Distributed Storage

18

Introduction to
Systems Software

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Network File System

When a file wants to move up the career ladder, it's gotta network.

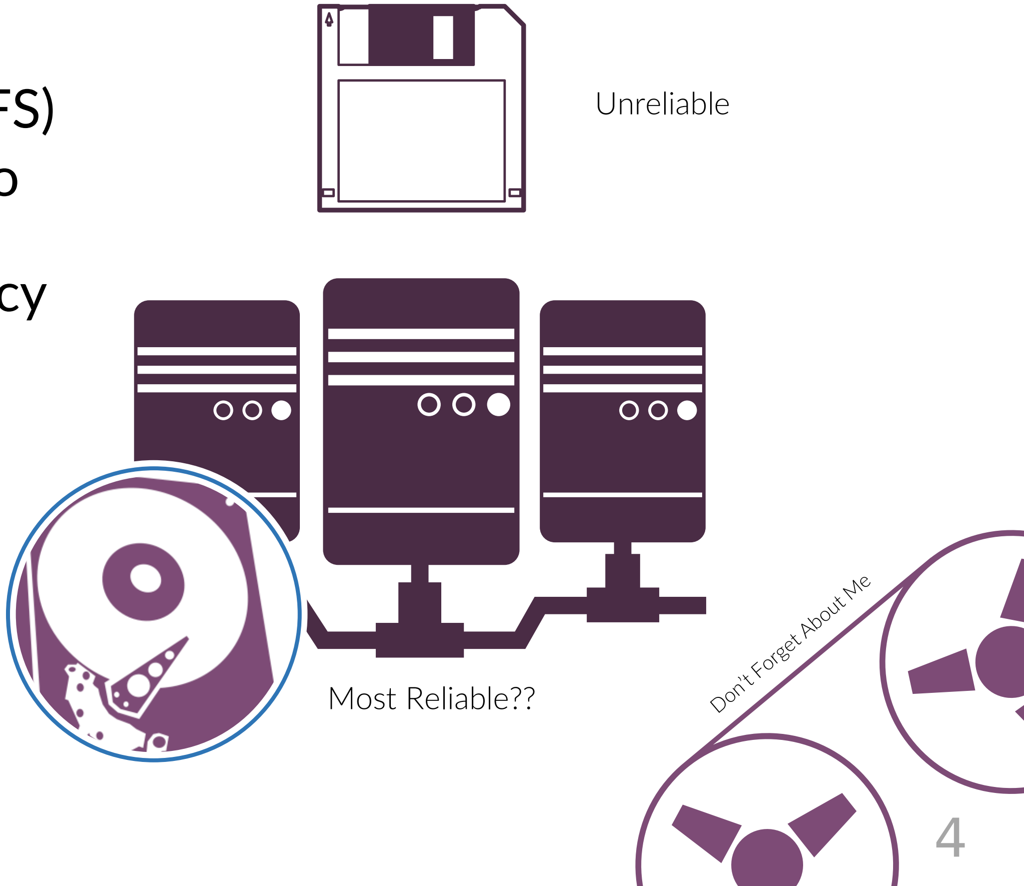
Problem

- **Storage is cheap.**
  - YES. This is a *problem* in a classical sense.
  - People are storing more stuff and want very strong storage guarantees.
  - Networked (web) applications are global and people want strong availability and stable speed/performance (wherever in the world they are.) *Yikes!*

- **More data == Greater probability of failure**
  - We want **consistency** (correct, up-to-date data)
  - We want **availability** (when we need it)
  - We want **partition tolerance** (even in the presence of downtime)
  - Oh. Hmm. Well, heck.
  - That's hard (technically impossible) so what can we do?

Lightning Round: Distributed Storage

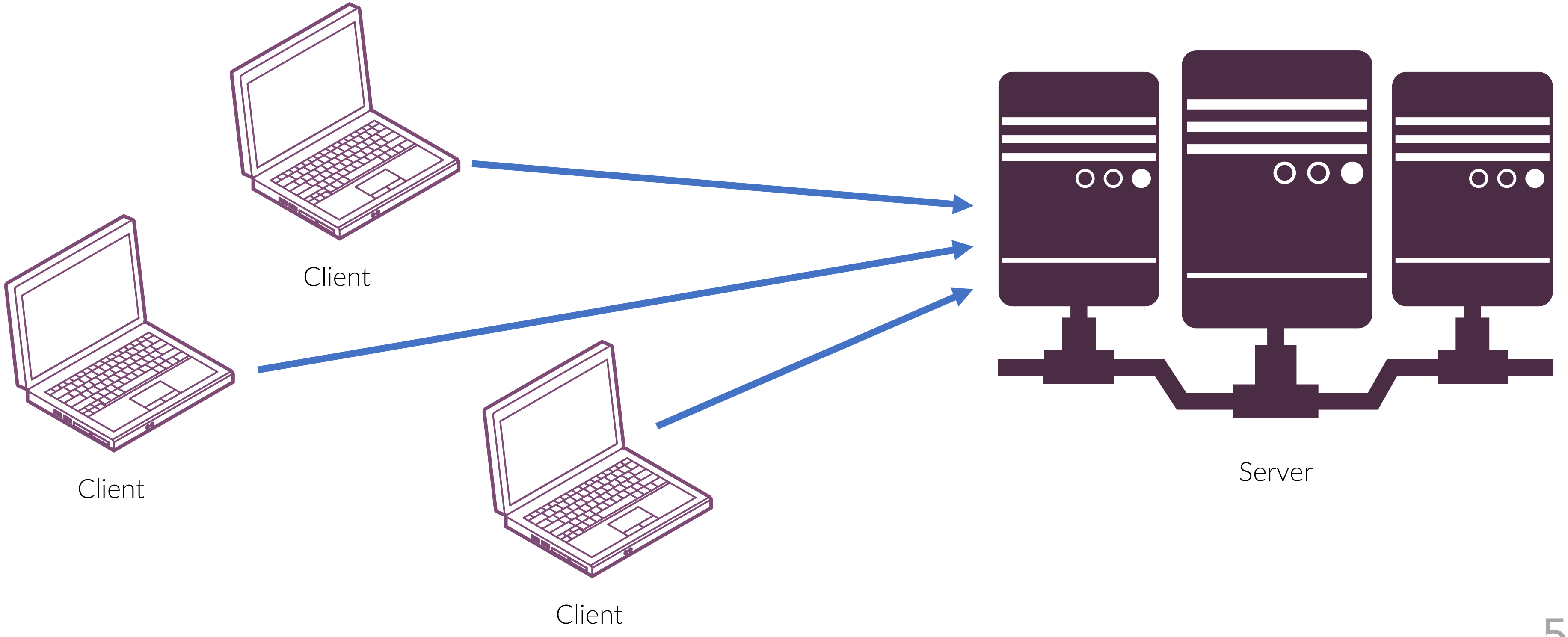
- Network File System (NFS)
  - We will gloss over details, here, but the papers are definitely worth a read.
  - NFS invented the Virtual File System (VFS)
  - Basically, though, it is an early attempt to investigate the *trade-offs* for client/server file consistency



There's more to it obviously.....

NFS System Model

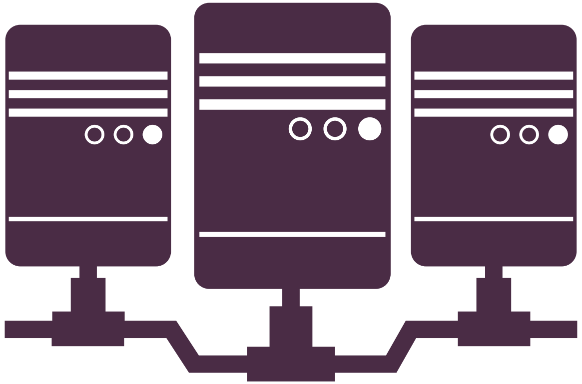
- Each client connects directly to the server. Files could be duplicated on client-side.



NFS Stateless Protocol

Set of common operations clients can issue: *(where is* `open`*?* `close`*?)*

`lookup`	Returns file handle for filename
`create`	Create a new file and return handle
`remove`	Removes a file from a directory
`getattr`	Returns file attributes (stat)
`setattr`	Sets file attributes
`read`	Reads bytes from file
`write`	Writes bytes to file



Commands sent to the server. (one-way)

Statelessness (Toward Availability)

- **NFS implemented an open (standard, well-known) and stateless (all actions/commands are independent) protocol.**

- **The `open()` system call is an example of a *stateful protocol*.**
  - The system call looks up a file by a path.
  - It gives you a file handle (or file descriptor) that represents that file.
  - You give that file handle to **read** or **write** calls. (not the path)
  - The file handle does not directly relate to the file. (A second call to open gives a different file handle)
  - If your machine loses power… the OS loses track of that handle…
    - you'll need to call `open()` again!

Statelessness (Toward Availability)

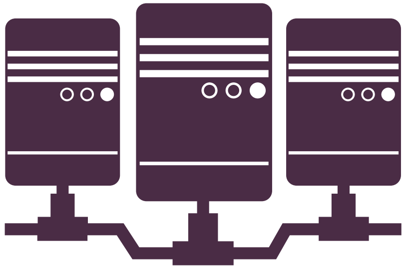
- Other stateless protocols: HTTP (but not FTP), IP (but not TCP), www
- So, in NFS, we don't have an `open()`.
- Instead we have an *idempotent* `lookup()` function.
  - Always gives us a predictable file handle. Even if the server crashes and reboots.
- Statelessness also benefits from *idempotent* read/write functions.
  - Sending the same write command twice in a row shouldn't matter.
- This means ambiguity of server crashes (did it do the thing I wanted?) doesn't matter. Just send the command again. No big deal. *(kinda)*
  - NFS's way of handling **duplicate requests**. (when you see one command repeatedly sent… like when a client panics and thinks the server is dead.)
- *Consider*: What about mutual exclusion?? (file locking) Tricky!

Statelessness And Failure (NFS) [best]

A client issues a series of writes to a file located on a particular server.

Client

Server



`lookup` →

← *fd*

`write(`*fd*`, `*offset*`: `*0*`, `*count*`: `*15*`)` →

← *success*

`write(`*fd*`, `*15*`, `*15*`)` →

← *success*

`write(`*fd*`, `*30*`, `*15*`)` →

← *success*

Local File

AAAAAAAAAAAAAAA
BBBBBBBBBBBBBBB
CCCCCCCCCCCCCCC

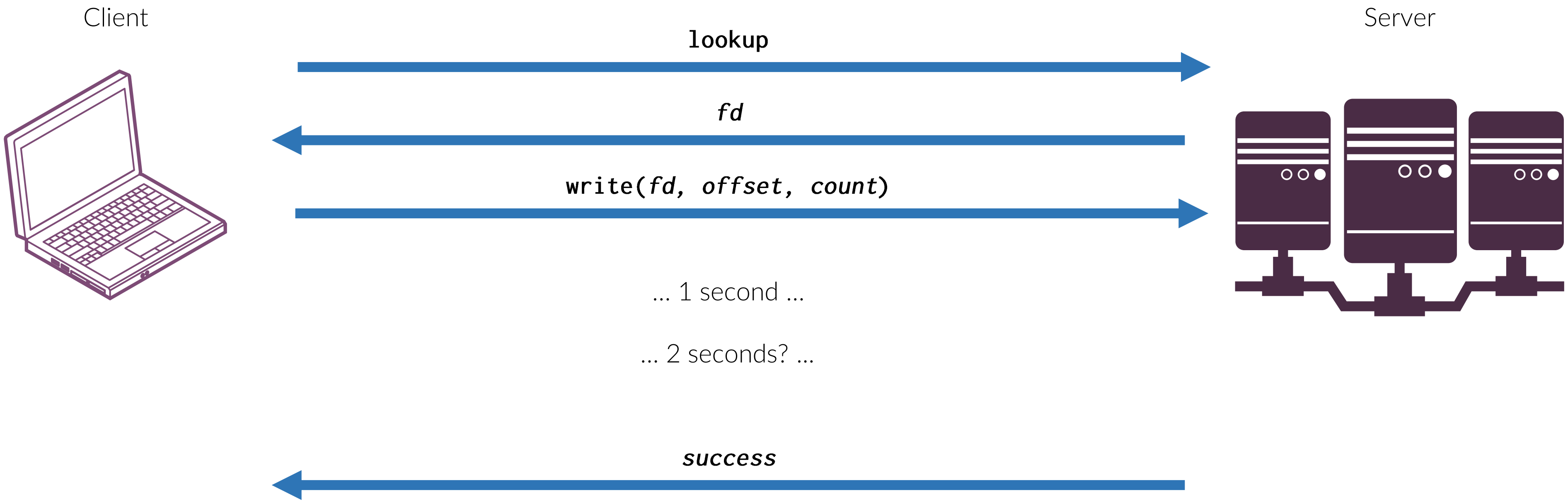
Remote File

AAAAAAAAAAAAAAA
BBBBBBBBBBBBBBB
CCCCCCCCCCCCCCC

Server-side Writes Are Slow

Problem: Writes are really slow…

(Did the server crash?? Should I try again?? Delay… delay… delay)

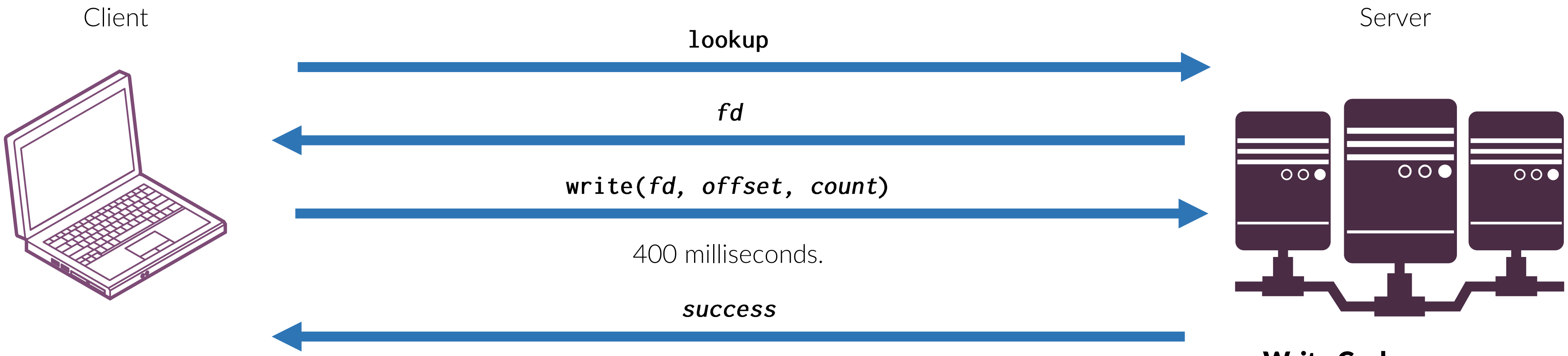


Time relates to the amount of data we want to write… *is there a good block size?*
1KiB? 4KiB? 1MiB? (bigger == slower, harsher failures; small == faster, but more messages)

Server-side Write Cache?

Solution: Cache writes and commit them when we have time.

(Client gets a respond much more quickly… but at what cost? There's always a *trade-off*)



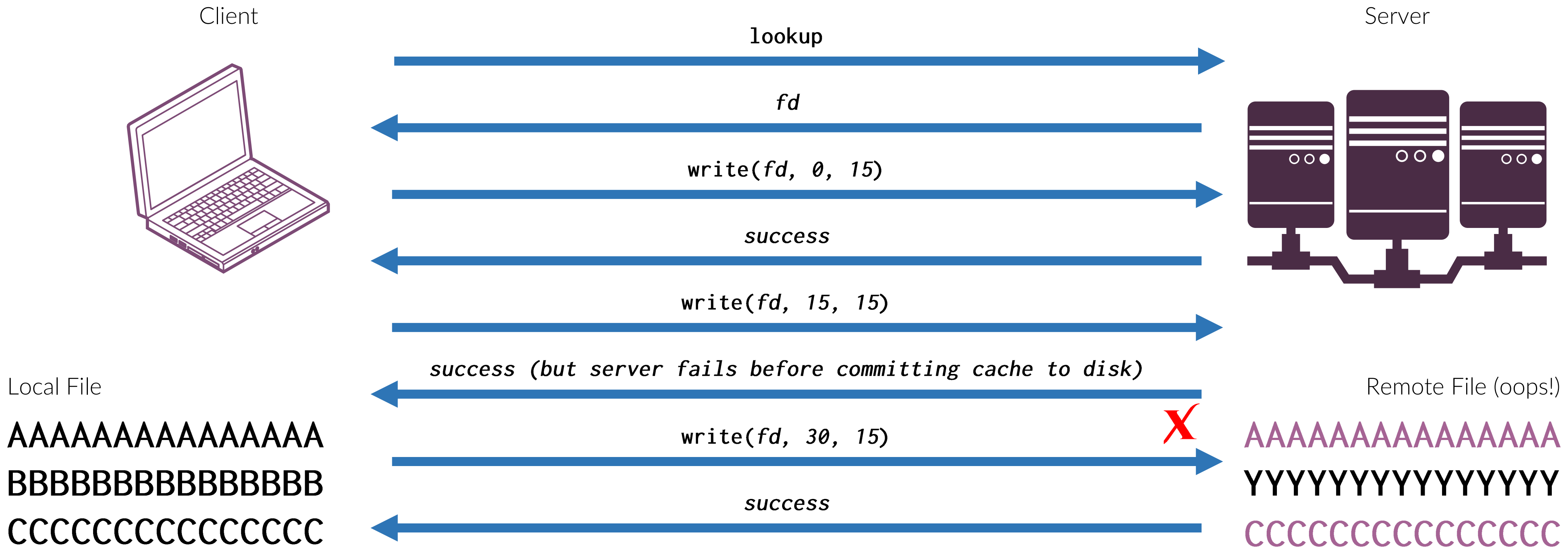
<u>Write Cache:</u>
Need to write this block at some point!

But what if… ***it doesn't?***

When should it write it back? Hmm. It is not that obvious.
(This is a particular tricky issue in distributed systems.)

Write Cache Failure (NFS)

A server must commit changes to disk if it tells client it succeeded…
If it *did fail*, and restarted quickly, the client would never know!

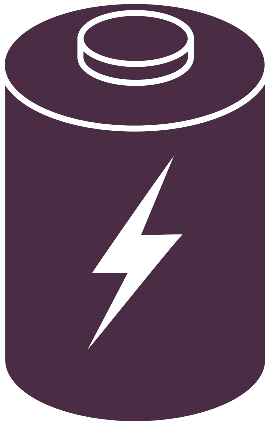


Fault Tolerance

- So, we can allow failure, but *only if we know if an operation succeeded.* (we are assuming a strong "eventual consistency")
  - This is, that, within a reasonable amount of time, the system entirely agrees on what the state (files on disk) look like.
    - This involves, in this case, writes… but those are really slow. Hmm.
- This is a form of **fault tolerance**.
  - The idea that our system can recover or keep making progress of a subset of the system is unavailable or unstable.
- [a basic conforming implementation of] NFS makes a *trade-off*.
  It gives you distributed data that is reliably stored at the cost of slow writes.
- Can we speed that up?

Strategies

- Problem: Slow to send data since we must wait for it to be committed.
  - Also, we may write (and overwrite) data repeatedly.
  - How to mitigate performance?
- Possibility: Send writes in smaller chunks.
  - Trade-offs: More messages to/from server.
- Possibility: We can cache writes at the client side.
  - Trade-offs:
    - Client side may crash.
    - Accumulated writes may stall as we send more data at once.
    - Overall difficulty in knowing when we writeback.
- Possibility: We mitigate likelihood of failure on server.
  - Battery-backed cache, etc. Not perfect… but removes client burden.
  - Make disks faster (Just make them as fast as RAM, right? NVRAM?) ☺
  - Distribute writeback data to more than one server. (partitioning! Peer-to-peer!!)



File System Structure

Or lack thereof…

Directories and Hierarchies

- Hierarchical directories are based on older types of computers and operating systems designed around severe limitations.
- NFS (+VFS) mounts remote servers to directories.
- This is convenient (easy to understand and configure) for smaller storage networks.
- However, two *different* files may have the same name and exist on two different machines.
  - How to differentiate? How to find what you want?

Reconsidering Normal (Name-Addressed)

- Currently, many everyday file systems haven't changed much.
  - They are **name-addressed**, that is, you look them up by their name.

- File lookups in hierarchies require many reads from disparate parts of disk as you open and read metadata for each directory.
  - This can be slow. OSes have heavy complexity and caching for directories.
  - Now, consider distributed file systems… if directories span machines!

- There are other approaches. Recall: Margo Seltzer in *Hierarchical File Systems are Dead* suggested a tag-based approach more in line with databases: offering indexing and search instead of file paths.

Content Addressing

- However, one approach “flips the script” and allows file lookups to be done on the *data of the file*.
- That seems counter-intuitive: looking up a file via a representation of its data. How do you know the data *beforehand*?
- With **content-addressing**, the file is stored with a name that is derived mathematically from its data as a hash. (MD5, SHA, etc)
- That yields many interesting properties we will take advantage of.

Hash Function Overview

Good Hash Functions:

- Are one-way (non-invertible)
  - Cannot compute original x from result of $hash(x)$
- Are deterministic
  - $hash(x)$ is equal to $hash(x)$ at any time on any other machine
- Are uniform
  - Are hashes have equal probability. That is:
  - The set H defined by taking a random set and applying $hash(x)$ results in a normal distribution.
- Continuous
  - Hashing two similar numbers should result in a dramatically different hash.
  - That is: $hash(x)$ should be unpredictably distant from $hash(x + 1)$

Basic Hashing

- For simple integrity, we can simply hash the file.

  $k = hash(file)$ is generated. Then key k can be used to open the file.

- When distributing the file, one can know it got the file by simply hashing what it received.
  - Since our hash function is ***deterministic*** the hash will be the same.
  - ***If it isn't, our file is corrupted.***

- In digital archival circles, this is called **fixity**.
  - The quality of data that denotes/verifies that it has not changed (remains fixed.)

Chunking (again... gross...)

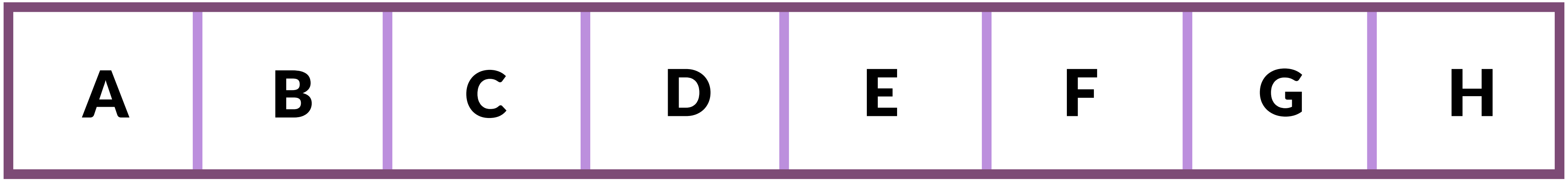
- **However, it would be nice to determine which *part* of the file was distributed incorrectly.**
  - Maybe we can ask a different source for just that part.
    - Hmm… that's an idea! (we'll get there)

- **Dividing up the file is called *chunking*, and there are things to consider: (*trade-offs!*)**
  - How big are the chunks… the more chunks, the more hashes; the more metadata!
  - Of course, the more chunks, the smaller the chunk; therefore, the less window for detecting corruption!

Chunking

- Take a file, divide it into chunks, hash each chunk.

vacation_video.mov




```
A = 912ec803b2ce49e4a541068d495ab570 ← md5(A)
B = 277f255555a1e4ff124bdacc528b815d
C = 0bdba65117548964bad7181a1a9f99e4
D = 495aa31ae809642160e38868adc7ee8e
E = 23c82b0ba3405d4c15aa85d2190e2cf0
F = b2e7af8aff7c2dd98536ce145d705e7f
G = ce3c4edbce0b4da2d9369e8d14e7677a
H = 93ab352ffd32037684257b39eddf33dd
```

Distribution (Detecting Failure)

- Client requests the hashes given. But receives chunks with hashes:

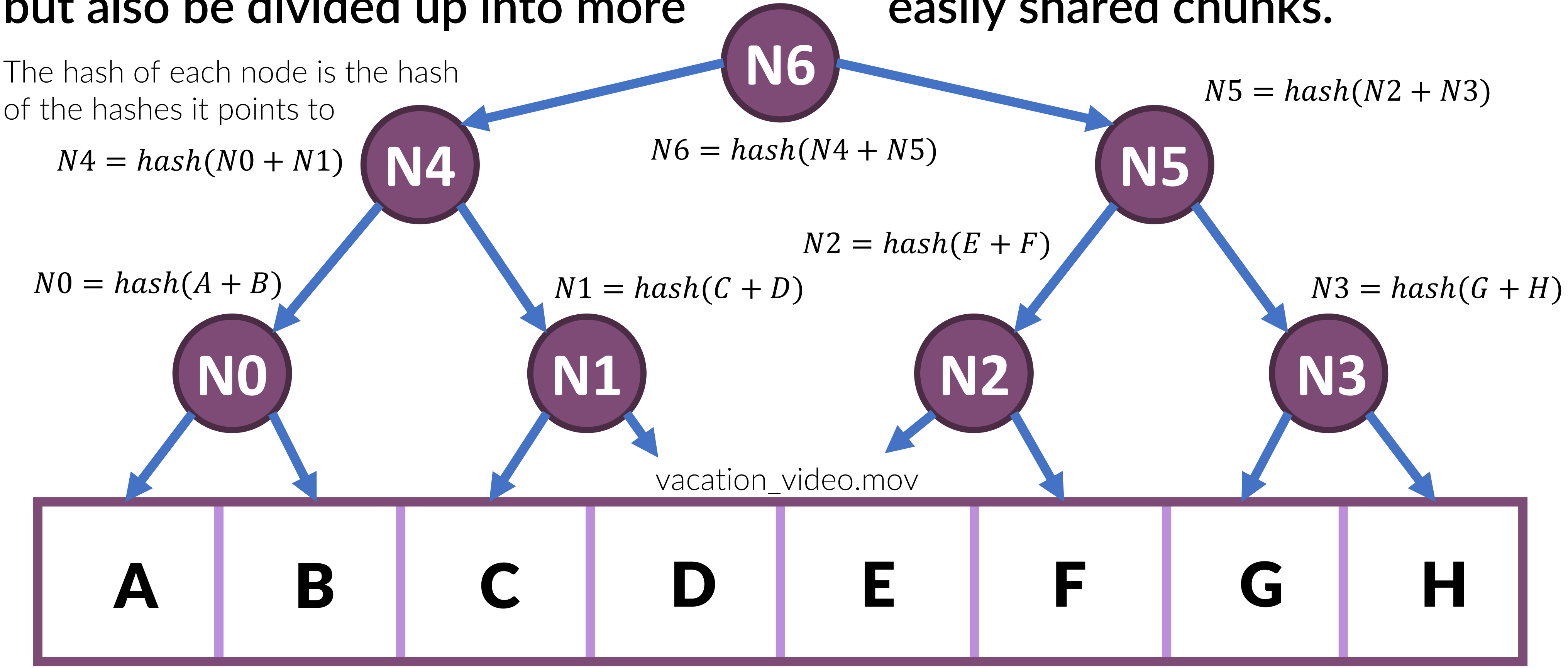
```
A = 912ec803b2ce49e4a541068d495ab570      A’ = 912ec803b2ce49e4a541068d495ab570
B = 277f255555a1e4ff124bdacc528b815d      B’ = 277f255555a1e4ff124bdacc528b815d
C = 0bdba65117548964bad7181a1a9f99e4      C’ = 0bdba65117548964bad7181a1a9f99e4
D = 495aa31ae809642160e38868adc7ee8e      D’ = 495aa31ae809642160e38868adc7ee8e
E = 23c82b0ba3405d4c15aa85d2190e2cf0      E’ = ecf5b19f62a8037f97217ed9cb9b98d9
F = b2e7af8aff7c2dd98536ce145d705e7f      F’ = b2e7af8aff7c2dd98536ce145d705e7f
G = ce3c4edbce0b4da2d9369e8d14e7677a      G’ = ce3c4edbce0b4da2d9369e8d14e7677a
H = 93ab352ffd32037684257b39eddf33dd      H’ = 93ab352ffd32037684257b39eddf33dd
```

vacation_video.mov

A	B	C	D	X	F	G	H

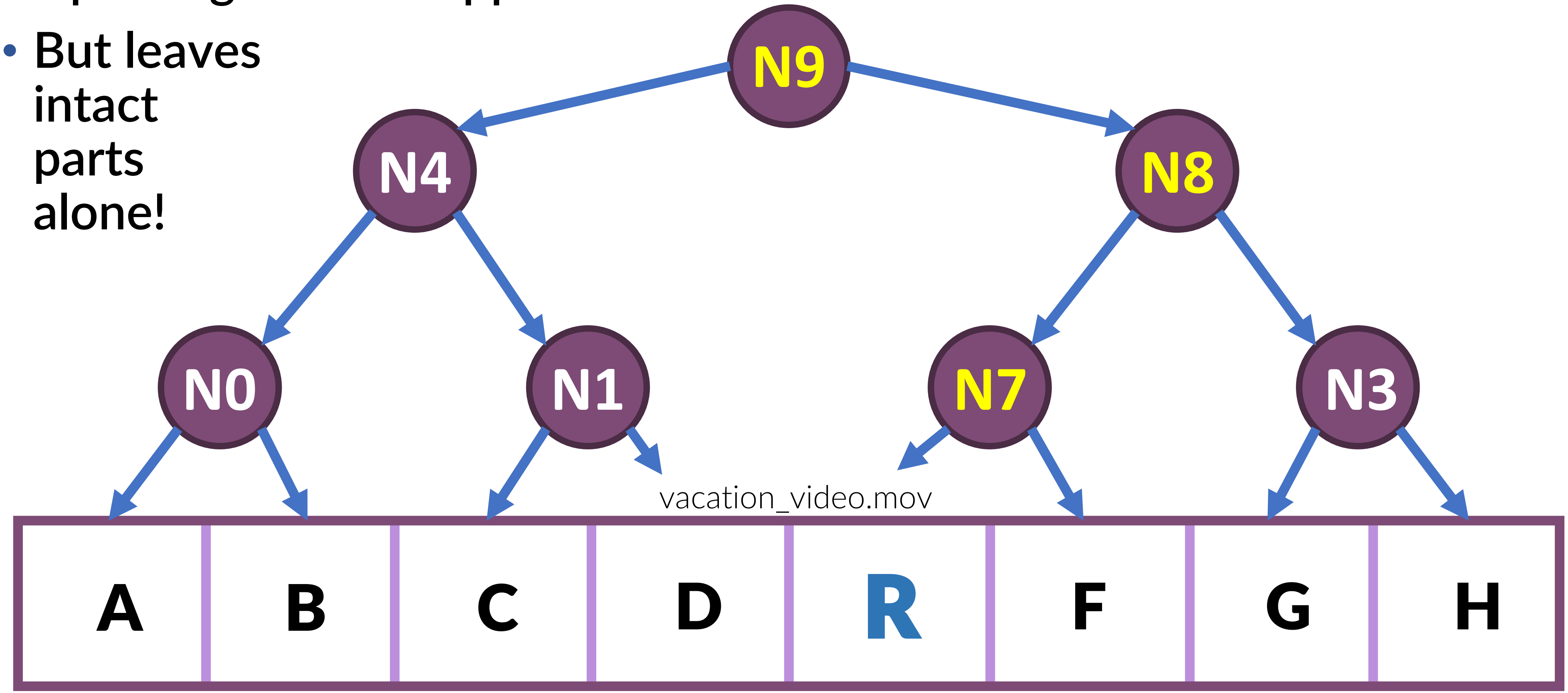
Merkle Tree/DAG

We can organize a file such that it can be referred to by a single hash, but also be divided up into more easily shared chunks.



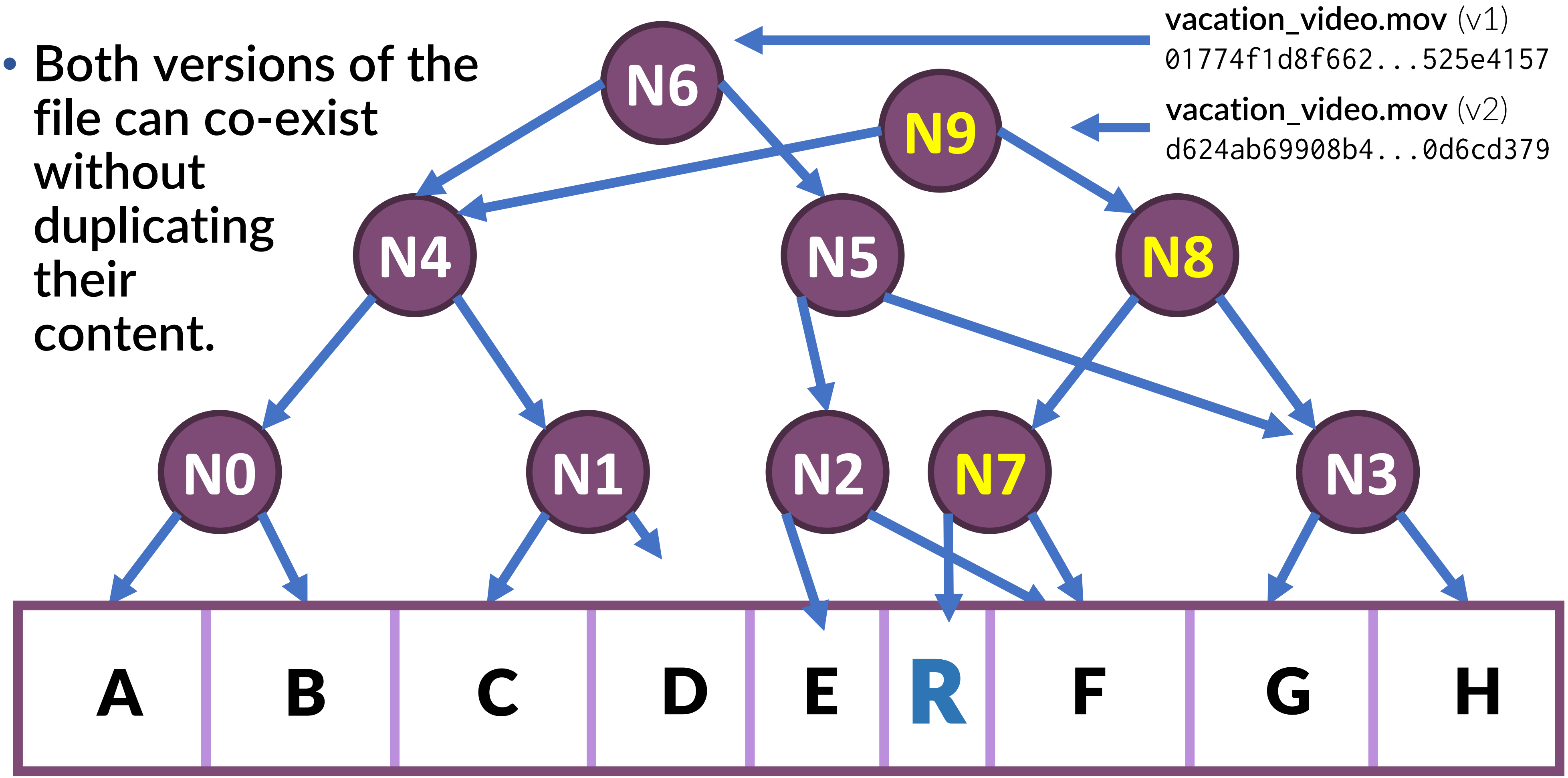
Merkle-based Deduplication

- Updating a chunk ripples.
- But leaves intact parts alone!

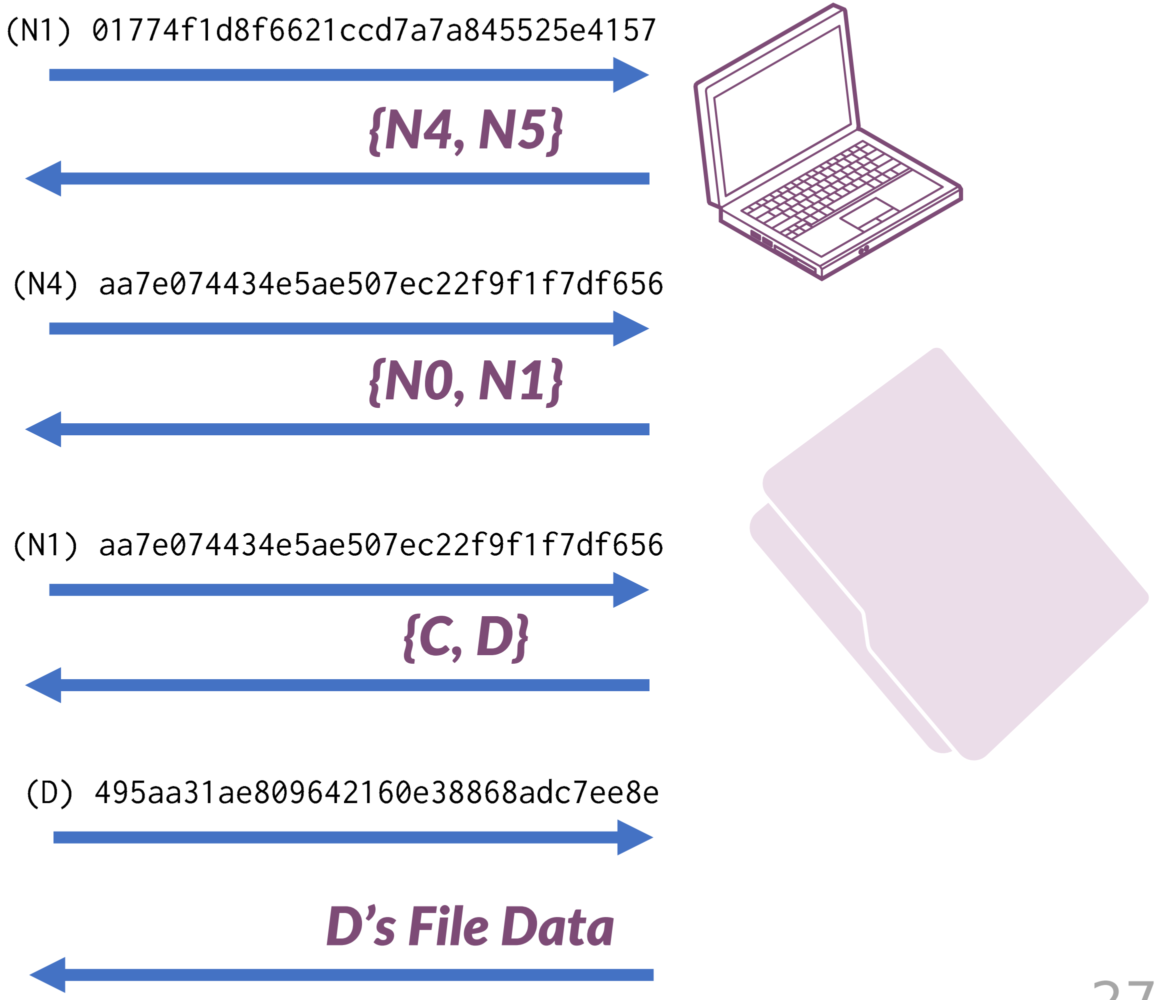


Deduplication

- Both versions of the file can co-exist without duplicating their content.



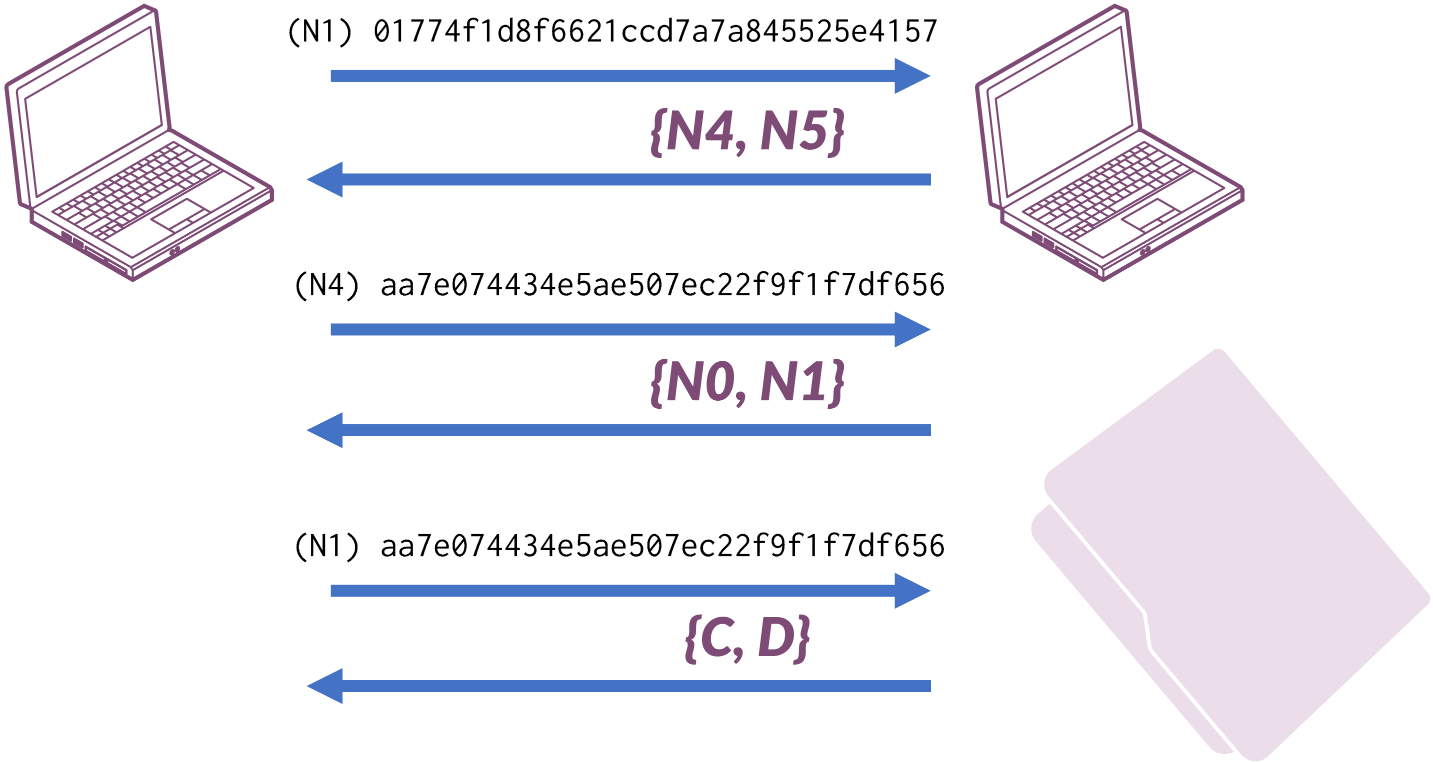
Distribution

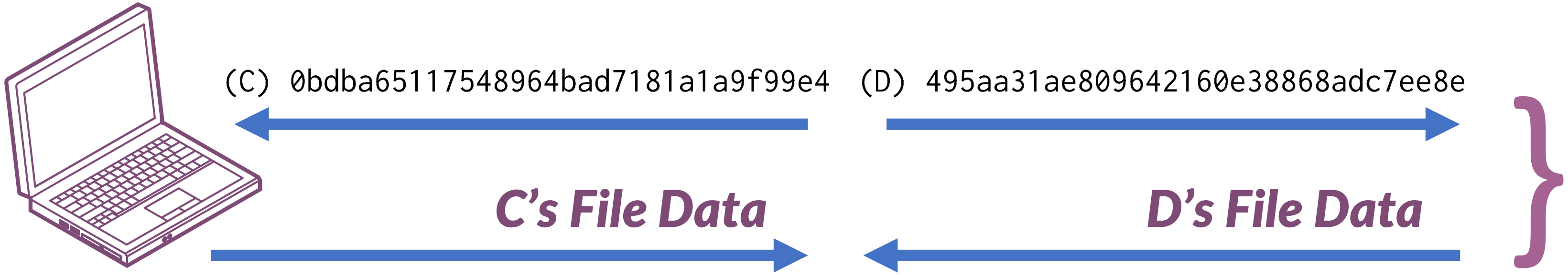


- I can ask a storage server for the file at that hash.
- It will give me the sub hashes.
- At each step, I can verify the information by hashing what I downloaded!

Distribution

- Nothing is stopping me from asking multiple servers.
- *But how do I know which servers have which chunk??* Hmm.





Concurrently gather two chunks at once!

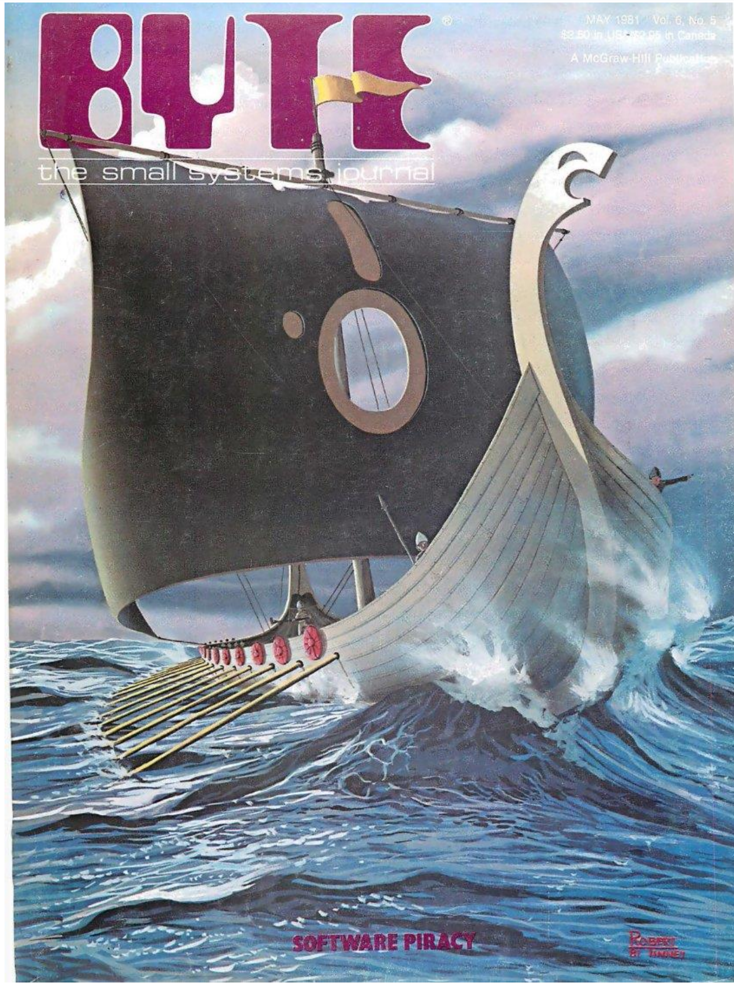
Peer-to-peer Systems

Let me… help you… download that new movie.

BitTorrent

- **A basic peer-to-peer system based on block swapping.**
  - These days built on top of Distributed Hash Tables (DHTs)

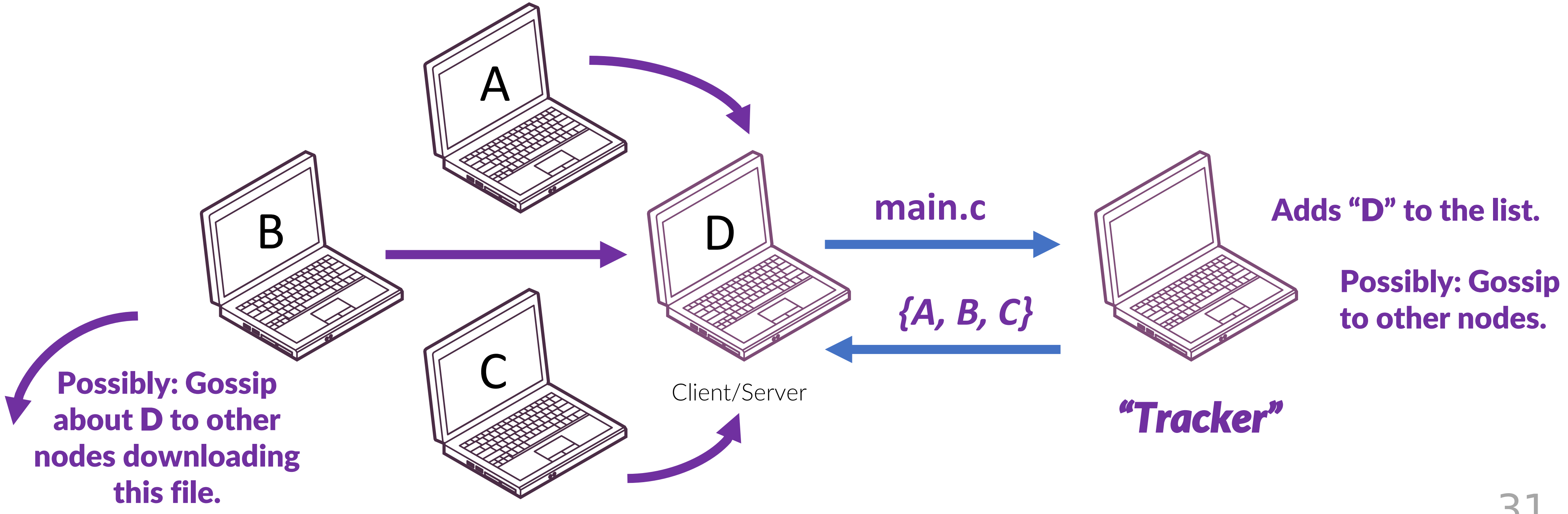
- **Known in non-technical circles for its use within software piracy.**
  - But it, or something similar, is used often!
  - Blizzard uses it for game download/WoW updates.
  - Downloading Linux/large software distributions.
  - AT&T said in 2015 that BitTorrent represented around 20% of total broadband bandwidth
    - I'm actually a bit skeptical.



BitTorrent System Model

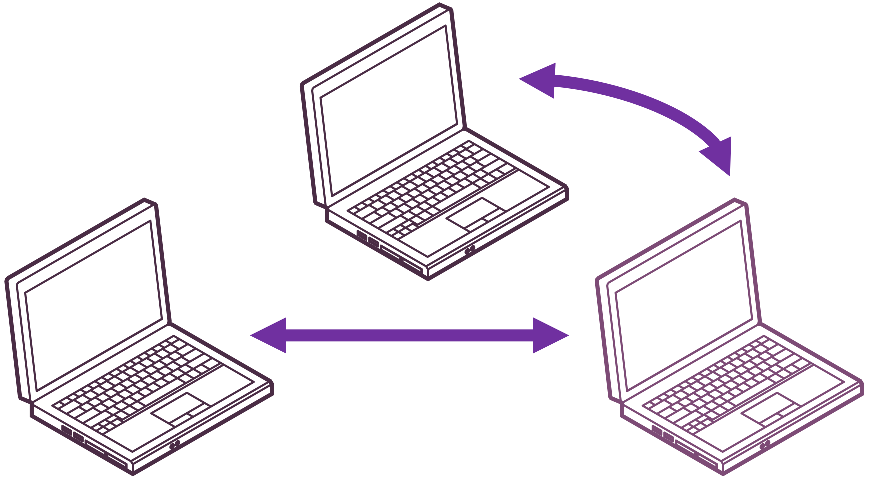
When a file is requested, a well-known node yields a peer list.

Our node serves as both client *and* server. (As opposed to unidirectional NFS)



Block Sharing

- Files are divided into chunks (blocks) and traded among the different peers.
- As your local machine gathers blocks, those are available for other peers, who will ask you for them.



Client/Server

- You can concurrently download parts of files from different sources.
- Peers can leave and join this network at any time.

Heuristics for Fairness

- **How to choose who gets a block? (No right/obvious answer)**
  - This is two-sided. How can you trust a server to give you the right thing?
  - Some peers are faster/slower than others.
  - In an open system: Some don't play fair. They take but never give back.
- **You could prioritize older nodes.**
  - They are less likely to suddenly disappear.
  - They are more likely to cooperate.
  - What if everybody did this... hmm... old nodes shunning young nodes...
- **You can only give if the other node gives you a block you need.**
  - Fair Block/Bit-swapping. Works as long as you *have some data*.
  - Obviously punishes first-timers (who don't have any data to give)
  - Incentivizes longevity with respect to cooperation.

(The Millennial Struggle, am I right?)

Charge Money???

Centralization Problems

- “Tracker” based solution introduces unreliable ***centralization***.

- Getting rid of that (decentralized tracking) means:
  - Organizing nodes such that it is easy to find data.
  - Yet, also, not requiring knowledge about where that data is.
  - And therefore, allowing data to move (migrate) as it sees fit.

- Many possible solutions. Most are VERY interesting and some are slightly counter-intuitive (hence interesting!)

Distributed Hash Tables (DHT)

- A distributed system devoted to decentralized key/value storage across a (presumably large or global) network.

- These are "tracker"-less. They are built to not require a centralized database matching files against peers who have them.

- Early DHTs were motivated by peer-to-peer networks.
  - Early systems (around 2001): Chord, Pastry, Tapestry
  - All building off one another.

Distributed Hash Tables: Basics

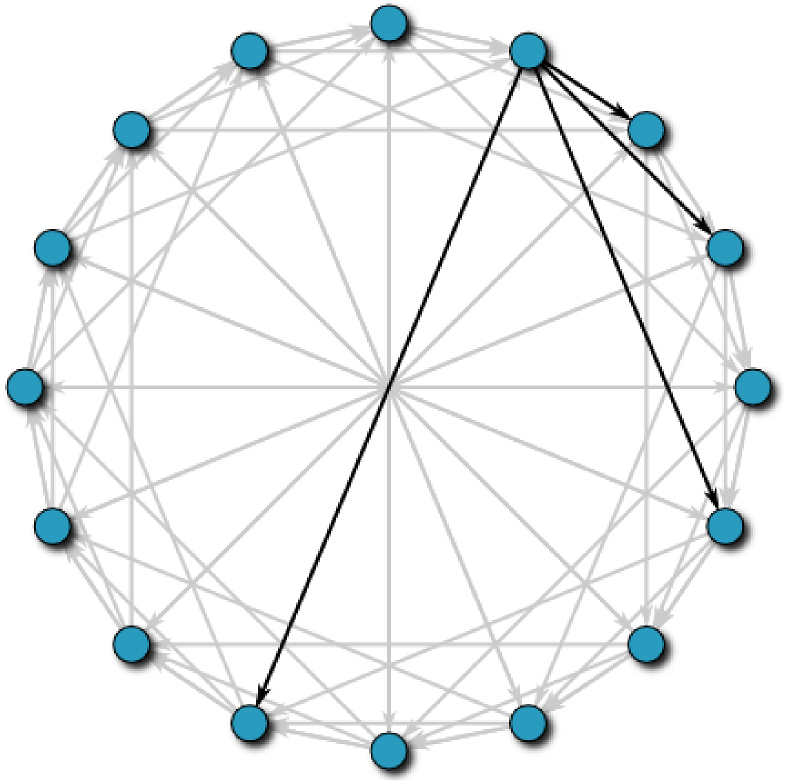
- Files are content-addressed and stored by their hash (key).

- Fulfills one simple function: $\text{value} = lookup(key)$
- However, the value could be anywhere! IN THE WORLD. Hmm.

- Mainly: find a way to relate the key to the location of the server that holds the value.

- The goal is at $O(\log N)$ queries to find data.
  - Size of your network can increase exponentially as lookup cost increases linearly. (Good if you want to scale to millions of nodes)

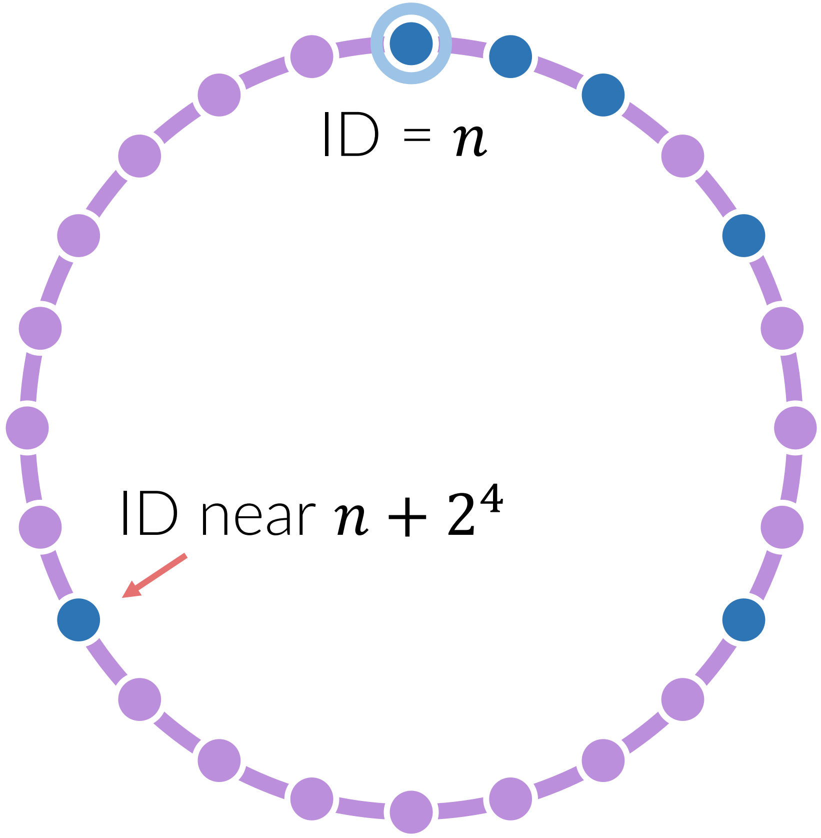
The Chord DHT



16 Node Network
(image via Wikipedia)

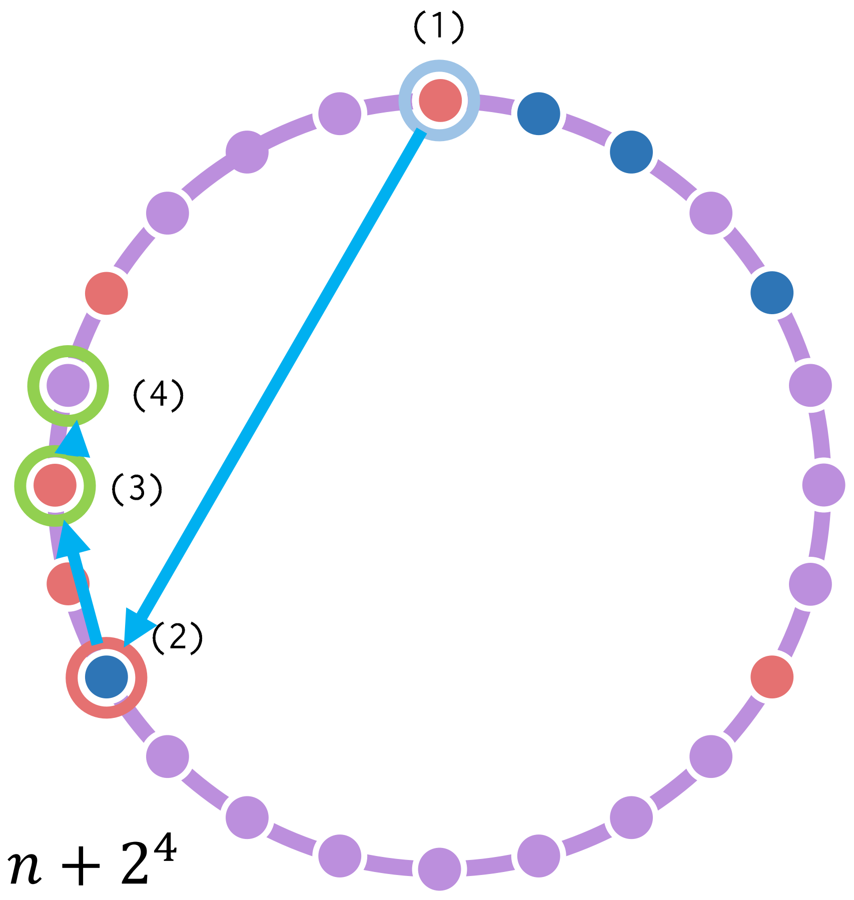
- Peers are given an ID as a hash of their IP address. (unique, uniform)
- Such nodes maintain information about files that have hashes that resemble their IDs. (Distance can be the difference: A-B)
- Nodes also store information about neighbors of successive distances. (very near, near, far, very far… etc)
- Organizes metadata across the network to reduce the problem to a binary search.
  - Therefore needs to contact $O(\log N)$ servers.
- To find a file, contact the server with an ID equal or slightly less than the file hash.
  - They will then reroute to their neighbors. Repeat.

The Chord System Model



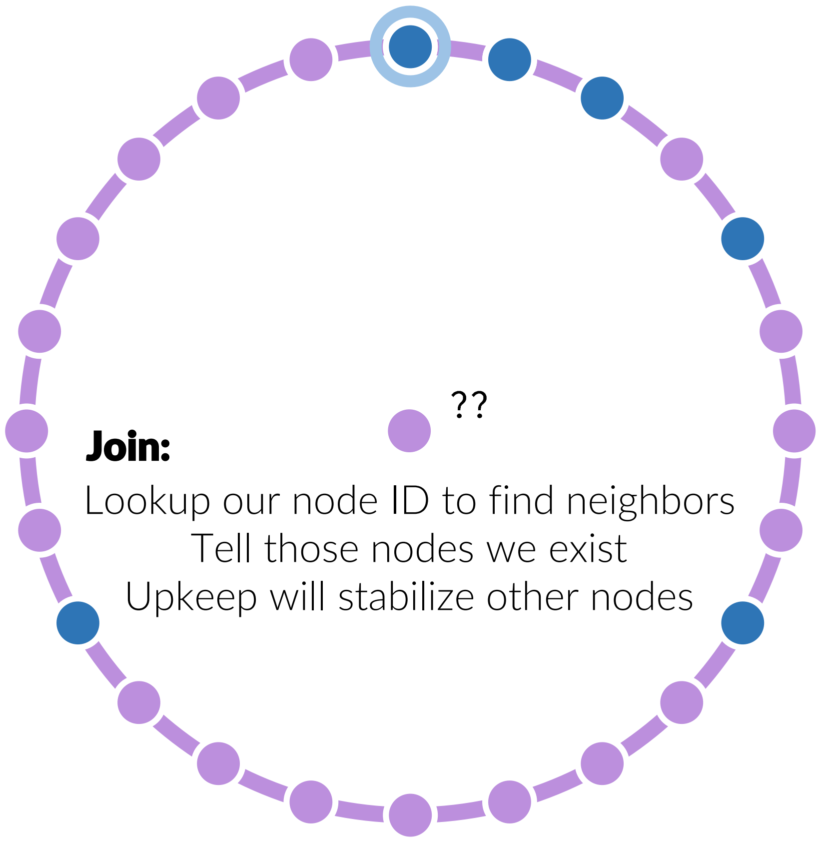
- **Nodes are logically organized into a ring formation sorted by their ID (n).**
  - IDs increase as one moves clockwise.
  - IDs should have the same bit-width as the keys.
  - For our purposes, keys are file hashes.
- **Nodes store information about neighbors with IDs relative to their own in the form: (m is key size in bits)**
  - $\left(n + 2^i\right) \bmod 2^m$ where $0 \leq \ i < m$
- **Imagine a ring with *millions* of nodes.**
  - 2^i diverges quickly!

Chord: Lookup



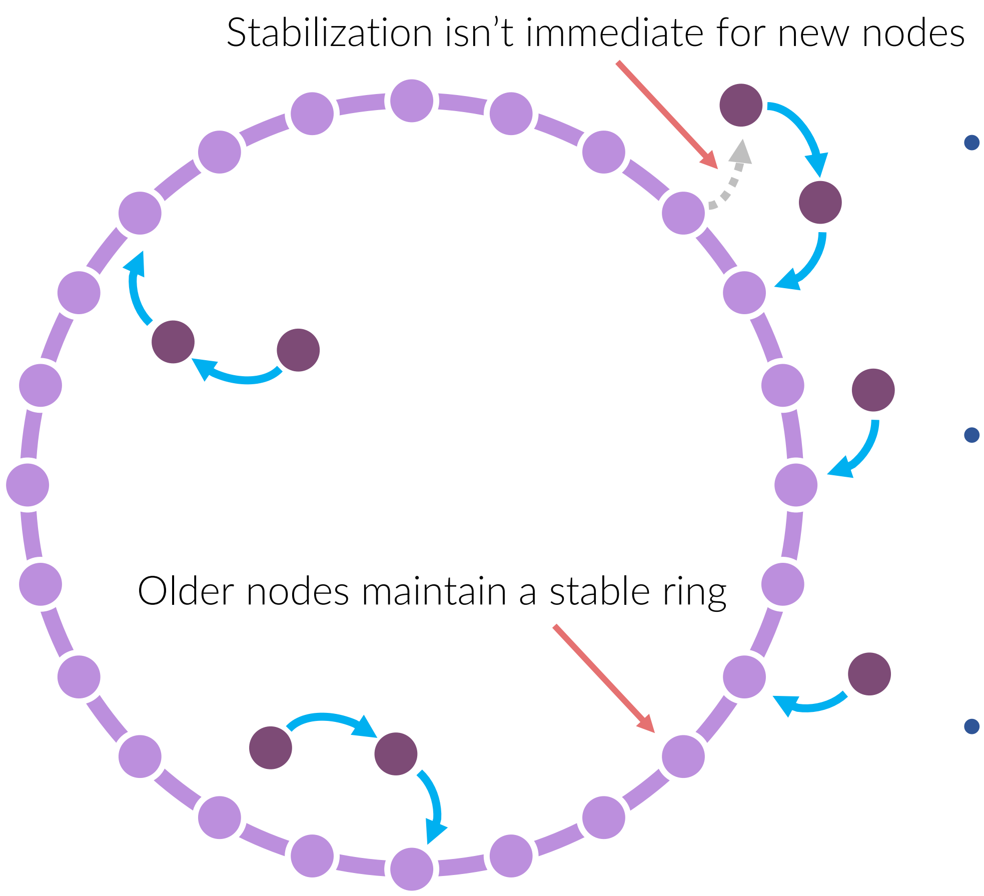
- **Notice how locality is encoded.**
  - Nodes know at most $\log m$ nodes.
  - Nodes know more "nearby" nodes.
- **When performing $lookup(key)$, the node only needs to find the node closest to that key and forward the request.**
- **Let's say key is far away from us.**
  - We will ask the node farthest from us (with the "nearest" ID less than the key)
- **This node, as before, also knows about neighbors in a similar fashion.**
  - Notice it's own locality! It looks up the same key. Binary search… $O(\log N)$ msgs.

Chord: Upkeep, Join



- Periodically, the node must check to ensure it's perception of the world (the ring structure) is accurate.
- It can ask its neighbor who their neighbor is.
  - If it reports a node whose ID is closer to $n + 2^i$ than they are… use them as that neighbor instead.
- This is done when a node enters the system as well.
  - All new neighbors receive information about, and responsibility for, nearby keys.

Problems with Chord



- **Maintaining the invariants of the distributed data structure is hard.**
  - That is, the ring shape.
- **When new nodes enter, they dangle off of the ring until nodes see them.**
- **That means, it doesn't handle short-lived nodes very well.**
  - Which can be very common for systems with millions of nodes!

Kademlia (Pseudo Geography)

- Randomly assign yourself a node ID ☺

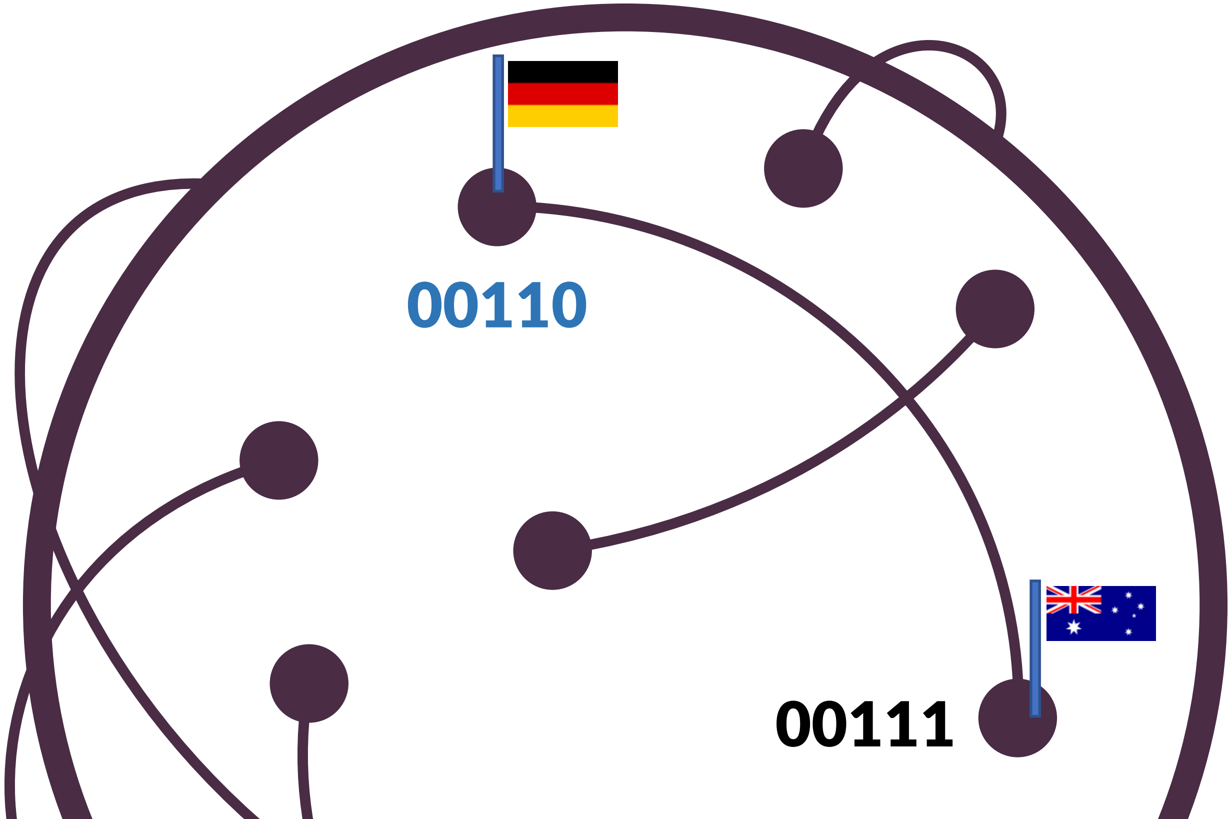
- Measure distance using XOR: $d(N_1, N_2) = N_1 \oplus N_2$ (Interesting…)
  - Unlike arithmetic difference (A – B) no two nodes can have the same distance to any key.
  - XOR has the same properties as Euclidian distance, but cheaper:
    - Identity: $d(N_1, N_1) = N_1 \oplus N_1 = 0$
    - Symmetry: $d(N_1, N_2) = d(N_2, N_1) = N_1 \oplus N_2 = N_2 \oplus N_1$
    - Triangle Inequality: $d(N_1, N_2) \leq d(N_1, N_3) + d(N_2, N_3)$

      $N_1 \oplus N_2 \leq (N_1 \oplus N_3) + (N_2 \oplus N_3)$ … Confounding, but true.

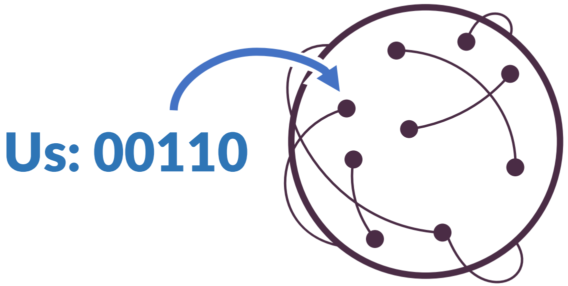
- Once again, we store keys near similar IDs.
  - This time, we minimize the distance:
    - Store key k at any node n that minimizes $d(n, k)$

Kademlia Network Topology

- Two “neighbors” may be entirely across the planet! (or right next door)



Kademlia Network Topology



Routing Table k-buckets

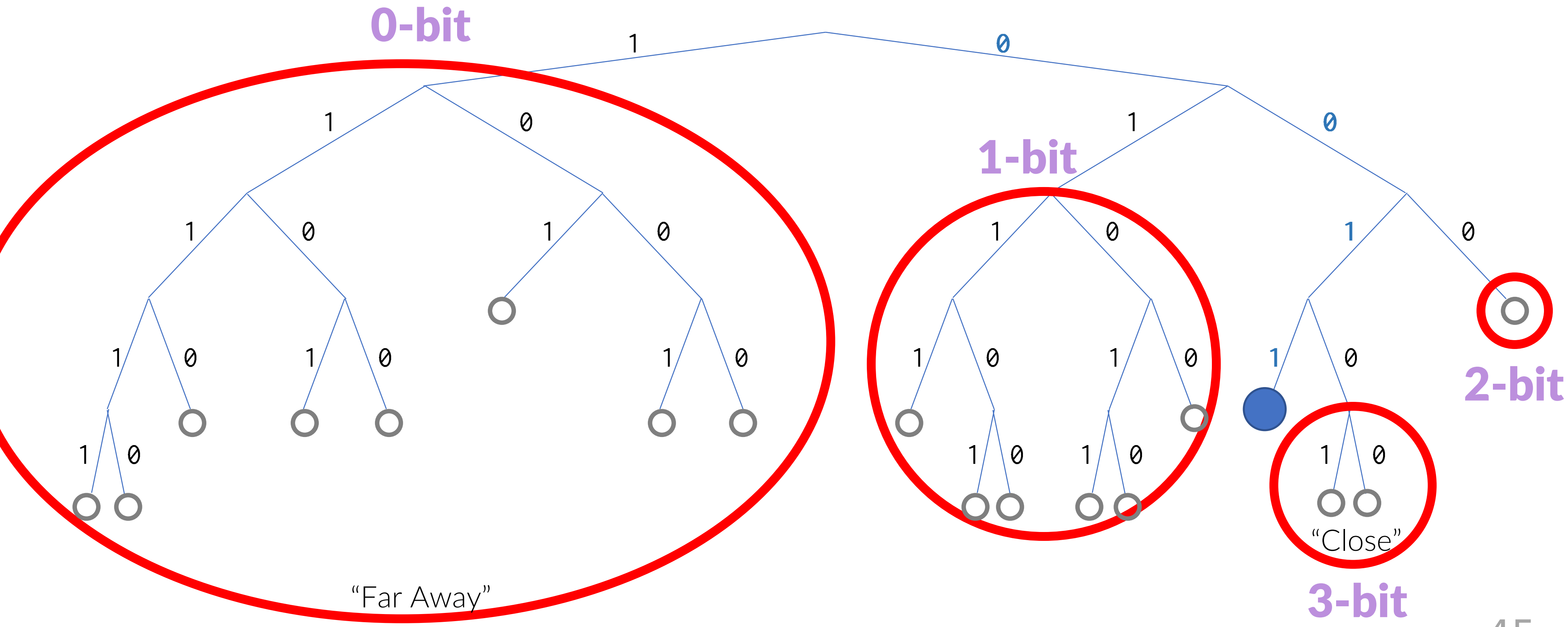
0-bit	1-bit	2-bit	3-bit	4-bit
10001	01001	00011	00100	00111
10100	01100	00010	00101	
10110	01010	00001		
11001	01001	00000		

"Them"

Note: 0-bit list contains half of the overall network!

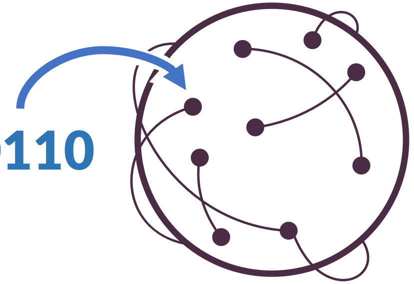
- **Each node knows about nodes that have a distance successively larger than it.**
  - Recall XOR is distance, so largest distance occurs **when MSB is different.**
- **It maintains buckets of nodes with IDs that share a prefix of k bits (matching MSBs)**
  - There are a certain number of entries in each bucket. (not exhaustive)
  - The number of entries relates to the replication amount.
- **The overall network is a trie.**
  - The buckets are *subtrees* of that trie.

Kademlia Routing (bucket visualization)



Kademlia Routing Algorithm

Us: 00110



Routing Table k-buckets

0-bit	1-bit	2-bit	3-bit	4-bit
10001	01001	00011	00100	00111
10100	01100	00010	00101	
10110	01010	00001		
11001	01001	00000		

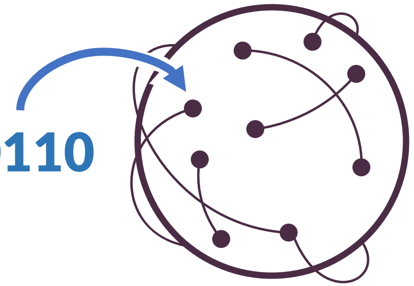
"Them"

Note: 0-bit list contains half of the overall network!

- Ask the nodes we know that are "close" to k to tell as about nodes that are "close" to k
- Repeat by asking *those* nodes which nodes are "close" to k until we get a set that say "I know k!!"
- Because of our k-bucket scheme, each step we will look at nodes that share an increasing number of bits with k.
  - *And because of our binary tree, we essentially divide our search space in half.*
  - Search: $O(\log N)$ queries.

Kademlia Routing Algorithm

Us: 00110



Routing Table k-buckets

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11001	01001	00000		

"Them"

Note: 0-bit list contains half of the overall network!

- **Finding $k = 00111$ from node 00110.**
  - Easy! Starts with a similar sequence.
  - It's hopefully at our own node, node 00111, or maybe node 00100…
- **Finding $k = 11011$ from 00110:**
  - Worst case! No matching prefix!
  - Ask *several* nodes with IDs starting with 1.
    - This is, at worst, half of our network… so we have to rely on the algorithm to narrow it down.
    - It hopefully returns nodes that start with 11 or better. (which eliminates another half of our network from consideration)
  - Repeat until a node knows about k.

Kademlia: Node Introduction

- **Contrary to Chord, XOR distance means nodes know exactly where they fit.**
  - How “far away” you are from any key doesn’t depend on the other nodes in the system. (It’s always your ID $\oplus$ key)

- **Regardless the join process is more or less the same:**
  - Ask an existing node to find your ID, it returns a list of your neighbors.
  - Tell your neighbors you exist and get their knowledge of the world
    - That is, replicate their keys and k-buckets.

- **As nodes contact you, record their ID in the appropriate bucket.**
  - When do you replace?? Which entries do you replace?? Hmm.

Applications

IPFS

- **IPFS (InterPlanetary File System)**
  - Divides files into hashes resembling a Merkle DAG.
  - Uses a variant of Kademlia to look up each hash and find mirrors.
  - Reconstructs files on the client-side by downloading from peers.
  - Some very shaky stuff about using a blockchain (distributed ledger) to do name resolution.
  - Is this the next big thing??? (probably not, but it is cool ☺)

Summary

- Here we look at a variety of distributed systems issues.

- I hope you are now excited at the potential of creating such systems!
  - The web is a giant distributed system… many of these issues come into play even in the simplest of websites.
  - Watch my friend Mikaela Patella's video "Web Development is Distributed Systems Programming"

- We have seen how protocol design needs to accommodate failure.
- We investigated ways of detecting forms of data failure and fixity.
- And how designs need to account of distance and lookup…
  - In the presence of possibly millions or billions of systems!!

- What's next? Well, take the Operating Systems course nearest you!