Tapestry: Decentralized Routing and Location

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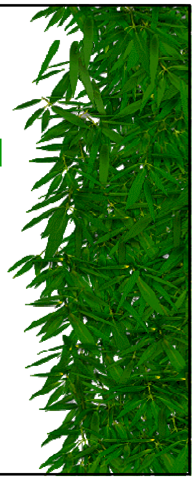
Ben Y. Zhao
CS Division, U. C. Berkeley



Challenges in the Wide-area

- Trends:
  - Exponential growth in CPU, b/w, storage
  - Network expanding in reach and b/w
- Can applications leverage new resources?
  - Scalability: increasing users, requests, traffic
  - Resilience: more components → inversely low MTBF
  - Management: intermittent resource availability → complex management schemes
- Proposal: an infrastructure that solves these issues and passes benefits onto applications

Driving Applications

- Leverage proliferation of cheap & plentiful resources: CPU's, storage, network bandwidth
- Global applications share distributed resources
  - Shared computation:
    - SETI, Entropia
  - Shared storage
    - OceanStore, Napster, Scale-8
  - Shared bandwidth
    - Application-level multicast, content distribution

Key: Location and Routing

- Hard problem:
  - Locating and messaging to resources and data
- Approach: wide-area overlay infrastructure:
  - Easier to deploy than lower-level solutions
  - Scalable: million nodes, billion objects
  - Available: detect and survive routine faults
  - Dynamic: self-configuring, adaptive to network
  - Exploits locality: localize effects of operations/failures
  - Load balancing

Talk Outline

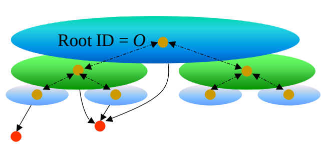
- Problems facing wide-area applications
- Tapestry Overview
- Mechanisms and protocols
- Preliminary Evaluation
- Related and future work

Previous Work: Location

- Goals:
  - Given ID or description, locate nearest object
- Location services (scalability via hierarchy)
  - DNS
  - Globe
  - Berkeley SDS
- Issues
  - Consistency for dynamic data
  - Scalability at root
  - Centralized approach: bottleneck and vulnerability

Decentralizing Hierarchies

- Centralized hierarchies
  - Each higher level node responsible for locating objects in a greater domain
- Decentralize: Create a tree for object *O* (really!)
  - Object *O* has its own root and subtree
  - Server on each level keeps pointer to nearest object in domain
  - Queries search up in hierarchy



Directory servers tracking 2 replicas

What is Tapestry?

- A prototype of a *decentralized, scalable, fault-tolerant, adaptive* location and routing infrastructure *(Zhao, Kubiatowicz, Joseph et al. U.C. Berkeley)*
- Network layer of OceanStore global storage system Suffix-based hypercube routing
  - Core system inspired by Plaxton, Rajamaran, Richa (SPAA97)
- Core API:
  - *publishObject(ObjectID, [serverID])*
  - *sendmsgToObject(ObjectID)*
  - *sendmsgToNode(NodeID)*

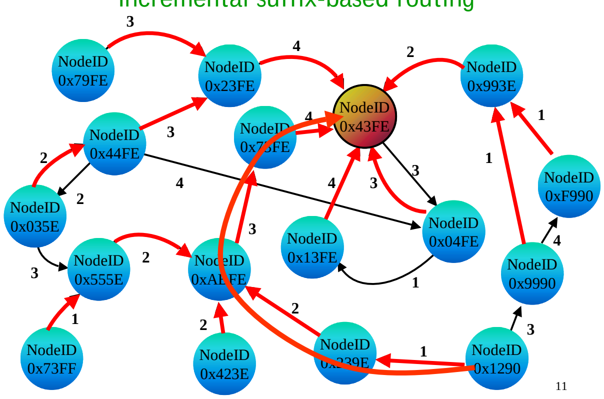
Incremental Suffix Routing

- Namespace (nodes and objects)
  - large enough to avoid collisions (~2^{160}?) (size *N* in *$Log_2(N)$* bits)
- Insert Object:
  - Hash Object into namespace to get ObjectID
  - For (*i=0, i<Log_2(N), i+j*) { //Define hierarchy
    - *j* is base of digit size used, (*j* = 4 → hex digits)
    - Insert entry into nearest node that matches on last *i* bits
    - When no matches found, then pick node matching (*i – n)* bits with highest ID value, terminate

Routing to Object

- Lookup object
  - Traverse same relative nodes as insert, except searching for entry at each node
  - For (*i=0, i<Log_2(N), i+n)*
    Search for entry in nearest node matching on last *i* bits
- Each object maps to hierarchy defined by single root
  - *f* (ObjectID) = RootID
- Publish / search both route incrementally to root
- Root node = *f* (*O*), is responsible for "knowing" object's location

Tapestry Mesh
Incremental suffix-based routing



Routing to Nodes

Example: Octal digits, 2^{18} namespace, 005712 → 627510

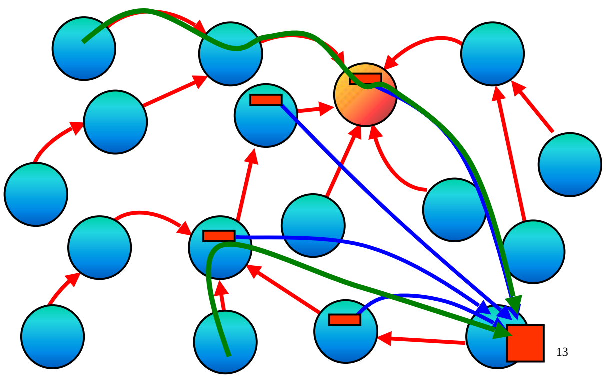
005712	0	1	2	3	4	5	6	7
340880	0	1	2	3	4	5	6	7
943210	0	1	2	3	4	5	6	7
834510	0	1	2	3	4	5	6	7
387510	0	1	2	3	4	5	6	7
727510	0	1	2	3	4	5	6	7
627510	0	1	2	3	4	5	6	7

Neighbor Map
For "5712" (Octal)

4	3	2	1
0712	x012	xx02	xxx0
1712	x112	5712	xxx0
2712	x212	xx22	5712
3712	x312	xx32	xxx3
4712	x412	xx42	xxx4
5712	x512	xx52	xxx5
6712	x612	xx62	xxx6
7712	5712	xx72	xxx7

Routing Levels

Object Location
Randomization *and* Locality



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Previous Work: PRR97

PRR97

- Key features:
  - Scalable: state: $bLog_b(N)$, hops: $Log_b(N)$
    b=digit base, N= |namespace|
  - Exploits locality
  - Proportional route distance
- Limitations
  - Global knowledge algorithms
  - Root node vulnerability
  - Lack of adaptability

Tapestry

- A *real* System!
  - Distributed algorithms
    - Dynamic root mapping
    - Dynamic node insertion
  - Redundancy in location and routing
  - Fault-tolerance protocols
  - Self-configuring / adaptive
  - Support for mobile objects
- Application Infrastructure

Fault-tolerant Location

- Minimized soft-state vs. explicit fault-recovery
- Multiple roots
  - Objects hashed w/ small salts → multiple names/roots
  - Queries and publishing utilize all roots in parallel
  - P(finding Reference w/ partition) = $1 – (1/2)^n$
    where n = # of roots
- Soft-state periodic republish
  - 50 **million** files/node, daily republish,
    b = 16, $N = 2^{160}$, 40B/msg,
    worst case update traffic: 156 kb/s,
  - expected traffic w/ 2^{40} real nodes: 39 kb/s

Fault-tolerant Routing

- Detection:
  - Periodic probe packets between neighbors
- Handling:
  - Each entry in routing map has 2 alternate nodes
  - Second chance algorithm for intermittent failures
  - Long term failures → alternates found via routing tables
- Protocols:
  - First Reachable Link Selection
  - Proactive Duplicate Packet Routing

Summary

- Decentralized location and routing infrastructure
  - Core design inspired by PRR97
  - Distributed algorithms for object-root mapping, node insertion
  - Fault-handling with redundancy, soft-state beacons, self-repair
- Analytical properties
  - Per node routing table size: $bLog_b(N)$
    - N = size of namespace, n = # of physical nodes
  - Find object in $Log_b(n)$ overlay hops
- Key system properties
  - Decentralized and scalable via random naming, yet has locality
  - Adaptive approach to failures and environmental changes

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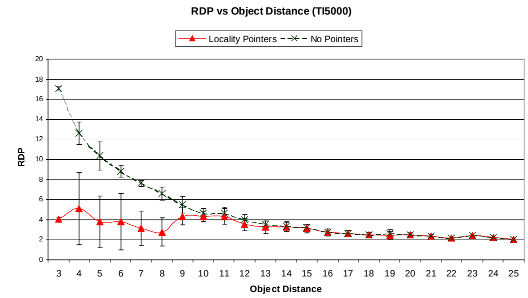
Evaluation Issues

- Locality vs. storage overhead
- Performance stability via redundancy
- Fault-resilient delivery via (FRLS)
- Routing distance overhead (RDP)
- Routing redundancy → fault-tolerance
  - Availability of objects and references
  - Message delivery under link/router failures
  - Overhead of fault-handling
- Optimality of dynamic insertion

Simulation Environment

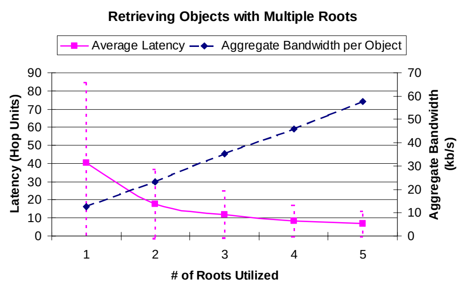
- Implemented Tapestry routing as packet-level simulator
- Delay is measured in terms of network hops
- Do not model the effects of cross traffic or queuing delays
- Four topologies: AS, MBone, GT-ITM, TIERS

Results: Location Locality



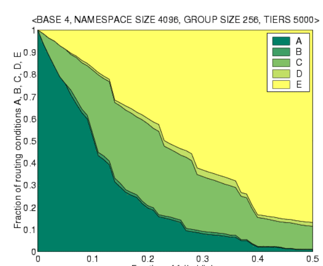
Measuring effectiveness of locality pointers (TIERS 5000)

Results: Stability via Redundancy



Parallel queries on multiple roots. Aggregate bandwidth measures b/w used for soft-state republish 1/day and b/w used by requests at rate of 1/s.

First Reachable Link Selection



- Use periodic UDP packets to gauge link condition
- Packets routed to shortest "good" link
- Assumes IP cannot correct routing table in time for packet delivery

	IP	Tapestry
A	✓	✓
B	✓	✗
C	✗	✓
D	✗	✗
E	No path exists to dest.	

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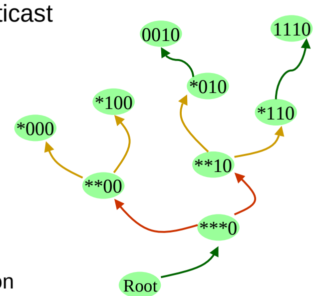
Example Application: Bayeux

- Application-level multicast
- Leverages Tapestry
  - Scalability
  - Fault tolerant data delivery
- Novel optimizations
  - Self-forming member group partitions
  - Group ID clustering for better b/w utilization



Related Work

- Content Addressable Networks
  - Ratnasamy et al., (ACIRI / UCB)
- Chord
  - Stoica, Morris, Karger, Kaashoek, Balakrishnan (MIT / UCB)
- Pastry
  - Druschel and Rowstron (Rice / Microsoft Research)

Ongoing Work

- Explore effects of parameters on system performance via simulations
- Show effectiveness of application infrastructure
  Build novel applications, scale existing apps to wide-area
  - Fault-tolerant Adaptive Routing
  - Examining resilience of decentralized infrastructures to DDoS
  - Silverback / OceanStore: global archival systems
  - Network Embedded Directory Services
- Deployment
  - Large scale time-delayed event-driven simulation
  - Real wide-area network of universities / research centers

For More Information

Tapestry:

http://www.cs.berkeley.edu/~ravenben/tapestry

OceanStore:

http://oceanstore.cs.berkeley.edu

Related papers:

http://oceanstore.cs.berkeley.edu/publications

http://www.cs.berkeley.edu/~ravenben/publications

ravenben@cs.berkeley.edu

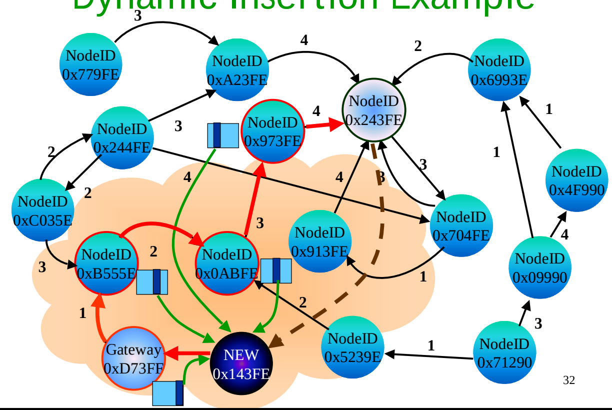
Backup Nodes Follow…

Dynamic Insertion

Operations necessary for *N* to become fully integrated:

- Step 1: Build up *N*'s routing maps
  - Send messages to each hop along path from gateway to current node *N'* that best approximates *N*
  - The i^{th} hop along the path sends its i^{th} level route table to *N*
  - *N* optimizes those tables where necessary
- Step 2: Send notify message via acked multicast to nodes with null entries for *N*'s ID, setup forwarding ptrs
- Step 3: Each notified node issues republish message for relevant objects
- Step 4: Remove forward ptrs after one republish period
- Step 5: Notify local neighbors to modify paths to route through *N* where appropriate

Dynamic Insertion Example



Dynamic Root Mapping

- Problem: choosing a root node for every object
  - Deterministic over network changes
  - Globally consistent
- Assumptions
  - All nodes with same matching suffix contains same null/non-null pattern in next level of routing map
  - Requires: consistent knowledge of nodes across network

PRR Solution

- Given desired ID *N*,
  - Find set *S* of nodes in existing network nodes *n* matching most # of suffix digits with *N*
  - Choose S_i = node in *S* with highest valued ID
- Issues:
  - Mapping must be generated statically using global knowledge
  - Must be kept as hard state in order to operate in changing environment
  - Mapping is not well distributed, many nodes in *n* get no mappings

Tapestry Solution

- Globally consistent distributed algorithm:
  - Attempt to route to desired ID N_i
  - Whenever null entry encountered, choose next "higher" non-null pointer entry
  - If current node *S* is only non-null pointer in rest of route map, terminate route, $f(N) = S$
- Assumes:
  - Routing maps across network are up to date
  - Null/non-null properties identical at all nodes sharing same suffix

Analysis

Globally consistent deterministic mapping
- Null entry → no node in network with suffix
- ∴consistent map → identical null entries across same route maps of nodes w/ same suffix

Additional hops compared to PRR solution:
- Reduce to coupon collector problem
  Assuming random distribution
- With $n * ln(n) + cn$ entries, P(all coupons) = $1\text{-}e^{-c}$
- For $n=b$, $c=b\text{-}ln(b)$,
  P(b^2 nodes left) = $1\text{-}b/e^b = 1.8 * 10^{-6}$
- # of additional hops ≅ $Log_b(b^2) = 2$

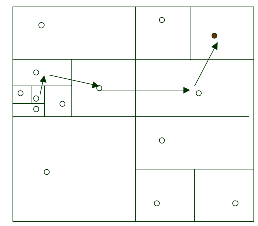
Distributed algorithm with minimal additional hops

Dynamic Mapping Border Cases

- Two cases
  - A. If a node disappeared, and some node did not detect it.
    - Routing proceeds on invalid link, fails
    - No backup router, so proceed to surrogate routing
  - B. If a node entered, has not been detected, then go to surrogate node instead of existing node
    - New node checks with surrogate after all such nodes have been notified
    - Route info at surrogate is moved to new node

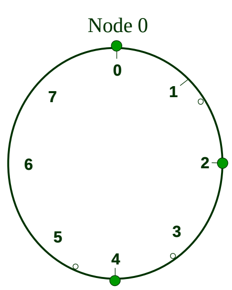
Content-Addressable Networks

- Distributed hashtable addressed in *d* dimension coordinate space
- Routing table size: *O(d)*
- Hops: expected $O(dN^{1/d})$
  - *N* = size of namespace in *d* dimensions
- Efficiency via redundancy
  - Multiple dimensions
  - Multiple realities
  - Reverse push of "breadcrumb" caches
  - Assume immutable objects



Chord

- Associate each node and object a unique ID in *uni-dimensional* space
- Object *O* stored by node with highest ID < *O*
- Finger table
  - Pointer for next node 2^i away in namespace
  - Table size: $Log_2(n)$
  - *n* = total # of nodes
- Find object: $Log_2(n)$ hops
- Optimization via heuristics



Pastry

- Incremental routing like Plaxton / Tapestry
- Object replicated at *x* nodes closest to object's ID
- Routing table size: $b(Log_bN)+O(b)$
- Find objects in $O(Log_bN)$ hops
- Issues:
  - Does not exploit locality
  - Infrastructure controls replication and placement
  - Consistency / security

Key Properties

- Logical hops through overlay per route
- Routing state per overlay node
- Overlay routing distance vs. underlying network
  - Relative Delay Penalty (RDP)
- Messages for insertion
- Load balancing

Comparing Key Metrics

- Properties

Properties	Tapestry	Chord	CAN	Pastry
– Parameter	Base b	None	Dimen d	Base b
– Logical Path Length	Log_bN	Log_2N	$O(d*N^{1/d})$	Log_bN
– Neighbor-state	$bLog_bN$	Log_2N	O(d)	$bLog_bN+O(b)$
– Routing Overhead (RDP)	O(1)	→O(1)	O(1) ?	O(1)?
– Messages to insert	$O(Log_b^2N)$	$O(Log_2^2N)$	$O(d*N^{1/d})$	$O(Log_bN)$
– Mutability	App-dep.	App-dep	Immut.	???
– Load-balancing	Good	Good	Good	Good

Designed as P2P Indices