CS 194: Lecture 28

Review, Part II

Location of exam: A1 HEARST ANNEX

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Special Topics

- DHTs (mostly covered in project)
- Sensornets
- Robust protocols
- Resource allocation
- Incentives

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Three Classes of DHT Applications

- Rendezvous: uses DHT to store current "location"
- Storage: uses DHT to store data objects
  - Case 1: only uses put/get interface
  - Case 2: data manipulated in an application-specific manner
- Routing: uses DHT to contact all DHT nodes along the path to the appropriate DHT "root".

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Rendezvous Applications

- Each client (telephony, chat, etc.) periodically stores the IP address (and other metadata) describing where they can be contacted
- When A wants to contact B, it first does a get on B's key, and then contacts B directly
- This can handle:
  - IP mobility
  - Chat
  - Internet telephony
  - DNS
  - The Web!

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Storage Applications

- File Systems
- Backup
- Archiving
- Electronic Mail
- Content Distribution Networks
- .....

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CFS Uses Self-authentication

Immutable block: (Content-Hash Block)

key = CryptographicHash(value)

encourages data sharing!

Mutable block: (Public-key Block)

key = K_{pub}

value = data + Sign[data]$_{K_{priv}}$

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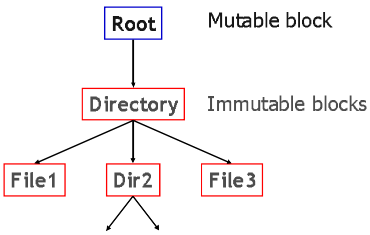
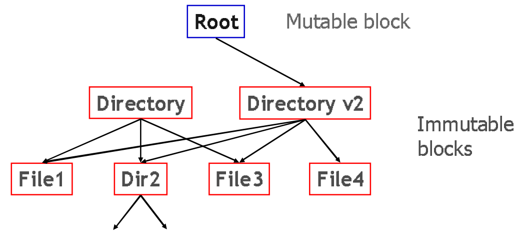
CFS



- This is a single-writer mutable data structure

Adding a File to a Directory



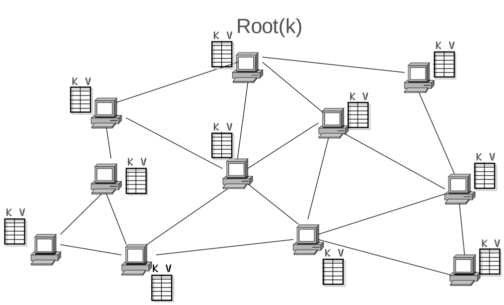
Usenet over a DHT

- Standard usenet: broadcast all articles to all N sites
- UsenetDHT: broadcast headers to all sites
  - store full articles in DHT (only once, not N times)
  - only transmit to site when requested
- Bandwidth/storage performance advantage function of:
  - header (H) to full (F) article ratio
  - fraction (R) of articles ever read at each site
  - total volume V of messages
- Bandwidth/Storage: roughly VNF vs V[NH + F + (N-1)RF]

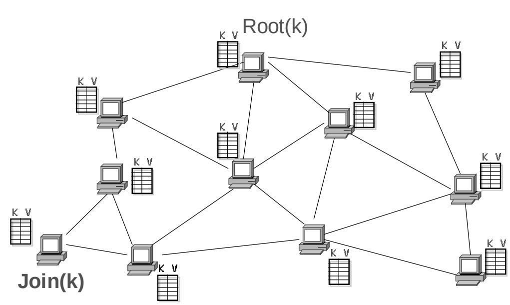
"Routing" Applications

- Examples:
  - Application-layer multicast
  - Video streaming
  - Event notification systems
  - ...
- Multicast:
  - Group is associated with key
  - "root" of group is node that owns key
  - Any node that wants to join sends message to root, leaving forwarding state along path
  - Message stops when it hits existing state for group
  - Data sent from root reaches all nodes

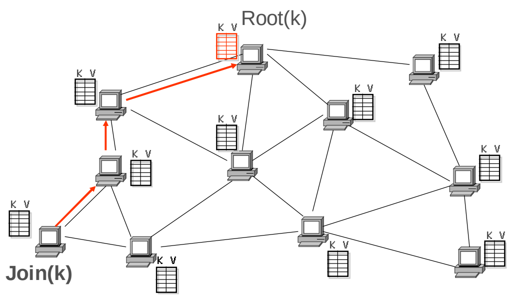
Multicast



Multicast Join



Multicast Join



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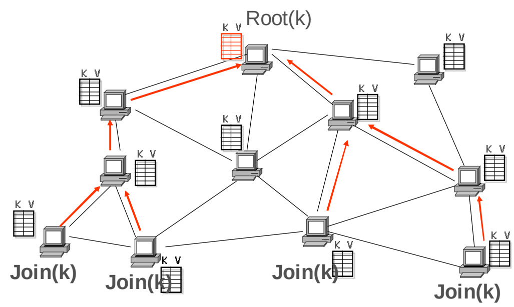
Multicast Join



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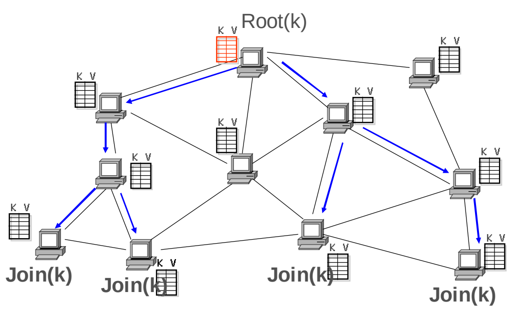
Multicast Send



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Four DHT Scenarios

- Donated distributed infrastructure
- Scalable enterprise applications
- Super-resilient applications
- “Tiny” applications

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Library or Service

- Library: DHT code bundled into application
  - Runs on each node running application
  - Each application requires own routing infrastructure
  - Allows customization of interface
  - Very flexible, but much duplication
- Service: single DHT shared by applications
  - Requires common infrastructure
  - But eliminates duplicate routing systems
  - Harder to get, and much less flexible, but easier on each individual app

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Why OpenDHT?

Consider FreeDB (the CD metadata database)

- Two options to implement large-scale FreeDB

1. Implement your own DHT:
   - Find 500 nodes you can use
   - Run DHT 24/7
   - Debug DHT problems when they occur
2. Use OpenDHT:
   - 58 lines of Perl

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Two Challenges

- Resource allocation
- Beyond rendezvous

Resource Allocation

- Two resource allocation issues:
  - Leave enough room for future puts
  - Allocate evenly between users

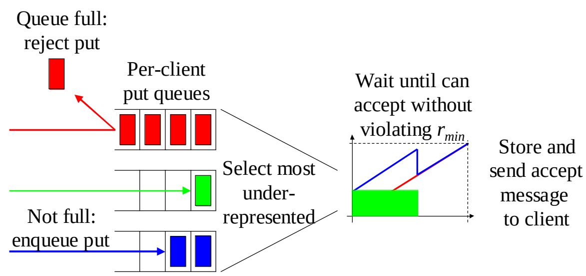
Storage Constraint Equation

- Rate reserved for future puts): r_{min}
- Disk capacity C
- Let S(t) be total number of current bytes that will still be on disk at time t
- A put of size b and TTL T can be accepted iff

$$S(t) + b + t \cdot r_{min} \leq C \text{ for } 0 \leq t \leq T$$

different notation than Sean's

Allocating Storage Fairly



The Big Decision: Definition of "most under-represented"

Using FQ-like Allocation Rule

- Equalize *rate* of commitments granted
  - Service granted to one client depends only on others putting "at same time"
- Mechanism inspired by Start-time Fair Queuing
  - Have virtual time, v(t)
  - Each put gets a start time S and finish time F
    - S = max[v(arrival), F(previous)]
    - v(t) = maximum start time of all accepted puts
    - F = S + B × T
  - Take client with smallest S at head of queue

Generality of Interface

Three classes of DHT interfaces:

- Routing: app-specific code at each hop
- Lookup: app-specific code at endpoint
- Storage: put/get

For a shared infrastructure that can't incorporate app-specific code, the only choice is put/get

- Limited flexibility
- Does convenience outweigh constraints?

Application-Specific Functionality

- How can you apply application-specific functionality to OpenDHT applications?
- Approach: use OpenDHT for routing, use external nodes nodes for application-specific processing
  - Application owner doesn't need to understand DHTs
  - Can write application assuming a lookup(key) operation just works
- Accomplished through a client library called ReDiR
  - takes application lookup(key) calls and returns with proper IP address (of external node) using put/get interface on OpenDHT
- Works for storage apps, and many routing apps can be converted to storage....

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Sensornet Characteristics

- Energy constraints: communication more expensive tham computation
- Harsh conditions: radio connectivity variable
- Self-organizing: no manual configuration
- Data-centric (not node-centric): users want data, but don't know which node has the data....

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Isn't the Internet Robust?

- Robustness was one of the Internet's original design goals
- Adopted failure-oriented design style:
  - Hosts responsible for error recovery
  - Critical state refreshed periodically
  - Failure assumed to be the common case
- Proof from experience: Internet has withstood some major outages with minimal service interruption
  - 9/11
  - Baltimore tunnel fire
  - etc.

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Counterexamples

- Arpanet routing problem
- Frequent routing failures due to misconfiguration
- Vulnerability to congestion control misbehavior
- Vulnerability to SYN floods
- .....

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General Lesson

- Most Internet protocols are design with (at most) two failure models in mind:
  - Participating nodes: fail-stop
  - Other nodes: malicious
    - Denial-of-service, spoofing, etc.
- They are usually vulnerable to participating nodes misbehaving:
  - Subverted nodes
  - Misconfigured nodes
  - Bug in software

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Semantic vs Syntactic Failures

- Syntactic failures:
  - Node doesn't respond, message ill-formed, etc.
- Semantic failure:
  - Node responds with well-formed message, that is semantically incorrect
- Internet designed for syntactic failures, not semantic ones

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Why Didn't Traditional Tools Work?

- Formal verification:
  - Verifies that <u>correct</u> protocol operation leads to the desired result
- Cryptographic authentication:
  - Verifies <u>who</u> is talking, but not <u>what</u> they say
- Fault-tolerance via consensus: (Byzantine techniques)
  - Requires that several nodes have enough information to do the required computation
  - In network routing, for instance, only the nodes at the end of a link know about its existence

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Some Guidelines

1. Value conceptual simplicity
2. Minimize your dependencies
3. Verify when possible
4. Protect your resources
5. Limit scope of vulnerability
6. Expose Errors

- #3 and #4 pose the most difficult technical challenges

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Lightweight Verification

- Checking for semantic correctness
- Not trying to guarantee correct behavior, merely trying to detect lying (even if after-the-fact) with some probability
- Mechanism must be lightweight enough to scale

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Explicit Congestion Notification (ECN)

- Bit in IP header flipped when routers experience congestion
  - Replaces packet drops with explicit signaling of congestion
- Receiver returns this bit back to sender in TCP header
  - Keeps sending bit until sender returns CWR
  - CWR = congestion window reduced
- ECN advantages:
  - Doesn't require drops
  - No confusion between corruption losses and congestion losses

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Problem

- ECN requires receiver to give information back to sender
- If receiver lies (doesn't return bit), then sender keeps increasing window
- Lying receiver gets more bandwidth than truthful ones or non-ECN-enabled ones

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Robust Congestion Signaling (Ideal)

- Use bits in IP header to send two separate signals:
  - Congestion-bit: on or off
  - Nonce: large random number
- When congestion bit is set, nonce is erased
- Receiver must send back cumulative sum of nonces in ACK
- When congestion is signaled, receiver can't see nonce, so must guess about it
  - If many nonce bits, this is very unlikely

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Robust Congestion Signaling (Real)

- Use ECN bits in IP header to send two separate signals:
  - Congestion-bit: on or off
  - Nonce: randomly 0 or 1
- When congestion bit is set, nonce is erased
- Receiver must send back cumulative sum of nonces in ACK
- When congestion is signaled, receiver can't see nonce, so must guess about it
  - Improbable it can continue to guess right

Protecting Resources

- Different contexts:
  - web servers: SYN cookies
  - routers: fair queueing
  - ....
- Will describe fair queueing
  - Can be used to support QoS
  - But was initially proposed to protect flows from each other

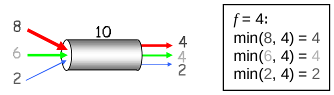
Fair Queueing (FQ)

- Implements max-min fairness: each flow receives $min(r_i, f)$ where
  - r_i – flow arrival rate
  - f – link fair rate (see next slide)
- Weighted Fair Queueing (WFQ) – associate a weight with each flow
  - We will ignore this for now

Fair Rate Computation: Example 1

- If link congested, compute f such that

$$\sum_i \min(r_i, f) = C$$



Another Example

- Rates: 1 3 5 7 8 9 15
- Capacity: 40
- Testing values of f:
  - f=5 has rates 1 3 5 5 5 5 5 so total is 29
  - f=6 has rates 1 3 5 6 6 6 6 so total is 33
  - f=7 has rates 1 3 5 7 7 7 7 so total is 37
  - f=8 has rates 1 3 5 7 8 8 8 so total is 40
  - f=9 has rates 1 3 5 7 8 9 9 so total is 42
  - .....
- Fair share is 8, so fair allocations are 1 3 5 7 8 8 8

Implementing Fair Queueing

- Fluid model: have queue for each flow, and serve each flow in a bit-by-bit round robin
- Packet model: send packets in the order that they would have finished in the fluid model

Implementing Fair Queueing

- Fluid model: have queue for each flow, and serve each flow in a bit-by-bit round robin
  - Let V(t) denote the "virtual time",which is the round number in progress at time t
  - $\partial V/\partial t = C/n(t)$ where n(t) is the number of flows with nonempty queues
- Packet model: send packets in the order that they would have finished in the fluid model
  - If you calculate finishing times in terms of V(t) rather than t, you don't have to change when new packets arrive

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Finish Time Calculation

- Define
  F_i^k = virtual finishing time of packet *k* of flow *i*
  a_i^k = arrival time of packet *k* of flow *i*
  L_i^k = length of packet *k* of flow *i*
- The finishing time of packet *k+1* of flow *i* is

$$F_i^{k+1} = \max(\ V(a_i^{k+1}),\ F_i^k) + L_i^{k+1}$$

- Hard part: calculating virtual time V(t)

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FQ Variations

- Use start or finish time of packet in service as the value of virtual time when new packet arrives
- Use start time rather than finish time for ordering packets

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Living in the Brave New World....

- Most modern Internet-scale distributed systems involve independent users
  - Web browsing, DNS, etc.
- Users typically care only about their own service
- Users may not want to use mandated algorithms, but instead will act to maximize their own welfare
- What happens when users behave selfishly, and what can you do about it?

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Selfish Behavior in Congestion Control

- Users adjust rate r_i to maximize utility U_i which is function of both bandwidth and delay d_i
- Delay d_i is function of all sending rates r_j
  - This is how users affect each other
  - Function for delays depends on packet scheduling algorithm
- A Nash equilibrium is a vector of r's such that no user can increase their U_i by unilaterally changing r_i
  - First order condition: $\partial U_i/\partial r_i = 0$

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Simple Poisson Model with FIFO Queue

- In Poisson model with FIFO queues (and link speed 1):

$$d_i = 1/(1-r_{tot})$$

- Assume $U_i = r_i/d_i$
- Then $U_i = r_i(1 - r_{tot})$

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Three Questions

- What is the result of selfish behavior? (Nash equilibrium)
  - $r_i = 1/(n+1)$ where n is number of users
  - $U_{tot} = (n+1)^{-2}$
- What is the socially optimal level of usage?
  - $r_i = 1/2n$
  - $U_{tot} = 1/4$
- What packet scheduling algorithm would have a Nash equilibrium with the socially optimal usage?
  - Fair queueing

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Designing for Selfishness

- Assume every user (provider) cares only about their own performance (profit)
- Give each user a set of actions
- Design a "mechanism" that maps action vectors into a system-wide outcome
  - Mechanism design
- Choose a mechanism so that user selfishness leads to socially desirable outcome
  - Nash equilibrium, or other equilibrium concepts

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Strategyproof Mechanism

- Clients have no incentive to lie
- They are asked to reveal their utility
- And no matter what other clients do, they are at least as well off telling the truth
- Examples:
  - second-price auction
  - VCG mechanisms

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