

authenticated data structures

Authenticated Data Structure (ADS)

- an ADS is a data structure that is “easy” to check for integrity, even for parts of it
- basics
 - it collects elements
 - it associates a cryptographic hash h with its content
 - h is called *root hash* or *basis*
 - value of $h \leftrightarrow$ content of the ADS
- integrity verification
 - each query comes with a *proof* that can be checked against h
 - each update can update h without knowing the whole ADS

typical use cases

- by using an ADS, a client can efficiently detect small tampering in large remotely-stored data set
 - when tampered data are retrieved
 - important to be sure to never use tampered data in business processes
- typical applications
 - legal
 - “legal” proof of correctness or tampering of storage
 - service level agreement verification
 - check backup integrity during partial restore
 - cloud storage
 - cryptocurrencies
 - Internet of Things

cloud storage example

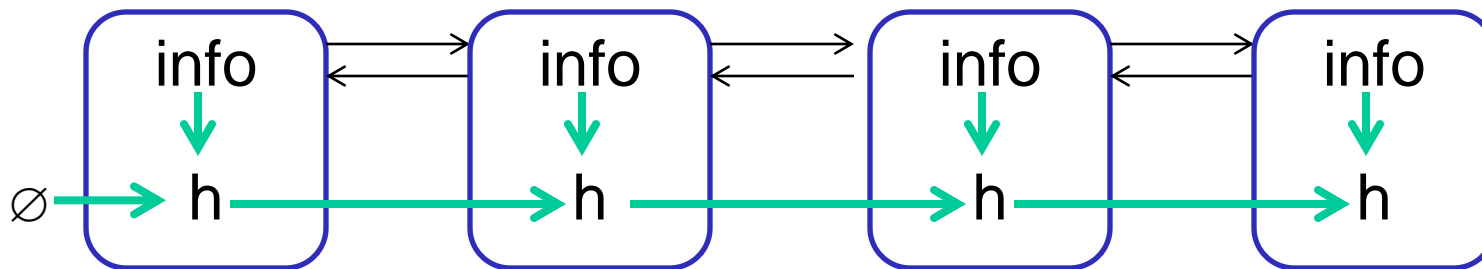
- cloud-based storage
 - virtually unlimited, cheap, **untrusted**
- local storage
 - limited, expensive, **trusted**
 - e.g. IoT device, smartphone, your PC
- idea:
 - store a large dataset on the cloud **with an ADS**
 - store **just h locally**
- clients read and write from the cloud
 - query results, with their proof, are checked against trusted local h
 - updates change remote dataset, remote ADS, and local trusted h

(some) ADS quality metrics

- as for regular data structures
 - time complexity for queries
 - time complexity for updates
 - space overhead
- plus...
 - time complexity for proof construction
 - time complexity for proof check
 - space complexity for proof

a very simple ADS: authenticated list

- a linked list plus...
- ... each element contain a field h
 $h = \text{hash}(\text{info} \mid \text{prev.h})$



- each h is a crypt. hash of current info and all previous info

authenticated list: (in)efficiency

- append an element $O(1)$
- update of info of a generic element $O(n)$
 - n is the number of elements
 - this is not $O(1)$, all following hashes should be updated!
- query $O(n)$
- proof space $O(n)$, time $O(n)$
 - it is made of previous h and all subsequent info
- closely related with blockchain
 - where append is the most important operation

other ADSes

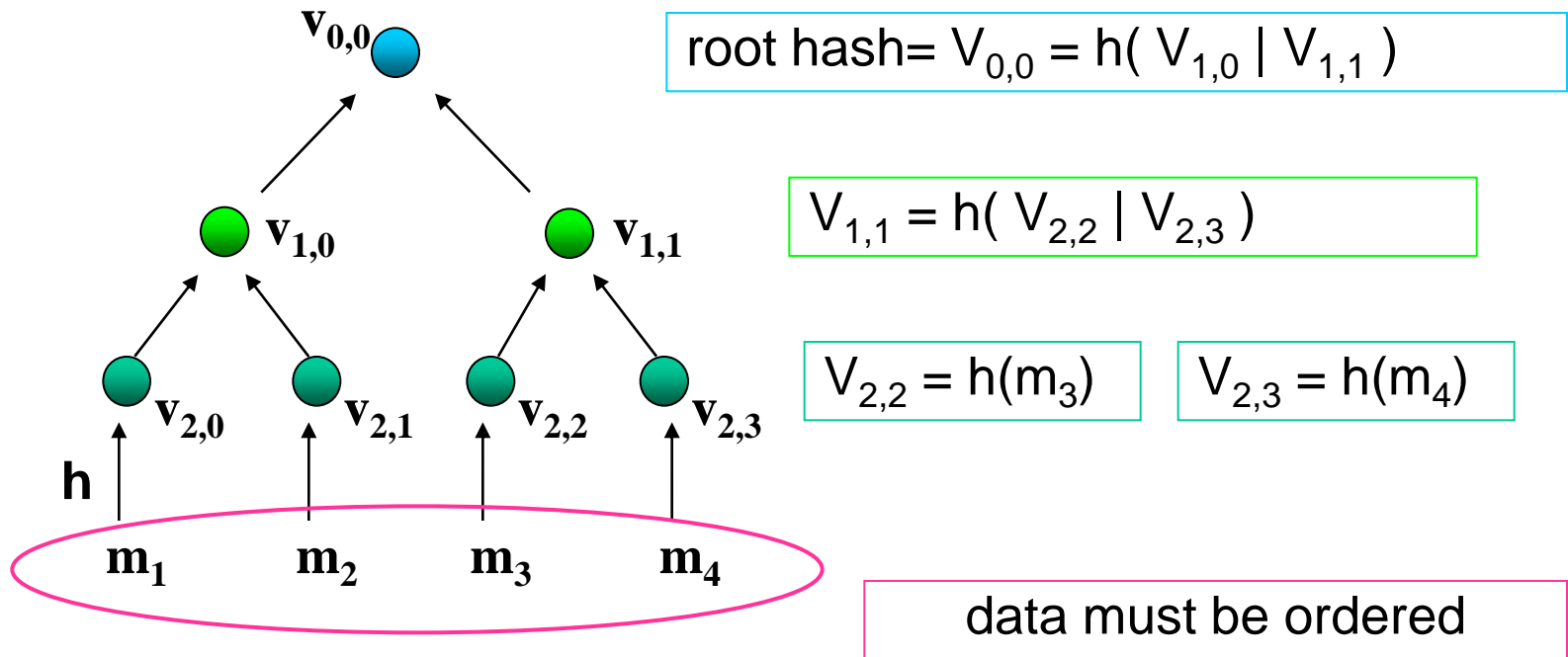
- Merkle Hash Tree (MHT)
 - a.k.a Merkle Tree or Hash Tree
- authenticated skip list
- DB-tree [1] (ADSes on databases)

- static or dynamic
 - e.g. for backup check a static data structure is ok
 - MHT are mostly used in their static flavor
- deterministic or randomized
 - skip list are typically randomized

[1] Pennino, D., Pizzonia, M., & Papi, A. (2019). Overlay Indexes: Efficiently Supporting Aggregate Range Queries **and Authenticated Data Structures in Off-the-Shelf Databases**. arXiv preprint arXiv:1910.11754.

MHT: how does it work

- a (balanced binary) tree
- each node v contains a hash of the data associated with leaves of the subtree rooted at v



$h(.)$ is a cryptographic hash function

MHT: query verification

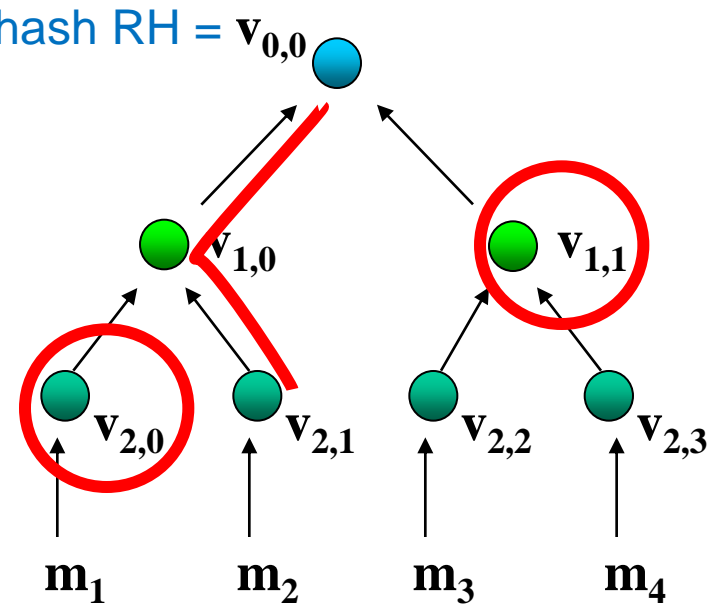
- proof for m_i :
 - consider the path p from m_i to root (excluded)
 - the proof is made of “steps”, one for each node v of p
 - each step is a pair
 - label **L** or **R** depending on how parent of v is entered
 - (hash in the) sibling of v

- example: m_2

– $p = v_{2,1} v_{1,0}$

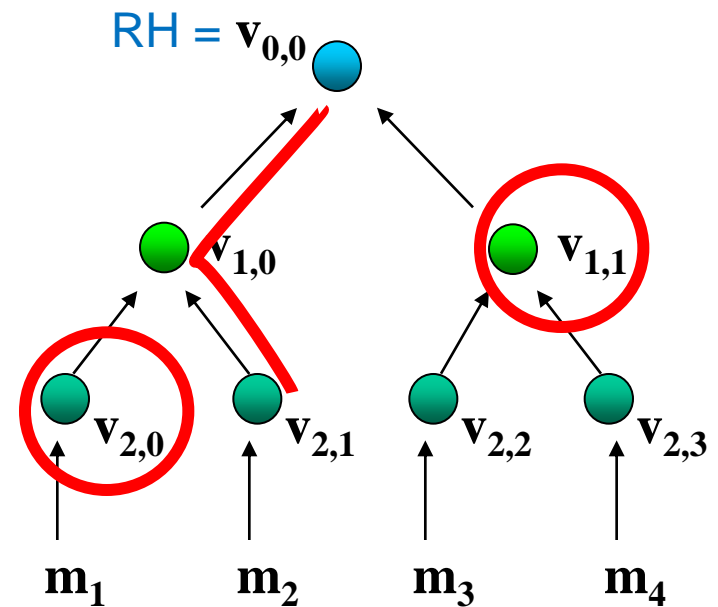
– proof

- R $v_{2,0}$
- L $v_{1,1}$



MHT: query verification

- suppose that verifier has a trusted version of the root hash: tRH
- procedure for integrity check
 - from proof re-compute RH, in the example
 $RH = h(h(v_{2,0} | h(m_2)) | v_{1,1})$
 - compare
 $RH == tRH$



MHT: query verification semantic

- client is sure that the data of the reply comes from the dataset associated with the trusted version of the root hash

MHT: query verification

- correctness (no false positives)
 - client reconstructs part of the MHT
- security (no false negatives)
 - i.e., tampering of data or MHT, but same RH
 - means that attacker has found a collision for the cryptographic hash

MHT: efficiency

- for a balanced MHT creating and checking a proof is efficient
- length of the proof is $O(\log n)$
 - n : size of the stored data

MHT: query verification (for empty result)

- proving absence is equivalent to proving two elements are consecutive
 - for ordered sets
- consider proofs for m and m' ($m < m'$)
- m and m' are consecutive iff the label sequences of their proofs satisfy the following system of regular expressions
 - labels of proof of $m = xLz$
labels of proof of $m' = yRz$
 $x = R^*$
 $y = L^*$
 - for perfectly balanced trees $|x|=|y|$, z possibly empty

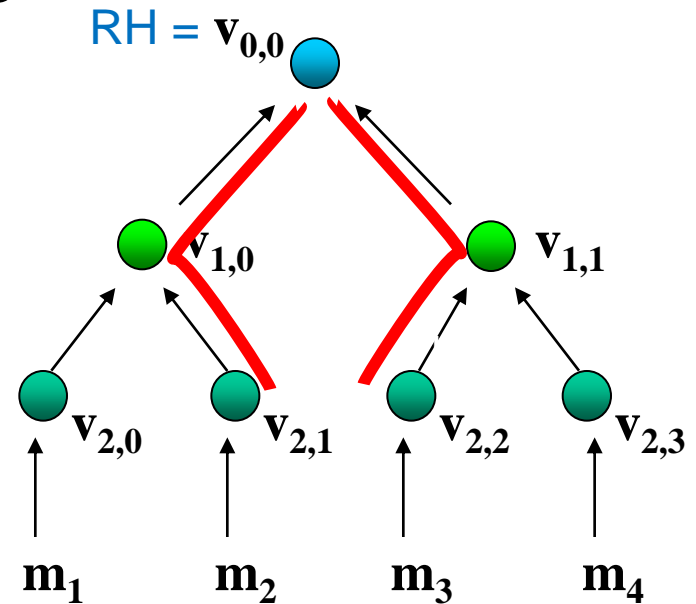
MHT: query verification (for empty result)

- check:
 - isolate common part in the two proofs (z)
 - check label sequences for the non common part of the paths (should be R^*L and L^*R)
- example: prove that $m_2 m_3$ are consecutive

- common path empty
 - just the root is common

– proof for m_2
RL

– proof for m_3
LR



MHT: query verification (for empty result)

correctness and security derive from...

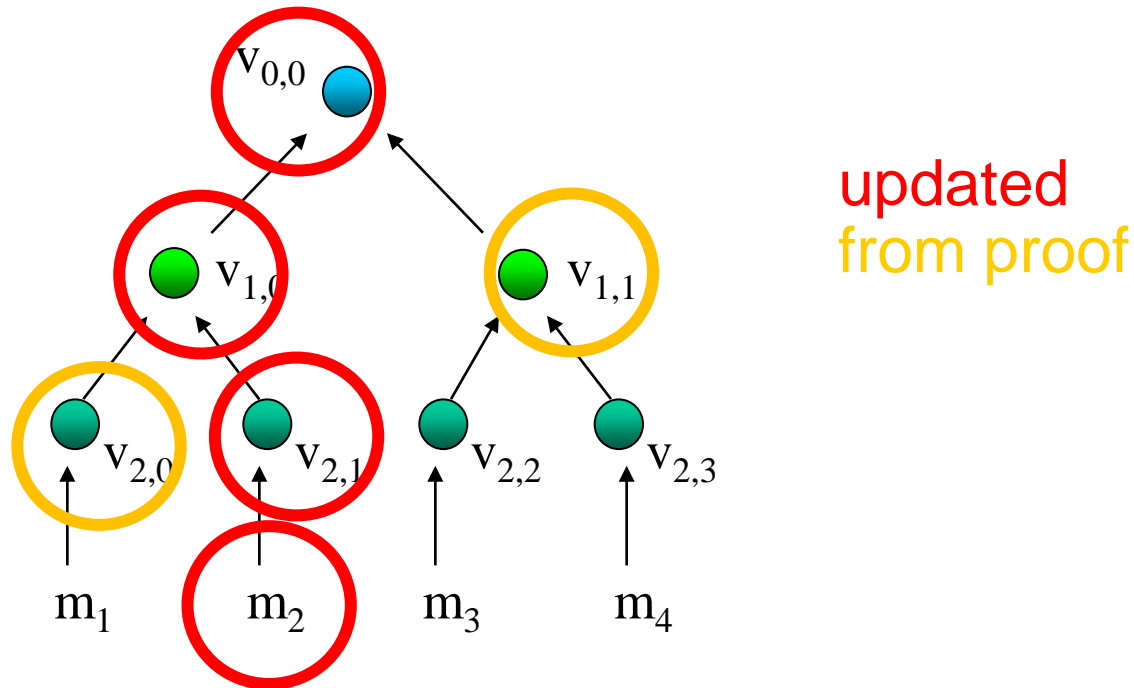
- correctness and security of proofs of m and m'
- correspondence between structure of the tree and the regular expressions

MHT: update

- we have to update m to a new version m'
 - root hash will change as well as several internal hashes
- procedure on the trusted side (e.g. client)
 - get proof p for m and check it
 - compute the new hashes of the path to the root following p substituting m' in place of m
 - the lastly computed hash is the new trusted root hash
- procedure on the untrusted side (e.g. server)
 - update the hashes of the path to the root substituting m' in place of m

MHT: update

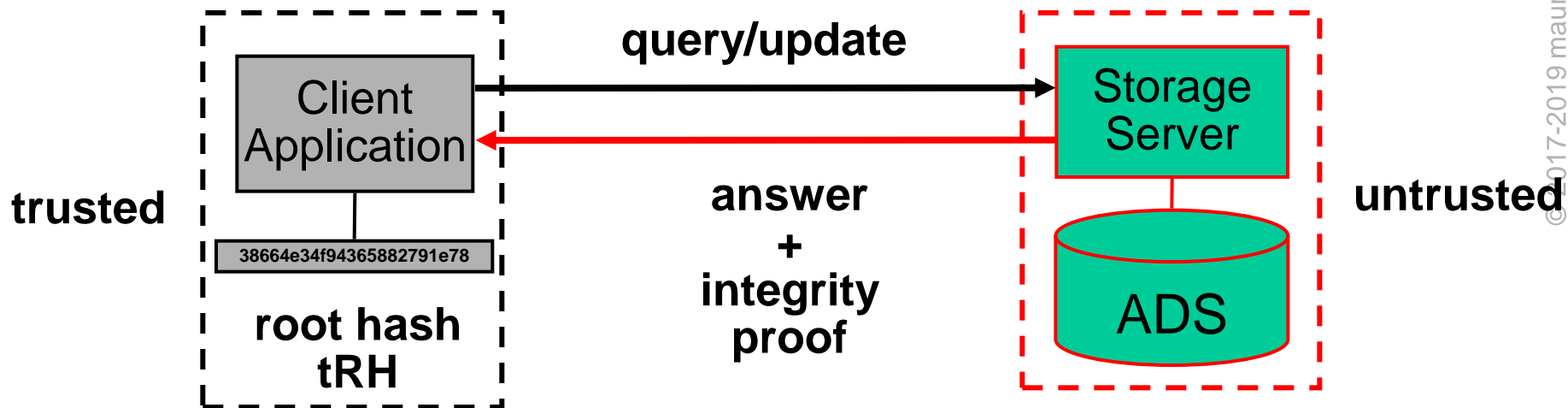
- example: update m_2 to a new version m_2'



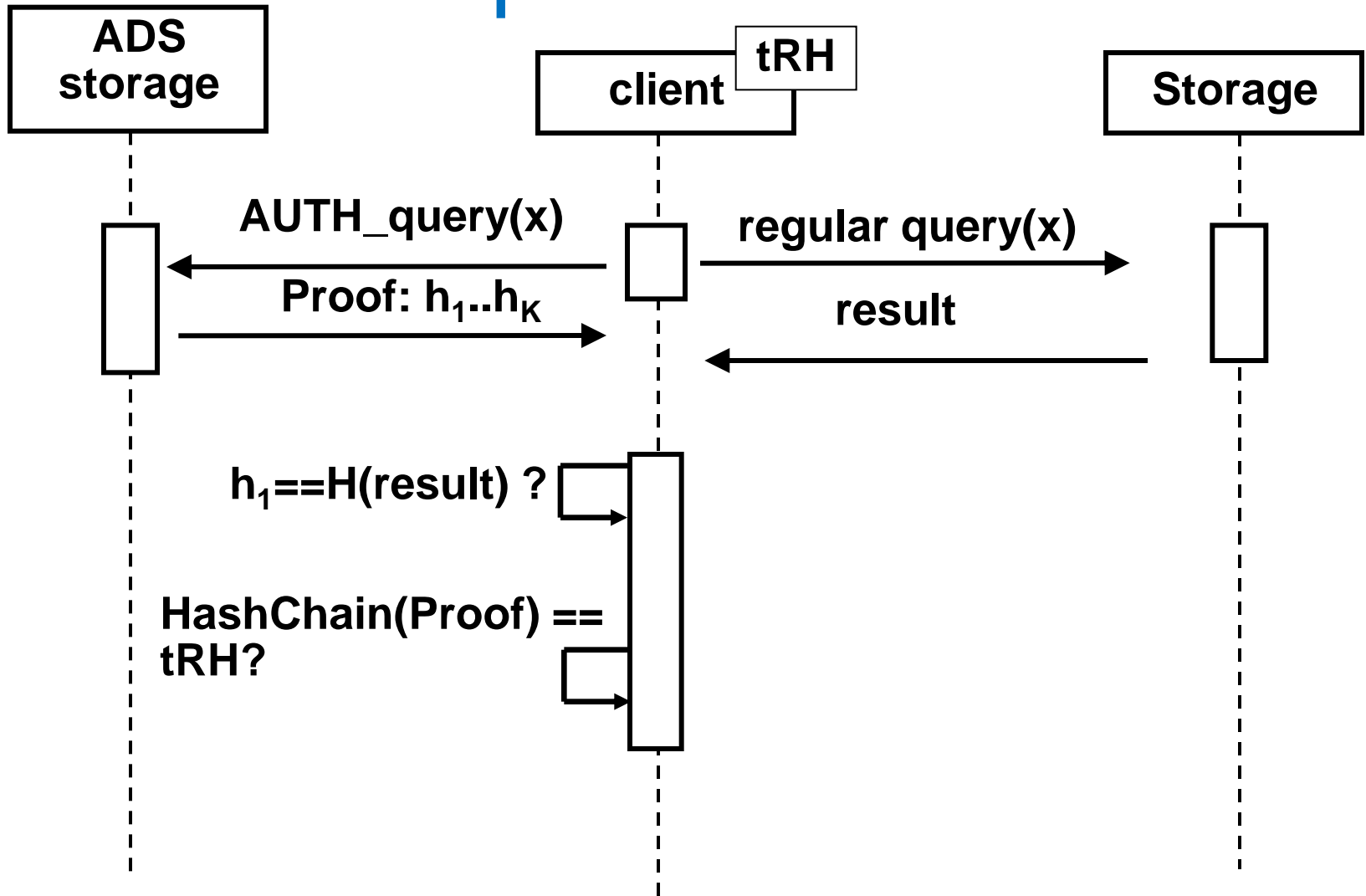
- $O(\log n)$ time for balanced trees

an ADS use case: check for malicious cloud server

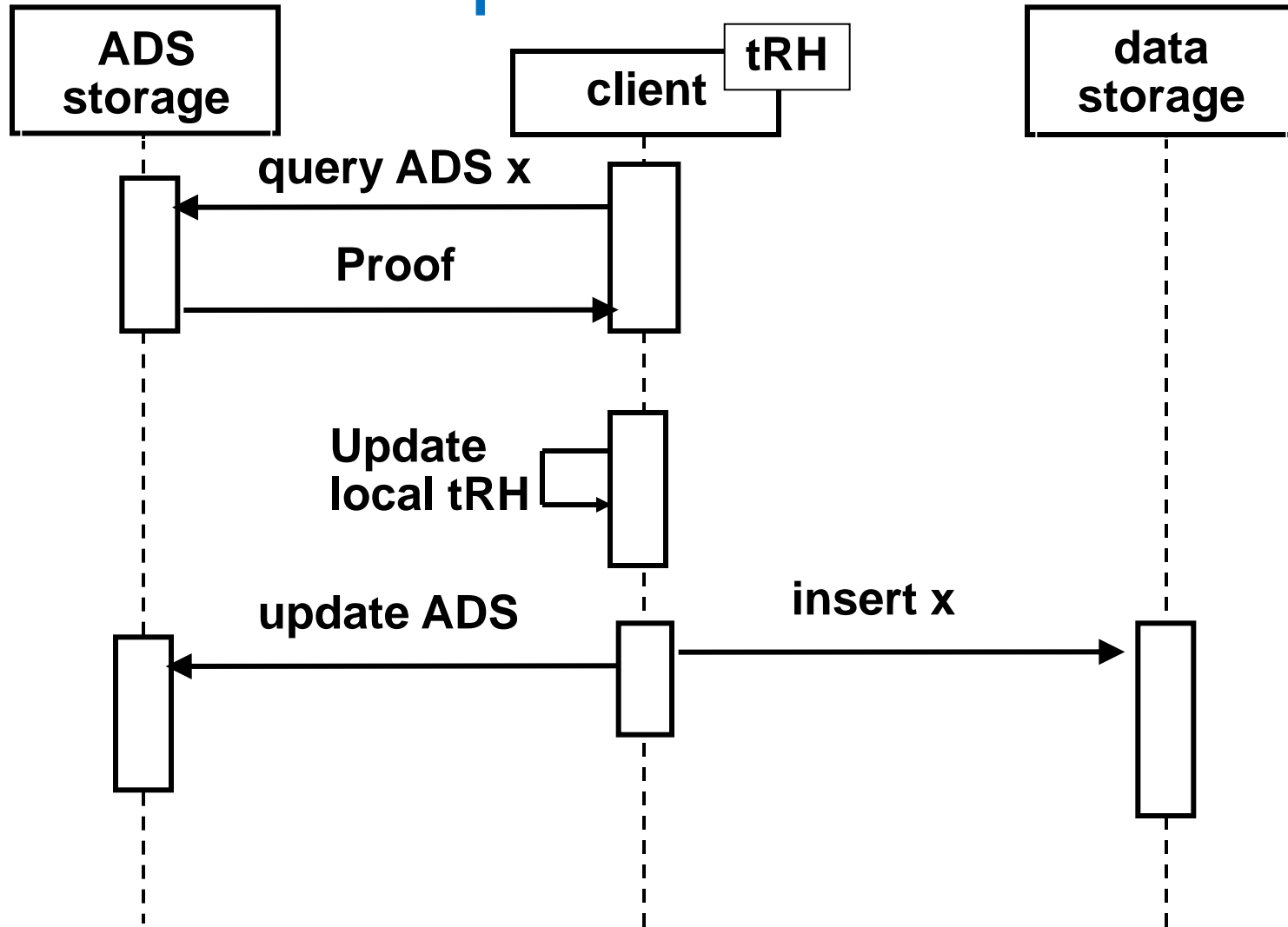
- client stores root hash locally
- ADS can be stored in cloud
- ADS can be applied to regular cloud storage
 - i.e., storage might not know about ADS
 - ADS should be properly represented in the storage



ADS authenticated query protocol



ADS authenticated update protocol



security remarks

- tampering with the ADS cannot lead to undetected data tampering
- if an ADS is lost, it could be re-created from data
- caveat: usually root hash depends not only by data but also from ADS internal structure (e.g. tree balancing)