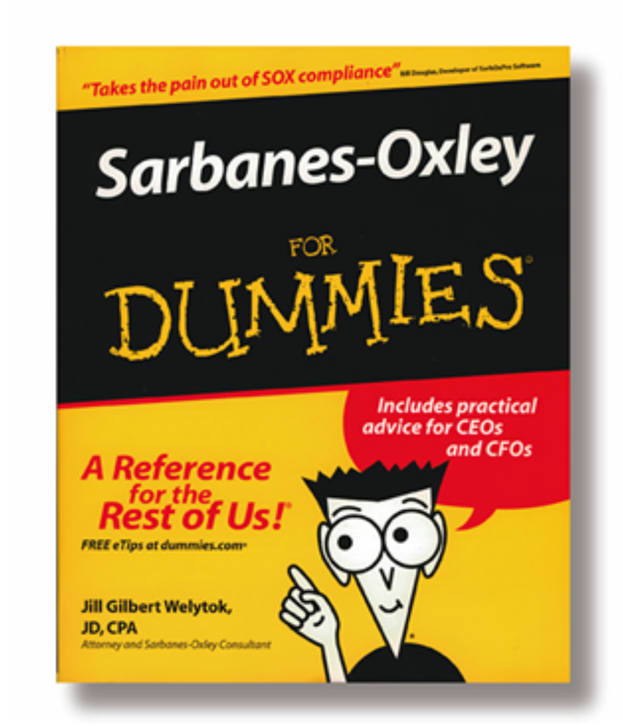
Efficient Data Structures for Tamper-Evident Logging

Scott A. Crosby

Dan S. Wallach

Rice University

Everyone has logs


"Takes the pain out of SOX compliance"
Sarbanes-Oxley
FOR DUMMIES
Includes practical advice for CEOs and CFOs
A Reference for the Rest of Us!
FREE eTips at dummies.com
Jill Gilbert Welytok, JD, CPA
Attorney and Sarbanes-Oxley Consultant

PCi Security Standards Council

HEALTH INSURANCE PORTABILITY and ACCOUNTABILITY ACT

HIPAA

ADMINISTRATIVE SIMPLIFICATION: PRIVACY, SECURITY, TRANSACTIONS

Tamper evident solutions

- Current commercial solutions
  - ‘Write only’ hardware appliances
  - Security depends on correct operation
- Would like cryptographic techniques
  - Logger **proves** correct behavior
  - Existing approaches too slow

Our solution

- History tree
  - Logarithmic for all operations
  - Benchmarks at >1,750 events/sec
  - Benchmarks at >8,000 audits/sec
- In addition
  - Propose new threat model
  - Demonstrate the importance of auditing

Threat model

- Forward integrity
  - Events prior to Byzantine failure are tamper-evident
    - Don’t know when logger becomes evil
  - Clients are trusted

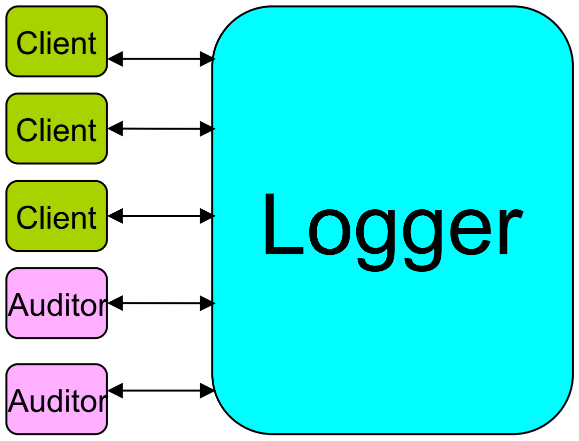
- Strong insider attacks
  - Malicious administrator
    - Evil logger
  - Clients may be mostly evil
    - Only trusted during insertion protocol

Limitations and Assumptions

- Limitations
  - – Detect misbehaviour, not prevent it
  - – Cannot prevent ‘junk’ from being logged
- Assumptions
  - – Privacy is outside our scope
    - Data may encrypted
  - – Crypto is secure

System design

- Logger
  - Stores events
  - Never trusted
- Clients
  - Little storage
  - Create events to be logged
  - Trusted only at time of event creation
  - Sends commitments to auditors
- Auditors
  - Verify correct operation
  - Little storage
  - Trusted, at least one is honest

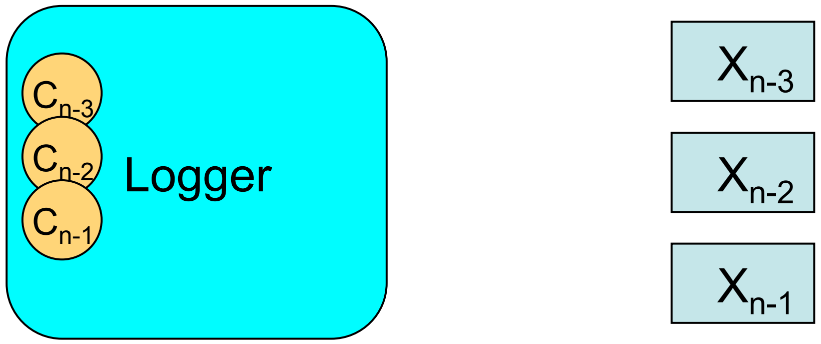


This talk

- Discuss the necessity of auditing
- Describe the history tree
- Evaluation
- Scaling the log

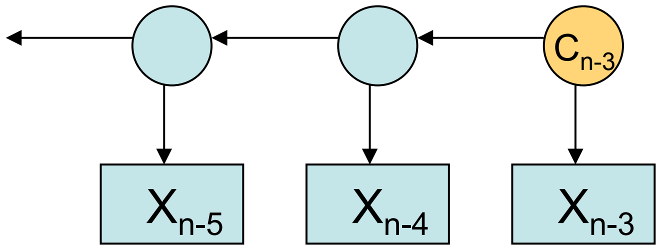
Tamper evident log

- Events come in
- Commitments go out
  - Each commits to the entire past



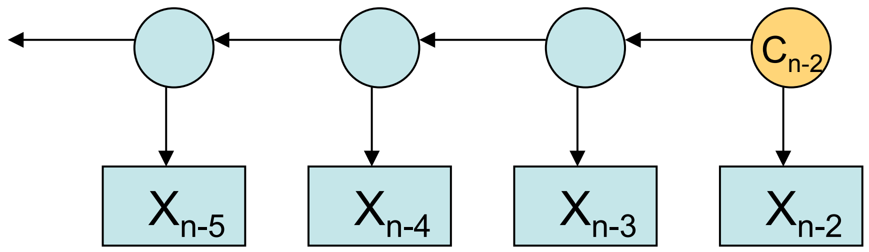
Hash chain log

- Existing approach [Kelsey,Schneier]
  - $C_n = H(C_{n-1} \| X_n)$
  - Logger signs C_n



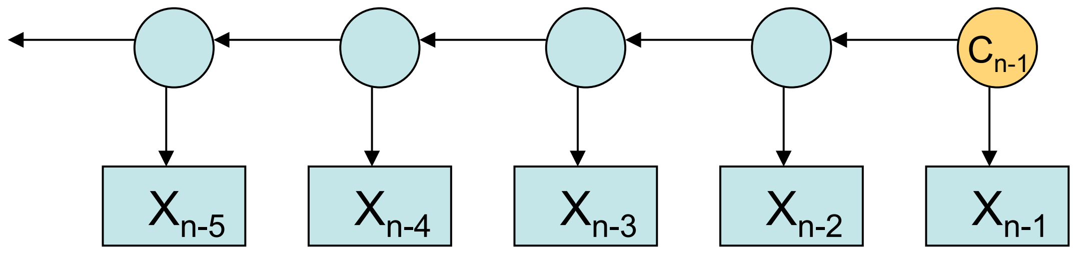
Hash chain log

- Existing approach [Kelsey,Schneier]
  - $C_n = H(C_{n-1} \| X_n)$
  - Logger signs C_n



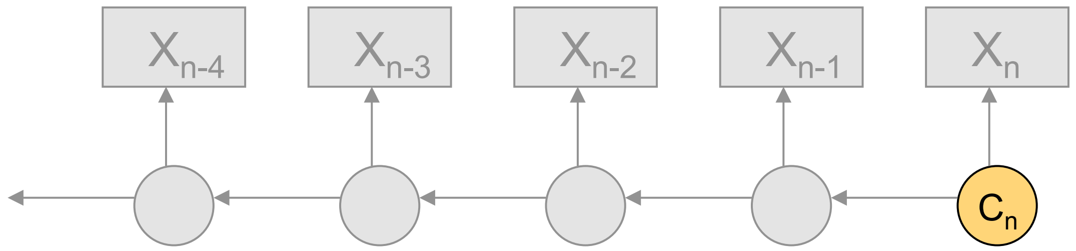
Hash chain log

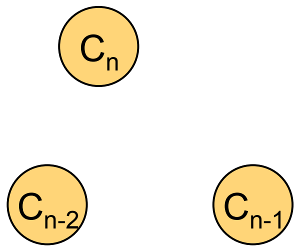
- Existing approach [Kelsey,Schneier]
  - $C_n = H(C_{n-1} \| X_n)$
  - Logger signs C_n



Problem

- We don’t trust the logger!



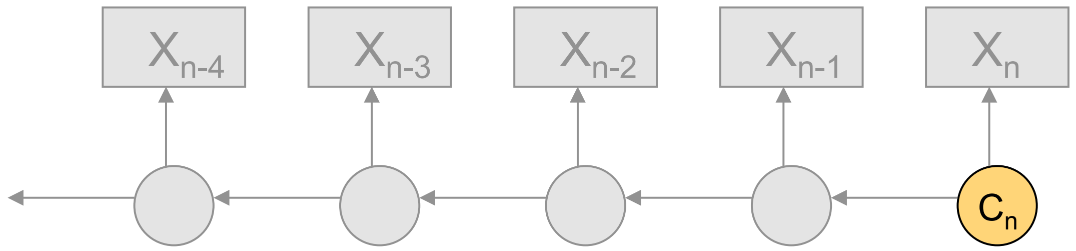


Logger returns a stream of commitments

Each corresponds to a log

Problem

- We don't trust the logger!



Does C_n really contain the just inserted X_n ?

Do C_{n-2} and C_{n-1} really commit the same historical events?

Is the event at index *i* in log C_n really X_i ?

Problem

- We don’t trust the logger!
  - Logger signs stream of log heads
  - Each corresponds to some log

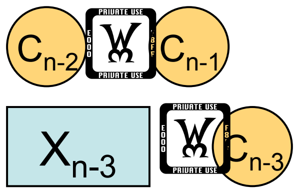
Does C_{n-3} really contain the just inserted $\boxed{X_{n-3}}$?

Do C_{n-2} and C_{n-1} really commit the same historical events?

Is the event at index *i* in log C_n really $\boxed{X_i}$?

Solution: Audit the logger

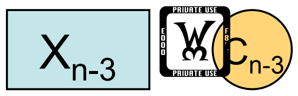
- Only way to detect tampering
  - Check the returned commitments
    - For consistency
    - For correct event lookup



- Previously
  - Auditing = looking historical events
    - Assumed to infrequent
    - Performance was ignored

Solution

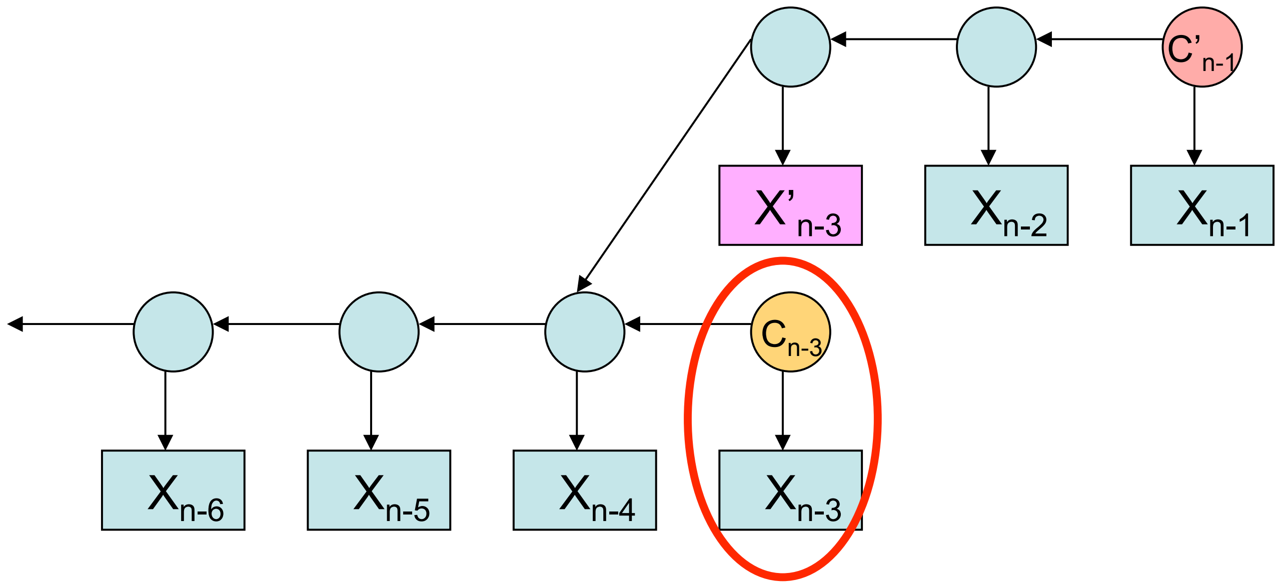
- Auditors check the returned commitments
  - For consistency
  - For correct event lookup



- Previously
  - Auditing = looking historical events
    - Assumed to infrequent
    - Performance was ignored

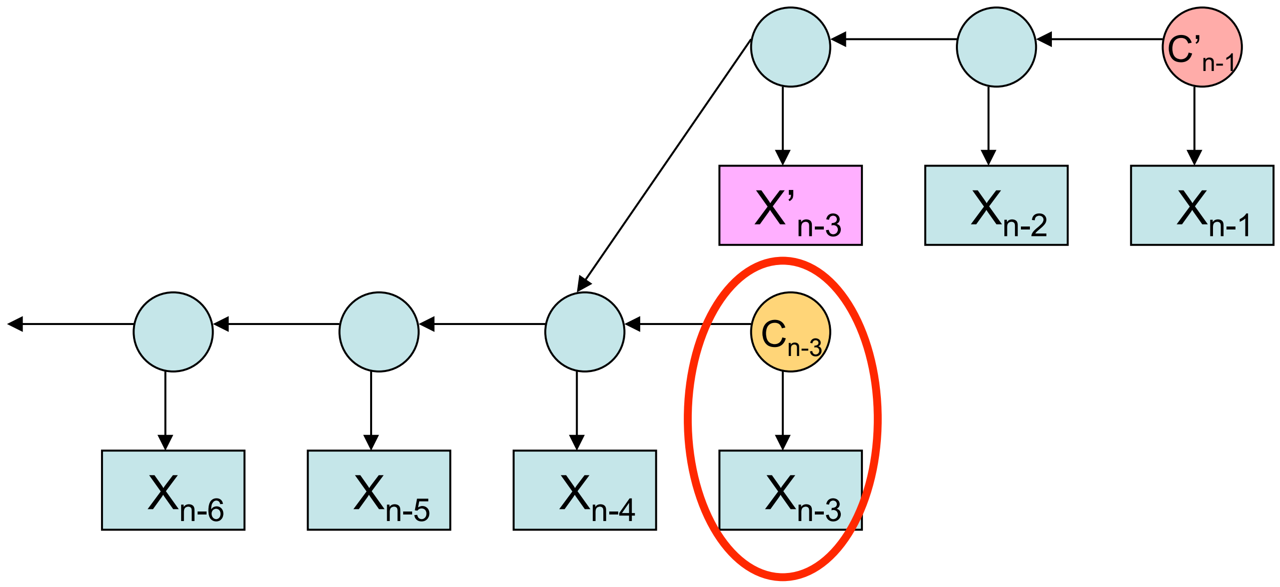
Auditing is a frequent operation

- If the logger knows this commitment will not be audited for consistency with a later commitment.



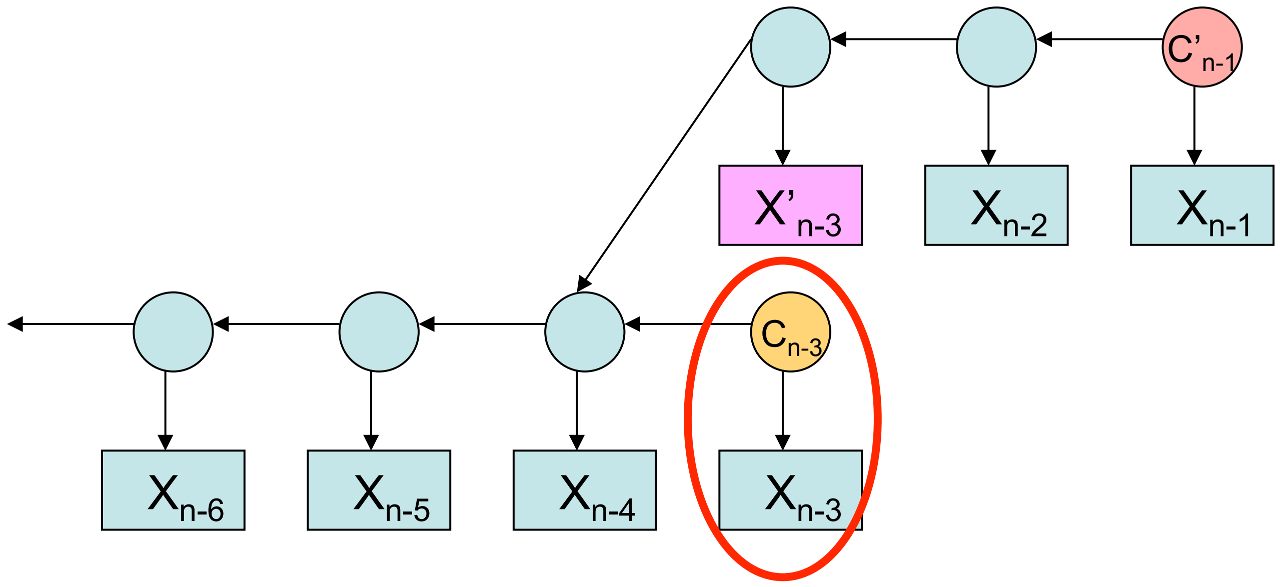
Auditing is a frequent operation

- Successfully tampered with a ‘tamper evident’ log
- Auditing required in forward integrity threat model



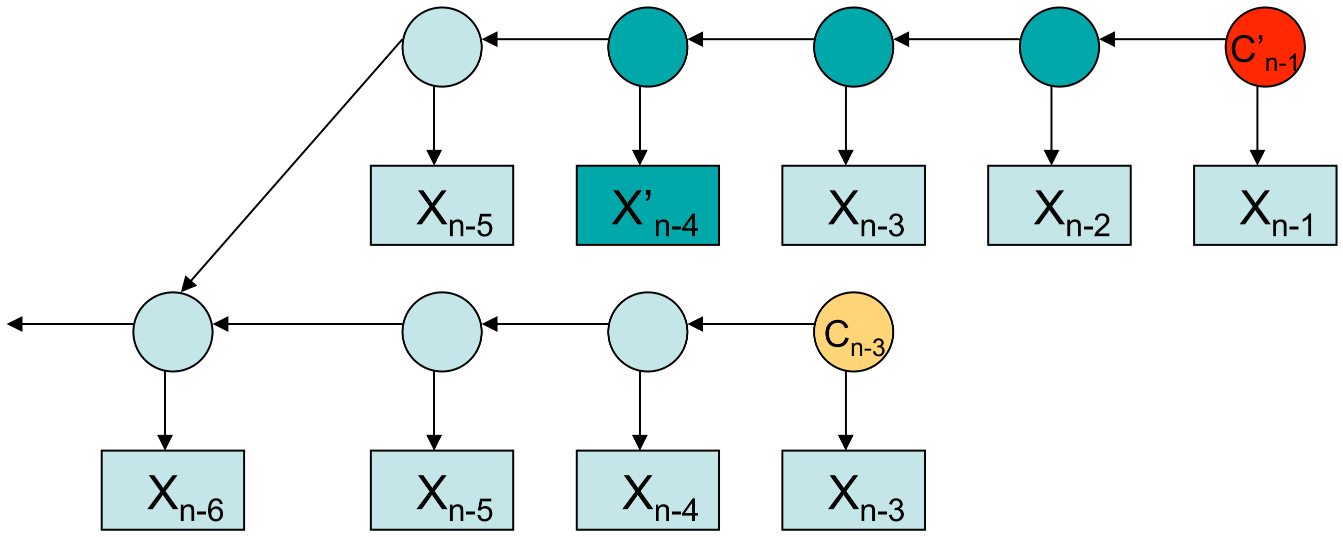
Auditing is a frequent operation

- Every commitment must have a non-zero probability of being audited



Forking the log

- Rolls back the log and adds on different events
  - Attack requires two commitments on different forks disagree on the contents of one event.
  - If system has historical integrity, audits must fail or be skipped



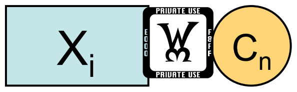
New paradigm

- Auditing cannot be avoided

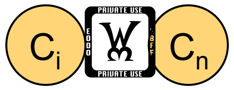
- Audits should occur
  - On every event insertion
  - Between commitments returned by logger

- How to make inserts *and audits* cheap
  - CPU
  - Communications complexity
  - Storage

Two kinds of audits

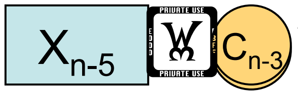
- Membership auditing


  - Verify proper insertion
  - Lookup historical events

- Incremental auditing


  - Prove consistency between two commitments

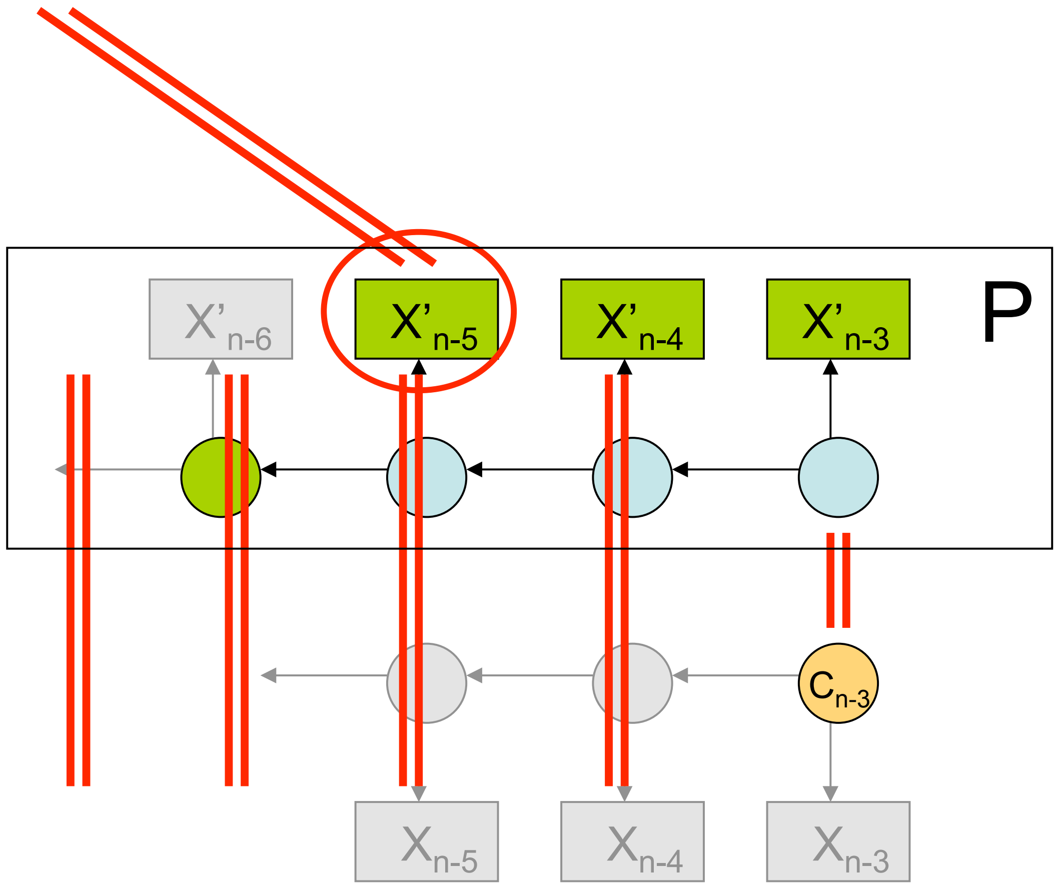
Membership auditing a hash chain

- Is 

?

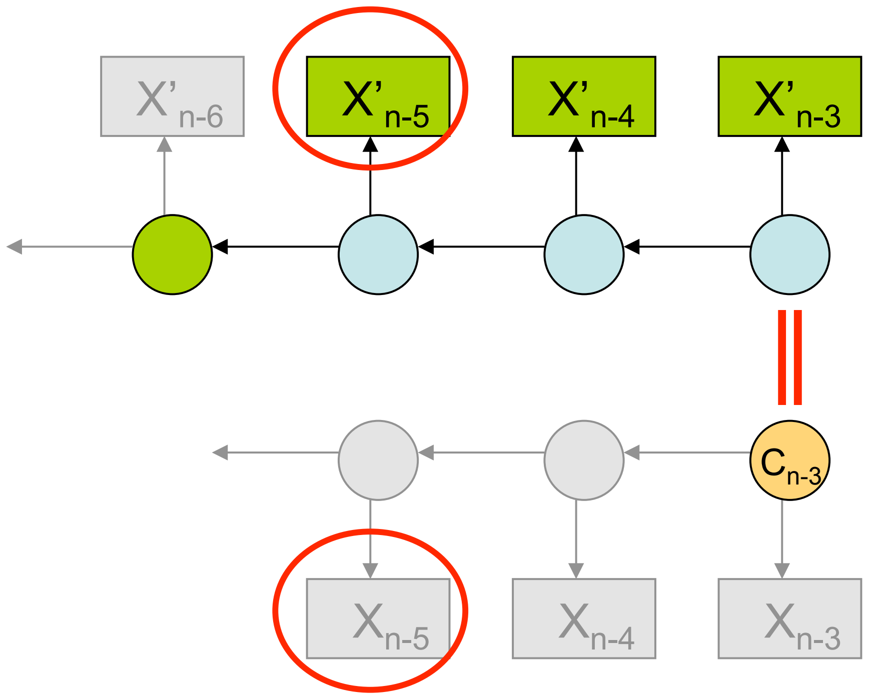
Membership auditing a hash chain

- Is X_{n-5} C_{n-3}?

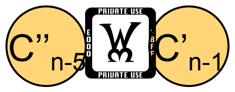


Membership auditing a hash chain

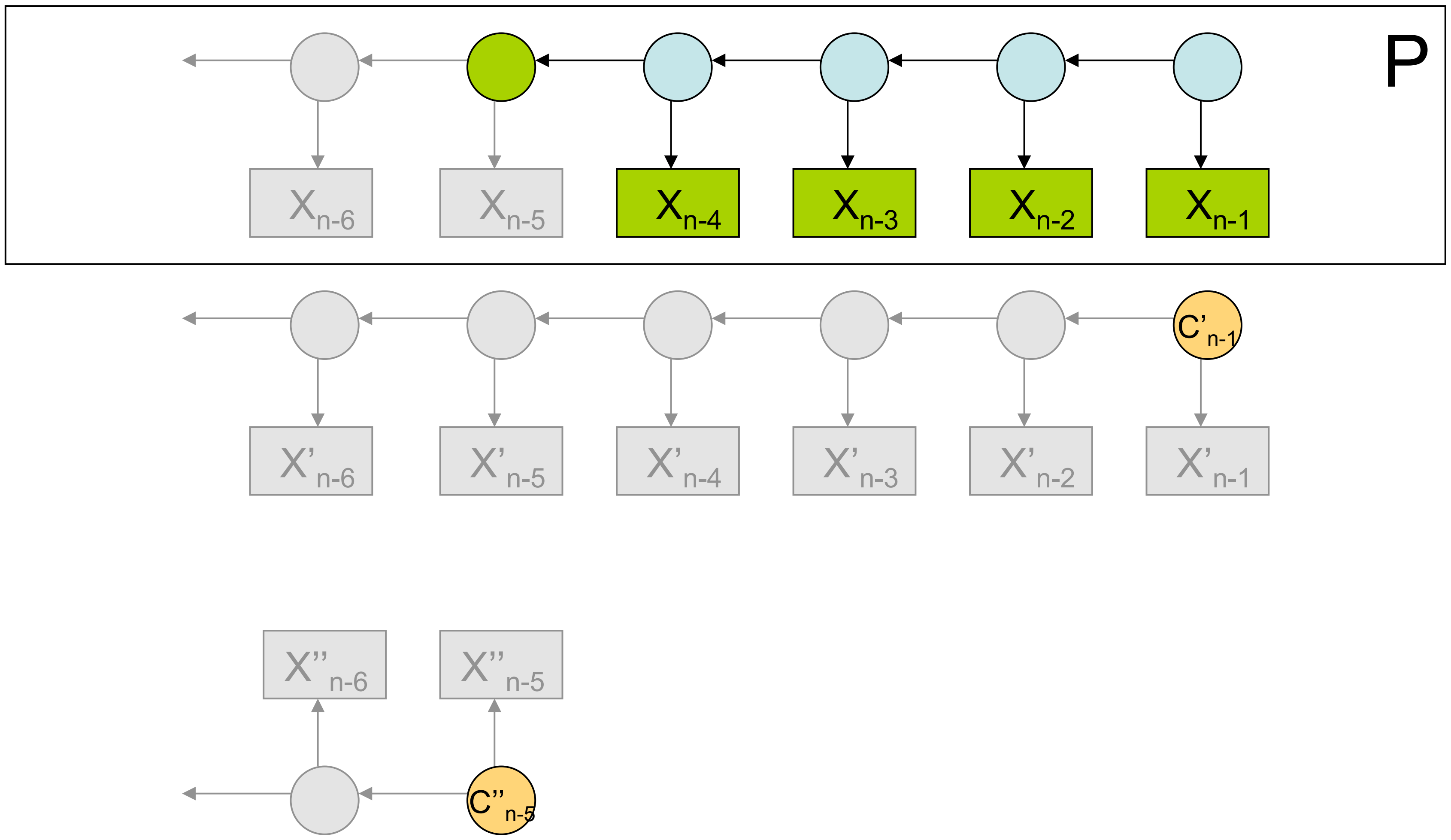
- Is X_{n-5} [illegible] C_{n-3}?



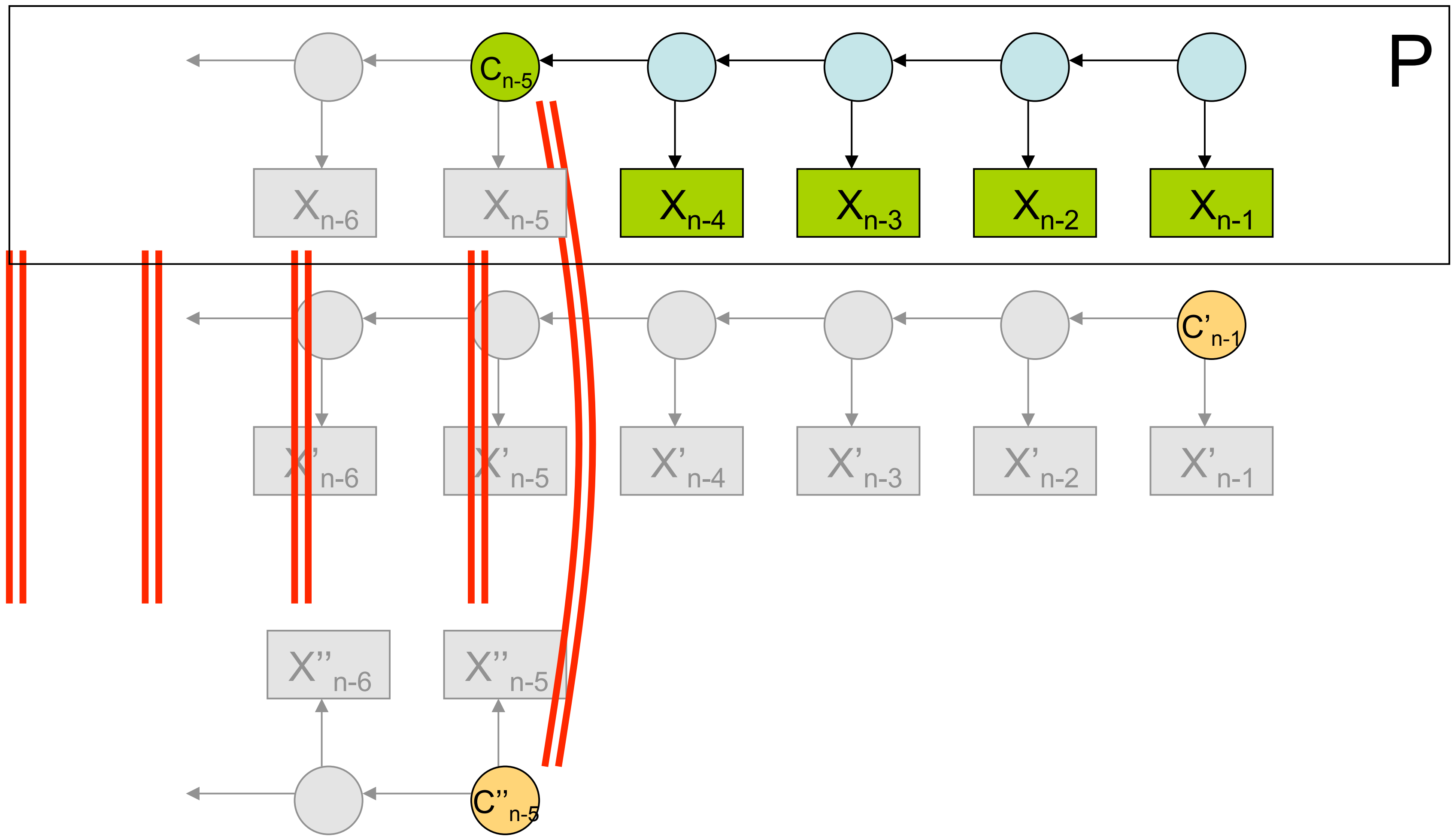
Incremental auditing a hash chain

- Are ?

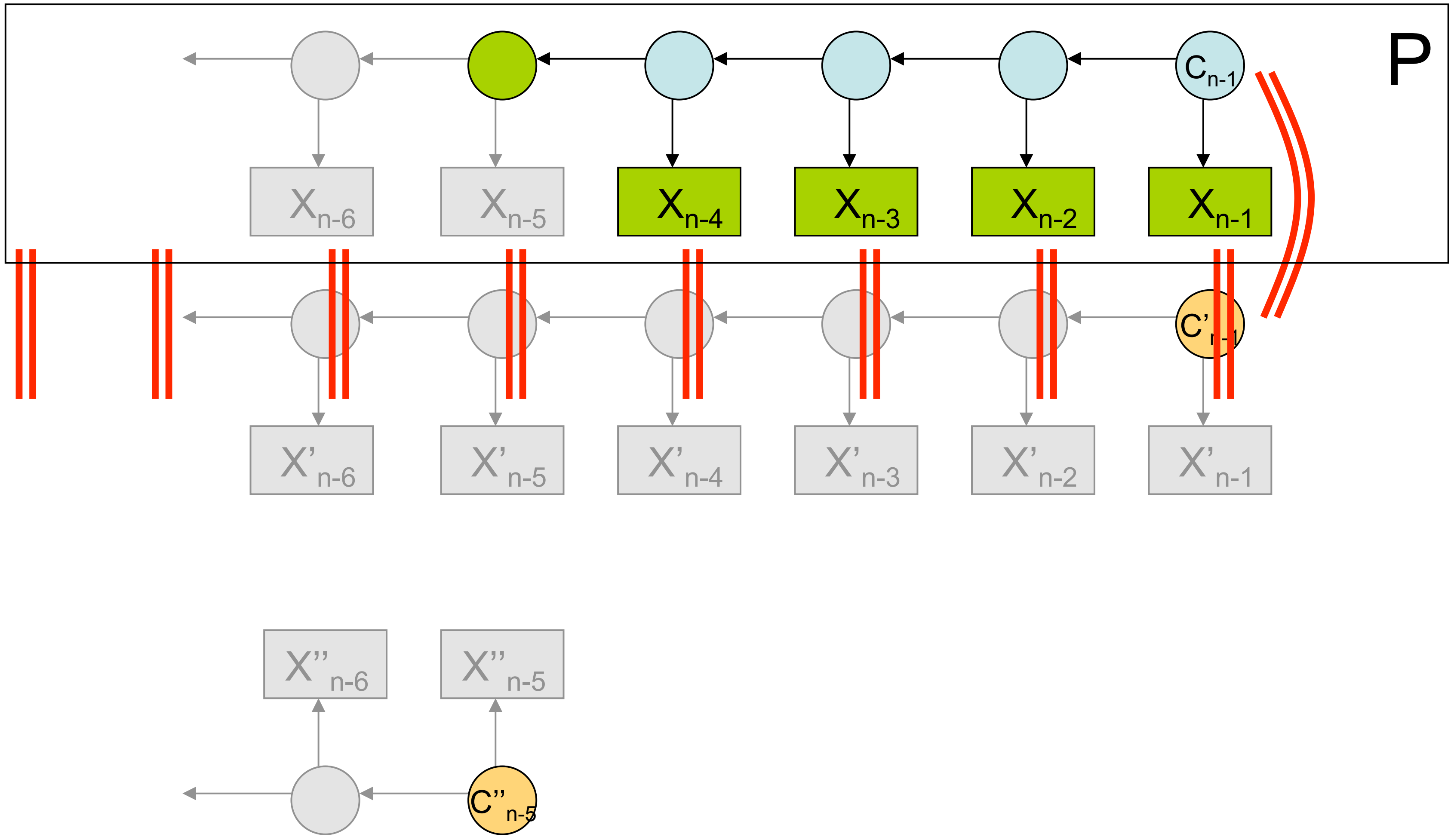
Incremental auditing a hash chain



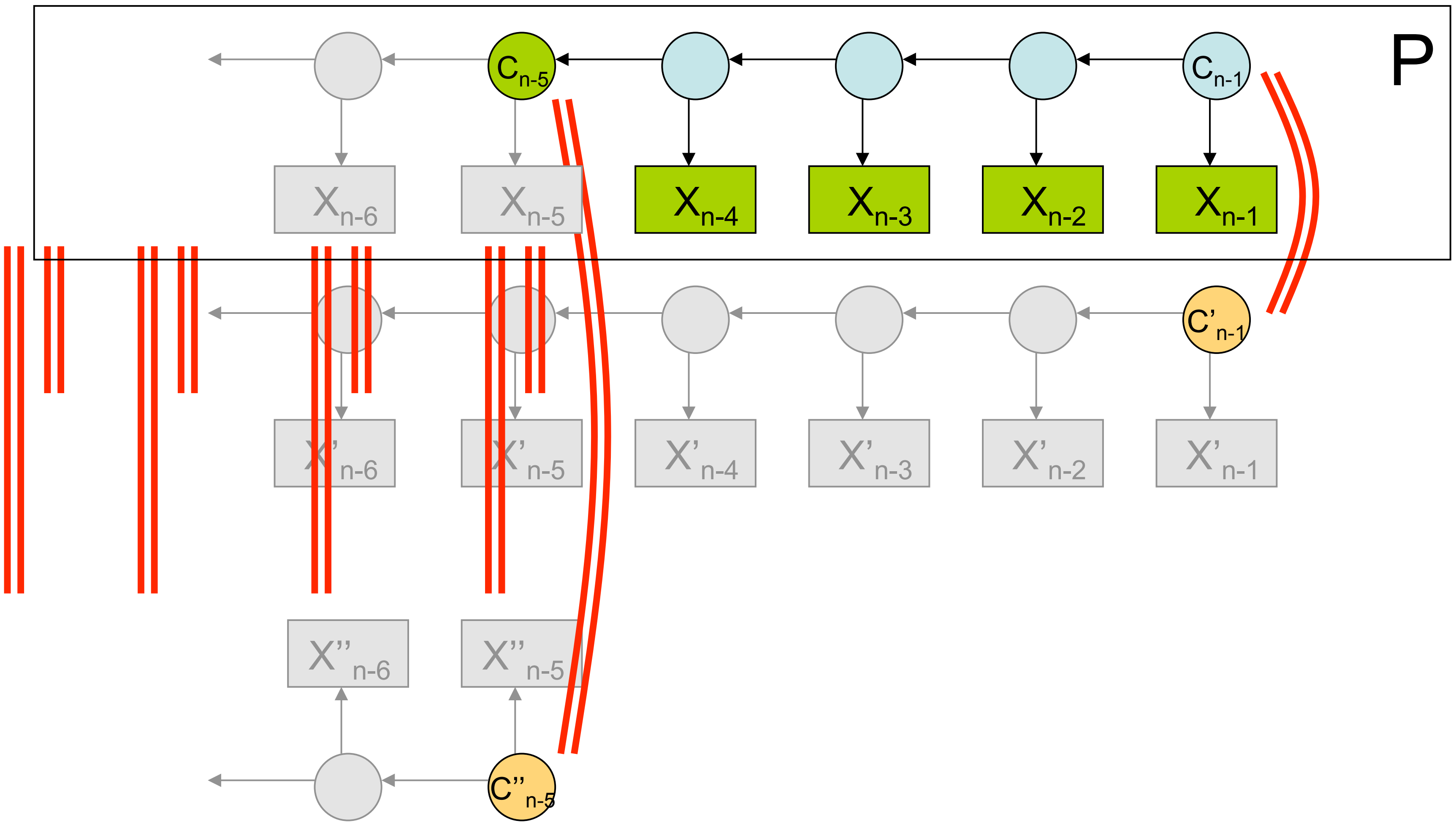
Incremental auditing a hash chain



Incremental auditing a hash chain



Incremental auditing a hash chain



Existing tamper evident log designs

- Hash chain
  - Auditing is linear time
  - Historical lookups
    - Very inefficient

- Skiplist history [Maniatis,Baker]
  - Auditing is still linear time
  - O(log n) historical lookups

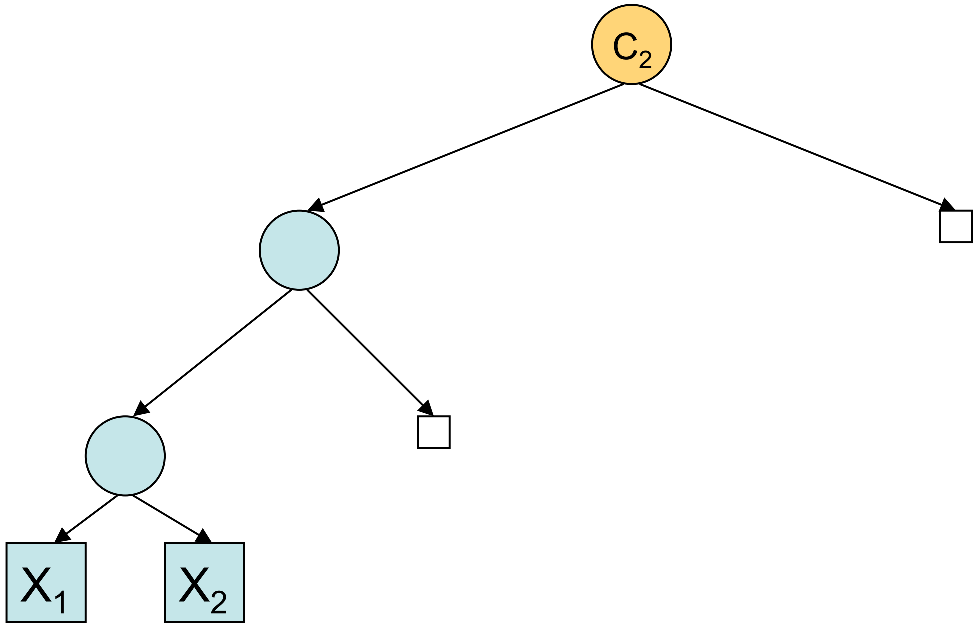
Our solution

- History tree
  - O(log n) instead of O(n) for all operations
  - Variety of useful features
    - Write-once append-only storage format
    - Predicate queries + safe deletion
    - May probabilistically detect tampering
      - Auditing random subset of events
      - Not beneficial for skip-lists or hash chains

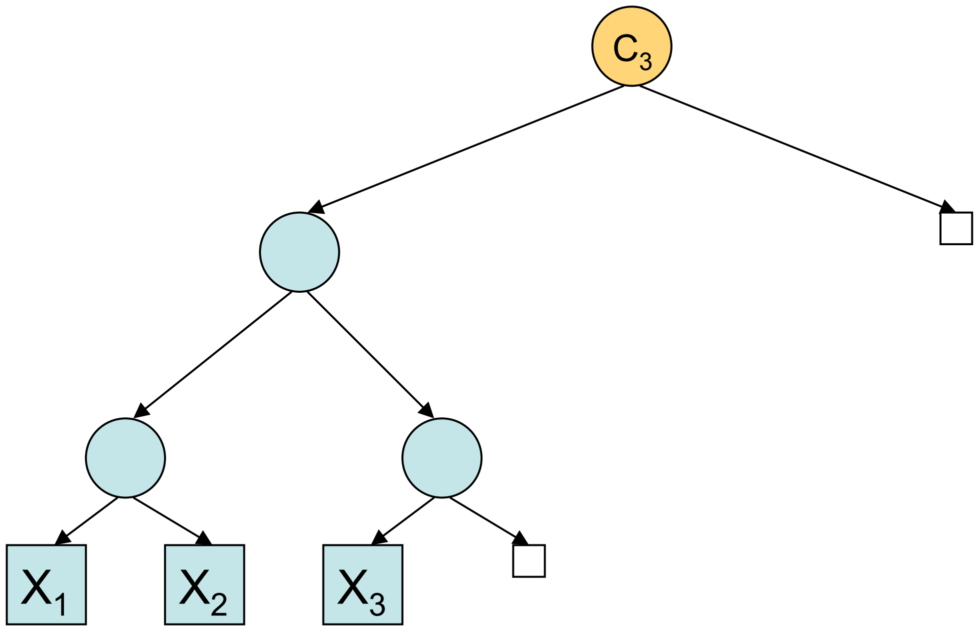
History Tree

- Merkle binary tree
  - Events stored on leaves
  - Logarithmic path length
    - Random access
  - Permits reconstruction of past version and past commitments

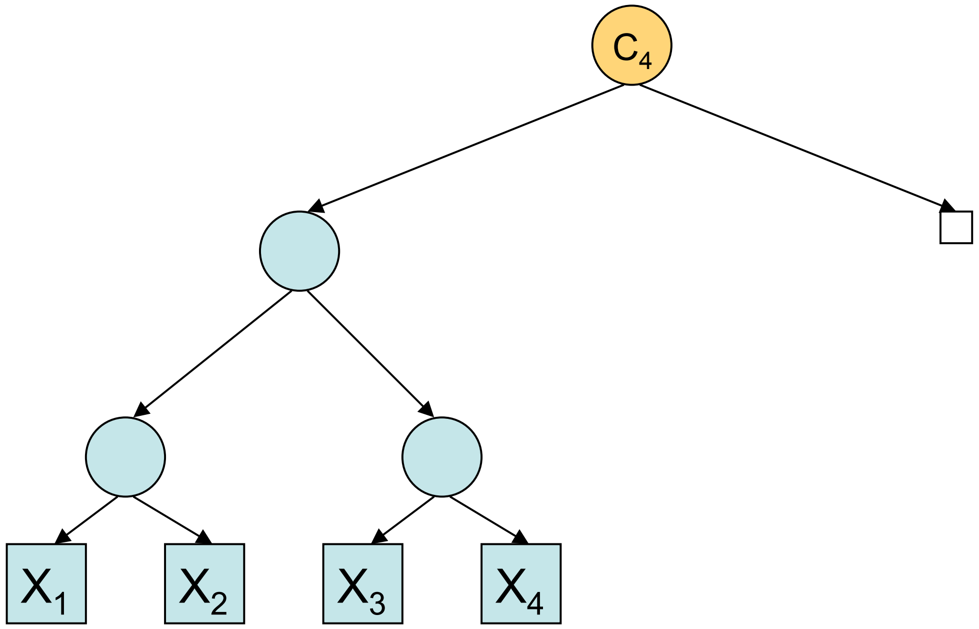
History Tree



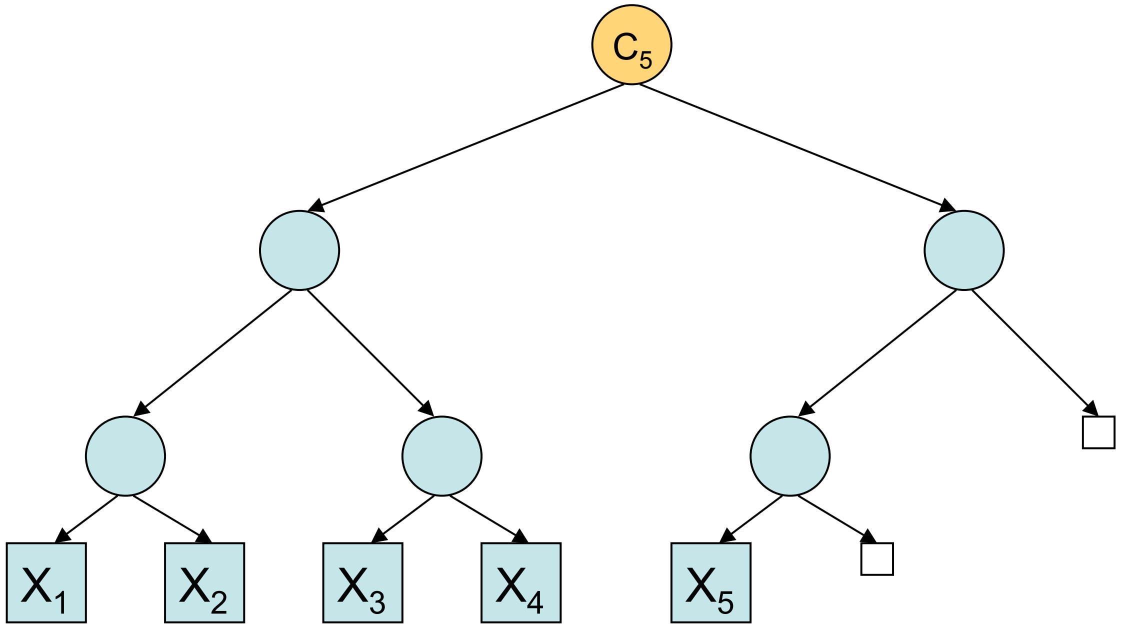
History Tree



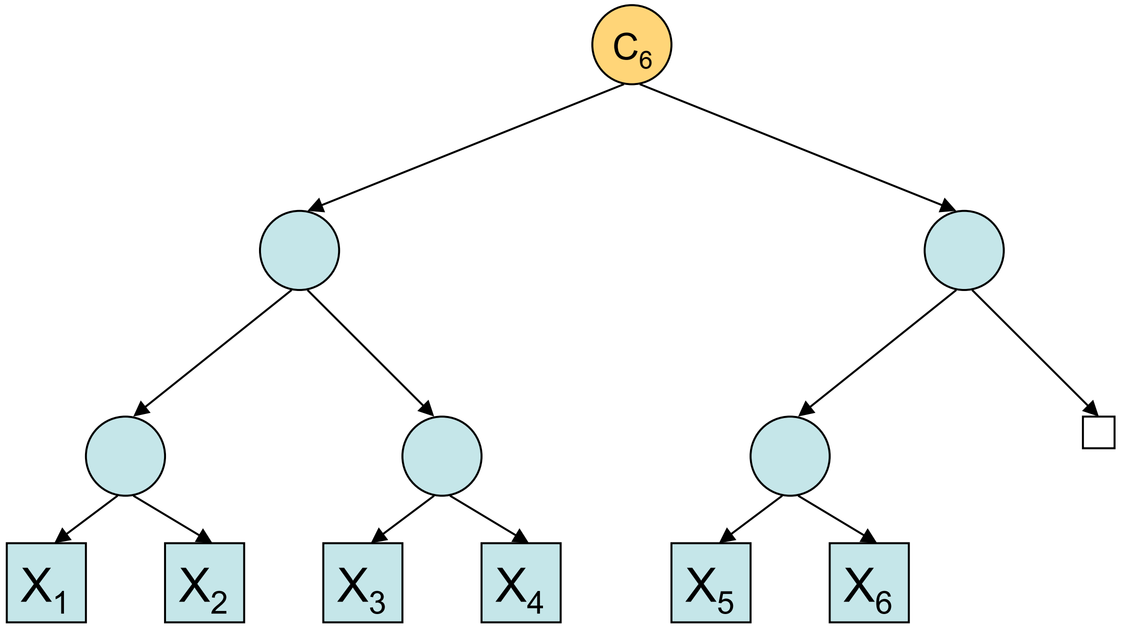
History Tree



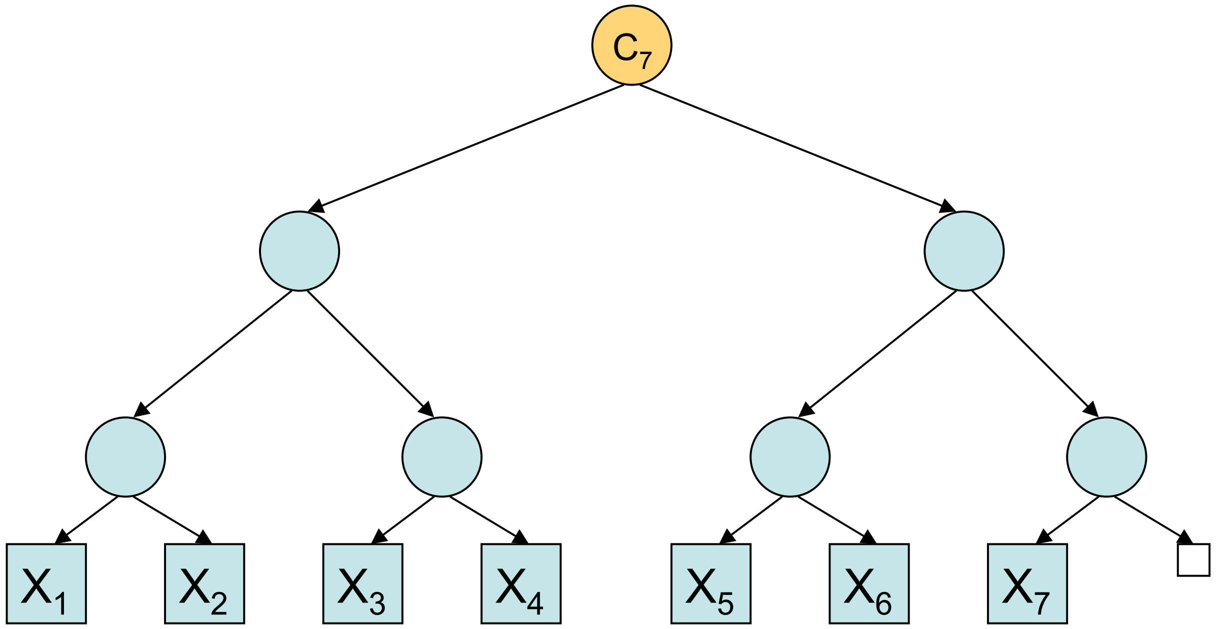
History Tree



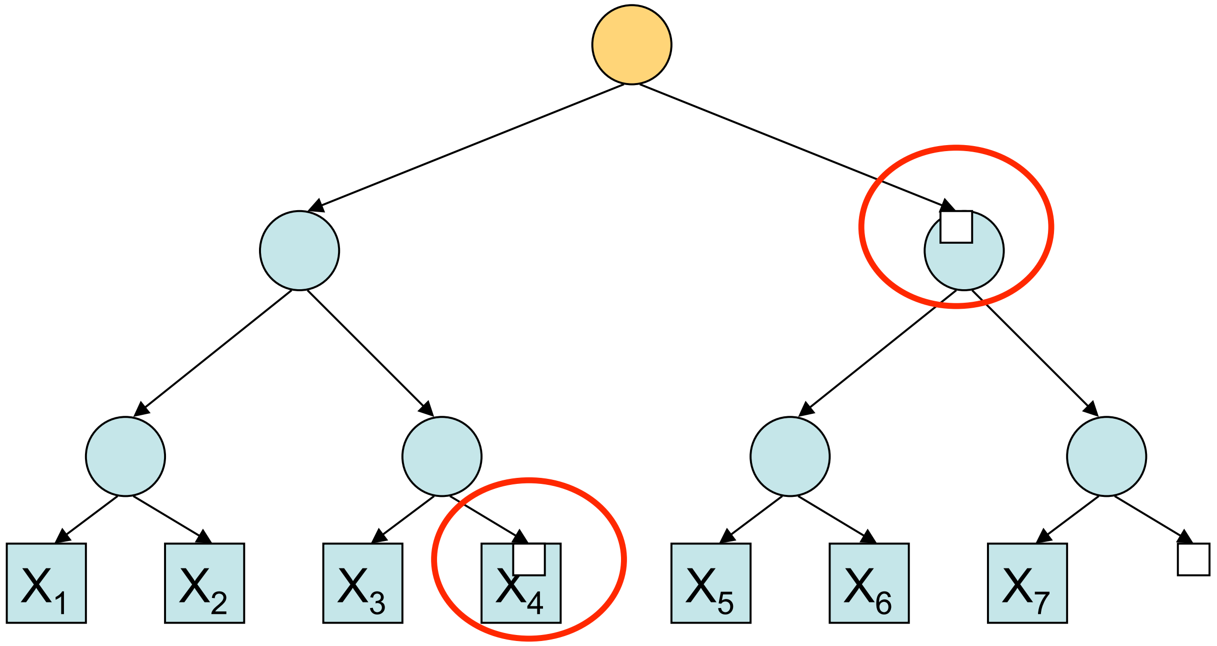
History Tree



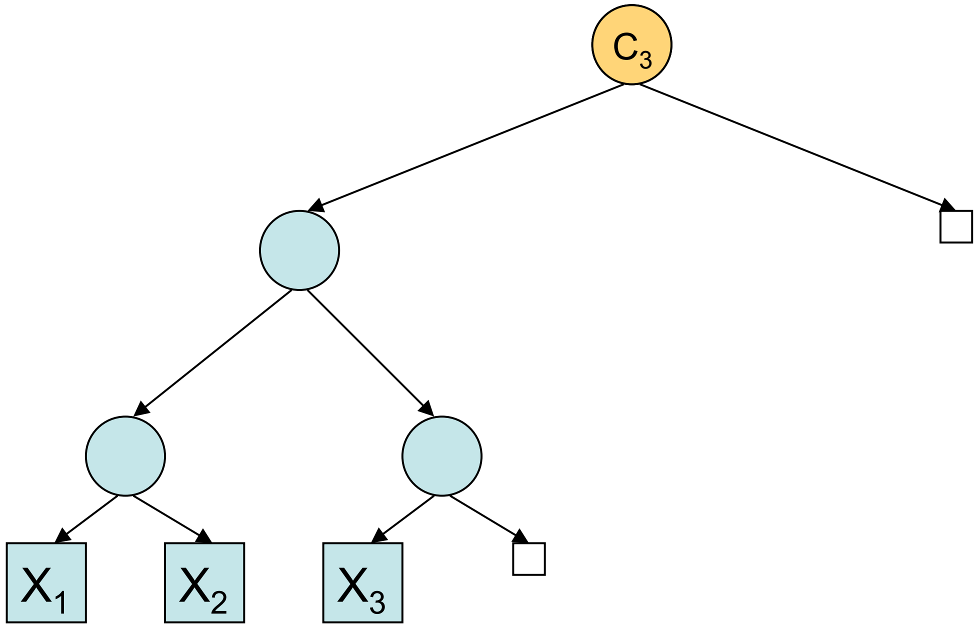
History Tree



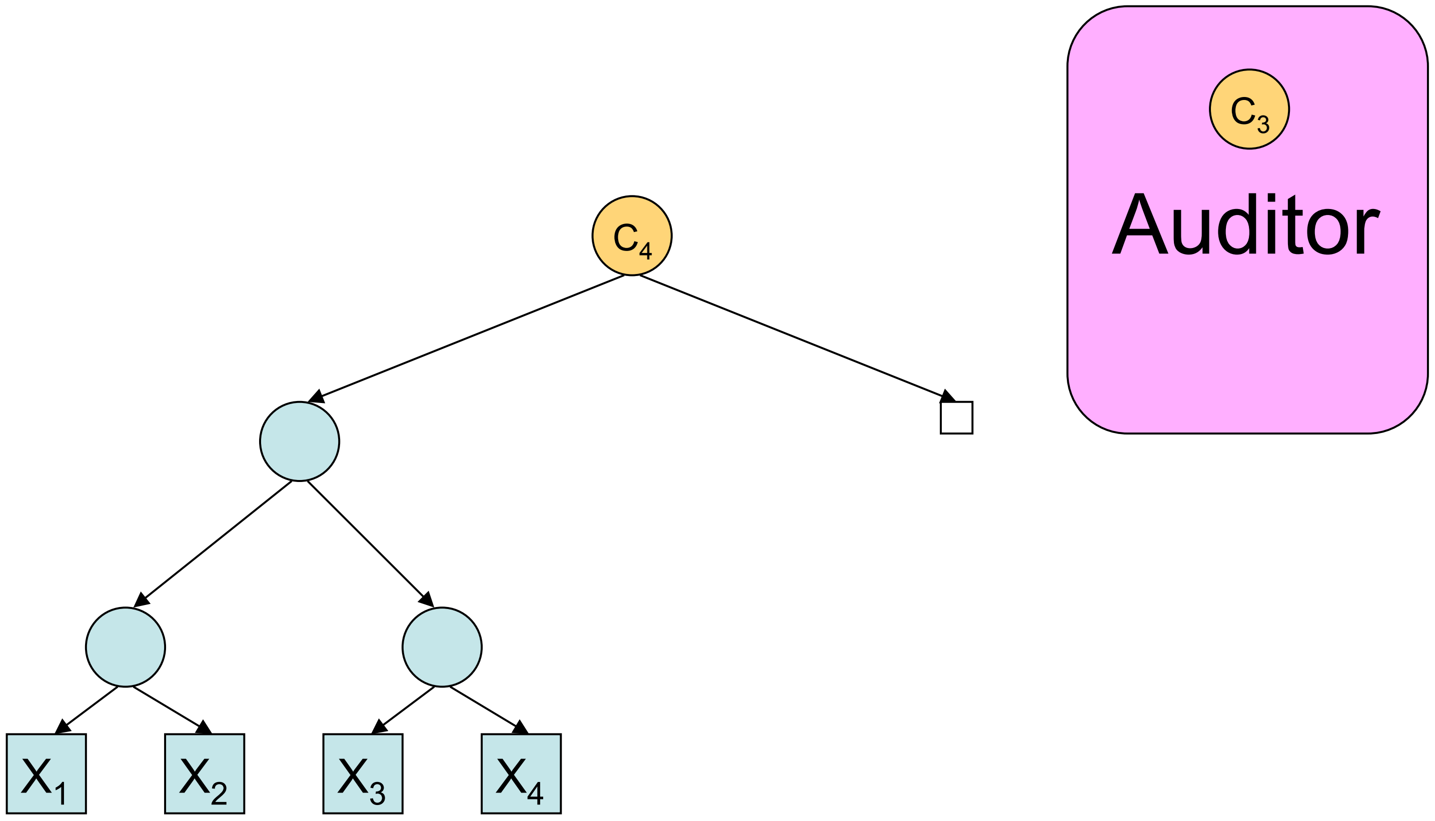
History Tree

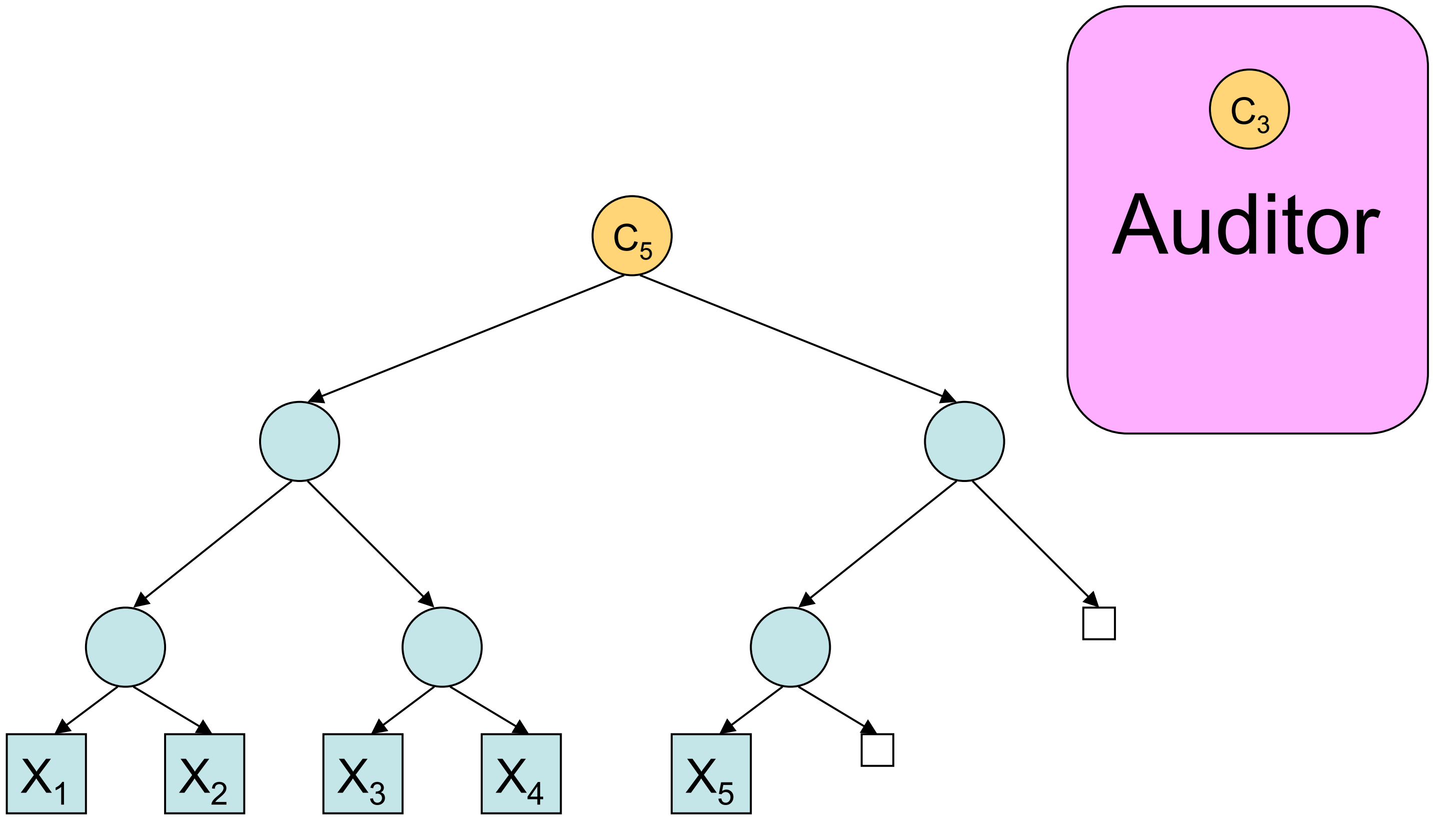


Incremental auditing

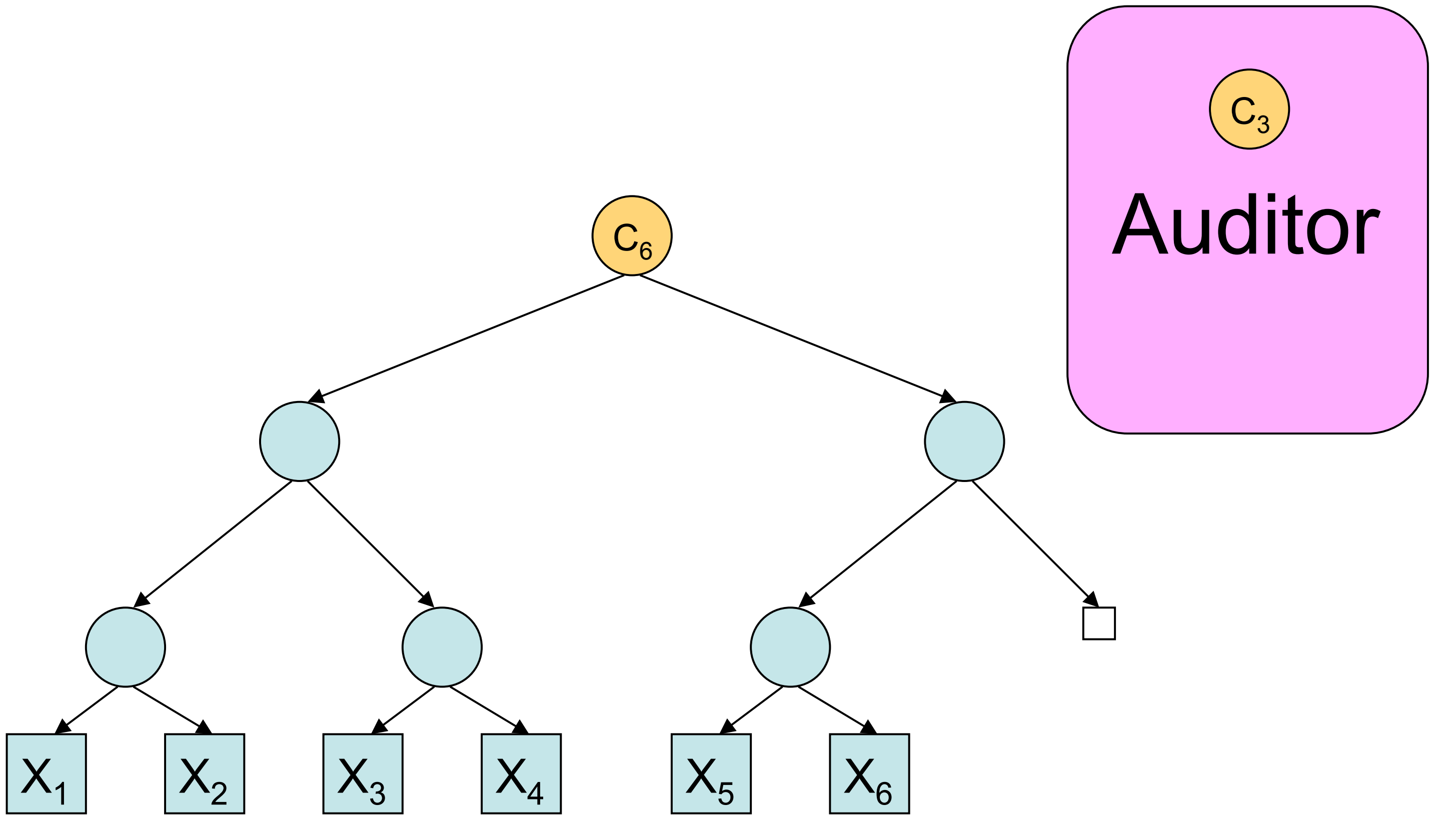

C_3
X_1
X_2
X_3

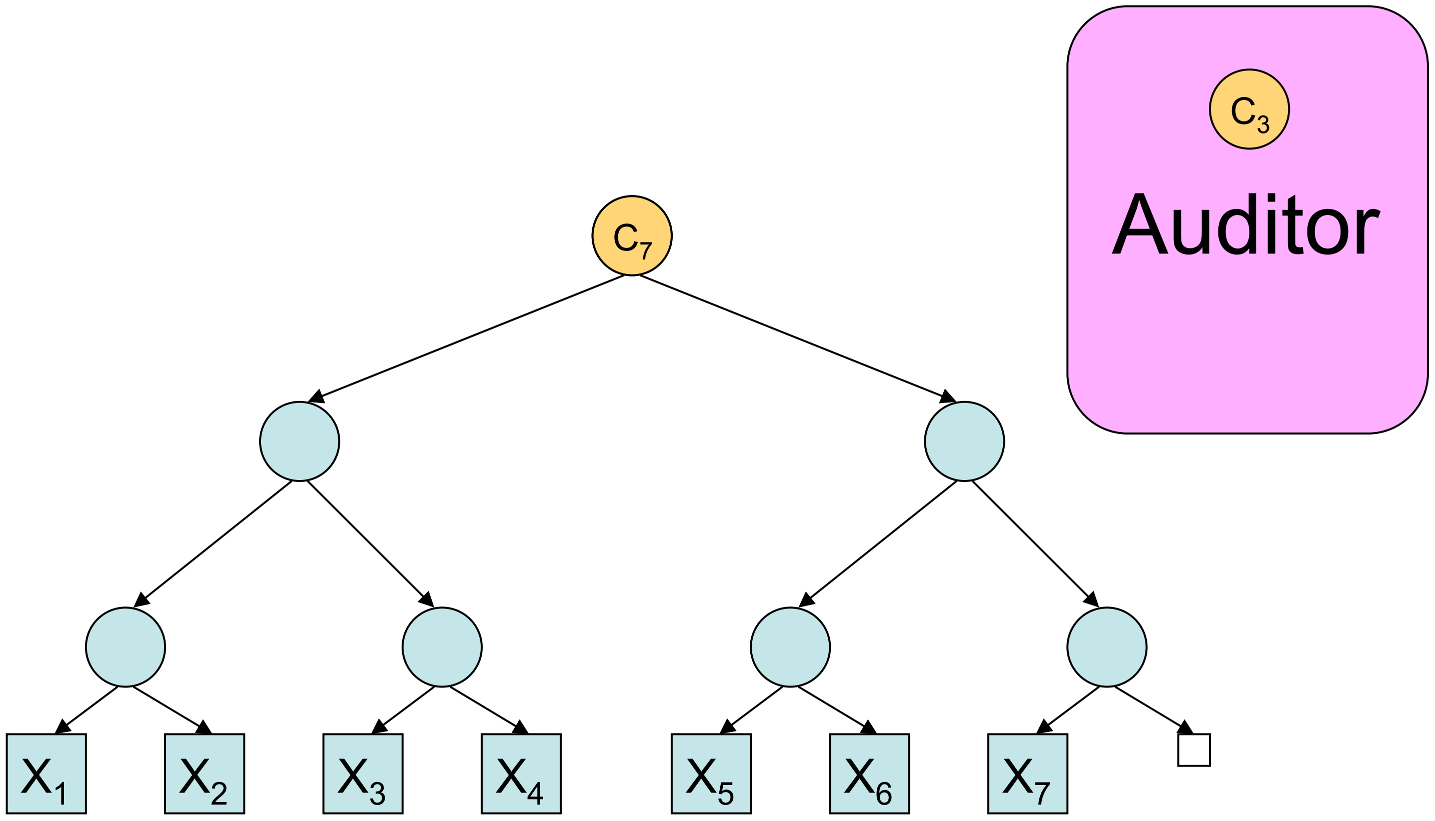
Auditor


C_4
X_1
X_2
X_3
X_4
C_3
Auditor



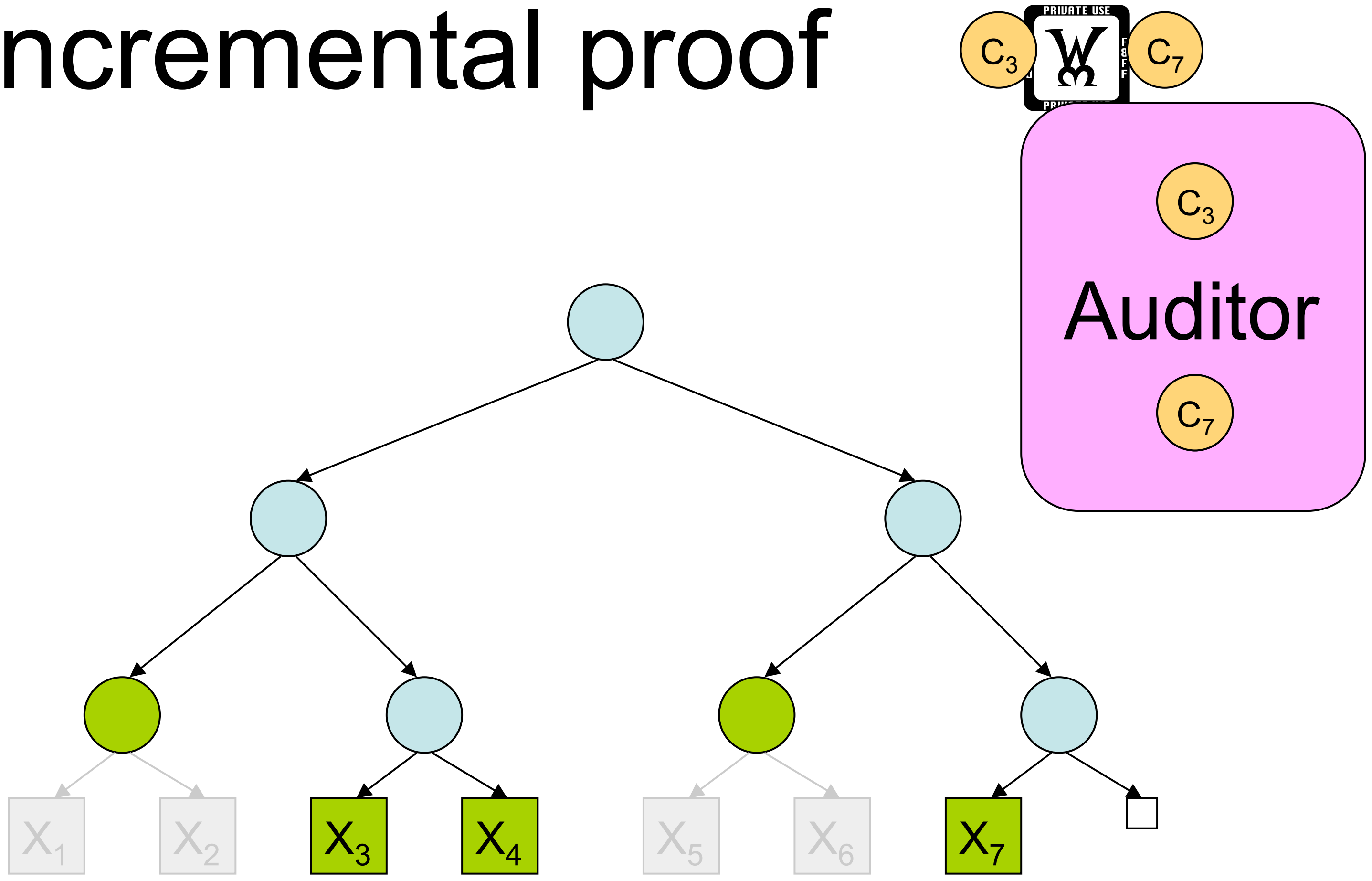
C_5
X_1
X_2
X_3
X_4
X_5
C_3
Auditor


C_3
Auditor
C_6
X_1
X_2
X_3
X_4
X_5
X_6

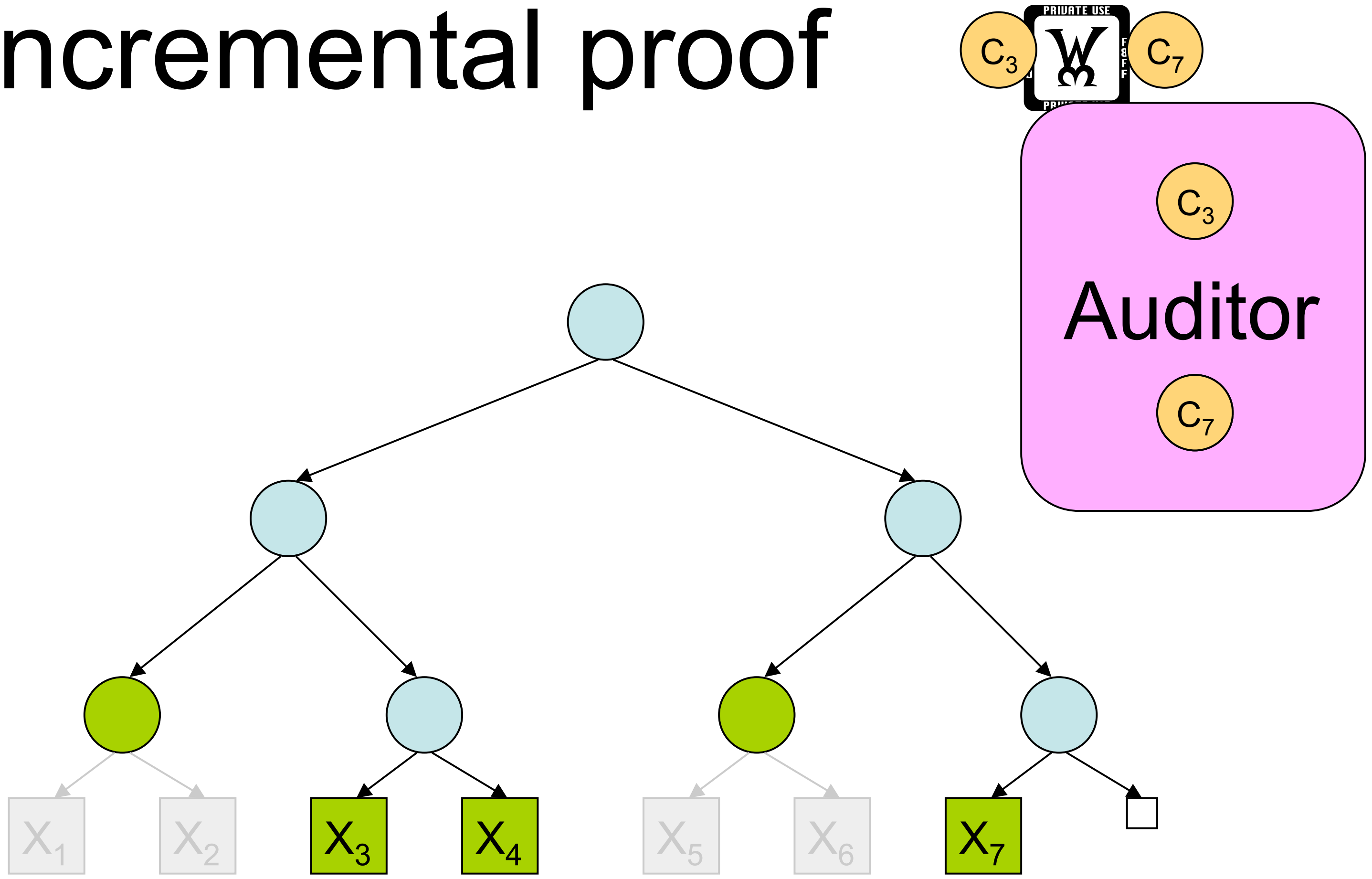


C_7
X_1
X_2
X_3
X_4
X_5
X_6
X_7
C_3
Auditor

Incremental proof

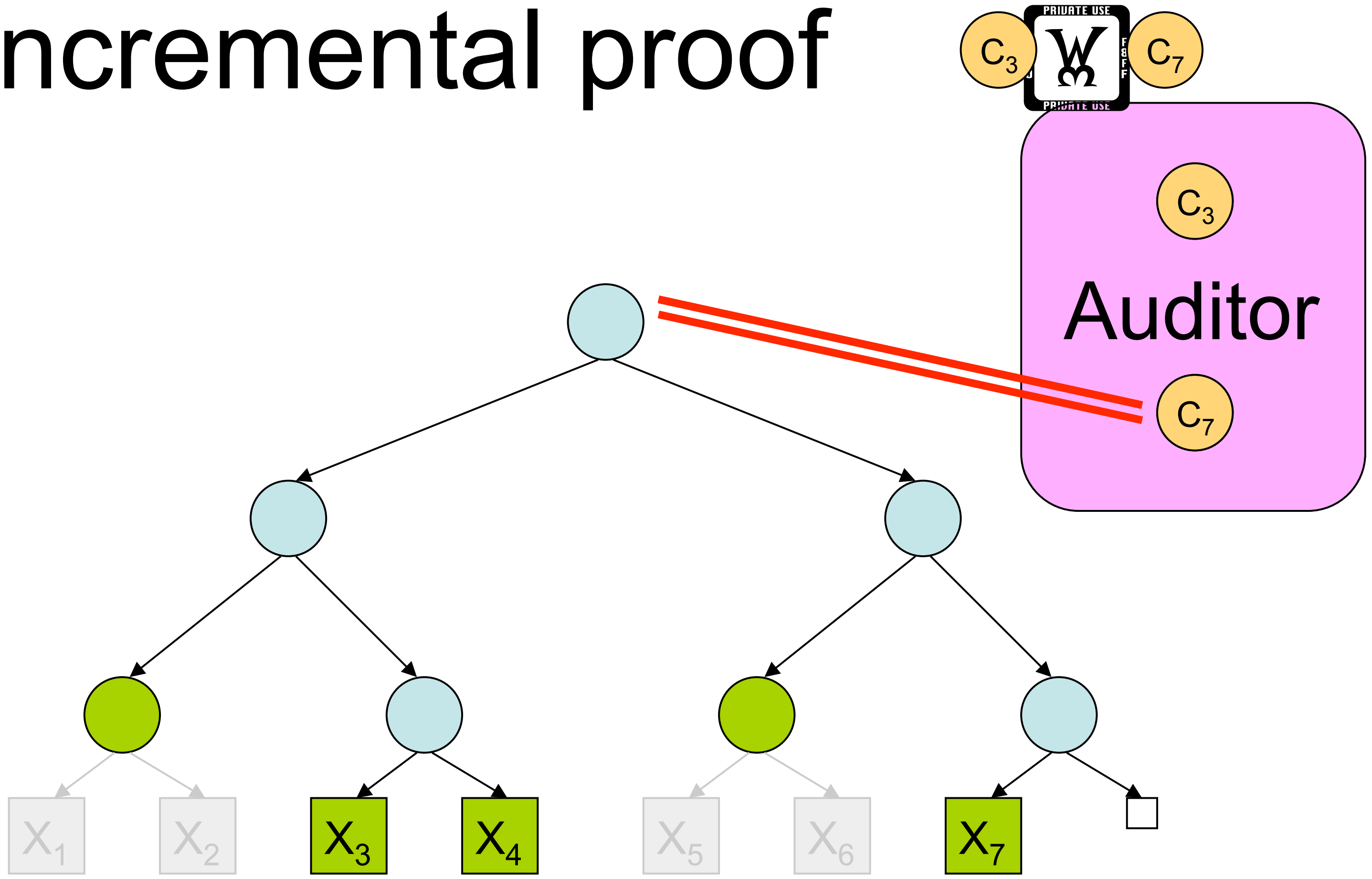


Incremental proof



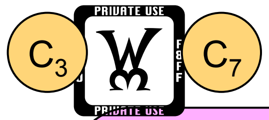
- P is consistent with c_7
- P is consistent with c_3
- Therefore c_7 and c_3 are consistent.

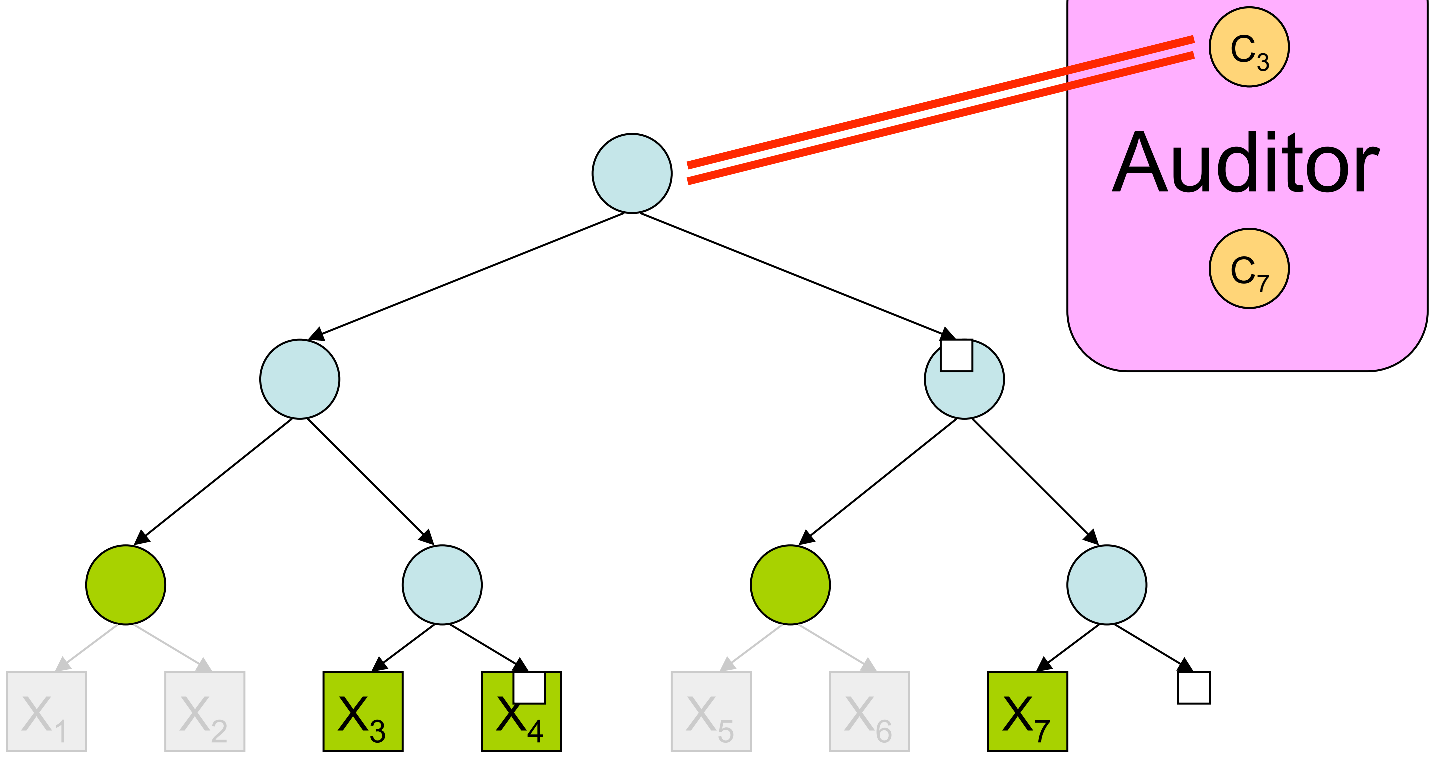
Incremental proof



- P is consistent with C_7
- P is consistent with C_3
- Therefore C_7 and C_3 are consistent.

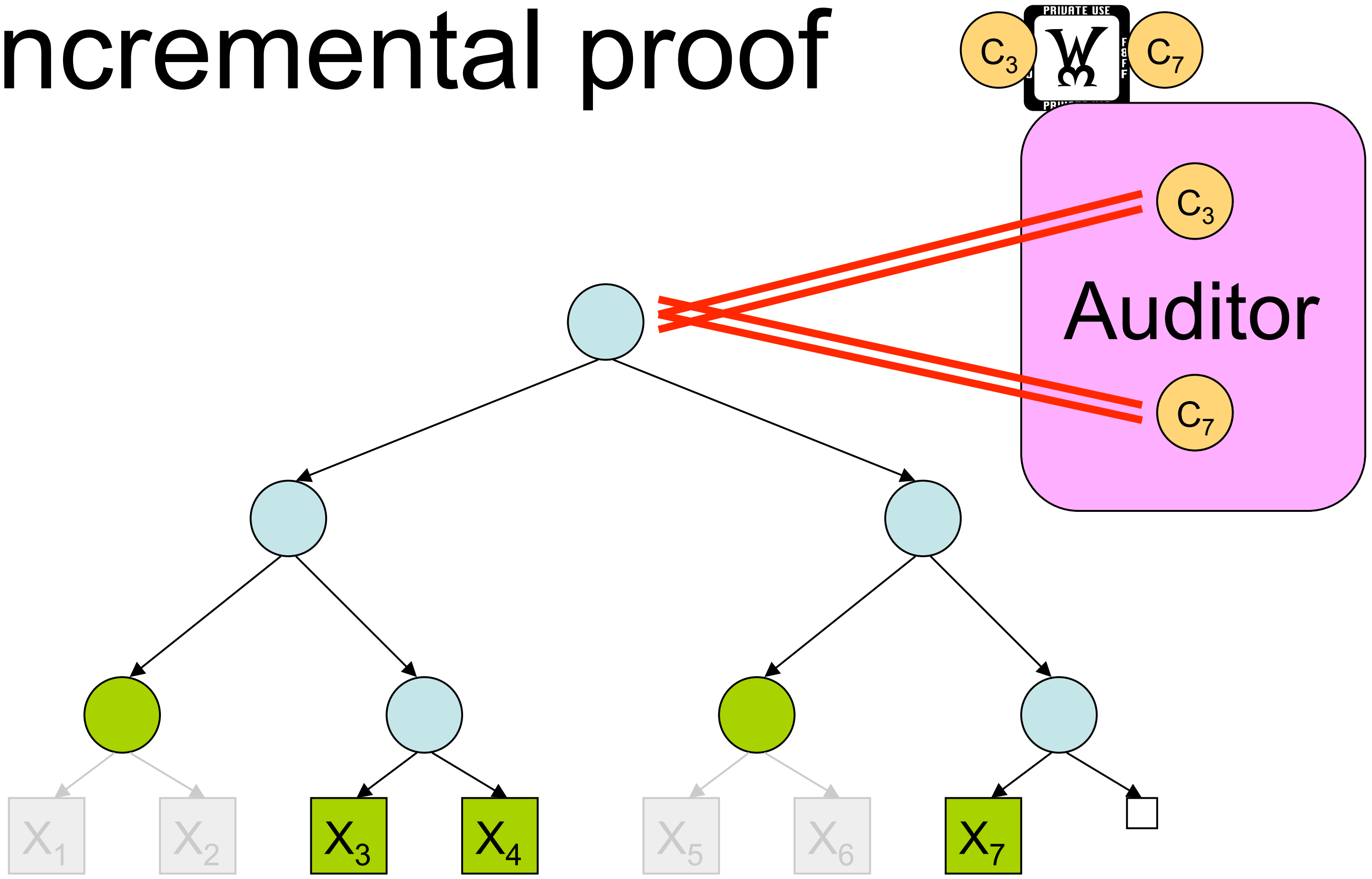
Incremental proof





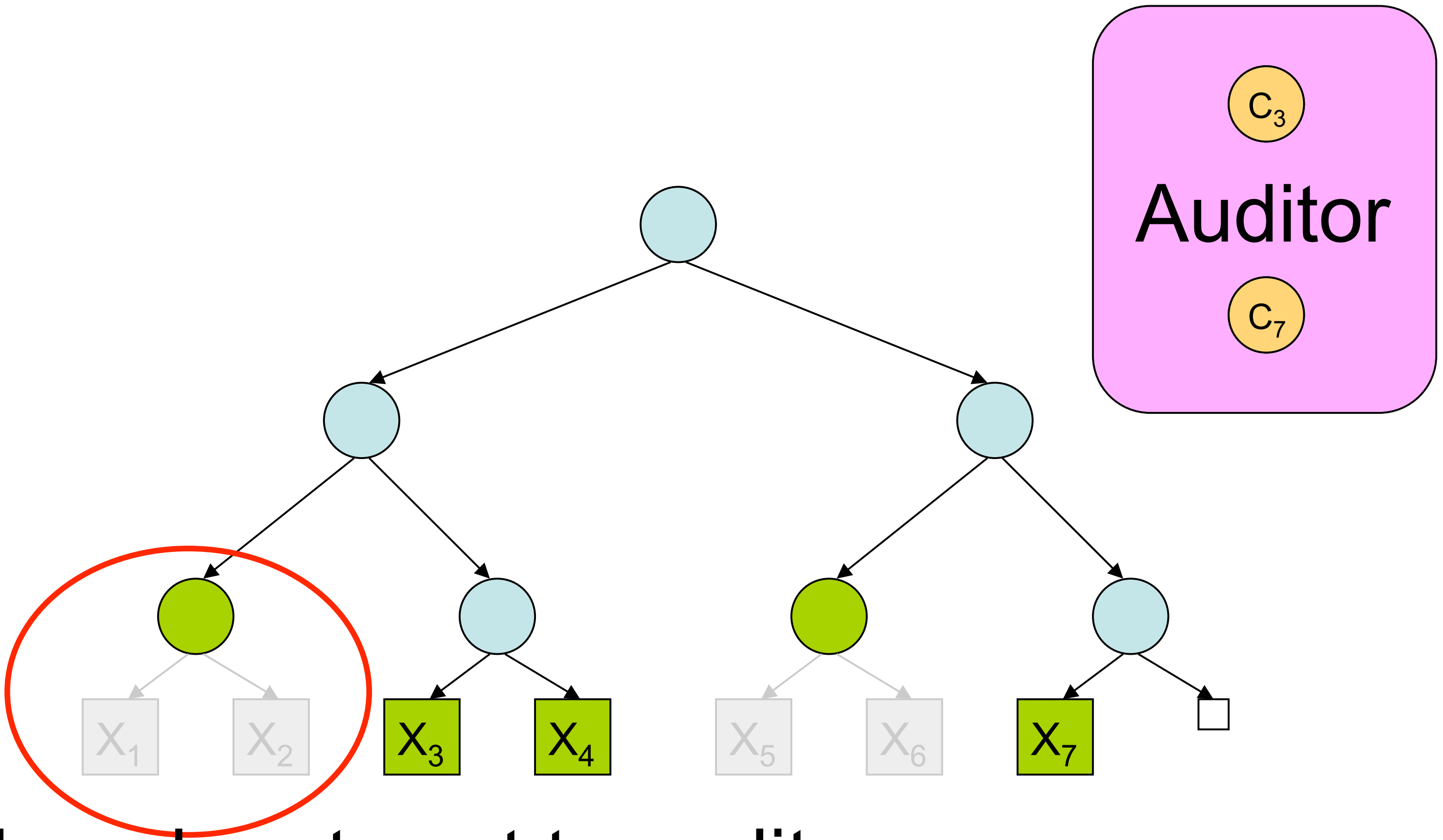
- P is consistent with C_7
- P is consistent with C_3
- Therefore C_7 and C_3 are consistent.

Incremental proof



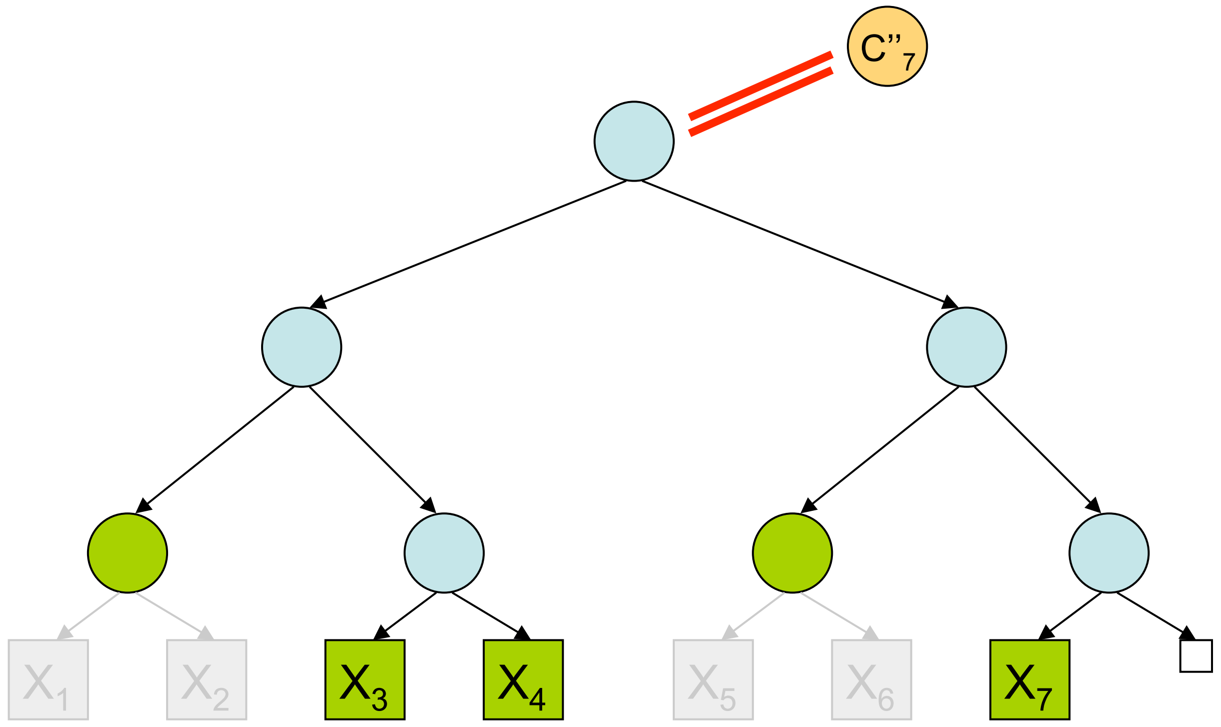
- P is consistent with C_7
- P is consistent with C_3
- Therefore C_7 and C_3 are consistent.

Pruned subtrees



- Although not sent to auditor
  - Fixed by hashes above them
  - c_3 , c_7 fix the same (unknown) events

Membership proof that X_3 C''_7

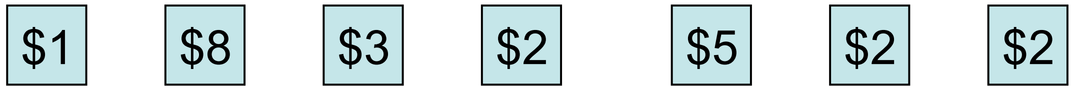


- Verify that C''_7 has the same contents as P
- Read out event X_3

Merkle aggregation

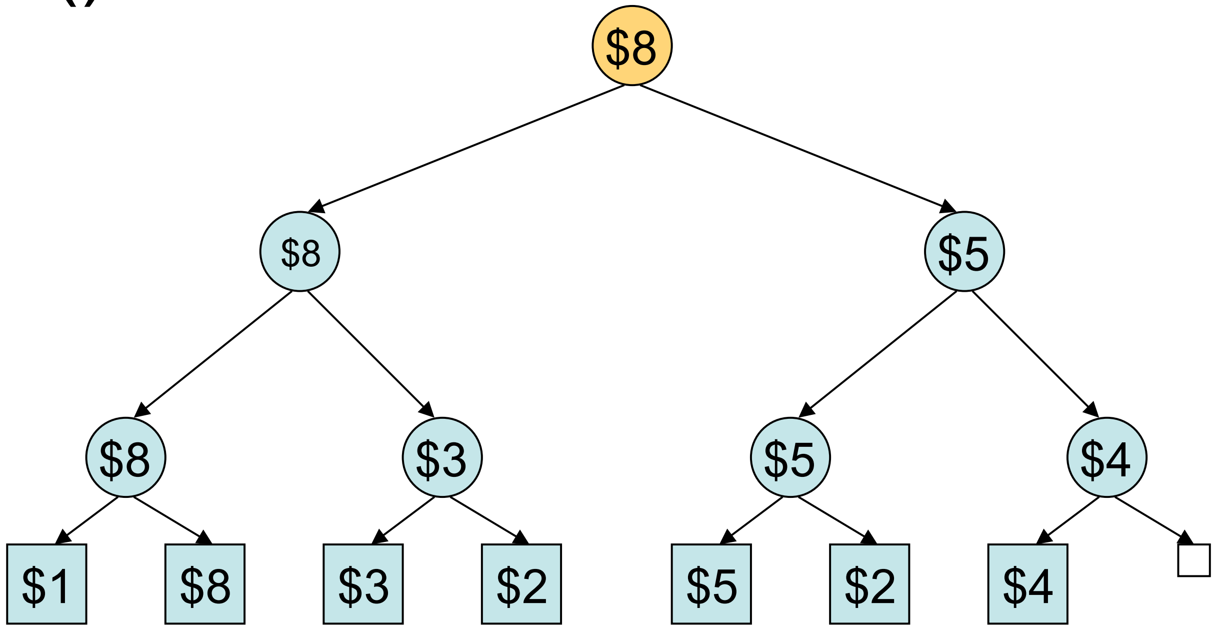
Merkle aggregation

- Annotate events with attributes



Aggregate them up the tree

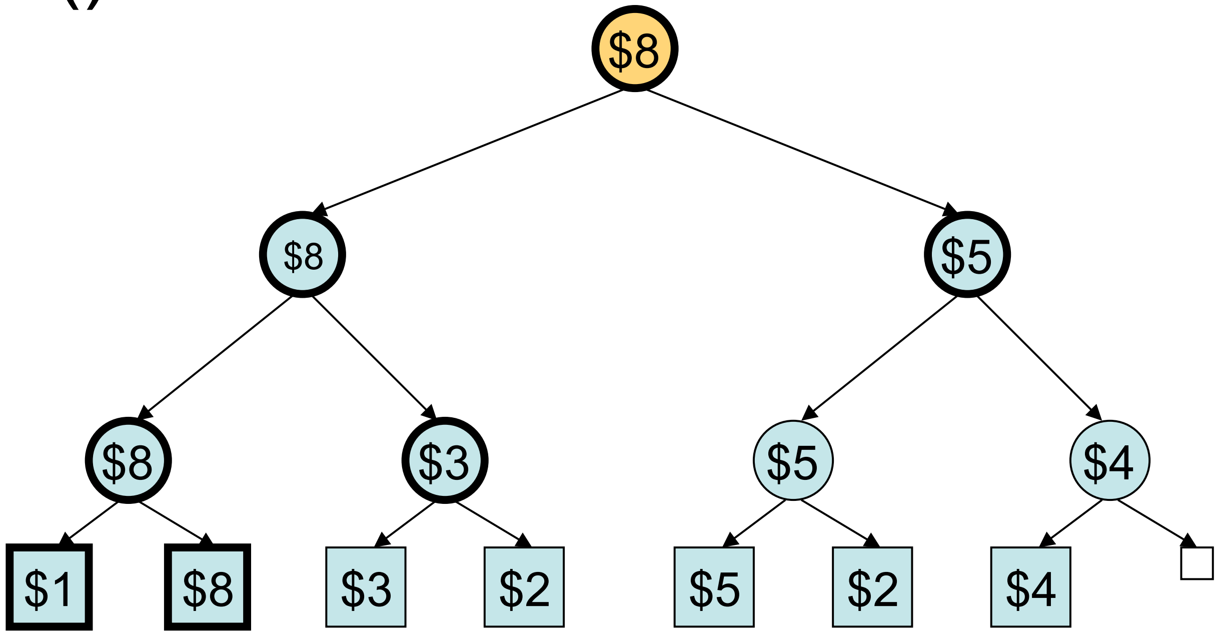
- Max()



Included in hashes and checked during audits

Querying the tree

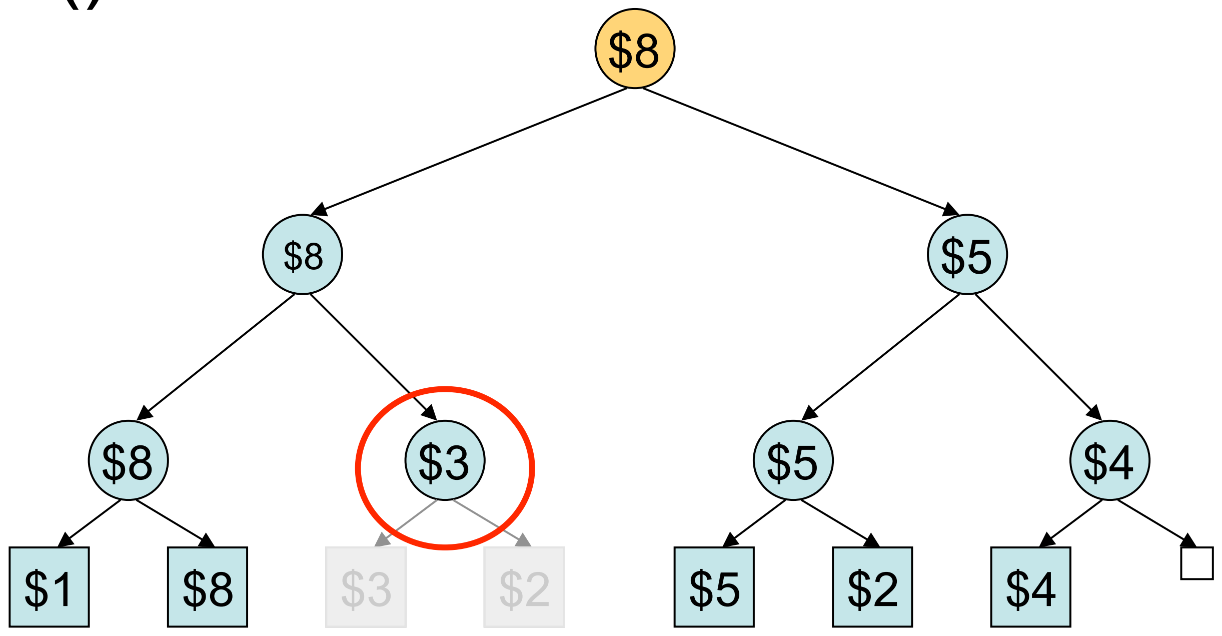
- Max()



Find all transactions over $6

Safe deletion

- Max()



Authorized to delete all transactions under $4

Merkle aggregation is flexible

- Many ways to map events to attributes
  - Arbitrary computable function
- Many attributes
  - Timestamps, dollar values, flags, tags
- Many aggregation strategies

  +, *, min(), max(), ranges, and/or, Bloom filters

Generic aggregation

- ([illegible],[illegible],[illegible])
  - [illegible] : Type of attributes on each node in history
  - [illegible] : Aggregation function
  - [illegible] : Maps an event to its attributes
- For any predicate P, as long as:
  - P(x) OR P(y) IMPLIES P(x[illegible]y)
  - Then:
    - Can query for events matching P
    - Can safe-delete events not matching P

Evaluating the history tree

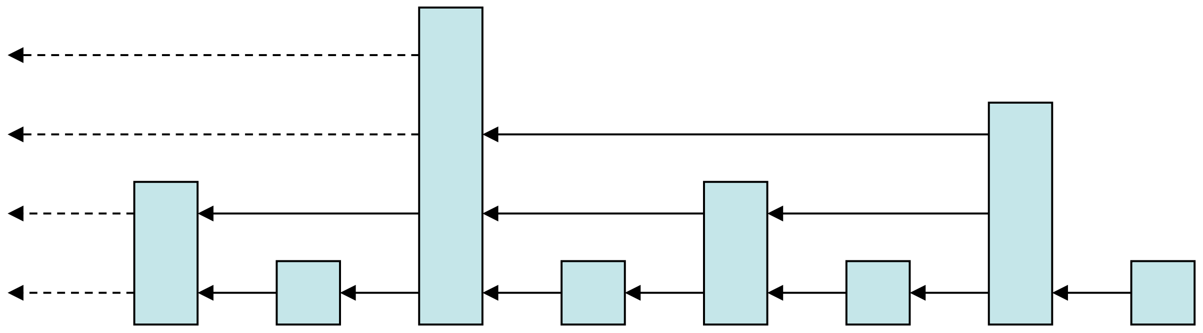
- Big-O performance
- Syslog implementation

Big-O performance

	C_j C_i	X_i C_j	Insert
History tree	O(log *n*)	O(log *n*)	O(log *n*)
Hash chain	O(*j*-*i*)	O(*j*-*i*)	O(1)
Skip-list history [Maniatis,Baker]	O(*j*-*i*) or O(*n*)	O(log *n*) or O(*n*)	O(1)

Skiplist history [Maniatis,Baker]

- Hash chain with extra links
  - Extra links cannot be trusted without auditing
    - Checking them
      - Best case: only events since last audit
      - Worst case: examining the whole history
  - If extra links are valid
    - Using them for historical lookups
      - O(log n) time and space



Syslog implementation

- We ran 80-bit security level
  - 1024 bit DSA signatures
  - 160 bit SHA-1 Hash
- We recommend 112-bit security level
  - 224 bit ECDSA signatures
    - 66% faster
  - SHA-224 (Truncated SHA-256)
    - 33% slower

- [NIST SP800-57 Part 1, Recommendations for Key Magament – Part 1: General (Revised 2007)]

Syslog implementation

- Syslog
  - Trace from Rice CS departmental servers
  - 4M events, 11 hosts over 4 days, 5 attributes per event
    - Repeated 20 times to create 80M event trace

Syslog implementation

- Implementation
  - Hybrid C++ and Python
  - Single threaded
  - MMAP-based append-only write-once storage for log
  - 1024-bit DSA signatures and 160-bit SHA-1 hashes
- Machine
  - Dual-core 2007 desktop machine
  - 4gb RAM

Performance

- Insert performance: 1,750 events/sec
  - 2.4% : Parse
  - 2.6% : Insert
  - 11.8% : Get commitment
  - 83.3% : Sign commitment
- Auditing performance
  - With locality (last 5M events)
    - 10,000-18,000 incremental proofs/sec
    - 8,600 membership proofs/sec
  - Without locality
    - 30 membership proofs/sec
  - < 4,000 byte self-contained proof size
    - Compression reduces performance and proof size by 50%

Improving performance

- Increasing audit throughput above
  - 8,000 audits/sec

- Increasing insert throughput above
  - 1,750 inserts/sec

Increasing audit throughput

- Audits require read-only access to the log
  - Trivially offloaded to additional cores
- For infinite scalability
  - May replicate the log server
    - Master assigns event indexes
    - Slaves build history tree locally

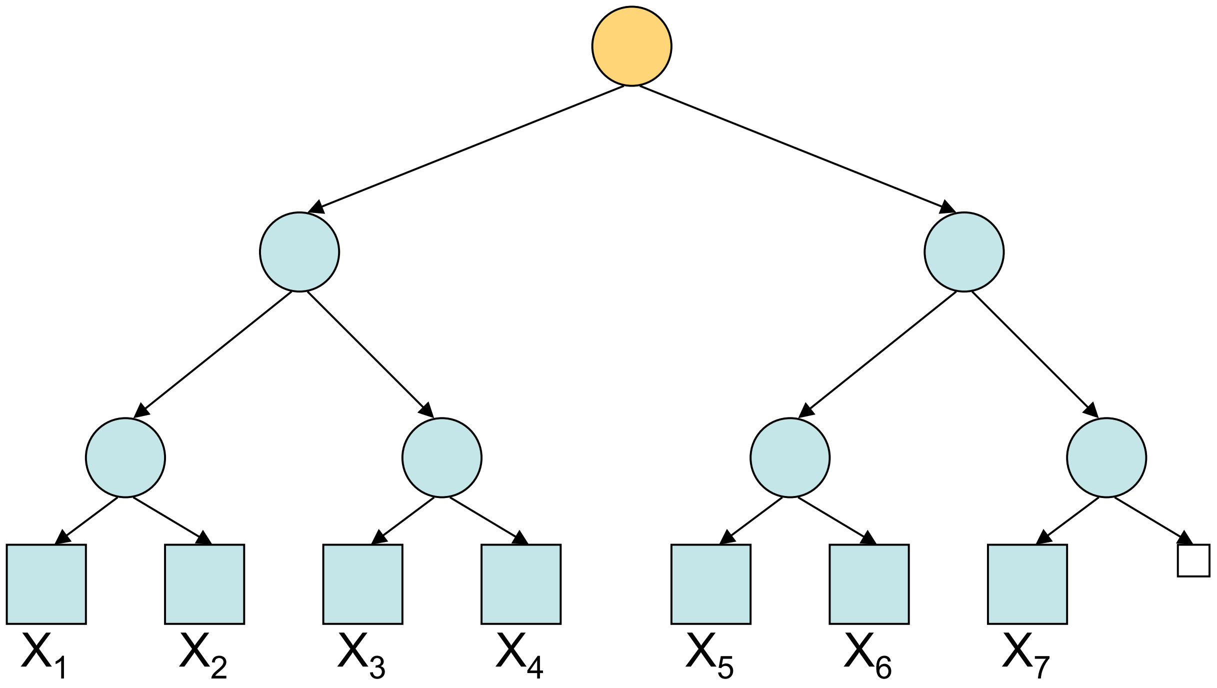
Increasing insert throughput

- Public key signatures are slow
  - 83% of runtime
- Three easy optimization
  - Sign only some commitments
  - Use faster signatures
  - Offload to other hosts
    - Increase throughput to 10k events/sec

More concurrency with replication

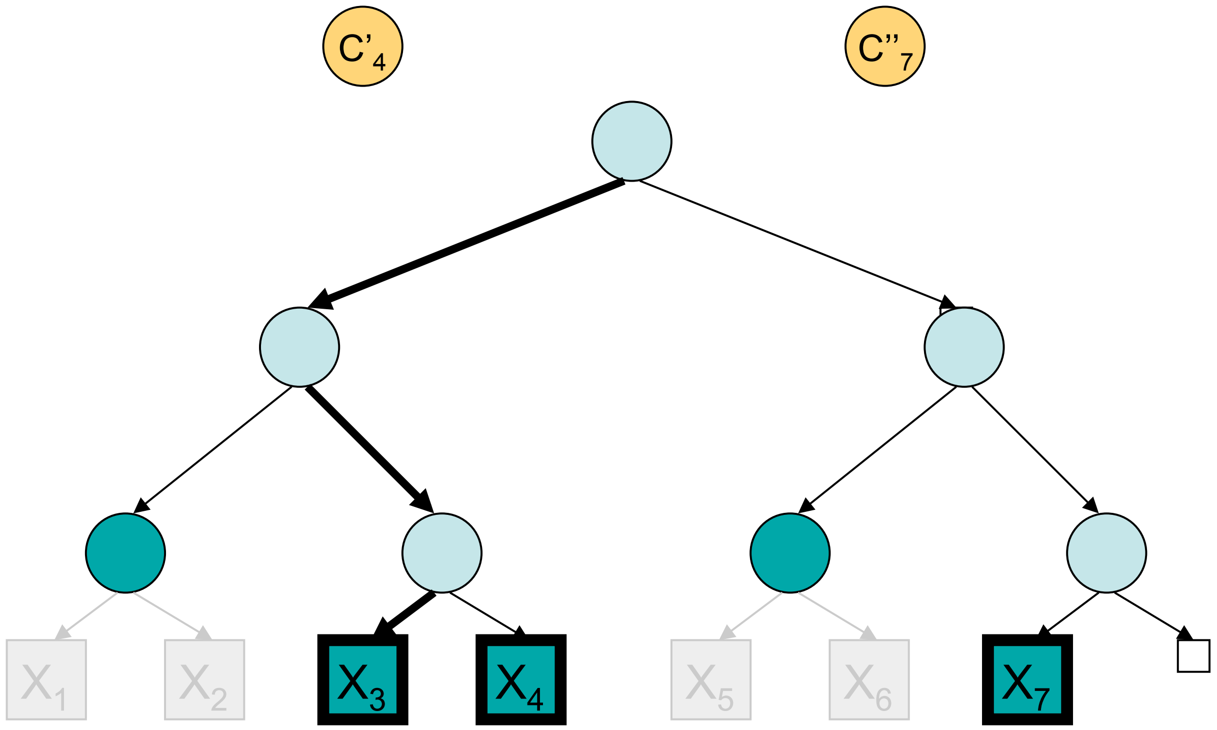
- Processing pipeline:
  - Inserting into history tree
    - O(1). Serialization point
    - Fundamental limit
      - Must be done on each replica
      - 38,000 events/sec using only one core
  - Commitment or proofs generation
    - O(log n).
  - Signing commitments
    - O(1), but expensive. Concurrently on other hosts

Storing on secondary storage



- Nodes are frozen (no longer ever change)
  - In post-order traversal
    - Static order
  - Map into an array

Partial proofs



- Can re-use node hashes from prior audits
  - (eg, incremental proof from C_3 to C_4)

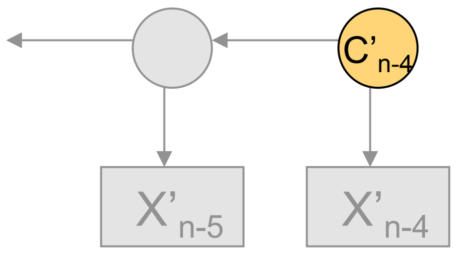
Conclusion

- New paradigm
  - Importance of frequent auditing
- History tree
  - Efficient auditing
  - Efficient predicate queries and safe deletion
  - Scalable
- Proofs of tamper-evidence will be in my PhD Thesis

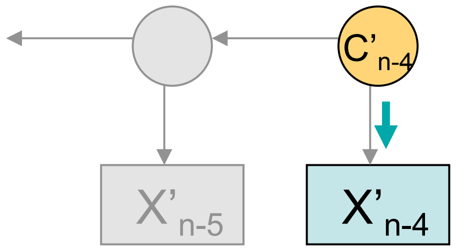
Questions

?

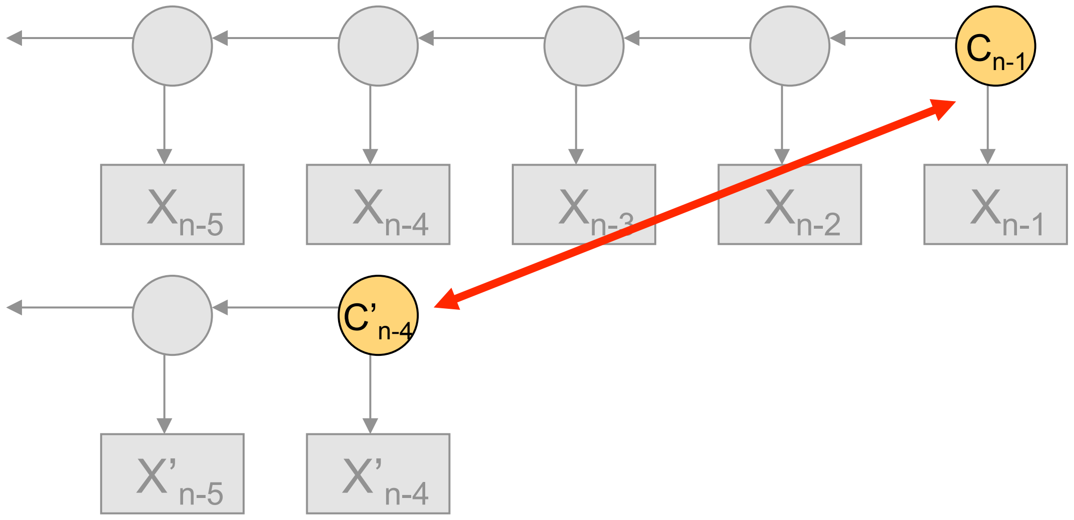
Historical integrity



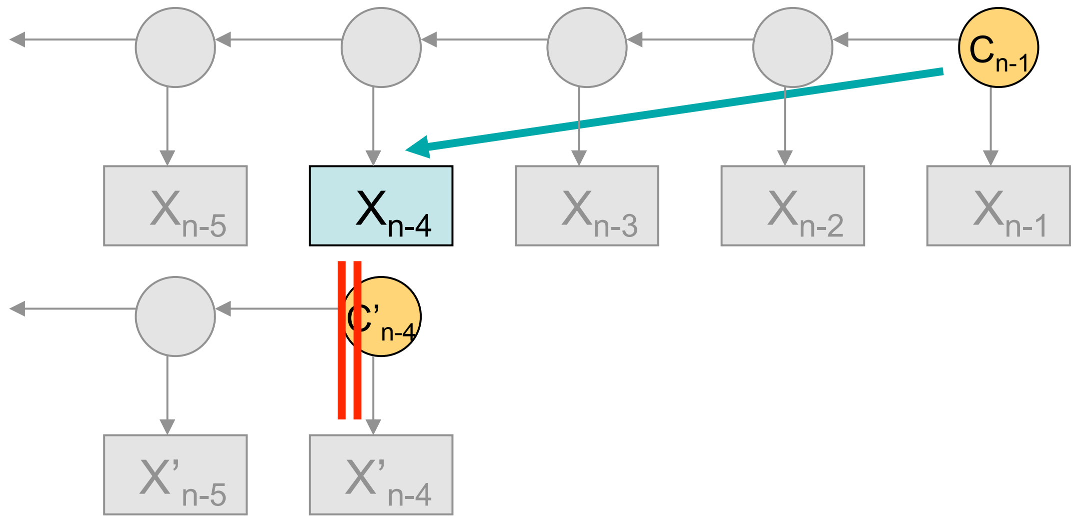
Historical integrity



Historical integrity

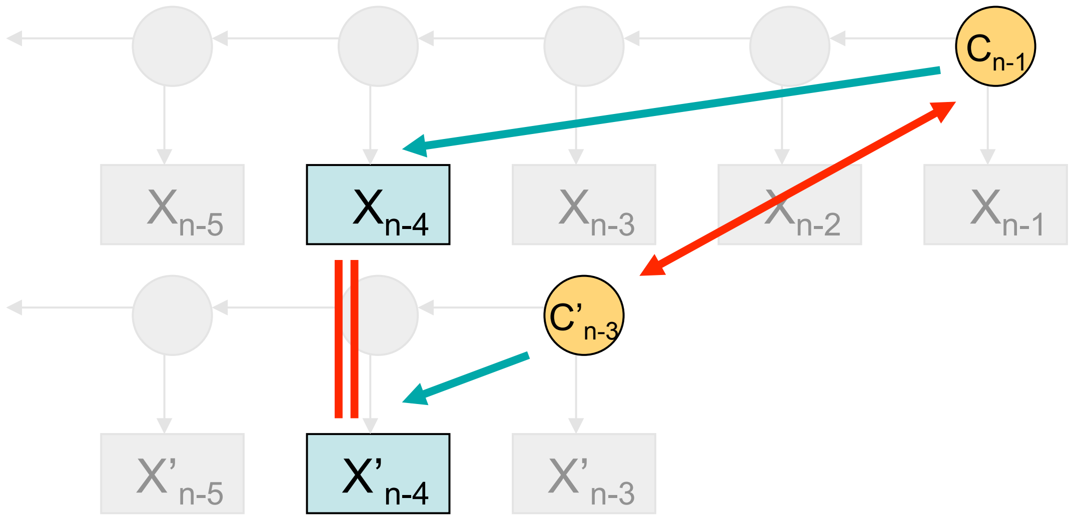


Historical integrity

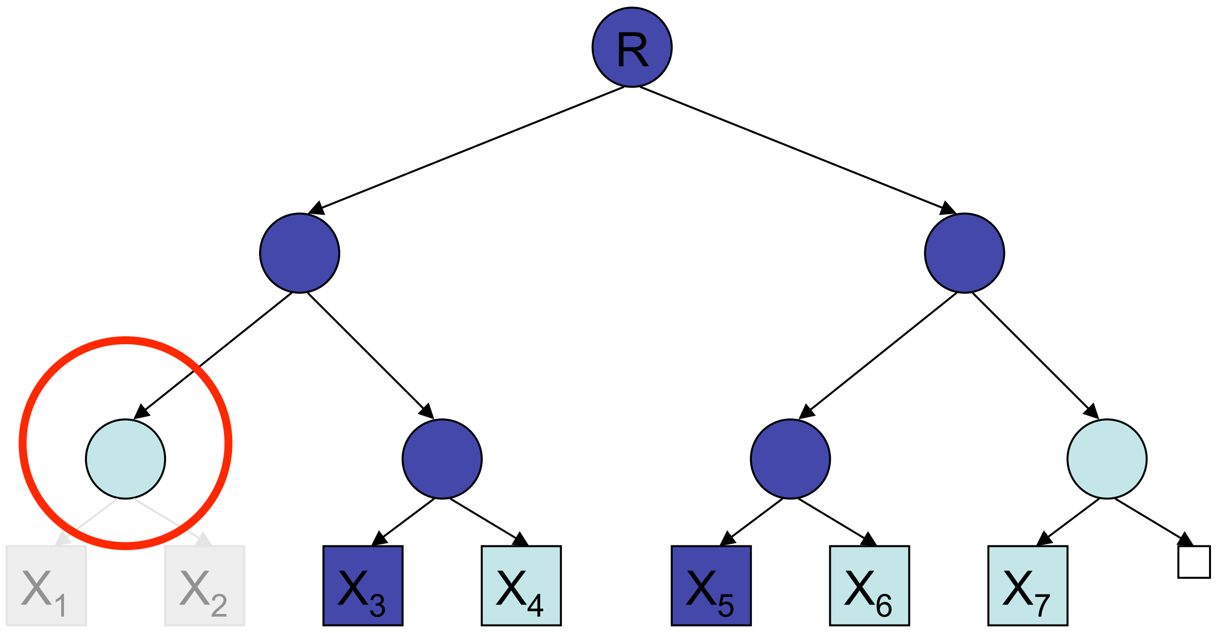


Defining historically integrity

- A logging system is tamper-evident when:
  - If there is a verified incremental proof between commitments C_j and C_k ($j<k$), then for all $i<j$ and all verifiable membership proofs that event i in log C_j is X_i and event i in log C_k is X'_i, we must have $X_i=X'_i$.



Safe deletion



- Unimportant events may be deleted
  - When auditor requests deleted event
    - Logger supplies proof that ancestor was not important