CS 555: Distributed Systems
[Tapestry & Chord]

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Frequently asked questions from the previous class survey

- Pastry
  - How do you determine the column, after you have found the matching row?
  - Leaf node changes ..
  - Locality, geography, and how variations in the routing table make the routing robust

Topics covered in this lecture

- Pastry (Wrap-up)
- Tapestry
- Chord
  - Mapping of data items
  - Data lookups
  - Finger Table construction
  - Assimilation of peers

PASTRY WRAP-UP

Repairing leaf sets

- Node that discovers the failure
  - Looks for a live node close to the failed node, and requests copy of that node's leaf set, L'
  - This should contain GUIDs that partly overlap those in the node that discovered failure
    - Include one that should replace the failed node
- Other neighboring nodes are informed
  - They perform a similar procedure

Locality

- Pastry routing structure is redundant
  - Multiple routes between pairs of nodes
- Construction of routing tables tries to take advantage of this redundancy
  - Reduce message transmission times by exploiting locality properties of underlying network

Routing table: Exploiting locality. [1/2]

- In the routing table, each row contains 16 entries
  - Entries in the ith row give addresses of 16 nodes with GUIDs with $i-1$ initial hexadecimal digits
  - I^{th} digit takes each of the possible hexadecimal values
- Well-populated Pastry system contains more nodes than can be contained in an individual routing table

Routing table: Exploiting locality. [2/2]

- When routing table is constructed choice is made for each position
  - Between multiple candidates
  - Based on *proximity* neighbor selection
- Locality metric
  - IP hops or measured latency

Performance of exploiting locality

- Since the information in the routing table is not comprehensive
  - Mechanism does not produce globally optimal routing
- Simulations show that
  - On average, the routing is 30-50% longer than the optimum

Coping with malicious nodes

- Small degree of *randomness* is introduced into route selection
- Randomized to yield a common prefix that is less than the maximum length
  - With a certain probability
- Routes are taken from an earlier row
  - Less optimal, but different than standard version
  - Client transmission succeed in the presence of small numbers of malicious nodes

TAPESTRY

Tapestry

- Routes messages to nodes based on GUIDs associated with the resources
  - Uses **prefix routing** in a manner similar to Pastry
- **160-bit** identifiers are used
  - To refer to both objects and nodes that perform routing actions
- For any resource with GUID G, there is a unique root node, with GUID R_G
  - R_G is *numerically closest* to G

Tapestry Routing [Summary]

- Uses local routing tables, which they also call **neighbor maps**, to route messages
- Routing is digit-by-digit
  - 4***➔ 42** ➔ 42A* ➔ 42AD
- This longest prefix routing is also used by classless interdomain routing (CIDR)

Tapestry: Routing messages

- Each node maintains a **routing table**
  - Entries include nodeIDs and IP addresses
- This routing table has <u>multiple levels</u>
  - Each level contains links to nodes matching a prefix up to a digit position in the ID
  - The ith entry in the jth level at node **N**?
    - Location of the closest node which begins with the $prefix(\mathbf{N}, j\text{-}1) + i$
    - E.g. 9th entry of the 4th level for node `325AE` is ?
      - `3259`

Tapestry Routing

- The router for the nth hop
  - Shares a prefix of length $\geq n$ with the destination ID
  - Looks in its $(n+1)^{th}$ level map for entry matching the next digit in the destination ID
- Guarantees that any node in the system can be reached in at most $log\ N$ logical hops
  - N is the size of the ID space i.e. $N = 2^{160}$

When a digit cannot be matched?

- Looks for a "close" digit in the routing table
- This approach is called **surrogate routing**
  - Results in mapping every identifier **G** to a unique root node G_R

Managing a dynamic environment

- Route reliably even when intermediate links are changing or faulty
- Exploit network **path diversity**
  - Via *redundant* routing paths
- Primary links are augmented by **backup-links**
  - Each sharing the same prefix

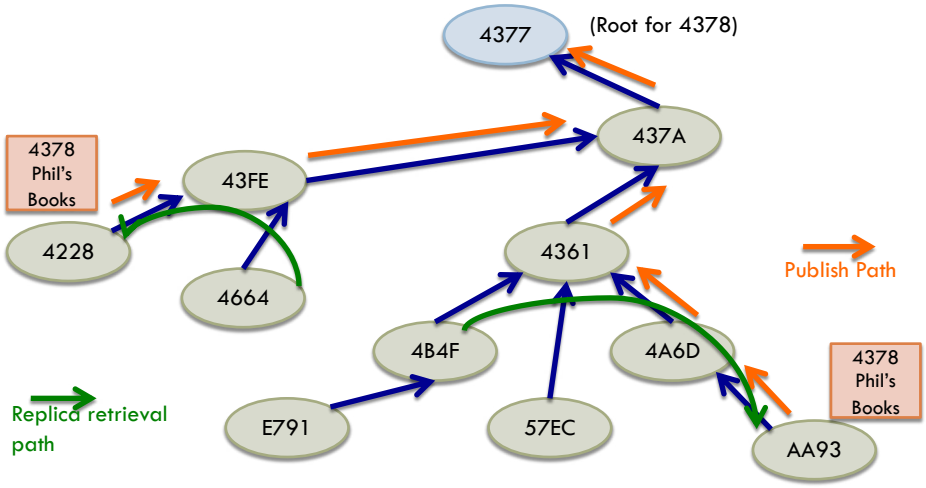
Managing multiple copies of the resource

- Hosts H holding replicas of **G** periodically invoke *publish(G)*
  - Ensures that newly arrived hosts become aware of the existence of **G**
- On each invocation of *publish(G)*
  - Message is routed from invoker towards node R_G
  - On receipt of a publish message R_G enters (G, IP_H)
    - The mapping between **G** and IP address of H
  - Each node in the publication path caches the same mapping

Managing multiple copies of the resource

- When nodes hold multiple (**G**, IP) mappings for the same GUID?
  - They are **sorted** by network distance to the IP address
- Results in *selection of nearest* available replica of the object

An example of managing replicas using Tapestry

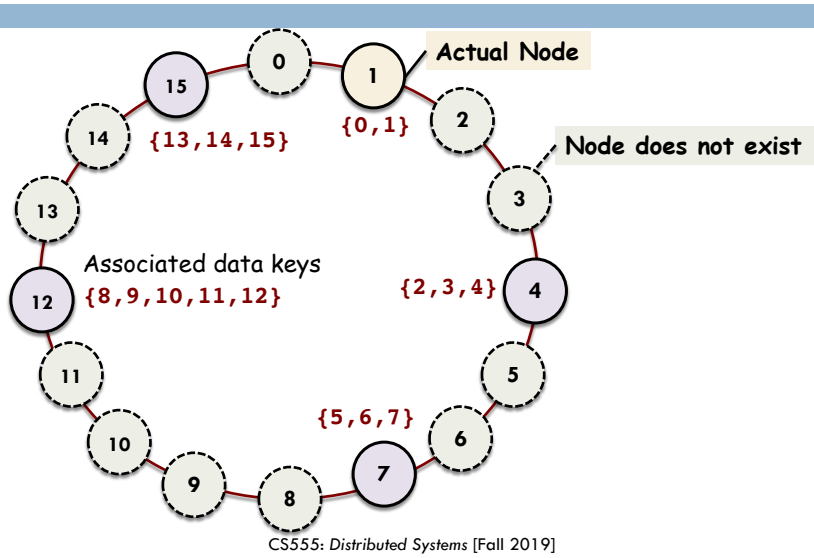


CHORD

The Chord System

- Assigns IDs to keys and nodes from the same 1-dimensional ID space
- Nodes are organized into a **ring**
- Data item with key **k** is mapped to a node with the **smallest** **id ≥ k**
  - Also referred to as successor(**k**)

Mapping of data items to nodes in Chord



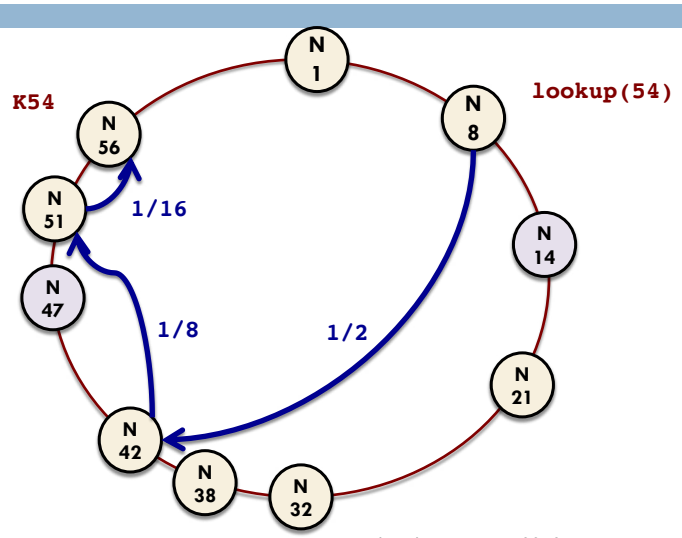
Chord lookups

- **N** is the number of possible nodes in the system
- Each node maintains a **finger table**
  - With log N entries
  - Entries contains IP addresses of nodes
    - Half-way around the ID space from it
    - 1/4th, 1/8th, … **in powers of two**
  - Ensures node can forward lookup query to at least ½ of the remaining ID-space distance to key
    - Lookups in *O(log N)*

Storing keys and forwarding lookups

- An entity with key k falls under the ***jurisdiction*** of node with the *smallest identifier* id
  - $id >= k$
  - Referred to as the successor of k or $succ(k)$
- A node ***forwards*** query for key k to node (in its FT) with highest ID $\leq k$
  - The exception is ONLY when the first entry is greater than k

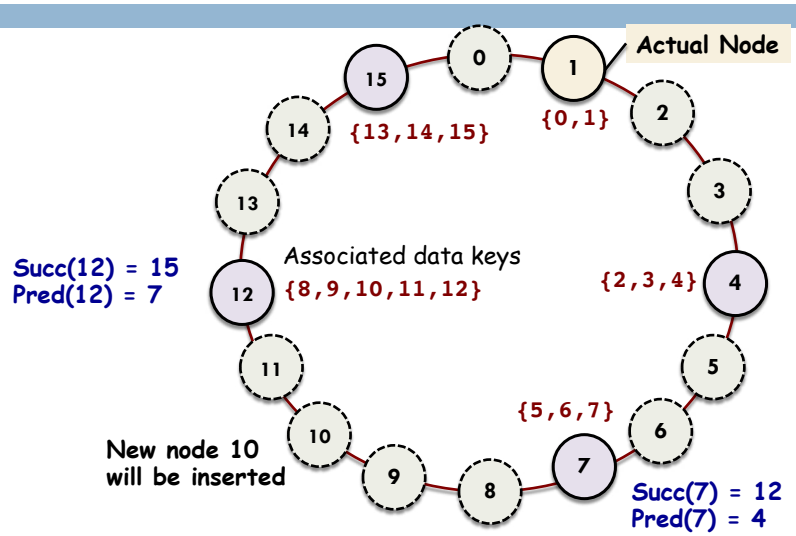
Chord lookup example for k=54



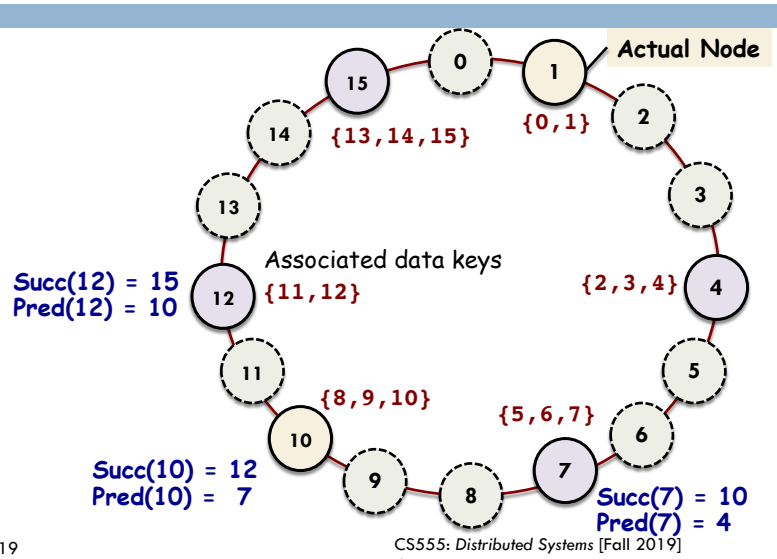
When a node wants to join

- Generate a random id
  - Probability of collisions is low
- **`lookup(id)`**
  - Will return successor(id)
- Contact *successor(id)* and its predecessor
  - Insert self in the ring
  - **Transfer** data items
    - All keys must be fetched from the new node's successor

An example of inserting a new node



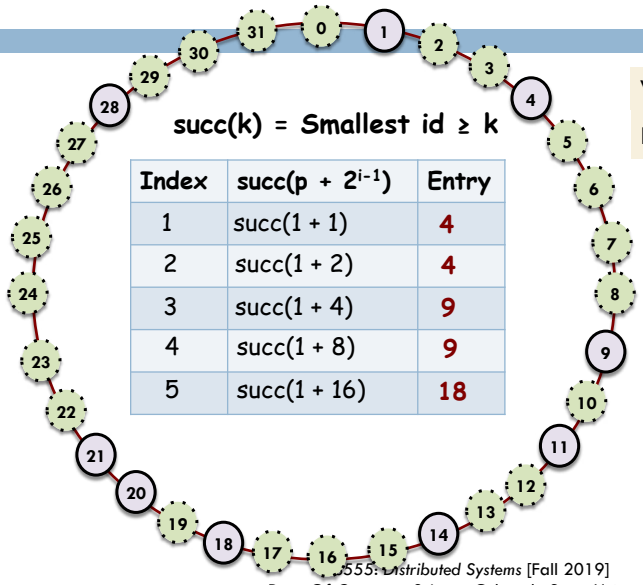
An example of inserting a new node



Finger Table in Chord

- Chord uses an m-bit identifier space
  - 2^m possible peers
- Each node, p, in Chord maintains a Finger Table with m-entries
  - $FT_p[i] = succ(p + 2^{i-1})$

Constructing the Finger Table: Node 1



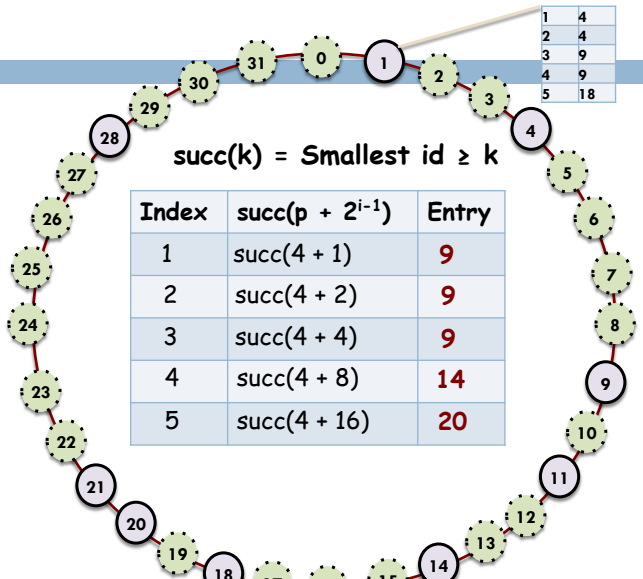
succ(k) = Smallest id ≥ k

Index	succ(p + 2^{i-1})	Entry
1	succ(1 + 1)	4
2	succ(1 + 2)	4
3	succ(1 + 4)	9
4	succ(1 + 8)	9
5	succ(1 + 16)	18

We are looking at a 5-bit ID space.

IDs go from 0 through ($2^5 - 1$)

Constructing the Finger Table: Node 4

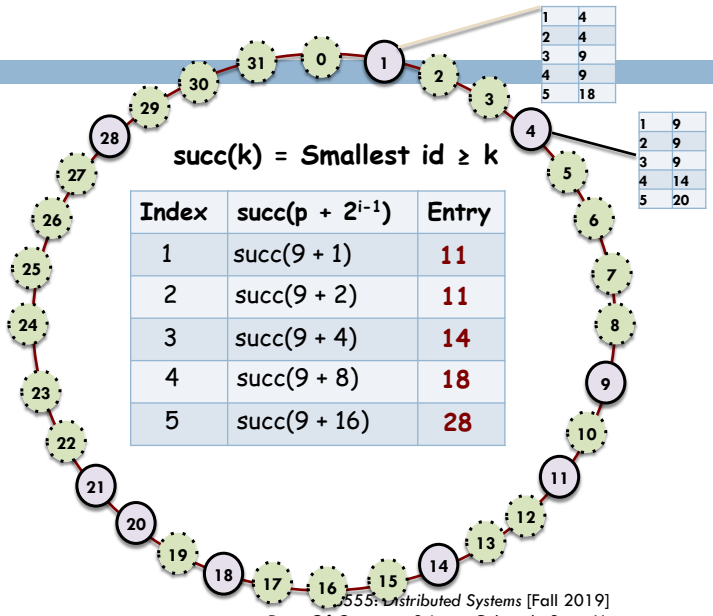


1	4
2	4
3	9
4	9
5	18

succ(k) = Smallest id ≥ k

Index	succ(p + 2^{i-1})	Entry
1	succ(4 + 1)	9
2	succ(4 + 2)	9
3	succ(4 + 4)	9
4	succ(4 + 8)	14
5	succ(4 + 16)	20

Constructing the Finger Table: Node 9



Index	succ(p + 2^{i-1})	Entry
1	succ(9 + 1)	11
2	succ(9 + 2)	11
3	succ(9 + 4)	14
4	succ(9 + 8)	18
5	succ(9 + 16)	28

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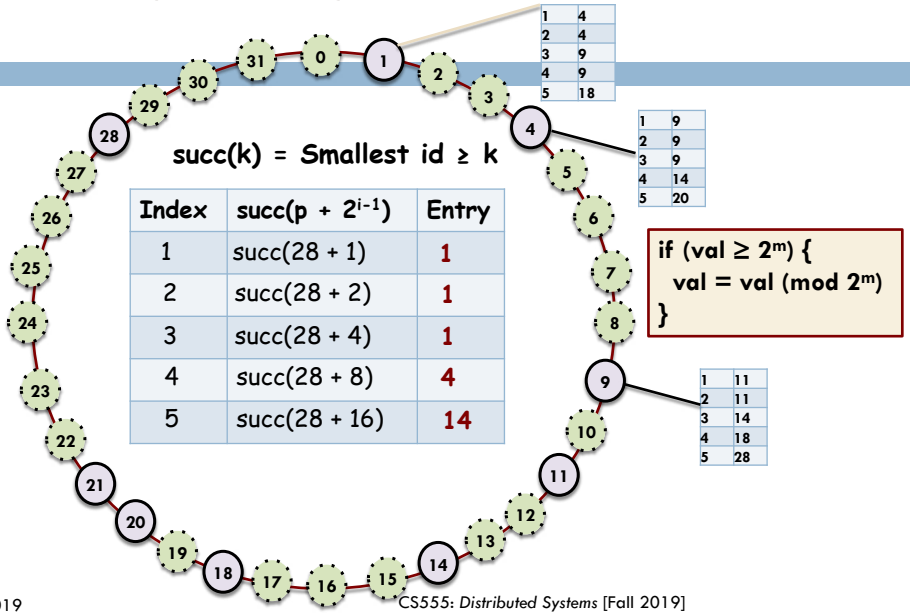
L7.33

Constructing the Finger Table: Node 28



Index	succ(p + 2^{i-1})	Entry
1	succ(28 + 1)	1
2	succ(28 + 2)	1
3	succ(28 + 4)	1
4	succ(28 + 8)	4
5	succ(28 + 16)	14

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Using the finger table to route queries: Make sure you don't overshoot

- To lookup a key k, node p will forward query to node q with index j in p's FT where:

Node with greatest ID less than or equal to k

$$q = FT_p[j] \leq k < FT_p[j+1]$$

OR

$$q = FT_p[1] \text{ when } p < k < FT_p[1]$$

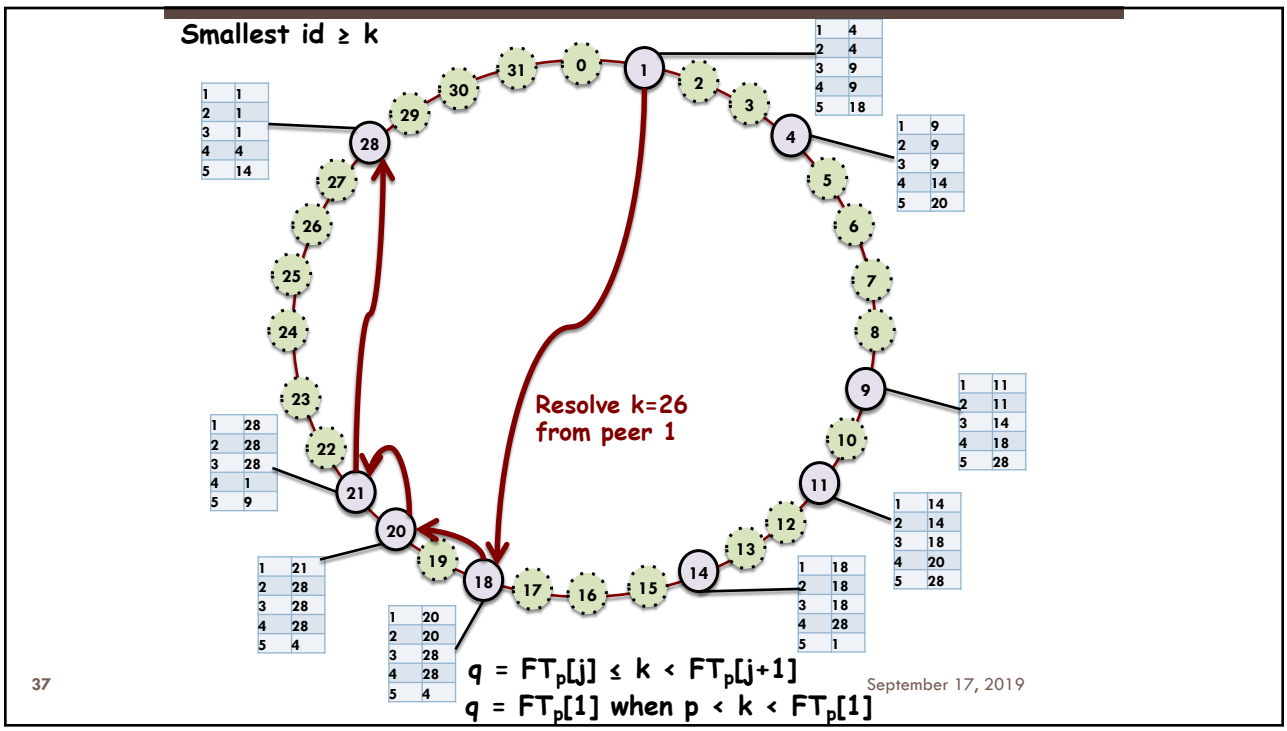
First entry ONLY if its ID is greater than k

Stop forwarding the query when you are the target node

- A node is ***responsible*** for keys that fall in the range

  key > predecessor

  key <= self


Smallest id ≥ k
Resolve k=26
from peer 1
q = FTp[j] ≤ k < FTp[j+1]
q = FTp[1] when p < k < FTp[1]
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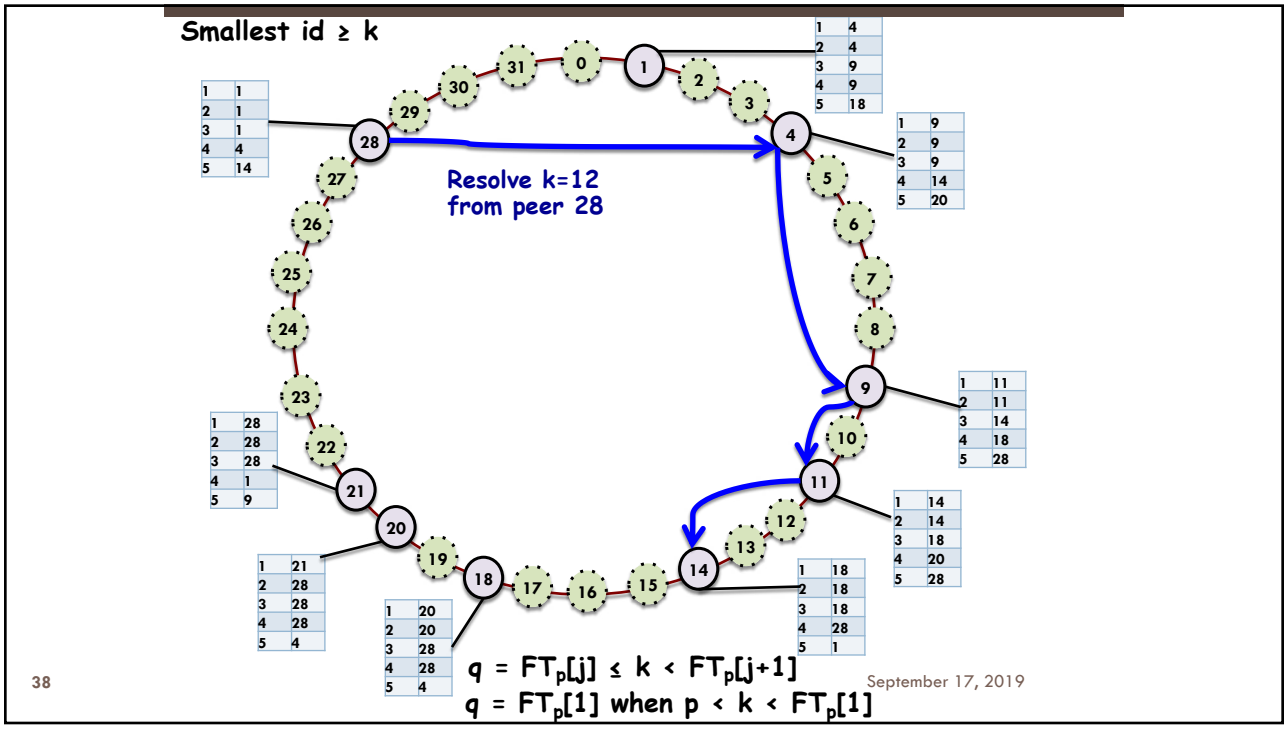
Smallest id ≥ k
Resolve k=12
from peer 28
q = FTp[j] ≤ k < FTp[j+1]
q = FTp[1] when p < k < FTp[1]
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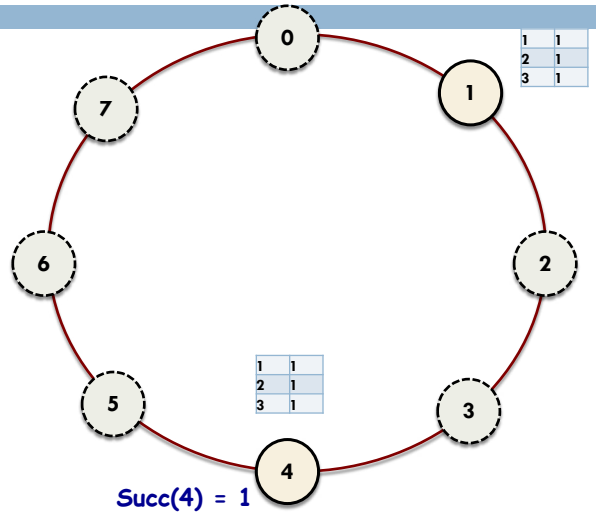
Keeping the finger table up-to-date: At node q, $FT_q[1]$ must be accurate

1. Contact $succ(q+1)$ {This is $FT_q[1]$}
   - Have it return its predecessor
2. If $q = pred(succ(q+1))$
   - Everything is fine
3. Otherwise:
   - There is a new node p such that $q < p \leq succ(q+1)$
   - $FT_q[1] = p$
   - Check if p has recorded q as its predecessor
     No? Go to step (1)

AN EXAMPLE OF NODES JOINING IN CHORD

An example of inserting a new node N-4: Node-4 comes in and contacts Node-1



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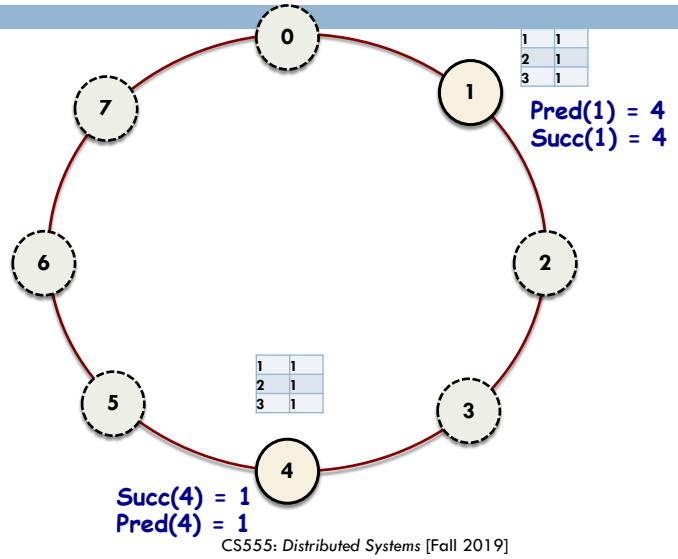
L7.**41**

Installing successor at Node-1



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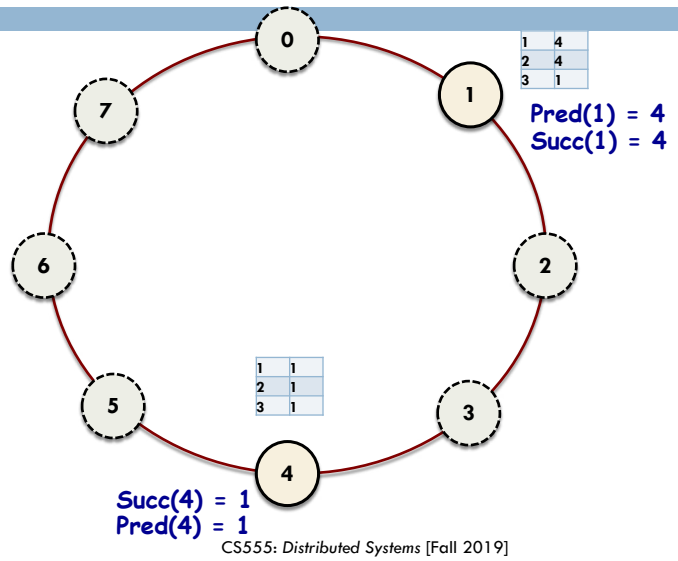
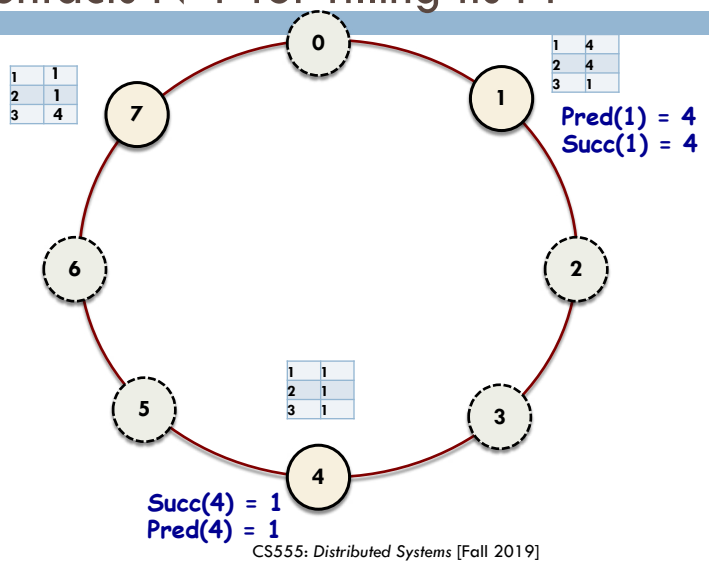
L7.**42**

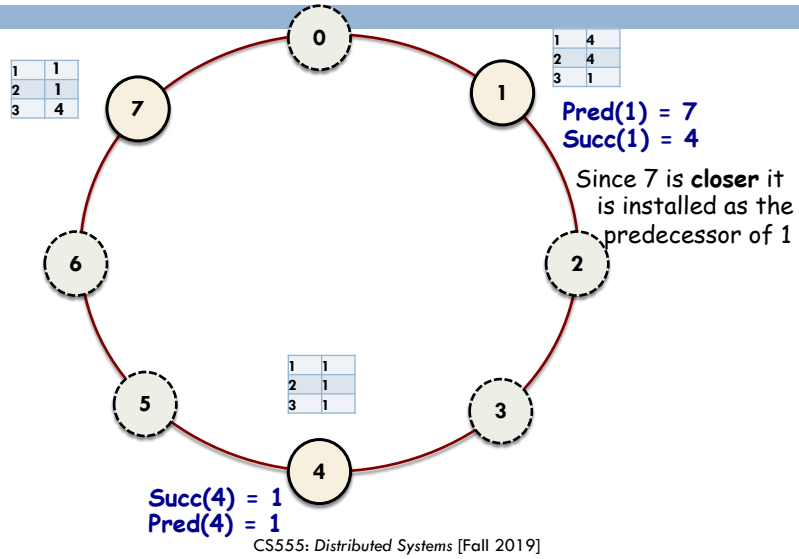
Updating the FT at N-1



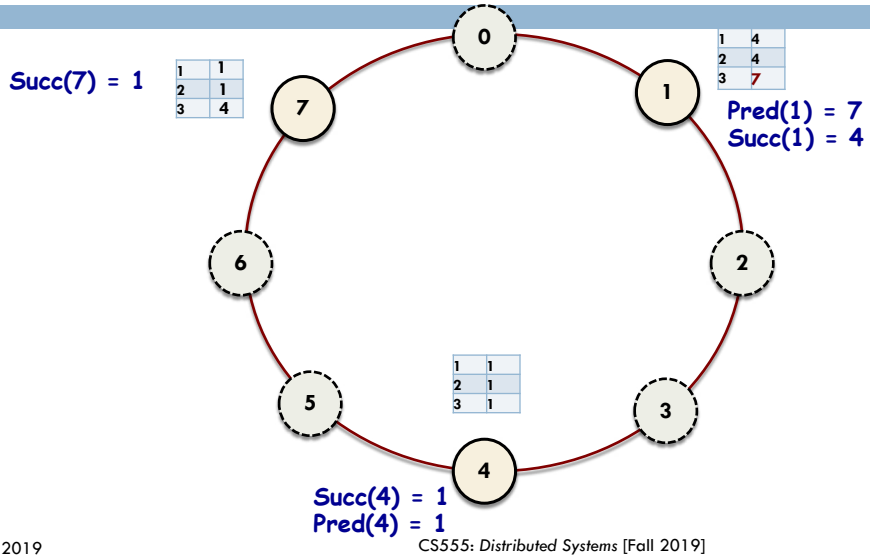
An example of inserting a new node N-7: N-7 contacts N-1 for filling its FT



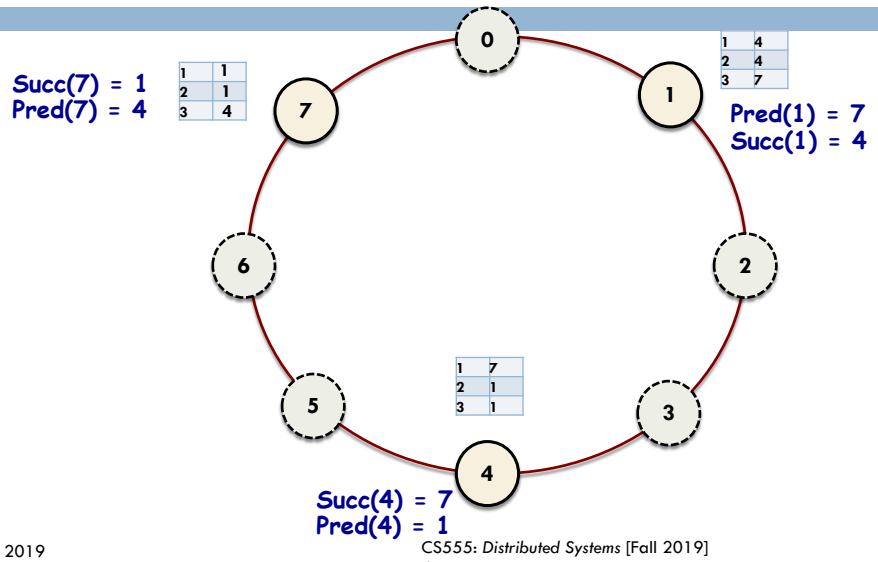
N-7 informs N-1 that it (N-7) is now N-1's predecessor



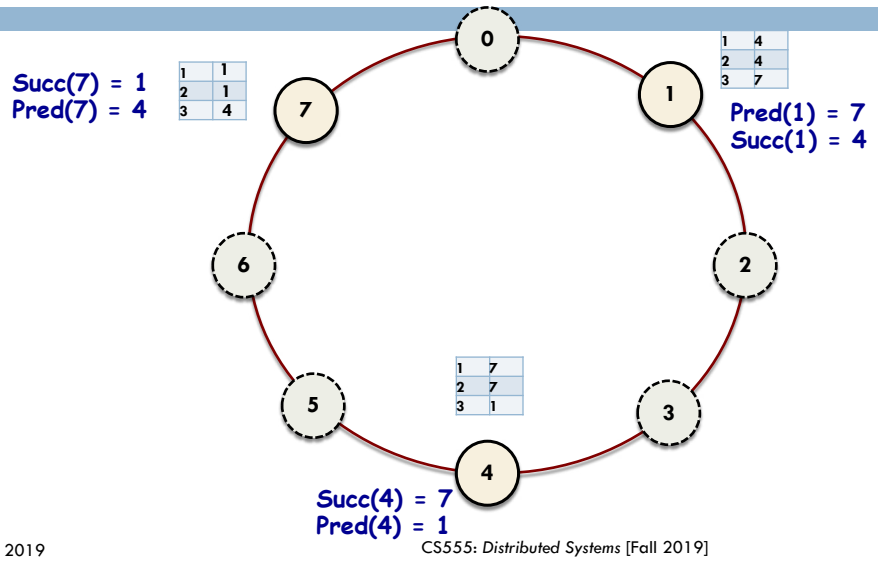
When N-1 updates its FT later on …



N-4 contacts N-1 to see if it is still its predecessor … and installs N-7 as its successor



When the FT at N-4 is updated …



The contents of this slide-set are based on the following references

- *Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van der Steen. 2nd Edition. Prentice Hall. ISBN: 0132392275/978-0132392273.* [Chapter 5]
- *Distributed Systems: Concepts and Design. George Coulouris, Jean Dollimore, Tim Kindberg, Gordon Blair. 5th Edition. Addison Wesley. ISBN: 978-0132143011.* [Chapter 10]