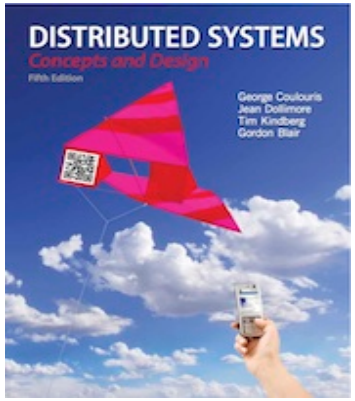
Slides for Chapter 10: Peer-to-Peer Systems



From Coulouris, Dollimore, Kindberg and Blair
Distributed Systems:
Concepts and Design

Edition 5, © Addison-Wesley 2012

Introduction [10.1]

- Motivational observations
  - Lots of resources at the edge of the Internet
  - If there is no central server no single point/entity for
    - Copyright liability
    - Cyber-attacking
    - Getting overloaded
- Goal: design a system that is
  - Fully decentralized
  - Self-organizing
  - Uses above observations

Introduction (cont.)

- Tipping Point: large enough % of always-on internet
  - Late 1990s
- Characteristics of peer-to-peer (P2P) systems:
  - Each user contributes resources to the system
  - All nodes have the same functional capabilities and responsibilities
    - "All the animals are equal, but some more equal than others."

      -- *Animal Farm* (paraphrase)
  - Correct operation does not depend on the existence of centrally administered systems
  - Can be designed to offer some kind of anonymity to providers and users of resources

Introduction (cont.)

- Key issue for each: placement of data so it
  - Is spread across huge # hosts
  - Can be efficiently accessed by users' apps
  - Balances workload
  - Ensures availability, even in the face of (relatively) volatile resources
- Most effective when used to store very large collections of **immutable** data

P2P system evolution

- Antecedents of P2P systems: DNS, USENET, research systems (Xerox PARC multiple)
- Generations of P2P system+apps
  1. Napster (2001): music exchange service
  2. File sharing apps (Freenet, Gnutella, Kazaa, BitTorrent)
  3. Middleware layer support (Pastry, Tapestry, CAN, Chord, …)
- 3G P2P middleware characteristics (offloading DADs)
  - Place resources on widely-distributed set of computers
  - Guarantees of request delivery in bounded # network hops
  - Place based on volatility/availability, trustworthiness of node
  - Resources identified w/GUIDs (usually secure hash: self-certifying)
    - Client can know not tampered
    - Q: how mutable/immutable can should/can the placed objects/files be?

Figure 10.1: Distinctions between IP and overlay routing for peer-to-peer applications

	IP	*Application-level routing overlay*
Scale	IPv4 is limited to 232 addressable nodes. The IPv6 name space is much more generous (2128), but addresses in both versions are hierarchically structured and much of the space is pre-allocated according to administrative requirements.	Peer-to-peer systems can address more objects. The GUID name space is very large and flat (>2128), allowing it to be much more fully occupied.
Load balancing	Loads on routers are determined by network topology and associated traffic patterns.	Object locations can be randomized and hence traffic patterns are divorced from the network topology.
Network dynamics (addition/deletion of objects/nodes)	IP routing tables are updated asynchronously on a best-efforts basis with time constants on the order of 1 hour.	Routing tables can be updated synchronously or asynchronously with fractions of a second delays.
Fault tolerance	Redundancy is designed into the IP network by its managers, ensuring tolerance of a single router or network connectivity failure. *n*-fold replication is costly.	Routes and object references can be replicated *n*-fold, ensuring tolerance of *n* failures of nodes or connections.
Target identification	Each IP address maps to exactly one target node.	Messages can be routed to the nearest replica of a target object.
Security and anonymity	Addressing is only secure when all nodes are trusted. Anonymity for the owners of addresses is not achievable.	Security can be achieved even in environments with limited trust. A limited degree of anonymity can be provided.

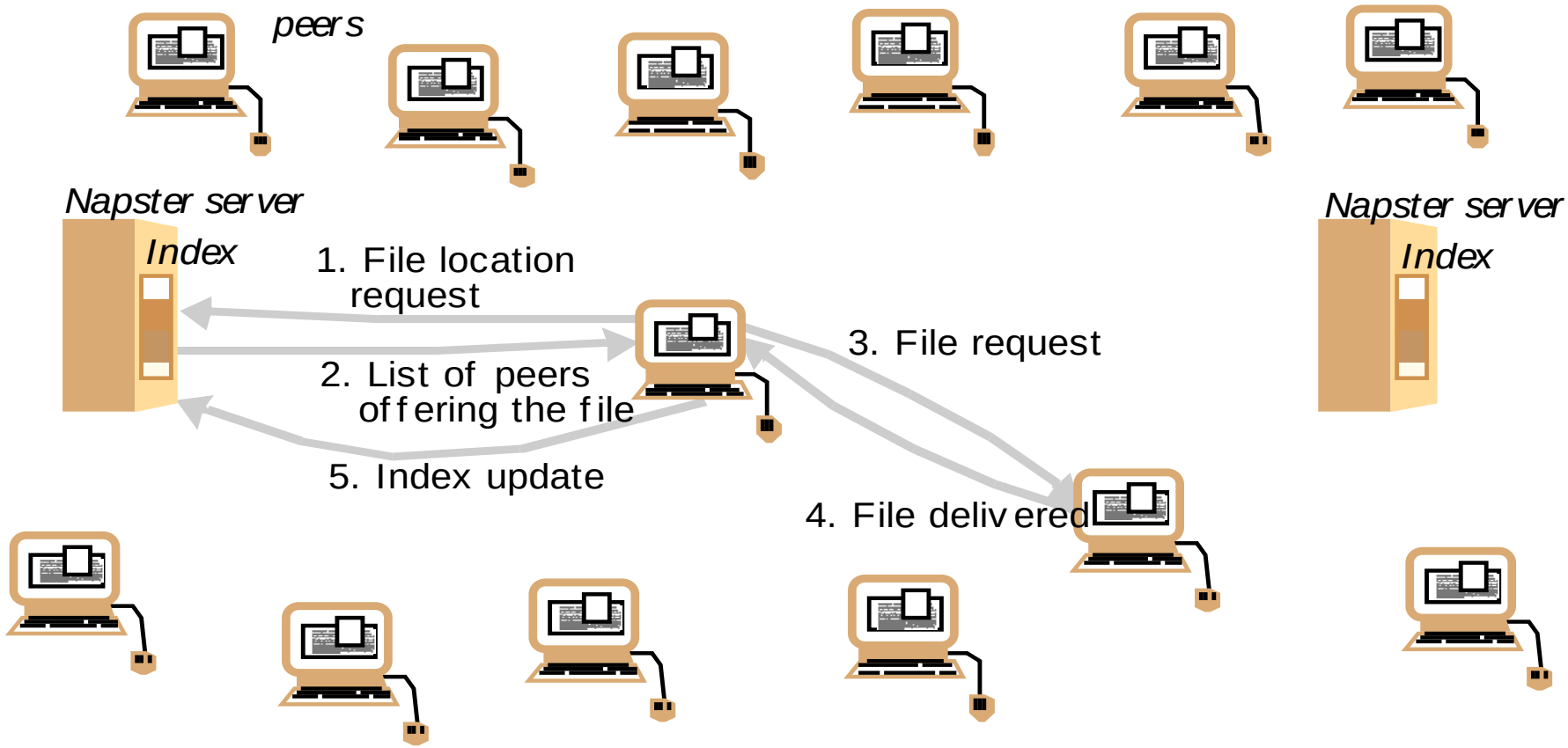
Distributed computation

- Lots of spare computing power on end-user computers
- E.g., SETI@home
  - HUGE amount of computations done
  - Unusual: no communication/coord. Between computers while processing the tasks (send to central server)
  - Other successor projects: protein folding, large prime numbers, …

Napster and its legacy [10.2]

- Napster launched in 1999 … music files mainly
- Architecture (Fig 10.2)
  - Centralized indexes
  - User supplied files (stored on their PCs)
- Shut down by legal proceedings
  - Centralized index servers deemed essential part of process
- Lessons learned
  - Feasible to build huge P2P sys. w/ (almost all) resources @edges
  - Network locality can be successfully exploited
- Limitations: replicated index not consistent. (Matters?)
- Application dependencies:
  - Music files never updated
  - No availability guarantees for a file (can download later)

Figure 10.2: Napster: peer-to-peer file sharing with a centralized, replicated index



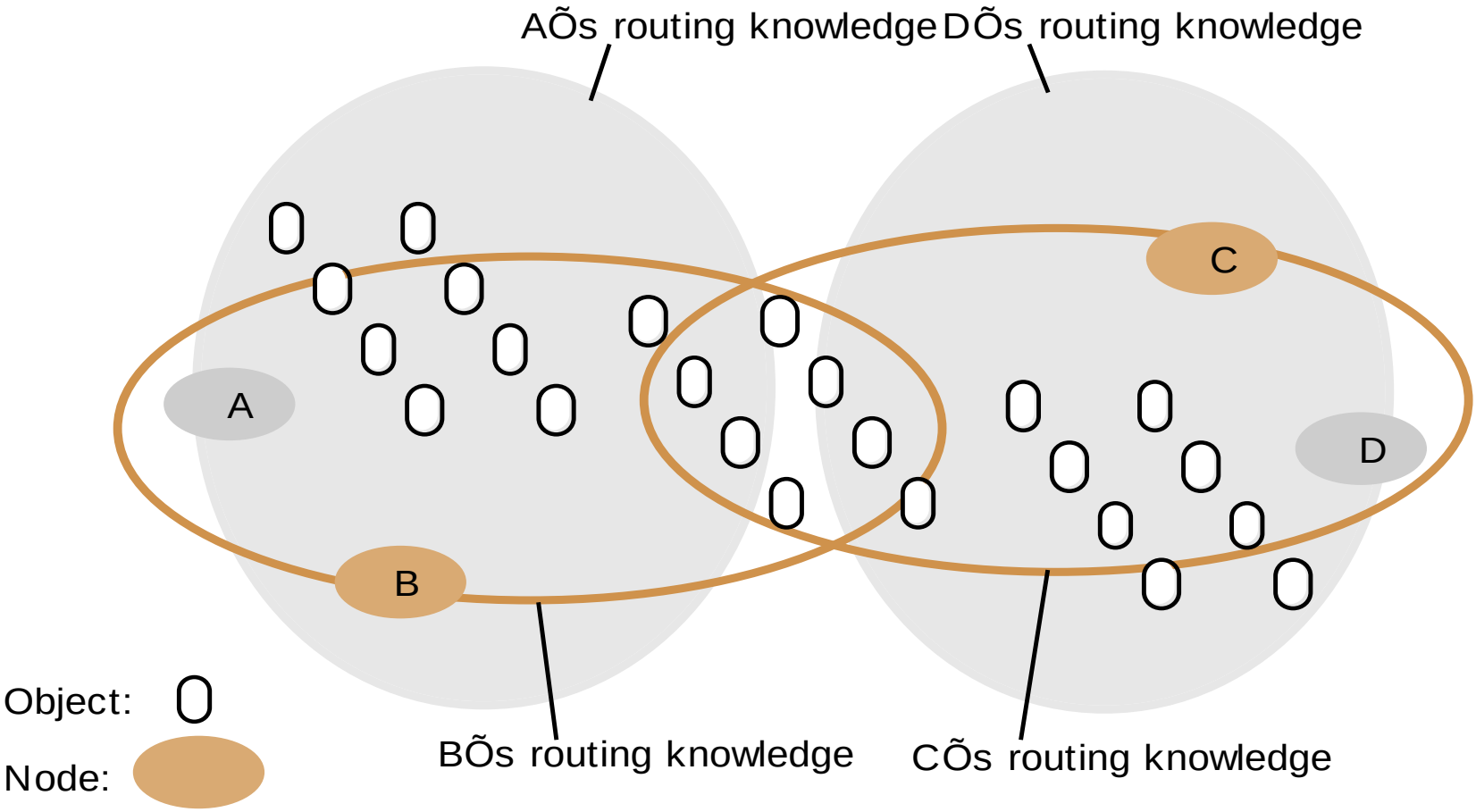
P2P MW [10.3]

- Key problem: provide mechanism to enable clients to access data resources fast & dependably from anywhere
  - 1G Napster: index replicas had complete copies of available files
  - 2G (Gnutella, freenet) partitioned & distributed indexes
- Functional requirements
  - Goal: simplify construction of P2P services
  - Enable clients to locate+get any individual resource
  - Add & remove resources
  - Add & remove participating hosts
  - Simple API independent of resource/data types

P2P MW (cont.)

- Non-functional requirements
  - Global scalability
  - Load balancing
  - Optimize for local interactions between neighboring peers
  - Accommodation for highly dynamic host availability
  - Security of data where (dynamic) trust varies widely
  - Anonyminity, deniability, resistance to censorship
    - "unsniffability"?
- Scalability ➔must partition knowledge of location of objects through network
  - Must be replicated (up to 16 times)
- All above is a very active area of research!

Figure 10.3: Distribution of information in a routing overlay



Routing overlays [10.4]

- **Routing overlay (RO)**: distributed algorithm that locates nodes and objects
  - May have been relocated, node down, …
  - Any node can access any object by routing request through series of nodes
  - GUIDs are “pure names” (AKA opaque identifiers): random bit patterns with no structure or location info
- Tasks for the RO (AKA **distributed hash tables**)
  - Route requests to objects
  - Inserting objects:
    - Compute GUID (from part or all of state); Verify uniqueness by lookup
    - Announce new object to RO
  - Delete objects
  - Node tracking: (rough) group membership on nodes

Routing overlays (cont.)

- DHT model: data item/object with GUID X stored at node
  - Whose GUID is numerically closest to X, and
  - R hosts whose GUIDs are next-closest numerically
  - Observe: same address space for nodes and objects
- More flexible: Distributed object location and routing (DOLR) model:
  - Location for replicas decided outside the routing layer
  - DORL layer notified of host addresses of each replica with `publish()` operation
  - Objects can have same GUID at different hosts; RO routes to a nearby one
- Both DHT (Pastry) and DOLR (Tapestry) use prefix routing
  - Uses part of GUID to find next node in path towards object

Routing overlays (cont.)

- Other routing schemes (all have distributed index schemes)
  - Chord: distance between GUID of selected node and the dest.
  - CAN: n-dimensional hypersace
  - Kademlia: XOR of pair of GUIDs as distance metric
  - BitTorrent: index → stub file with GUID, URL of tracker → file

Figure 10.4: Basic programming interface for distributed hash table (DHT) as implemented by the PAST API over Pastry

put(GUID, data)

The *data* is stored in replicas at all nodes responsible for the object identified by *GUID*.

remove(GUID)

Deletes all references to *GUID* and the associated data.

value = get(GUID)

The data associated with *GUID* is retrieved from one of the nodes responsible it.

Figure 10.5: Basic API for distributed object location and routing (DOLR) as implemented by Tapestry

publish(GUID)

GUID can be computed from the object (or some part of it, e.g. its name). This function makes the node performing a *publish* operation the host for the object corresponding to *GUID*.

unpublish(GUID)

Makes the object corresponding to *GUID* inaccessible.

sendToObj(msg, GUID, [n])

Following the object-oriented paradigm, an invocation message is sent to an object in order to access it. This might be a request to open a TCP connection for data transfer or to return a message containing all or part of the object's state. The final optional parameter *[n]*, if present, requests the delivery of the same message to n replicas of the object.

Overlay case studies: Pastry, Tapestry [10.5]

- 10.5: overlay case studies
  - Pastry: straightforward and effective
  - Tapestry: more complex, supporting wider range of locality approaches
- 10.6: “Application” case studies: Squirrel, OceanStore, Ivy
  - “Application”, some really higher-level middleware (a service)
  - Squirrel/Pastry: web cache
  - OceanStore/Tapestry: file storage
  - Ivy/overlay: file storage

Pastry routing overlay [10.5.1]

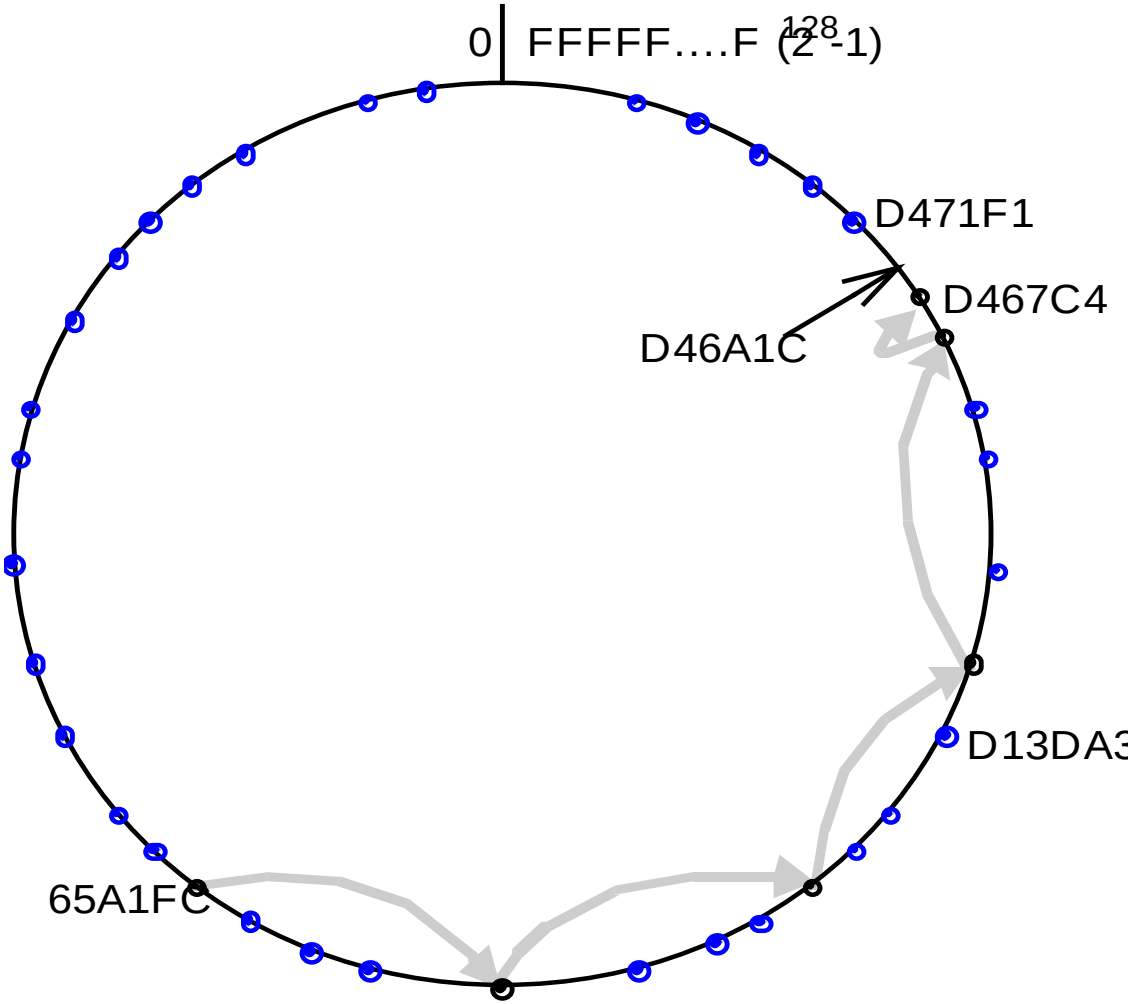
- Main characteristics as per 10.4
  - All nodes and objects assigned 128-bit GUID
    - Nodes: secure hash over node's public key (provided)
    - Objects: secure hash or over name or part of data
    - (Very unlikely) clashes in GUIDs detected and remediated
  - Scalability: network with N nodes, pastry routes to GUID in *O(log n)* steps
    - Node inactive at last hop: finds nearest active one
    - Active nodes route to numerical nearest neighbor
    - Naively, "nearest" and *O(log N)* are in terms of logical overlay topology, not network!
    - But uses locality metric based on network distance
    - Can scale to thousands of hosts
    - New nodes can construct their routing table in *O(log N)* messages
    - Same complexity for detecting and reconfiguring with failure

Pastry routing algorithm

- Buildup: describe simplified, inefficient form (Stage 1), then full (Stage 2) with routing table
- Stage 1
  - **Leaf set** (each active node): vector *L* (size *2l*) with GUIDs & IP addrs of numerically closest nodes (*l* above and *l* below)
    - *l* is typically 8
  - Failure recovery fast: leaf set reflects current (configuration) state (up to some max rate of failures)
  - GUID space circular: [0, 2^{128-1}] with wraparound
  - Routing is trivial
    - Compare GUID of incoming message to node's own
    - Send to node in L closest to message's GUID (likely ~*l* nodes closer)
  - Inefficient: requires ~N/2l (logical) hops on average

Figure 10.6: Circular routing alone is correct but inefficient

Based on Rowstron and **Druschel** [2001]



The dots depict live nodes. The space is considered as circular: node 0 is adjacent to node (2128-1). The diagram illustrates the routing of a message from node 65A1FC to D46A1C using leaf set information alone, assuming leaf sets of size 8 (l = 4). This is a degenerate type of routing that would scale very poorly; it is not used in practice.

Full Pastry routing algorithm (Stage 2)

- Each node maintains tree-structured routing table
  - GUIDs and IP addrs spread throughout the 2^{128} GUID space
  - Not uniformly spread: more dense closer to the node's GUID
- Structure of routing table
  - GUIDs viewed as hex values, classified by prefixes
  - As many rows as hex digits in GUID, e.g., 128/4=32
  - Each row contains 15 entries, one for each value of the digit except for the one for the host node's GUID
  - Each table entry points to one of the multiple nodes whose GUIDs have the relevant prefix (the one trying to forwards towards)
    - Non-null: contains [GUID, IP addr] of a node with a longer prefix than node
    - Null: no such node known: forward to any node in leaf set or routing table with same prefix length but numerically closer

Figure 10.7: First four rows of a Pastry routing table

p =	GUID prefixes and corresponding nodehandles n															
0	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
	n	n	n	n	n	n		n	n	n	n	n	n	n	n	n
1	60	61	62	63	64	65	66	67	68	69	6A	6B	6C	6F	6E	6F
	n	n	n	n	n		n	n	n	n	n	n	n	n	n	n
2	650	651	652	653	654	655	656	657	658	659	65A	65B	65C	65D	65E	65F
	n	n	n	n	n	n	n	n	n	n		n	n	n	n	n
3	65A0	65A1	65A2	65A3	65A4	65A5	65A6	65A7	65A8	65A9	65AA	65AB	65AC	65AD	65AE	65AF
	n		n	n	n	n	n	n	n	n	n	n	n	n	n	n

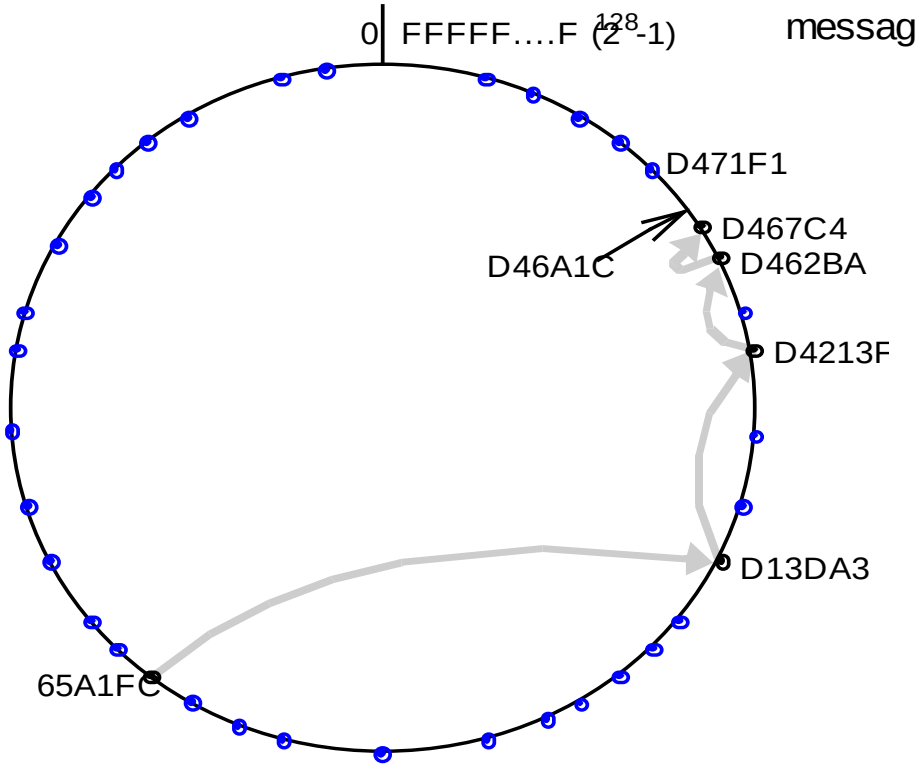
(Z) (X) (W) (Y)

The routing table is located at a node whose GUID begins 65A1. Digits are in hex. The *n*'s represent [GUID, IP address] pairs specifying the next hop to be taken by messages addressed to GUIDs that match each given prefix. Grey- shaded entries indicate that the prefix matches the current GUID up to the given value of *p*: the next row down or the leaf set should be examined to find a route.

E.g., from **65A1** to **653**2 **(W)** or **60**14 **(X)** or **65A3** **(Y)** or **8**2CB **(Z)**

Figure 10.8: Pastry routing example

Based on Rowstron and Druschel [2001]



Routing a message from node 65A1FC to D46A1C. With the aid of a well-populated routing table the message can be delivered in ~ $\log_{16}(N)$ hops.

Figure 10.9: Pastry's routing algorithm

To handle a message M addressed to a node D (where $R[p,i]$ is the element at column i, row p of the routing table):

1. If ($L_{-l} < D < L_l$) { // the destination is within the leaf set or is the current node.
2. Forward M to the element L_i of the leaf set with GUID closest to D or the current node A.
3. } else { // use the routing table to despatch M to a node with a closer GUID
4. find p, the length of the longest common prefix of D and A. and i, the $(p+1)^{th}$ hexadecimal digit of D.
5. If ($R[p,i] \neq null$) forward M to $R[p,i]$ // route M to a node with a longer common prefix.
6. else { // there is no entry in the routing table
7. Forward M to any node in L or R with a common prefix of length i, but a GUID that is numerically closer.

}

}

Pastry host integration

- New nodes use joining protocol
  - get R and L
  - Lets other nodes know they must change cause they are joined
  - Steps at node X
    1. Compute suitable GUID for X
    2. Make contact with (locally) nearby Pastry node (A), send a **join request** to it
       - Destination = X (!!!)
    3. Pastry routes request to node with GUID numerically closest to X (Z)
       - E.g., route is A→B→C→D→Z
       - Along way, {A,B,C,D,Z} send relevant parts of their R and L to X
- Text has more details on the properties it provides (not covering but testable)
  - E.g., A's first row good candidate for first row of X
  - E.g., Z is numerically closest to X, so its L is good candiate for X's
  - Initial entries updates as per discussion below on fault tolerance

Pastry host failure or departure

- Node X deemed failed when node N can’t contact X
- Must repair leaf sets (L) containing X
  - N finds live node close to X, gets it leaf set L’
  - L’ will partly overlap L, find one with appropriate value to replace X
  - Other neighboring nodes informed, they do same
- Repairing routing tables on “when discovered basis”
  - Routing still works if some nodes in table not live, try if fails

Pastry locality and fault tolerance

- Locality
  - Routing structure highly redundant: many paths from X to Y
  - Construction of R tries to use most “local” routes, ones closest to actual network topology (more candidates than fit in R)
- Fault tolerance
  - Assumed live until can’t contact
  - Nodes send **heartbeat messages** to left neighbor in L
    - That won’t spread to a lot of nodes very fast…
    - Also does not hand malicious nodes trying to thwart correct routing
  - Ergo, clients needing reliable delivery use at-least-once delivery mechanism, repeating multiple times if no response
    - Gives Pastry more time to fix L and R
  - Other failures or malicious nodes: add tiny amount of randomness to route selection (see text)

Pastry dependability

- MSPastry uses same routing algorithm, similar host mgt
  - Adds dependability measures
  - Adds performance optimizations for host management algorithms
- Dependability measures
  - Use ACKS each hop in routing; timeout ➔ find alt. route & suspect
  - Heartbeat message timeout by detecting node (neighbor to right)
    - Contact rest of nodes in L: node failure notify, ask for replacements
    - Terminated even with multiple simultaneous failures
- Performance optimizations
  - Run simple gossip protocol periodically (20 min) exchange info
    - Repair failed entries
    - Prevent slow deterioration of locality properties

Pastry evaluation

- Exhaustive (simulation) performance eval of MSPastry
  - Looked at impact on performance and dependability:
    - Join/leave rate
    - Dependability mechanisms used
- Dependability results
  - 0% IP message loss rate ➔ failure to deliver 1.5/100K requests
  - 5% IP message loss rate ➔ failure to deliver 3.3/100K requests, 1.6/100K delivered to wrong node
    - (Per-hop ACKS ensure eventually get there)
- Performance results (scale to thousands of nodes)
  - Metric: stretch (relative delay penalty): ratio over direct UDP/IP ➔ ~1.8 with 0% msg loss, ~2.2 with 5% network msg loss
- Overhead: control traffic less than 2 msgs/minute/node

Tapestry [10.5.2]

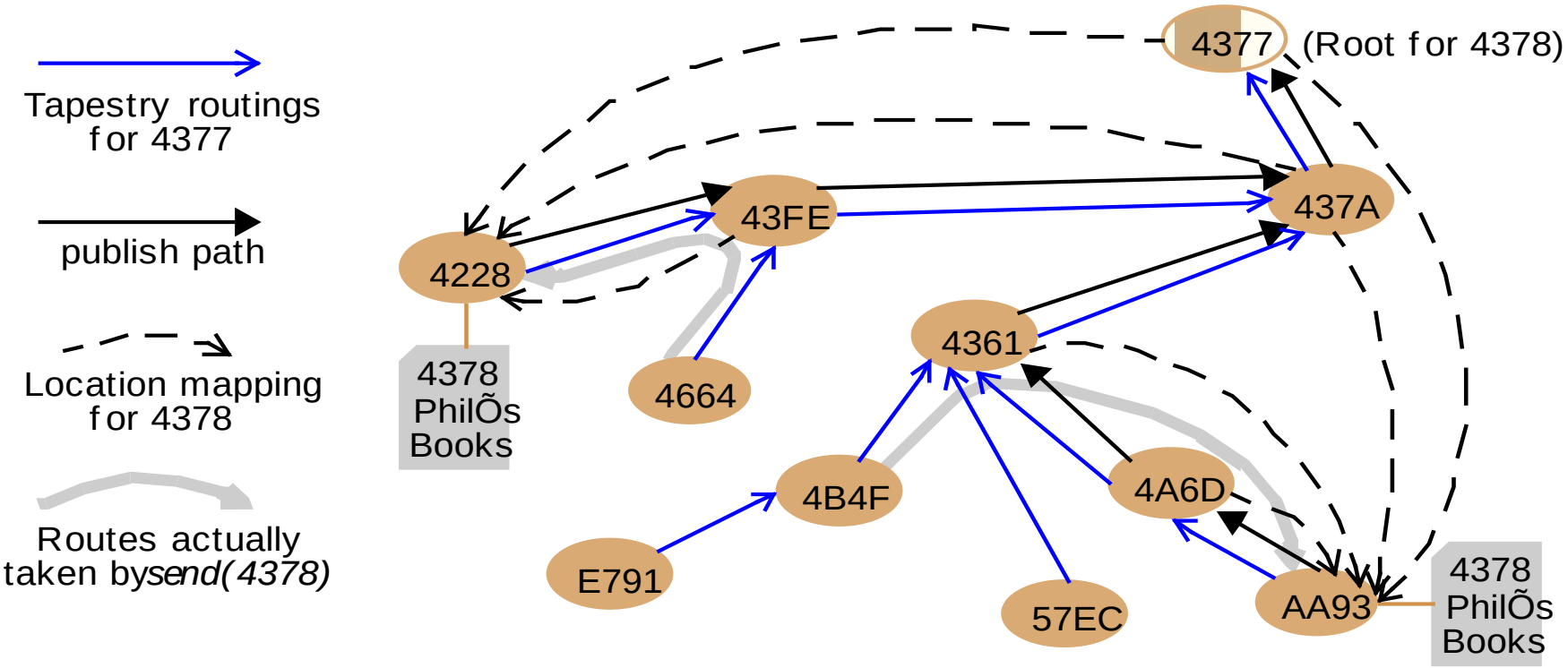
- Similar to Pastry: DHT, routes messages based on GUID prefixes
- Different:
  - DHT hidden behind API via a DOLR interface (like Fig 10.5)
  - Register/announce at storing nodes: `publish(GUID)`
- Hiding DHT allows for more optimizations, including locality
  - Place close (in network distance) to frequent users
  - Possible with Pastry?
- 160-bit identifiers
  - **GUID**: objects
  - **NodeID**: computers performing routing operations, or hosting objs

Tapestry (cont.)

- Basic scheme for resource w/GUID G
  - Unique root node NodeID (text typo: “GUID”) R_G numerically closest to G
  - Hosts H with replica of G publishes periodically (for newly arrived nodes)
    - Message routed towards R_G
    - R_G enters into routing table <G, IP_H>: mapping between G and the given node that sent publish (one of the replicas); AKA **location mapping**
    - Each node along path also enters this
  - Multiple <G, IP_H> entries at a node: sort by network distance (round-trip time)
  - Lookup of object: route towards , first node with a location mapping for G diverts it to IP_H

Figure 10.10: Tapestry routing

From [Zhao et al. 2004]



Replicas of the file *PhilÕs Books*(G=4378) are hosted at nodes 4228 and AA93. Node 4377 is the root node for object 4378. The Tapestry routings shown are some of the entries in routing tables. The publish paths show routes followed by the publish messages laying down cached location mappings for object 4378. The location mappings are subsequently used to route messages sent to 4378.

From structured to unstructured P2P [10.5.3]

- So far considered **structured P2P**
  - Overall global policy governing:
    - Topology of network
    - Placement of objects in network
    - Routing or searching used to locate objects
  - I.e.,
    - A specific (distributed) data structure underpinning the overlay
    - Set of algorithms operating over that structure
  - Can be expensive maintaining the structs if highly dynamic

Unstructured P2P

- No overall control over topology or placement
- Overlay created in *ad hoc* manner with simple local rules
  - Joining node contacts **neighbors** (connected to others…)
  - Can have different rules along the way
  - Very resistant to node failure: self-organizing
- Downsides
  - No logarithmic (or any) guarantees on routing hops
  - Risk of excessive message traffic to locate objects
- Big picture
  - Unstructured P2P dominant in the Internet (Gnutella, FreeNet, BitTorrent)
  - 2008-9 study says 43%-70% of all Internet traffic P2P file sharing

Figure 10.11: Structured versus unstructured peer-to-peer systems

	Structured peer-to-peer	*Unstructured peer-to-peer*
Advantages	Guaranteed to locate objects (assuming they exist) and can offer time and complexity bounds on this operation; relatively low message overhead.	Self-organizing and naturally resilient to node failure.
Disadvantages	Need to maintain often complex overlay structures, which can be difficult and costly to achieve, especially in highly dynamic environments.	Probabilistic and hence cannot offer absolute guarantees on locating objects; prone to excessive messaging overhead which can affect scalability.

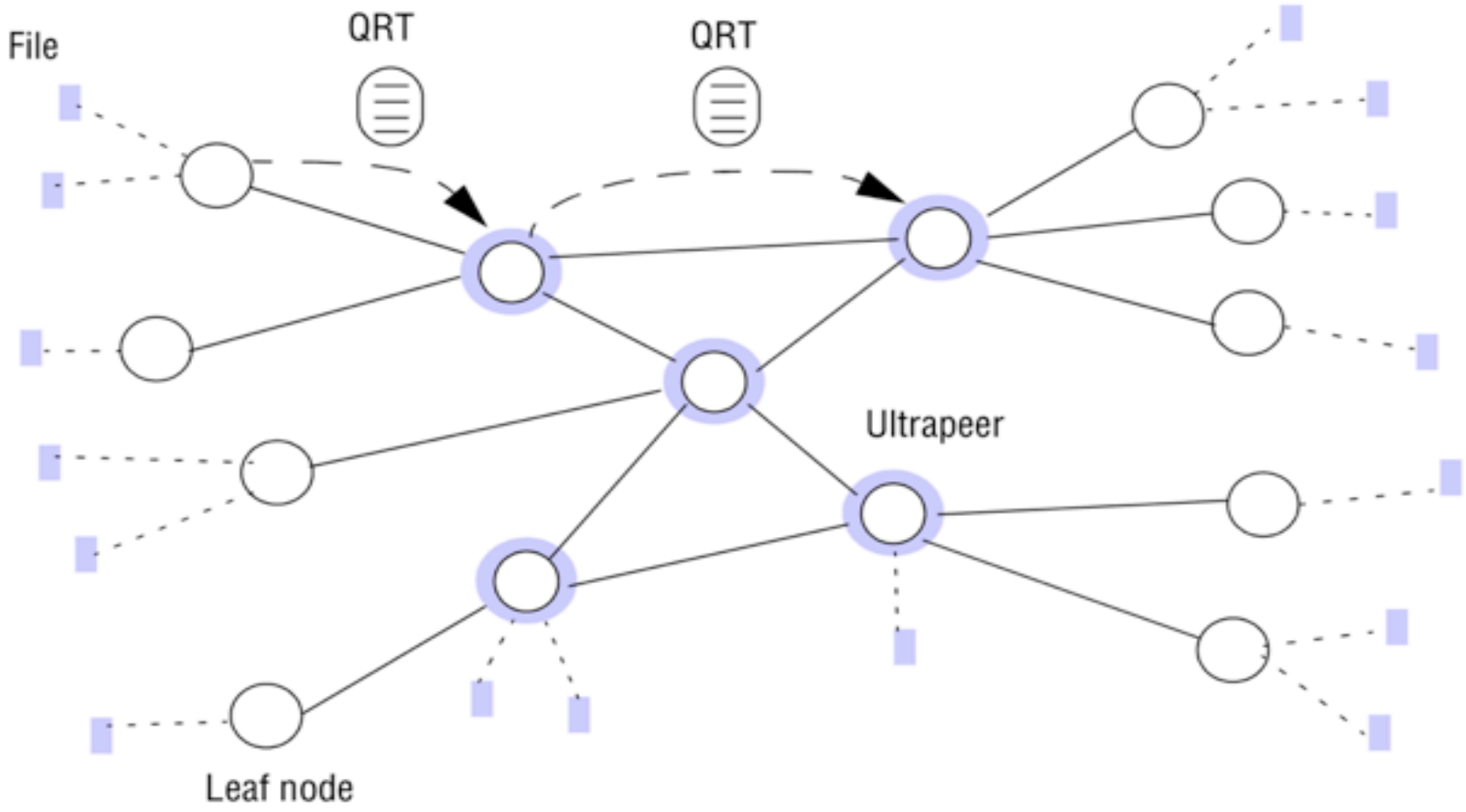
Unstructured P2P (cont.)

- Recall P2P file sharing: all nodes offer to store files for anyone
- Strategies for searching: initiating node can
  - Naïve: **flood neighbors** (who flood neighbors…): Gnutella 0.4
  - **Expanded ring search**: series of searches with increasing TTL (observation: many requests met locally, esp with good replication)
  - **Random walks**: set of a number of walkers randomly looking
  - **Gossiping**: send to a given neighbor with certain probability
    - Probability dynamiclly tuneable: base on (1) experience (2) current context
  - Bottom line: helps significantly reduce overhead (and increase scalability)
- Replication can greatly help (different for each strategy)

Gnutella case study

- No longer uses naïve flooding ☺
- Change #1: hybrid architecture
  - Some nodes “more equal than others”: ultrapeers (like original skype’s super nodes: heavily connected >= 32)
  - Leaves connect with small # ultrapeers
- Change #2: query routing protocol (QRP) using QRT table
  - Goal: reduce #queries from nodes
  - Exchanges info a lot on file locations
  - More clever on forwarding: only forward where think will find it (see book)

Figure 10.12: Key elements in the Gnutella protocol



Application case studies: Squirrel, OceanStore, Ivy [10.6]

- Middleware/apps layered above the routing overlay layer
- Squirrel web caching: by Pastry chefs
  - Idea: offload dedicated web caching servers/clusters

Web caching 101

- HTTP GET can come from browser cache, proxy web cache, or origin (destination of GET)
- When receive GET command in proxy or browser: possibilities cache miss, uncacheable, cache hit
- Objects stored with metadata: modification time & optional TTL & optional eTag (hash from page contents)
- Cache checks TTL: if not fresh asks next level if valid (conditional get cGET)
  - If-Modified-Since: given last modification
  - If-None-Match: given eTag

Squirrel basics

- Apply SHA-1 secure hash to URL of cashed objects: 120-bit Pastry GUID
  - Not used to validate, so no need to hash entire object/page
    - End-to-end argument: can be compromised along the way so don't bother in the middle
- Simple (most effective) version: node with GUID numerically closest becomes object's home node
  - Squirrel looks in cache, uses Get or cGet appropriately via Pastry to home node

Squirrel evaluation

- Environment: simulation using very realistic active proxy traces
- Reduction in total external bandwidth: local squirrel cashes had ~same hit rate as centralized cache server (29%, 38%)
- Perceived latency: cache hits greatly reduce
- Load on client nodes (CPU, storage)
  - Each node only served for other nodes 0.31/minute
- Bottom line: performance (for user at client) comparable to centralized cache

OceanStore file store [10.6.2]

- Tapestry weavers wove OceansStore
- Goals:
  - Very large scale and incrementally scalable
  - Persistent storage for mutal data
  - Require: long-term persistence and reliability
  - Dynamic network and computer nodes
- Support for both mutable and immutable objects

OceanStore (cont.)

- Replica consistency mechanism: similar to Bayou
- Privacy and integrity: encrypting data, Byzantine agreement for updates
  - Trustworthiness of individual hosts not assumed
- Prototype called Pond built early 2000s

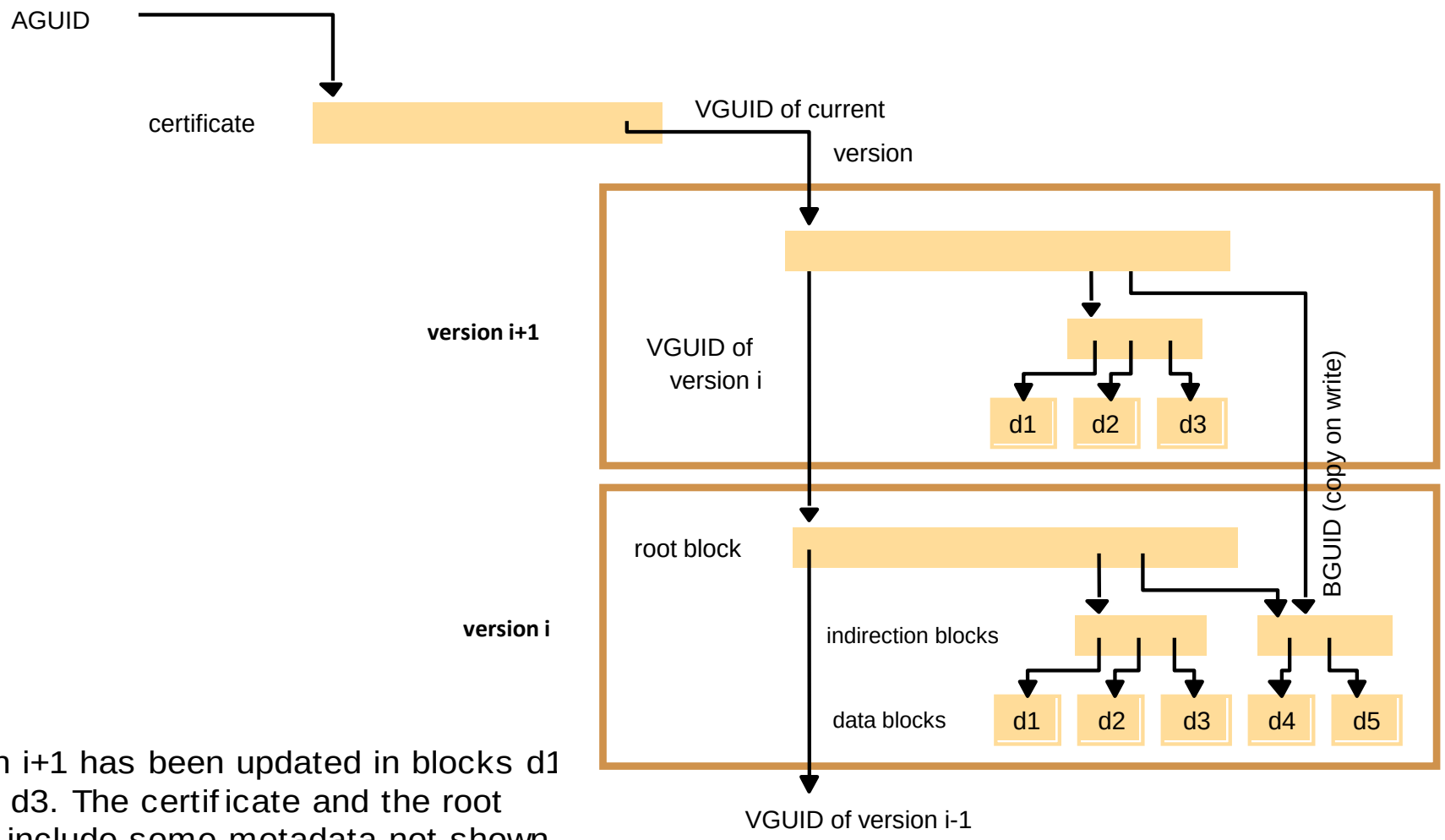
OceanStore storage organization

- Data objects are file-like, stored in blocks
  - Keep ordered sequence of immutable versions ~forever
  - Unix-like:
    - **Root block** storing metadata
    - Other **indirection blocks** (like Unix inodes) used if needed
  - More indirection: associate persistently textual or other external name with the sequence of versions
- GUID flavors
  - AGUID: an object
  - BGUID: for indirection blocks and data blocks
  - VGUID: BGUID for root block for each version

Figure 10.14: Types of identifier used in OceanStore

Name	*Meaning*	*Description*
BGUID	block GUID	Secure hash of a data block
VGUID	version GUID	BGUID of the root block of a version
AGUID	active GUID	Uniquely identifies all the versions of an object

Figure 10.13: Storage organization of OceanStore objects



Version i+1 has been updated in blocks d1 d2 and d3. The certificate and the root blocks include some metadata not shown. All unlabelled arrows are BGUIDs.

OceanStore storage organization (cont.)

- Association from AGUID to sequence of versions recorded in a signed certificate
  - Stored and replicated by primary copy scheme, AKA passive replication (CptS 562..)
- Per trust model, construction of each new certificate agreed on by small set of hosts, **inner ring**
- Not covering rest of storage organizaion for time constraints … read for self later

OceanStore performance

- Prototype for proving feasibility, in Java, not production
- Several file benchmarks w/simple NSF client emulation
  - WAN: Substantially exceeds NFS for reading
  - WAN: within factor of 3 for NFS updates & directories
  - LAN: much worse
- Conclusion
  - May be effective over Internet on files that do not change much
  - Using instead of NSF questionable even over a LAN
  - But unfair comparison: using PKIs and trust management

Figure 10.15: Performance evaluation of the Pond prototype emulating NFS

	LAN		*WAN*		*Predominant operations in benchmark*
Phase	*Linux NFS*	*Pond*	*Linux NFS*	*Pond*	
1	0.0	1.9	0.9	2.8	Read and write
2	0.3	11.0	9.4	16.8	Read and write
3	1.1	1.8	8.3	1.8	Read
4	0.5	1.5	6.9	1.5	Read
5	2.6	21.0	21.5	32.0	Read and write
Total	4.5	37.2	47.0	54.9	

Ivy file system [10.6.3]

- Not covering in class
- Ivy testable for 564, read for exam