Introduction to Git

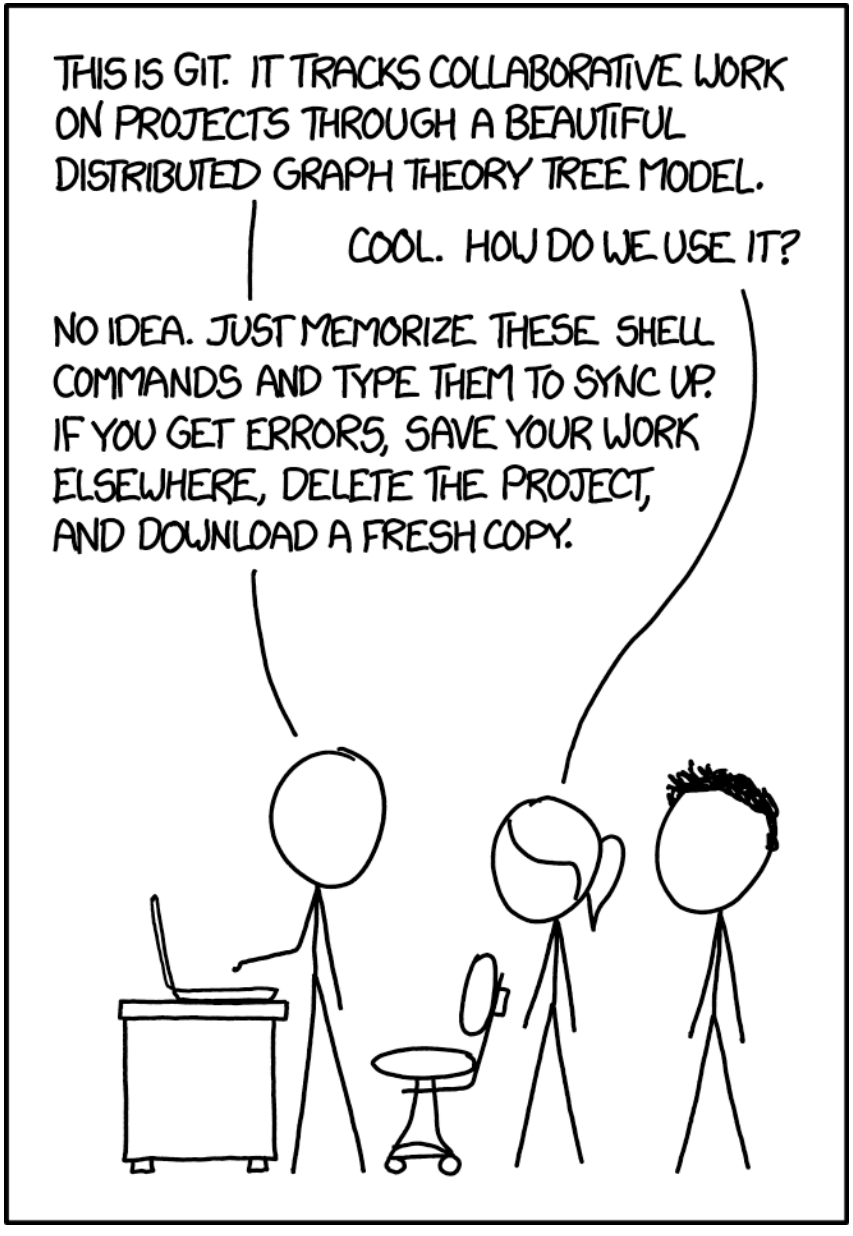
"The stupid[1] content tracker"

Naoki Pross — np@0hm.ch

XX. March 2025

[1] *git* (British) – a foolish or worthless person

Obligatory XKCD



Plan for Today

1. A tiny bit of graph theory and even less cryptography
2. Understand (instead of memorizing) Git
3. Flex on your friends by finding what caused a bug using a logarithmic search over the directed acyclic graph that represents the change history
4. Put it on your CV and profit

Table of Contents

What do we want?

The Problem

Synchronize data across multiple computers, with multiple people working on (possibly the same) files.

Linus' Wishes (The guy who invented Git)

- Synchronization *always* works
- Teamwork is possible and efficient
- Works offline
- Fast

neither *intuitive nor easy to use* were not on his list!

Other Solutions?

Popular at Linus' Time

CVS Slow to synchronize. CVS requires a centralized server which can get overloaded, was usually set up by the company IT.

E-Mail People sent patch files to each other via email.

Popular Tools Today

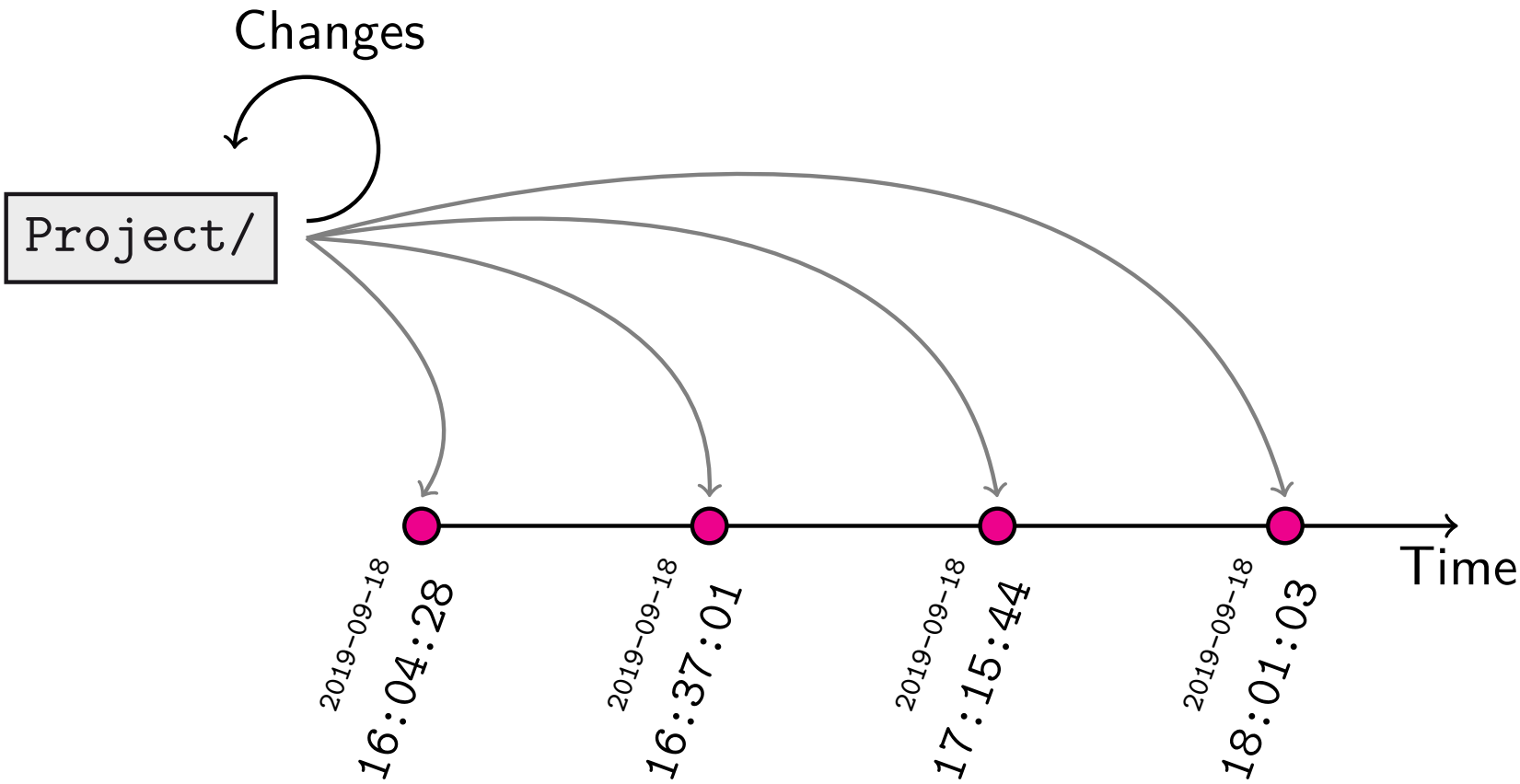
Cloud Storage Does not work offline. Their whole business model is against you. You have no (real) control over when to sync. Also, sharepoint is garbage. No way to compare changes.

Mercurial Less popular than Git, used by Mozilla.

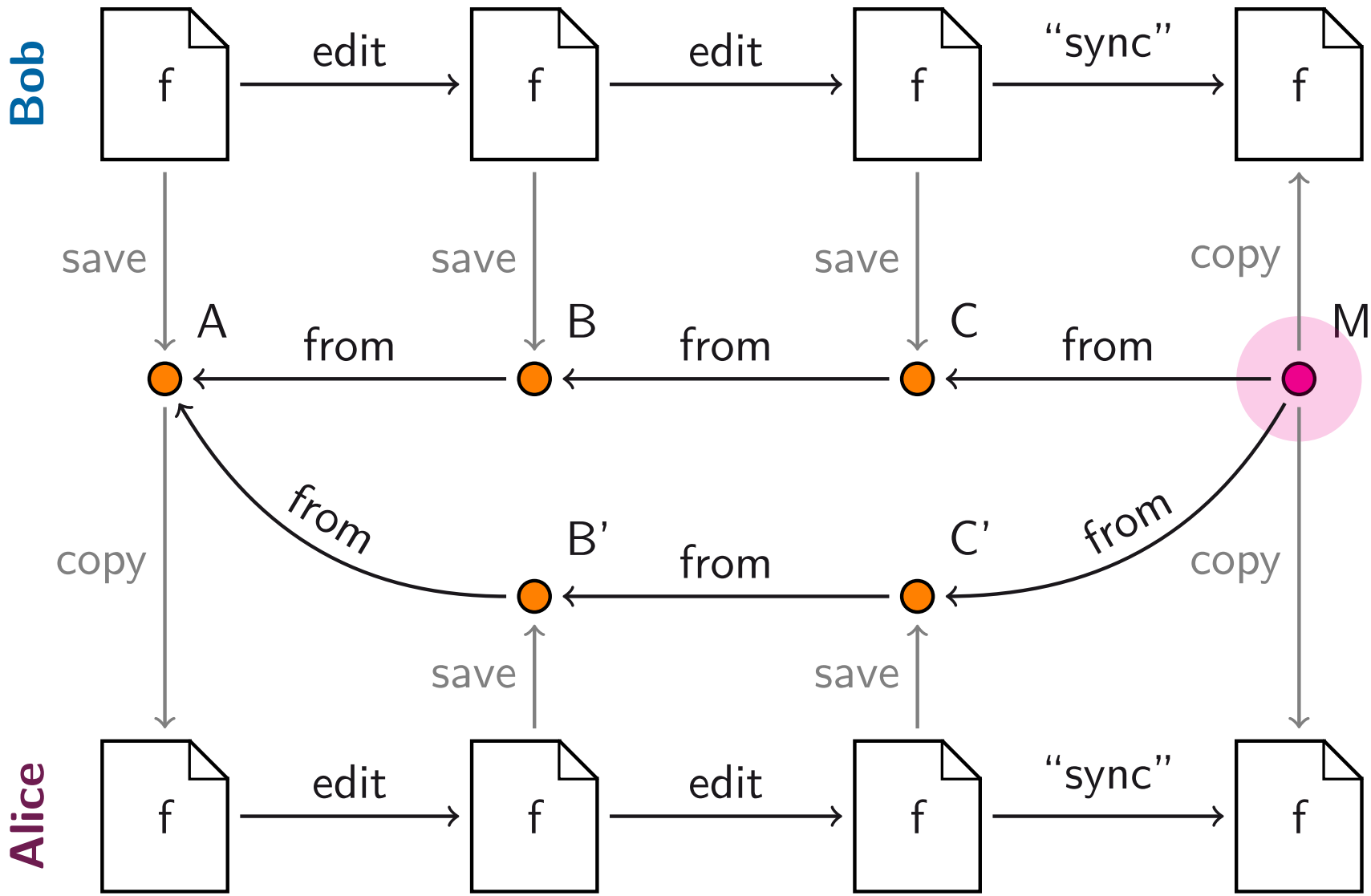
Jujitsu Git-compatible VCS, even less popular and very new.

Table of Contents

Solving the Problem: Snapshots



Solving the Problem: Concurrent Changes I



Solving the Problem: Concurrent Changes II

High Level Overview

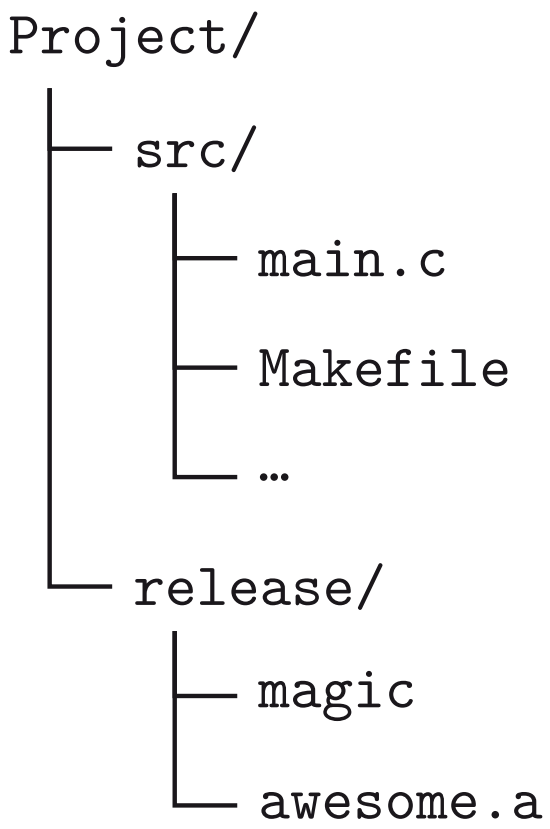
Store changes using a *directed acyclic graph* (DAG) called the *commit graph*.

- Nodes are saved points in time called *commits*
- Arcs point to state from which change was made
- Commits with multiple children (A) are *branching commits*
- Commits with multiple parents (M) are *merge commits*

Problems

1. We care about file content not the files itself
2. How do we merge changes?
3. Alice and Bob are not working on the same computer

Solving the Problem: Multiple Files



Filesystem Jargon

Tree Folder / Directory

Blob Binary Large OBject, raw data (bits) of file content[a]

File Blob + Metadata (Name, Date, …)

Solution

Treat all blobs as single entity with metadata. Examples:

- Rename file ⇒ Same blob, commit name change
- Move file ⇒ Same blob, commit change tree

[a] Demo: `hexdump` vs `stat`

Mathematical Digression: DAG

Directed Acyclic Graph

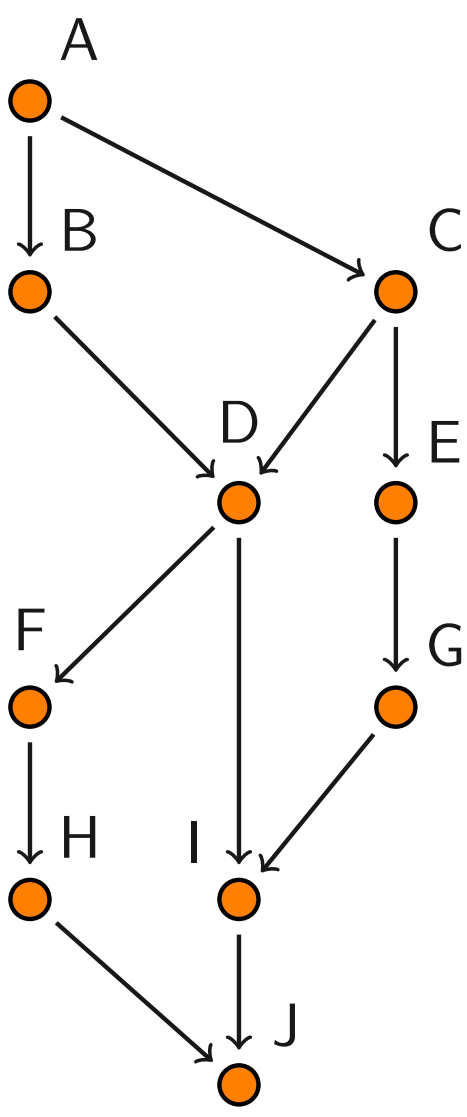
A DAG $G = (V, A)$ is defined by a finite set of vertices V and a finite set of *arcs* A and may not contain loops.

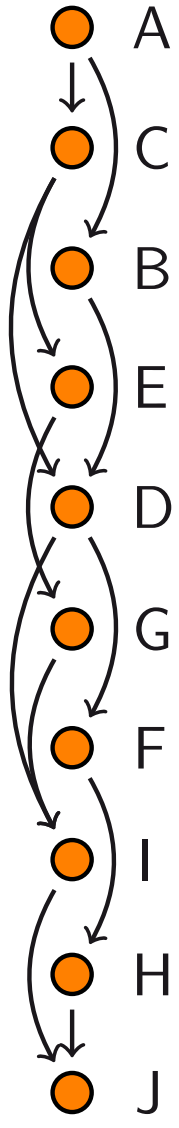
Partial Order

DAG have a partial order relation $u \succ v$ for comparable $u, v \in V$.

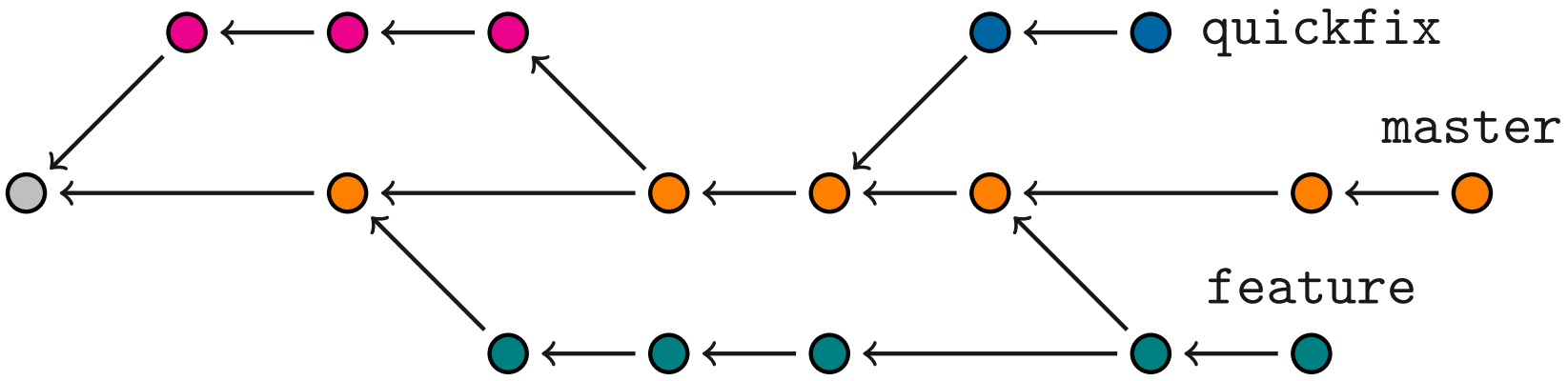
Topological Order

A DAG $G = (V, A)$ has a total order $\succ^*$ by having that for all $(u, v) \in A$ $u \succ^* v$. If G has a Hamiltonian path $\succ^*$ is unique.





Solving the Problem: Concurrent Changes III



Branch (informal)

Branches are subgraphs (subtrees) from a common anchestor in the commit graph.

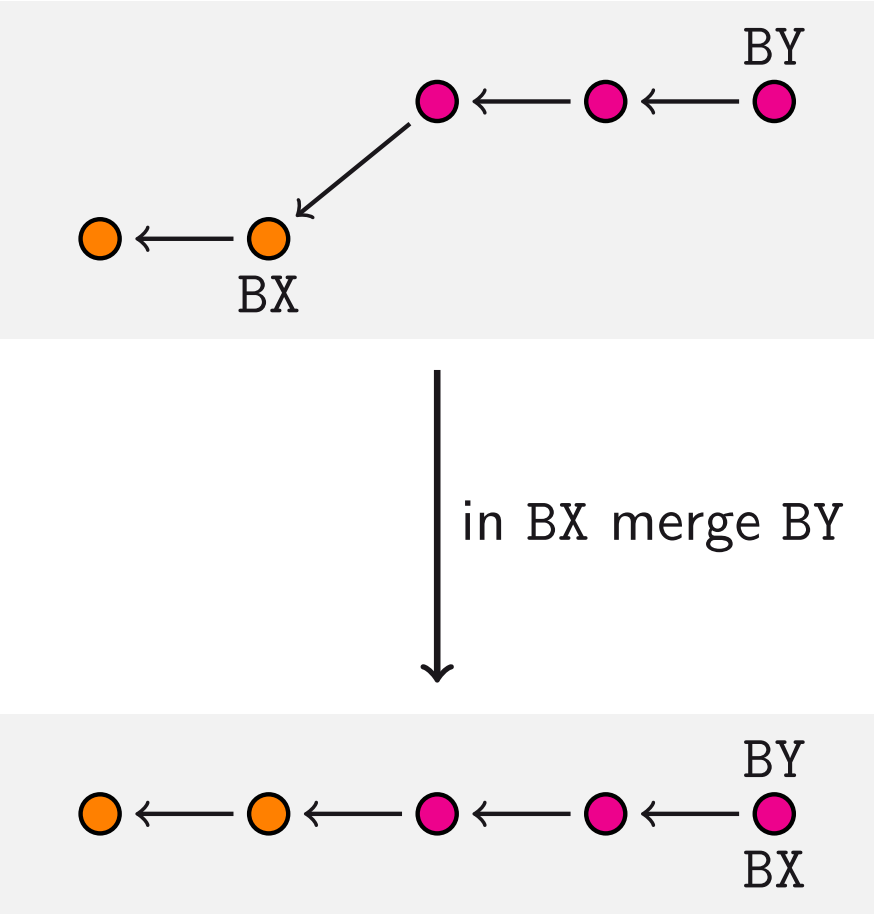
Naming Branches

Branch names are labels on their most recent commit.

Examples

- `quickfix` branch is from `master`
- Magenta (no name) branch was merged into `master`
- `master` branch was merged into `feature`

Solving the Problem: Fast-Forward-Merge



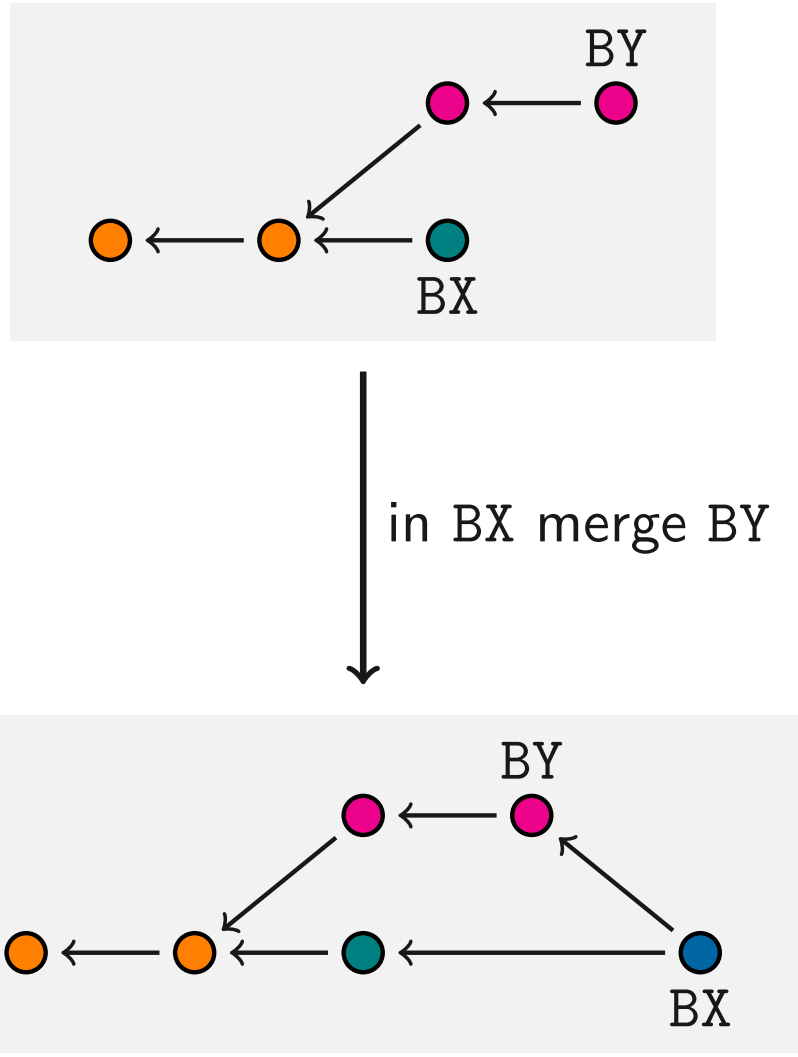
History

1. From an existing branch BX (with orange commits) a branch BY added new commits (magenta)
2. We merge BY into BX

FF-Merge

Apply changes of commits in BY starting at BX until you get to BY. Or BX just needs to "catch up" to BY. No new commits are created.

Solving the Problem: 3-Way-Merge I



History

1. Branches BX and BY have new commits (magenta and green resp.) and share a common history (orange)
2. We merge BY into BX

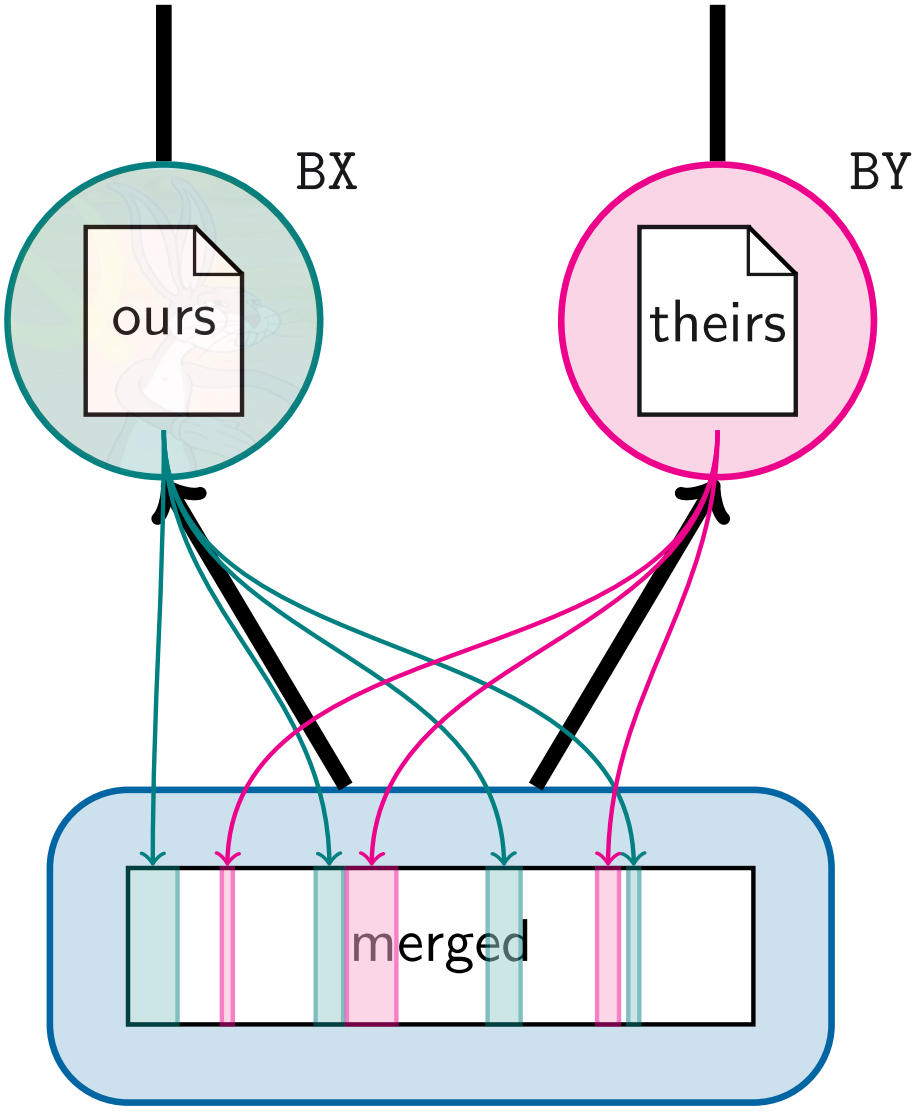
Observations

When you merge you are in BX importing changes from BY

- "our" changes are from BX
- "their" changes are from BY

Need to make choices, which get saved in a new merge commit.

Solving the Problem: 3-Way-Merge II



Merge BY into BX

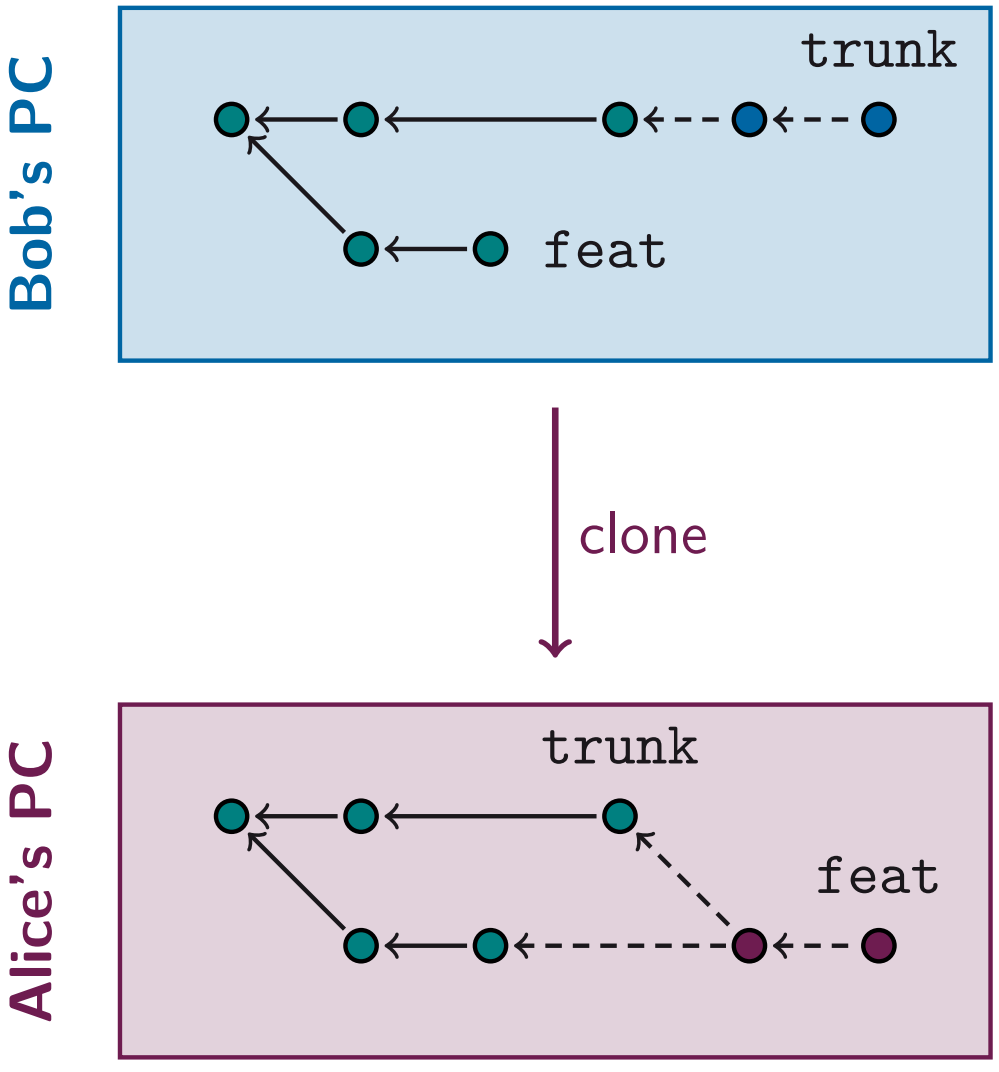
3-Way-Merge

- Use a (3-way-merge) algorithm to merge trees and blobs from each commit
- If not possible the user has to choose between 'our' changes and 'their' changes

Merge Conflict

When the algorithm cannot merge the file automatically it is called *merge conflict*.

Solving the Problem: Multiple Computers I



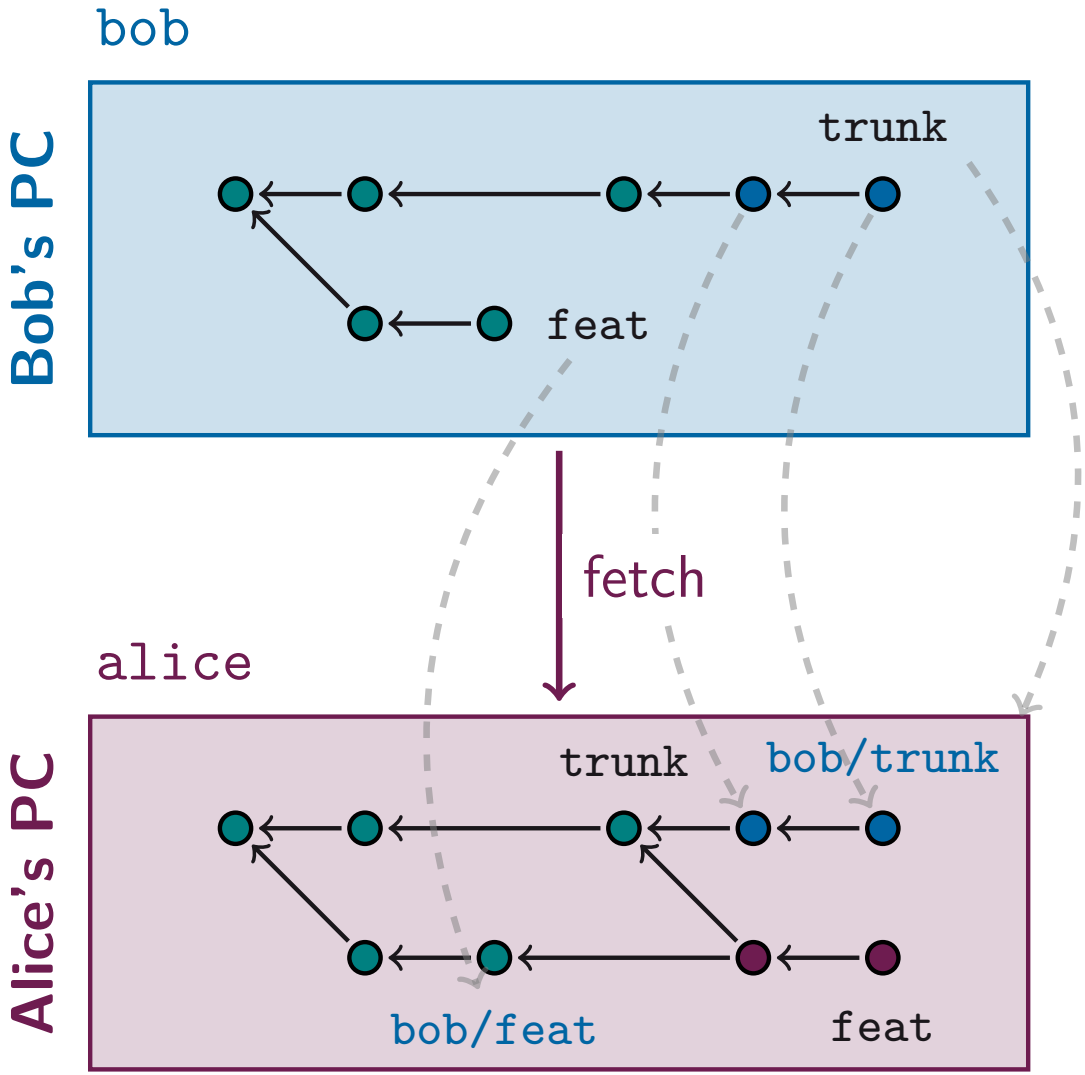
Remotes and Clone

Other computers are called *remotes*. Clone means you copy the commit graph on the remote machine onto yours.

Example

1. Alice has cloned Bob's (green) commit graph
2. Alice has merged `trunk` onto `feat` and made changes
3. Bob has also made changes on `trunk`

Solving the Problem: Multiple Computers II



Fetch

Copy the changes of the remote git graph into your local git graph.

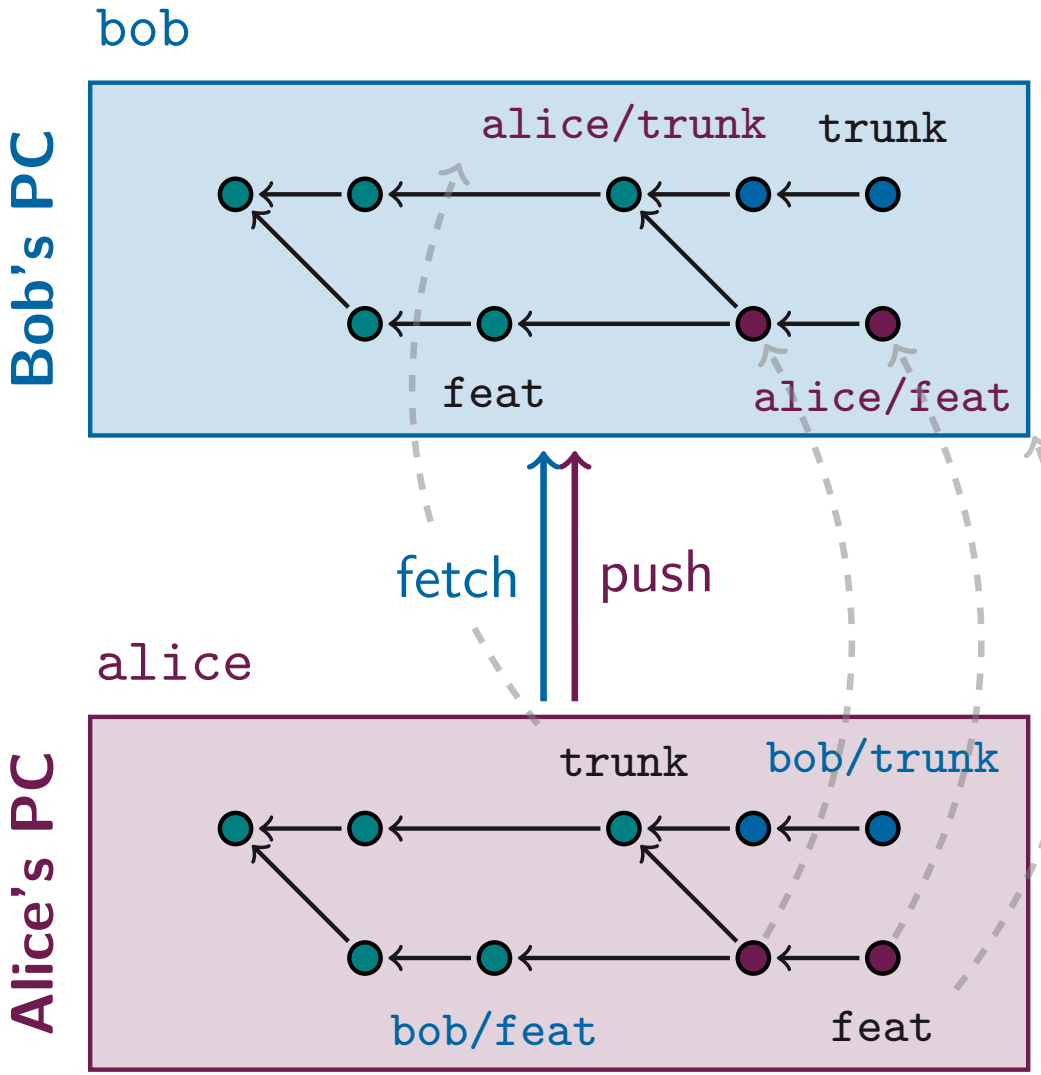
Running Example

Alice fetches Bob's changes.

Remote Branches

A branch that represents changes done in another machine. When a graph is cloned, the machine from which it was cloned has the default name `origin`.

Solving the Problem: Multiple Computers III



Push

Copy the changes of your local git graph to the remote machine.

Running Example

This is the same as if Bob had fetched Alice's changes.

Network Access

In practice you cannot directly access other people's machines, so people use a third computer to which both parties have access (more later).

Solving the Problem: Multiple Computers IV

$$\text{pull} = \text{fetch} + \text{merge}$$

Table of Contents

Mathematical Digression: Hashes and Merkle DAG

"One-way fast" functions

Hash Function

A (cryptographic) *hash* function is an $h : \Omega \to \{0,1\}^d$ for a fixed hash length d such that:

1. Given $y = h(x)$ it is hard to find x
2. It is hard to find $x, y \in \Omega$ s.t. $h(x) = h(y)$
3. Given $h(x)$ it is hard to find y s.t. $h(x) = h(y)$
4. Given $h(x)$ and a function f it is hard to find $h(f(x))$

Hashes are *not* unique!

Merkle DAG

A Merkle DAG is a DAG $G = (V, A)$ with a hash

$$h : V \times \{0,1\}^d \to \{0,1\}^d$$

that defines a label function

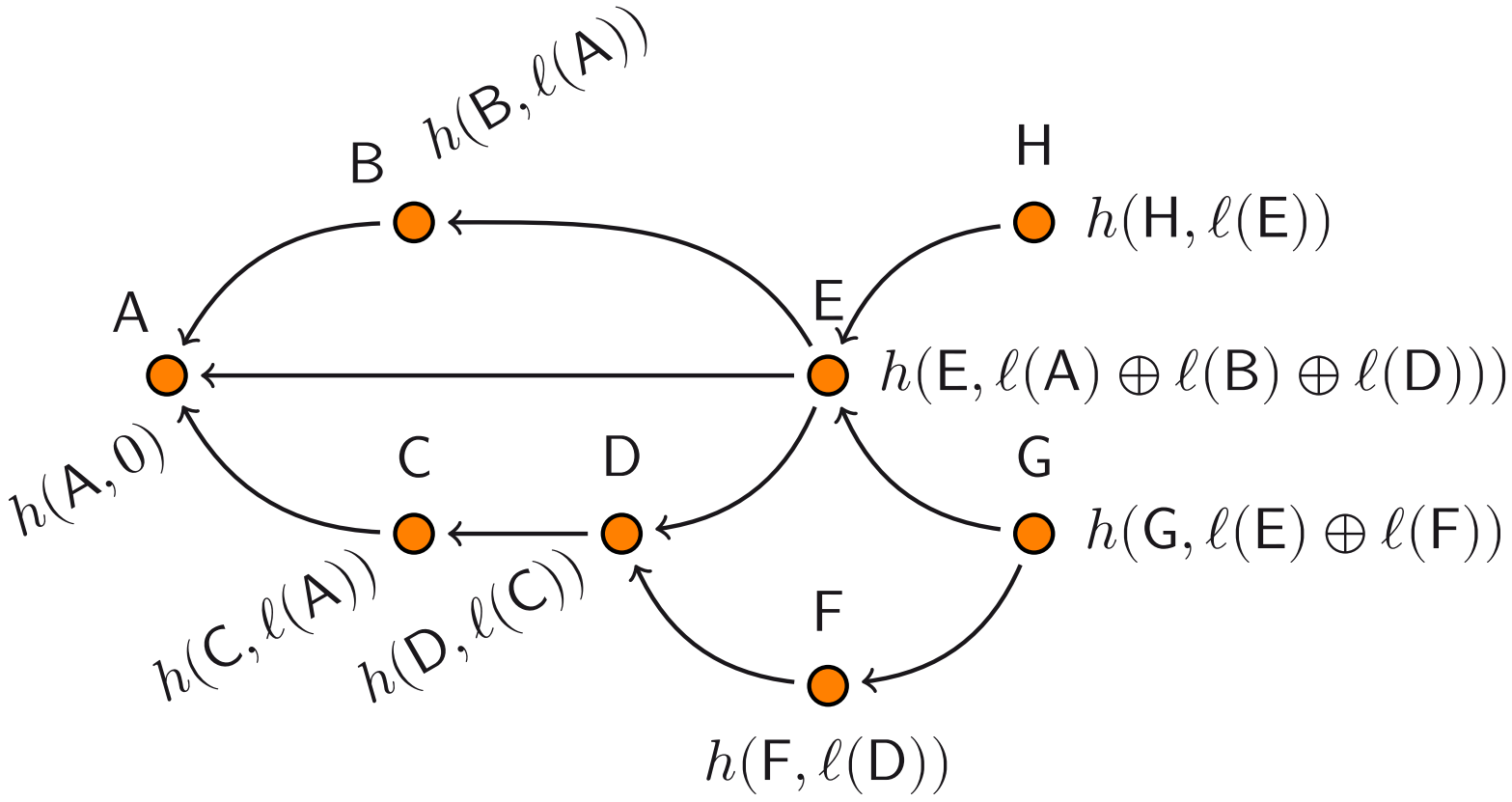
$$\ell(v) = h\left(v, \sum_{u \in \mathrm{n}^+(v)} \ell(u)\right)$$

Properties

- Immutable data structure
- Cryptographic verification

Mathematical Digression: Visualizing Merkle DAGs

To compute the label of a node, you need to first compute the label of all nodes on which it depends. Changing a label has a cascading effect on descendents.



Technicality: Sum symbol represents hash concatenation.

Git Commits

Commit Contents

- Content (Blobs and Trees) hash
- Parent(s) commit(s) hash(es)
- Metadata: Author, Date, Message

Example

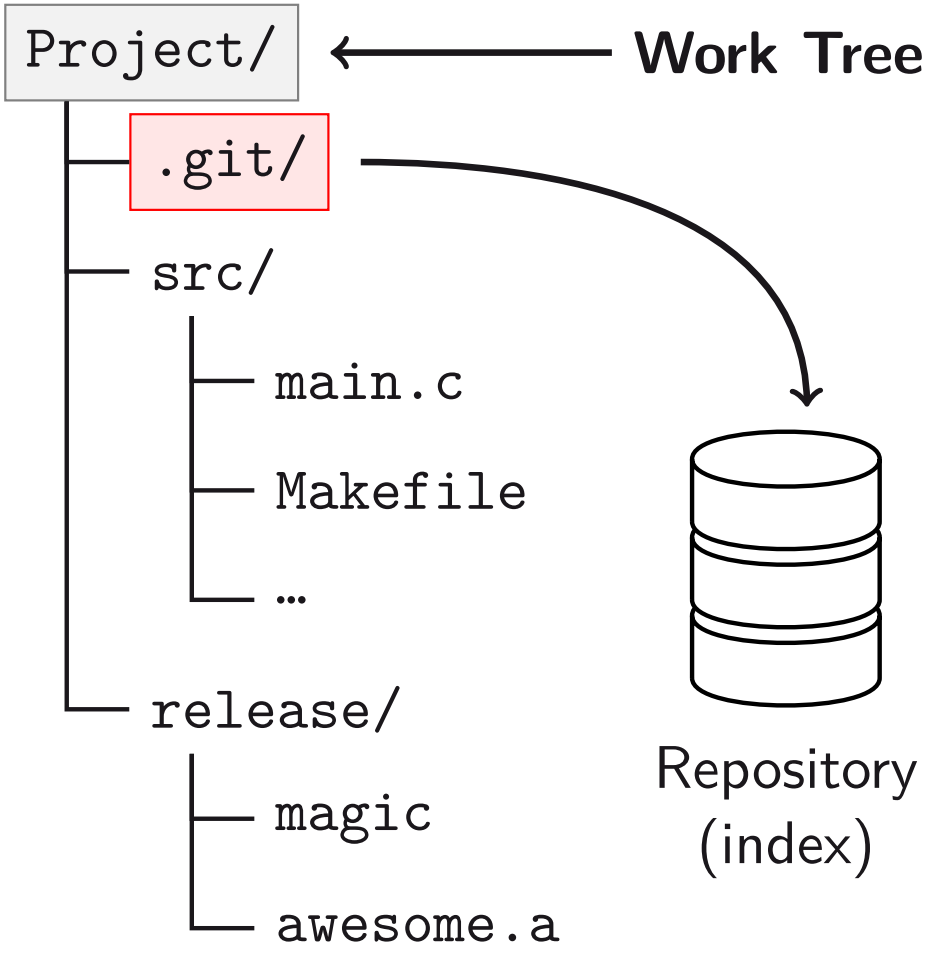
```
commit 1cfdf5c198f1c74c2f894067baf4670f5bca8e70
Author: Nao Pross <np@0hm.ch>
Date:   Wed Feb 9 19:53:06 2022 +0100

  Fix arrayobject.h path on Debian based distros

  On Debian Linux and its derivatives such as Ubuntu and LinuxMint, Python
  packages installed through the package manager are kept in a different
  non-standard directory called 'dist-packages' instead of the normal
  'site-packages' [1].

  To detect the Linux distribution the 'platform' library (part of the
  Python stdlib) provides a function 'platform.freedesktop_os_release()'
```

Git Repositories



Work Tree

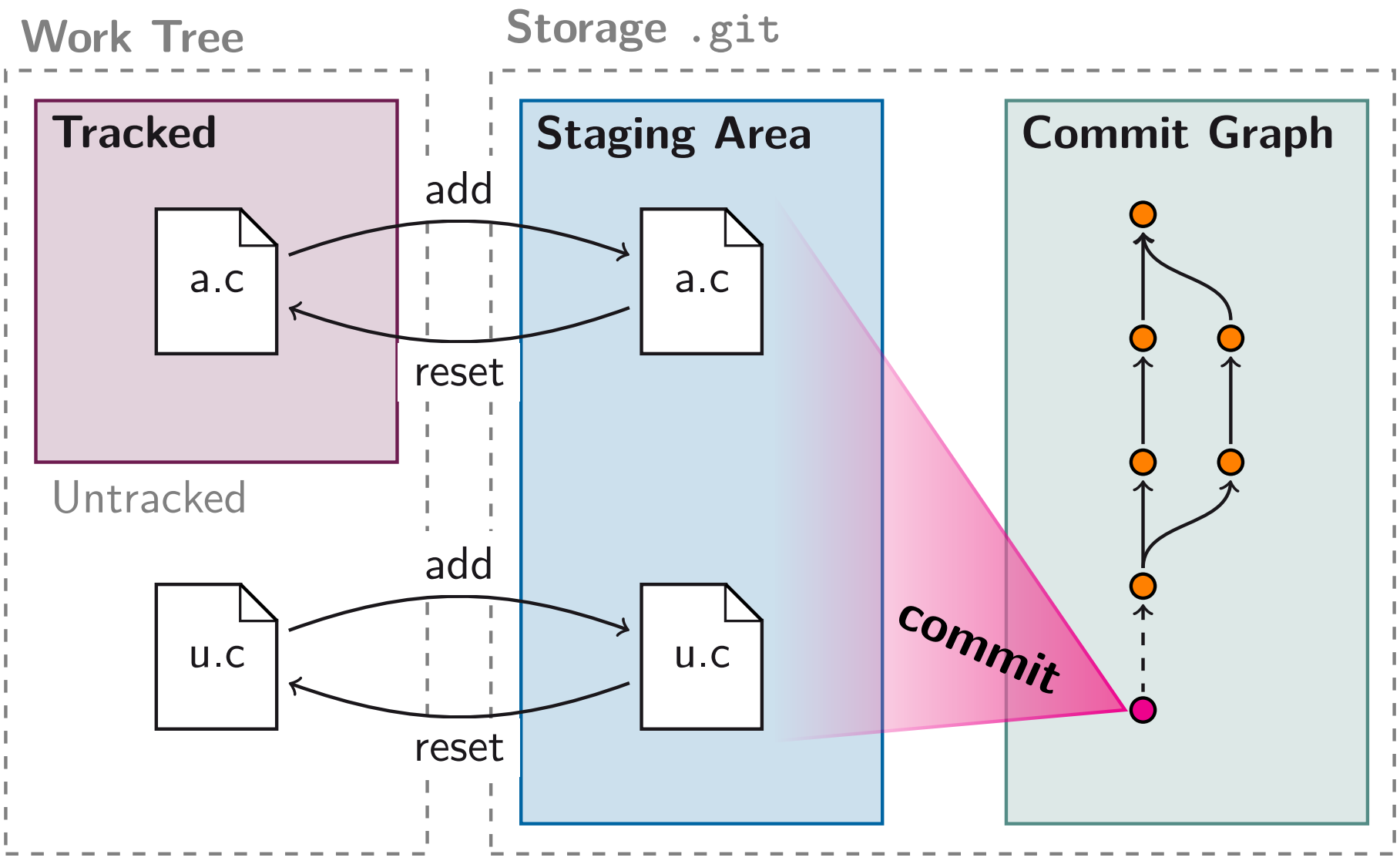
Root of your project, contains (hidden) `.git`.
Never delete `.git`.

Repository

- Commit graph (Blobs, ...)
- Staging Area (will come next)

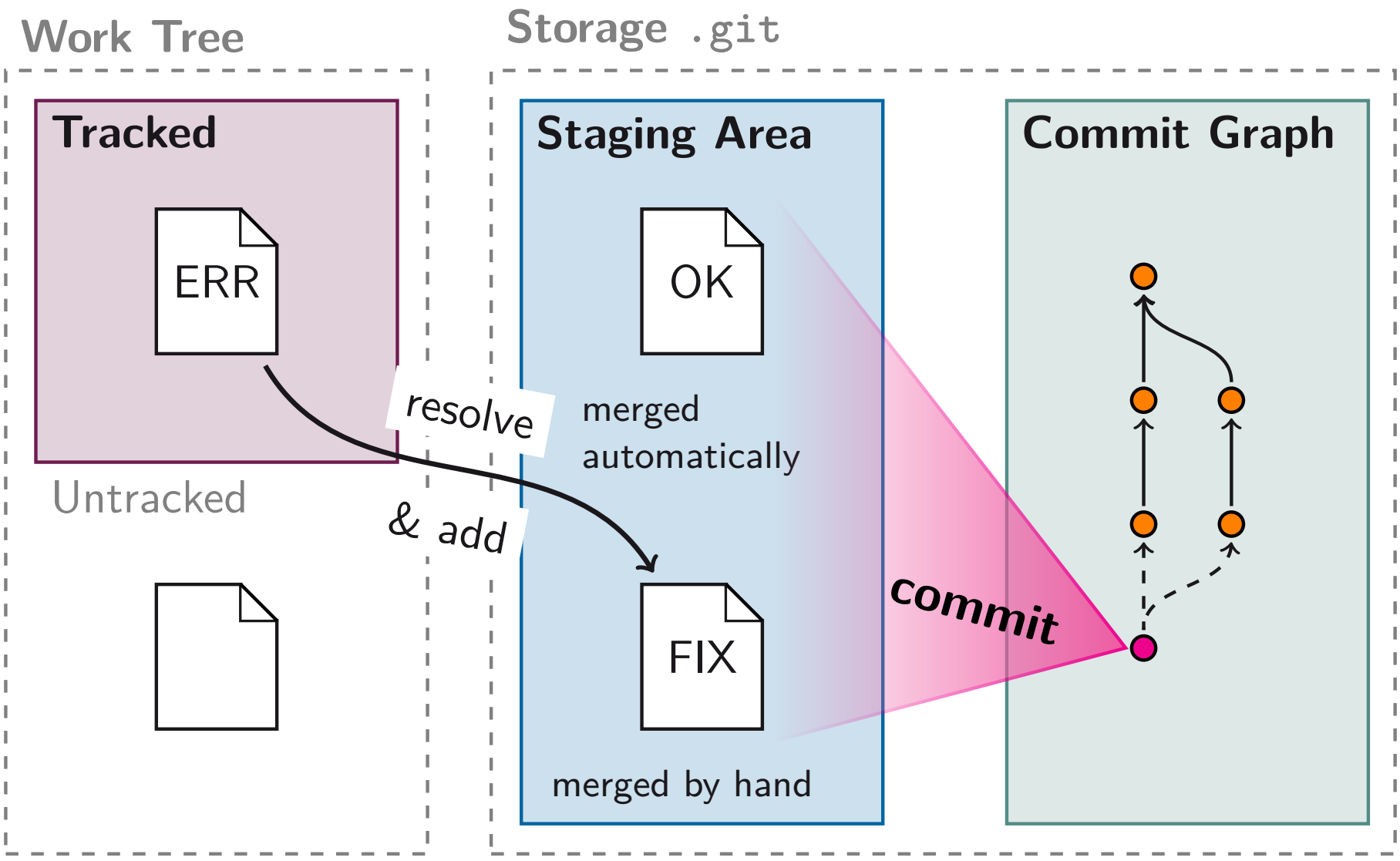
Table of Contents

The 3 (or 4) Conceptual Areas of Git



Branches, Remotes and your HEAD

Auomatic Merge Failed (Conflicts)



Restoring Changes from the Past

Graphical User Interfaces

Command Line Interface

If you learn to use Git on the terminal you are set forever, but

- you have to think (tip: use `git status`!)

Graphical Interfaces

A good GUI that does not hide complexity

- Sublime Merge

Alternatives

- SourceTree, GitKraken
- TortoiseGit (integrates with Windows Explorer)

Bad GUI (why? It tries to hide complexity until you inevitabily screw up something, and then you have no clue what is going on)

- GitHub Desktop

More at `https://git-scm.com/downloads/guis`

What is a Commit Anyways?

Trunk, Feature Branches

Releases and Tags

Git Services (GitHub, GitLab, ...)

Forking Projects

Forking and Pull / Merge Requests

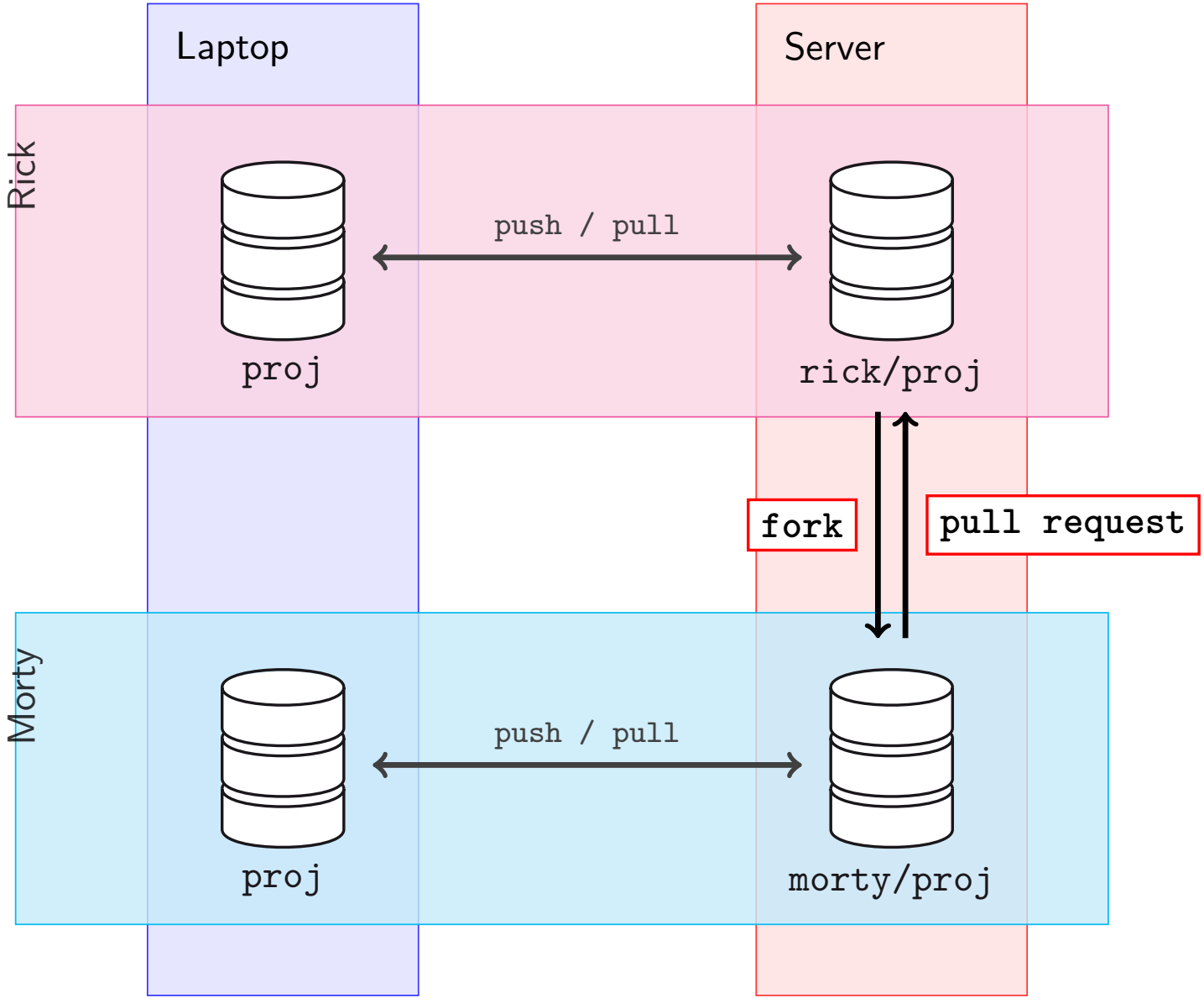
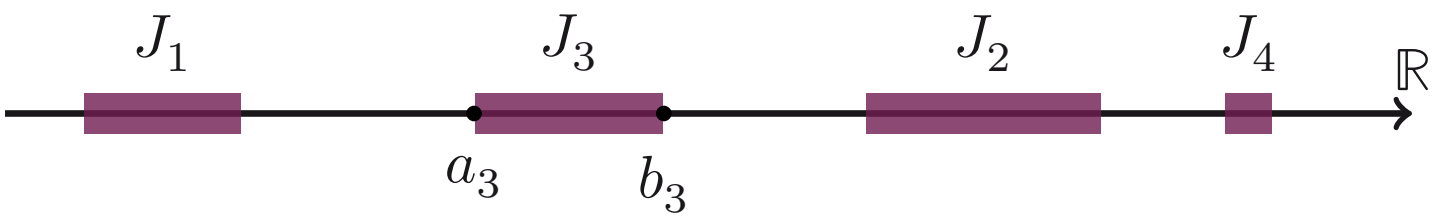


Table of Contents

Mathematical Digression: Logarithmic Search I



Toy Problem

Given a set of disjoint intervals $S = \{J_1, \ldots, J_n\}$, $J_i \subset \mathbb{R}$, $\log_2(n) \in \mathbb{N}$ find to which interval belongs $q \in \bigcup_i J_i$.

Naive Solution

For every $J \in S$ interval check if $q \in J$. This is $O(n)$.

Total Order in S

Intervals $[a, b) \in S$ can be ordered. Define $J_i \succ J_j$ if $a_i > a_j$.

Logarithmic Search Intuition

If $q \notin J = [a, b)$ then either

- $q > a$ so $q \in J' \succ J$
- $q < a$ and $q \in J' \prec J$

Mathematical Digression: Logarithmic Search II

Logarithmic Search Intuition

If $q \notin J = [a, b)$ then either

- $q > a$ so $q \in J' \succ J$
- $q < a$ and $q \in J' \prec J$

Idea

Recursively apply intuition.

Complexity (Landau)

Base b logarithmic search is $O(\log_b(n))$. In this case $b = 2$ (two options $q > a$ or $q < a$), so it usually called *binary* search.

Logarithmic Search

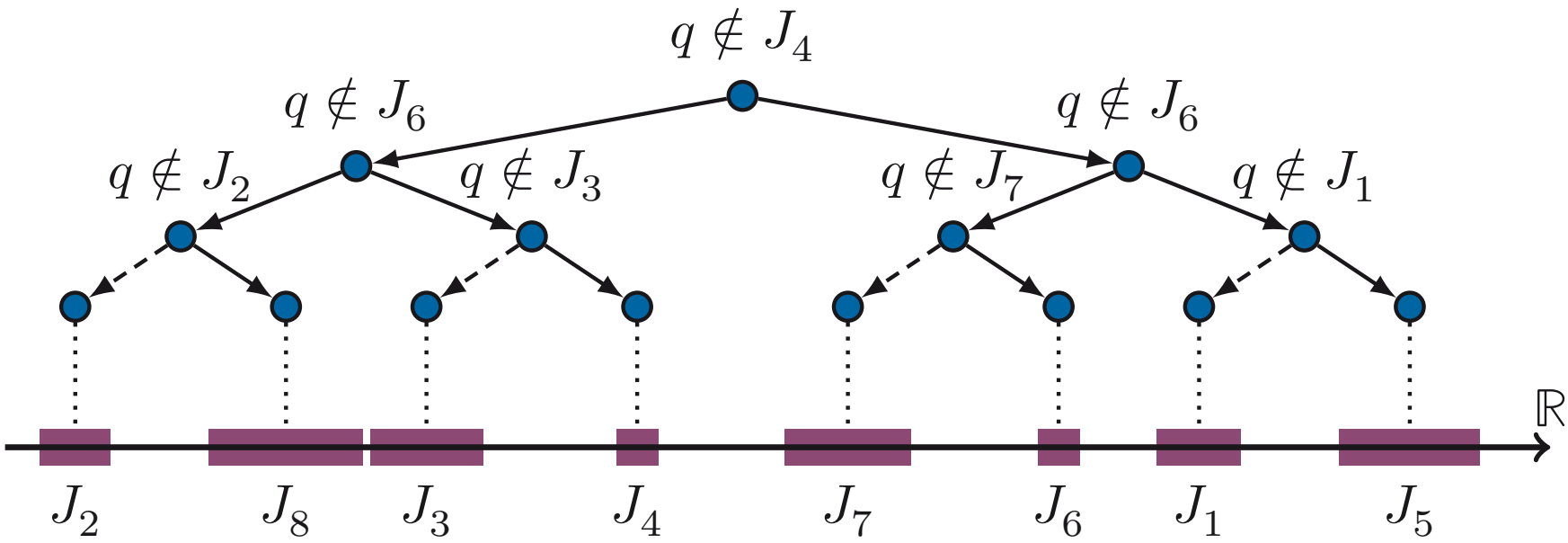
Start with $Q = S$ then

1. take $J \in Q$ in the "middle" of Q and if $q \in Q$ we are done
2. otherwise
   1. if $q > a$ repeat with $Q := \{J' \in Q : J' \succ J\}$
   2. if $q < a$ repeat with $Q := \{J' \in Q : J' \prec J\}$

Does not check every $J \in S$ (fast for large n!).

Mathematical Digression: Logarithmic Search III

We can visualize the decisions of logarithmic searching as a tree. The decision goes to the left or right branch depending on whether $q < a$ or $q > a$ respectively. Obseve that the tree has depth $3 = \log_2(8)$.



Git Bisect Theory

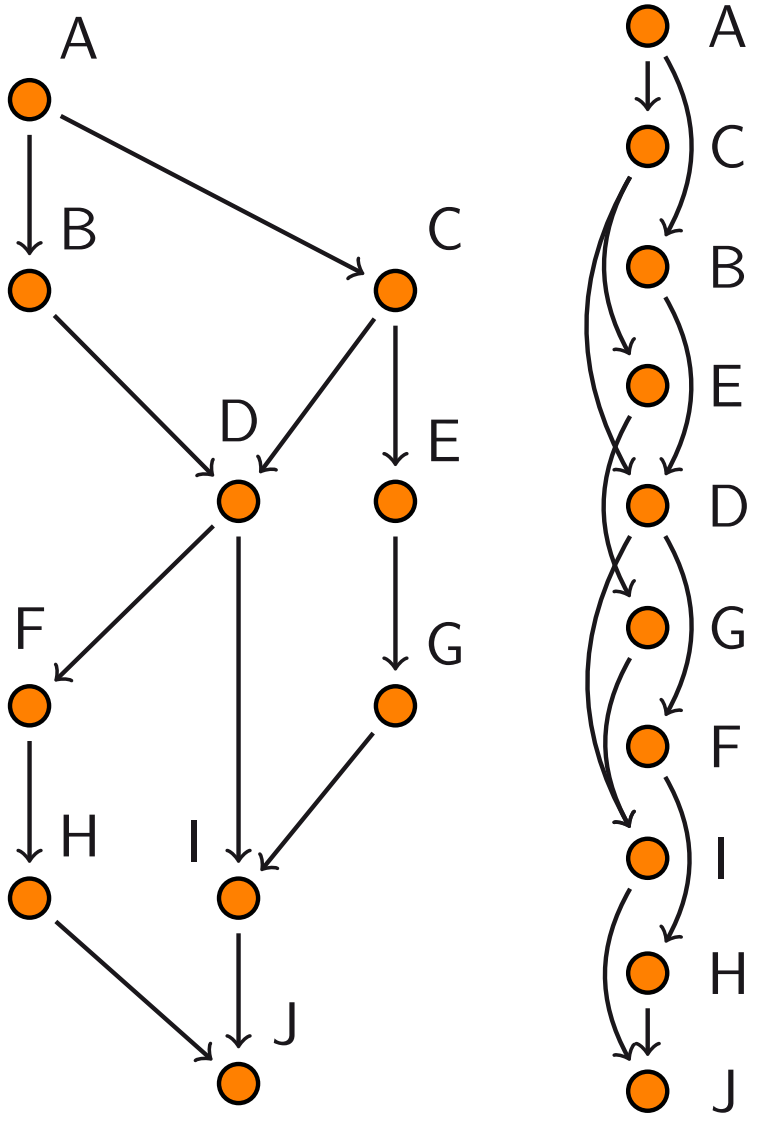
Purpose

You are looking for a commit that caused something, e.g.

- Introduced a bug
- Deleted / added something
- Anything really

Rough Idea

1. Take commit graph $G = (V, A)$ we want to find $\bar{v} \in V$ that did above
2. Topologically sort G, i.e. add order $\succ^*$ to V
3. Logarithmic search $\bar{v}$ in G



Git Bisect Practice

You want to find the commit that did X. Initialization:

1. `git bisect start`
2. `git bisect bad` (current commit is bad, no X)
3. `git bisect good 258dbc1` (commit 258dbc1… was good, has X)

Git will checkout (go back in time to) a commit between the good one and the bad one and you have to say

- `git bisect good`
- `git bisect bad`
- `git bisect skip` (cannot test this commit for X)

Process repeats a few time ($\approx$ log of # of commits between good and bad). If you have a script e.g. `check.py` that returns 0 for good, 125 for skip, any other number for bad, it can be automated

- `git bisect run check.py`

That's (most of) it

Learn More

Git and its ecosystem have many more features

- Stash, Rebase, Blame, ...
- LFS (Large File Storage) for big (gigabytes) files
- Email "old school" workflow (e.g. `sr.ht` and Linux Kernel)
- Integration with CI (e.g. GitHub Actions, GitLab Workers)