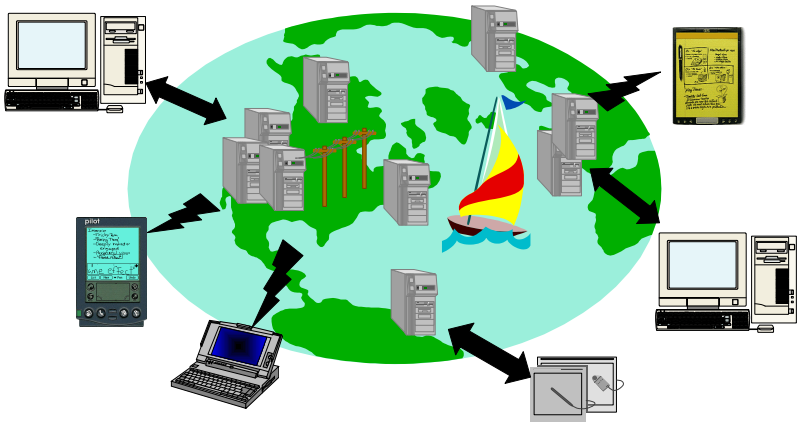
OceanStore
Global-Scale Persistent Storage



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OceanStore Context: Ubiquitous Computing

- Computing everywhere:
  - Desktop, Laptop, Palmtop
  - Cars, Cellphones
  - Shoes? Clothing? Walls?
- Connectivity everywhere:
  - Rapid growth of bandwidth in the interior of the net
  - Broadband to the home and office
  - Wireless technologies such as CMDA, Satelite, laser

Questions about information:

- Where is persistent information stored?
  - *Want: Geographic independence for availability, durability, and freedom to adapt to circumstances*
- How is it protected?
  - *Want: Encryption for privacy, signatures for authenticity, and Byzantine commitment for integrity*
- Can we make it indestructible?
  - *Want: Redundancy with continuous repair and redistribution for long-term durability*
- Is it hard to manage?
  - *Want: automatic optimization, diagnosis and repair*
- Who owns the aggregate resouces?
  - *Want: Utility Infrastructure!*

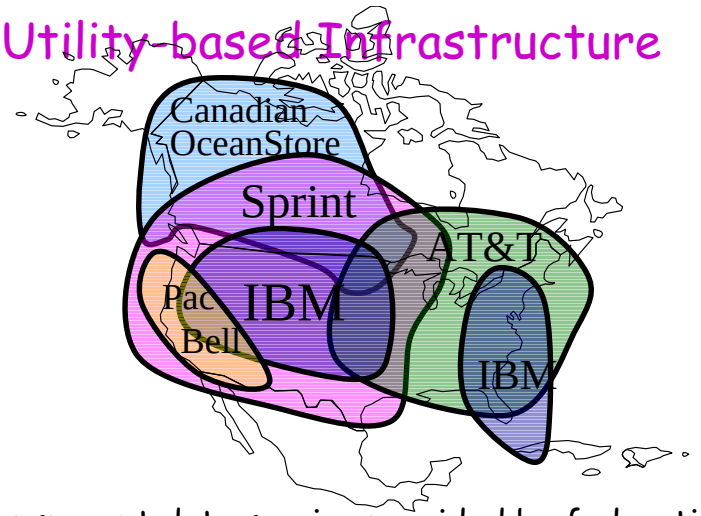
First Observation: Want Utility Infrastructure

- Mark Weiser from Xerox:
  Transparent computing is the ultimate goal
  - Computers should disappear into the background
- In storage context:
  - Don't want to worry about backup
  - Don't want to worry about obsolescence
  - Need lots of resources to make data secure and highly available, BUT *don't want to own them*
  - Outsourcing of storage already becoming popular
- Pay monthly fee and your "data is out there"
  - Simple payment interface
    ⇒ one bill from one company

Second Observation: Want Automatic Maintenance

- Can't possibly manage billions of servers by hand!
- System should automatically:
  - Adapt to failure
  - Repair itself
  - Incorporate new elements
- Can we guarantee data is *available* for 1000 years?
  - New servers added from time to time
  - Old servers removed from time to time
  - Everything just works
- *Many* components with *geographic* separation
  - System not disabled by natural disasters
  - Can adapt to changes in demand and regional outages
  - *Gain in stability through statistics*

Utility-based Infrastructure



- Transparent data service provided by federation of companies:
  - Monthly fee paid to one service provider
  - Companies buy and sell capacity from each other

OceanStore: Everyone's Data, One Big Utility

"The data is just out there"

- How many files in the OceanStore?
  - Assume 10^{10} people in world
  - Say 10,000 files/person (very conservative?)
  - So 10^{14} files in OceanStore!
  - If 1 gig files (ok, a stretch), get 1 mole of bytes!

Truly impressive number of elements…
… but small relative to physical constants

Aside: new results: 1.5 Exabytes/year (1.5×10^{18})

Outline

- Motivation
- Assumptions of the OceanStore
- Specific Technologies and approaches:
  - Naming
  - Routing and Data Location
  - Conflict resolution on encrypted data
  - Replication and Deep archival storage
  - Oceanic Data Market
  - Introspection for optimization and repair
- Conclusion

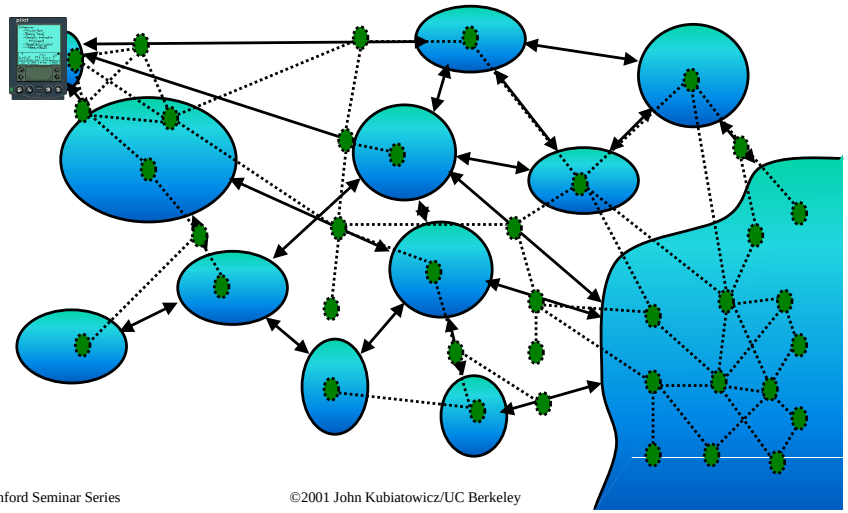
OceanStore Assumptions

- Untrusted Infrastructure:
  - The OceanStore is comprised of untrusted components
  - Only ciphertext within the infrastructure
- Responsible Party:
  - Some organization (*i.e. service provider)* guarantees that your data is consistent and durable
  - Not trusted with *content* of data, merely its *integrity*
- Mostly Well-Connected:
  - Data producers and consumers are connected to a high-bandwidth network most of the time
  - Exploit multicast for quicker consistency when possible
- Promiscuous Caching:
  - Data may be cached anywhere, anytime
- Optimistic Concurrency via Conflict Resolution:
  - Avoid locking in the wide area
  - Applications use object-based interface for updates

Use of Moore's law gains

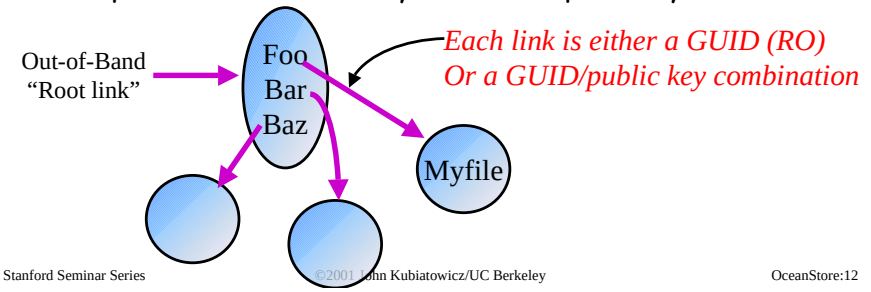
- Question: Can we use Moore's law gains for something other than just raw performance?
  - Growth in computational *performance*
  - Growth in network *bandwidth*
  - Growth in *storage* capacity
- Examples:
  - Stability through Statistics
    - Use of redundancy of servers, network packets, *etc.* in order to gain more predictable behavior
    - *Systems version of Thermodynamics!*
  - Extreme Durability (1000-year time scale?)
    - Use of erasure coding and continuous repair
  - Security and Authentication
    - Signatures and secure hashes in many places
  - Continuous dynamic optimization

Basic Structure: Irregular Mesh of "Pools"



Secure Naming

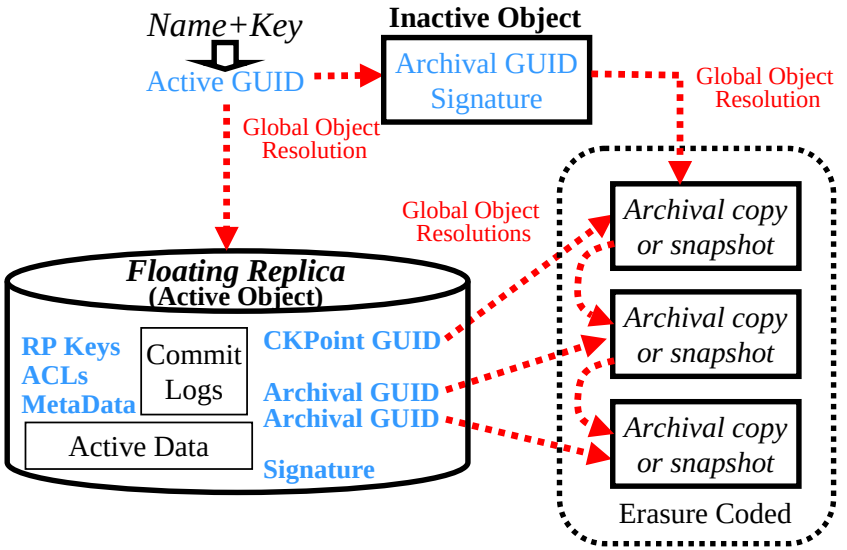
- Unique, location independent identifiers:
  - Every *version* of every unique entity has a permanent, *Globally Unique ID (GUID)*
  - All OceanStore operations operate on GUIDs
- Naming hierarchy:
  - Users map from names to GUIDs via hierarchy of OceanStore objects (*ala SDSI)*
  - Requires set of "root keys" to be acquired by user



Unique Identifiers

- Secure Hashing is key!
  - Use of 160-bit SHA-1 hashes over information provides uniqueness, unforgeability, and verifiability:
  - *Read-only data*: GUID is hash over actual information
    - Uniqueness and Unforgeability: the data is what it is!
    - Verification: check hash over data
  - *Changeable data*: GUID is combined hash over a human-readable name + public key
    - Uniqueness: GUID space selected by public key
    - Unforgeability: public key is indelibly bound to GUID
    - Verification: check signatures with public key
- Is 160 bits enough?
  - Birthday paradox requires over 2^{80} unique objects before collisions worrisome
  - Good enough for now

GUIDs ⇒Secure Pointers



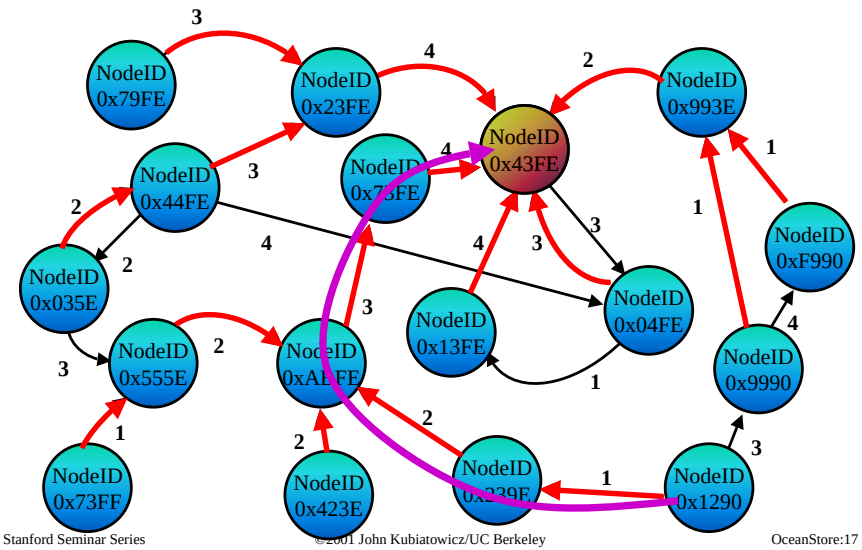
Routing and Data Location

- Requirements:
  - Find data quickly, wherever it might reside
    - Locate nearby data without global communication
    - Permit rapid data migration
  - Insensitive to faults and denial of service attacks
    - Provide multiple routes to each piece of data
    - Route around bad servers and ignore bad data
  - Repairable infrastructure
    - Easy to reconstruct routing and location information
- Technique: Combined Routing and Data Location
  - Packets are addressed to GUIDs, not locations
  - Infrastructure gets the packets to their destinations and verifies that servers are behaving

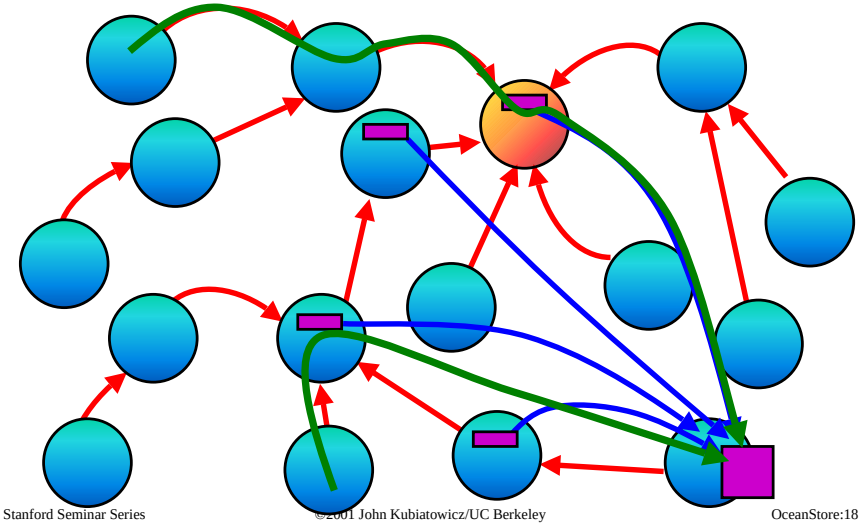
Two-levels of Routing

- Fast, probabilistic search for "routing cache":
  - Built from *attenuated* bloom filters
  - Approximation to gradient search
  - *Not going to say more about this today*
- Redundant *Plaxton Mesh* used for underlying routing infrastructure:
  - Randomized data structure with locality properties
  - Redundant, insensitive to faults, and repairable
  - Amenable to continuous adaptation to adjust for:
    - Changing network behavior
    - Faulty servers
    - Denial of service attacks

Basic Plaxton Mesh
Incremental suffix-based routing



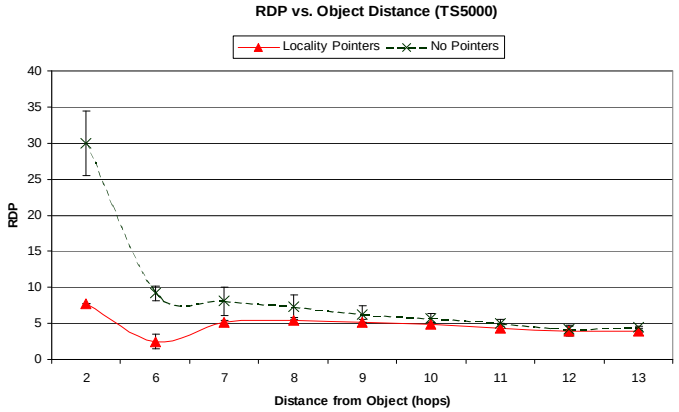
Use of Plaxton Mesh
Randomization *and* Locality



Use of the Plaxton Mesh: The Tapestry Infrastructure

- As in original Plaxton scheme:
  - Scheme to directly map GUIDs to root node IDs
  - Replicas publish toward a document root
  - Search walks toward root until pointer located⇒*locality!*
- OceanStore enhancements for reliability:
  - Documents have multiple roots (Salted hash of GUID)
  - Each node has multiple neighbor links
  - Searches proceed along multiple paths
    - Tradeoff between reliability and bandwidth?
  - Routing-level validation of query results

How important are the pointers?



- Transit-Stub IP network of 5000 nodes
- 100 Tapestry overlay nodes

Automatic Maintenance

- All Tapestry state is Soft State
  - State maintained during transformations of network
  - Periodic restoration of state
- Self-Tuning of link structure
- Dynamic insertion:
  - New nodes contact small number of existing nodes
  - Integrate themselves automatically
  - Later, introspective optimization will move data to new servers
- Dynamic deletion:
  - Node detected as unresponsive
  - Pointer state routed around faulty node (signed deletion requests authorized by servers holding data)

OceanStore Consistency via Conflict Resolution

- Consistency is form of optimistic concurrency
  - An update packet contains a series of *predicate-action* pairs which operate on encrypted data
  - Each predicate tried in turn:
    - If none match, the update is *aborted*
    - Otherwise, action of first true predicate is *applied*
- Role of Responsible Party
  - All updates submitted to Responsible Party which chooses a final total order
  - Byzantine agreement with threshold signatures
- This is powerful enough to synthesize:
  - ACID database semantics
  - release consistency (build and use MCS-style locks)
  - Extremely loose (weak) consistency

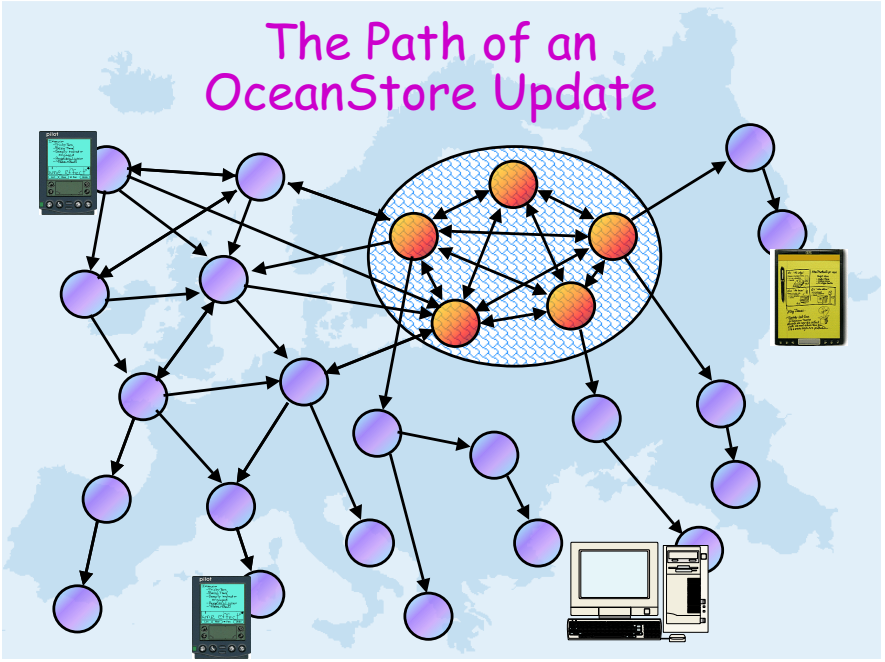
Oblivious Updates on Encrypted Data?

- Tentative Scheme:
  - Divide data into small blocks
  - Updates on a per-block basis
  - Predicates derived from techniques for searching on encrypted data
- Still exploring other options

TimeStamp
Client ID
{Pred1, Update1}
{Pred2, Update2}
{Pred3, Update3}
Client Signature

Unique Update ID is hash over packet

The Path of an OceanStore Update



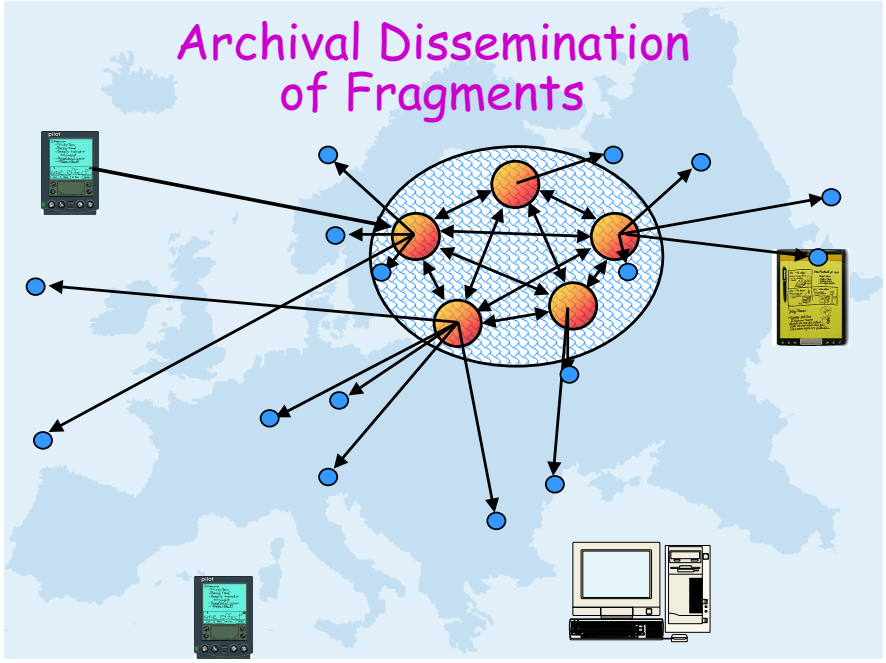
Automatic Maintenance

- Byzantine Commitment for inner ring:
  - Can tolerate up to 1/3 faulty servers in inner ring
    - Bad servers can be arbitrarily bad
    - Cost ~n^2 communication
  - Continuous refresh of set of inner-ring servers
    - Proactive threshold signatures
    - Use of Tapestry ⇒membership of inner ring unknown to clients
- Secondary tier self-organized into overlay dissemination tree
  - Use of Tapestry routing to suggest placement of replicas in the infrastructure
  - Automatic choice between *update* vs *invalidate*

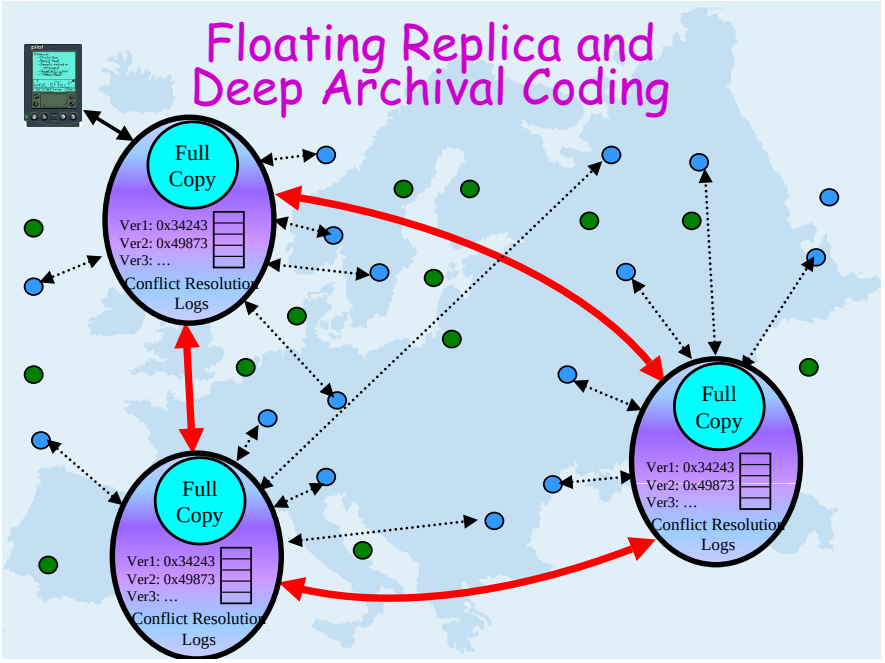
Data Coding Model

- Two distinct forms of data: active and archival
- *Active Data* in Floating Replicas
  - Per object virtual server
  - Logging for updates/conflict resolution
  - Interaction with other replicas to keep data consistent
  - May appear and disappear like bubbles
- *Archival Data* in Erasure-Coded Fragments
  - M-of-n coding: Like hologram
    - Data coded into *n* fragments, any *m* of which are sufficient to reconstruct (e.g m=16, n=64)
    - Coding overhead is proportional to n÷m (e.g 4)
    - *Law of large numbers advantage to fragmentation*
  - Fragments are self-verifying
  - OceanStore equivalent of stable store
- Most data in the OceanStore is archival!

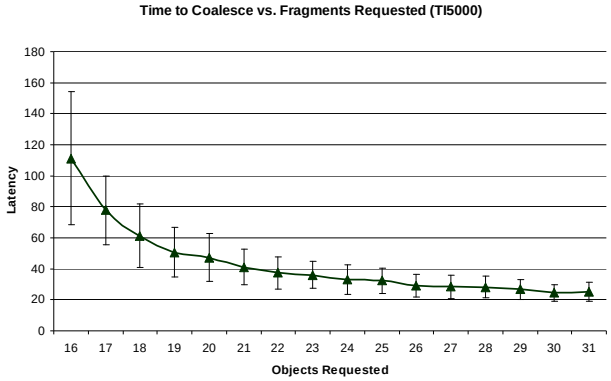
Archival Dissemination of Fragments



Floating Replica and Deep Archival Coding



Statistical Advantage of Fragments



- Latency *and* standard deviation reduced:
  - Memory-less latency model
  - Rate $\frac{1}{2}$ code with 32 total fragments

Automatic Maintenance

- Tapestry knows every location of fragment
  - Reverse pointer traversing permits multicast heartbeat from server of data to:
    - Everyone who has a pointer to data on that server
    - Or: Everyone who is one or two hops from server
  - Permits infrastructure to notice:
    - Servers going away for a while
    - Or, going away forever!
- Continuous sweep through data
  - Simple calculation of 1 mole repair
    - Rate $\frac{1}{4}$, 10 billion servers, 64 fragments,
    - 1 Mbit/sec bandwidth

Introspective Optimization

- Monitoring and adaptation of routing substrate
  - Optimization of Plaxton Mesh
  - Adaptation of second-tier multicast tree
- Continuous monitoring of access patterns:
  - Clustering algorithms to discover object relationships
    - Clustered prefetching: demand-fetching related objects
    - Proactive-prefetching: get data there *before* needed
  - Time series-analysis of user and data motion
- Continuous testing and repair of information
  - Slow sweep through all information to make sure there are sufficient erasure-coded fragments
  - Continuously reevaluate risk and redistribute data
  - Diagnosis and repair of routing and location infrastructure
  - *Provide for 1000-year durability of information?*

Can You Delete (Eradicate) Data?

- *Eradication* is antithetical to *durability!*
  - If you can eradicate something, then so can someone else! (denial of service)
  - Must have "eradication certificate" or similar
- Some answers:
  - Bays: limit the scope of data flows
  - Ninja Monkeys: hunt and destroy with certificate
- Related: Revocation of keys
  - Need hunt and re-encrypt operation
- Related: Version pruning
  - Temporary files: don't keep versions for long
  - Streaming, real-time broadcasts: Keep? Maybe
  - Locks: Keep? No, Yes, Maybe (auditing!)
  - Every key stroke made: Keep? For a short while?

First Implementation [Java]:

- Event-driven state-machine model
- Included Components
  - ✓ Initial floating replica design
    - Conflict resolution and Byzantine agreement
  - ✓ Routing facility (Tapestry)
    - Bloom Filter location algorithm
    - Plaxton-based locate and route data structures
  - ✓ Introspective gathering of tacit info and adaptation
    - Language for introspective handler construction
    - Clustering, prefetching, adaptation of network routing
  - ✓ Initial archival facilities
    - Interleaved Reed-Solomon codes for fragmentation
    - Methods for signing and validating fragments
- Target Applications
  - ✓ Unix file-system interface under Linux ("legacy apps")
  - – Email application, proxy for web caches, streaming multimedia applications

OceanStore Conclusions

- OceanStore: everyone's data, one big utility
  - Global Utility model for persistent data storage
- OceanStore assumptions:
  - Untrusted infrastructure with a responsible party
  - Mostly connected with conflict resolution
  - Continuous on-line optimization
- OceanStore properties:
  - Provides security, privacy, and integrity
  - Provides extreme durability
  - Lower maintenance cost through redundancy, continuous adaptation, self-diagnosis and repair
  - Large scale system has good statistical properties

For more info:

- OceanStore vision paper for ASPLOS 2000
  "OceanStore: An Architecture for Global-Scale Persistent Storage"
- OceanStore web site:
  http://oceanstore.cs.berkeley.edu/