CSx55: DISTRIBUTED SYSTEMS [DHTs]

Pastry
This is just sad
Really, really bad
I am drawing a blank
The engine refuses to crank
It has nothing to with Pastry
with its nifty routing tree
As for Pastry in verse?
I doubt I have written anything worse

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Frequently asked questions from the previous class survey

- ☐ When pushing a file to a DHT, how does it deal with the pushing of data that already exists? If there's a file "ABC" and I upload it, what would happen tries to upload it again? Does it overwrite the existing data in an "update" style or will it reject the file?
- ☐ Dealing with exceedingly rare hash collisions?
- ☐ Do the finger tables in Chord update when nodes are added/removed?
- ☐ How long would a node hold on to the forwarding pointer?
- ☐ Do nodes in Chord (or any DHT) know about some random node?

Topics covered in this lecture

- ☐ Pastry

PASTRY

Pastry

- All nodes and objects are assigned 128-bit GUIDs
- Applies secure hash function to:
  - The public-key assigned to each node ➔ Node GUID
  - The object's name or some part of the object's stored state

Resulting GUIDs have usual properties of secure hash values

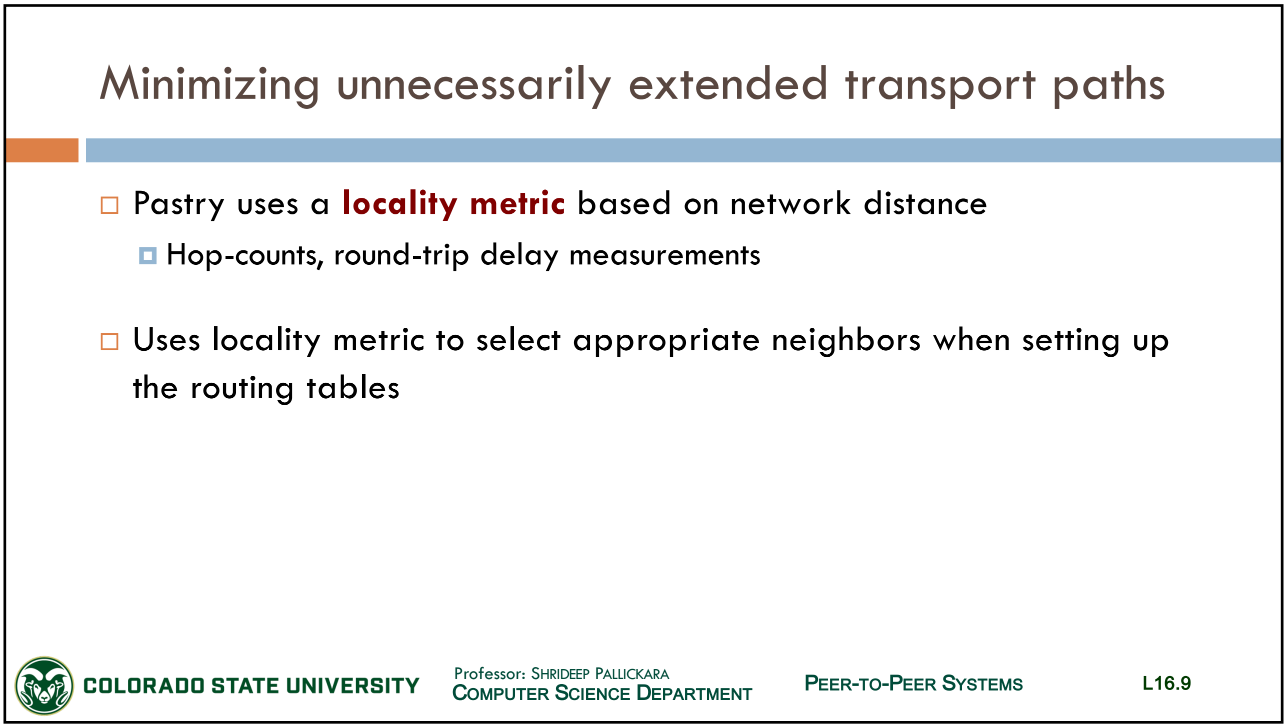
- They are **randomly distributed** in the range
  $0 - (2^{128} - 1)$
- Provide no clue about the values from which they were computed
- **Collisions** in the GUID space (for nodes and objects) are *extremely unlikely*

The Pastry routing

- The number of nodes in the network, N
- The algorithm will correctly route messages addressed to any GUID in $O(\log N)$ steps
  - Delivered to an active node whose GUID is *numerically closest* to it
- **Active nodes** take responsibility for processing requests addressed to all objects in their *numerical neighborhood*

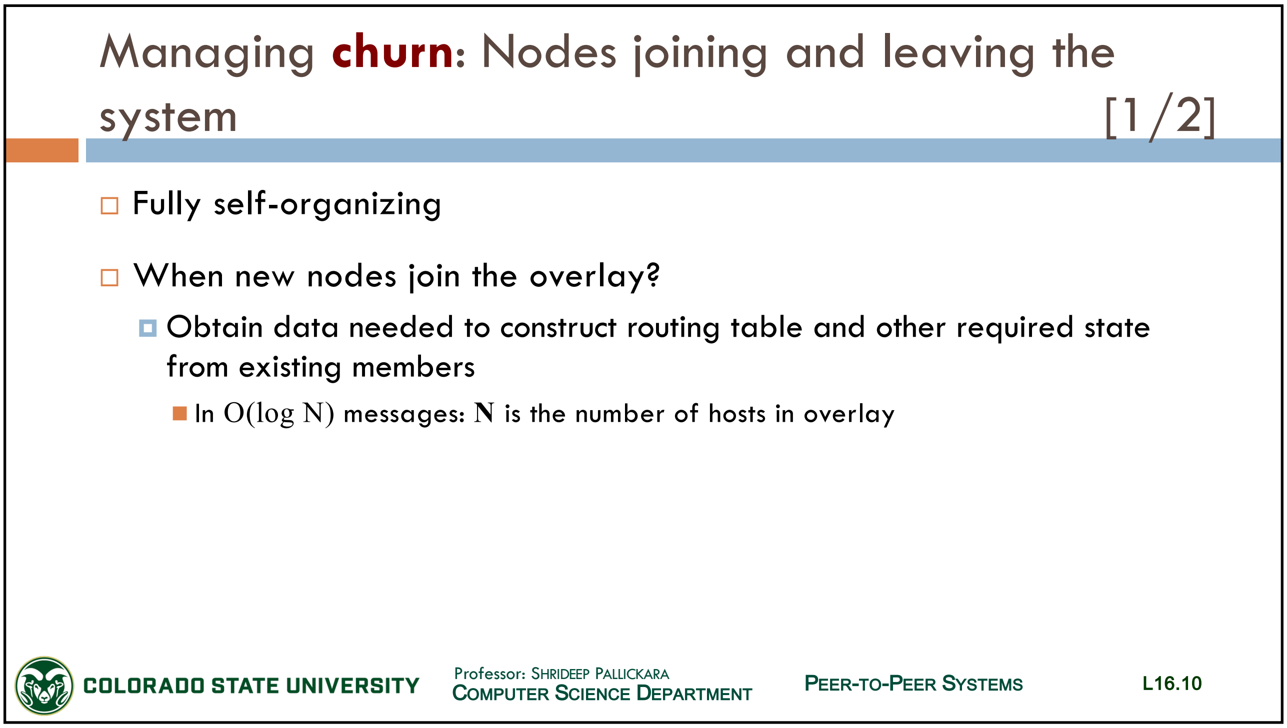
Pastry routing

- Routing transfers message to a node that is **closer** to its destination
- Closeness is in an *artificial* space
  - The space of GUIDs



Minimizing unnecessarily extended transport paths

- Pastry uses a **locality metric** based on network distance
  - Hop-counts, round-trip delay measurements
- Uses locality metric to select appropriate neighbors when setting up the routing tables



Managing **churn**: Nodes joining and leaving the system [1/2]

- Fully self-organizing
- When new nodes join the overlay?
  - Obtain data needed to construct routing table and other required state from existing members
    - In $O(\log N)$ messages: N is the number of hosts in overlay

Managing **churn**: Nodes joining and leaving the system [2/2]

- When a node fails or departs?
  - Remaining nodes detect its absence
  - Nodes **cooperatively reconfigure** to reflect required changes in routing structure
    - In O(log N) messages

THE PASTRY ROUTING ALGORITHM

We will look at the routing algorithm in two parts

- STAGE I: A simplified form
  - Routes messages correctly but inefficiently without a routing table
- STAGE II: A modified approach that uses a **routing table**
  - Full routing algorithm
  - Routes requests to any node in $O(\log N)$ messages

STAGE 1:
SIMPLIFIED PASTRY ALGORITHM

Pastry GUID space

- Is treated as a **circular** space
  - Similar to Chord
- GUID 0's lower neighbor is $2^{128}-1$

Stage I

- Each active node stores a **leaf set**
  - A vector L of size $2l$
  - Contains GUIDs and and IP addresses of nodes
    - With GUIDs that are numerically closer *on either side* of its own
    - l above and l below
- Leaf sets are maintained as nodes join and leave

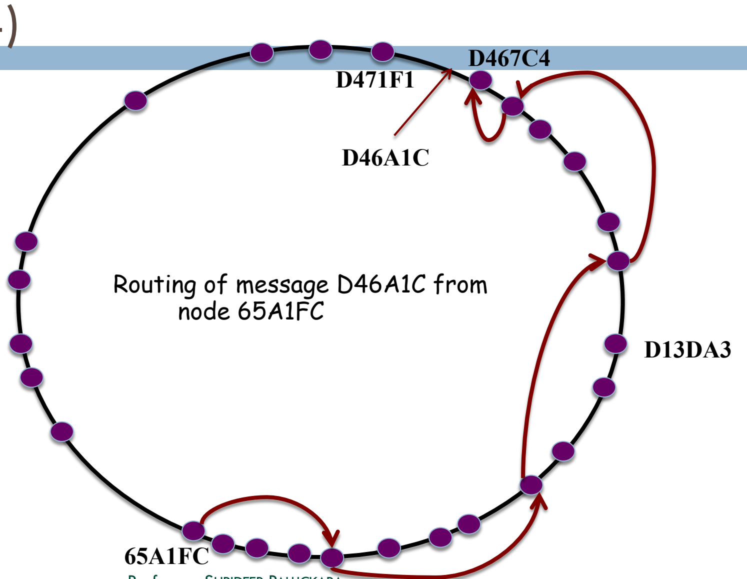
Invariant of the Pastry system

- Leaf sets reflect a *recent state* of the system, and that they **converge on the current state**
  - In the face of failures up to some maximum failure rate

Stage 1:

- Leaf set for a node contains the GUIDs and IP addresses of the node's *immediate* neighbors
- With correct leaf sets of size at least 2?
  - Message routing to any node is possible
  - Node **A** that receives a message **M** with destination address **D**
    - Compares **D** with its own GUID **A** and with each of the GUIDs in the leaf-set
    - Forwards **M** to nodes in leaf-set that are numerically closest to **D**

STAGE 1: Pastry routing example with leaf sets of size 8 (l=4)



Stage 1: Routing analysis

- It will require about $N/2l$ hops to deliver a message in a network with N nodes
- Number of hops is very inefficient

STAGE 2:
THE FULL PASTRY ALGORITHM

Stage 2: Pastry Routing

- Each node maintains a **tree-structured** routing table
- Table contains GUIDs and IP addresses for nodes spread throughout the 2^{128} possible GUID values
  - *Increased density of coverage* for GUIDs numerically closer to its own

Structure of the routing table

- GUIDs are viewed as **hexadecimal** values
- Table *classifies* GUIDs based on their hexadecimal **prefixes**
- Table has as many rows as there are hexadecimal digits in a GUID
  - For a 128-bit GUID? 128/4 = 32 rows
- Any row n contains 15 entries
  - 1 for each possible value of the n^{th} hexadecimal digit
  - Excludes values in the local node's GUID

Structure of the routing table at node 65A1

p =	**GUID prefixes and corresponding node handles n**															
0	0 n	1 n	2 n	3 n	4 n	5 n	**6**	7 n	8 n	9 n	A n	B n	C n	D n	E n	F n
1	60 n	61 n	62 n	63 n	64 n	**65**	66 n	67 n	68 n	69 n	6A n	6B n	6C n	6D n	6E n	6F n
2	65 0 n	65 1 n	65 2 n	65 3 n	65 4 n	65 5 n	65 6 n	65 7 n	65 8 n	65 9 n	**65 A**	65 B n	65 C n	65 D n	65 E n	65 F n
3	65 A0 n	**65 A1**	65 A2 n	65 A3 n	65 A4 n	65 A5 n	65 A6 n	65 A7 n	65 A8 n	65 A9 n	65 AA n	65 AB n	65 AC n	65 AD n	65 AE n	65 AF n

Each entry points to one of the potentially *many* nodes whose GUIDs have a relevant prefix

Pastry's Routing Algorithm

```
If ($L_{-l} < D < L_l$) {
    /** Destination is within leaf set or is the current node */
    Forward M to element $L_i$ of the leafset with GUID closest to D or the current node A
} else {
    /** Use the routing table to dispatch M to
        a node with a closer GUID */
}
```

Using the Routing Table: Core concept

- Compare the hexadecimal digits of **D** with those of **A** (this is the GUID of the current node where the message is being processed)
- Comparison proceeds from left-to-right to discover the length, p, of their longest common prefix
  - Used as row offset
  - The fist non-matching digit of **D** is used as the column offset
    - This gets us to the required element in the routing table
    - Construction of the routing table ensures that this element (if not empty) contains the IP address of node whose GUID has (p +1) prefix digits in common with **D**

Using the routing table to dispatch **M** to a node with a closer GUID [1/3]

- $R[p, i]$: Element at row p and column i of the routing table
- **Find**
  - p: the length of the longest common prefix of **D** and **A**
  - i: the $(p+1)^{th}$ hexadecimal digit of **D**

Using the routing table to dispatch **M** to a node with a closer GUID [2/3]

- If ($R[p, i] \neq null$) forward **M** to $R[p, i]$
  - Route **M** to a node with a longer common prefix
- This step comes into play when:
  - **D** does not fall within the numeric range of current node's leaf set
  - Relevant routing table entries are available

Using the routing table to dispatch **M** to a node with a closer GUID [3/3]

- If ($R[p, i]$) is null ?
  - Forward **M** to any node in **L** or **R** with a common prefix of length p but a *numerically closer* GUID
- **D** falls outside the numeric range of leaf set and there isn't a relevant routing table entry
  - Rare!
  - If it is in **R**?
    - Then it must be closer to **D** than any node in **L**
    - We are improving on Stage 1

INTEGRATING NEW NODES INTO PASTRY

Adding new nodes

- New nodes use a joining protocol
- Join protocol allows
  - The new node to acquire their routing table and leaf set contents
  - Notifying other nodes of changes that they must make to their tables

Let's look at the join protocol involving a new node

- New node's GUID is **X**
- Nearby node that this new node contacts is **A**
- Node **X** sends a special join request message to **A**
  - Giving **X** as its destination
- Node **A** dispatches the join message via Pastry
- Pastry will route message to an existing node with GUID numerically closest to **X**
  - Let's call this the destination node **Z**

Routing and transmissions relating to the join message

- The join message is routed through the network
  - **A**, **Z** and intermediate nodes (**B**, **C**, …)
- This results in the transmission of **relevant parts** of their routing tables and leaf sets to **X**
- **X** examines and constructs its own routing table and leaf set from them

How **X** builds its own routing table [1/2]

- First row of **X** depends on the value of **X**'s GUID
  - To minimize routing distances, table should be constructed to route messages via neighboring nodes
  - **A** is a neighbor of **X**, so first row of **A**'s table A_0 is a good initial choice for the first row of **X**'s table X_0

How **X** builds its own routing table [2/2]

- **A**'s table is not relevant for for the second row
  - GUIDs for **X** and **A** may not share the first hexadecimal digit
- But the routing algorithm ensures that
  - **X** and B's GUID do share the first hexadecimal digit
    - Second row of **B**'s routing table B_1 is a suitable initial value for X_1
- Similarly, C_2 is suitable for X_2 and so on

Leaf sets for **X**

- Since **Z**'s GUID is numerically closest to **X**'s
  - **X**'s ideal leaf set will differ from **Z**'s by just one member
- **Z**'s leaf set is an adequate approximation
  - Eventually optimized through interaction with the neighbors

Once **X** has constructed the its leaf set and routing table …

- **X** sends their contents to all *nodes* identified in the **leaf set** and the **routing table**
- The nodes that receive these updates, *adjust* their own tables to **incorporate** the node

HOST FAILURE OR DEPARTURE

Detection and coping with node failures

- When a node’s immediate neighbors (in the GUID space) cannot communicate with it?
  - The node is considered failed
- Necessary to **repair** leaf sets and routing tables that contain the failed GUID
  - Leaf sets are repaired *proactively*
  - Routing tables at the other nodes are updated on a “*when discovered basis*”

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's 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]

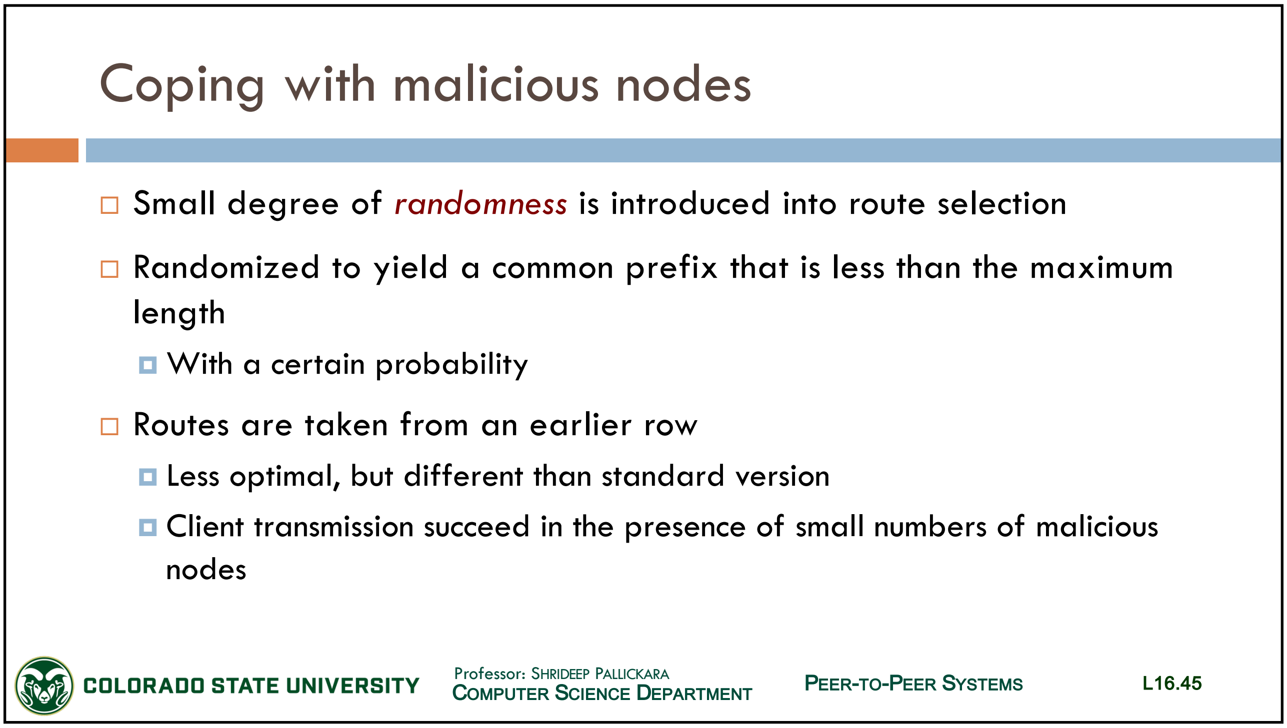
- In the routing table, each row contains 16 entries
  - Entries in the i^{th} row give addresses of 16 nodes with GUIDs with $i-1$ initial hexadecimal digits
  - I^{th} digit takes each of the possible hexadecimal values
- Well-populated Pastry system contains more nodes than can be contained in an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

Routing table: Exploiting locality. [2/2]

- When routing table is constructed, a 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

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

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