CHORD

- Chord is a protocol implementing for a peer-to-peer distributed hash table
- A distributed hash table stores key-value pairs by assigning keys to different computers (nodes)
- A node stores the values for all the keys it is responsible for
- Chord specifies how keys are to be assigned to nodes, and how a node can discover the value for a given key by first locating the node responsible for that key
- Chord is one of the four original distributed hash table protocols, along with CAN, Tapestry, and Pastry

The material of this section is mainly drawn from: Sigcomm '01: "Chord: A Scalable Peertopeer Lookup Service for Internet Applications", by Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan

CHORD

- Peer-to-peer systems and applications are distributed systems without any centralized control or hierarchical organization, where the software running at each node is equivalent in functionality
- The core operation in most peer-to-peer systems is efficient location of data items
- Chord is a scalable protocol for lookup in a dynamic peer-to-peer system with frequent node arrivals and departures

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CHORD

- **The Chord protocol supports just one operation: given a key, it maps the key onto a node**
- Depending on the application using Chord, that node might be responsible for storing a value (address, a document, or an arbitrary data item) associated with the key
- Chord uses a variant of **consistent hashing** to assign keys to Chord nodes

The material of this section is mainly drawn from: Sigcomm ’01: “Chord: A Scalable Peertopeer Lookup Service for Internet Applications”, by Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, Hari Balakrishnan

CHORD

- **Consistent hashing**
  - tends to balance load, since each node receives roughly the same number of keys, and
  - involves relatively little movement of keys when nodes join and leave the system
- Each Chord node needs “routing” information about only a few other nodes
- Because the routing table is distributed, a node resolves the hash function by communicating with a few other nodes
- In the steady state, in an *N* node system, each node maintains information only about O(log(N) other nodes and resolves all lookups via O(log(N)) messages to other nodes
- Chord maintains its routing information as nodes join and leave the system
- With high probability each such event results in no more than $O(\log(N)^2)$ messages

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CHORD

- Chord maps keys onto nodes, traditional name and location services (e.g. DNS) provide a direct mapping between keys and values
- A value can be an address, a document, or an arbitrary data item

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CHORD

- DNS provides a host name to IP address mapping
- Chord requires no special servers, while DNS relies on a set of special root servers
- DNS names are structured to reflect administrative boundaries
- Chord imposes no naming structure
- DNS is specialized to the task of finding named hosts or services
- Chord can also be used to find data objects that are not tied to particular machines

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CHORD

- Load balance
  - Chord acts as a distributed hash function, spreading keys evenly over the nodes
- Decentralization:
  - Chord is fully distributed: no node is more important than any other
- Scalability:
  - The cost of a Chord lookup grows as the log of the number of nodes
- Availability:
  - Chord automatically adjusts its internal tables to reflect newly joined nodes as well as node failures, ensuring that, barring major failures in the underlying network, the node responsible for a key can always be found
- Flexible naming:
  - Chord places no constraints on the structure of the keys it looks up
  - The Chord key-space is flat

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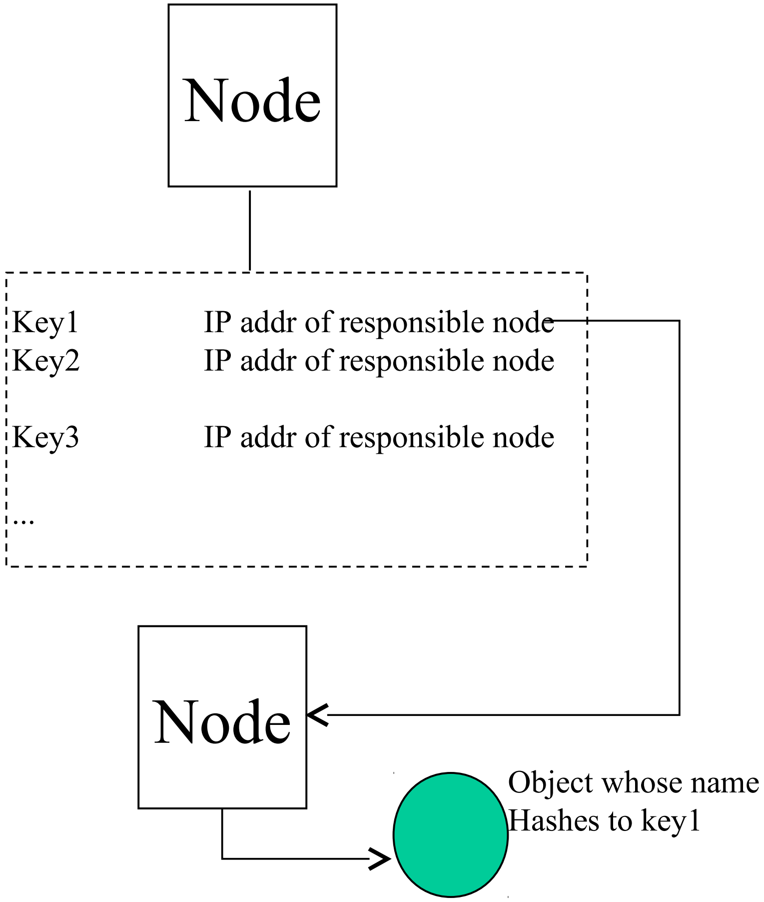
CHORD

- The Chord software takes the form of a library to be linked with the client and server applications that use it
- The application interacts with Chord in two main ways
  - First, Chord provides a *lookup(key)* algorithm that yields the IP address of the node responsible for the key
  - Second, the Chord software on each node notifies the application of changes in the set of keys that the node is responsible for



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CHORD

- At its heart, Chord provides fast distributed computation of a hash function mapping keys to nodes responsible for them
- It uses **consistent hashing**, which has several good properties
  - With high probability the hash function balances load (all nodes receive roughly the same number of keys)
  - With high probability, when an *Nth* node joins (or leaves) the network, only an O(1/*N*) fraction of the keys are moved to a different location (this is clearly the minimum necessary to maintain a balanced load)

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CHORD

- Chord improves the scalability of consistent hashing by avoiding the requirement that each node knows about every other node
- A Chord node needs only a small amount of “routing” information about other nodes
- Because this information is distributed, a node resolves the hash function by communicating with a few other nodes
- In an *N*-node network, each node maintains information only about *log(N)* other nodes, and a lookup requires *O(log(N))* messages
- Chord must update the routing information when a node joins or leaves the network
- Join or leave requires $O(log(N)^2)$ messages

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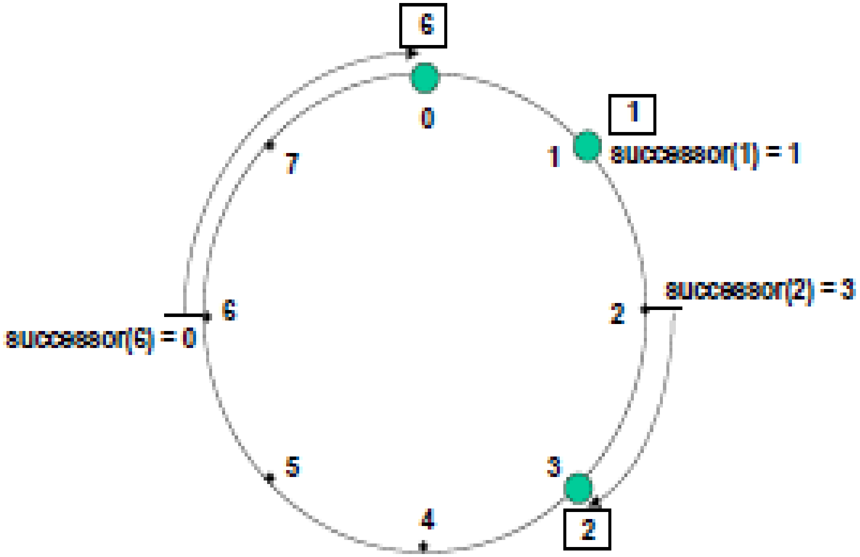
CHORD-consistent hashing

- The consistent hash function assigns each node and key an *m*-bit identifier using a base hash function such as SHA-1
- A node’s identifier is chosen by hashing the node’s IP address, while a key identifier is produced by hashing the key
- We will use the term “key” to refer to both the original key and its image under the hash function
- Similarly, the term “node” will refer to both the node and its identifier under the hash function
- The identifier length must be large enough to make the probability of two nodes or keys hashing to the same identifier negligible

CHORD-consistent hashing

- Consistent hashing assigns keys to nodes as follows
- Identifiers are ordered in an identifier circle modulo 2^m
- Key *k* is assigned to the first node whose identifier is equal to or follows the identifier of *k* in the identifier space
- This node is called the successor node of key *k*, denoted by *successor(k)*
- If identifiers are represented as a circle of numbers from 0 to 2^{m-1}, then *successor(k)* is the first node clockwise from *k*



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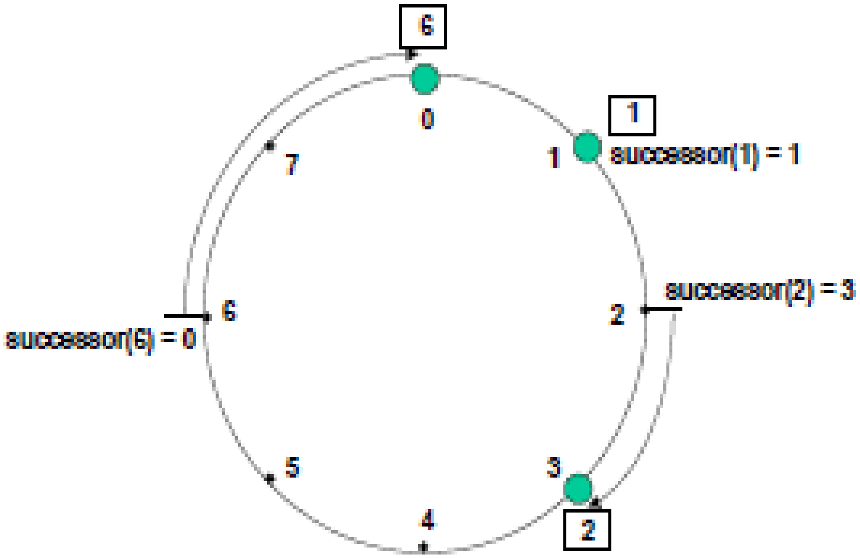
CHORD-consistent hashing

- The figure shows an identifier circle with *m* = 3
- The circle has three nodes: 0, 1, and 3
- The successor of identifier 1 is node 1, so key 1 would be located at node 1
- Similarly, key 2 would be located at node 3, and key 6 at node 0



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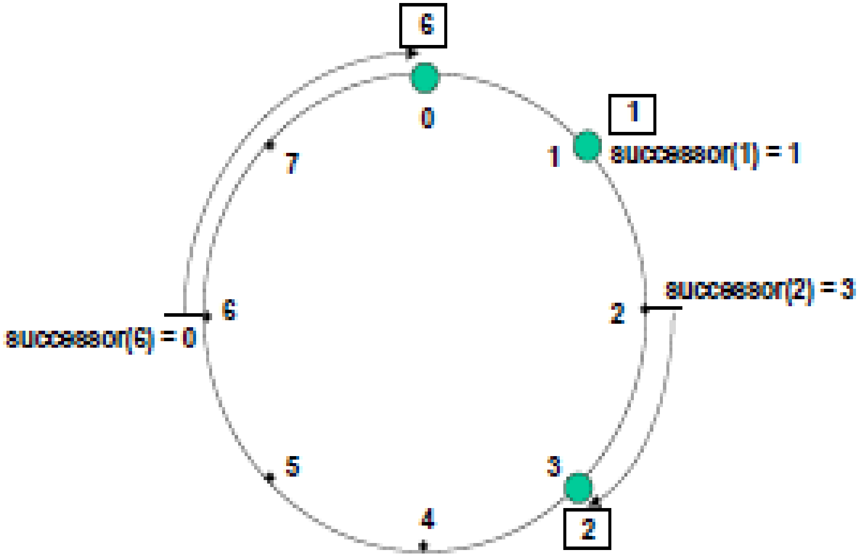
CHORD-consistent hashing

- Consistent hashing is designed to let nodes enter and leave the network with minimal disruption
- To maintain the consistent hashing mapping when a node *n* joins the network, certain keys previously assigned to *n*'s successor now become assigned to *n*
- When node *n* leaves the network, all of its assigned keys are reassigned to *n*'s successor
- No other changes in assignment of keys to nodes need occur
- In the example, if a node were to join with identifier 7, it would capture the key with identifier 6 from the node with identifier 0



CHORD-scalable key location

This is an entry of the node's *n* finger table
This table is referred to as *n.finger*
The *i*th entry of the table is *n.finger[i]*

- Let *m* be the number of bits in the key/node identifiers
- Each node *n* maintains a routing table with (at most) *m* entries, called the finger table
- The *k*th entry in the table at node *n* contains the identity of the first node *s* that succeeds *n* by at least 2^{k-1} on the identifier circle, i.e., $s = successor(n+2^{k-1})$
- We call node *s* the *k*th finger of node *n*, and denote it by *n.finger[k].node*
- **A finger table entry includes both the Chord identifier and the IP address (and port number) of the relevant node**
- Note that the first finger of *n* is its immediate successor on the circle
- For convenience we often refer to it as the successor rather than the first finger

Notation	Definition
$finger[k].start$	$(n + 2^{k-1}) \bmod 2^m, 1 \leq k \leq m$
$.interval$	$[finger[k].start, finger[k+1].start)$
$.node$	first node $\geq n.finger[k].start$
successor	the next node on the identifier circle; $finger[1].node$
predecessor	the previous node on the identifier circle

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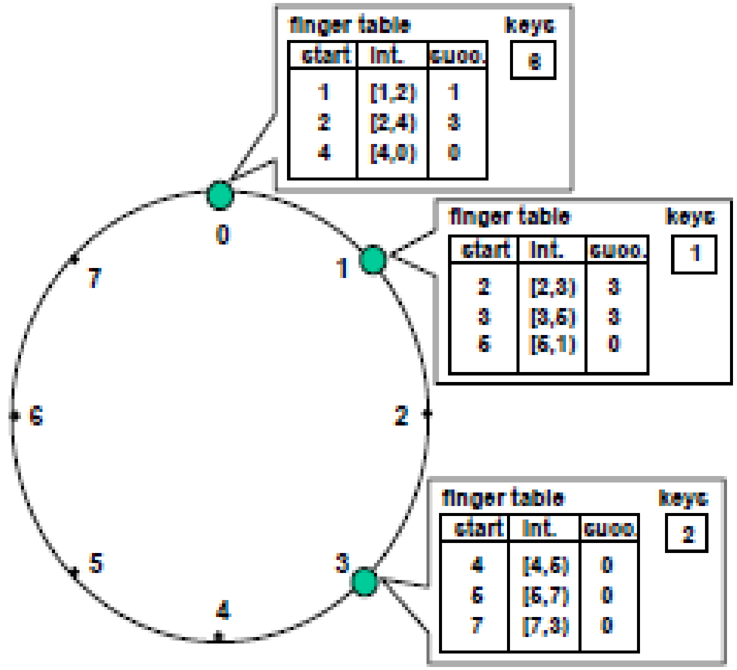
CHORD-scalable key location

- In the example, the finger table of node 1 points to the successor nodes of identifiers
  - $(1+2^0) \bmod 8 = 2$
  - $(1+2^1) \bmod 8 = 3$
  - $(1+2^2) \bmod 8 = 5$

- The successor of identifier 2 is node 3
- The successor of identifier 3 is node 3
- The successor of identifier 5 is node 0



(b)

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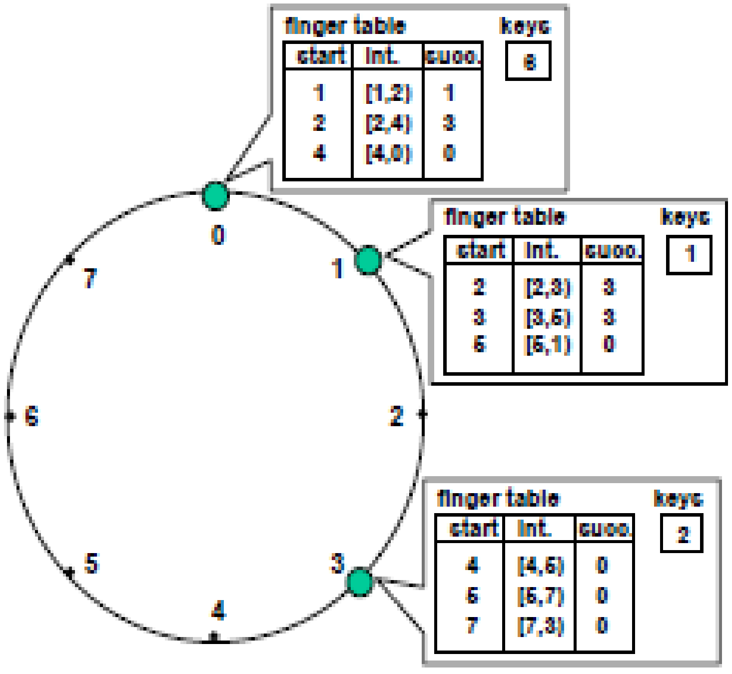
CHORD-scalable key location

- This scheme has two important characteristics
- First, each node stores information about only a small number of other nodes, and knows more about nodes closely following it on the identifier circle than about nodes farther away
- Second, a node's finger table generally does not contain enough information to determine the successor of an arbitrary key
- For example, node 3 does not know the successor of 1, as 1 's successor (node 1) does not appear in node 3's finger table



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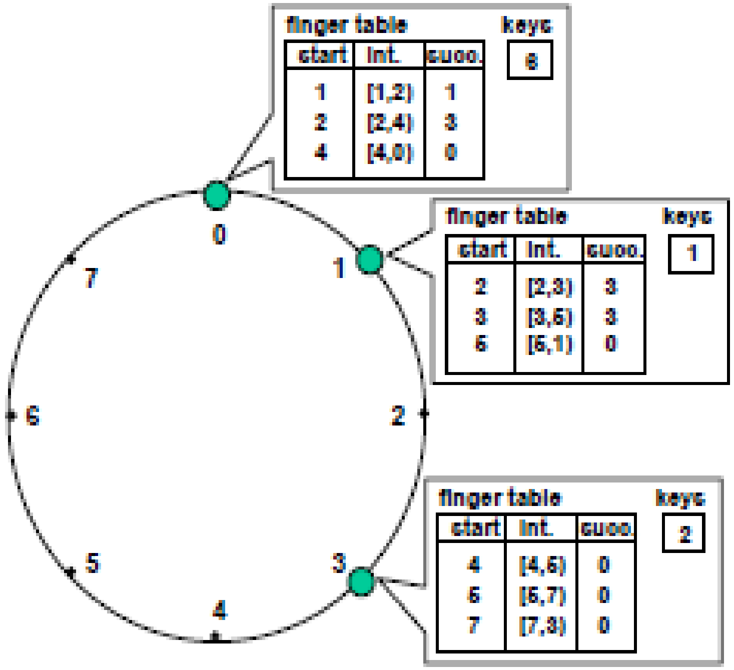
CHORD-scalable key location

- What happens when a node *n* does not know the successor of a key *k*?
- If *n* can find a node whose ID is closer than its own to *k*, that node will know more about the identifier circle in the region of *k* than *n* does
- Thus, *n* searches its finger table for the node *j* whose ID most immediately precedes *k*, and asks *j* for the node it knows whose ID is closest to *k*
- By repeating this process, *n* learns about nodes with IDs closer and closer to *k*



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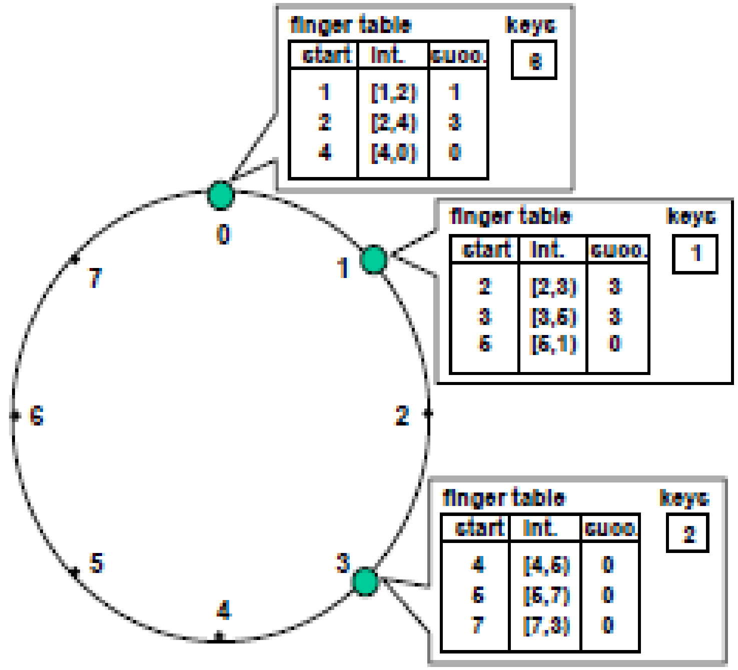
CHORD-scalable key location

- As an example, consider the Chord ring in Figure
- Suppose node 3 wants to find the successor of identifier 1
- Since 1 belongs to the circular interval [7, 3), it belongs to 3.*finger[3].interval*
- Node 3 therefore checks the third entry in its finger table, which is 0
- Because 0 precedes 1, node 3 will ask node 0 to find the successor of 1
- In turn, node 0 will infer from its finger table that 1's successor is the node 1 itself, and return node 1 to node 3



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CHORD-scalable key location

- The finger pointers at repeatedly doubling distances around the circle cause each iteration of the loop to halve the distance to the target identifier
- From this intuition follows a theorem:
- *With high probability, the number of nodes that must be contacted to find a successor in an n-node network is O(log(N))*

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CHORD-node joins

- In a dynamic network, nodes can join (and leave) at any time
- The main challenge in implementing these operations is preserving the ability to locate every key in the network
- To achieve this goal, Chord needs to preserve two invariants:
  - 1. Each node's successor is correctly maintained
  - 2. For every key *k*, node *successor(k)* is responsible for *k*
- In order for lookups to be fast, it is also desirable for the finger tables to be correct
- *With high probability, any node joining or leaving an N-node Chord network will use $O(\log^2 N)$ messages to re-establish the Chord routing invariants and finger tables*

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CHORD-node joins

- To simplify the join and leave mechanisms, each node in Chord maintains a *predecessor pointer*
- A node's predecessor pointer contains the Chord identifier and IP address of the immediate predecessor of that node
- It can be used to walk counterclockwise around the identifier circle

CHORD-node joins

- To preserve the invariants stated above, Chord must perform three tasks when a node *n* joins the network:
  - 1. Initialize the predecessor and fingers of node *n*
  - 2. Update the fingers and predecessors of existing nodes to reflect the addition of *n*
  - 3. Notify the higher layer software so that it can transfer state (e.g. values) associated with keys that node *n* is now responsible for

CHORD-node joins

- We assume that the new node learns the identity of an existing Chord node *n*' by some external mechanism
- Node *n* uses *n*' to initialize its state and add itself to the existing Chord network, in three phases as follows

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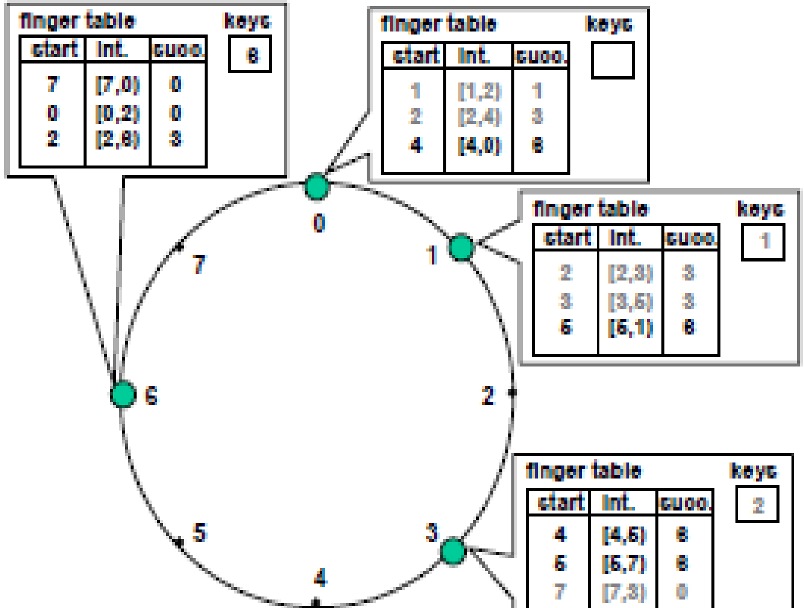
CHORD-node joins

- Phase 2: **Updating fingers of existing nodes**
- Node *n* will need to be entered into the finger tables of some existing nodes
- For example, in the Figure, node 6 joins and becomes the third finger of nodes 0 and 1, and the first and the second finger of node 3



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CHORD-stabilization

- If joining nodes have affected some region of the Chord ring, a lookup that occurs before stabilization has finished can exhibit one of three behaviors
- The common case is that all the finger table entries involved in the lookup are reasonably current, and the lookup finds the correct successor in O(log N) steps
- The second case is where successor pointers are correct, but fingers are inaccurate
- This yields correct lookups, but they may be slower
- In the final case, the nodes in the affected region have incorrect successor pointers, or keys may not yet have migrated to newly joined nodes, and the lookup may fail
- The higher-layer software using Chord will notice that the desired data was not found, and has the option of retrying the lookup after a pause
- This pause can be short, since stabilization fixes successor pointers quickly

Eclipse attacks on CHORD

- In an "Eclipse" attack, a set of malicious, colluding overlay nodes arranges for a correct node to peer only with members of the coalition
- If successful, the attacker can mediate most or all communication to and from the victim
- Furthermore, by supplying biased neighbor information during normal overlay maintenance, a modest number of malicious nodes can eclipse a large number of correct victim nodes

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