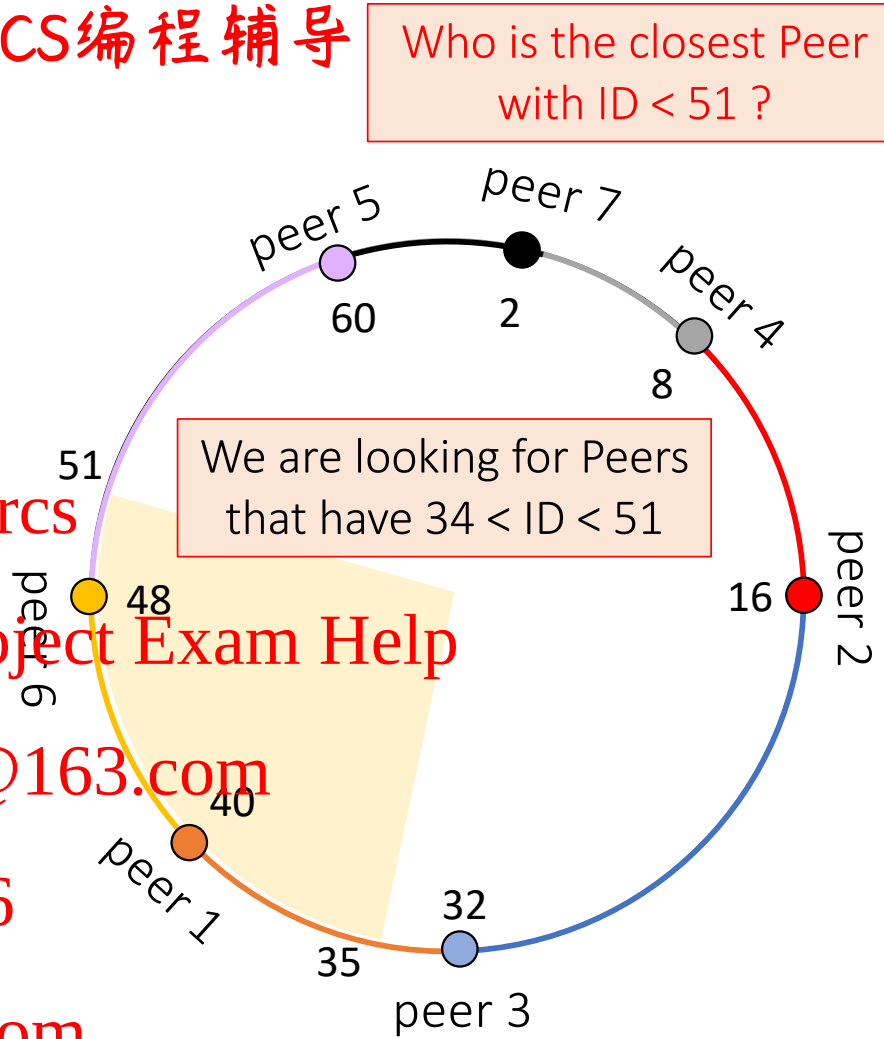

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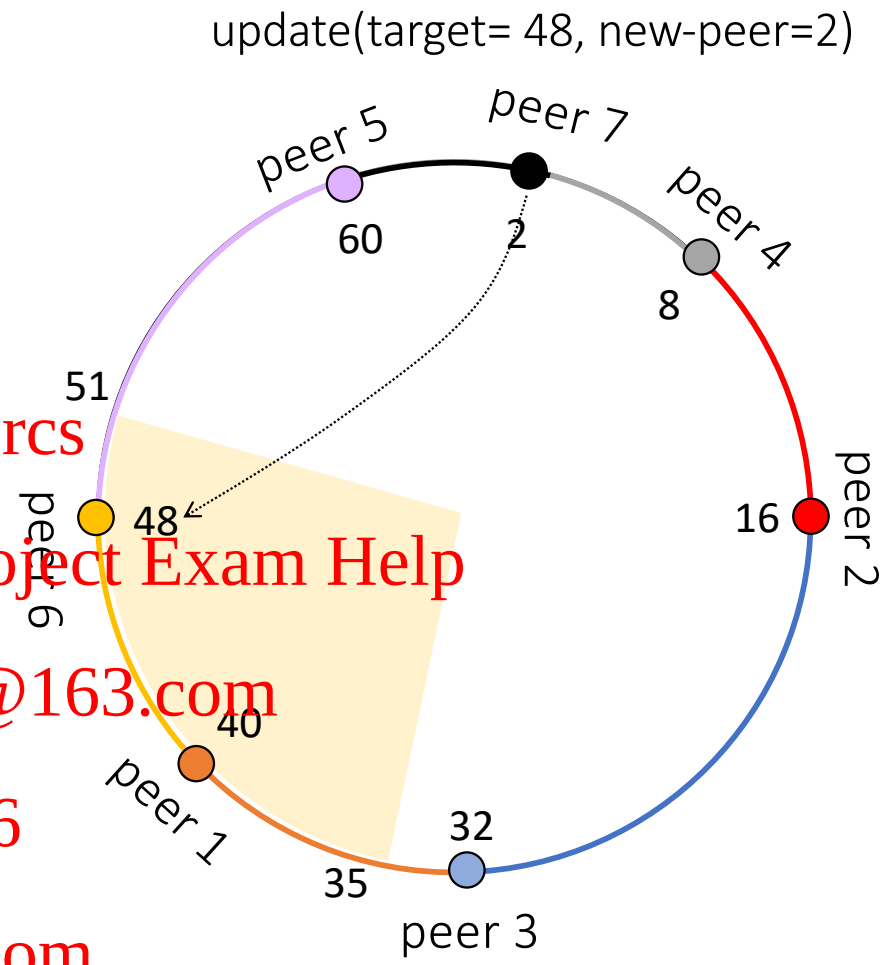


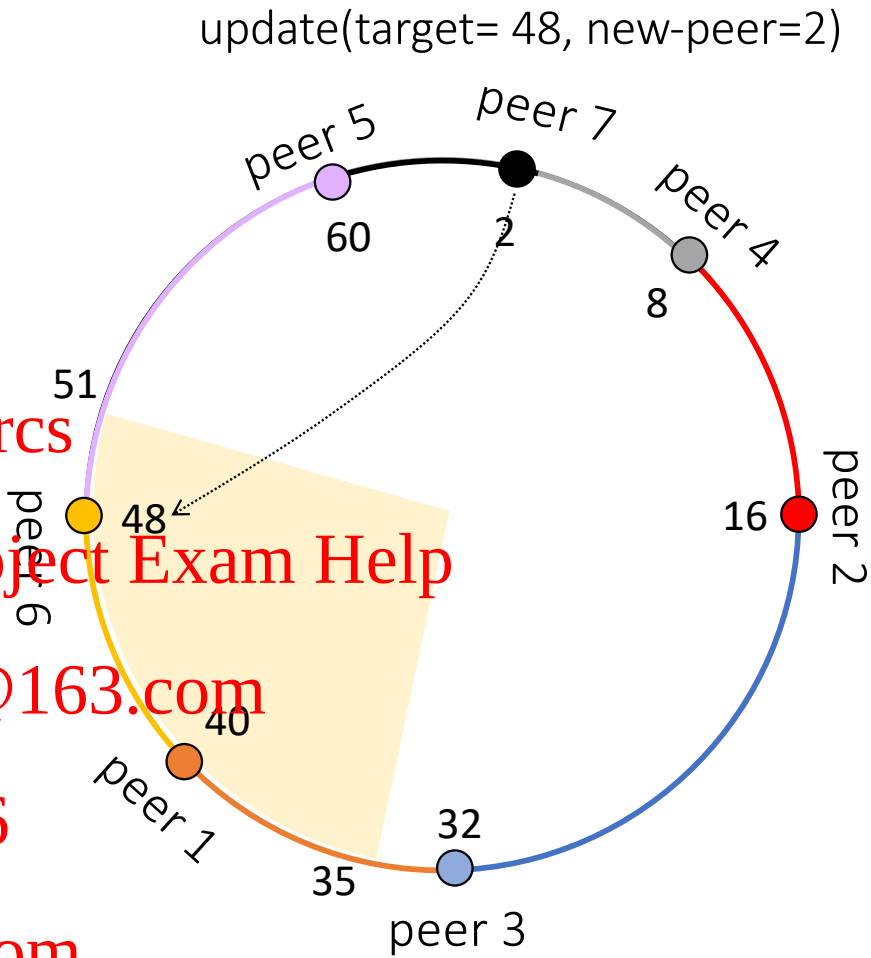
Chord: joining t[redacted]work

Steps to trigger update:

- Notify succ/pred pointers
- Safe to move resource mapping
- Now? Trigger finger tables update for the other peers!

peer 6

i	key id	successor
0	$48 + 2^0 \bmod 64 = 49$	peer 5
1	$48 + 2^1 \bmod 64 = 50$	peer 5
2	$48 + 2^2 \bmod 64 = 52$	peer 5
3	$48 + 2^3 \bmod 64 = 56$	peer 5
4	$48 + 2^4 \bmod 64 = 0$	peer 4
5	$48 + 2^5 \bmod 64 = 16$	peer 2



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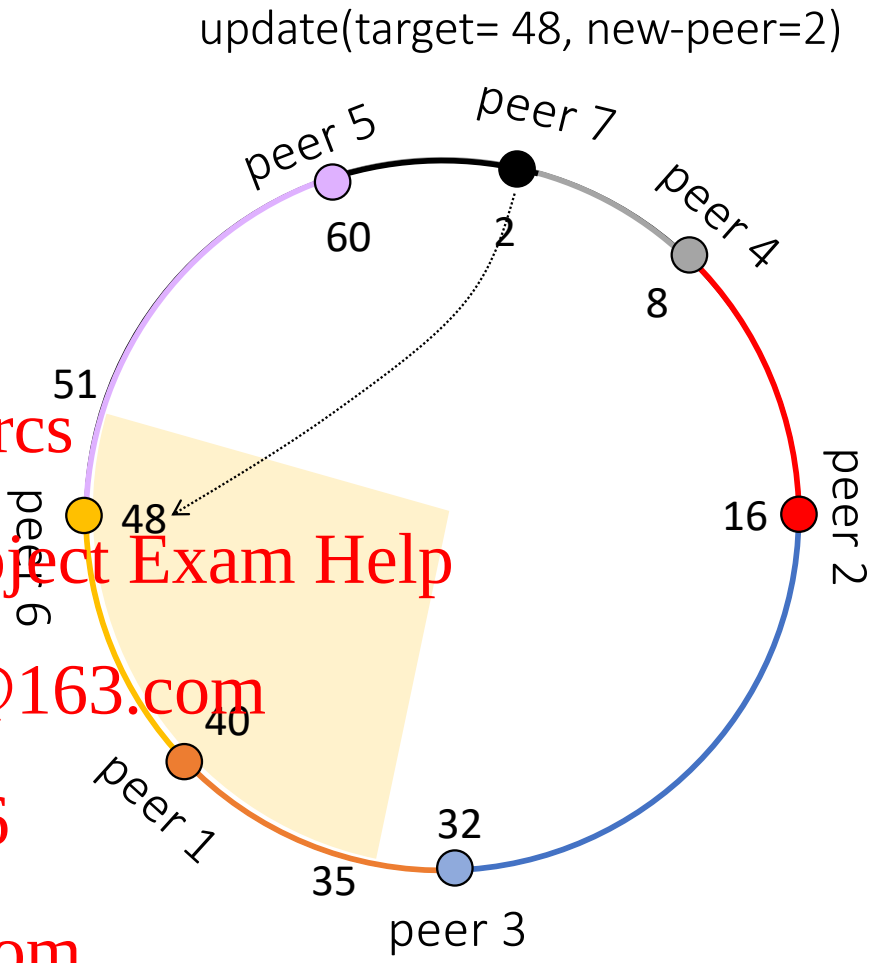
4	$48 + 2^4 \bmod 64 = 0$	**peer 7**
5	$48 + 2^5 \bmod 64 = 16$	peer 2



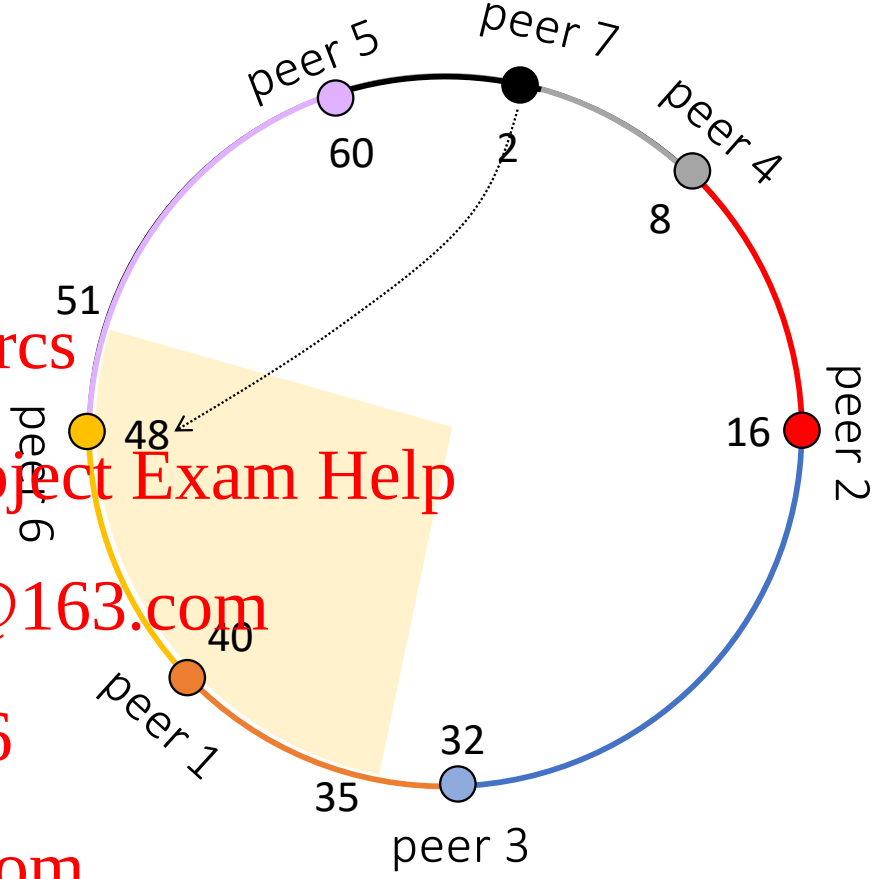
Chord: joining the network

Steps to trigger update:

- Notify succ/pred pointers
- Safe to move resource mapping
- Now? Trigger finger tables update for the other peers!

Notes:

- Now Peer 6 is fine!
- But, Peer 1 might not be!



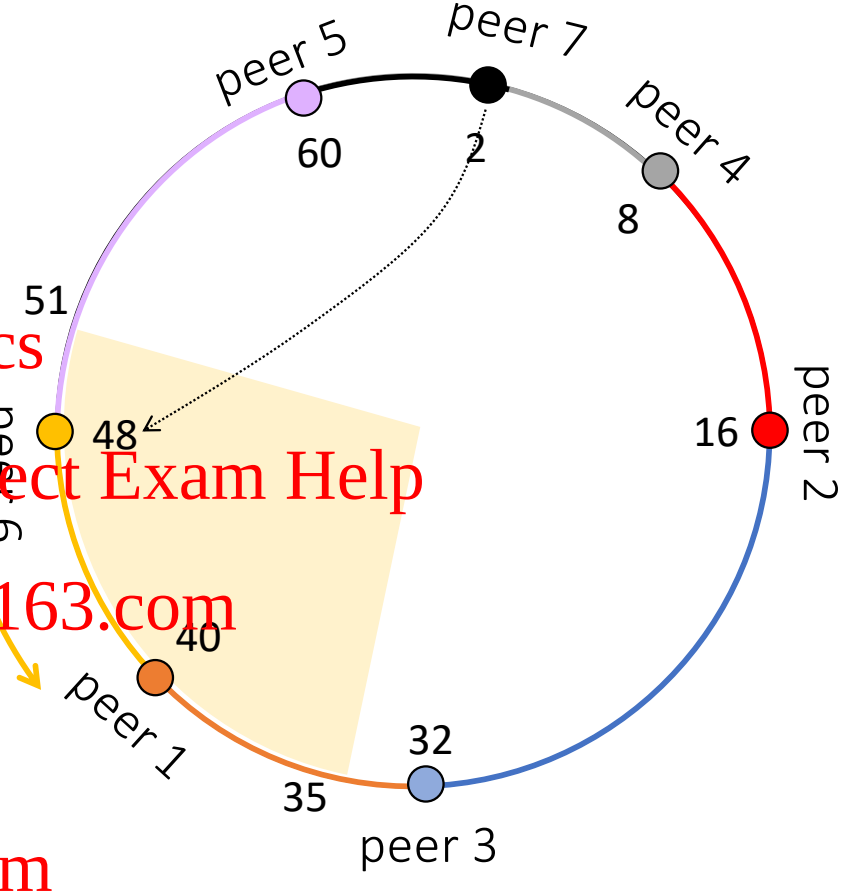
Chord: joining t[redacted]work

Steps to trigger update:

- Notify succ/pred pointers
- Safe to move resource mapping
- Now? Trigger finger tables update for the other peers!

Notes:

- Now Peer 6 is fine!
- But, Peer 1 might not be!
- Peer 6 sends a message to Peer 1 to warn a potential Finger table update!



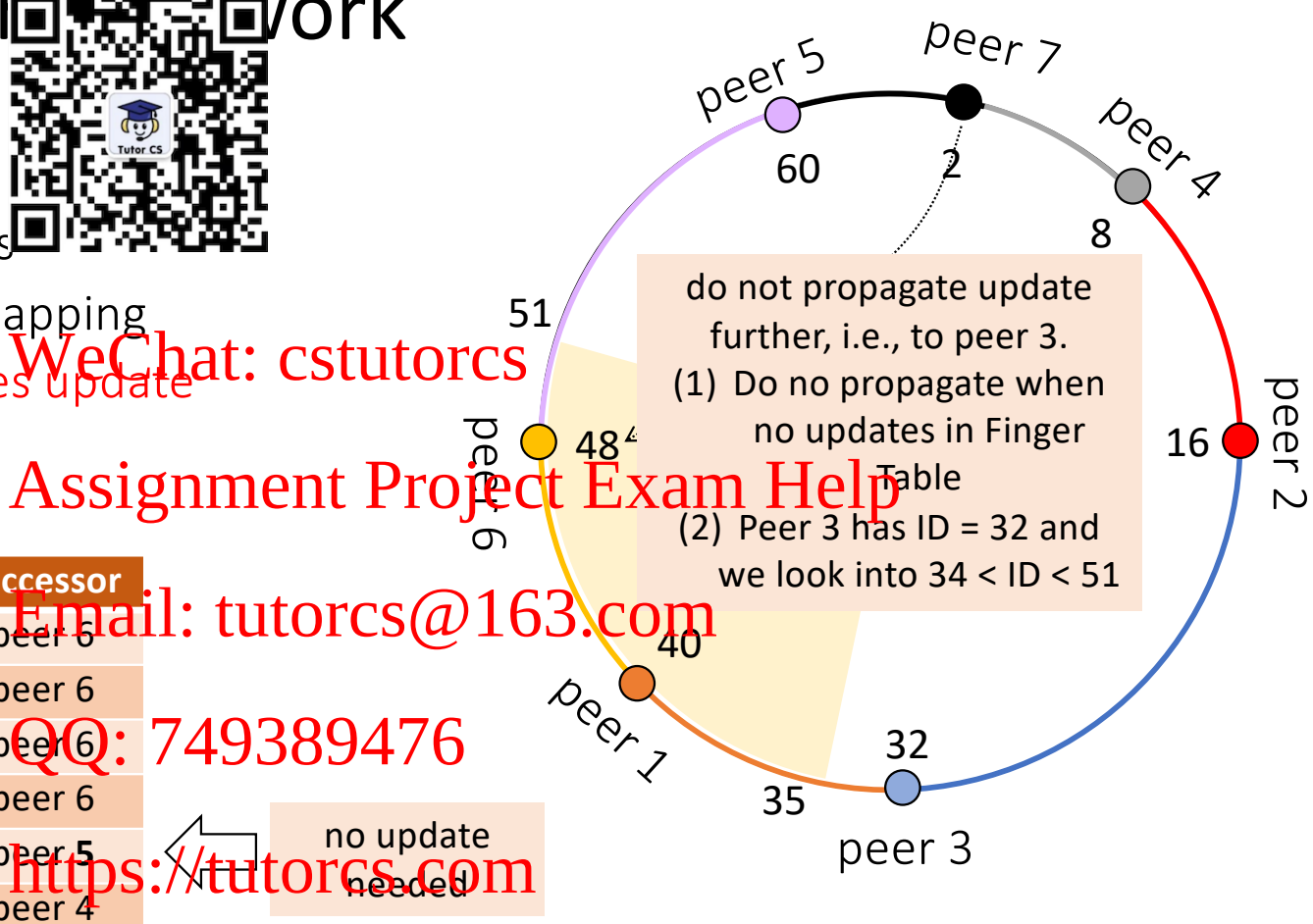
Chord: joining t[redacted]work

Steps to trigger update:

- Notify succ/pred pointers
- Safe to move resource mapping
- Now? Trigger finger tables update for the other peers!

peer 1

i	key id	successor
0	$40 + 2^0 \bmod 64 = 41$	peer 6
1	$40 + 2^1 \bmod 64 = 42$	peer 6
2	$40 + 2^2 \bmod 64 = 44$	peer 6
3	$40 + 2^3 \bmod 64 = 48$	peer 6
4	$40 + 2^4 \bmod 64 = \mathbf{56}$	peer 5
5	$40 + 2^5 \bmod 64 = 8$	peer 4



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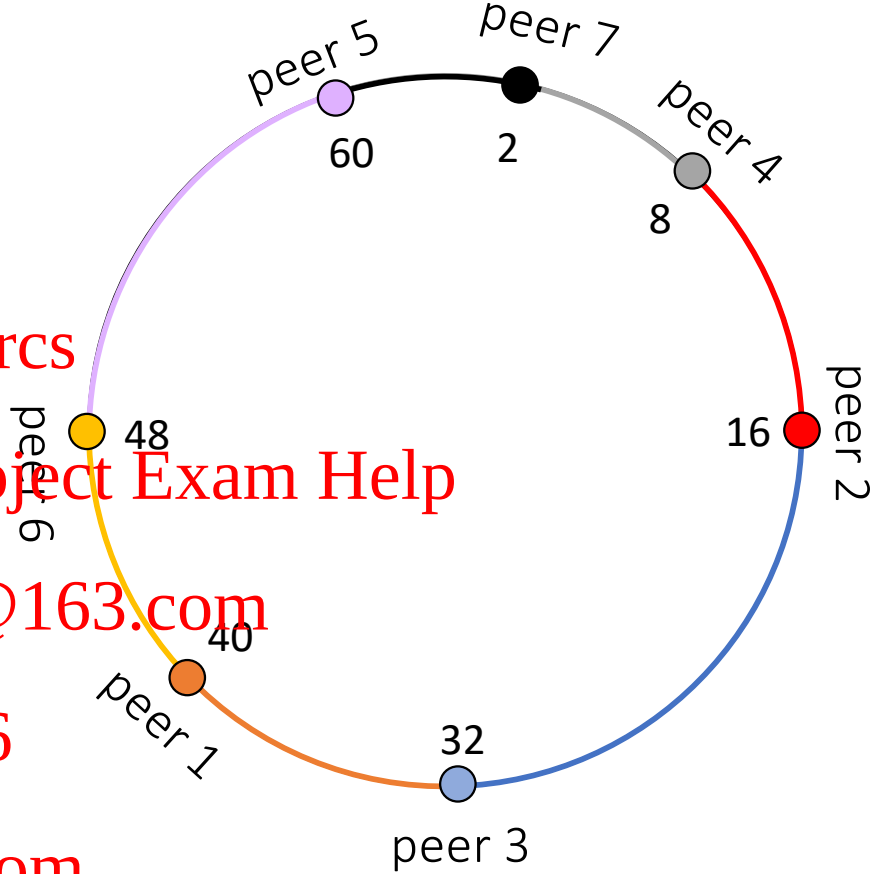


Notes:

- The cases i = (5,4) now completed!
- What about i = 3 now?
- i = 3 means $Peer_{ID} + 2^3 = Peer_{ID} + 8$
- Who are the Peers that might fall in Peer 7 authority field for i= 3 ?

Chord: joining t[redacted]work

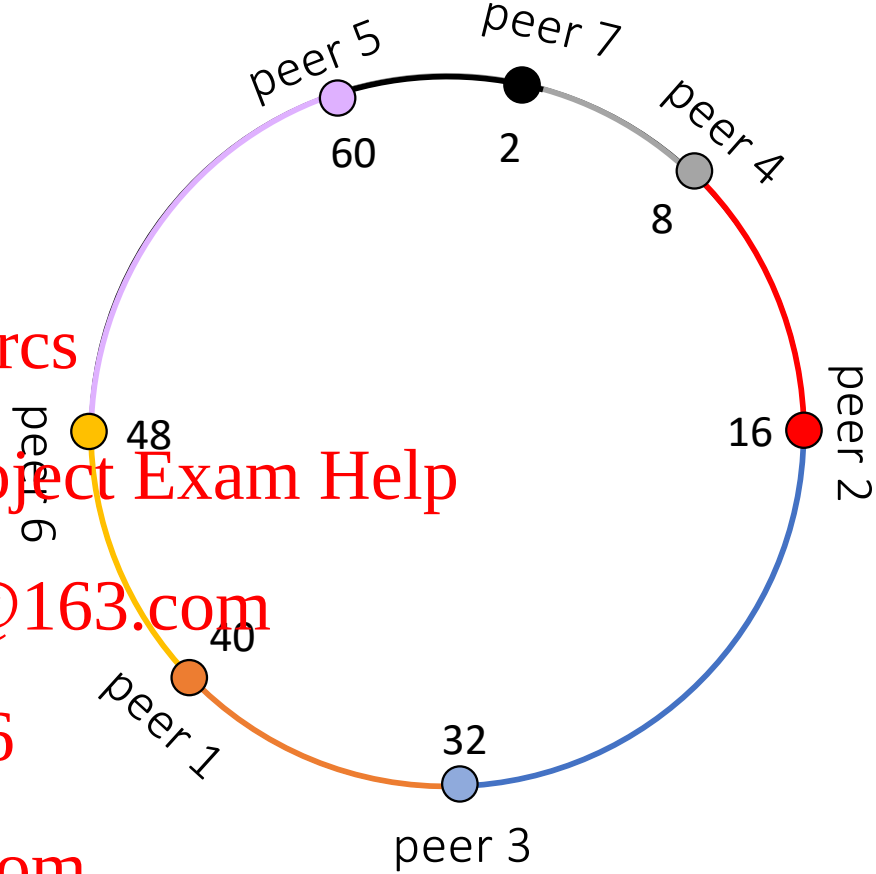
Steps to trigger update:

- Notify succ/pred pointers
- Safe to move resource mapping
- Now? Trigger finger tables update for the other peers!

Notes:

- The cases i = (5,4) n[redacted]mpleted!
- What about i = [redacted]
- i = 3 mea[redacted] = $Peer_{ID}$ + 8
- Who [redacted]s that might fail/in Peer 7 [redacted]nity field for i= 3 ?

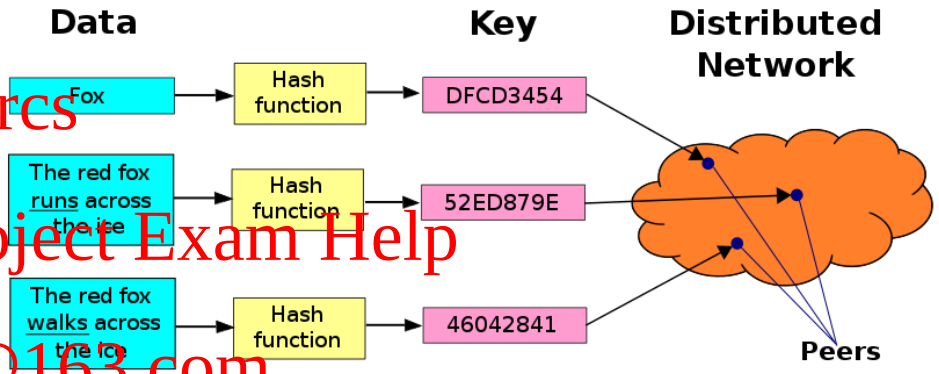
This is an iterative process!!



DHT recap

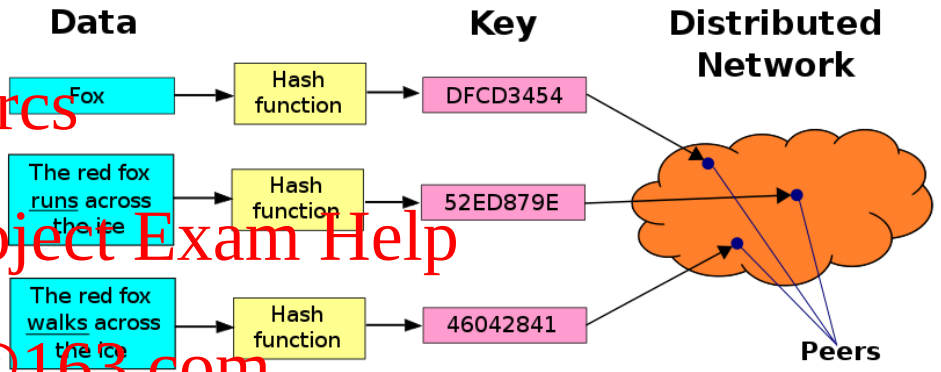
- DHT is a class of a decentralized distributed system that provides a lookup service like a hash table: (key, value) pairs are stored in a DHT

- Keys are unique identifiers which map to values, which in turn can be anything from addresses, to documents, to arbitrary data.



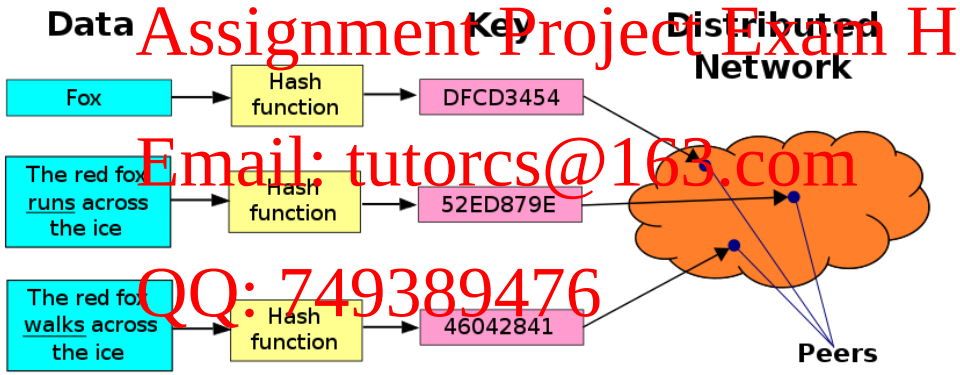
DHT recap

- DHTs can form the infrastructure that can be used to build more services like P2P
- WARNING: not only that!
- Do not associate DHT to only P2P!



DHT recap

- It is an approach for Key-[illegible]e --> The value is stored in a database in the form of a two-value tuple [illegible]e identifier(key) and other is the actual data(Value), and hence it is called as Key Value Store.



The key-value abstraction

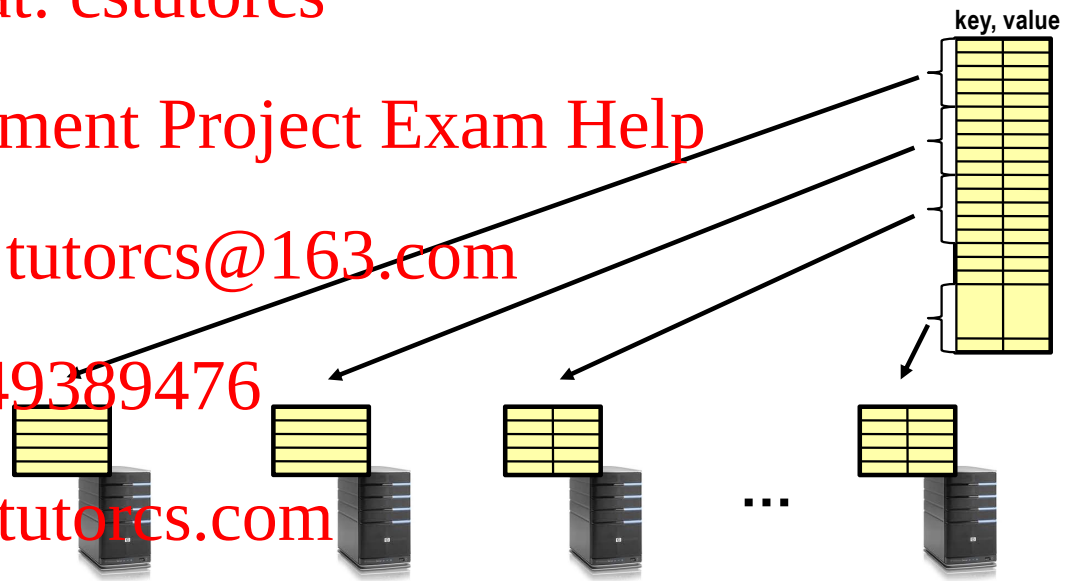
- (twitter.com): user ID --> information about that user (e.g., posting history, photos, friends..)
- (amazon.com): item number --> information about it
- (kayak.com): flight number --> information about flight (e.g., availability)
- (yourbank.com): account number --> information about it

The key-value abstraction (cont'd)

- It's a dictionary data-structure
- But distributed. (Too much data, you can maintain them in a single server)
- Sound familiar? Here the connection with DHTs!
- It is not surprising that key-value stores reuse many techniques from DHTs

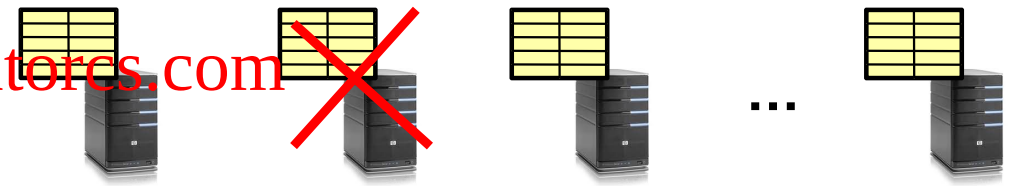
Too much data to contain in a single server

Key Idea: partition set of [illegible] across many machines



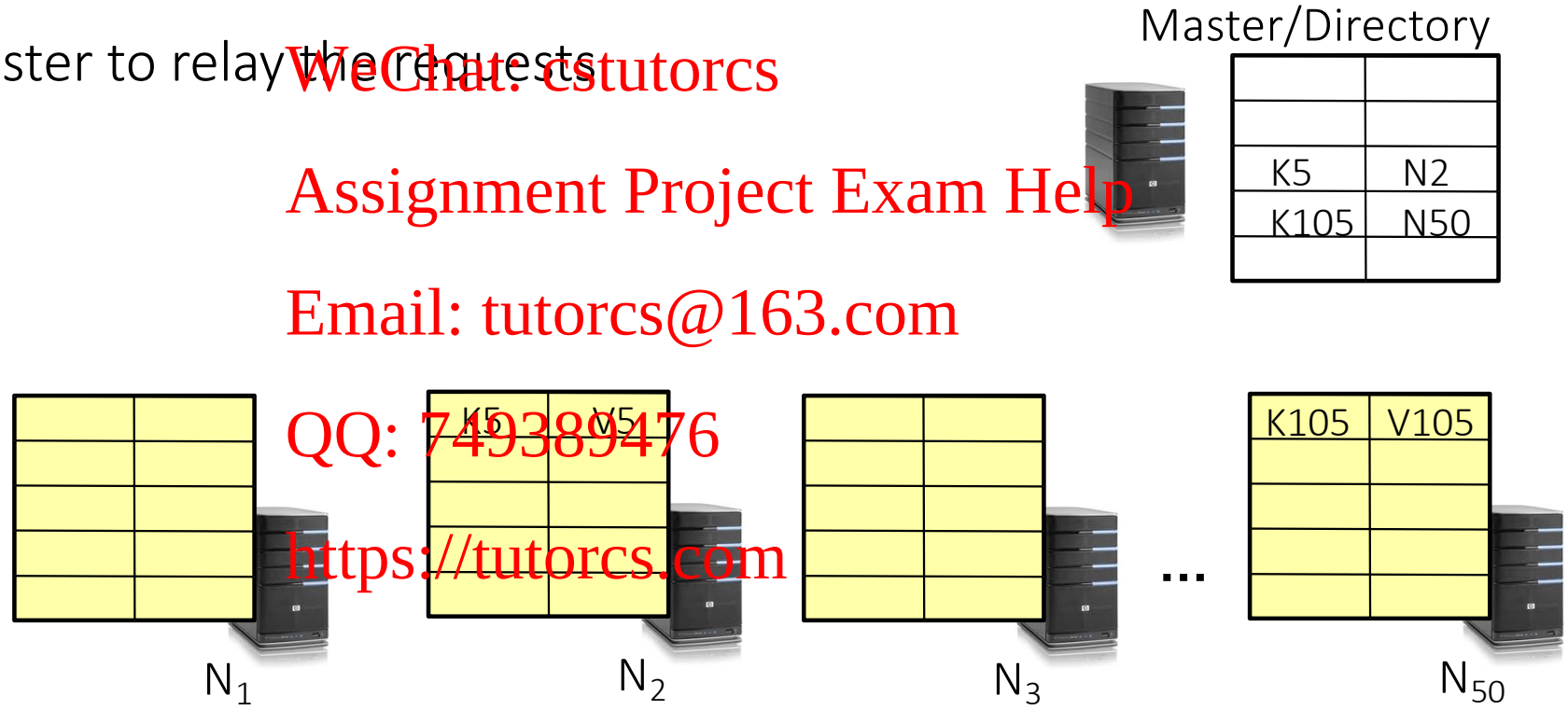
Challenges

- **Fault Tolerance:** handle machine failures without losing data and without degradation in performance
- **Scalability:**
  - Need to scale to thousands of machines
  - Need to allow easy addition of new machines
- **Consistency:** maintain data consistency in face of node failures and message losses



Directory-based architecture: recursive query

- Have a node maintain the mapping between **keys** and the **machines (nodes)** that store the **values** associated with the **keys**.
- Having the master to relay the requests



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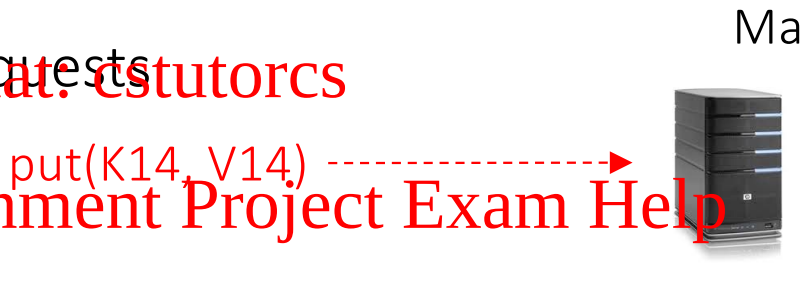

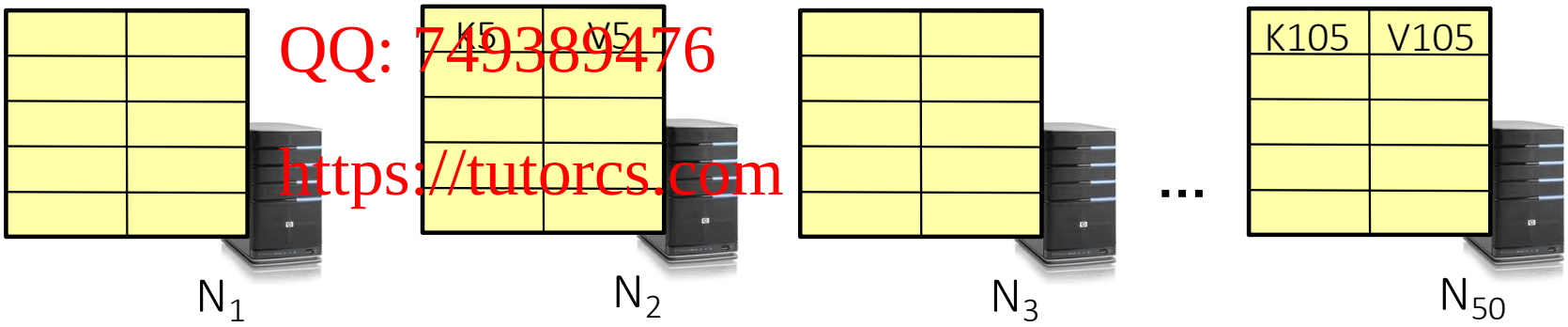

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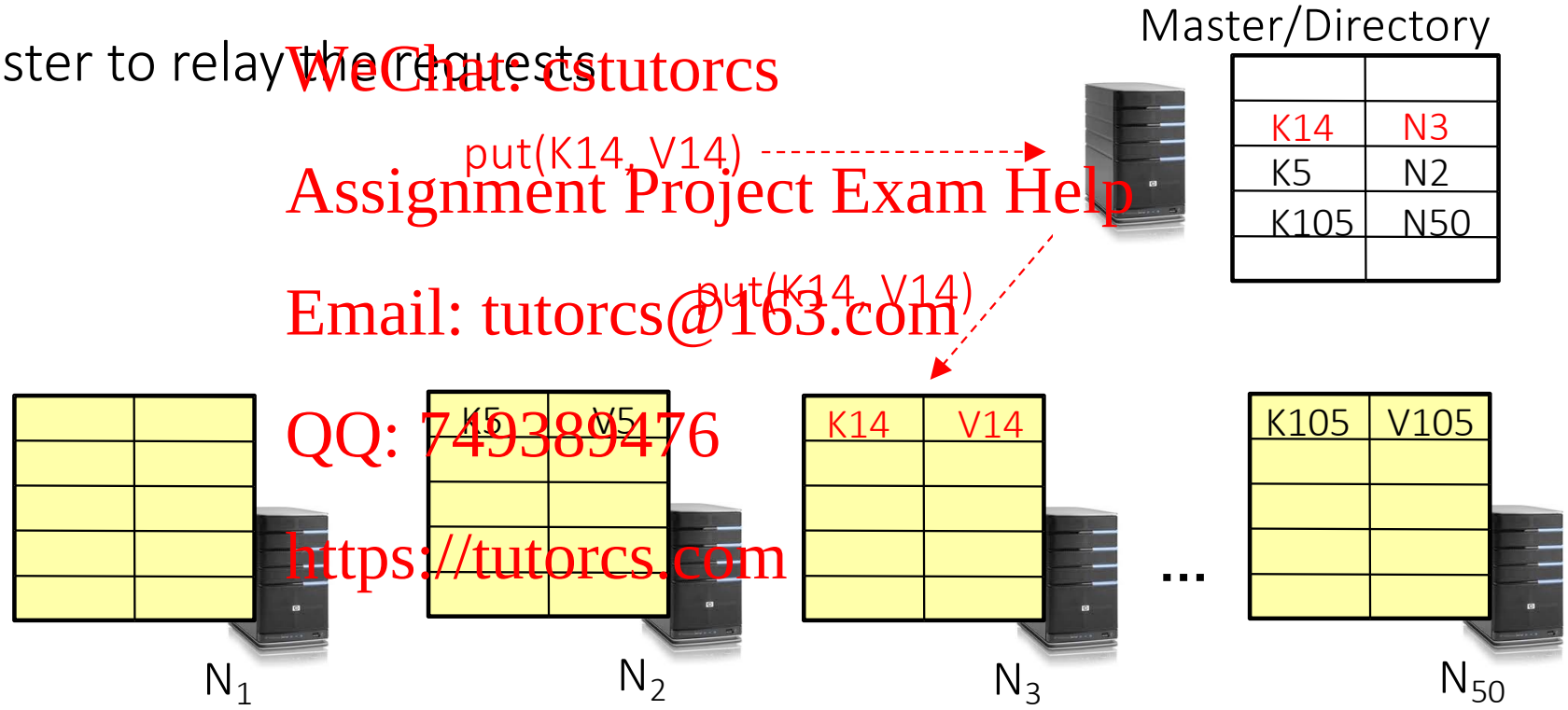

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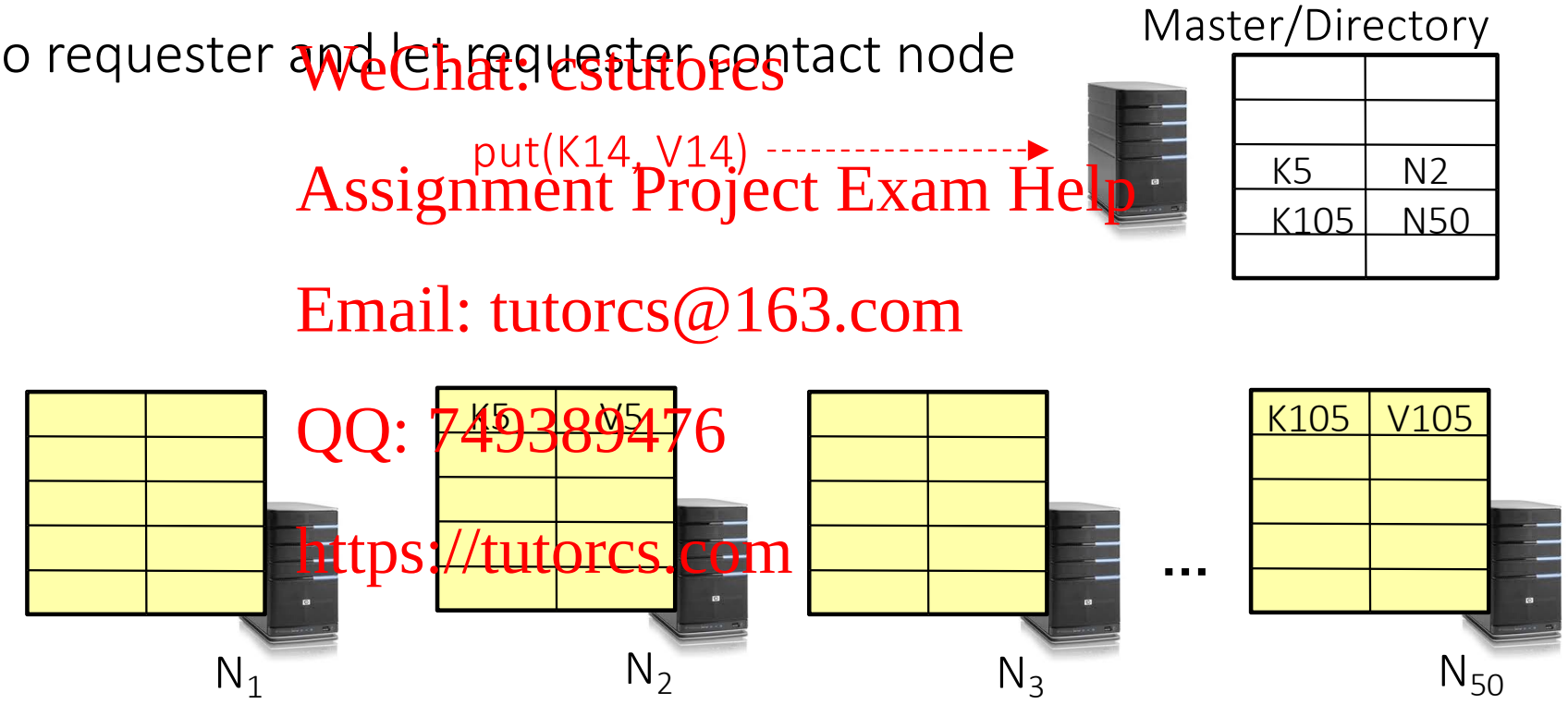

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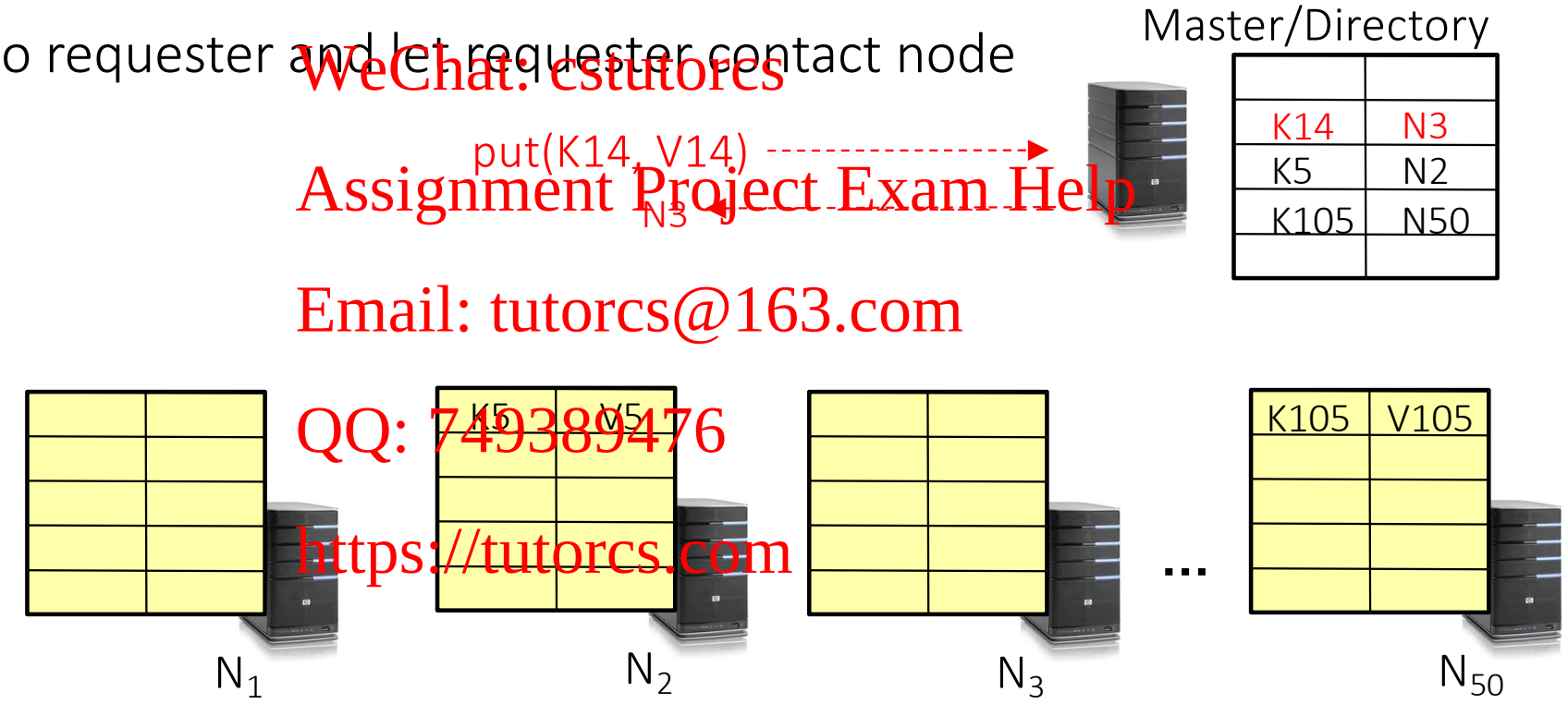

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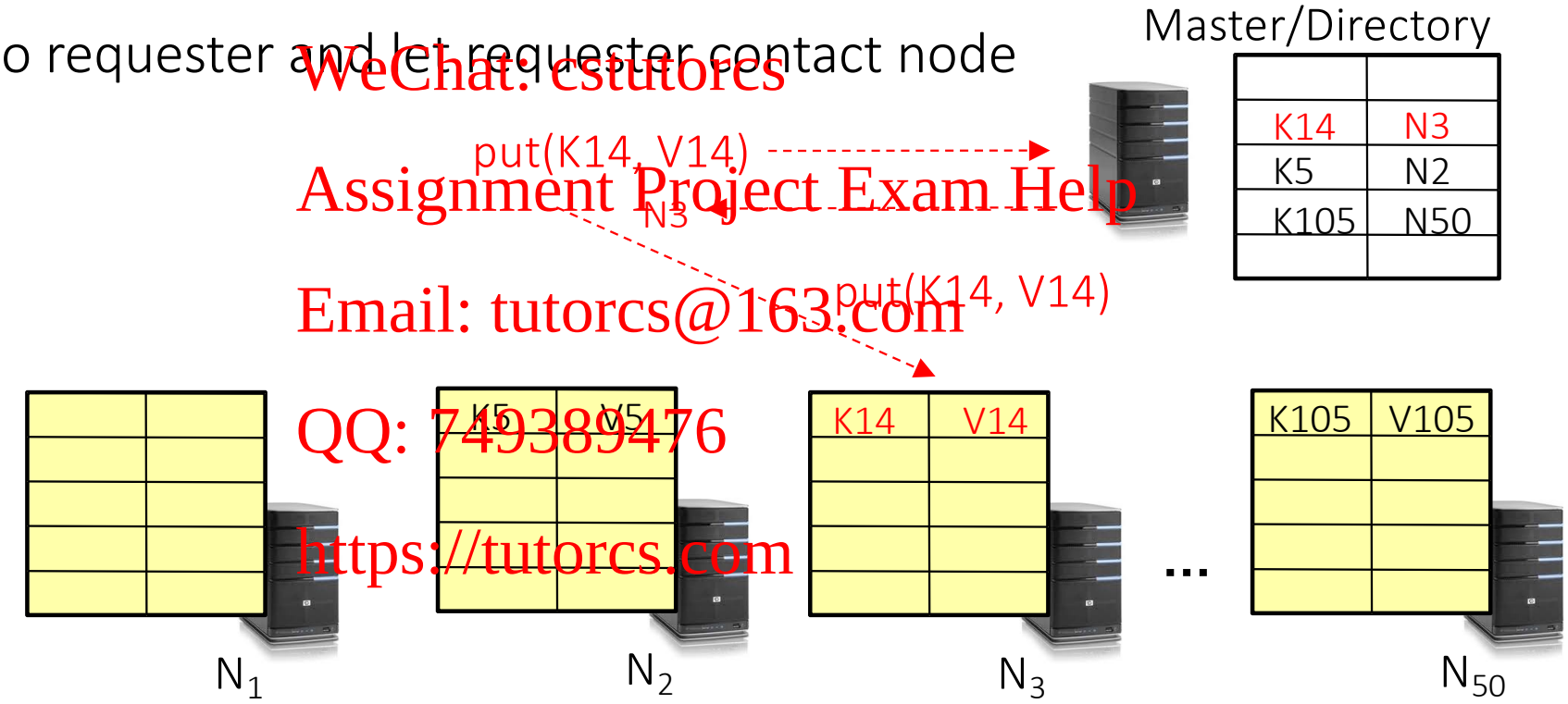
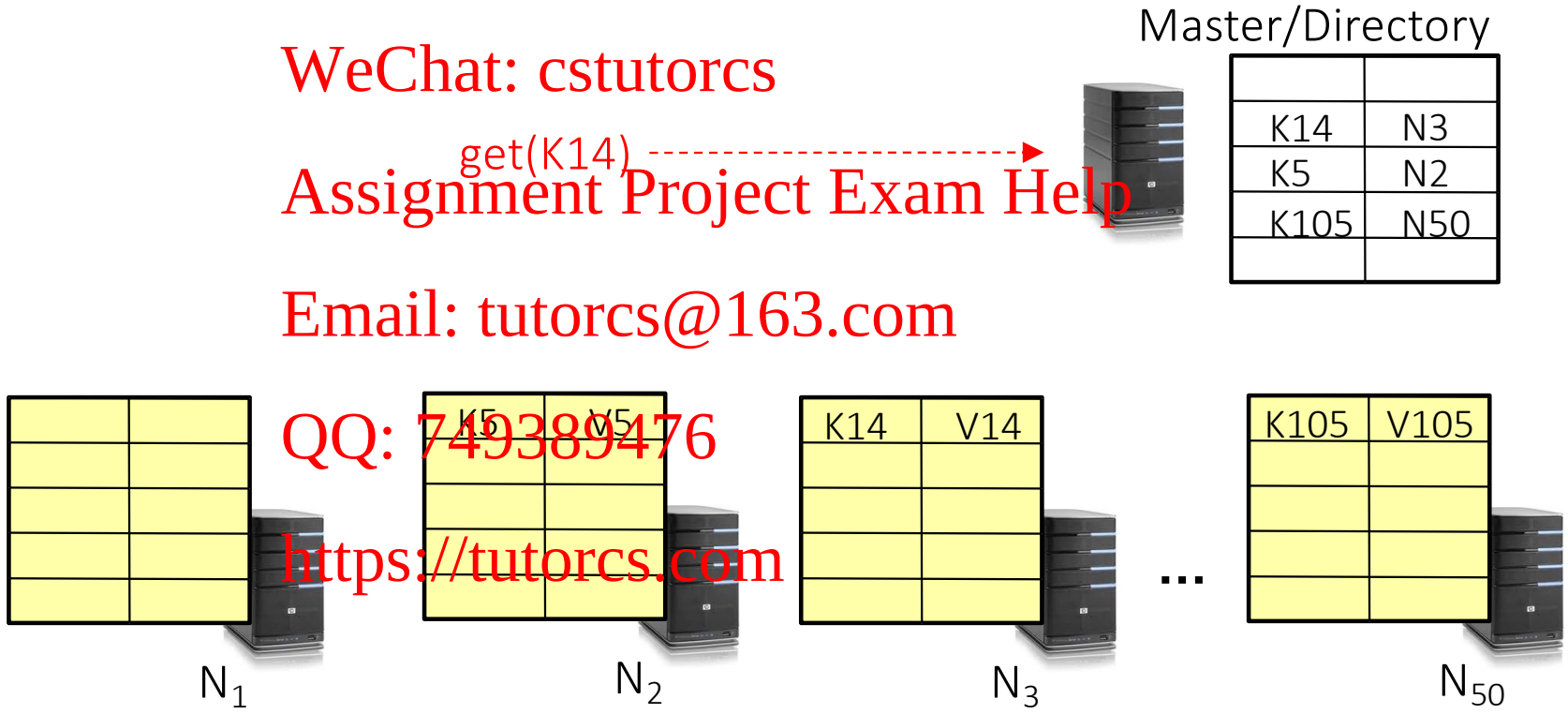


Directory-based architecture: iterative query

- The same solution applies to retrieve a value…



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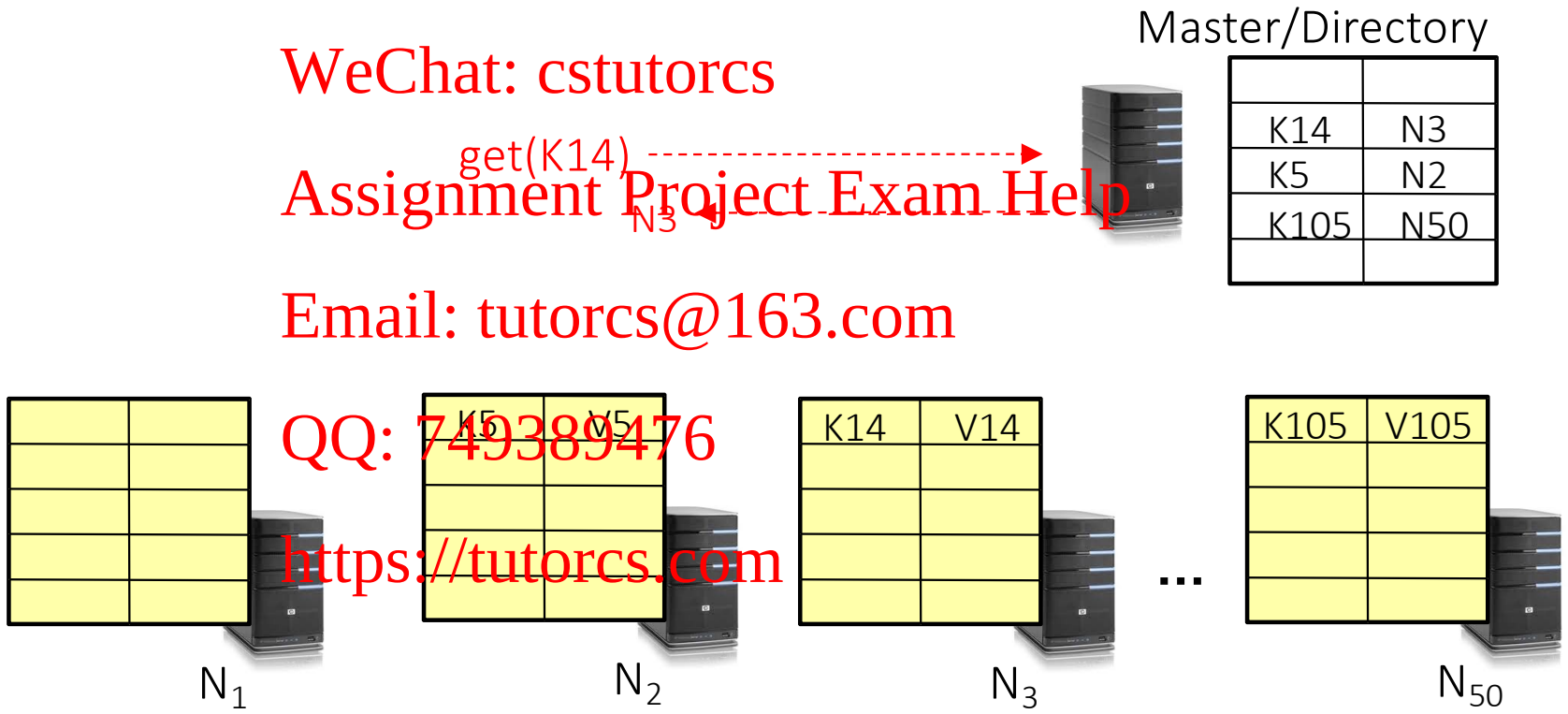

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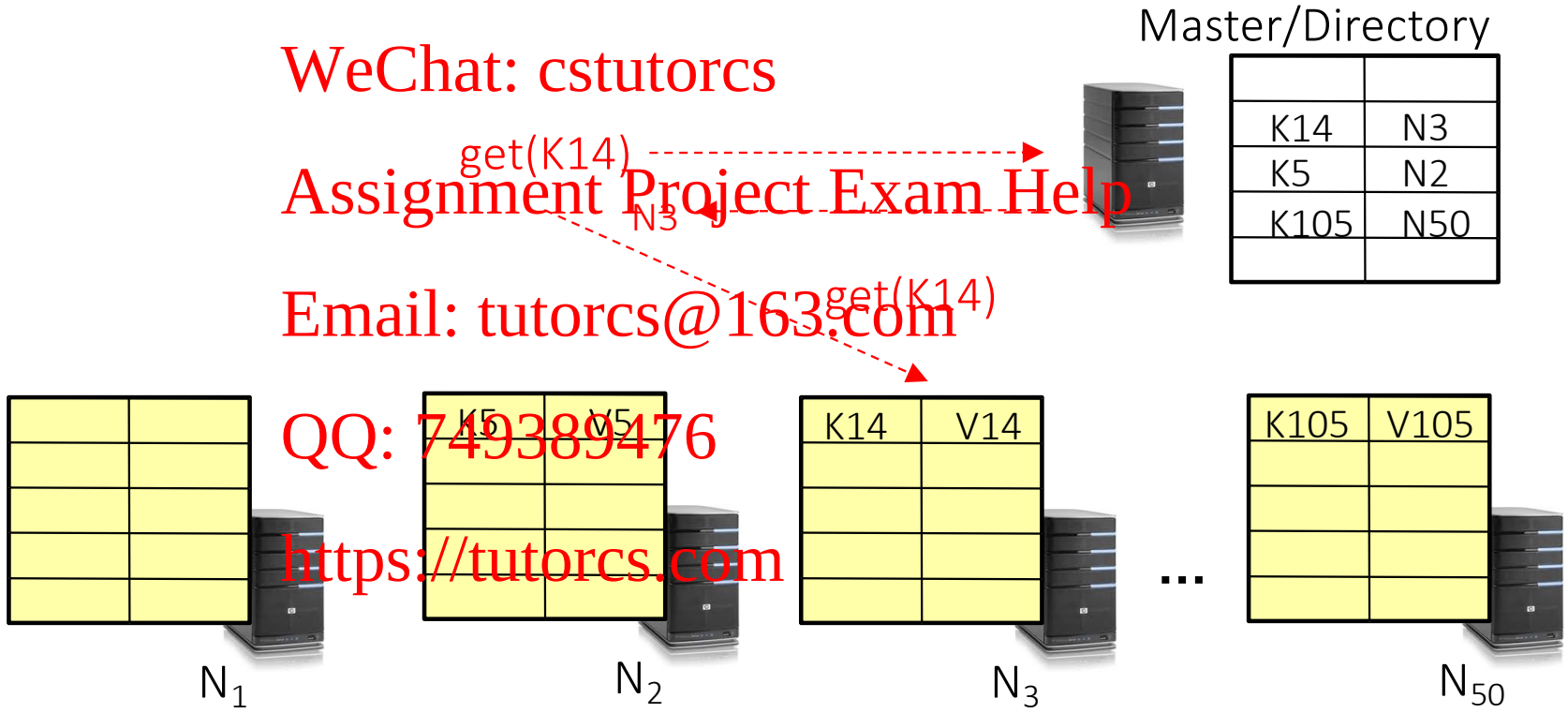

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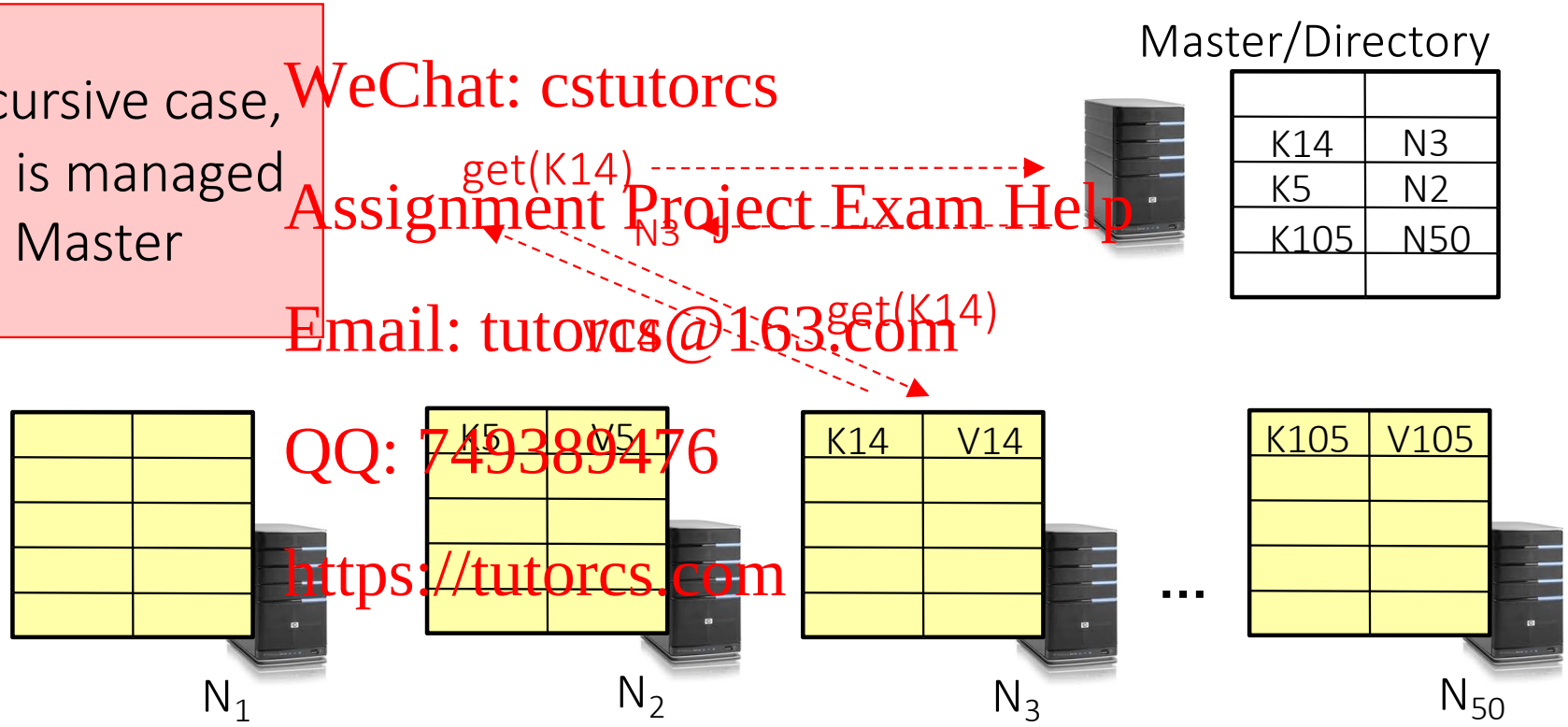
For the recursive case, everything is managed by the Master



Iterative vs recursive query

- Recursive Query (Master ir
  - Advantages:
    - Faster, as typically master/directory closer to nodes
    - Easier to maintain consistency, as master/directory can serialize puts()/gets()
  - Disadvantages: scalability bottleneck, as all "Values" go through master

- Iterative Query
  - Advantages: more scalable
  - Disadvantages: slower, harder to enforce data consistency

Key questions

- put(key, value): where do you store a new (key, value) tuple?
- get(key): where is the value associated with a given "key" stored?

- …do the above while providing:
  - Fault Tolerance
  - Scalability
  - Consistency

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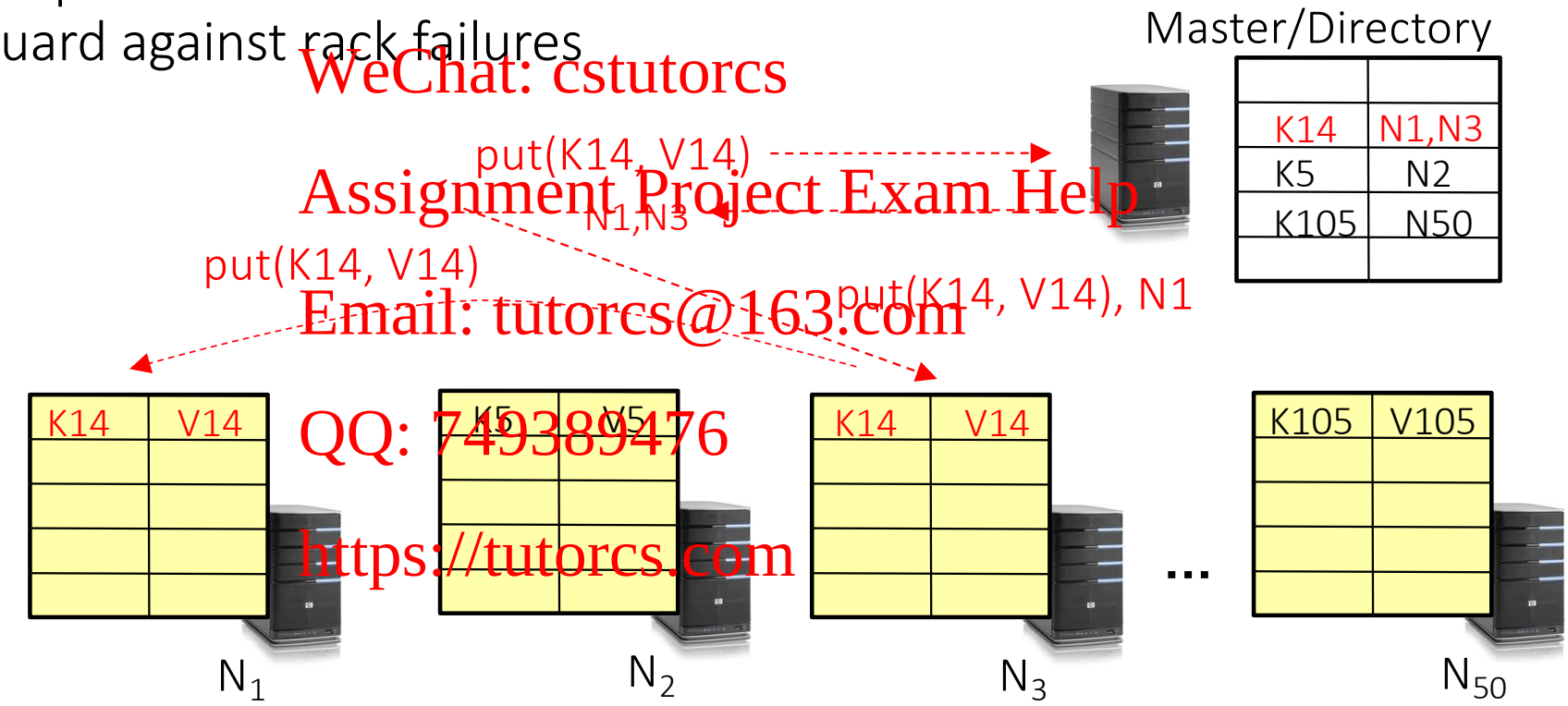
Fault tolerance: Primary/backup

- Replicate value on several nodes
- Usually, place replicas on different racks in a datacenter to guard against rack failures



Fault tolerance: Chubby

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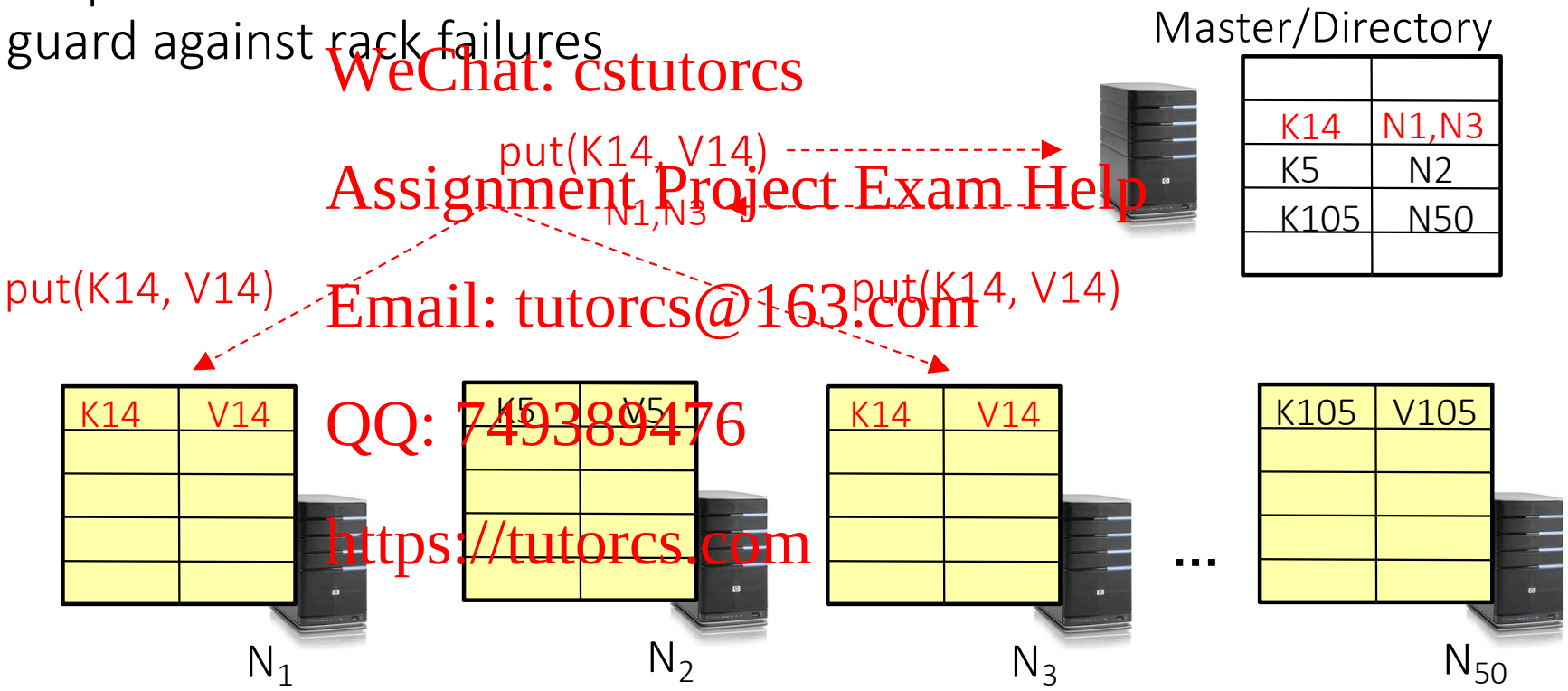

Replication chal

- Need to make sure that a v licated correctly

- How do you know a value has been replicated on every node?
  - Wait for acknowledgements from every node

- What happens if a node fails during replication?
  - Pick another node and try again

- What happens if a node is slow?
  - Slow down the entire put()? Pick another node?

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In general, with multiple replicas:

Slow puts and fast gets

Key questions

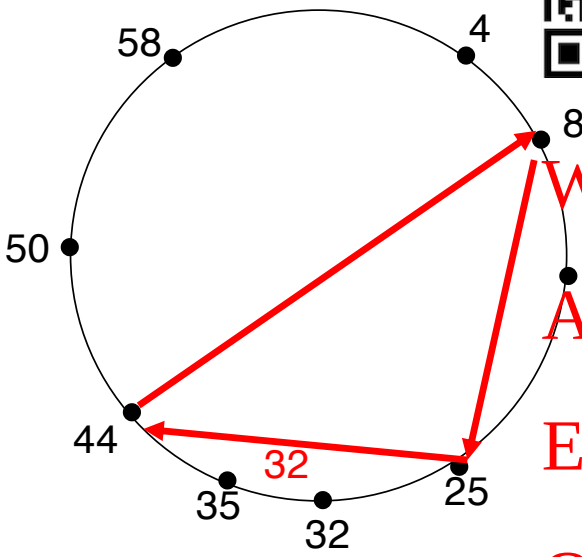
- put(key, value): where do you store a new (key, value) tuple?
- get(key): where is the value associated with a given "key" stored?

- …do the above while providing:
  - Fault Tolerance
  - Scalability
  - Consistency

Scalability

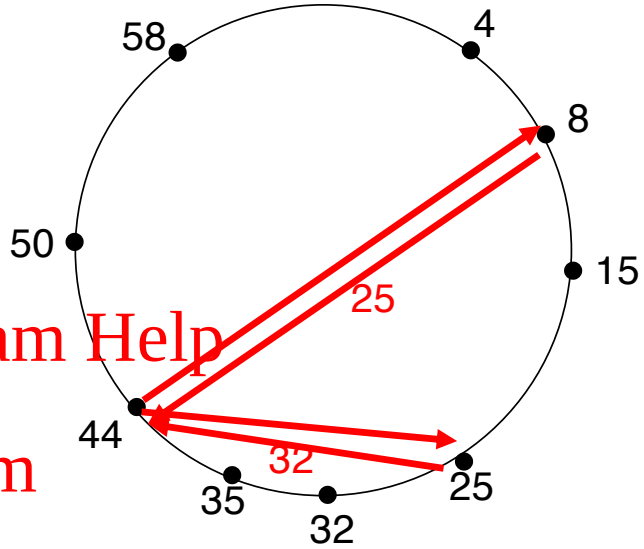
- **Storage:** use more nodes
- **Request throughput:**
  - Can serve requests from all nodes on which a value is stored in parallel
  - Master can replicate a popular value on more nodes
- **Master/directory scalability:**
  - Replicate it
  - Partition it, so different keys are served by different masters/directories (do you remember Chord? ☺)

Scalability with



Recursively example:

node 44 issue query(31)



Iteratively example:

node 44 issue query(31)

Scalability: load balancing

- Directory keeps track of the availability at each node
  - Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  - Move values from the heavy loaded nodes to the new node
- What happens when a node fails?
  - Need to replicate values from fail node to other nodes

Key questions

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- …do the above while providing:
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Consistency

- How close does a distribut emulate a single machine in terms of read and write semantics?

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- Q: Assume put(K14, V14') and put(K14, V14'') are concurrent, what value ends up being stored?

Consistency

- How close does a distributed system emulate a single machine in terms of read and write semantics?

- Q: Assume **put(K14, V14')** and **put(K14, V14'')** are concurrent, what value ends up being stored?

- A: assuming **put()** is atomic, then either **V14'** or **V14''**, right?

Consistency

- How close does a distributed system emulate a single machine in terms of read and write semantics?

- Q: Assume a client calls **put(K14, V14)** and then **get(K14)**, what is the result returned by **get()**?

Consistency

- How close does a distributed system emulate a single machine in terms of read and write semantics?

- Q: Assume a client calls **put(K14, V14)** and then **get(K14)**, what is the result returned by **get()**?

- A: It should be V14, right?

Consistency

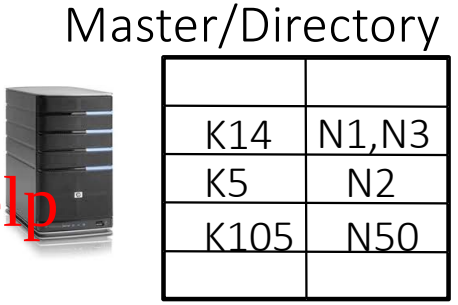
- How close does a distribut emulate a single machine in terms of read and write semantics?

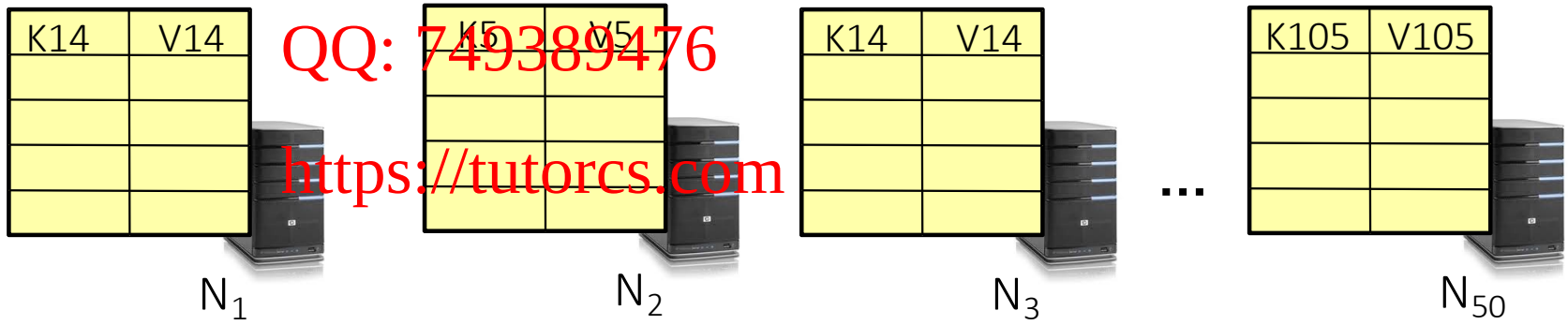
Above semantics, not trivial to achieve in distributed systems!!!!

Concurrent writ

- If concurrent updates (i.e., [illegible] me key) may need to make sure that updates happen in the same order

put(K14, V14') ----------►





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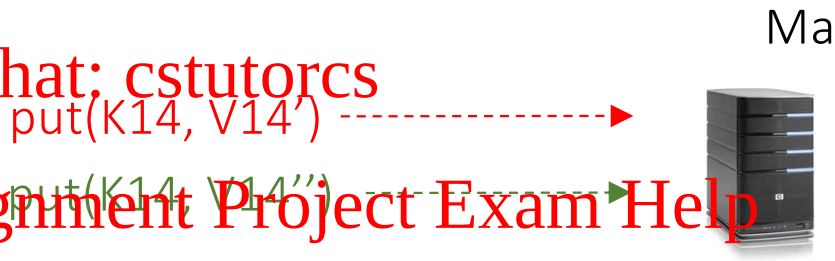

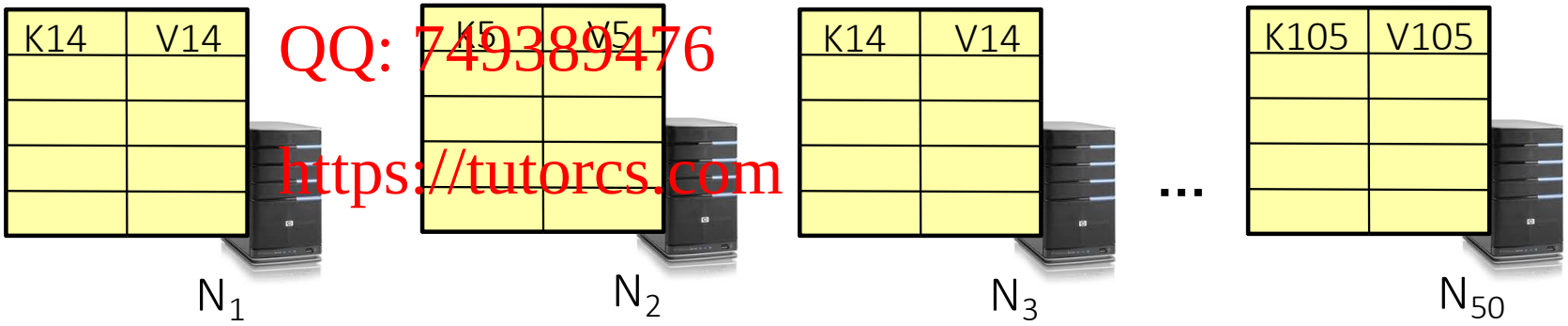

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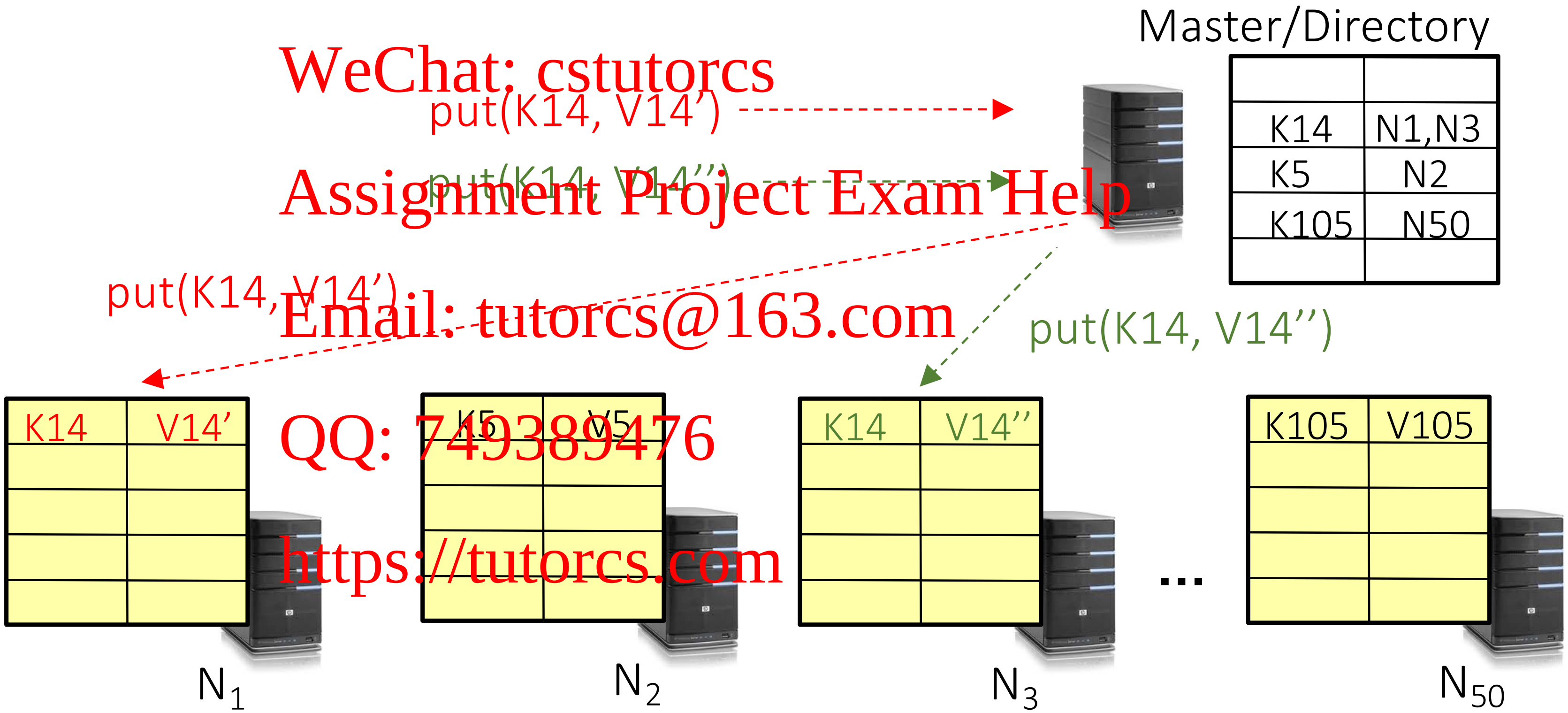
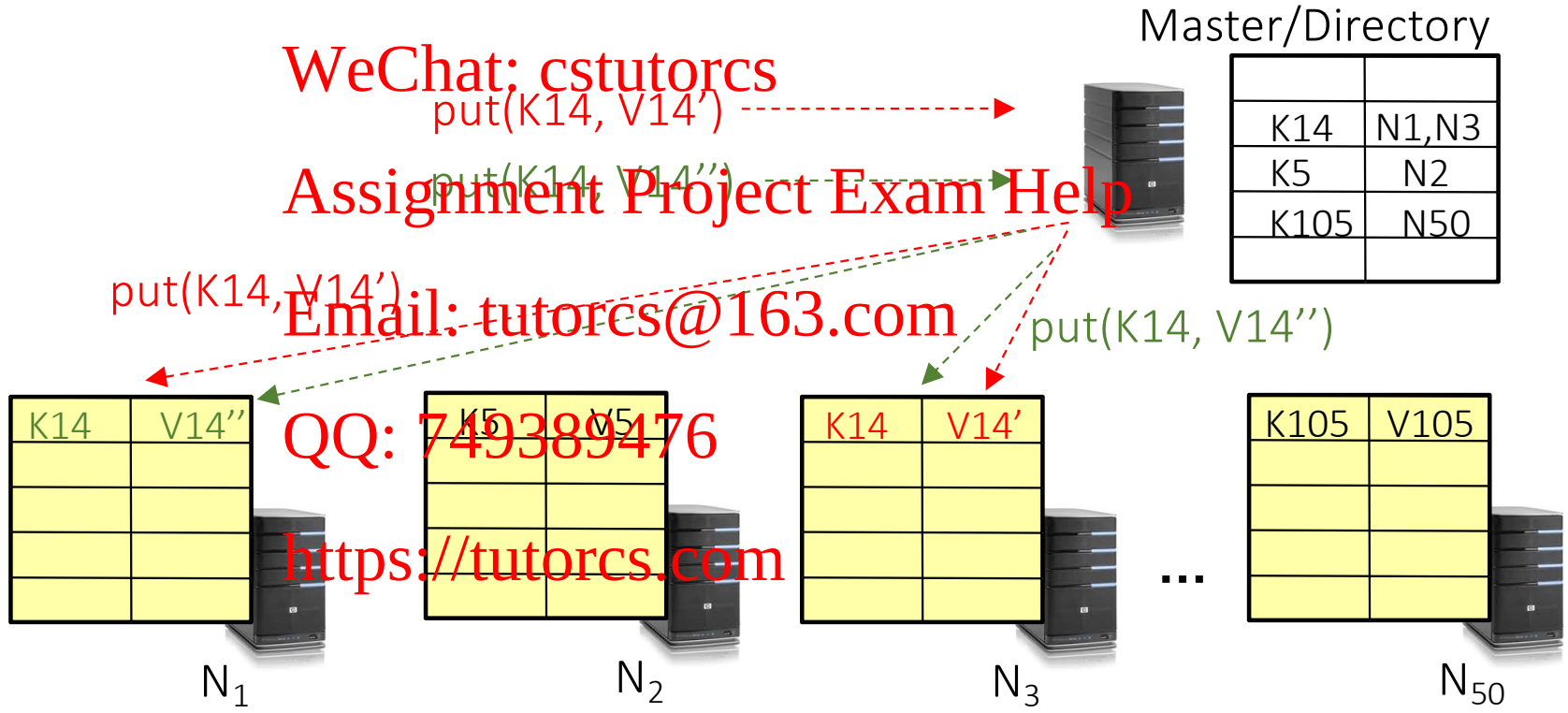


Concurrent writ

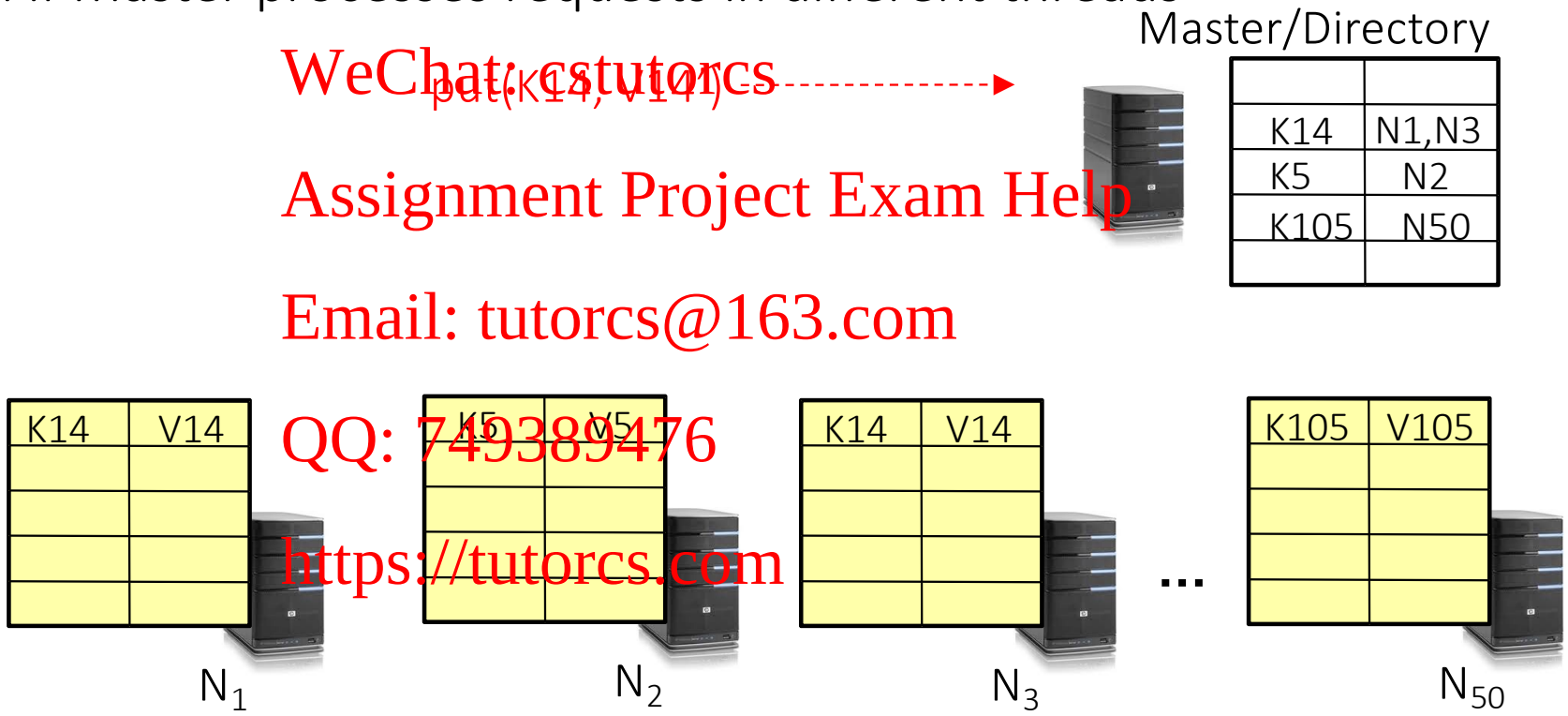
- put(K14, V14') and put(K14, V14'') reach N1 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

- If concurrent updates (i.e., ... me key) may need to make sure that updates happen in the same order



Read after write

- Read not guaranteed to return result of latest write
  - Can happen if Master processes requests in different threads



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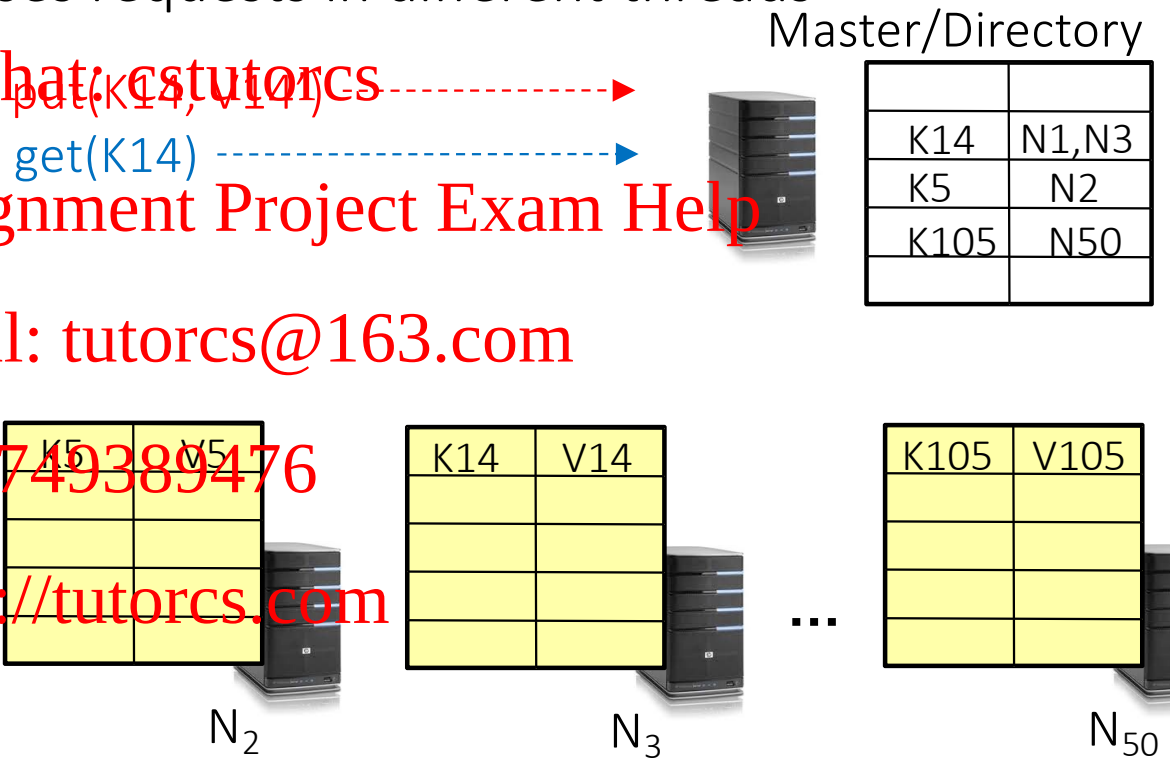

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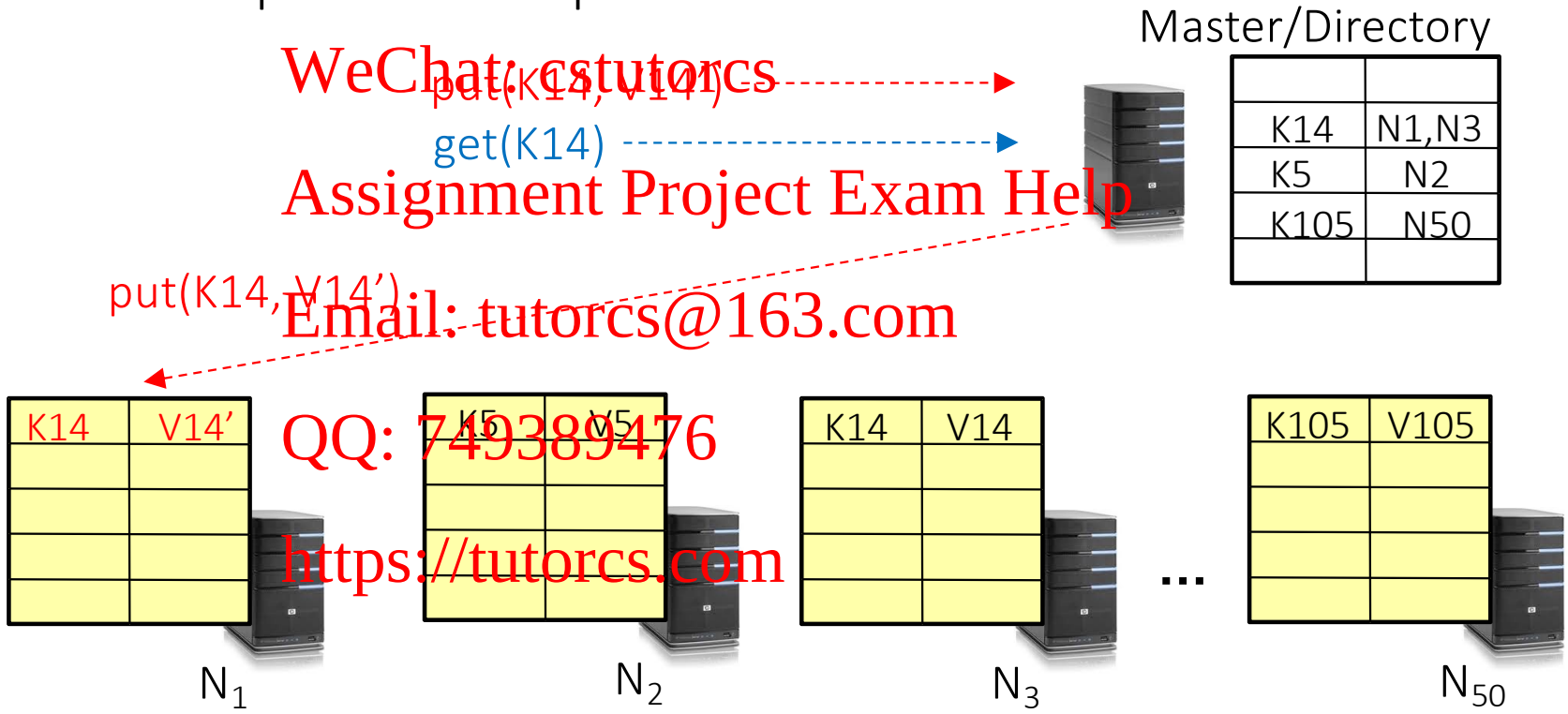

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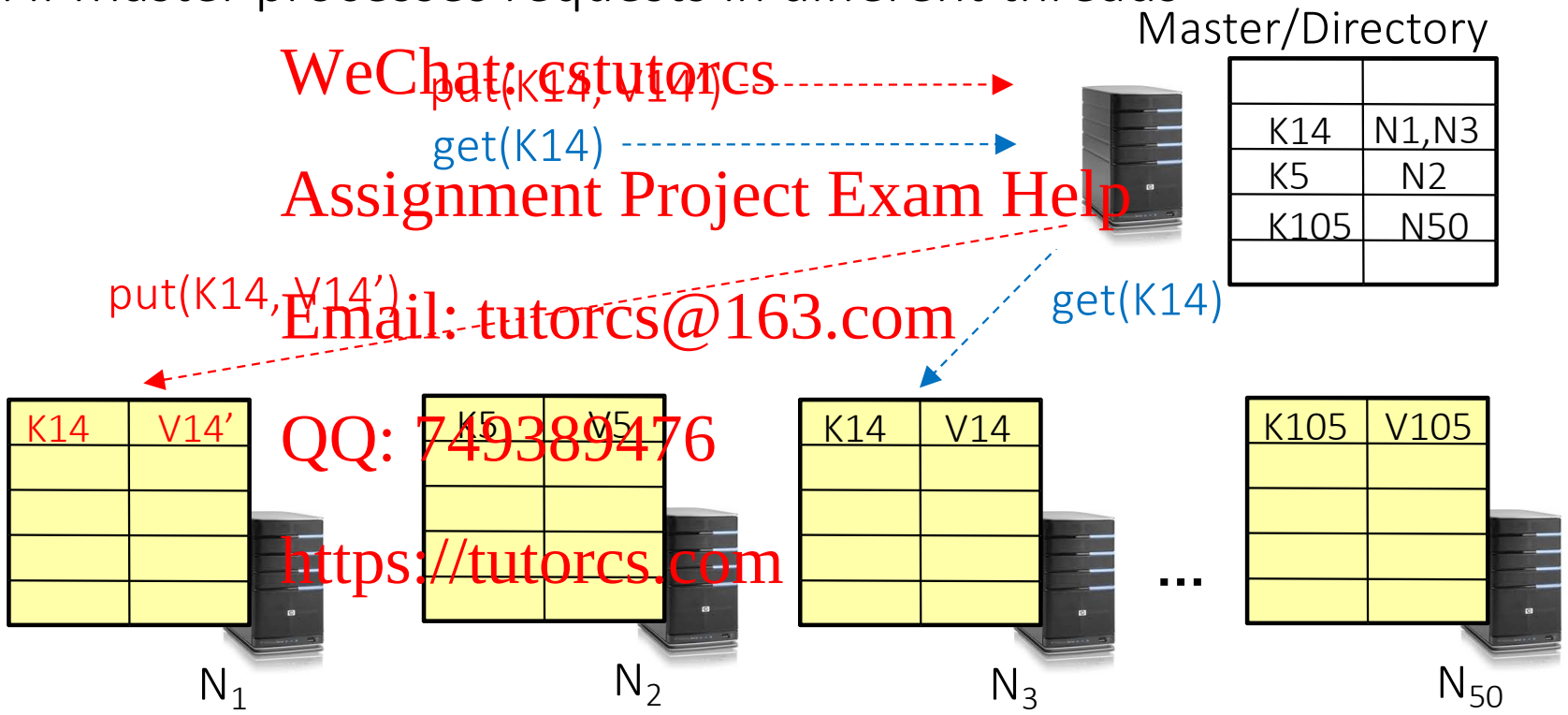

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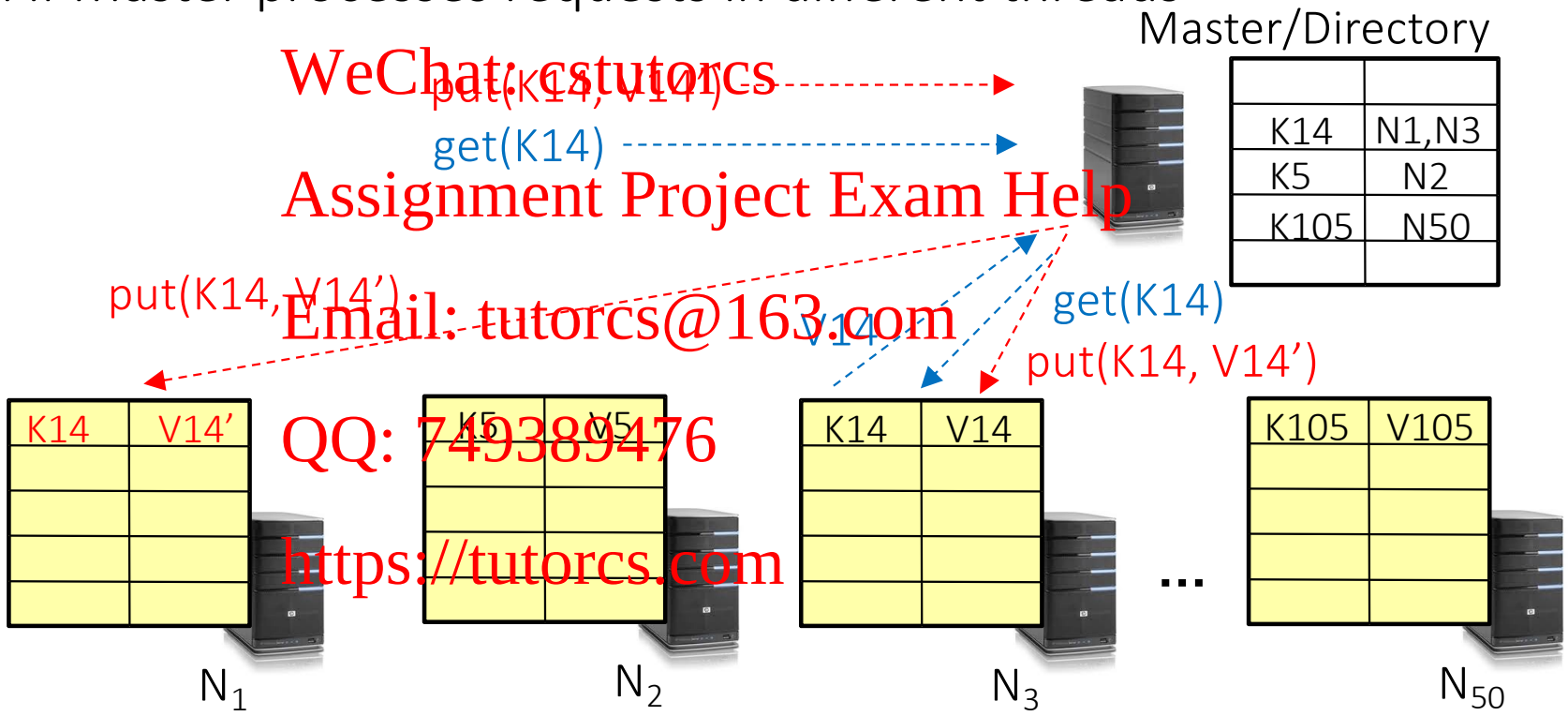

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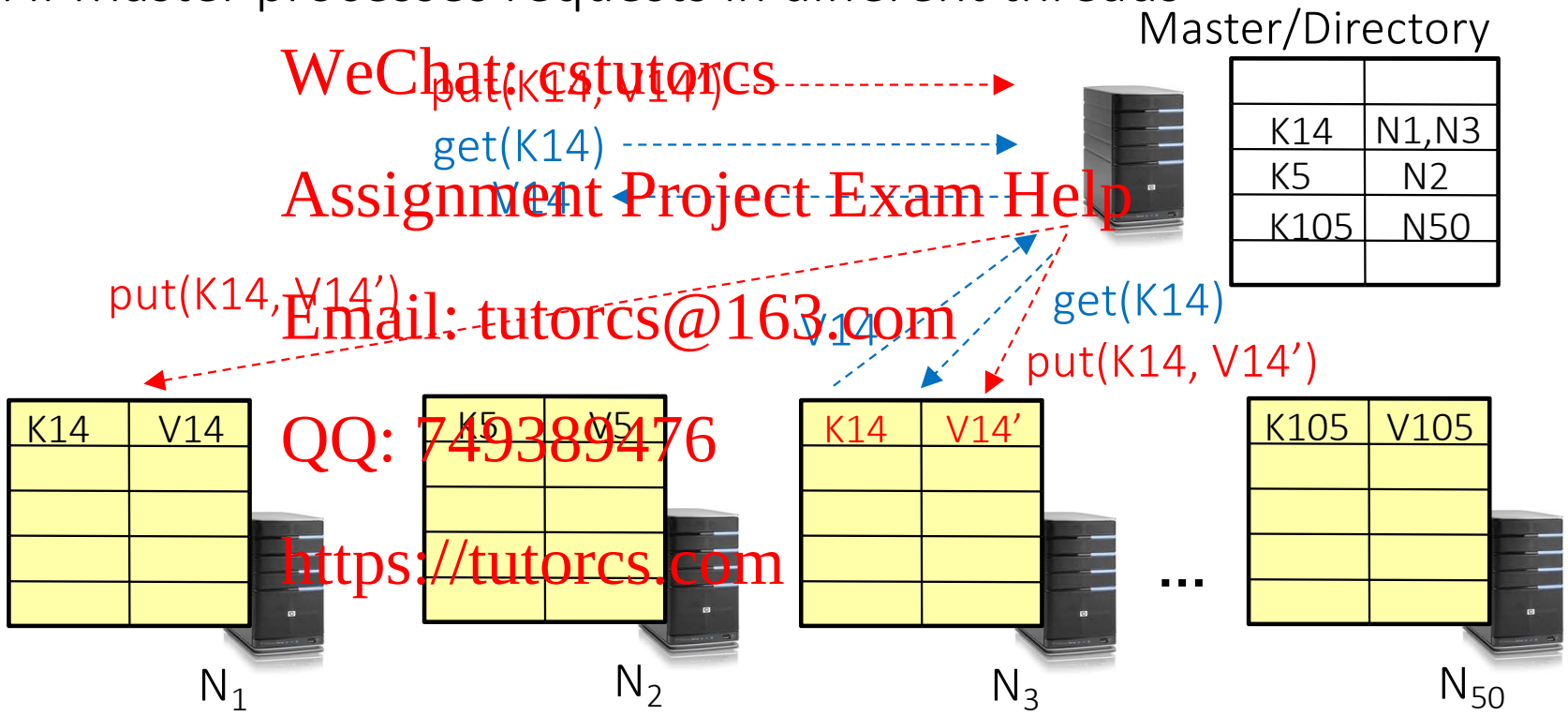
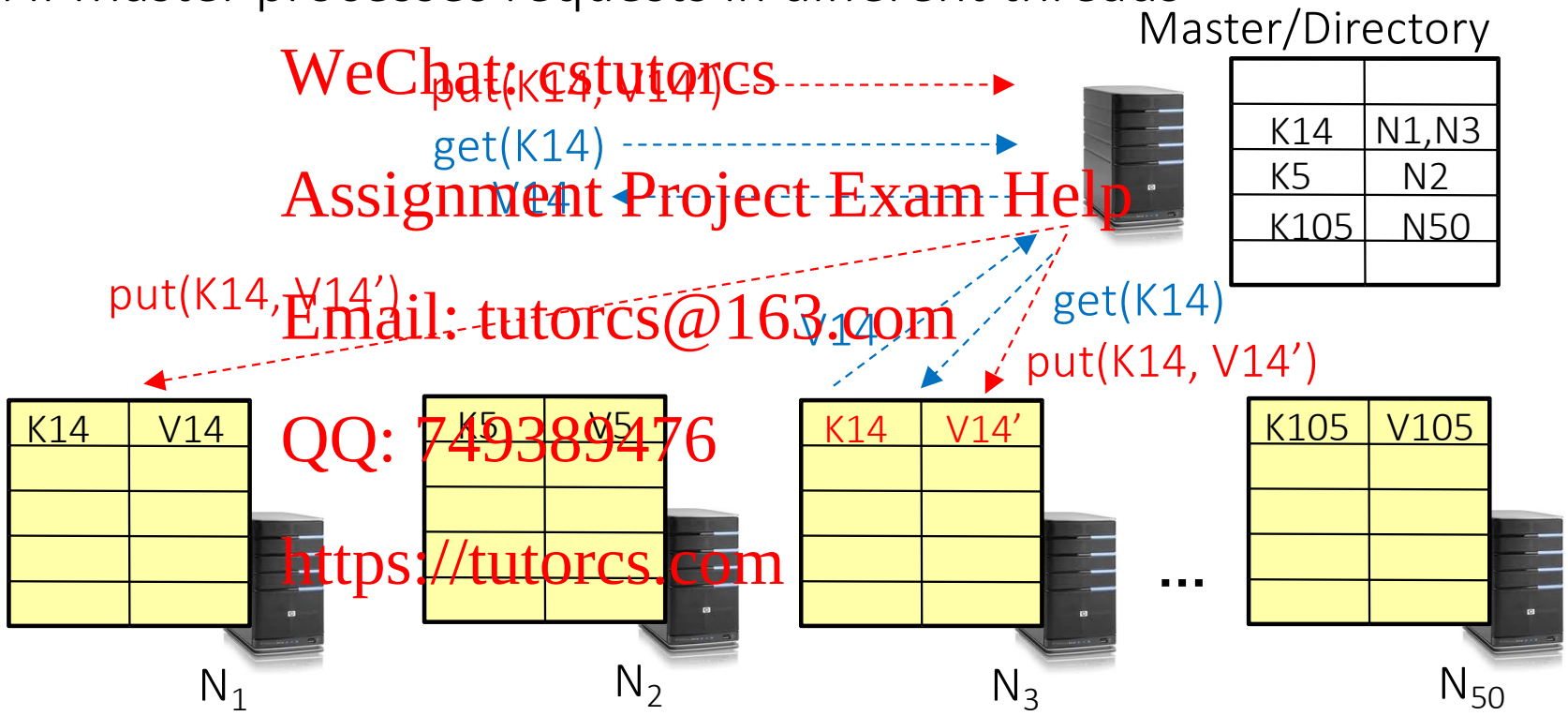


Read after write

- get(K14) happens right after put(K14, V14')
- get(K14) reaches N3 before put(K14, V14')!

- Read not guaranteed to return value of latest write
  - Can happen if Master processes requests in different threads



The return of ar[redacted]end

- Does this remind you some[redacted]

The return of an old friend

- Does this remind you some

- Yes, all the consistency models/protocols we have seen apply also here!

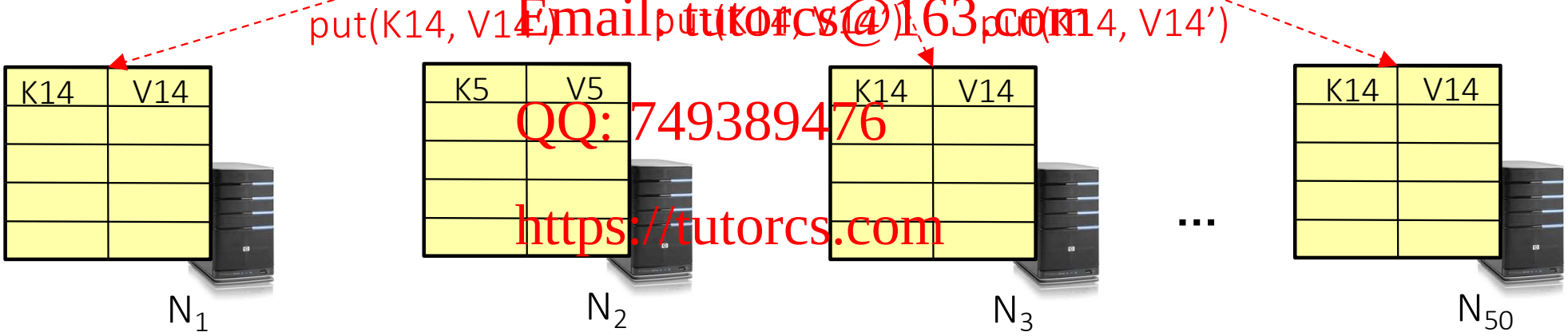
Quorum consen

- Define a replica set of size
  - **put()** waits for acks from at least W replicas
  - **get()** waits for responses from at least R replicas

- Why may you use W+R > N+1?

Quorum consen

- N=3, W=2, R=2
- Replica set for K14: {N1, N3
- Assume put() on N3 fails



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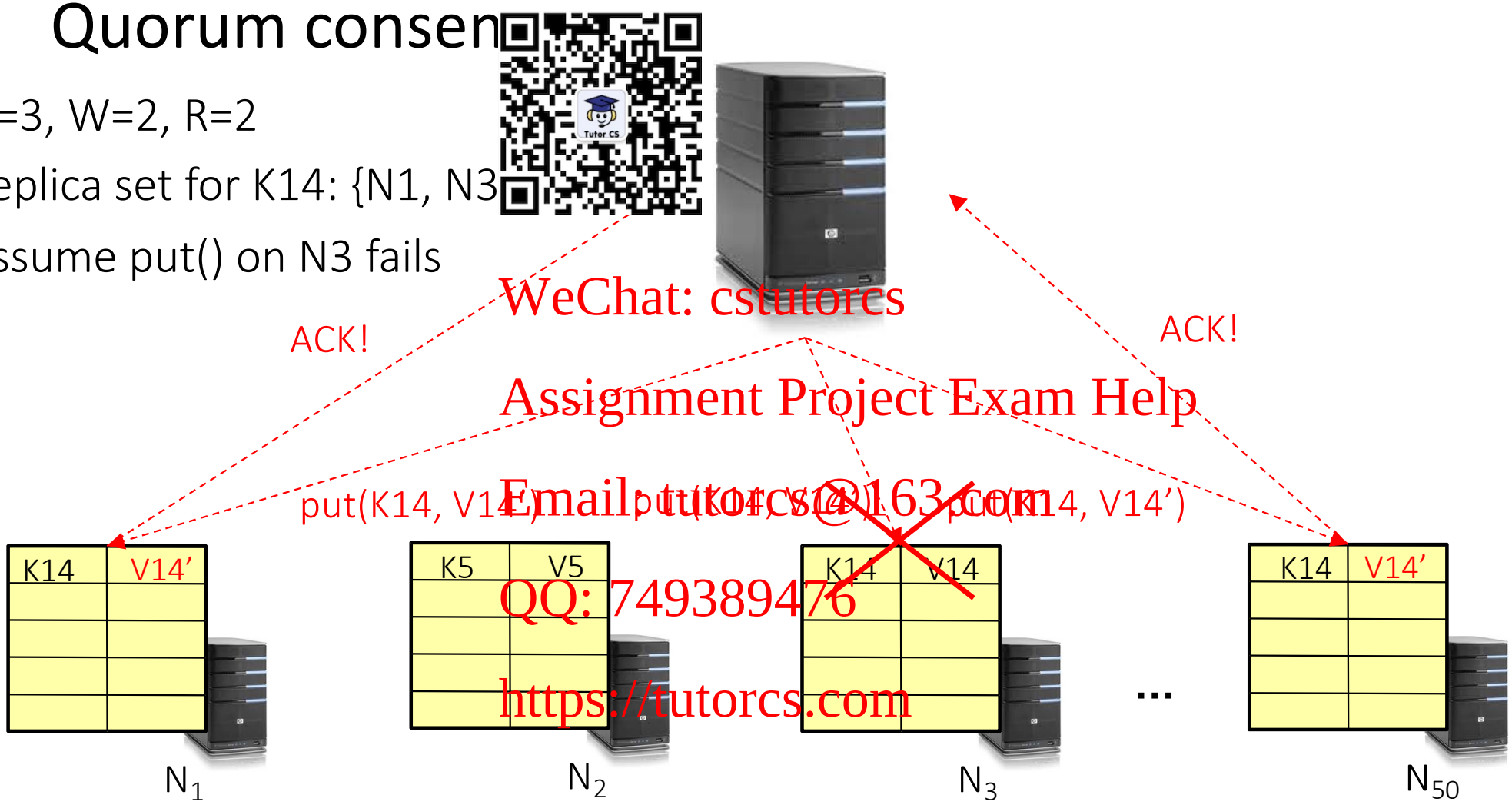

Quorum consen

Now, for get() need to wait fo
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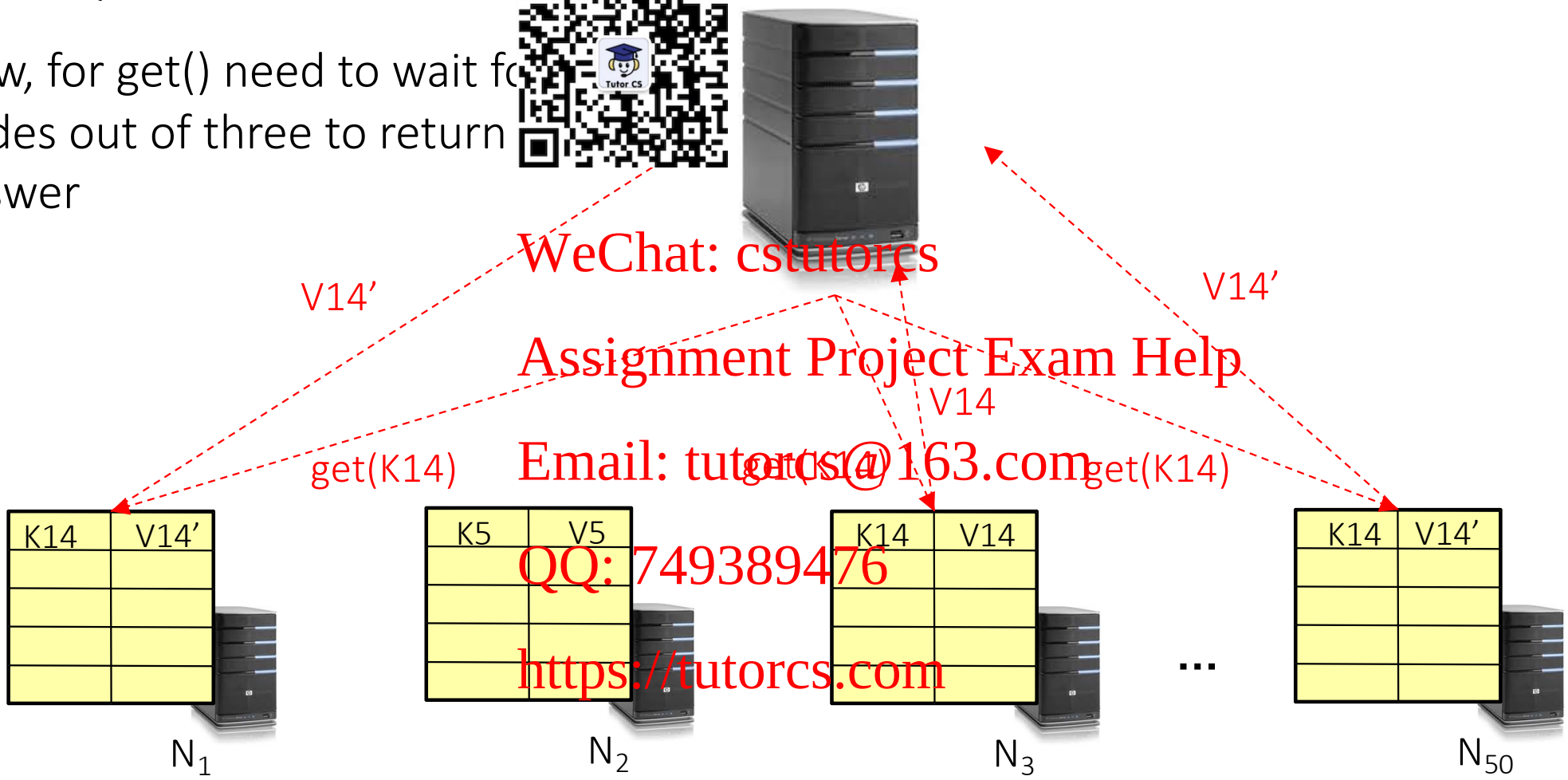


Memcached: a key-value Store example

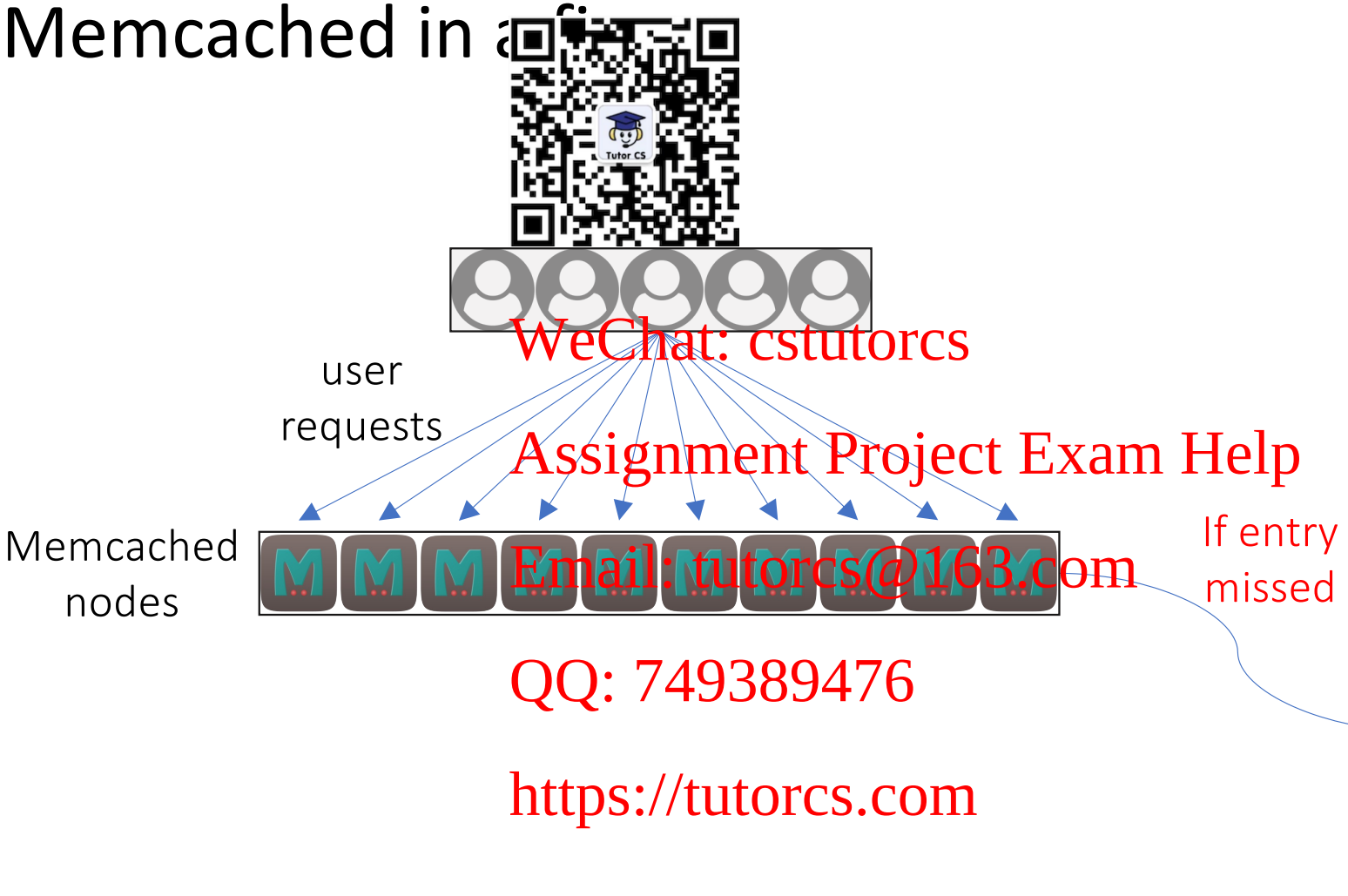
- Memcached is an in-memory key-value store for small chunks of arbitrary data (strings, objects) from results of database calls, API calls, or page rendering

- Memcached's APIs provide a very large hash table distributed across multiple machines.

  - If table is full: subsequent inserts cause older data to be purged in least recently used (LRU) order.

- Applications using Memcached typically layer requests and additions into RAM before falling back on a slower backing store, such as a database.

Memcached in a



Memcached: wh[redacted]use it?

- Often used for small objec[redacted]

- Anything what is more expensive to fetch from elsewhere, and has sufficient hitrate, can be placed in memcached
  - How often will object or data be used?
  - How expensive is it to generate the data?
  - What is the expected hitrate?

Memcached: trade-offs

- Why YES:
  1. to reduce the load on the database by caching data BEFORE
  2. improve the entire application response time (much faster hitting the RAM than the disk or the database)

- Why NO:
  1. Memcache is held in RAM. This is a finite resource.
  2. Adding complexity to a system just for complexities sake is a waste. If the system can respond within the requirements without it - leave it alone

Memcached: software architecture

- Client–server architecture

- **The servers** maintain a key–value associative array and do not communicate each other

- **The clients** populate this array and query it by key. They know all servers

- If a client wishes to set or read the value corresponding to a certain key, the client's library first computes a hash of the key to determine which server to use.

- The servers keep the values in RAM; if a server runs out of RAM, it discards the oldest values.

Memcached: so[redacted]architecture

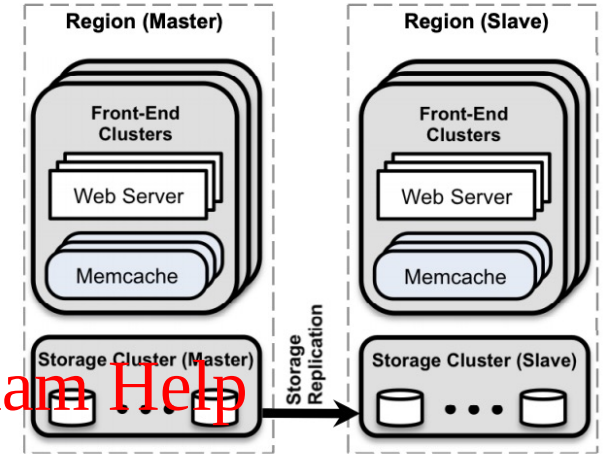
- Clients must treat Memcac[redacted]ransitory cache

- They cannot assume that data stored in Memcached is still there when they need it.

- Other databases, such as MemcacheDB, Couchbase Server, provide persistent storage while maintaining Memcached protocol compatibility.

Facebook: a real-world scenario

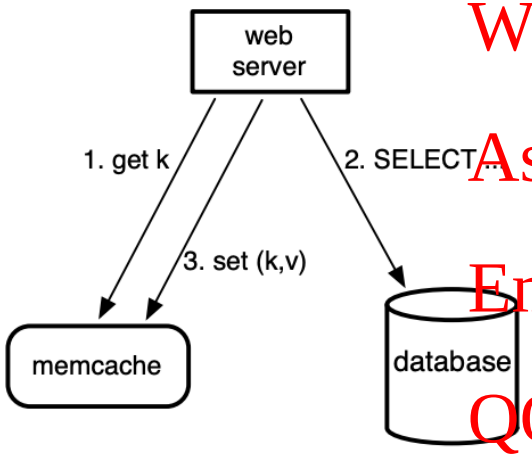
- Need to support very heavy read load
  - Over 1 billion reads/second
- Geographically distributed
- Support a constantly evolving product



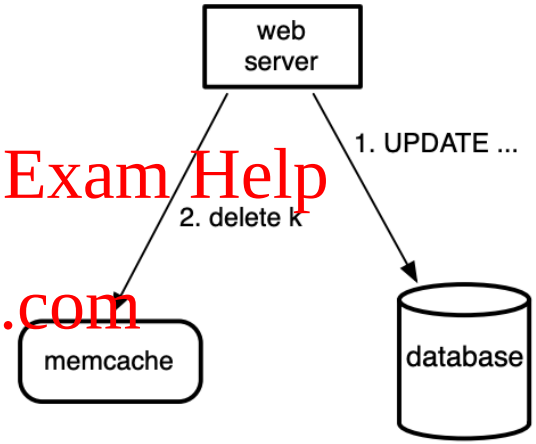
Scaling Memcache at Facebook, USENIX NSDI 2013

Facebook: a real-world scenario

- Memcache as a demand-filled look-aside cache



Read path for a web server on a cache miss



The write path

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Recap on Key-Value Stores

- Very large-scale storage sy
- Two operations
  - put(key,value)
  - value = get(key)
- Challenges
  - Fault tolerance → replication
  - Scalability → serve get()'s in parallel, replicate/cache hot tuples
  - Consistency → quorum consensus