University of Illinois at Urbana-Champaign
Dept. of Electrical and Computer Engineering

ECE 101: Exploring Digital Information Technologies for Non-Engineers Spring 2023

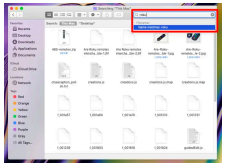
File Systems: Consistency and Cloud Storage

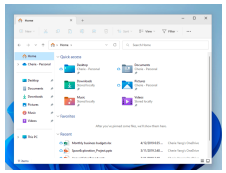
How do you store documents on your computer?

- On the Desktop
- In the Downloads folder
- Somewhere on your computer
- In a carefully organized folder structure
- On the cloud: Google Drive, iCloud, Dropbox etc.

How do you retrieve your files?

- Navigate to the right folder - you know exactly where you saved it.
- Search by keyword and date





Do you worry about space and organization?

- Technology has brought us **effectively unlimited virtual storage**
- Also enables us to **collaborate remotely** on shared documents.

Getting to Your Files in the Cloud

Cloud services are assumed to have several properties.

We **assume** that our files in the cloud are
- **available** (accessible at all times),
- **reliable** (no errors in stored content), and
- **consistent** (everyone sees the same thing, all the time).

But first, just to make sure you're aware…

All Services Provided "As Is", Without Warranty

None of these companies guarantees you anything—certainly not for free.*

If they decide to stop doing business with you,
- whether because it's not in their interest or
- because they go out of business, or
- they sell to another company who doesn't want your business,
- your data are gone.

You may want to have a copy somewhere?

*If you pay, I suggest reading the fine print carefully.

Working on a Document

- You usually type stuff into a document
- If you type in something you didn't mean to, you delete it
- If you accidentally deleted something you didn't mean to, you "UNDO" it.

A History of Operations needed to Undo

To support "Undo", **programs must keep a log of operations**.

Each log entry
- **could be undone** (in reverse order)
- by inverting the operation:
- paste becomes cut, and
- key-press becomes backspace.

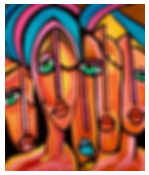
LOG
1. Pressed 'H'
2. Pressed 'e'
3. Pressed 'l'
4. Pressed 'l'
5. Pressed 'o'
6. Pasted ", world!"

Not All Operations can be Inverted

Some operations have no exact inverse.

Consider an image editing tool.
- A user blurs the image,
- which performs local averaging.

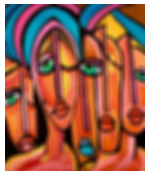
Many possible original images
- produce the same final image, so
- **the only way to undo** a blur
- **is to preserve a copy** of the original.



Cheap Memory Broadens Set of Reversible Operations

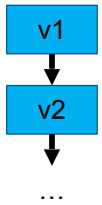
In early systems,
- operations of this type could not be undone:
- keeping a copy was too expensive.

As memory became cheaper,
- **programs** started **keep**ing **snapshots**—
- copies of earlier versions of the user's data—
- so as **to support undo**.



Versioning Useful for Long-Term

An **undo log rarely persists** across sessions.



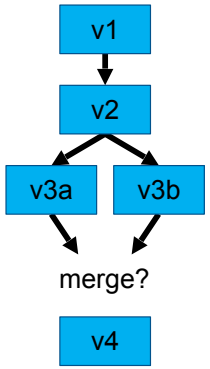
Example: open a file and undo the last operation … from a week ago?

Instead, create **snapshots / versions** are more useful over the longer term.

Merging Alternative Versions Can be Challenging

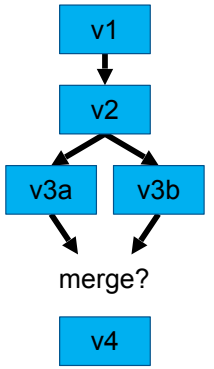
But long-term storage
introduces the problem of divergent versions…

How can we merge changes?



Automatic Merges Fail Frequently

Making merge work without human oversight is difficult.



Even today,
- **shared code repositories** such as Github
- **support** independent, **disconnected development**,
- and **automated merges** do sometimes **fail**.

Order of Operations Matter in Final Result

Consider banking operations.

Your bank account contains **$5**.

You have a **$500** paycheck to deposit.

And you want a **$7** bubble tea.

You decide
- to deposit the paycheck (requires communication from ATM or bank to your account about your deposit),
- then buy a bubble tea (requires communication from Bubble Tea store to your account).

Two operations to be merged.

Addition, the Underlying Operator, is Commutative

Operations to be done on your account at the bank server …

1. Add **$500** to balance.
2. Subtract **$7** from balance.

These operations can be reordered.

However, reordering may have side effects.

Reordering Operations is Not Always Helpful

In particular, many banks,
- seeing the "Subtract" operation first,
- approve the operation
- **but** also subtract an additional overdraft "protection"* fee of **$50**.

In the end, your account has

5 – 7 – 50 + 500 = $448.

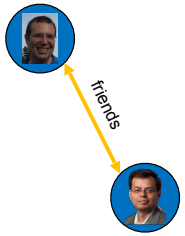
Some Operations are Idempotent

- idem- = identical, -potent = power
- meaning that an **operation has the same effect no matter how many times one performs the operation**.

In a social network, for example:

Mark X as friend of Y

If I switch machines (phone/tablet/computer), see an old version, and apply the same operation again, no problem. Same result again.



Many Tools Do Not Provide Strong Consistency

But … wait a minute.

Why would I ever "see an old version?"

If a service is showing me data,
- which version do I see?
- which version do others see?

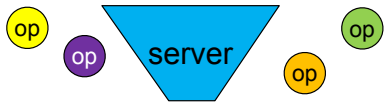
Shouldn't those questions have the same answer at all times?

Yes, of course we'd like that. Life would be easy.

But **that's not our universe**.

One Simple Approach: Pick a Place for the Correct Version

Often, the best solution
- is to define the **version at some server**
- (in one place)
- to be **the correct one**.



To make changes, send operations to that server.

The **server**
- **serializes operations** into some order
- and applies them one at a time.

Companies Design Operations to Reduce Inconsistency

Companies need to think carefully
- about how to **formulate operations**
- so as to make them **less prone to errors**
- **and** less likely to lead to obviously **inconsistent behavior**.

Inconsistencies Do Still Occur with Many Tools

You've probably still seen cases.

For example, a social network that simply rejects your comment or reply.

Yet, when you try again, everything works fine.

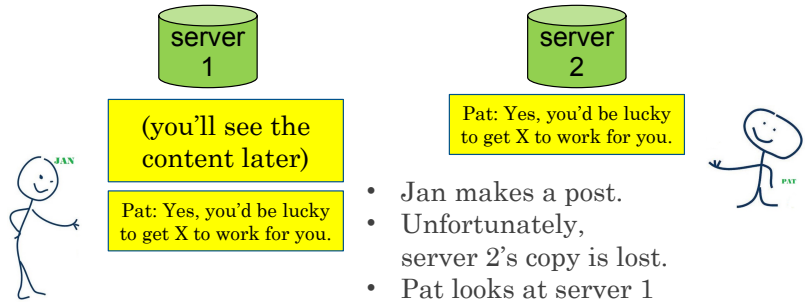
Such failures
- **sometimes indicate problems**
- **with merging your operation**
- with others that have already been applied.

Lack of Consistency Can Lead to Bigger Problems

Realistically, most people do not often work interactively with others around the world.

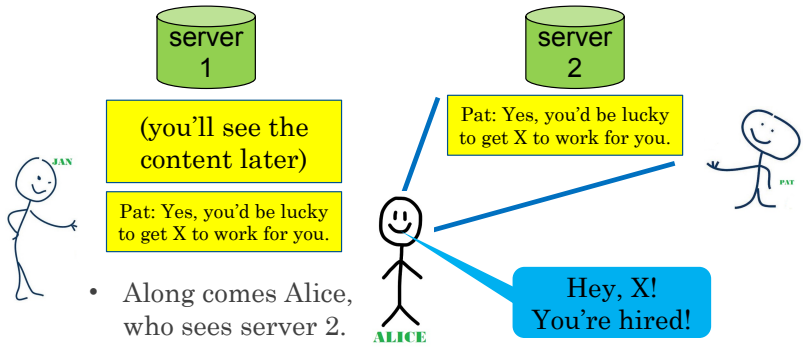
Inconsistency can lead to more **serious problems**, however.

What Can Go Wrong? Let's See an Example



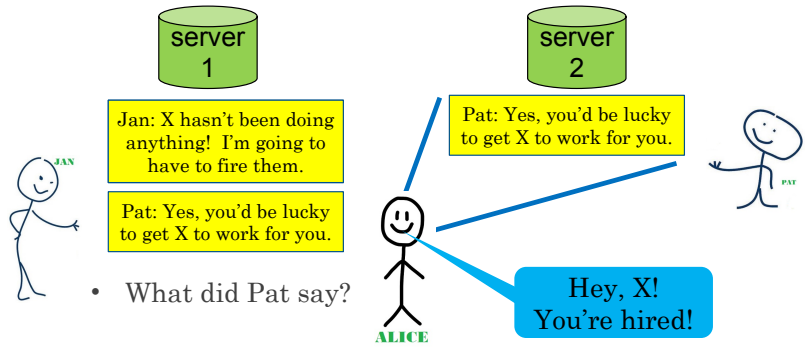
- Jan makes a post.
- Unfortunately, server 2's copy is lost.
- Pat looks at server 1 and replies.

Alice Unknowingly Acts on Incomplete Information



- Along comes Alice, who sees server 2.

Pat's Words Change the Meaning of Jan's!



- What did Pat say?

Allowing Inconsistency Reduces User Response Times

So why does anyone tolerate inconsistency?

For speed!

No One Really Cares that much about Consistency

In a social network,
- most followers don't actually care
- about other followers' comments,
- nor about the order of their comment
- relative to those of other followers.

Most Companies' Systems Do Try to Avoid Inconsistency

The **systems do** make some **attempt to avoid inconsistency**.

For example,
- one can reply to comments, and
- replies are only visible if the original comment is visible.

Desired Properties of Cloud Service

Here are some of the properties that **we want** with our cloud storage and editing tools:
- **available** (accessible at all times),
- **reliable** (no errors in stored content), and
- **consistent** (everyone sees the same thing, all the time).

Consistency is somewhat difficult, but service providers still try to provide it.

Most Services Provide Eventual Consistency

- Operations are serialized at a server.
- Eventually every one perceives the same order of operations. But not necessarily immediately.
- Push model actively forwards updates to users (Distributed file systems, such as Box, Dropbox, and Google Drive)
- Pull model waits for users to request updates

Social Network Updates Generally Pulled from Server

Social networks use primarily a pull model.

Since users typically view
- only the most recent activity in the social graph,
- pushing all updates is generally a waste of bandwidth.

Only a **handful of changes** are **pushed**:
- those needed **to support active notifications**.
- (Notifications that show up when you open an app can also be pulled.)

Availability and Reliability are More Important

These same companies place more **emphasis on availability and reliability**.

We **talked about** these ideas **in social networks**.

File services are similar: your posts, photos, and videos are just a bunch of files.

Collaborative editing tools do require good definitions of operations and somewhat stronger (or at least faster) consistency guarantees to avoid irritating human users.

Availability: Your Data Located Near You

What about availability?

Here, too, the **techniques are** fairly **similar**.

Imagine working on a text document.

The **primary copy** of that document is stored **at a datacenter close to you**.

Within the datacenter, the **exact position** of your file is **selected using** an approach similar to TAO's **shard model**.

For the same reason: load balancing.

Additional Copies of Your Data Kept Elsewhere

But **that's not the only copy** of your file!

If the **disk** with your file **fails**, **or**
- (less likely) the optical **fibers** to the datacenter are all **cut**, **or**
- (even less likely) a **meteorite strikes** the datacenter,

other datacenters have a copy, too!

It just **takes a little longer**
(more msec, not seconds)
to get your data.

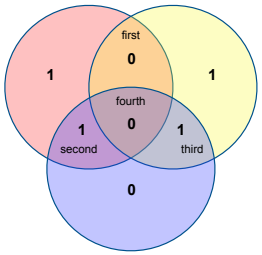
Reliability Supported Using Codes

Reliability is also an issue.

All **digital storage** systems **break down** over time.

To protect your file data,
- **companies use coding** techniques
- (remember the Hamming code?).

Codes are used
- **to protect against changes on disk**, and
- on-disk data are periodically "scrubbed"
- to correct any errors that have popped up.



Reliability Supported Using Codes

Similarly, **codes are used**
- **to store** data **across multiple drives**,
- **increasing bandwidth and**
- **protecting against failure** of any drive.

In this case, the 5-out-of-7 variant
- of the Hamming code would work perfectly:*
- if you store across 7 disks,
  - so long as no more than 2 fail,
  - you can recover all of the data!

*That particular code is not common in practice for disk systems, but the idea is the same.

Sharing Supported Using Access Control Lists

One more topic: sharing.

Sharing of documents (posts, and so forth)
- typically **managed with**
- an Access Control List (**ACL**),
- a list of rules.

The **rules** are **checked one at a time** until a match is found.

ACL
1. ALLOW MySecretAccount
2. DENY unless <Friend>
3. DENY BirthdayFriend
4. ALLOW

With the ACL shown, my secret account as well as all of my friends, except the one friend I'm trying to surprise, can see the document.

Reminder: You are Guaranteed Nothing.

Here's the fine print from one popular set of services. It is essentially identical to the wording introduced by the Berkeley Software Distribution's ***FREE*** version of Unix, TCP, and so forth.

These days, however, most companies use the same rules even if you are a paying customer. Even banks. It's scary.

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Law. The only way you can ever expect to have any guarantee from modern software.

Terminology You Should Know from These Slides

- cloud storage
- available
- reliable
- consistent
- operations (and examples)
- undo/invert, log, and versions
- context (for an operation)
- idempotent
- serialization (by a server)
- causality violation (the Jan and Pat example)
- eventual consistency
- push/pull for updates
- access control lists (ACLs, for sharing)

Concepts You Should Know from These Slides

- properties assumed by users of cloud storage
- not all operations can be inverted easily
- why merging versions can be hard
- why the exact form of an operation matters
- providing strong consistency by using a single location
- effect of delay on exposing inconsistency
- speed benefit of providing only weak consistency
- how availability and reliability are typically supported
- basic use of an access control list (ACL)