## Domain

- Structured peer-to-peer overlay networks
  - Sometimes called DHTs, DOLRs, CASTs, ...
  - Examples: CAN, Chord, Pastry, Tapestry, ...
- Contrasted with unstructured P2P networks
  - Gnutella, Freenet, etc.
- Today talking about Pastry and Tapestry

## Service Model

- Let $\mathcal{I}$ be a set of identifiers
  - Such as all 160-bit unsigned integers
- Let $\mathcal{N}$ be a set of nodes in a P2P system
  - Some subset of all possible (IP, port) tuples
- Structured P2P overlays implement a mapping $\text{owner}: \mathcal{I} \rightarrow \mathcal{N}$
  - Given any identifier, deterministically map to a node
- Properties
  - Should take $O(\log |\mathcal{N}|)$ time and state per node
  - Should be roughly load balanced

## Service Model (con't.)

- Owner mapping exposed in variety of ways
  - In Chord, have function
    
    $$n = \text{find_successor}(i)$$
  - In Pastry and Tapestry, have function
    
    $$\text{route_to_root}(i, m)$$
- In general, can be iterative or recursive
  - Iterative = directed by querying node
  - Recursive = forwarded through network
- May also expose $\text{owner}^{-1}: \mathcal{N} \rightarrow \mathcal{P}(\mathcal{I})$
  - Which identifiers given node is responsible for
### Other Service Models

- Other models can be implemented on owner
- Example: Distributed hash table (DHT)

```c
void put (key, data) {
    n = owner (key)
    n.hash_table.insert (key, data)
}

data get (key) {
    n = owner (key)
    return n.hash_table.lookup (key)
}
```

### Lecture Overview

- Introduction
- PRR Trees
  - Overview
    - Locality Properties
  - Pastry
    - Routing in Pastry
    - Leaving a Pastry network
  - Tapestry
    - Routing in Tapestry
    - Object location in Tapestry
- Multicast in PRR Trees
- Conclusions

### PRR Trees

- Work by Plaxton, Rajaraman, Richa (SPAA ’97)
  - Interesting in a distributed publication system
  - Similar to Napster in interface
  - Only for static networks (set N does not change)
  - No existing implementation (AFAIK)
- Pastry and Tapestry both based on PRR trees
  - Extend to support dynamic node membership
  - Several implementations

### PRR Trees: The Basic Idea

- Basic idea: add injective function `node_id N → I`
  - Gives each node a name in the identifier space
- `owner (i) = node whose node_id is "closest" to i`
  - Definition of closest varies, but always over I
- To find owner (i) from node with identifier j
  1. Let `p = longest matching prefix between i and j`
  2. Find node k with longest matching prefix of |p|+1 digits
  3. If no such node, j is the owner (root)
  4. Otherwise, forward query to node k
- Step 2 is the tricky part
PRR Trees: The Routing Table

- Each node $n$ has $O(b \log_b |N|)$ neighbors
  - Each $L_x$ neighbor shares $x$ digits with $n$
  - Set of neighbors forms a routing table

PRR Trees: Routing

- To find owner (47E2)
  - Query starts at node 3AF2
  - Resolve first digit by routing to 4633
  - Resolve second digit by routing to 47DA, etc.

PRR Trees: Routing (con’t.)

- Problem: what if no exact match?
  - Consider the following network
    - Who is the owner of identifier 3701?
  - Network is well formed
    - Every routing table spot that can be filled is filled
    - Can route to all node identifiers
  - Owner of 3701 not well defined
    - Starting from 1000, it’s node 3800
    - Starting from 2000, it’s node 3600
  - Violation of service model

PRR Trees: Handling Inexact Matches

- Want owner function to be deterministic
  - Must have a way to resolve inexact matches
- Solved different ways by each system
  - I have no idea what PRR did
  - Pastry chooses numerically closest node
    - Can break ties high or low
  - Tapestry performs “surrogate routing”
    - Chooses next highest match on per digit basis
- More on this later
Locality in PRR Trees

- Consider a node with id=1000 in a PRR network
  - At lowest level of routing table, node 1000 needs neighbors with prefixes 2-, 3-, 4-, etc.
  - In a large network, there may be several of each
- Idea: choose the “best” neighbor for each prefix
  - Best can mean lowest latency, highest bandwidth, etc.
- Can show that this choice gives good routes
  - For certain networks, routing path from query source to owner no more than a constant worse than routing path in underlying network
  - I'm not going to prove this today, see PRR97 for details

Locality in PRR Trees: Experiments

Pastry Introduction

- A PRR tree combined with a Chord-like ring
  - Each node has PRR-style neighbors
  - And each node knows its predecessor and successor
    - Called its leaf set
- To find owner (i), node n does the following:
  - If i is r's leaf set, choose numerically closest node
  - Else, if appropriate PRR-style neighbor, choose that
  - Finally, choose numerically closest from leaf set
- A lot like Chord
  - Only leaf set necessary for correctness
  - PRR-neighbors like finger table, only for performance

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  - Routing in Tapestry
  - Object location in Tapestry
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Pastry Routing Example

- PRR neighbors in black
- Leaf set neighbors in blue
- Owner of 3701 is now well-defined
- From 1000
  - Resolve first digit routing to 3800
  - At 3800, see that we’re done
    (Numerically closer than 3600)
- From 2000
  - Resolve first digit routing to 3600
  - At 3600, 3701 is in leaf set
    - In range 2000-3800
  - Route to 3800 b/c numerically closer

Notes on Pastry Routing

- Leaf set is great for correctness
  - Need not get PRR neighbors correct, only leaf set
  - If you believe the Chord work, this isn’t too hard to do
- Leaf set also gives implementation of owner⁻¹(n)
  - All identifiers half-way between n and its predecessor to half-way between n and its successor
- Can store k predecessors and successors
  - Gives further robustness as in Chord

Joining a Pastry Network

- Must know of a “gateway” node, g
- Pick new node’s identifier, n, U.A.R. from I
- Ask g to find the m = owner (n)
  - And ask that it record the path that it takes to do so
- Ask m for its leaf set
- Contact m’s leaf set and announce n’s presence
  - These nodes add n to their leaf sets and vice versa
- Build routing table
  - Get level i of routing table from node i in the join path
  - Use those nodes to make level i of our routing table

Pastry Join Example

- Node 3701 wants to join
  - Has 1000 as gateway
  - Join path is 1000→3800
    - 3800 is the owner
  - 3701 ties itself into leaf set
- 3701 builds routing table
  - L0 neighbors from 1000
    - 1000, 2000, and 3800
  - L1 neighbors from 3800
    - 3600
- Existing nodes on join path consider 3701 as a neighbor
Pastry Join Notes

- Join is not “perfect”
  - A node whose routing table needs new node should learn about it
    - Necessary to prove O(log |N|) routing hops
  - Also not guaranteed to find close neighbors
- Can use routing table maintenance to fix both
  - Periodically ask neighbors for their neighbors
  - Use to fix routing table holes; replace existing distant neighbors
- Philosophically very similar to Chord
  - Start with minimum needed for correctness (leaf set)
  - Patch up performance later (routing table)

Pastry Join Optimization

- Best if gateway node is “close” to joining node
  - Gateway joined earlier, should have close neighbors
  - Recursively, gateway’s neighbors’ neighbors are close
  - Join path intuitively provides good initial routing table
  - Less need to fix up with routing table maintenance
- Pastry’s optimized join algorithm
  - Before joining, find a good gateway, then join normally
- To find a good gateway, refine set of candidates
  - Start with original gateway’s leaf set
  - Keep only a closest few, then add their neighbors
  - Repeat (more or less—see paper for details)

Leaving a Pastry Network

- Do not distinguish between leaving and crashing
  - A good design decision, IMHO
- Remaining nodes notice leaving node n down
  - Stops responding to keep-alive pings
- Fix leaf sets immediately
  - Easy if 2+ predecessors and successors known
- Fix routing table lazily
  - Wait until needed for a query
  - Or until routing table maintenance
  - Arbitrary decision, IMHO

Dealing with Broken Leaf Sets

- What if no nodes left in leaf set due to failures?
  - Can use routing table to recover (MCR93)
    - Choose closest nodes in routing table to own identifier
    - Ask them for their leaf sets
    - Choose closest of those, recurse
- Allows use of smaller leaf sets
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Tapestry Routing

- Only different from Pastry when no exact match
  - Instead of using next numerically closer node, use node with next higher digit at each hop
- Example:
  - Given 3 node network: nodes 0700, 0F00, and FFFF
  - Who owns identifier 0000?
  - In Pastry, FFFF does (numerically closest)
  - In Tapestry, 0700 does
  - From FFFF to 0700 or 0F00 (doesn’t matter)
  - From 0F00 to 0700 (7 is next highest digit after 0)
  - From 0700 to itself (no node with digit between 0 and 7)

Notes on Tapestry Routing

- Mostly same locality properties as PRR and Pastry
- But compared to Pastry, very fragile
- Consider previous example: 0700, 0F00, FFFF
  - What if 0F00 doesn’t know about 0700?
  - 0F00 will think it is the owner of 0000
  - 0700 will still think it is the owner
  - Mapping won’t be deterministic throughout network
- Tapestry join algorithm guarantees won’t happen
  - All routing table holes than can be filled will be
  - Provably correct, but tricky to implement
  - Leaf set links are bidirectional, easier to keep consistent

Object Location in Tapestry

- Pastry was originally just a DHT
  - Support for multicast added later (RKC+01)
- PRR and Tapestry are DOLRs
  - Distributed Object Location and Routing
- Service model
  - publish (name)
  - route_to_object (name, message)
- Like Napster, Gnutella, and DNS
  - Service does not store data, only pointers to it
  - Manages a mapping of names to hosts
A Simple DOLR Implementation

- Can implement a DOLR on owner service model

```java
publish (name) {
    n = owner (name)
    n.add_mapping (name, my_addr, my_port)
}

route_to_object (name, message) {
    n = owner (name)
    m = n.get_mapping (name)
    m.send_msg (message)
}
```

Problems with Simple DOLR Impl.

- No locality
  - Even if object stored nearby, owner might be far away
  - Bad for performance
  - Bad for availability (owner might be behind partition)
- No redundancy
  - Easy to fix if underlying network has leaf/successor sets
  - Just store pointers on owner’s whole leaf set
    - If owner fails, replacement already has pointers
  - But Tapestry doesn’t have leaf/successor sets

Tapestry DOLR Implementation

- Insight: leave “bread crumbs” along publish path
  - Not just at owner

```java
publish (name) {
    foreach n in path_to_owner (name)
        n.add_mapping (name, my_addr, my_port)
}

route_to_object (name, message) {
    foreach n in path_to_owner (name)
        if ((m = n.get_mapping (name)) != null) {
            m.send_msg (message); break;
        }
}
```

Tapestry DOLR Impl.: Experiments
Tapestry DOLR Impl. Notes

- Bread crumbs called “object pointers”
- PRR show that overlay path from query source to object is no worse than a constant longer than underlying network path
  - Just like in routing in a PRR tree
- True for two reasons:
  1. Hops early in path are short (in network latency)
  2. Paths converge early
- Path convergence is a little subtle
  - Two nearby nodes often have same early hops
  - Because next hop based on destination, not source
  - And because neighbor choice weighted on latency

Path Convergence Examples

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Multicast in PRR Trees

- PRR Tree gives efficient paths between all nodes
  - Uses application nodes as routers
- Since control routers, can implement multicast
  - Seems to have been thought of simultaneously by:
    • Pastry group, with SCRiBE protocol (RNC+01)
    • Tapestry group, with Bayeux protocol (ZZJ+01)
- I’ll talk about SCRiBE
SCRIBE Protocol

- Like Tapestry object location, use bread crumbs
- To subscribe to multicast group $i$
  - Walk up tree towards owner ($i$), leaving bread crumbs
  - If find pre-existing crumb, leave one more and stop
- To send a message to group $i$
  - Send message to owner ($i$)
  - Owner sends message to each bread crumb it has
    - Its children who are subscribers or their parents
    - Each child recursively does the same

SCRIBE Example

SCRIBE Notes

- Multicast evaluation points
  - Stretch, also called Relative Delay Penalty (RDP)
  - Network Stress
- SCRIBE has constant RDP
  - Assuming Pastry is a good PRR tree
- SCRIBE has low network stress
  - Harder to see, but due to choosing neighbors by latency
  - Demonstrated in simulations (CJK03)

Conclusions

- PRR trees are a powerful P2P primitive
  - Can be used as a DHT
    - Path to owner has low RDP
    - Chord can be “hacked” to do the same
  - Can be used as a DOLR
    - Finds close objects when available
    - No clear way to get this from Chord
    - Can be used for application-level multicast
    - Also no clear way to get this from Chord
- More work to support dynamic membership
  - Pastry uses leaf sets like Chord
  - Tapestry has own algorithm
For more information

- **Pastry**
  [http://research.microsoft.com/~anr/pastry/pubs.htm](http://research.microsoft.com/~anr/pastry/pubs.htm)
- **Tapestry**