Verkle Trees:
Ver(y Short Mer)kle Trees

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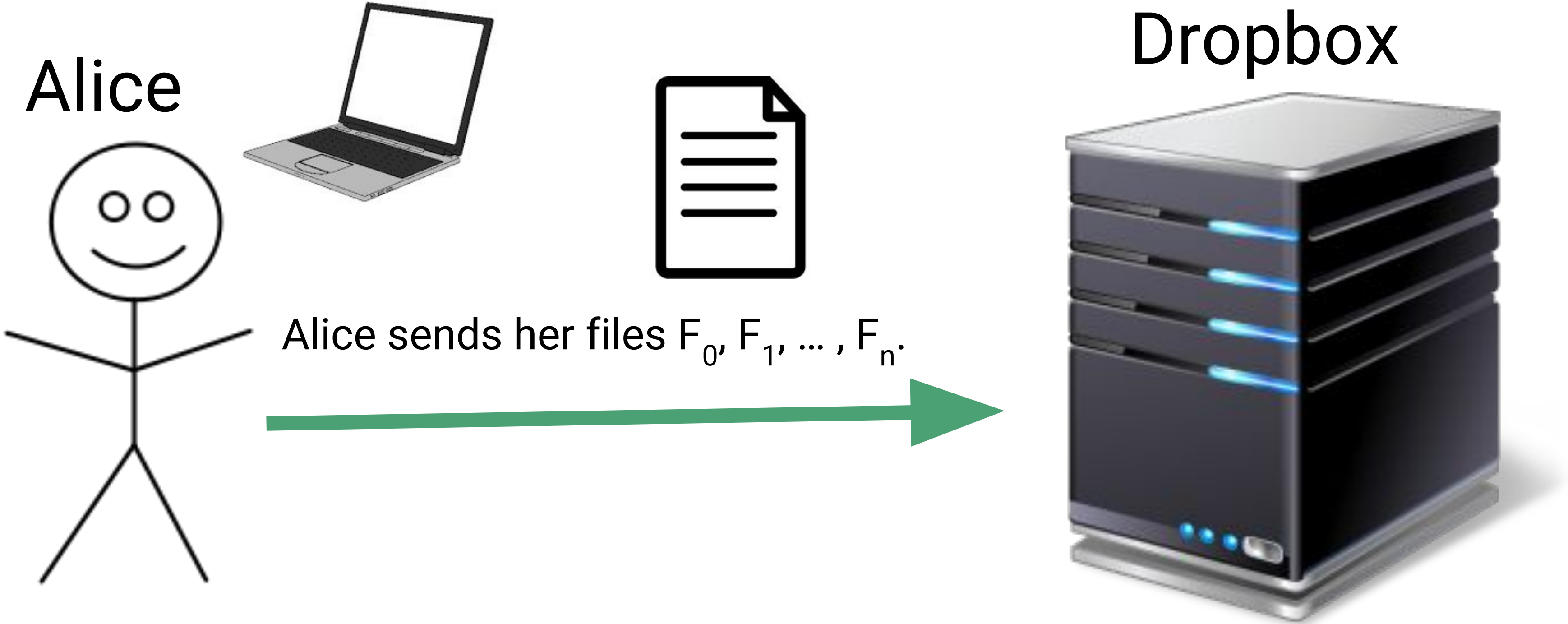
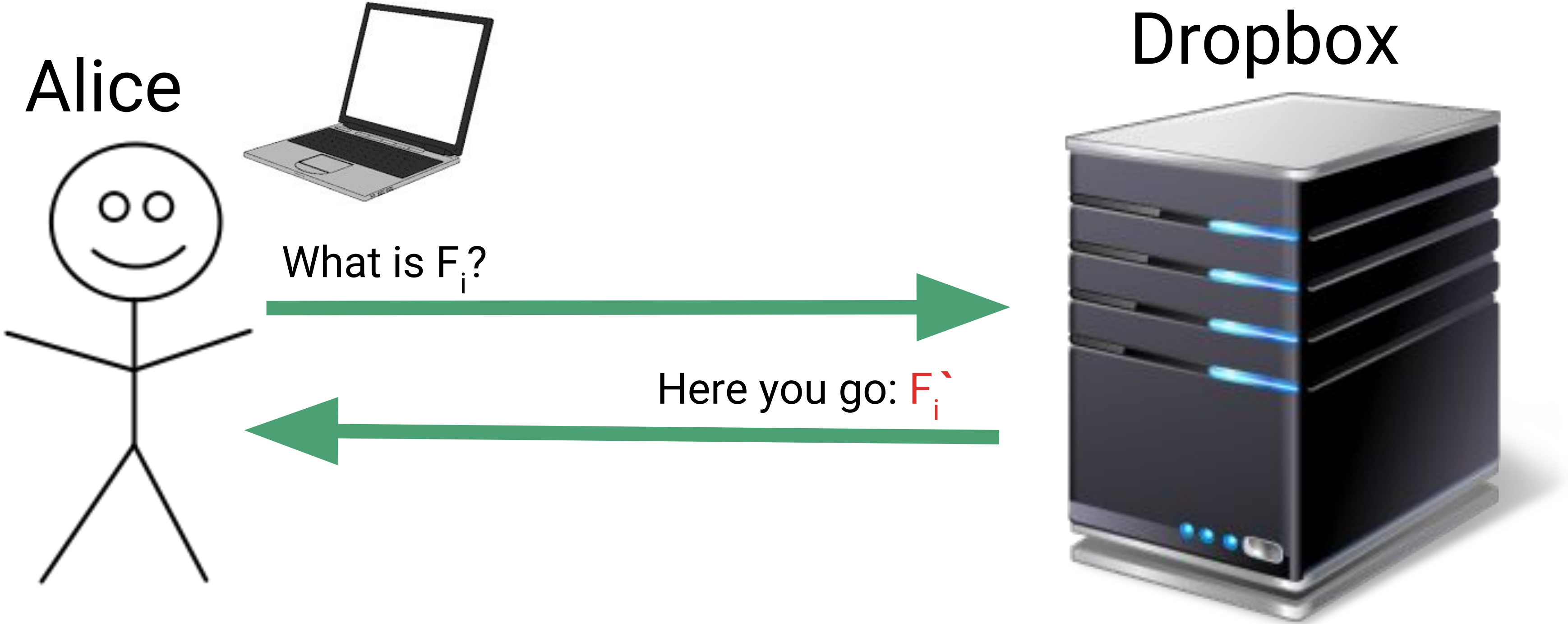
Mentored by Alin Tomescu

PRIMES Computer Science Conference - 10/13/18

Storing Files Remotely

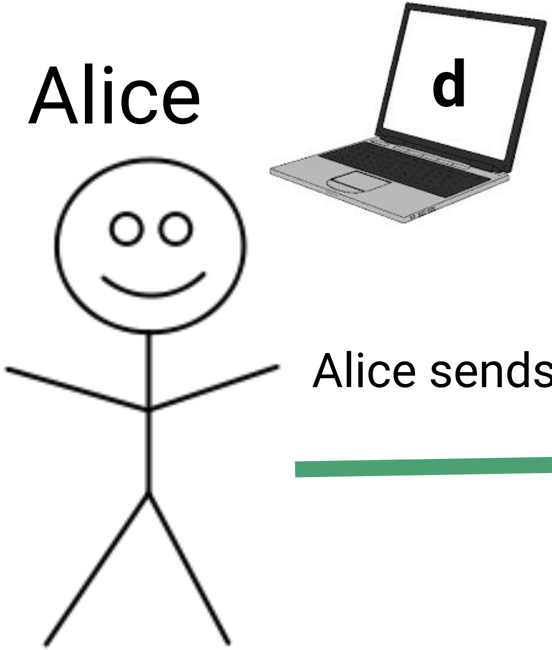


Storing Files Remotely



Proving/Verifying Integrity

Alice

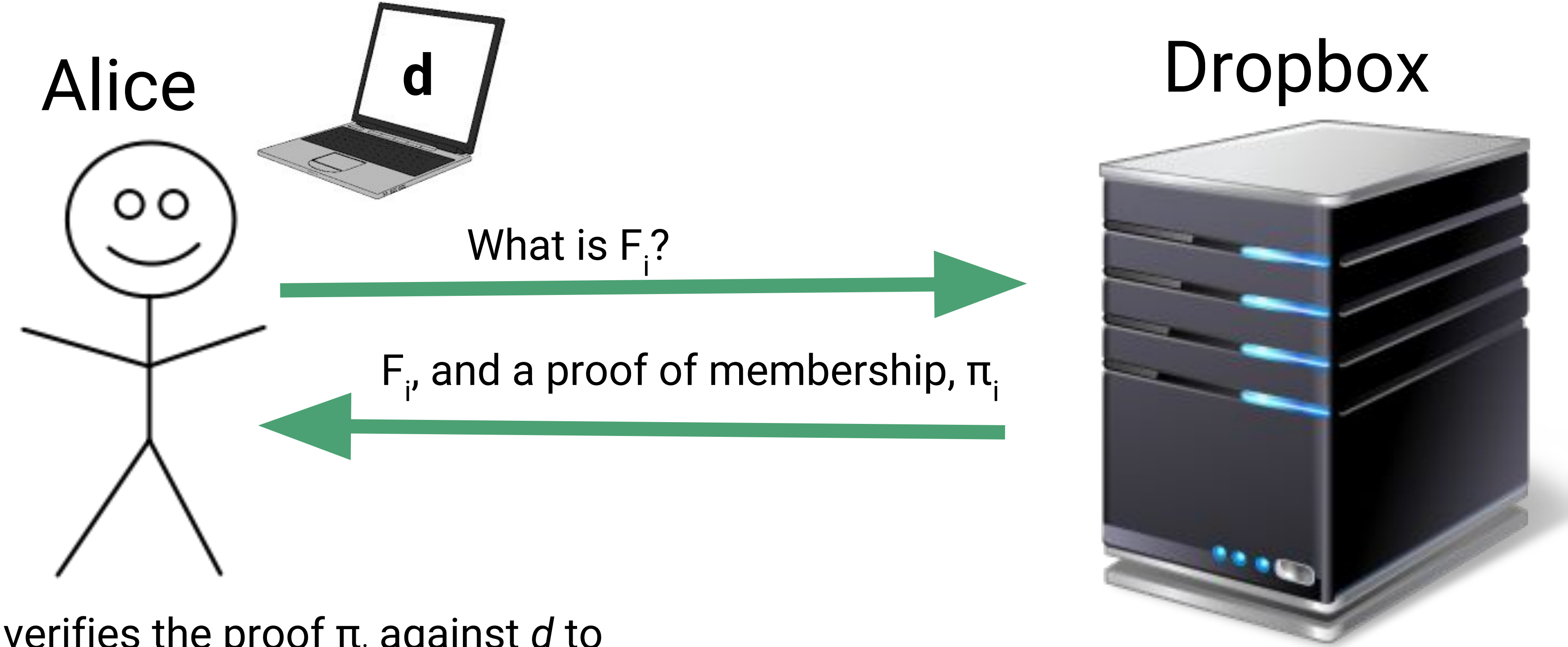


Dropbox

Alice sends her files $F_0, F_1, \dots, F_n$.

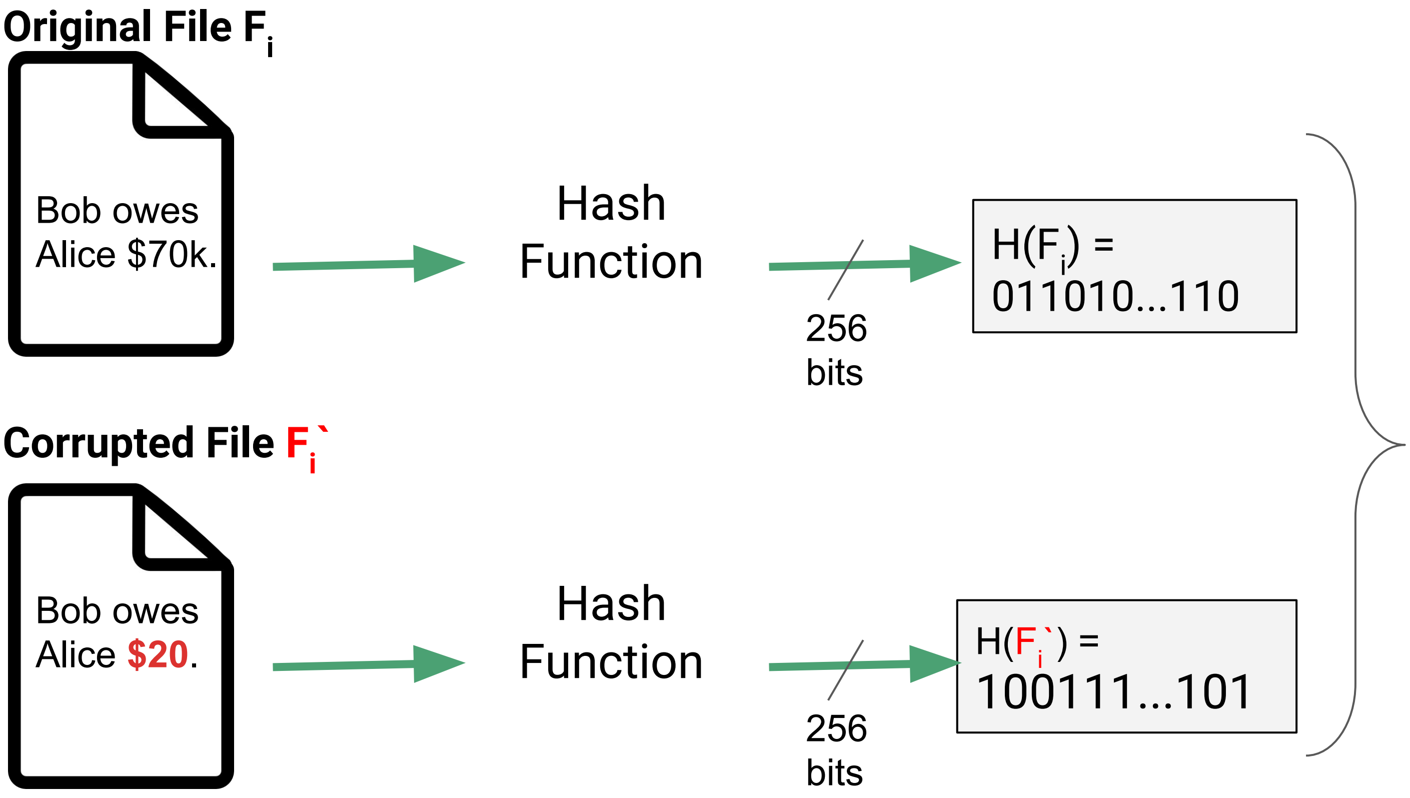
Alice generates a **digest** *d* of her files.

Proving/Verifying Integrity



Alice verifies the proof π_i against *d* to make sure F_i has not been modified.

Secure Hash Functions



Ideally,

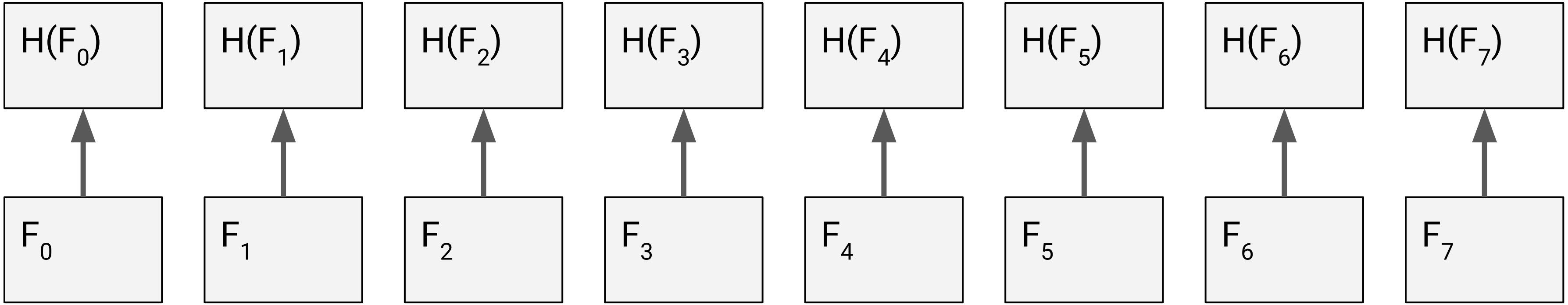
finding any two distinct files, F_1, F_2, s.t.

$H(F_1) = H(F_2)$

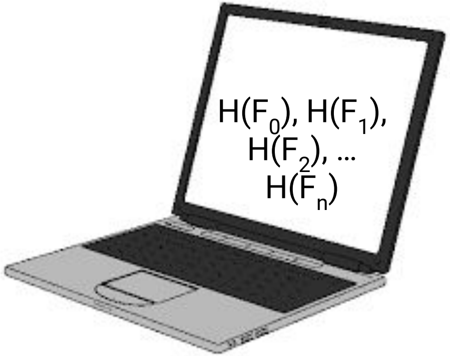
takes 2^{128} attempts.

A Simple Scheme for Verifying File Integrity

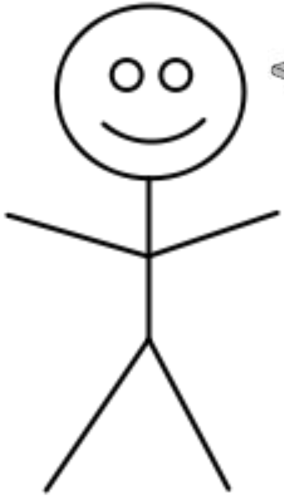
Alice hashes each of her files:



Proving/Verifying Integrity: Simple Scheme



Alice

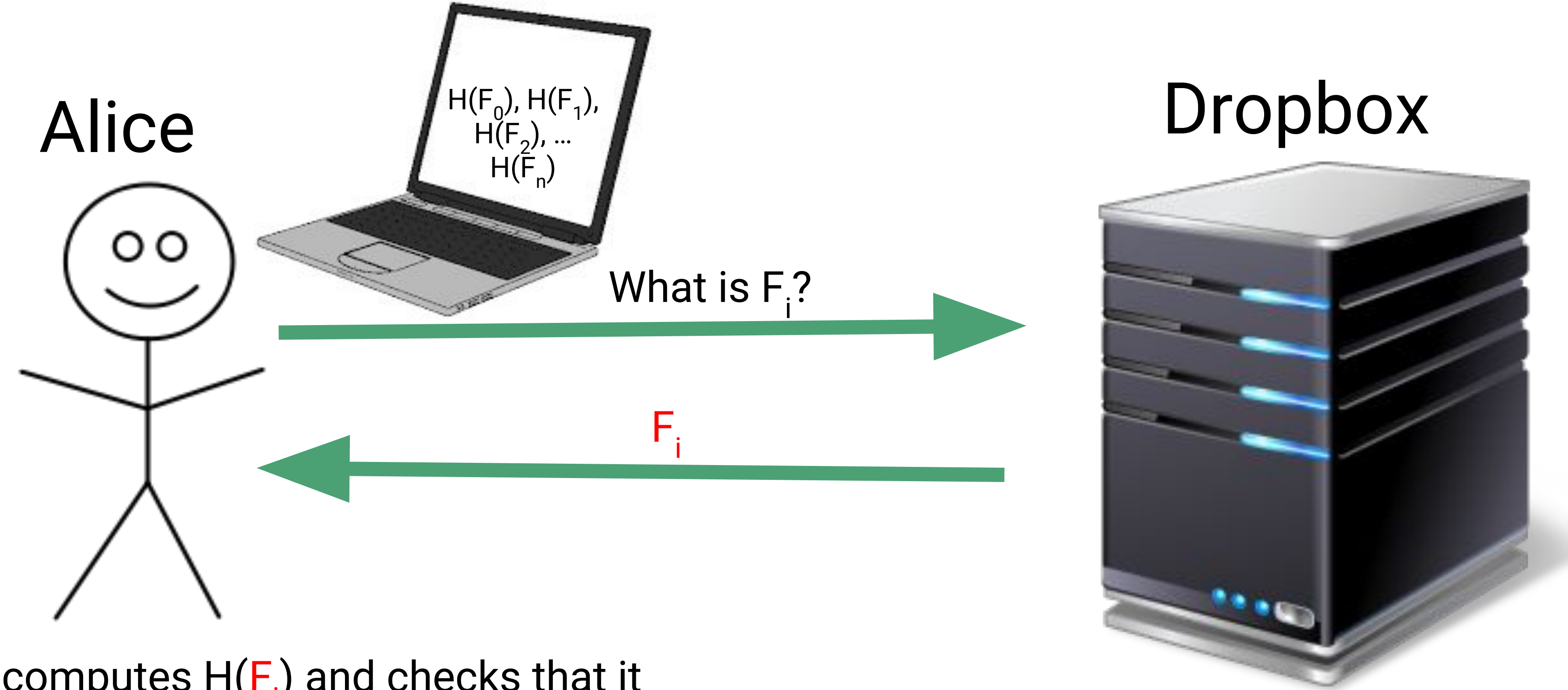


Dropbox

Alice sends her files F_0, F_1, ... , F_n.

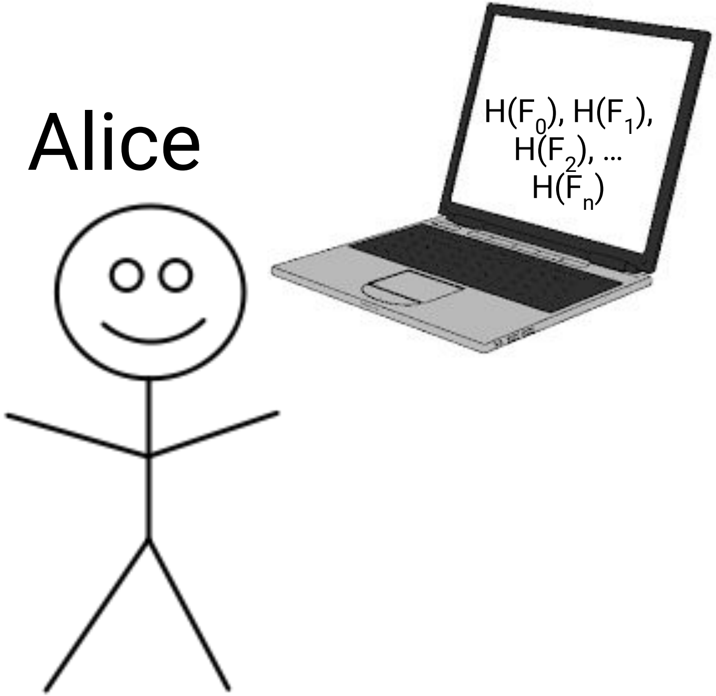
Alice computes and stores the hashes locally.

Proving/Verifying Integrity: Simple Scheme



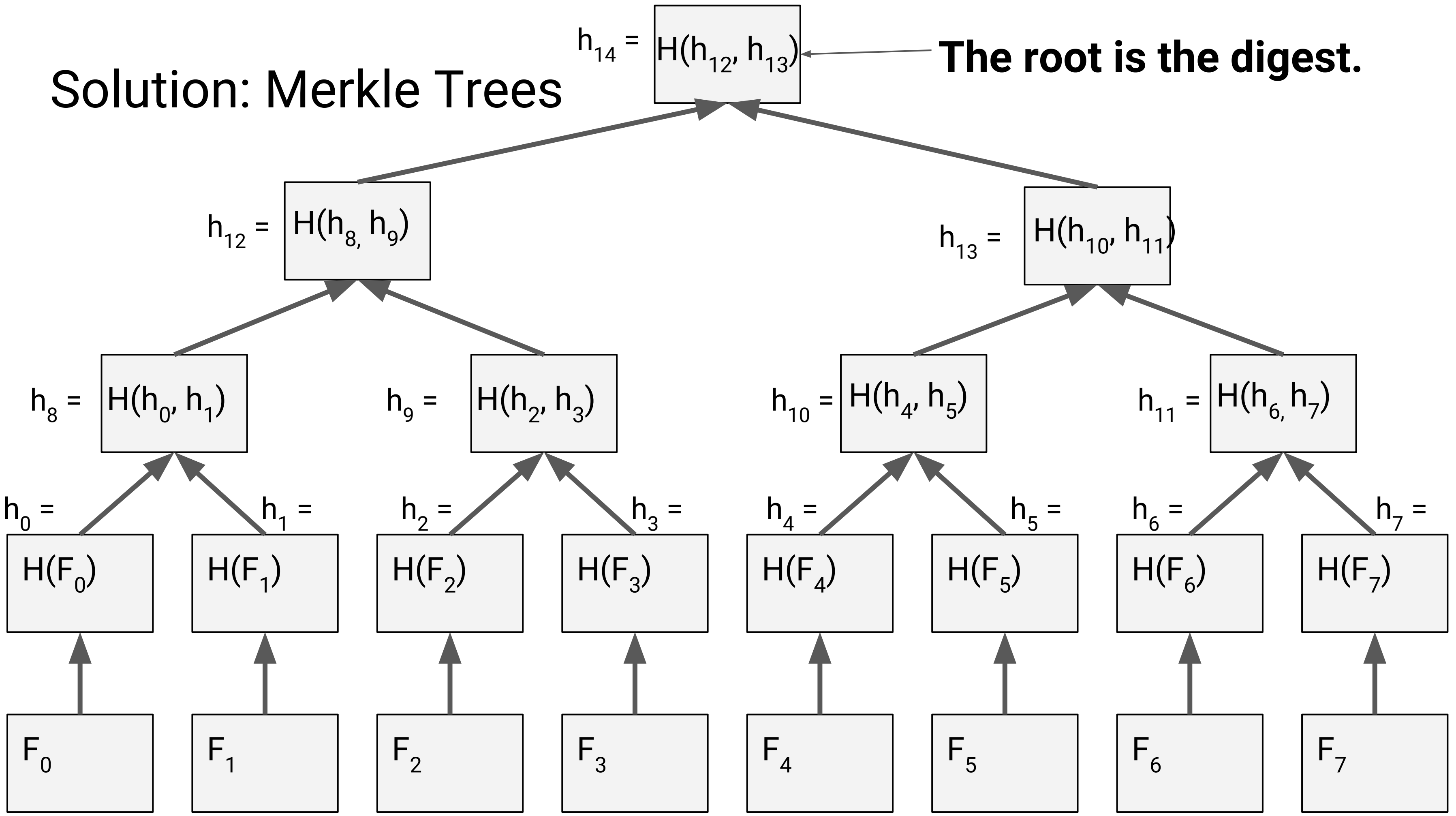
Alice computes $H(F_i)$ and checks that it equals stored $H(F_i)$.

Problem: Alice has to store n hashes.

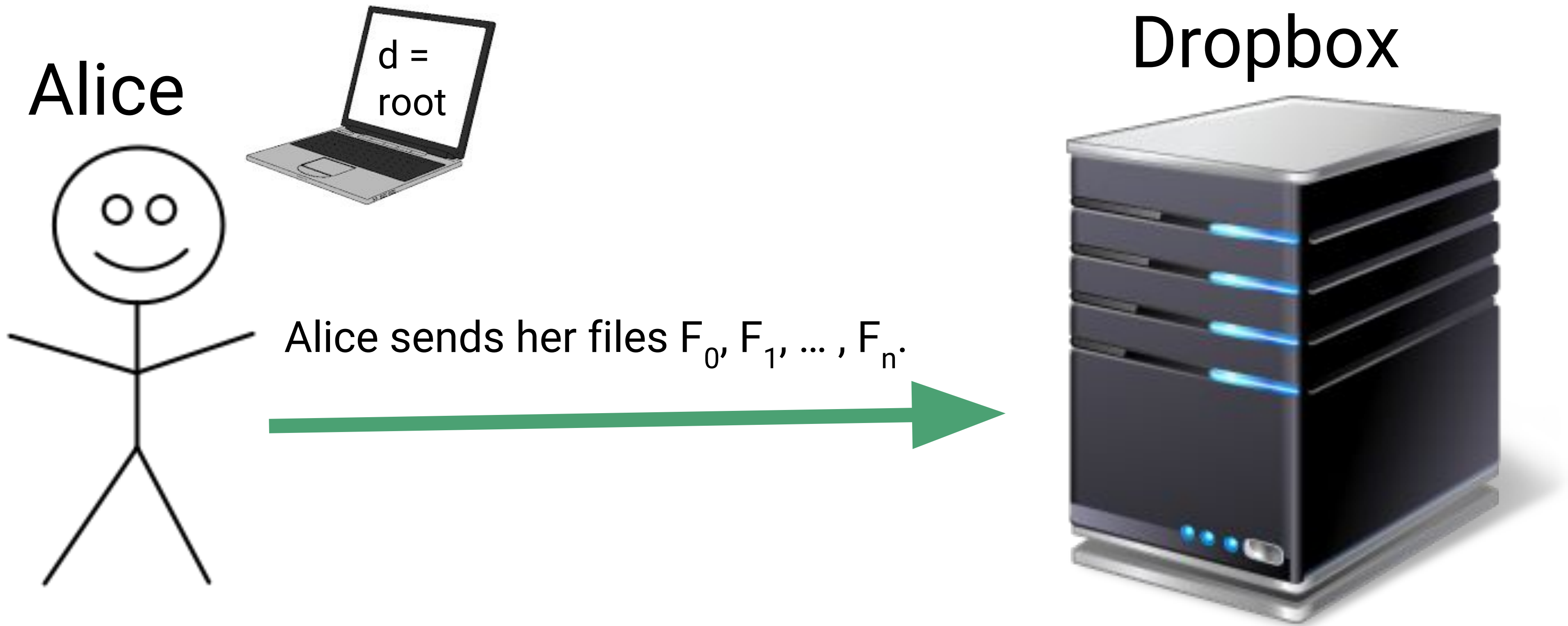


Alice's digest must be constant-sized.

Solution: Merkle Trees

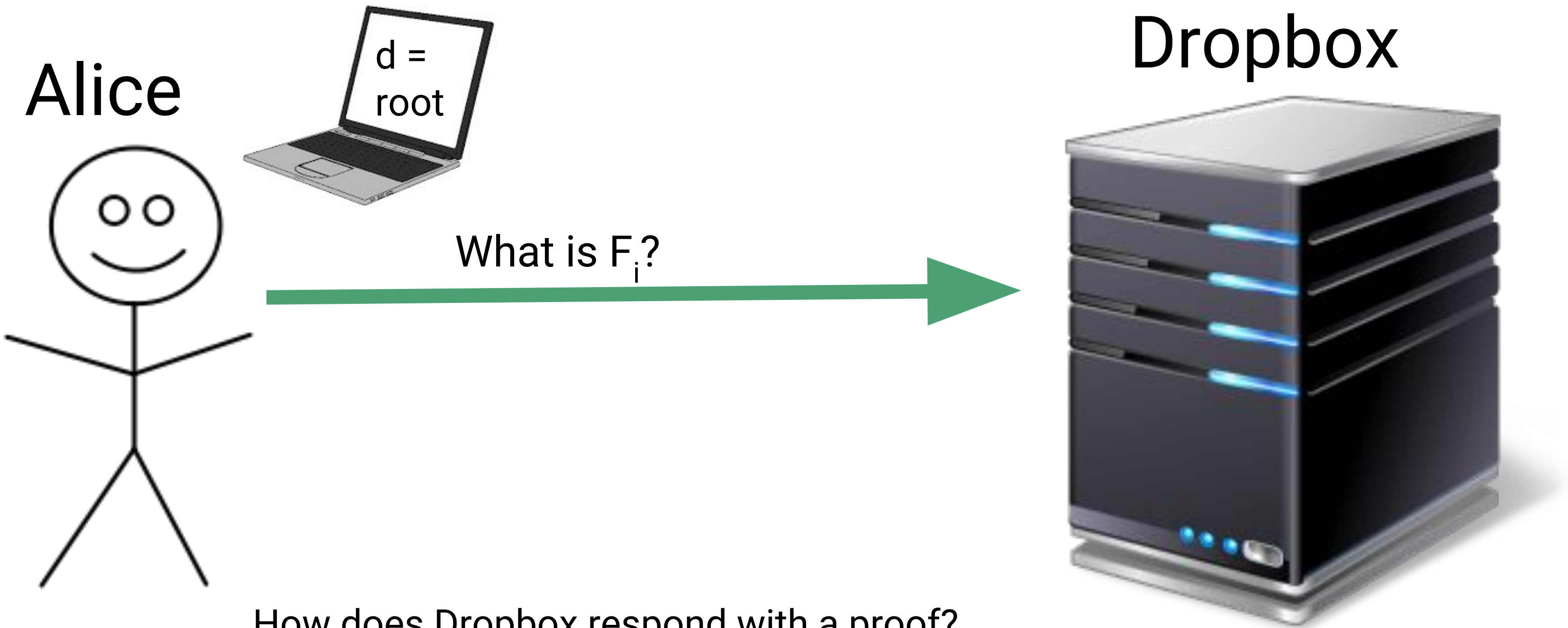


Proving/Verifying Integrity: Merkle Tree



Alice computes the Merkle tree
and stores the root locally.

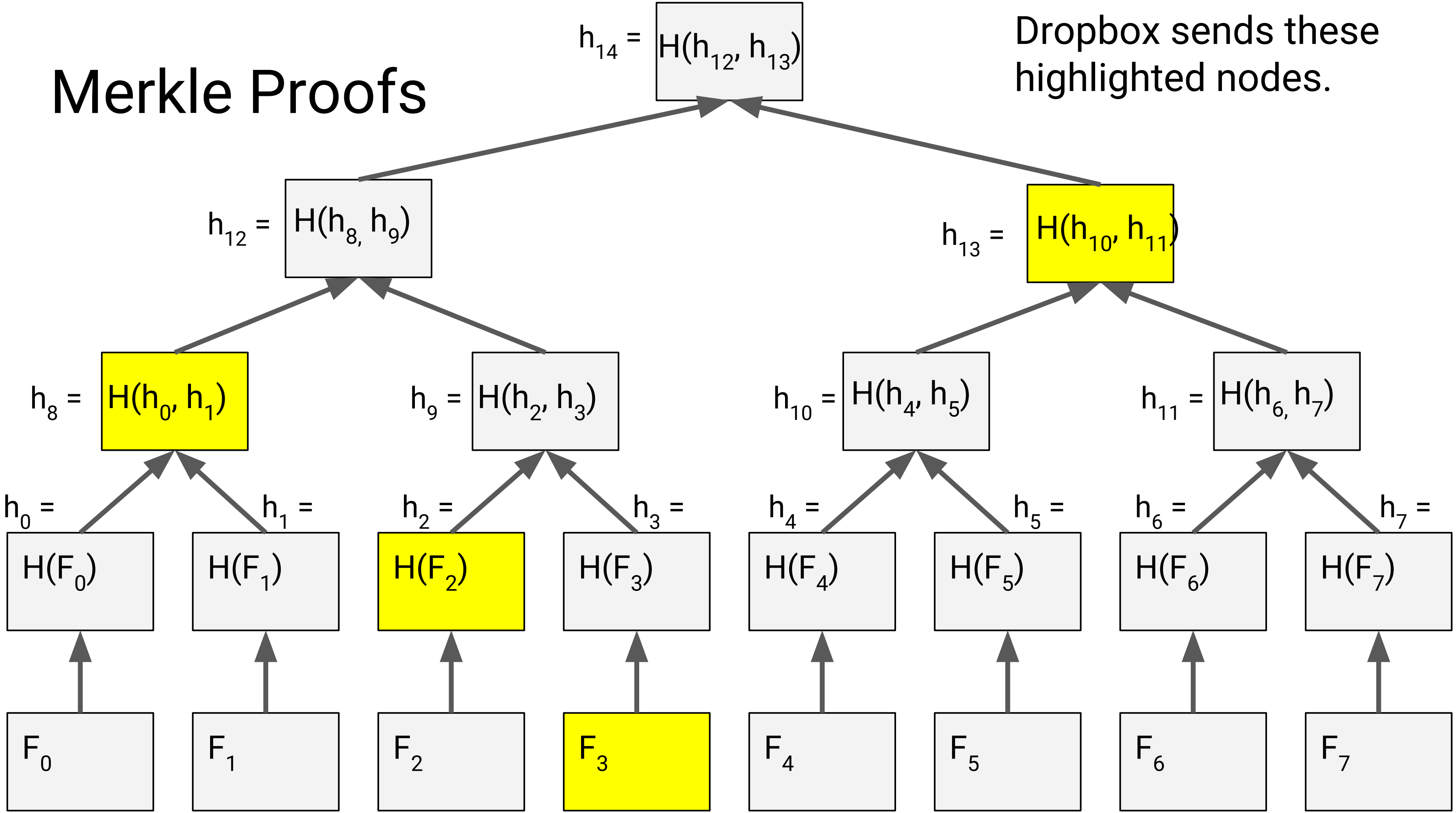
Proving/Verifying Integrity: Merkle Tree



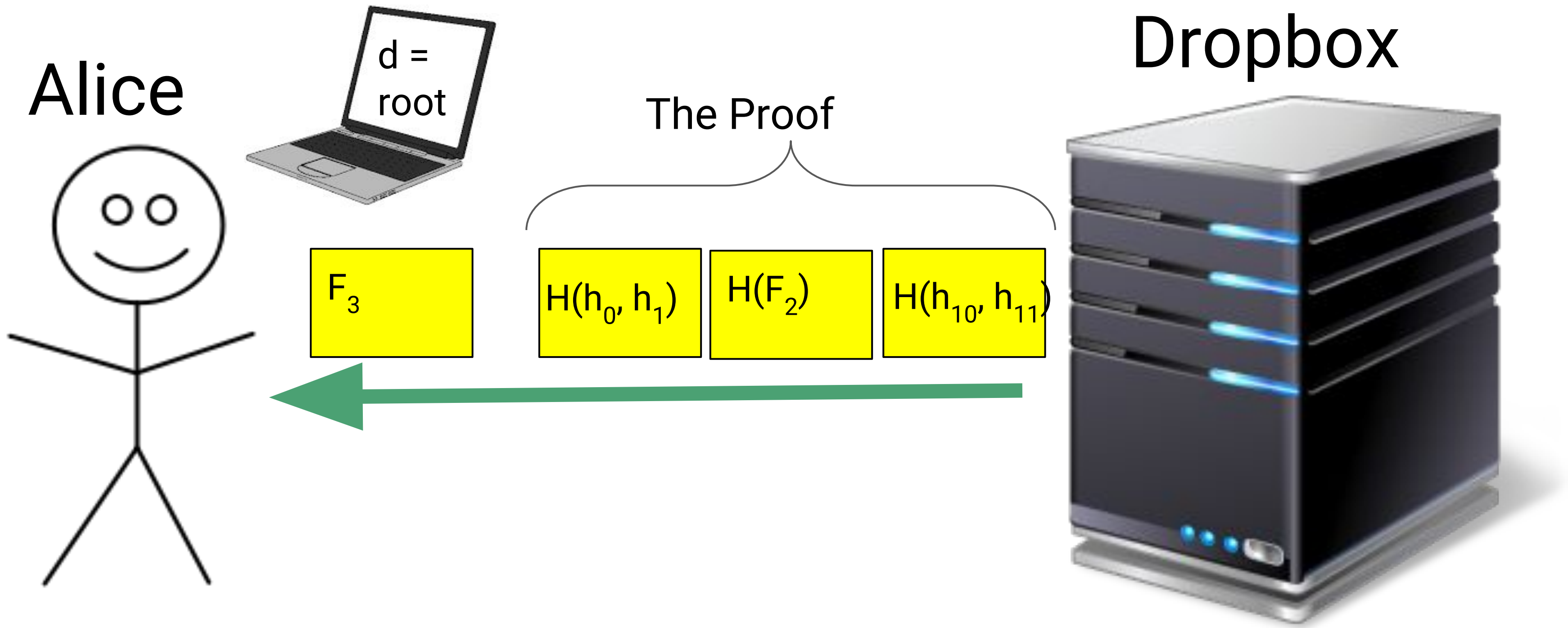
How does Dropbox respond with a proof?

Merkle Proofs

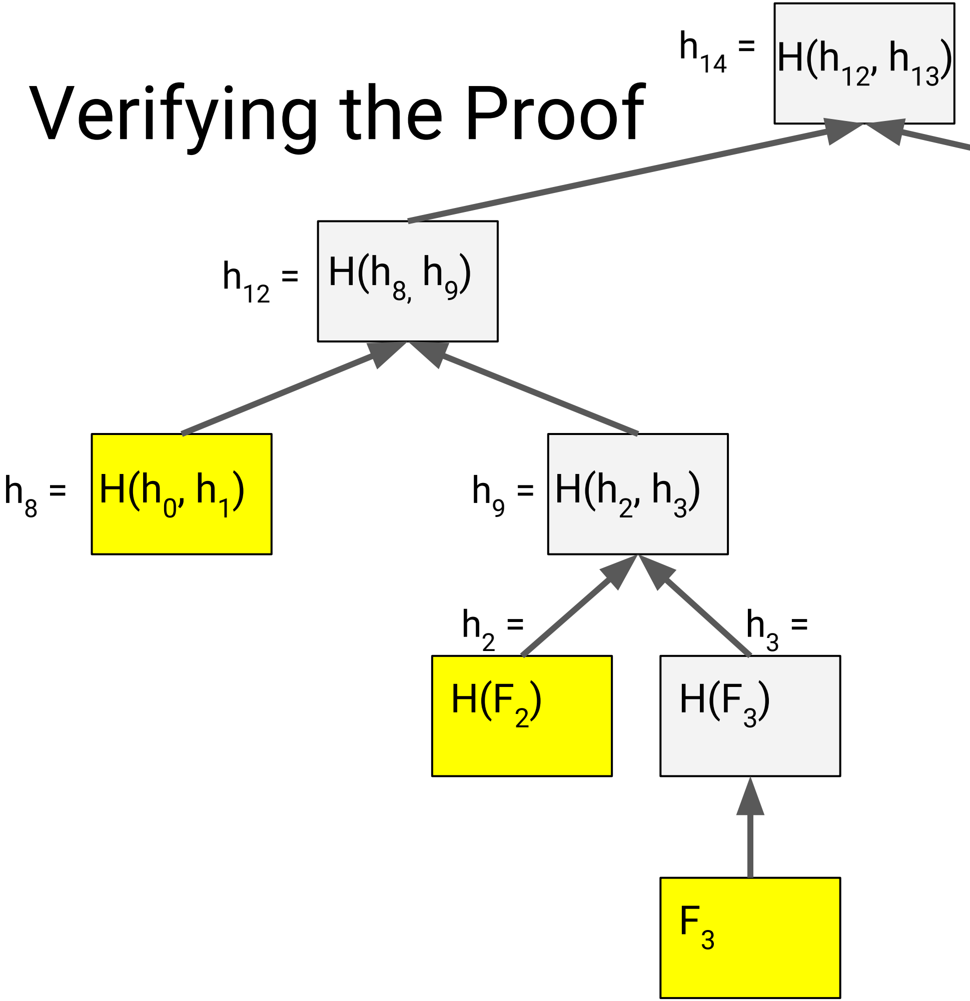
Dropbox sends these highlighted nodes.



Proving/Verifying Integrity: Merkle Tree



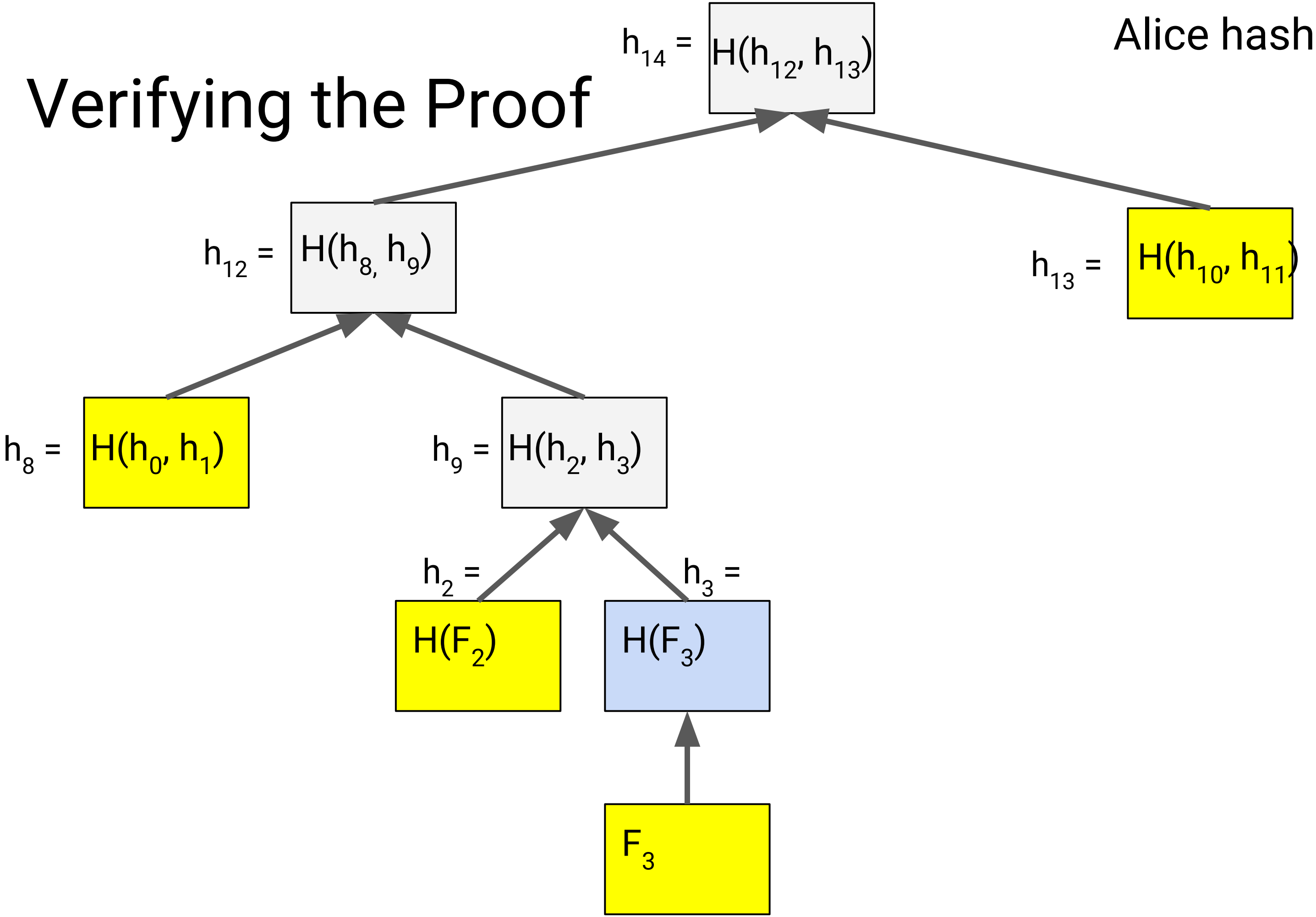
Verifying the Proof



Alice computes the root starting from F_3 with these highlighted proof.

Verifying the Proof

Alice hashes up the tree.



Verifying the Proof

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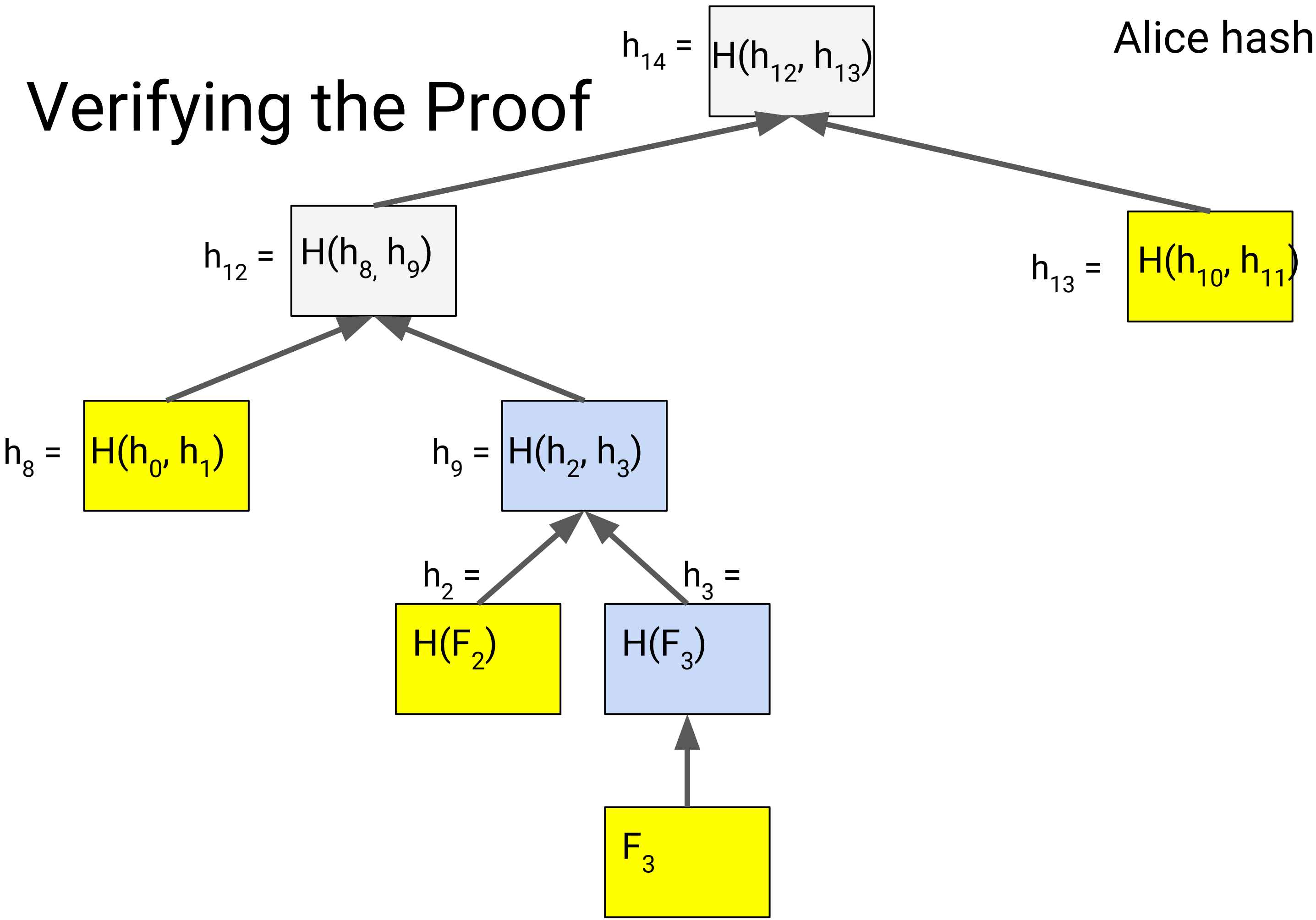

Verifying the Proof

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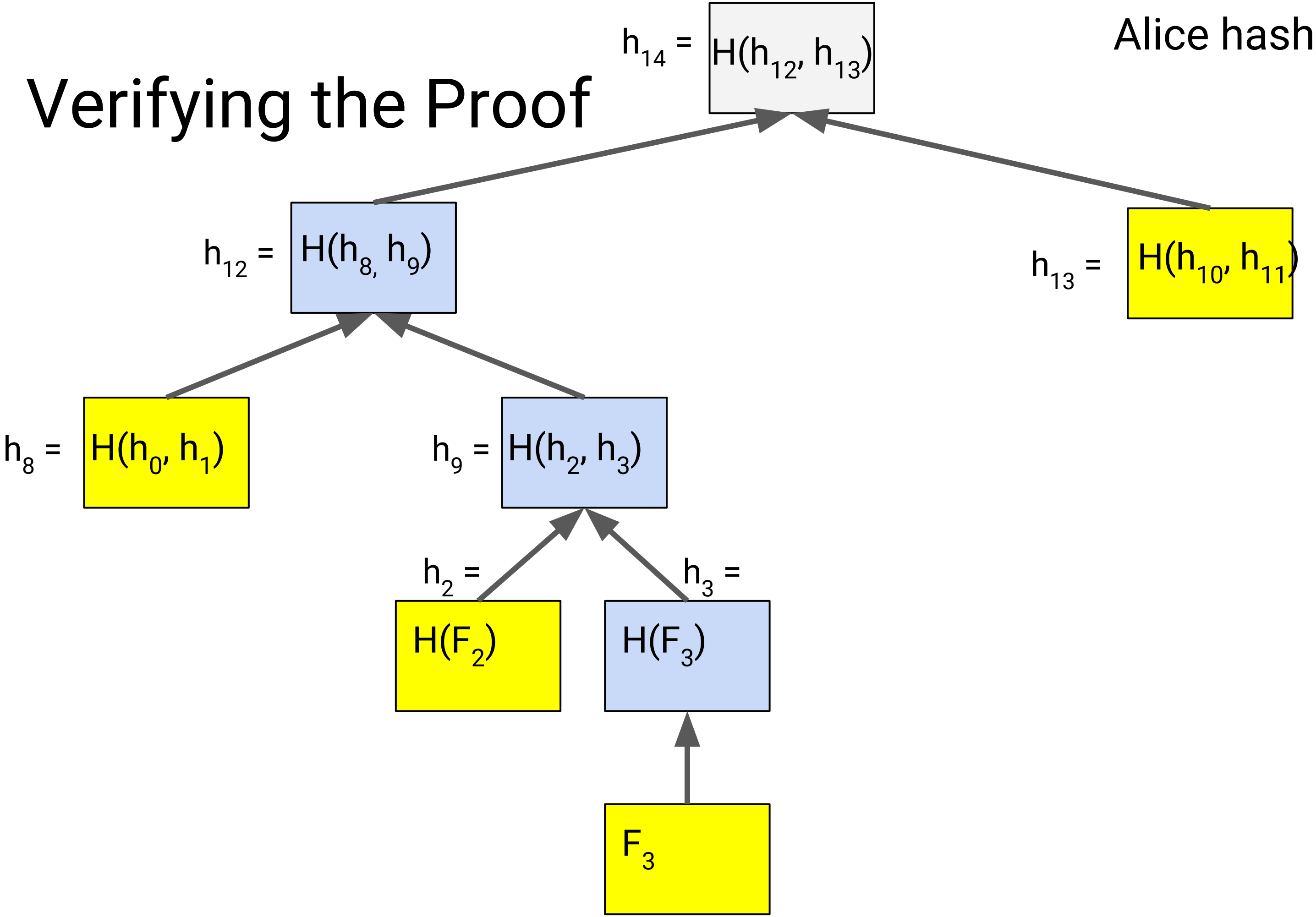
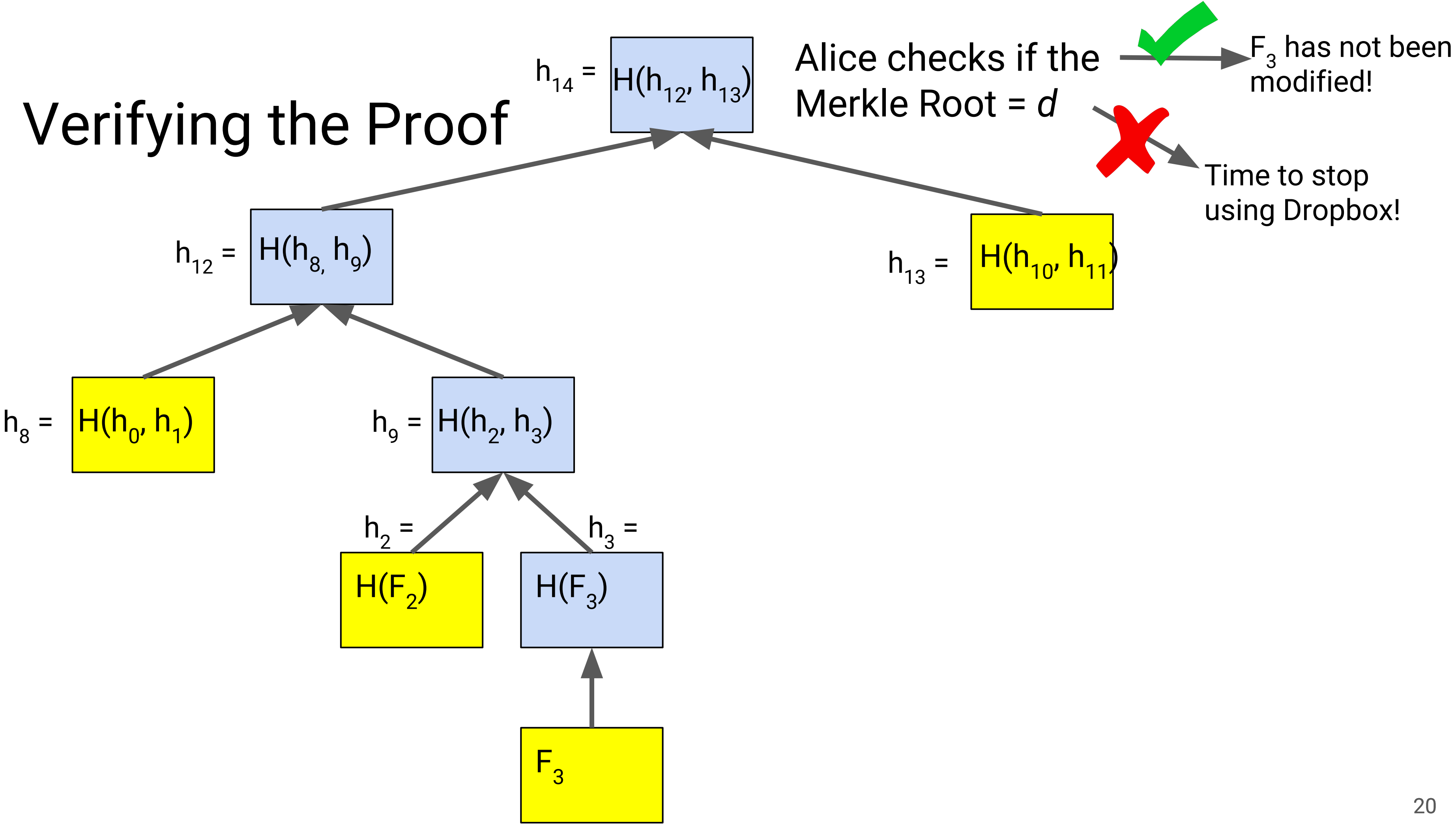
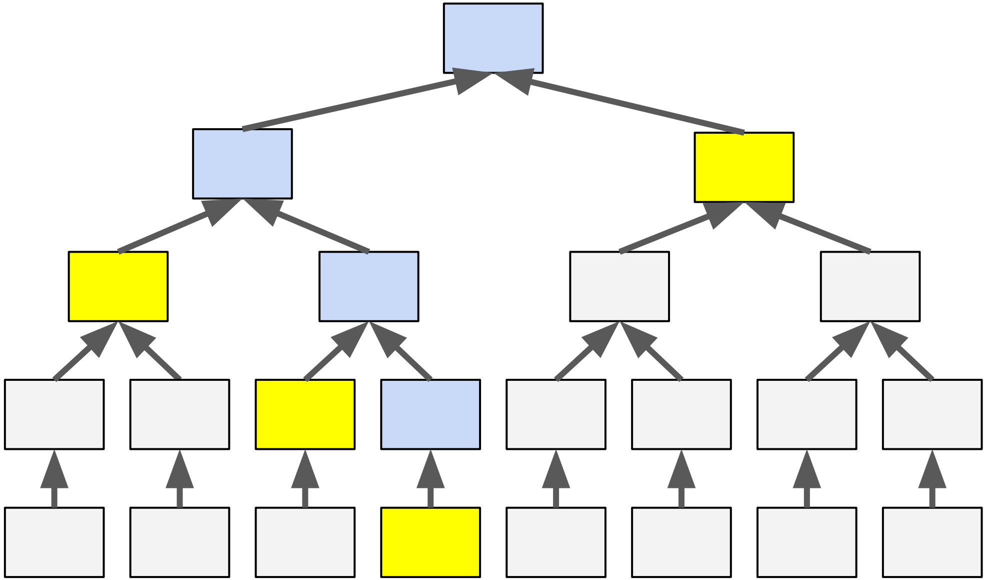


Verifying the Proof



Everyone loves Merkle Trees!

- They're beautiful.
- They're efficient.



n = number of leaves (files)

	Merkle Tree
Construct Tree	O(n)
Proof size	O(log n)
Update File	O(log n)

Problem: Many small files ⇒ Merkle proofs too large.

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- Suppose Alice has one billion ≈ 2^{30} files.

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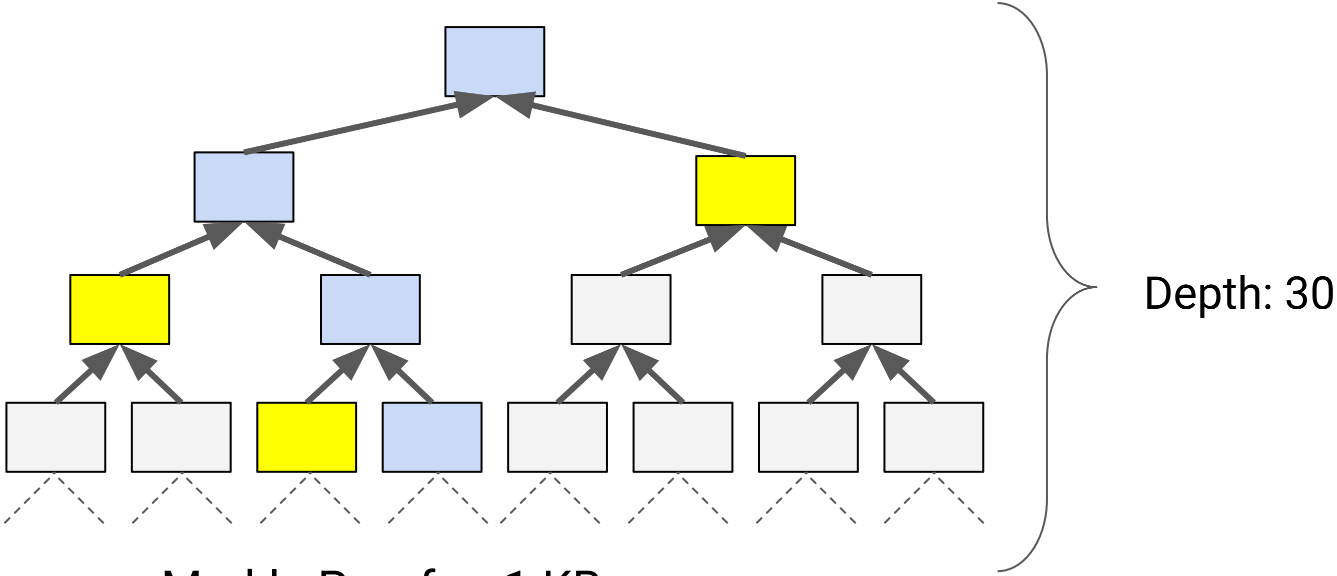
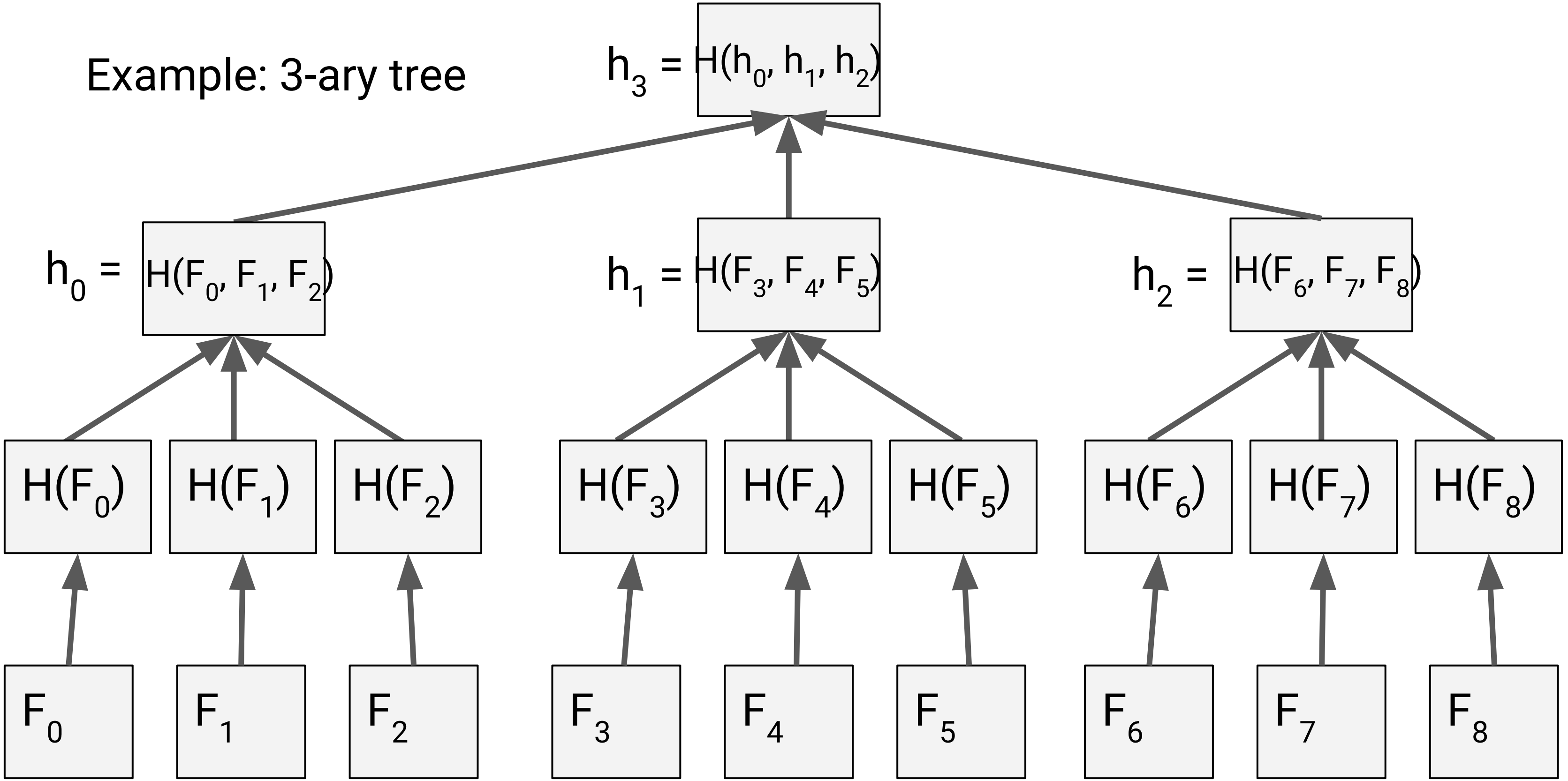


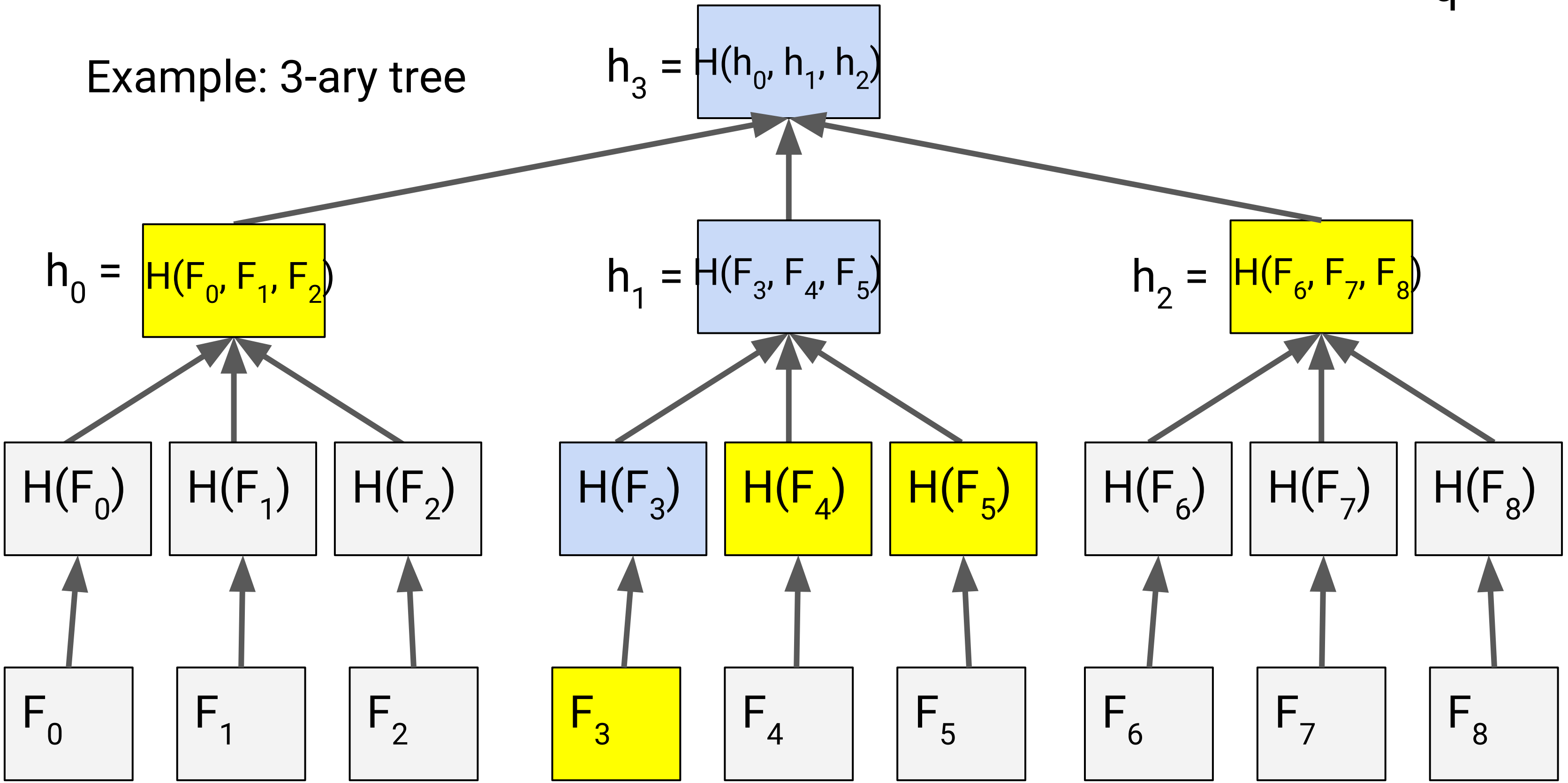
Merkle Proof: ~ 1 KB
(in addition to the file itself)

Possible Solution: q-ary Merkle Tree



Problem: The Proof Becomes Bigger, $O(q \log_q n)$

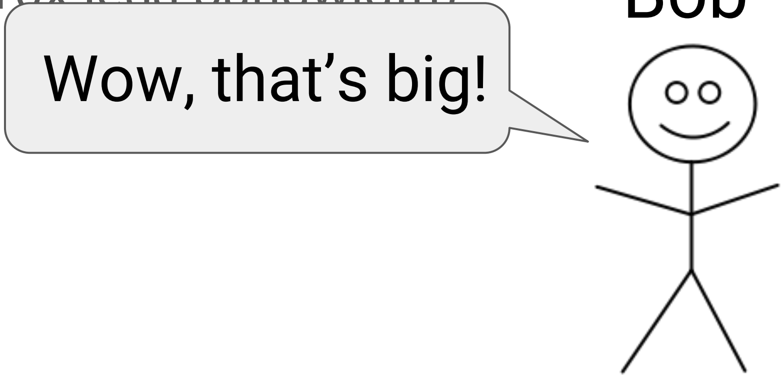
Example: 3-ary tree



Our Work: Verkle Trees reduce the proof size

- We pick a q.
- We reduce the proof size from $\log_2 n$ to $\log_q n = \log_2 n / \log_2 q$.
- Factor of **$\log_2 q$ less bandwidth!**
- At the cost of **q times more computation**
- (e.g., $q = 1024 \Rightarrow \log_2(q) = 10$x less bandwidth)

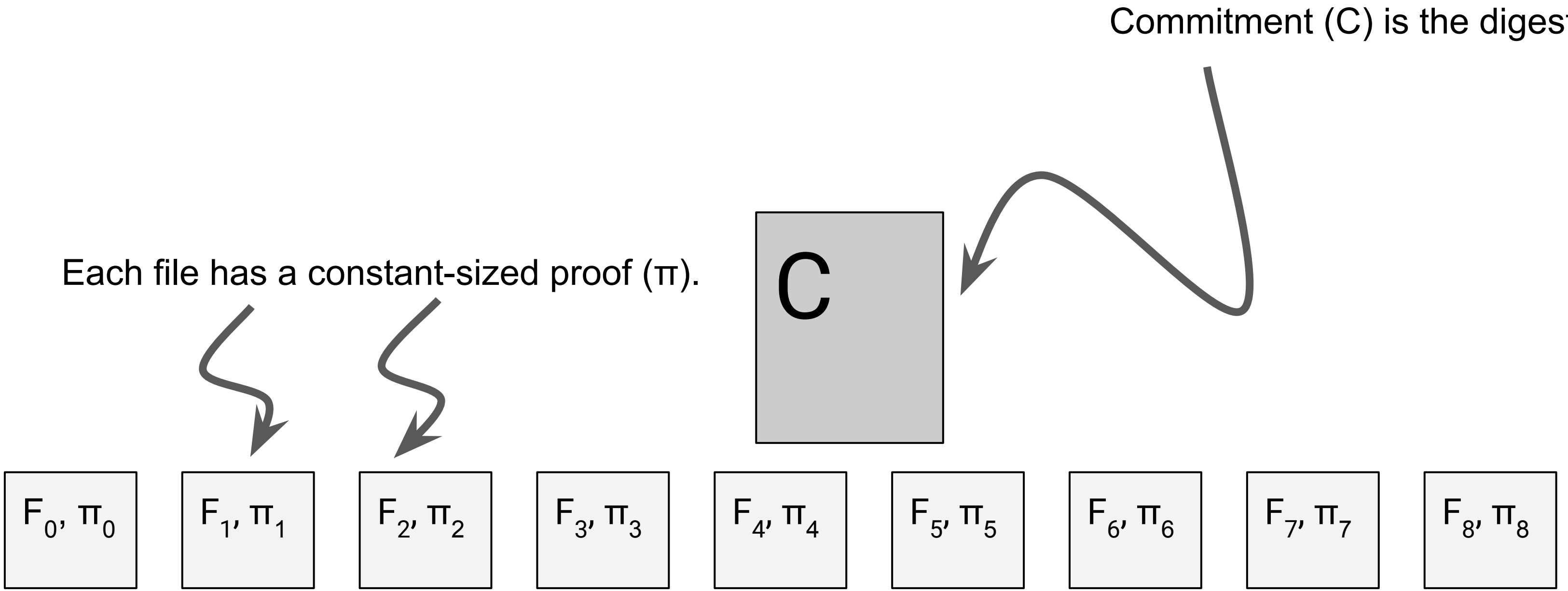
Bob



Does this matter? (Hint: Yes)

- Merkle hash trees are everywhere in cryptography:
  - Consensus Protocols
  - Public-Key Directories
  - Cryptocurrencies
  - Encrypted Web Applications
  - Secure File Systems

Vector Commitment (VC) Schemes by Catalano and Fiore (2013)

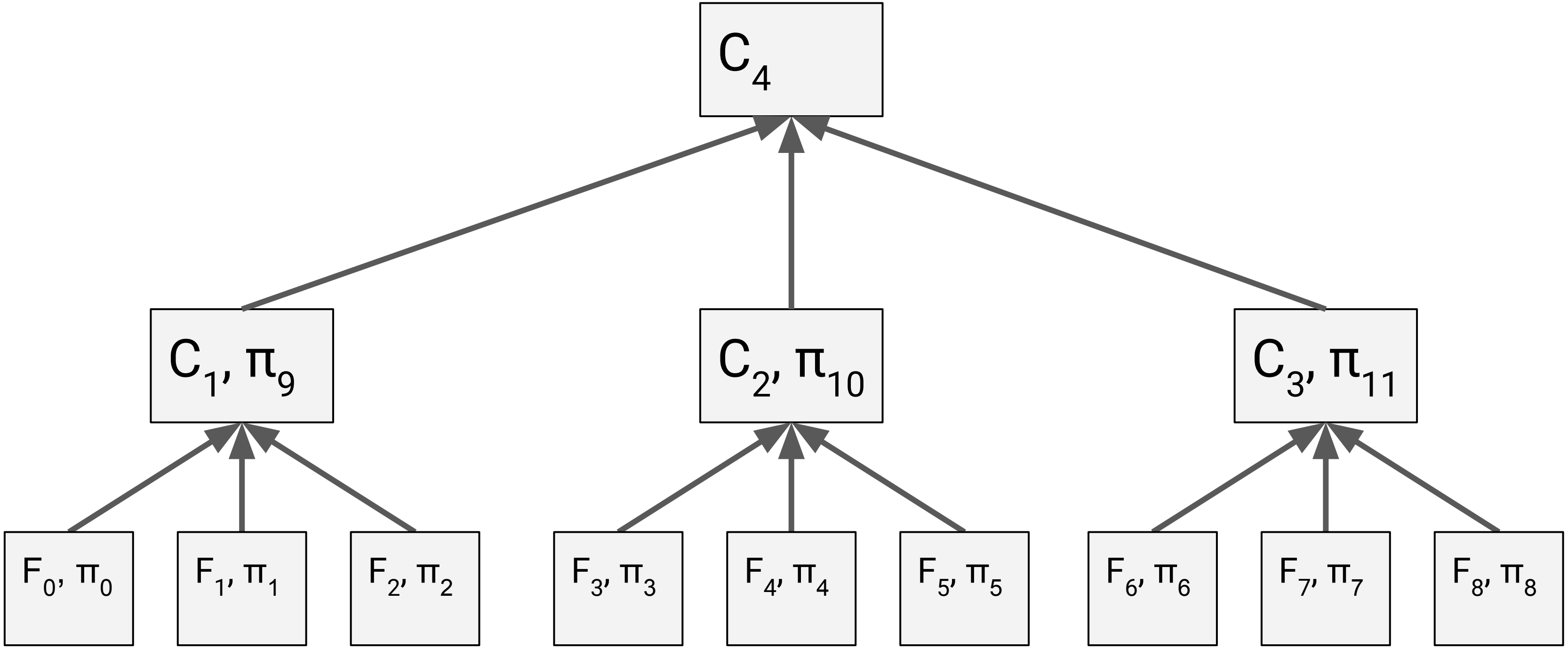


VC Schemes are Computationally Impractical

Scheme/op	Construct	Proof size
Merkle	$O(n)$	$O(\log_2 n)$
VC scheme	$\mathbf{O(n^2)}$	$O(1)$

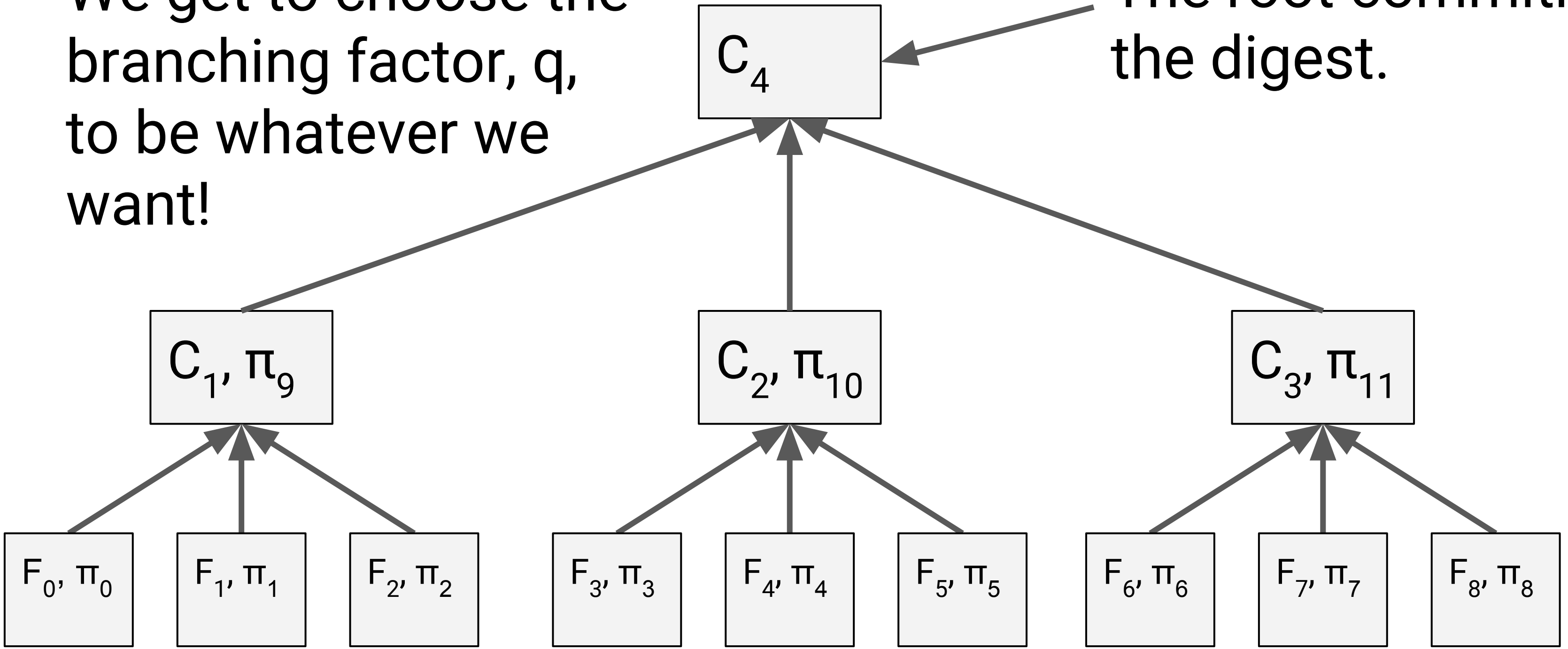
Our Solution: Replace Hash Functions with VC Schemes

This is the Verkle Tree.



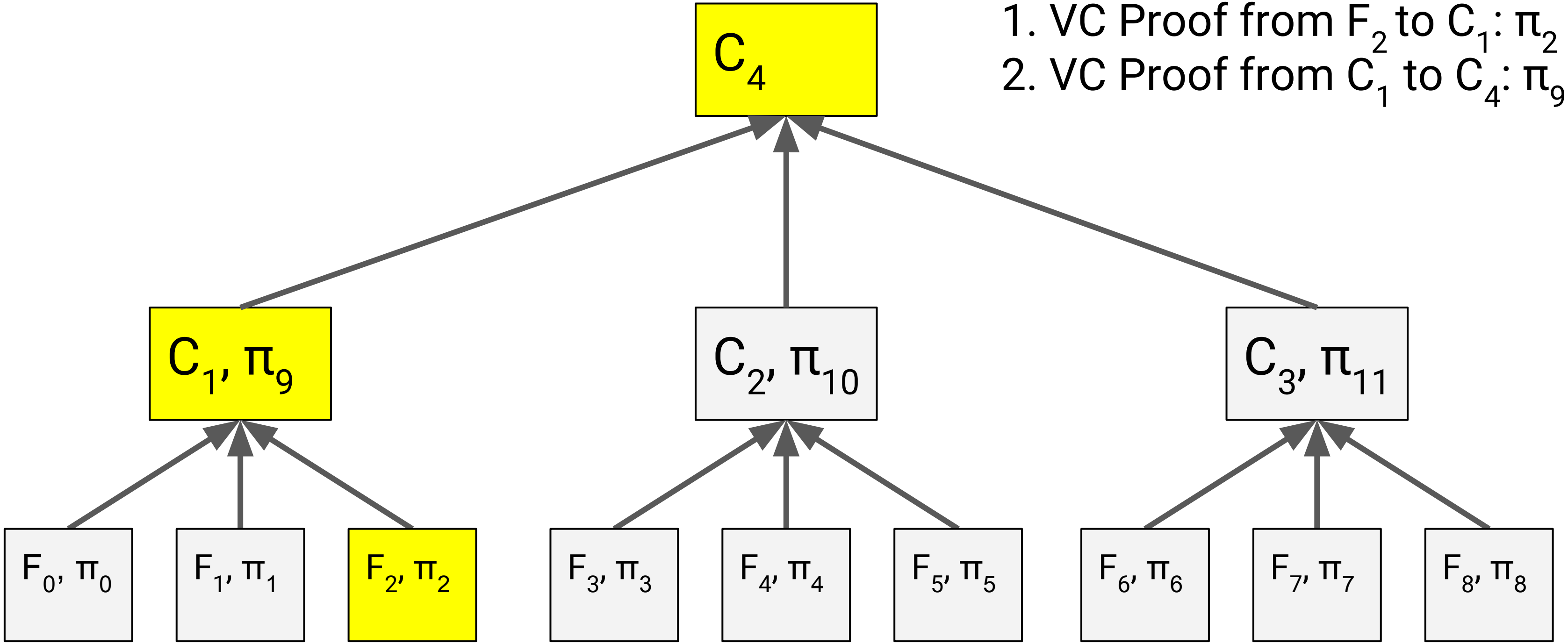
We now have a Verkle Tree!

We get to choose the branching factor, q, to be whatever we want!



The root commitment is the digest.

Alice Receives $\log_q n$ Constant-Sized π's.



Alice verifies:

1. VC Proof from F_2 to C_1: π_2
2. VC Proof from C_1 to C_4: π_9

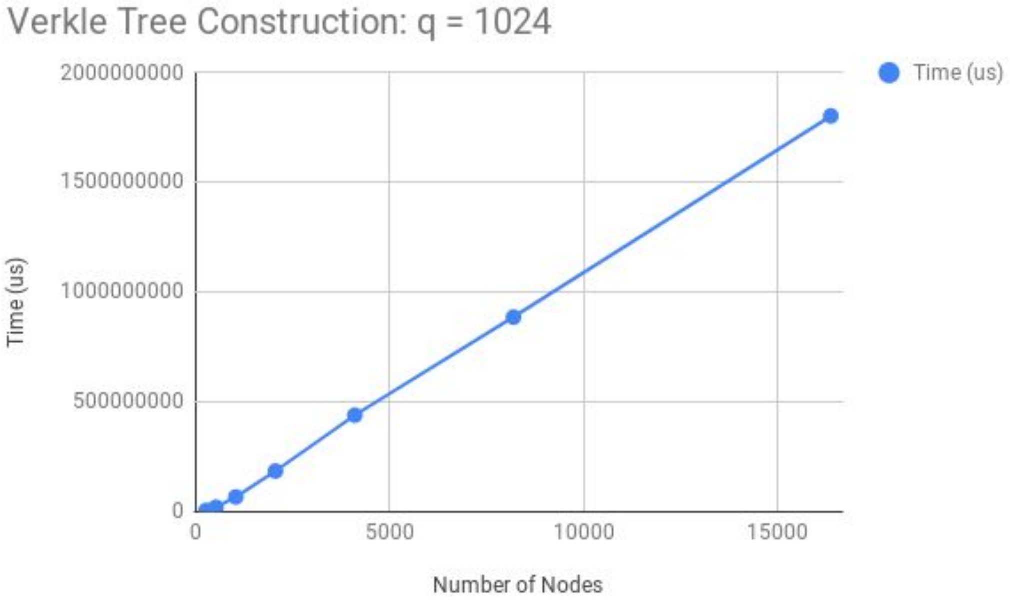
Comparison

Scheme/op	**Construct**	**Update file**	**Proof size**
Merkle	**$O(n)$**	$O(\log_2 n)$	**$O(\log_2 n)$**
q-ary Merkle	**$O(n)$**	$O(q \log_q n)$	**$O(q \log_q n)$**
VC scheme	**$O(n^2)$**	**$O(n)$**	**$O(1)$**
q-ary Verkle	*$O(qn)$*	*$O(q \log_q n)$*	*$O(\log_q n)$*

Verkle Trees let us trade off proof-size vs. construction time.

My Contribution

- I proved complexity bounds for Verkle Trees.
- I implemented Verkle Trees in C++.
- I am measuring performance.



Acknowledgements

- Thank you Alin!
- Thank you PRIMES!
- Thank you Mom and Dad!