CS 555: Distributed Systems [P2P Systems]

Shrideep Pallickara
Computer Science
Colorado State University

Frequently asked questions from the previous class survey

- Byzantine failures vs malicious nodes
- Vector clock updates during multicast
- Clock sizes and when do these become untenable?
  - Vector
  - Matrix
- P2P systems
  - How many copies are required to prevent failures in P2P systems

Topics covered in this lecture

- Peer to Peer (P2P) Systems
  - P2P middleware and requirements
  - Overlays
  - The P2P lookup problem
  - Implementing DHTs
- Chord

P2P Middleware

P2P middleware is designed to orchestrate

- Automatic **placement** of resources (data items, objects, files, etc.)
- Subsequent location (**discovery**) of distributed resources

How different P2P generations cope with this issue

- 1st Generation
  - Maintain a **centralized index** of available files
  - Files are stored at the peers
- 2nd Generation
  - Systems such a Gnutella & Freenet employ **partitioned distributed indexes**
- 3rd Generation
  - Rely on **Overlays**

Requirements for P2P systems

- Functional
  - Specific behaviors or functions that must be supported
- Non-functional (or evaluation metrics)
  - Criteria that can be used to judge the operation of a system

Functional requirements for P2P middleware

- Locate and communicate with *any* resource made available to the system
  - Even though resources are dispersed over a large number of nodes
- The ability to **add and remove** both resources and nodes at will

Non-functional requirements for P2P systems

- Scalability
- Load balancing
- Dynamic host availability

Non-functional requirements: Load balancing

- Achieved via **random placement** of resources
- **Replicas** of heavily used resources are created

Accommodate highly dynamic host availability

- Host computers are free to join or leave at any time
- Provide a dependable service, from unreliable nodes
- As nodes join the system
  - Must be integrated into the system
  - Load must be redistributed to exploit their capabilities
- As nodes leave the system (voluntarily or involuntarily)?
  - Redistribute their load and resources
    - Replication levels for some resources must be preserved

Systems that we will look at

Systems that we will observe closely

- 1st Generation
  - Napster
- 3rd Generation
  - Chord
  - Pastry
  - Tapestry
- Unstructured P2P or 2nd Generation
  - Gnutella and BitTorrent

Napster

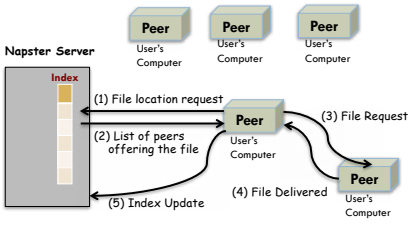
Napster

- First application in which demand for massively scalable storage and retrieval arose
  - Downloading of digital music files
- Became very popular soon after its launch
- At its peak
  - **Several million** users
  - Thousands swapped music files *simultaneously*

Key features of the architecture

- Centralized indexes
- Users supplied the files
  - Stored and accessed on their personal computers
- Clients add their own music files to the pool of shared resources
  - Transmit a link to Napster's indexing service for each available file
  - Shared resources at the "*edge of the internet*"

Napster Architecture



Overlays
[Used in 3rd Generation P2P Systems]

Overlays

- A distributed algorithm takes the responsibility of locating nodes and objects
  - This is the routing overlay
- Denotes that the middleware is a layer that is responsible for routing requests
  - From a client to the host that holds the requested object

But why call it an overlay?

- Denotes that it implements a *routing mechanism* in the **application layer**
  - This is different from routing mechanisms deployed at the network level, e.g., IP
- A logical hop in the routing overlay, encompasses multiple underlying router hops

What does the routing overlay do?

- Ensures any node can access any object
- Routes requests through a **sequence** of nodes
  - Exploits (local) knowledge at each of the intermediate nodes to locate the destination object
- If there are multiple replicas of objects?
  - Overlay maintains knowledge of all available replicas, and then delivers request to the nearest "live" node

Overlay vs IP Routing

Overlay Routing vs IP Routing

- There are several similarities between the two
- Why have a separate mechanism?
  - The legacy nature of IP
  - The legacy's impact is too strong for it to be overcome
    - Hard to support P2P applications directly

IP Routing vs Overlay routing: Scale

- IP
  - IPv4 is limited to 2^{32} nodes
  - IPv6 is 2^{128}
  - But addresses are hierarchically structured
    - Much of the space is pre-allocated to meet administrative requirements
- Overlay
  - GUID namespace is very large (2^{128} or 2^{160})
  - The namespace is also flat allowing for it to be much more fully occupied

IP Routing vs Overlay routing: Load Balancing

- IP
  - Loads are determined by network topology and associated network patterns
- Overlays
  - Object locations can be randomized, so …
  - Traffic patterns can be divorced from the network topology

IP Routing vs Overlay routing: Network dynamics

- IP
  - Routing tables are *updated asynchronously* on a best-effort basis
  - Typically on the order of an hour
- Overlays
  - Can be updated synchronously or asynchronously
  - Fractions of seconds

IP Routing vs Overlay routing: Fault tolerance

- IP
  - Redundancy provided by network managers
    - To handle router or network connectivity failure
  - N-fold replication is costly
- Overlay
  - Routes and object references can be replicated n-fold
    - Tolerance of (n-1) failures of nodes or connections

IP Routing vs Overlay routing: Target identification

- IP
  - Each IP address maps to exactly one node
- Overlay
  - Message can be routed to nearest replica of a target object

Main task of a routing overlay

1. Routing of requests to objects
2. Insertion of objects
3. Deletion of objects
4. Node additions and removals

Calculation of Globally Unique Identifiers (GUIDs)

- This is computed from all or part of the state of the object
- Function delivers a value that is, with a very high probability, unique
  - One way hash functions, such as SHA-1 or MD5 are often used

Why are overlay systems also called Distributed Hash Tables (DHTs)?

- Randomly distributed identifiers are used to determine resource
  - Placements
  - Retrievals

In the DHT model, a data item with GUID X

- Is stored at the node whose GUID is numerically close to X
- If the replication factor is *r*?
  - Then it is stored at the *r* hosts whose GUIDs are next-closest to it numerically

A quick tour of how different P2P systems solve this

- Prefix routing
- Exploiting distance measures

Prefix routing

- Routes for delivery of messages based on values of GUIDs to which they are addressed
- Narrow search for the next node along the route by applying a **binary mask**
  - Selects an increasing number of hexadecimal digits from the destination GUID after each hop
- Used in Pastry and Tapestry

Exploiting different measures of distance to narrow search for next hop destination

- Chord
  - Numerical difference between GUIDs of the selected node and the destination node
- CAN
  - Uses distance in a d-dimensional hyperspace into which nodes are placed
- Kadmelia
  - Uses XOR of pairs of GUIDs as a metric for distance between nodes

A final note about GUIDs

- These are not human readable
- Client applications must obtain GUIDs for resources of interest through some indexing service
  - Human readable names or search requests
- For e.g., BitTorrent
  - Web index search leads to a sub file containing details of desired resource
    - GUID
    - URL of tracker: Host that holds up to date list of network providers willing to supply the file

THE P2P LOOKUP PROBLEM

The peer-to-peer (P2P) lookup problem

- How do you **find** a data item in a large collection of peers?
- Lookup must be scalable and decentralized
  - Without hierarchy

The lookup problem: Centralized Approach

- Maintain central database
- Maintain table that maps file name to server that holds content
  - NAPSTER
- Problems
  - Reliability — **Single point of failure**
  - Scalability — **Database bottleneck for all requests**
  - Vulnerability — **Targeted denial of service attacks**

The lookup problem: Broadcast

- **Flood** the network with requests looking for **X**
- When a node receives the request:
  - Check local repository
  - If it has **X**, node responds back with a message
- Scaling problems
  - ALL discovery requests sent to ALL nodes
  - ALL nodes process **every** discovery request

Broadcast costs can be reduced by organizing nodes into a hierarchy

- Searches start at the top
  - Traverse single path to the node that holds the desired data
- Directed traversal more frugal than broadcast
- Problems
  - Nodes at the **top** of the tree take **larger fraction** of load than leaf nodes
  - Requires expensive hardware
    - Loss of tree root (or node close to it) catastrophic

Distributed hash tables

- Few constraints on the structure of the keys
- REQUIREMENTS
  - Data identified using numeric **keys**
  - Nodes must be willing to store keys **for each other**

Storage and retrieval in distributed hash tables

- Data items are *inserted* and *found* by specifying a unique **key** for the data
- Underlying algorithm must determine ***which node*** is responsible for storing the data

Distributed Storage using DHTs: Publishing a file

- **Convert** file-name to numeric key
  - Using one-way hash functions like MD5 or SHA-1
- Call **`lookup(key)`**
  - Returns IP address of node responsible for key
- **Send file** to be stored at node <u>returned by</u> `lookup`

Distributed Storage using DHTs: Retrieving a file

1. Obtain name of file
2. Convert it to a key using one-way hash function
3. Call `lookup(key)`
4. Ask resulting node, from (3), for a copy of the file

Implementing DHTs

Implementing DHTs: 3 core elements

- **Mapping** keys to nodes
- **Forwarding** a lookup for a key to the appropriate node
- Building **routing tables**

Implementing DHTs: **Mapping keys to nodes**

- Must be load balanced
- Done using one-way hash functions
  - MD5 (128-bit) or SHA-1 (160-bit)
- Ensures that content is distributed **uniformly**

Implementing DHTs
Forwarding lookups

- Any node that receives query for key
  - Must forward it to a node whose ID is ***closer*** to the key
- Above rule guarantees that query ***eventually arrives*** at the closest node
- For e.g.:
  - Node has ID 346, and key has ID 542
  - Forwarding to node 495 gets it numerically closer

Implementing DHTs:
Building routing tables

- Multiple nodes participate in locating content
- Each node must know about **some other** nodes
  - To forward lookup requests
  - Successor
    - The node with the ***closest succeeding*** ID
  - Other nodes
    - For efficiency in routing

Distributed hash tables:
Identifiers

- Data items are assigned an identifier from a large random space
  - 128-bit UUIDs or 160-bit SHA1 digests
- **Nodes are also assigned a number from the same identifier space**

Crux of the DHT problem

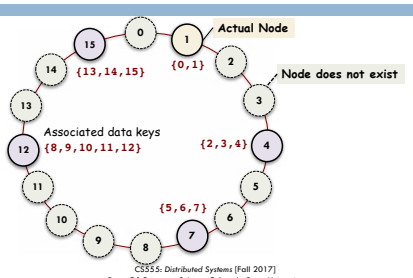
- Implement an efficient, **deterministic** scheme to
  - Map data items to node
- When you **look up** a data item
  - Network address of node holding the data is returned

CHORD

The Chord System

- Assigns IDs to keys and nodes from the same 1-dimensional ID space
- Nodes are organized into a **ring**
- Data item with key **`k`** is mapped to a node with the **smallest** **`id ≥ k`**
  - Also referred to as `successor(k)`

Mapping of data items to nodes in Chord



Chord lookups

- **N** is the number of possible nodes in the system
- Each node maintains a **finger table**
  - With log N entries
  - Entries contains IP addresses of nodes
    - Half-way around the ID space from it
    - 1/4th, 1/8th, … **in powers of two**
  - Ensures node can forward lookup query to at least ½ of the remaining ID-space distance to key
    - Lookups in *O(log N)*

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

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