Cryptosystems: Theory and Practice

Introduction & Course Overview

Slides adapted from Raluca Ada Popa & Emily Stark

Cryptosystems

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- What systems?
    - Database, messaging, ML training & inference, blockchain
- What crypto?
    - Homomorphic encryption, ORAM, PIR, MPC, differential privacy, zero-knowledge

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- What important problems do these systems address?
- Learn how cryptosystems are designed and implemented
  - Which cryptographic tools are used?
  - How to use these cryptographic tools to build secure systems?
  - What systems techniques are used?
- Are these systems used in practice? What are difficulties in deploying these systems?

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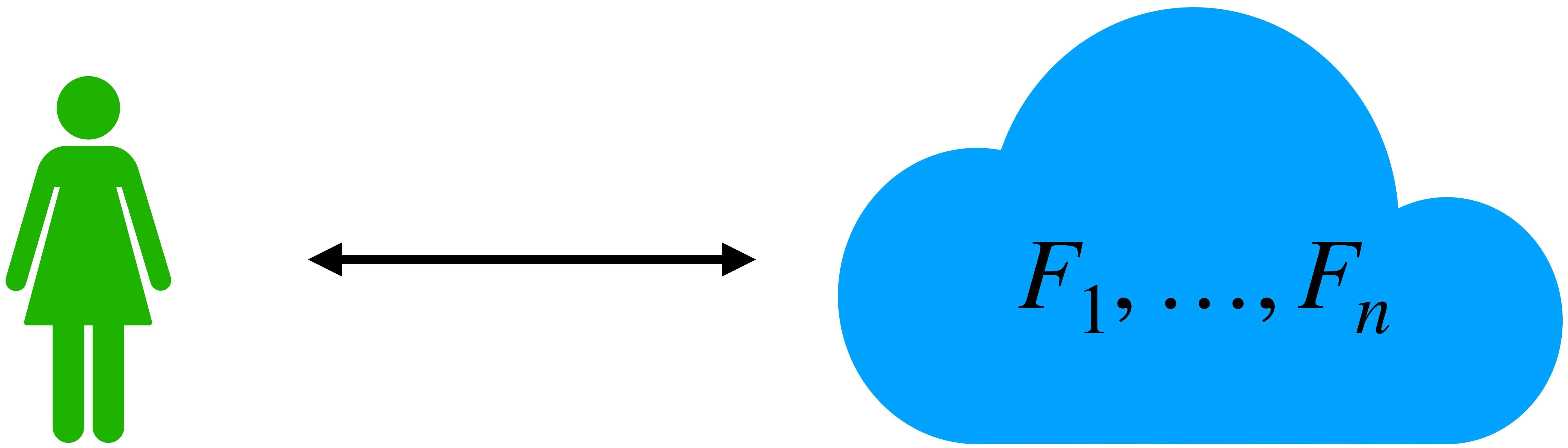

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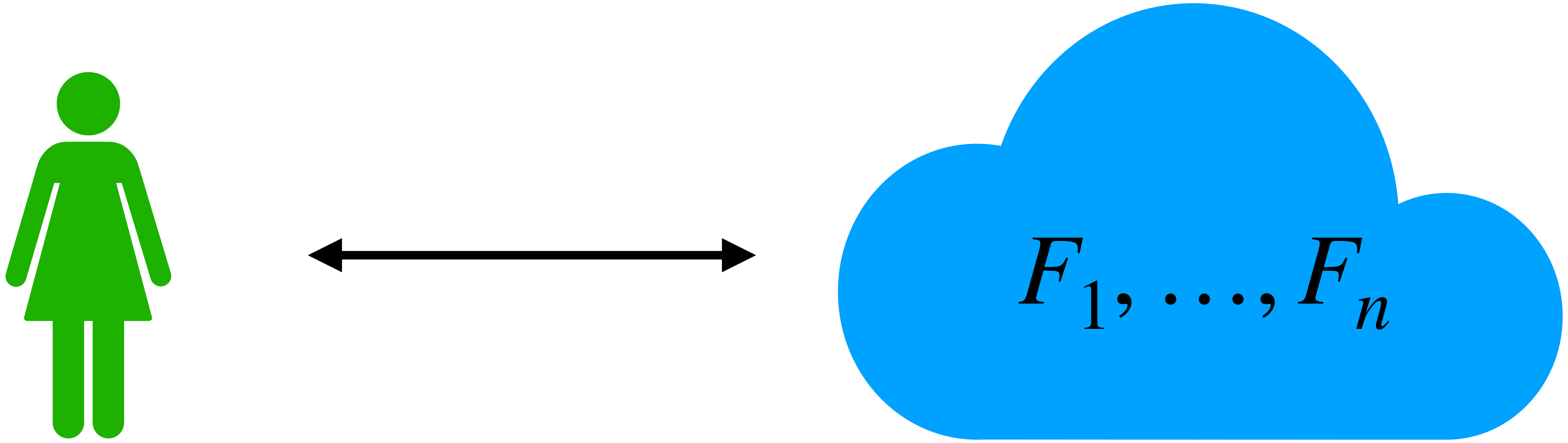
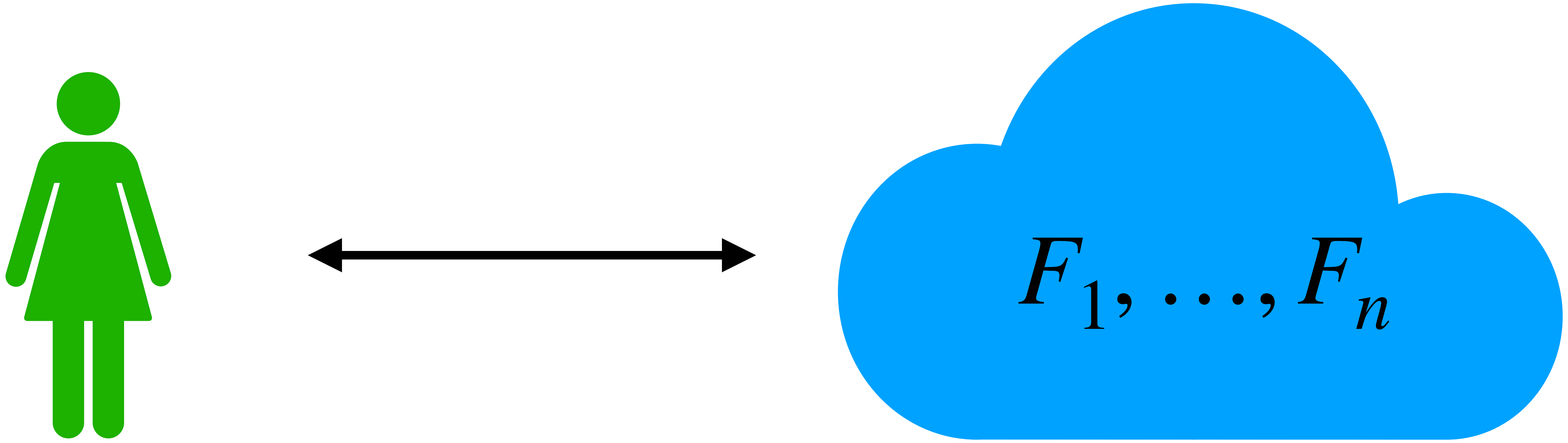
- Alice has files $F_1, \ldots, F_n$ and wants to store them in the cloud
- Alice does not entirely trust the cloud with respect to data integrity



A scenario…

- Alice has files $F_1, \ldots, F_n$ and wants to store them in the cloud
- Alice does not entirely trust the cloud with respect to data integrity
- When she retrieves file i, how can she verify that the untrusted cloud did not modify the file?



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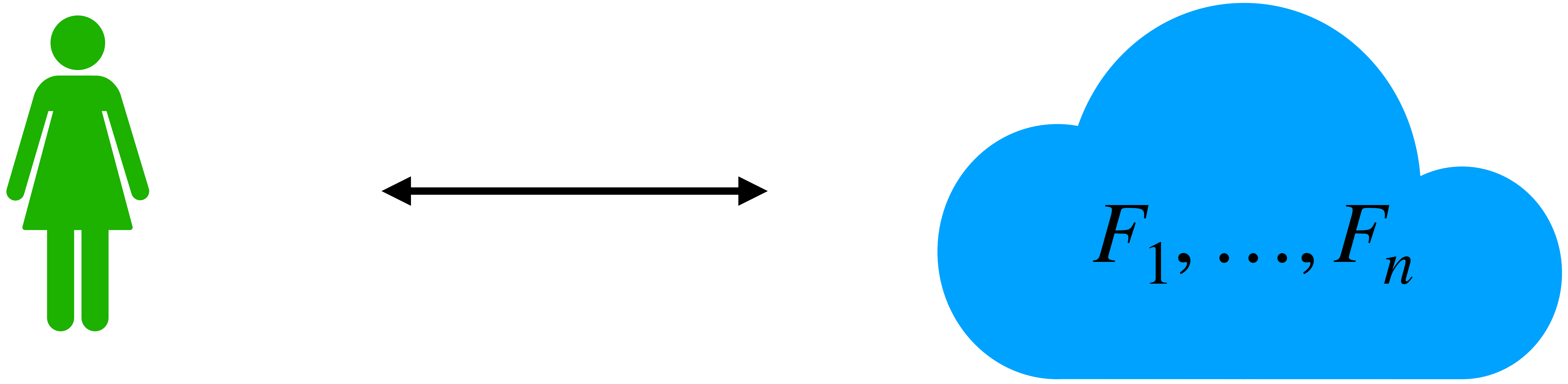
- In order words, it is computationally hard for the adversary to find two messages x and y such that their hashes are the same

A first attempt



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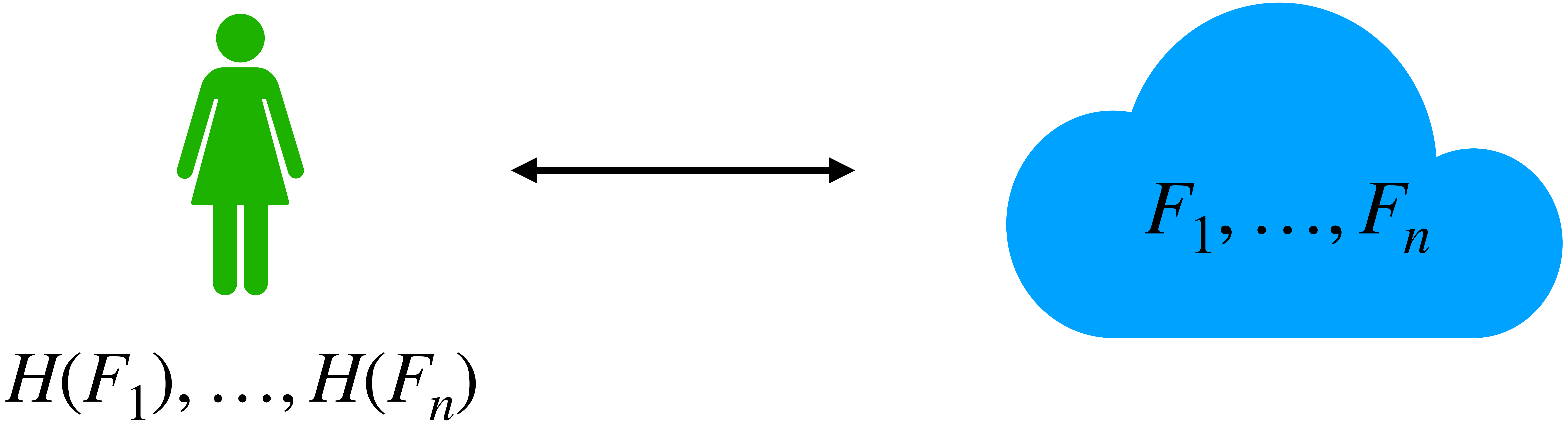

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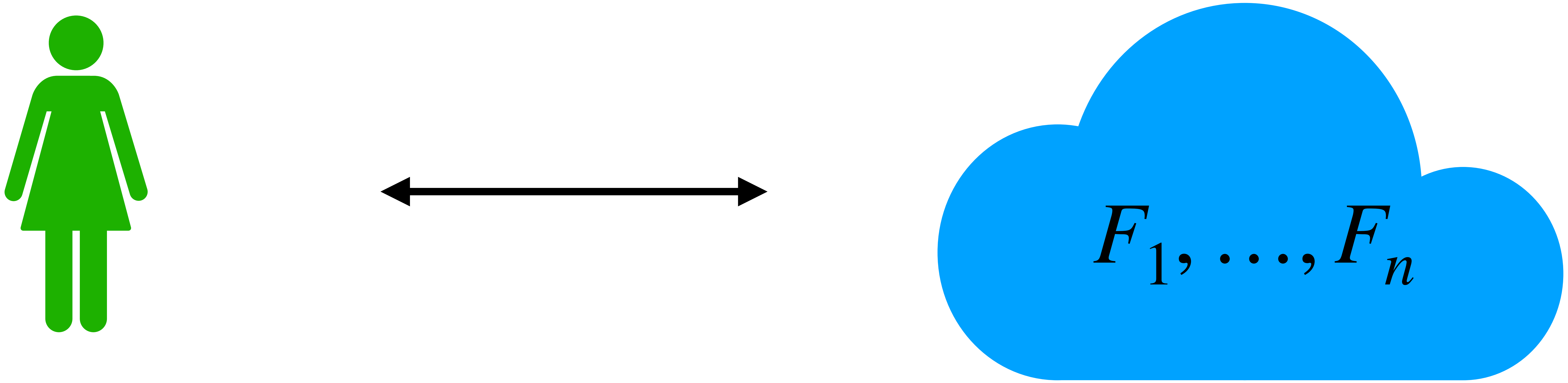

$H(F_1), \ldots, H(F_n)$

Problem: large amount of client storage

Merkle tree

- Invented by Ralph Merkle in 1979
- Used in many theoretic constructions and practical crypto systems

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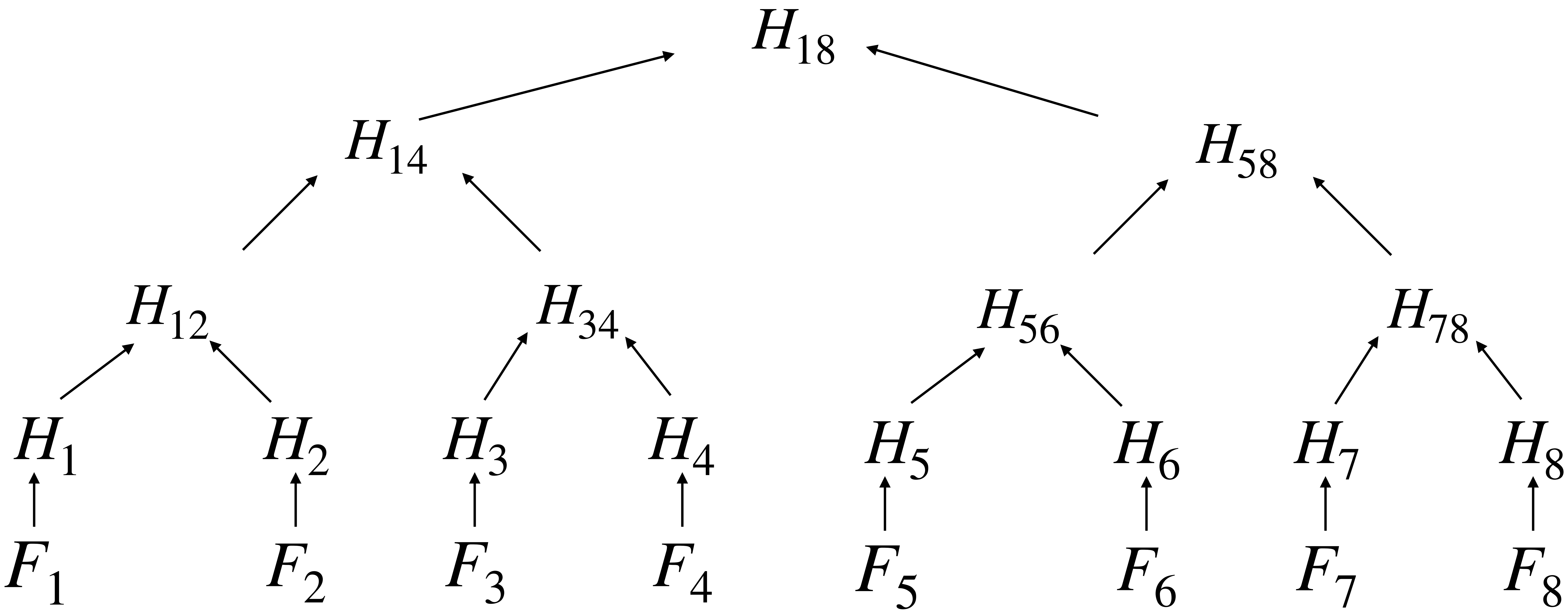

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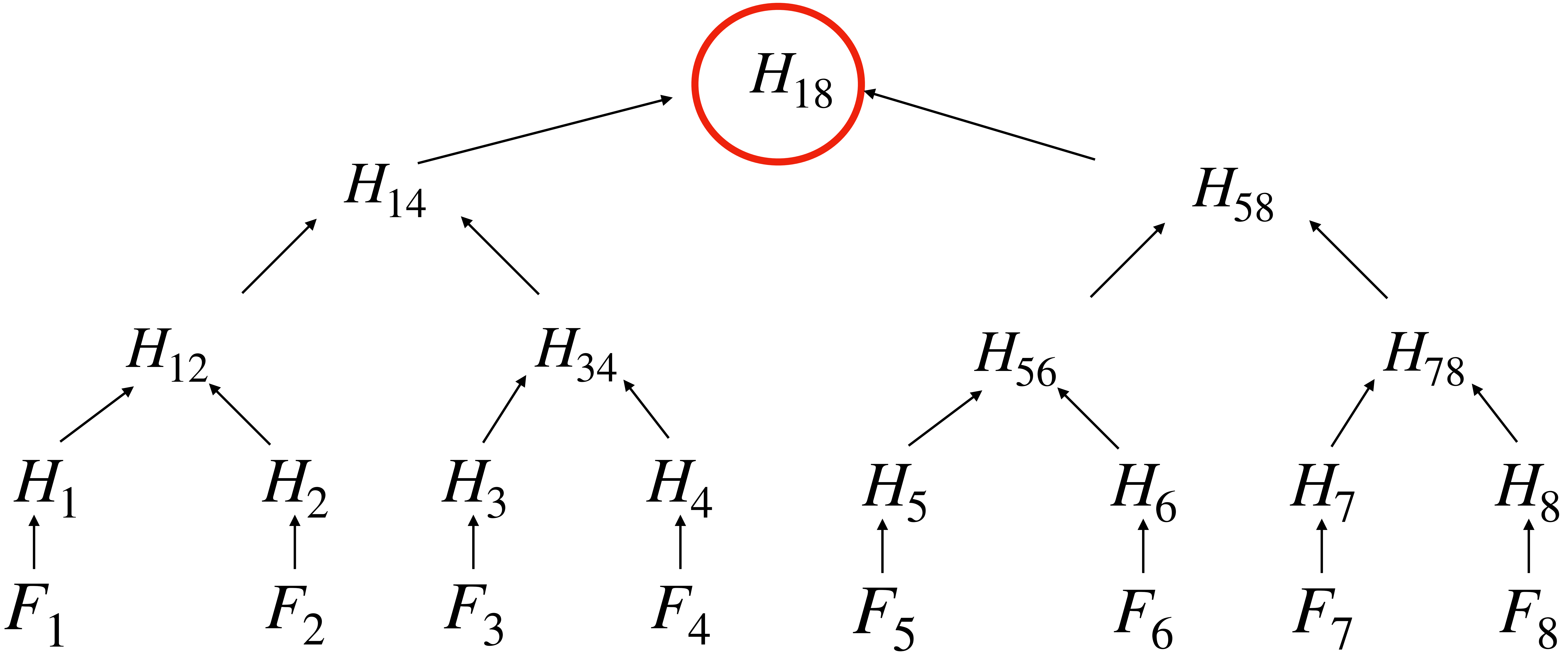

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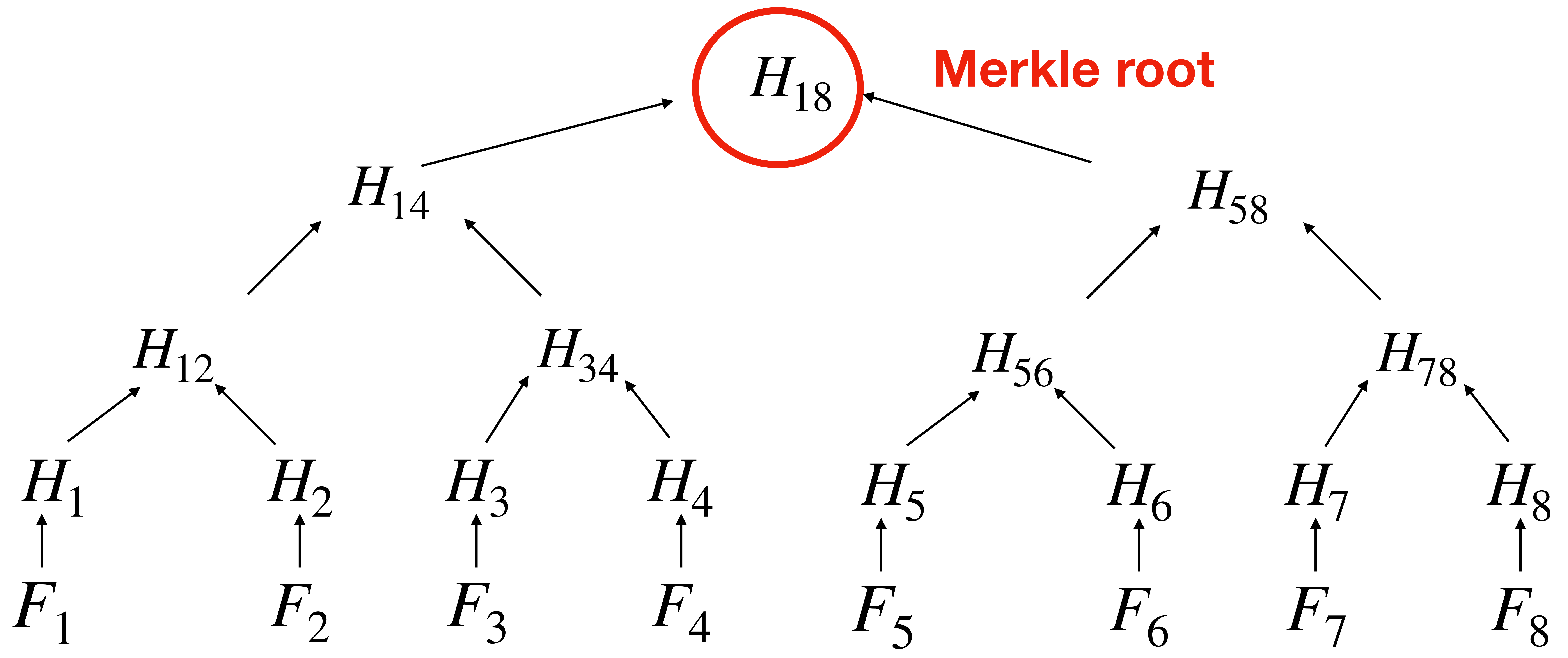
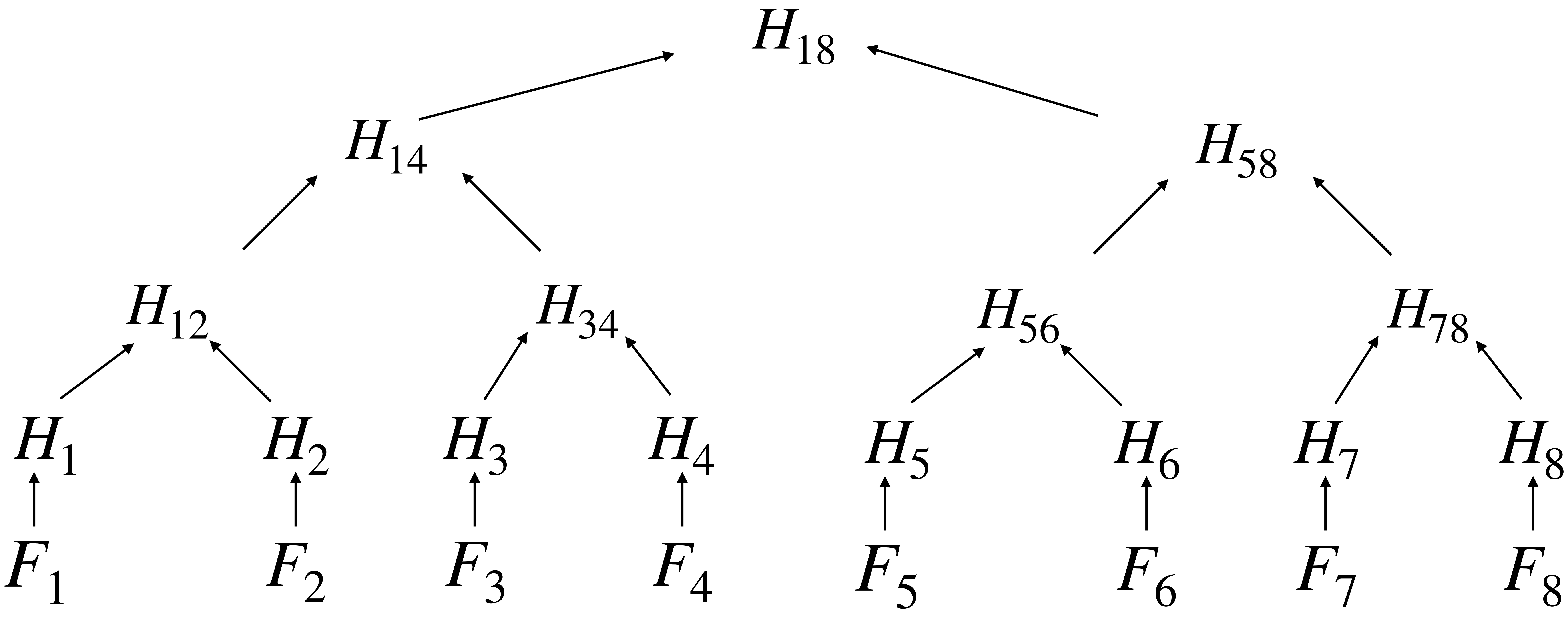
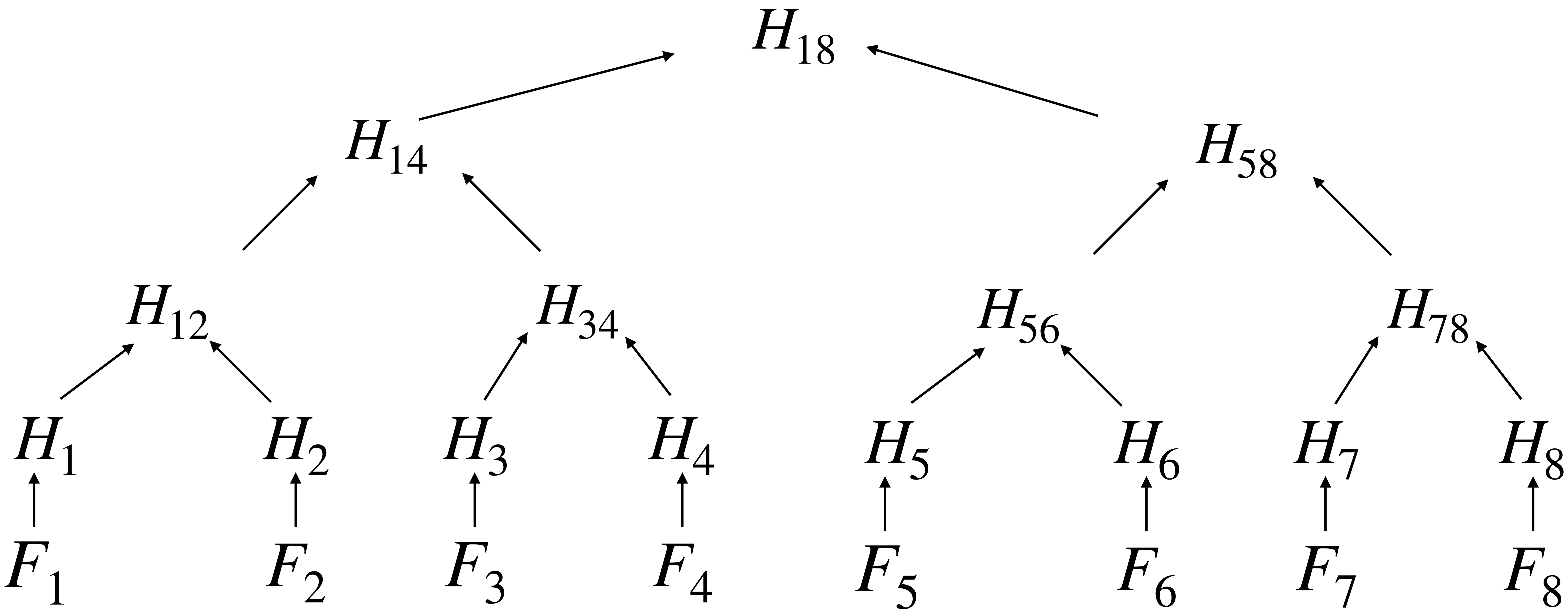


Merkle proof



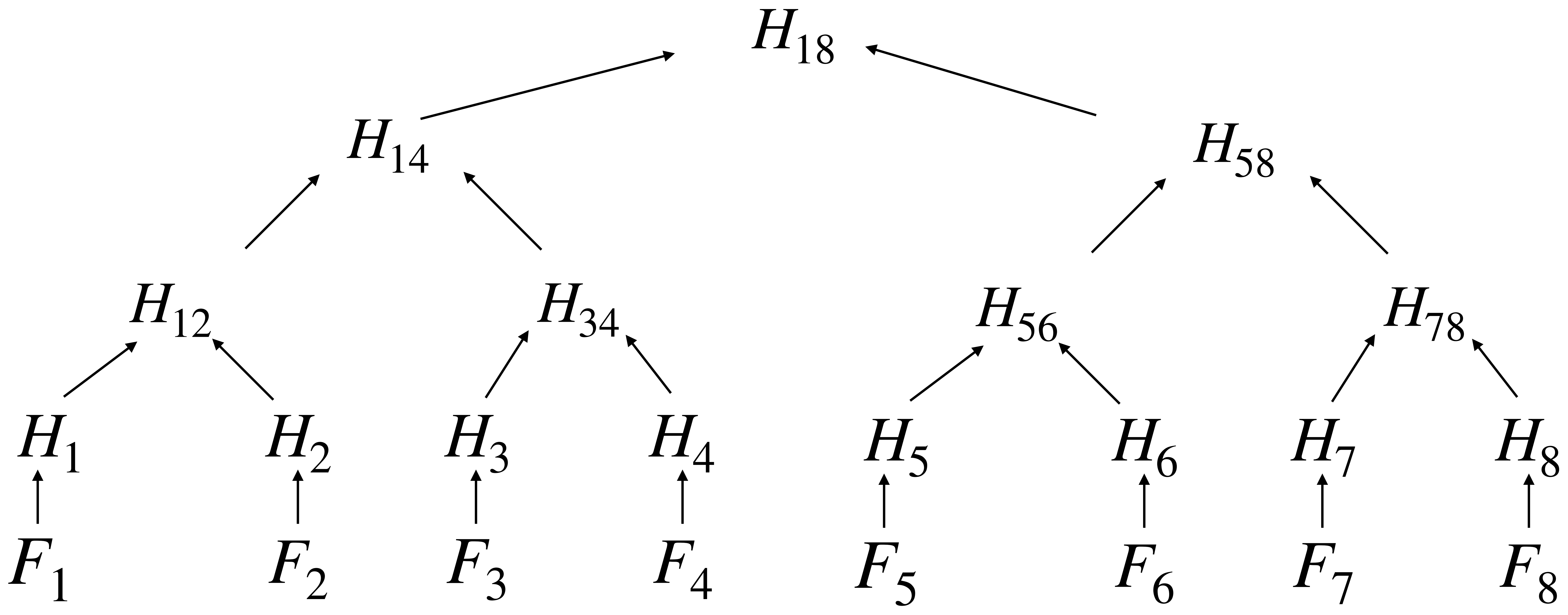
Merkle proof

- Alice wants to retrieve F_2



Merkle proof

- Alice wants to retrieve F_2
- Given this summary, how can F_2 be authenticated to Alice?



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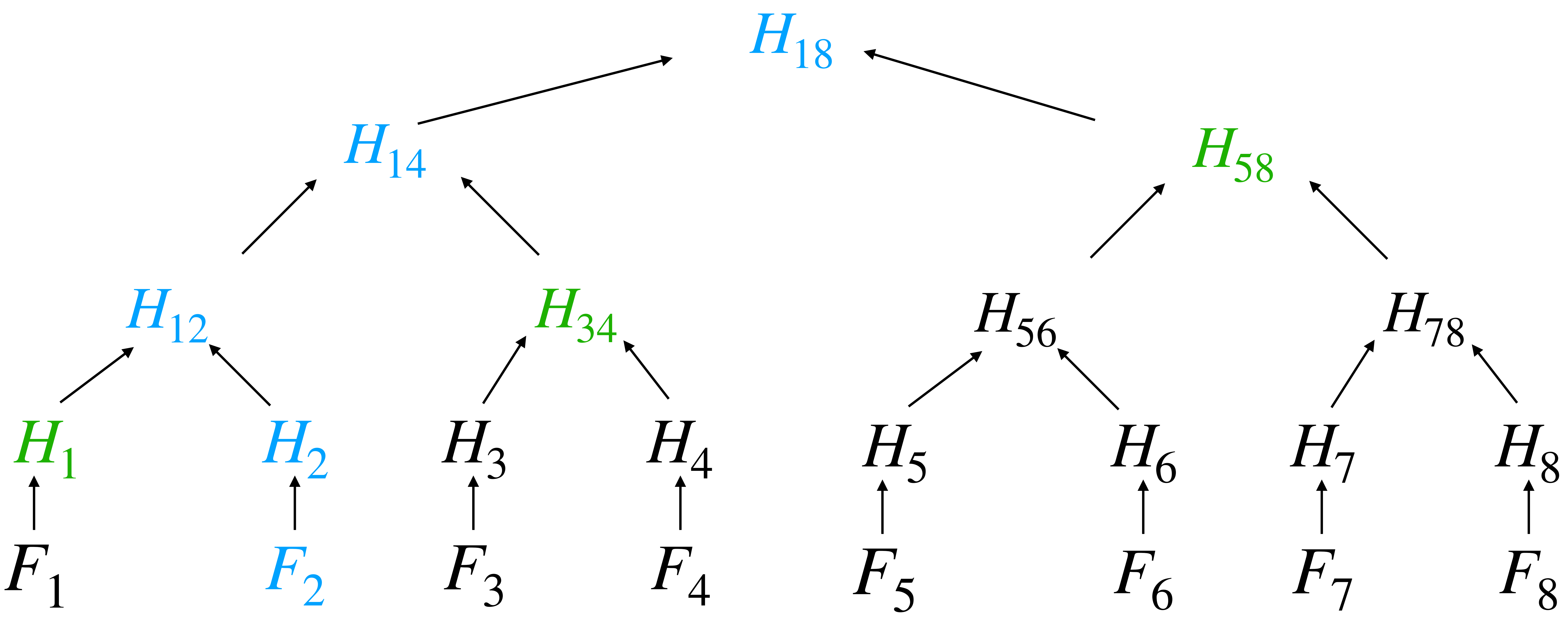
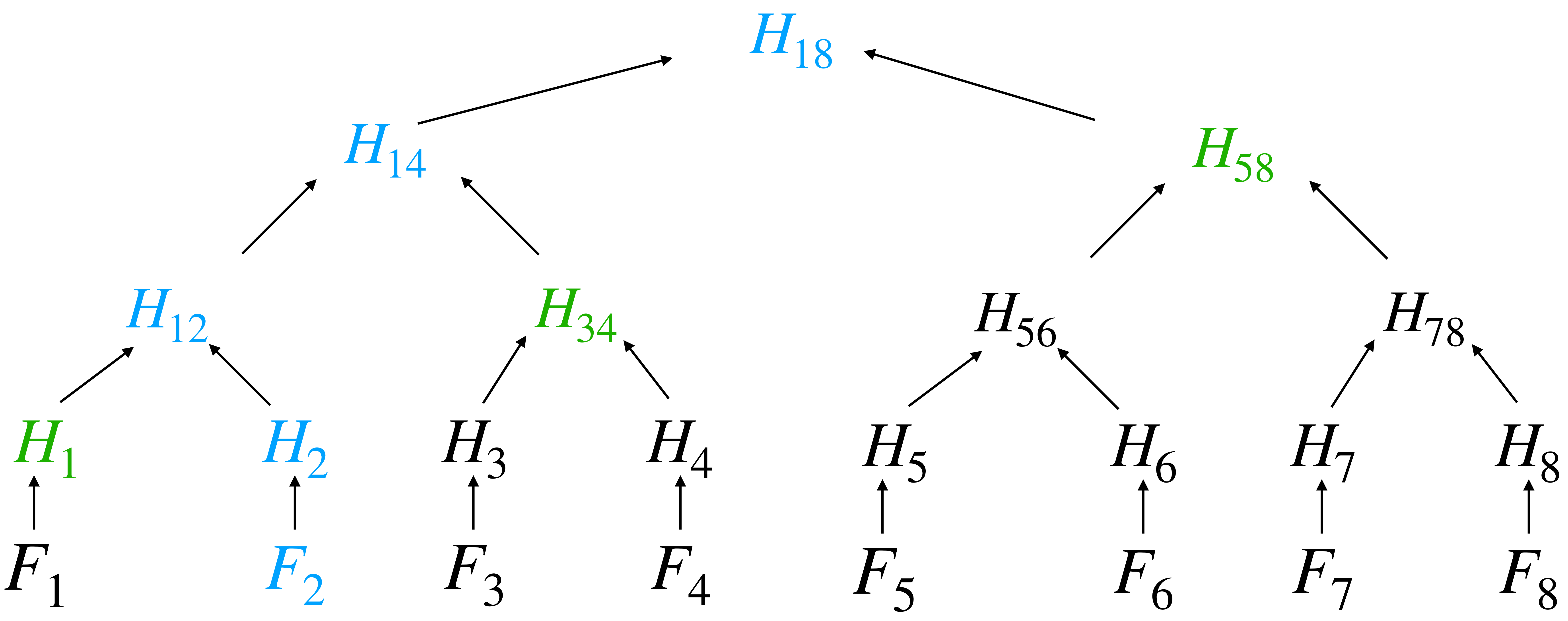


Merkle proof

- The server provides a Merkle proof, which are the siblings of nodes from F_2 to the root: H_1, H_{34}, H_{58}



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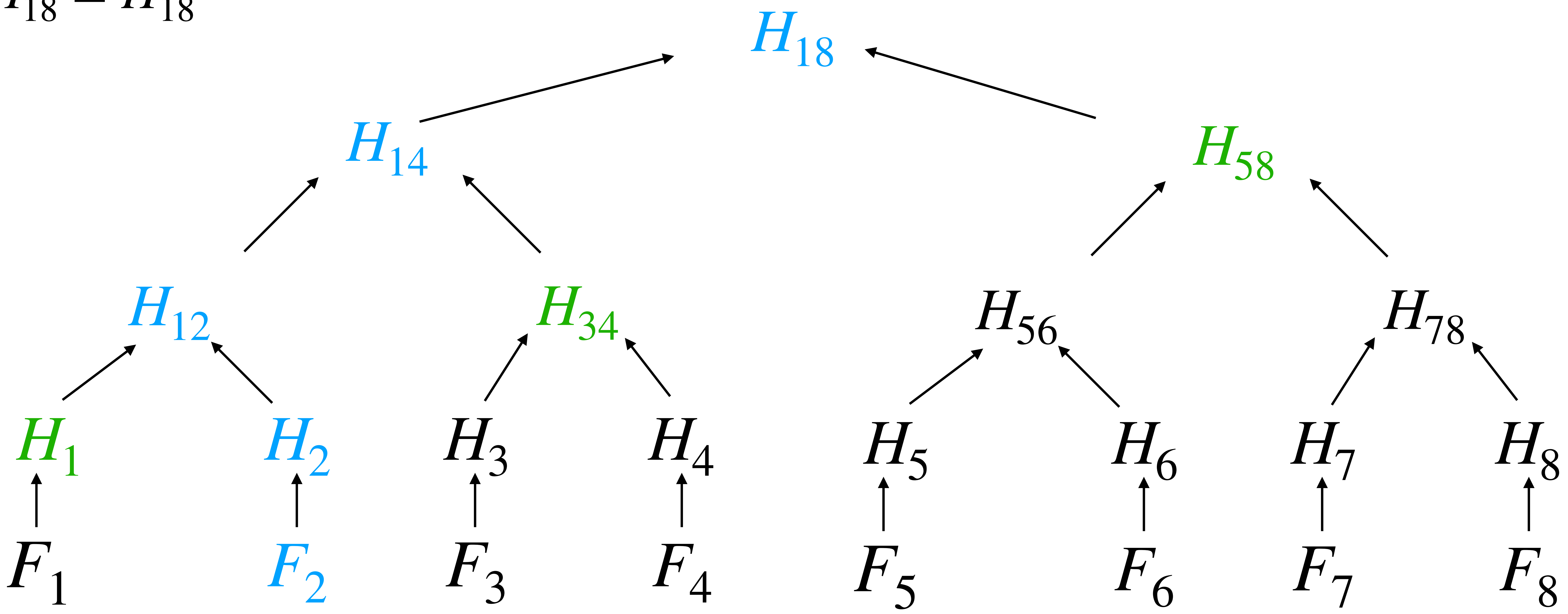
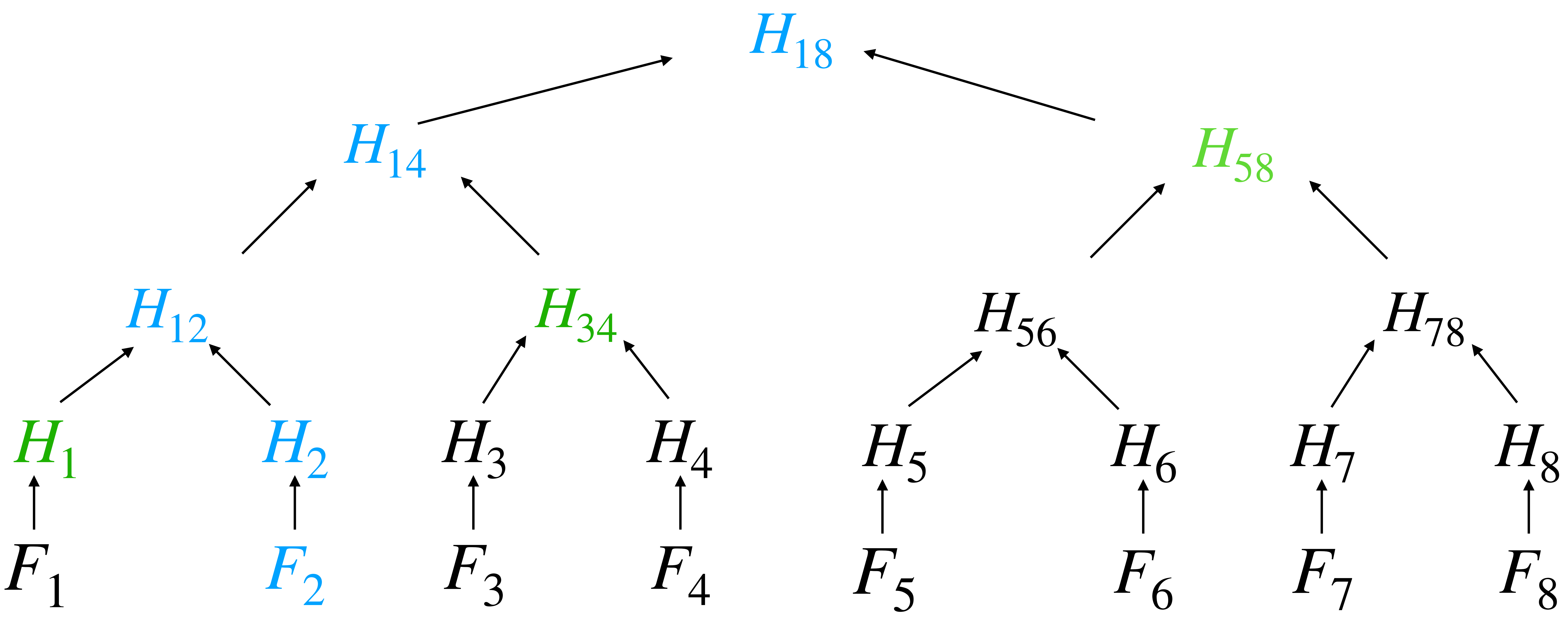
- Alice verifies that $\hat{H}_2 \leftarrow H(F_2), \hat{H}_{12} = H(H_1, \hat{H}(2)), \hat{H}_{14} \leftarrow H(\hat{H}_{12}, H_{34}), \hat{H}_{18} = H(\hat{H}_{14}, H_{58})$ and that $H_{18} = \hat{H}_{18}$



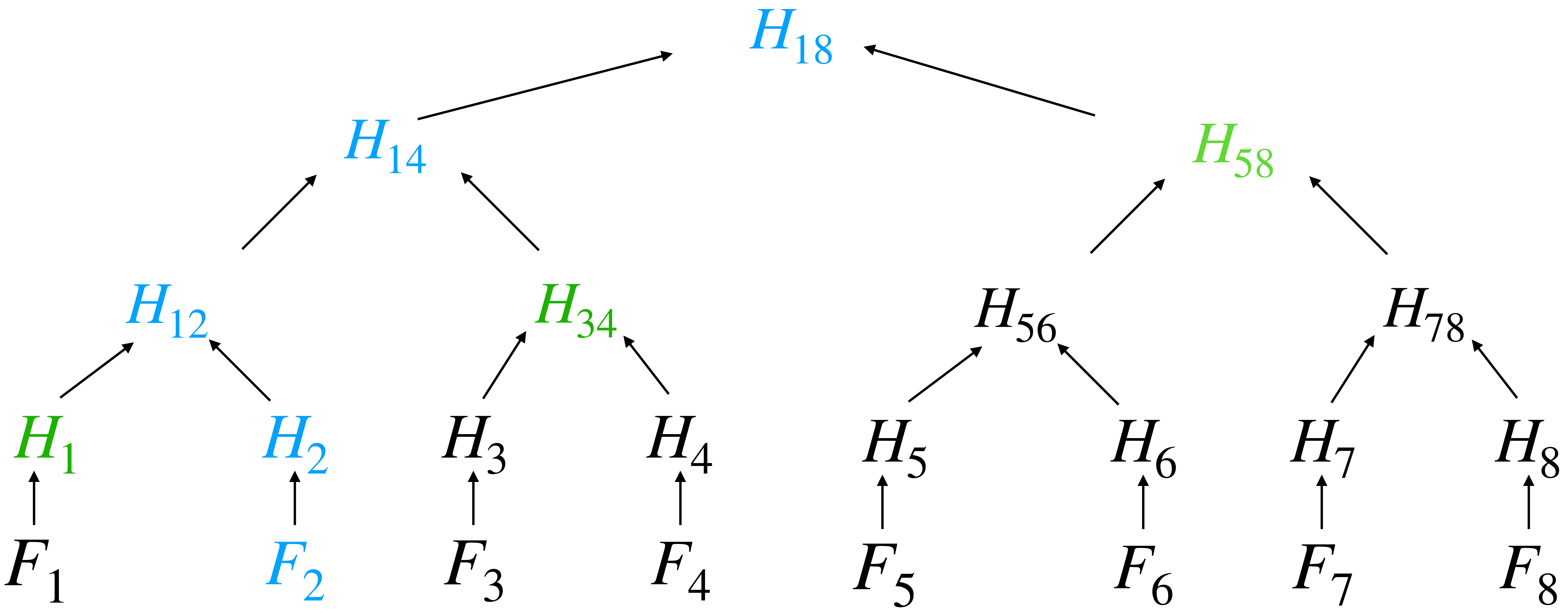
Proof of security?

- **Theorem (Merkle proof consistency):** It is infeasible to output a Merkle root h and two inconsistent proofs π_i and π_i' for two different inputs x_i and x_i' at the ith leaf in the tree of size n.



Proof of security?

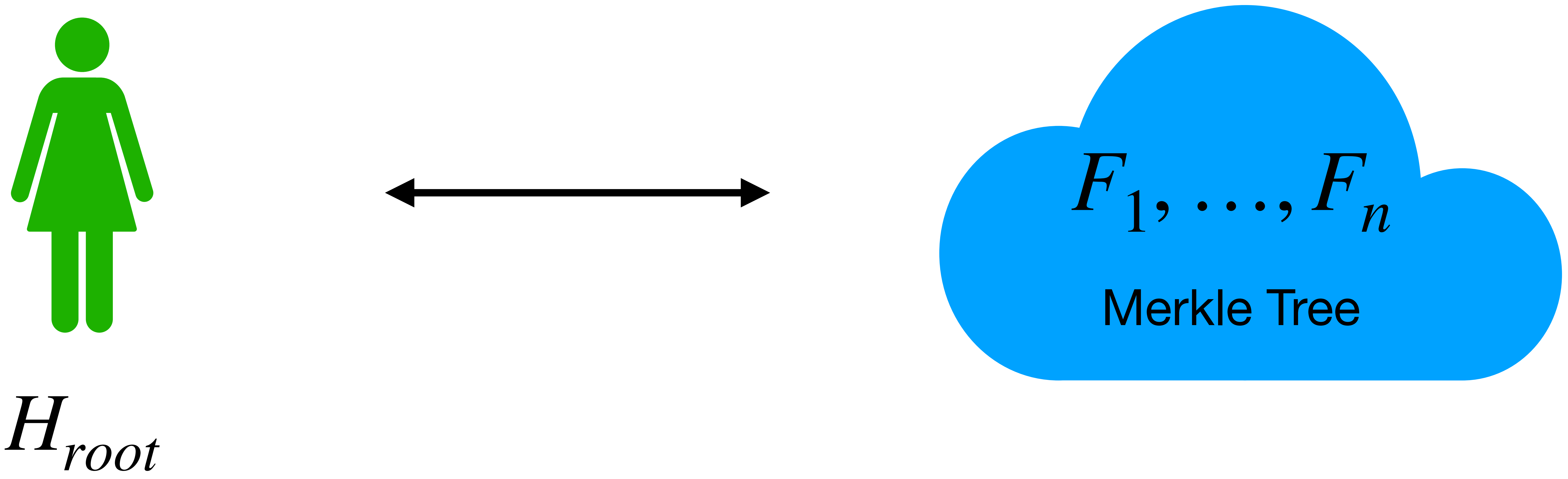
- If $F_2 \neq F_2'$ but the computed root hashes are the same, then there must exist some level $j \in [k]$ where there is a collision. But collision at level j implies a break in the collision-resistance of H



Asymptotics

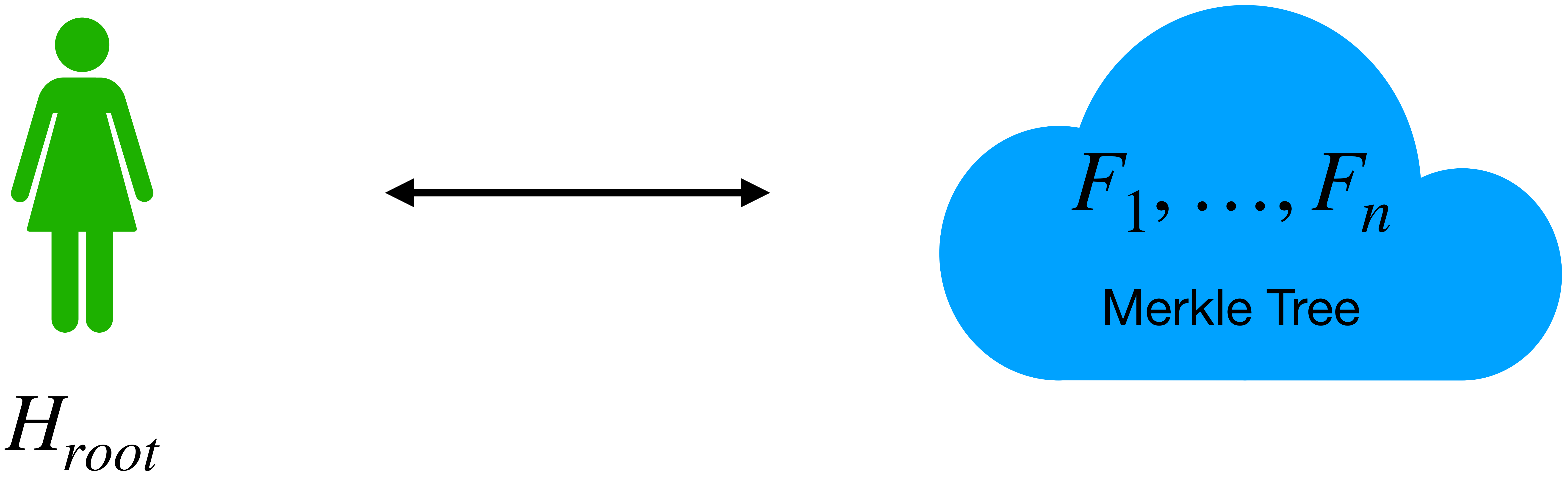
- n number of data items, m hash size
- Size of Merkle tree: $O(nm)$
- Size of Merkle root: $O(m)$
- Size of Merkle proof: $O(m \log n)$

A better attempt



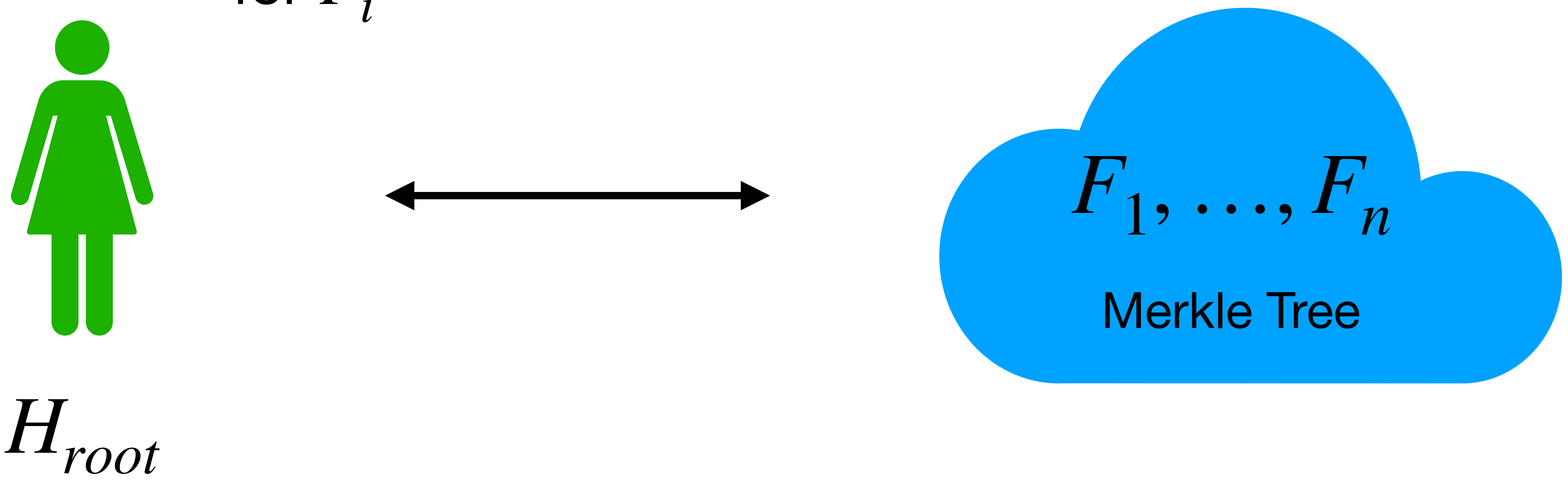
A better attempt

- Alice keeps the Merkle root H_{root}



A better attempt

- Alice keeps the Merkle root H_{root}
- Asks the server for a Merkle proof for F_i



Certificate transparency

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The attacker who penetrated the Dutch CA DigiNotar last year had complete control of all eight of the company's certificate-issuing servers during the operation and he may also have issued some rogue certificates that have not yet been identified. The final report from a security company commissioned to investigate the DigiNotar attack shows that the compromise of the now-bankrupt certificate authority was much deeper than previously thought.

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- Using Merkle trees, these independent parties can verify “summary” of the logged certificates and detect inconsistencies

Parties

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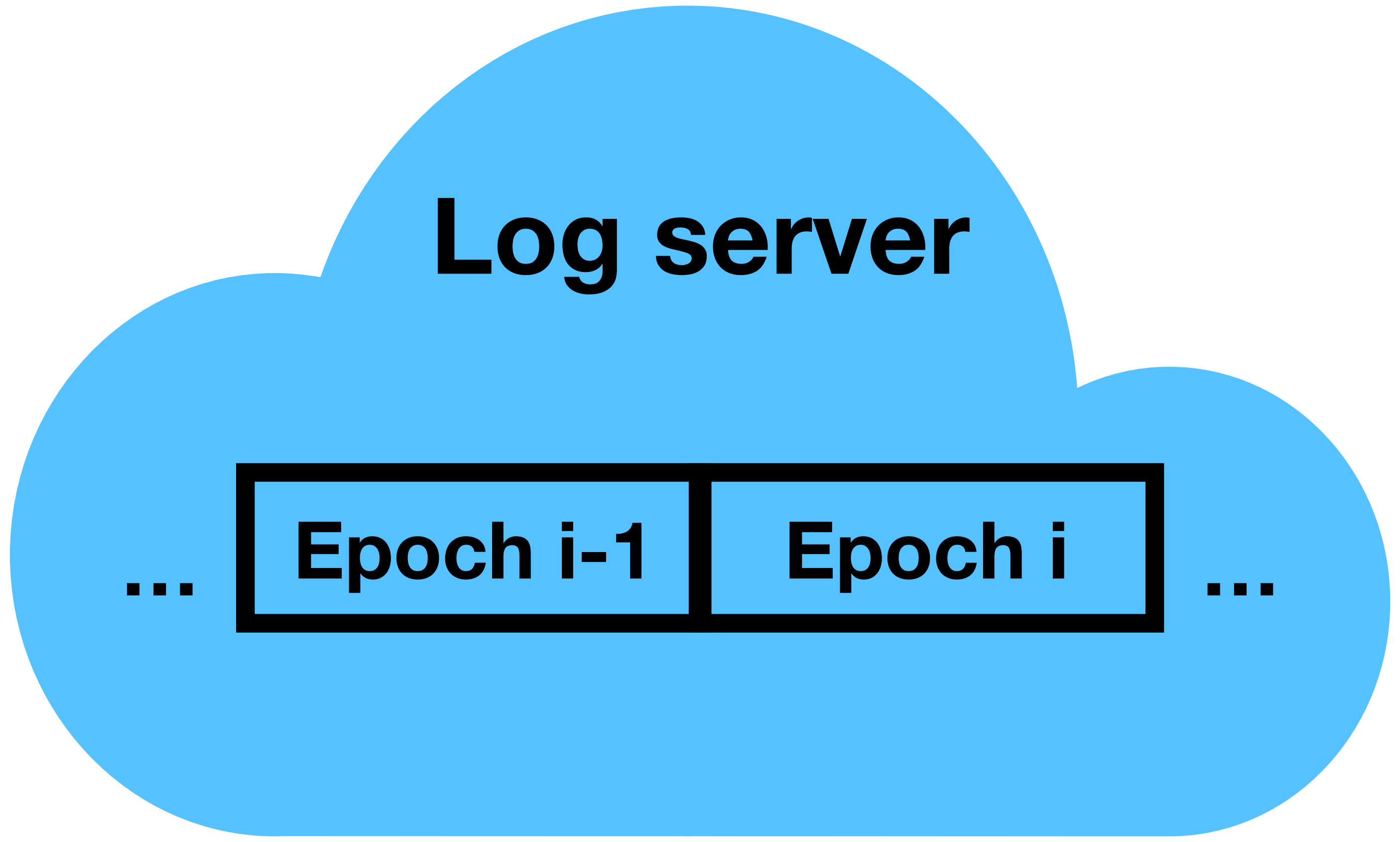
  - Trusted to check each certificate that it receives

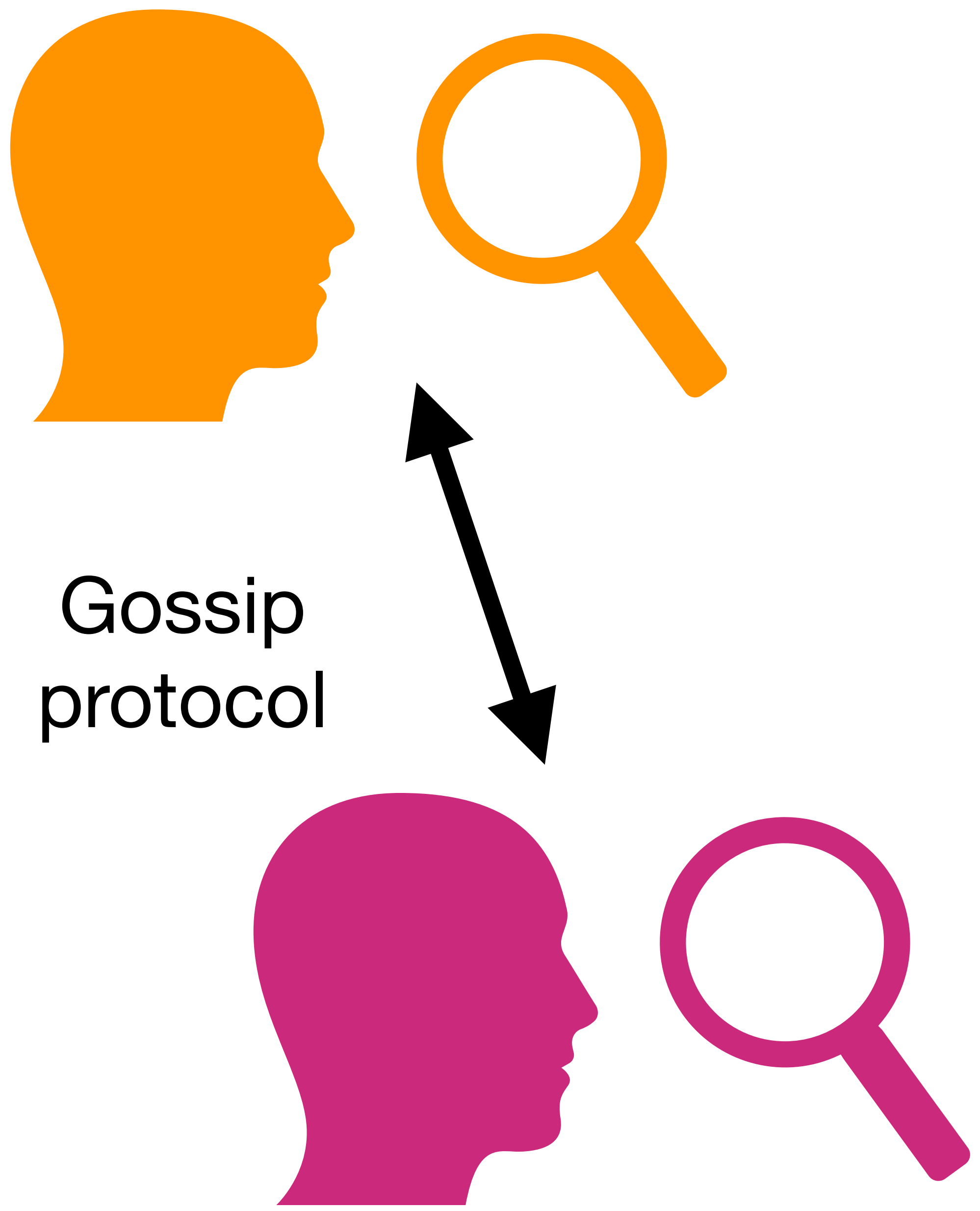
Certificate transparency

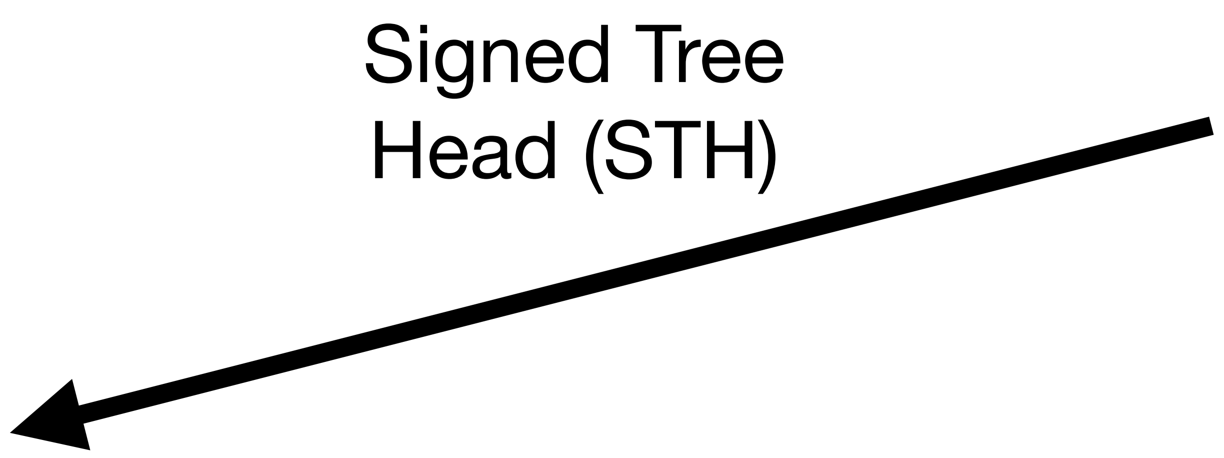
- Log servers store certificates in logs
- Construct Merkle trees over entire logs
- Divide certificates into epochs
- Periodically "checkpoint" and produce summaries of epochs (Signed Tree Head)

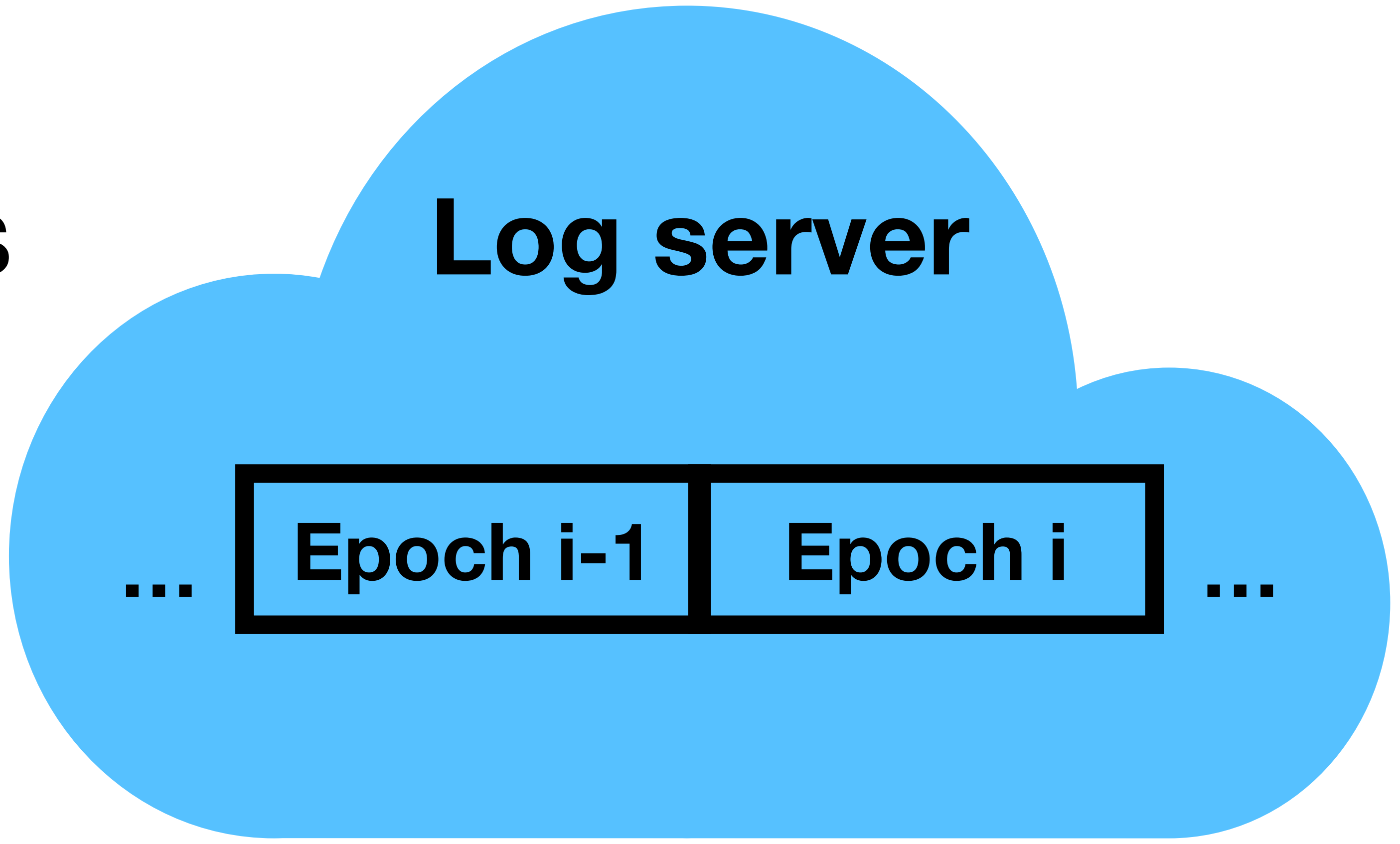


Certificate transparency

- Auditors check for extension proofs of tree nodes
- Auditors check consistency with each other to prevent “split view attacks” via gossip protocols





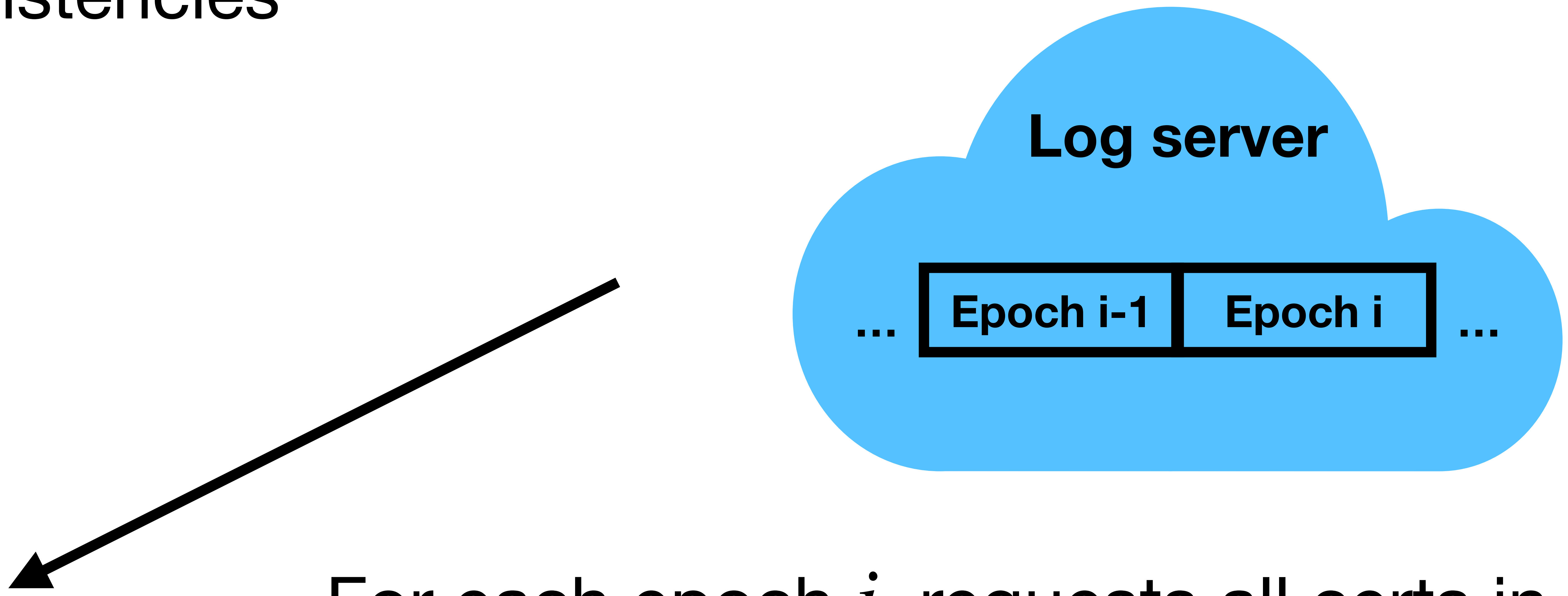


Consistency proof:

- Server proves that H^{i}_{root} is an extension of H^{i-1}_{root}

Certificate transparency

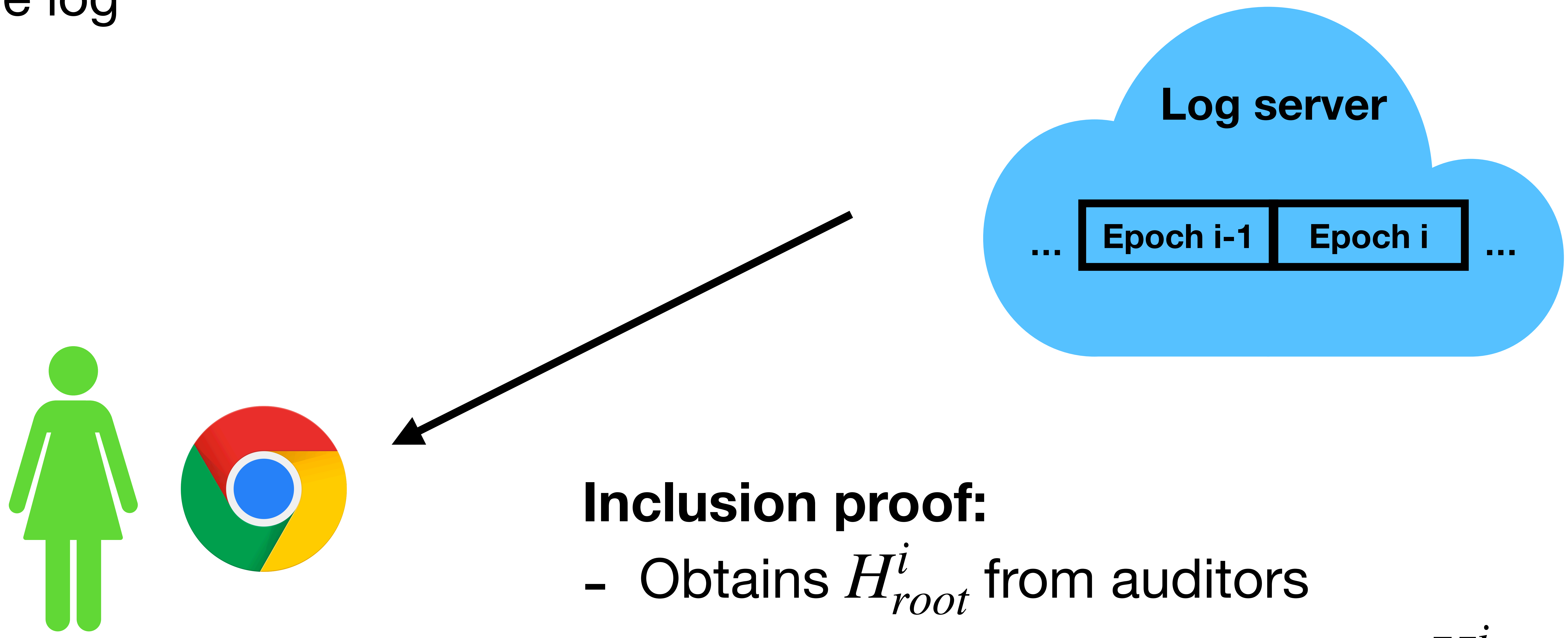
- Domain owners and independent monitors can verify logged certificates and detect inconsistencies



  - For each epoch i, requests all certs in the epoch from the log server
  - Checks them against H_{root}^{i} and H_{root}^{i-1} from the auditors
  - Checks that bank.com's certs are valid

Certificate transparency

- End users check that a website certificate is indeed valid and included in the log



Inclusion proof:

- Obtains H^{i}_{root} from auditors
- Log server proves that cert is in H^{i}_{root} by supplying the Merkle proof

Security analysis

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  - “*Verifying that a given certificate is included in a summary is called SCT verification, and no major web browsers actually do it yet.*”
    - Scalability issue: logs cannot handle the load of every end user contacting them for every TLS connection
    - Privacy: inclusion proof reveals to the log which certificate/domain information, which is a violation of user’s privacy

Other resources on certificate transparency

- A Google talk on CT: https://www.youtube.com/watch?v=6PrAVzjZeOI
- RFC for CT: https://datatracker.ietf.org/doc/rfc6962/
- Log proofs: https://sites.google.com/site/certificatetransparency/log-proofs-work
- Challenges in SCT verification: https://www.agwa.name/blog/post/how_will_certificate_transparency_logs_be_audited_in_practice

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- Class website at https://wzheng.github.io/15-829/index.html
- Guest speakers

Assignments

- Paper reviews (20%)
- Paper presentations + in-class discussions (30%)
- Research project (50%)

Paper reviews

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  - *What important problem is it addressing?*
  - *What are the techniques used in the paper?*
  - *What are the limitations & future work to be done?*

Paper presentations & discussion

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  - Lead class discussion around the last discussion

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    - November 29, December 1: project presentations

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  - September 29: 1 - 2 page project proposal due
  - Week of October 25: project check in
  - November 29, December 1: project presentations
  - December 10: project write ups due; format is a 6-page, double column workshop paper

Today’s reading

- “How to Read a Paper” by S. Keshav

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Books are not scrolls.
Scrolls must be read like the Torah from one end to the other.
Books are random access – a great innovation over scrolls.
Make use of this innovation! Do NOT feel obliged to read a book from beginning to end.
Permit yourself to open a book and start reading from anywhere.
In the case of mathematics or physics or anything especially hard, try to find something anything that you can understand.
Read what you can.
Write in the margins. (You know how useful that can be.)
Next time you come back to that book, you'll be able to read more.
You can gradually learn extraordinarily hard things this way.

- Manuel Blum