Conflict Resolution (OT), Crypto, and Untrusted Cloud Services

COS 418: *Distributed Systems*
Lecture 17

Michael Freedman

Warning:

This lecture jumps around

But there is some logic
+ crypto background for blockchain

2

Today's Topics

- **Conflict resolution**
  - Operational Transformation (OT)
- **Crypto Introduction**
  - Crypto (encryption, digital signatures), hash functions
- **Untrusted Cloud Storage (SPORC)**
  - OT + crypto + fork* consistency
- **Next lecture: Bitcoin and blockchains and consensus, oh my!**

3

Conflict Resolution

4

Concurrent writes can conflict

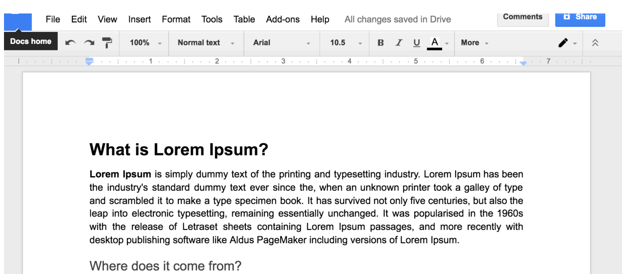
- Encountered in many different settings:
  - Peer-to-peer (Bayou)
  - Multi-master: single cluster (Dynamo), wide-area (COPS)
- Potential solutions
  - "Last writer wins"
    - Thomas Write Rule for DBs with timestamp-based concurrency control: Ignore outdated writes
  - Application-specific merge/update: Bayou, Dynamo

General approach: Encode ops as incremental update

- Consider banking (double-entry bookkeeping):
  - Initial: Alice = $50, Bob = $20
  - Alice pays Bob $10
    - Option 1: set Alice to $40, set Bob to $30
    - Option 2: decrement Alice -$10, incremental Bob +$10
      - #2 better, but can't always ensure Alice >= $0
- Works because common mathematical ops are
  - Commutative: $A \circ B == B \circ A$
  - Invertible: $A \circ A^{-1} == 1$

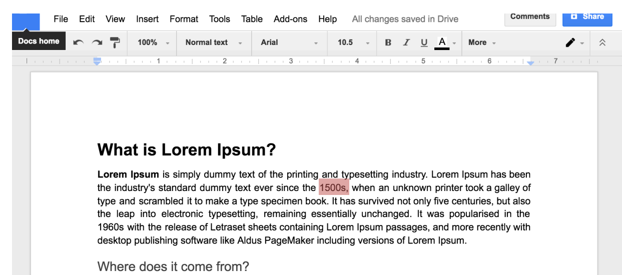
Consider shared word processing

- How do I insert a new word?
  - Send entire doc to server? Not efficient
  - Send update operation!

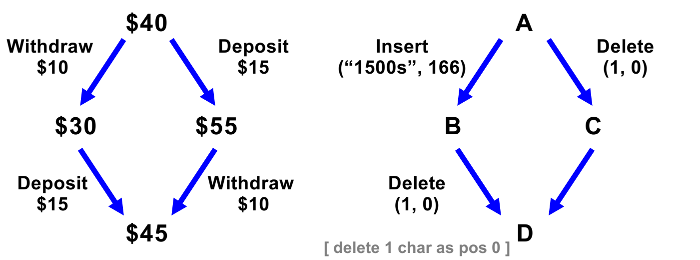


Consider shared word processing

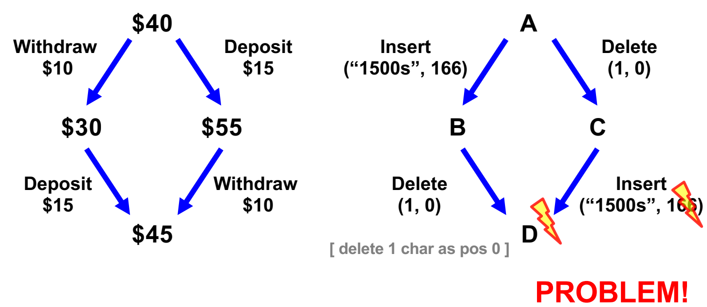
- How do I insert a new word?
  - Send entire doc to server? Not efficient
  - Send update operation! insert (string, position) = insert("1500s", 166)
  - Warning: Insert (rather than replace) shifted position of all following text



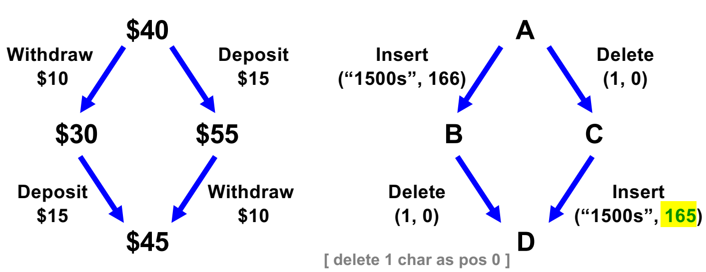
Operations must be commutative



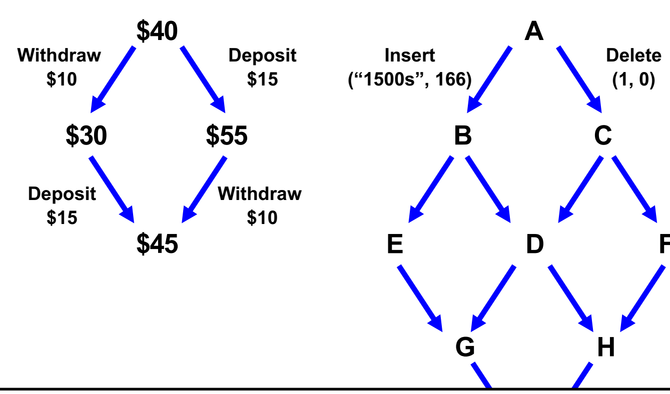
Operations must be commutative



Operations must be commutative



Operations must be commutative



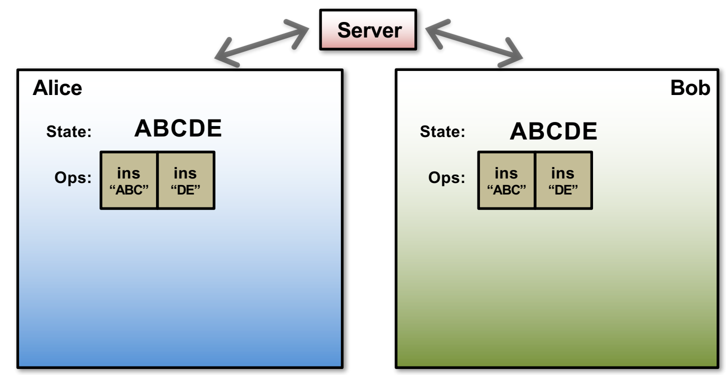
Operational Transformation (OT)

- State of system is *S*, ops *a* and *b* performed by concurrently on state *S*
- Different servers can apply concurrent ops in different sequential order
  - Server 1:
    - Receives *a*, applies *a* to state *S*: $S \circledcirc a$
    - Receives b (which is dependent on *S*, not $S \circledcirc a$)
    - Transforms b across all ops applied since S (namely a): $b' = \mathrm{OT}(b, \{a\})$
    - Applies b' to state: $S \circledcirc a \circledcirc b'$
  - Server 2
    - Receives b, applies b to state: $S \circledcirc b$
    - Receives *a*, performs transformation $a' = \mathrm{OT}(a, \{b\})$,
    - Applies *a'* to state: $S \circledcirc b \circledcirc a'$
- Servers 1 and 2 have identical final states: $S \circledcirc a \circledcirc b' == S \circledcirc b \circledcirc a'$

13

Operational Transformation (OT)

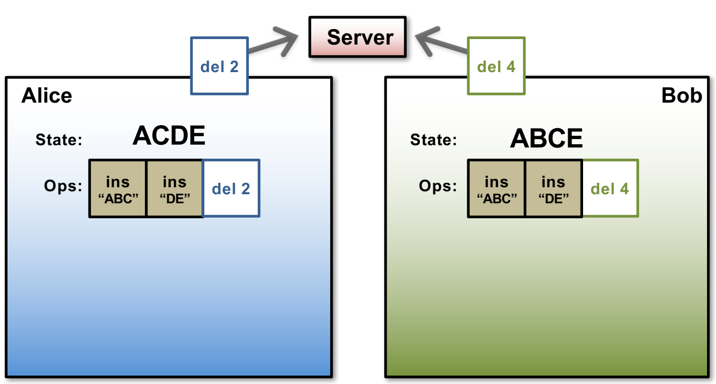
(Used in Google Docs, EtherPad, etc.)



14

Operational Transformation (OT)

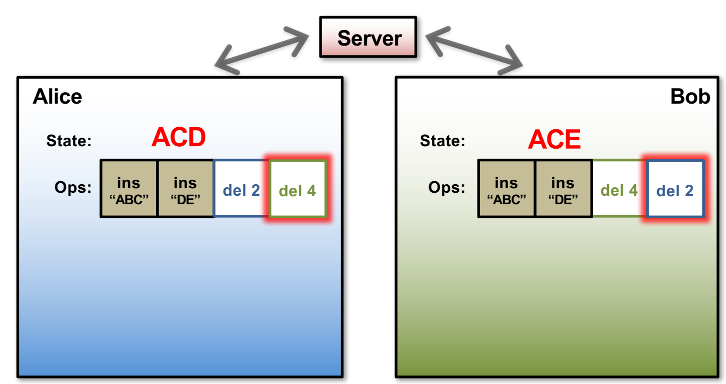
(Used in Google Docs, EtherPad, etc.)



15

Operational Transformation (OT)

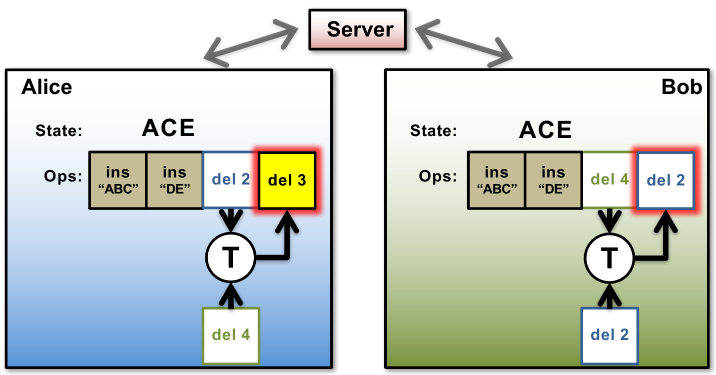
(Used in Google Docs, EtherPad, etc.)



16

Operational Transformation (OT)

(Used in Google Docs, EtherPad, etc.)



17

Intro to crypto in 15 minutes

19

What is Cryptography?

- From Greek, meaning "secret writing"
- Confidentiality: encrypt data to hide content
- Include "signature" or "message authentication code"
  - Integrity: Message has not been modified
  - Authentication: Identify source of message

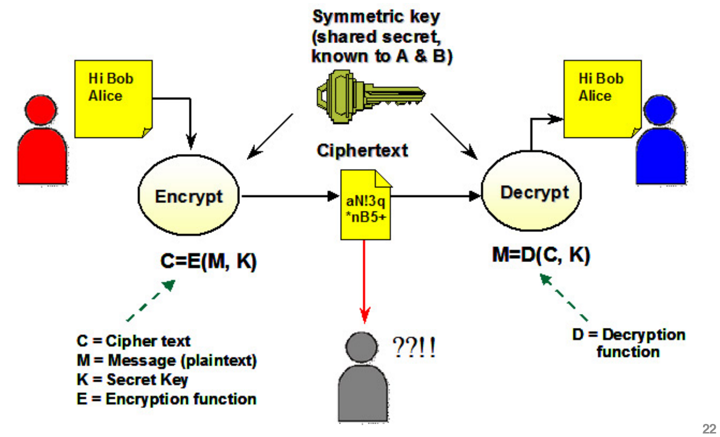
plaintext $\xrightarrow{\text{encryption}}$ ciphertext $\xrightarrow{\text{decryption}}$ plaintext

- Modern encryption:
  - *Algorithm* public, *key* secret and provides security
  - Symmetric (shared secret) or asymmetric (public-private key)

Symmetric (Secret Key) Crypto

- Sender and recipient share common key
  - **Main challenge: How to distribute the key?**
- Provides dual use:
  - Confidentiality (encryption)
  - Message authentication + integrity (MAC)
- 1000x more computationally efficient than asymmetric

Symmetric Cipher Model



Public-Key Cryptography

- **Each party has (public key, private key)**
- **Alice's public key PK**
  - Known by anybody
  - Bob uses PK to encrypt messages *to* Alice
  - Bob uses PK to verify signatures *from* Alice
- **Alice's private/secret key: sk**
  - Known only by Alice
  - Alice uses sk to decrypt ciphertexts sent to her
  - Alice uses sk to generate new signatures on messages

Public-Key Cryptography

- (PK, sk) = generateKey(keysize)
- **Encryption API**
  - ciphertext = encrypt (message, PK)
  - message = decrypt (ciphertext, sk)
- **Digital signatures API**
  - Signature = sign (message, sk)
  - isValid = verify (signature, message, PK)

(Simple) RSA Algorithm

- Generating a key:
  - Generate composite **n = p * q**, where p and q are secret primes
  - Pick public exponent **e**
  - Solve for secret exponent **d** in $d \cdot e \equiv 1 \pmod{(p-1)(q-1)}$
  - Public key = (e, n), private key = d

- Encrypting message m: $c = m^e \bmod n$
- Decrypting ciphertext c: $m = c^d \bmod n$

- **Security** due to cost of factoring large numbers
  - Finding **(p,q)** given **n** takes $O(e^{\log n \log \log n})$ operations
  - n chosen to be 2048 or 4096 bits long

25

Cryptographic hash function

(and using them in systems)

26

Cryptography Hash Functions I

- Take message *m* of arbitrary length and produces fixed-size (short) number *H(m)*

- One-way function
  - Efficient: Easy to compute *H(m)*
  - **Hiding property:** Hard to find an *m*, given *H(m)*
    - Assumes "m" has sufficient entropy, not just {"heads", "tails"}
  - **Random:** Often assumes for output to "look" random

27

Cryptography Hash Functions II

- Collisions exist: | possible inputs | >> | possible outputs |

  … but hard to find

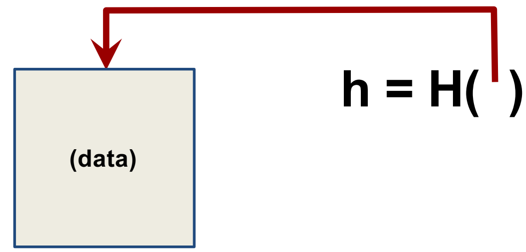
- Collision resistance:
  - Strong resistance: Find any m != m' such that H(m) == H(m')
  - Weak resistance: Given m, find m' such that H(m) == H(m')
  - For 160-bit hash (SHA-1)
    - Finding any collision is birthday paradox: 2^{160/2} = 2^80
    - Finding specific collision requires 2^160

28

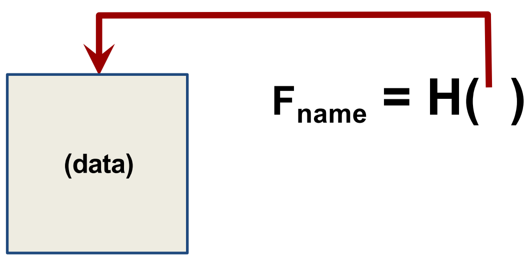
Example use #1: Passwords

- Can't store passwords in a file that could be read
  - Concerned with insider attacks / break-ins
- Must compare typed passwords to stored passwords
  - Does H (input) == H (password) ?
- Memory cheap: build table of all likely password hashes?
  - Use "salt" to compute h = H (password || salt)
  - Store salt as plaintext in password file, not a secret
  - Then check whether H (input, salt) == h

Hash Pointers

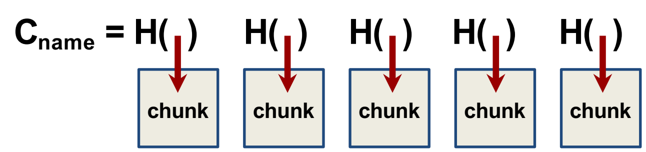


Self-certifying names



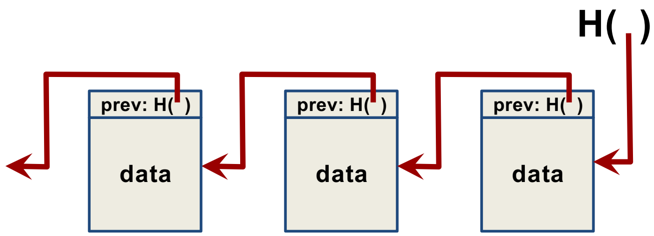
- P2P file sharing software (e.g., Limewire)
  - File named by F_{name} = H (data)
  - Participants verify that H (downloaded) == F_{name}

Self-certifying names



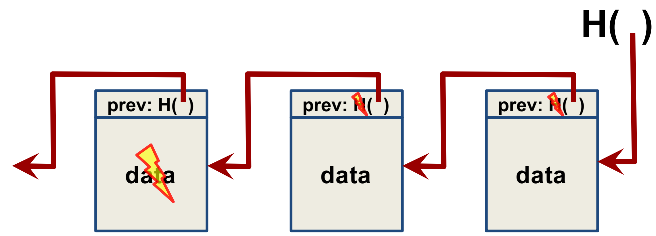
- BitTorrent
  - Large file split into smaller chunks (~256KB each)
  - Torrent file specifies the name/hash of each chunk
  - Participants verify that H (downloaded) == C_{name}
  - Security relies on getting torrent file from trustworthy source

Hash chains



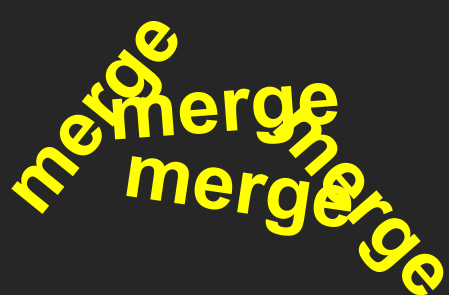
Creates a “tamper-evident” log of data

Hash chains



If data changes, all subsequent hash pointers change

Otherwise, found a hash collision!



Untrusted Cloud Storage

Operational Transformation
+
Hash Chains & Digital Signatures
+
Fork* Linearizability

SPORC:
Group Collaboration using Untrusted Cloud Resources

Ariel J. Feldman, William P. Zeller,
Michael J. Freedman, Edward W. Felten

OSDI 2010

SPORC goals

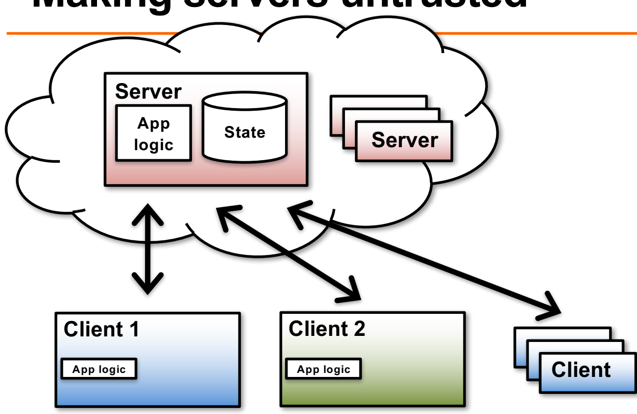
Practical **cloud apps**

- Flexible framework
- Real-time collaboration
- Work offline

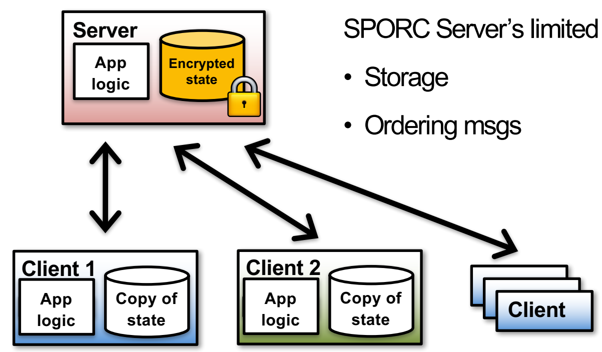
Untrusted servers

- Can't read user data
- Can't tamper with user data without risking detection
- Clients can recover from tampering

Making servers untrusted



Making servers untrusted

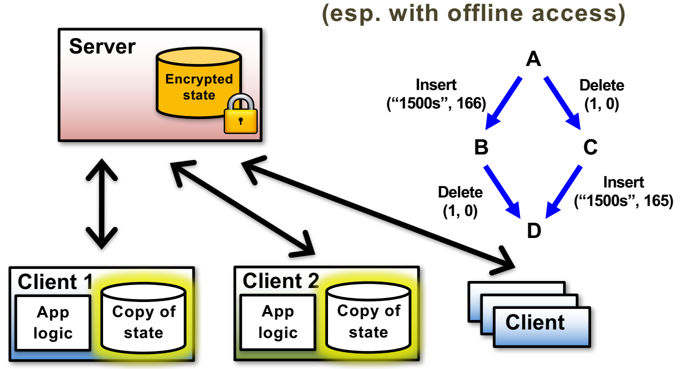


SPORC Server's limited role:

- Storage
- Ordering msgs

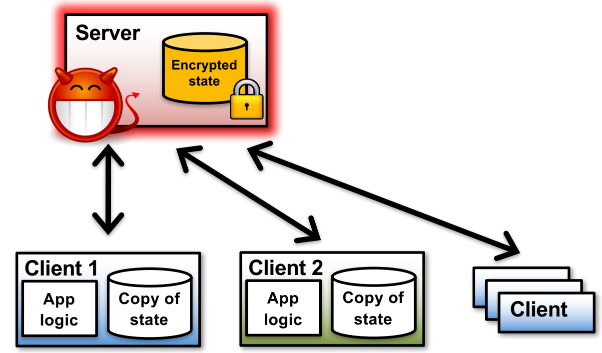
Problem #1 — How do you keep clients' local copies consistent?

(esp. with offline access)



41

Problem #2: How do you deal with a malicious server?

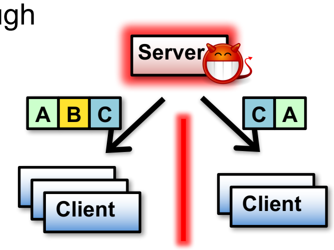


42

Dealing with a malicious server

Digital signatures aren't enough

Server can equivocate



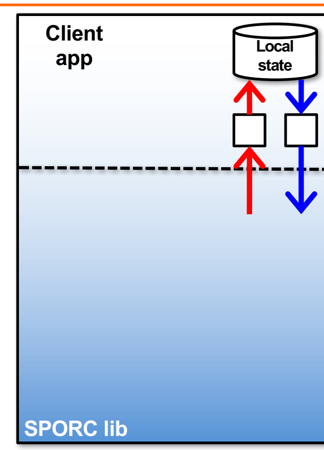
fork* consistency [LM07]

- **Honest server:** linearizability
- **Malicious server:** Alice and Bob detect equivocation after exchanging 2 messages
- Embed hash chain in every msg

Server can still fork the clients, but can't unfork

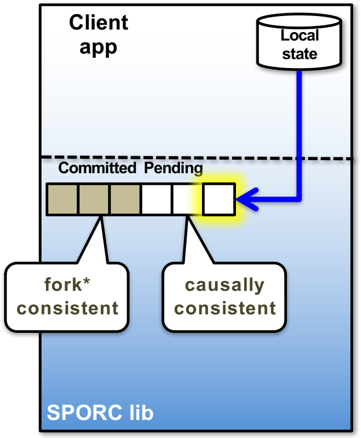
43

System design



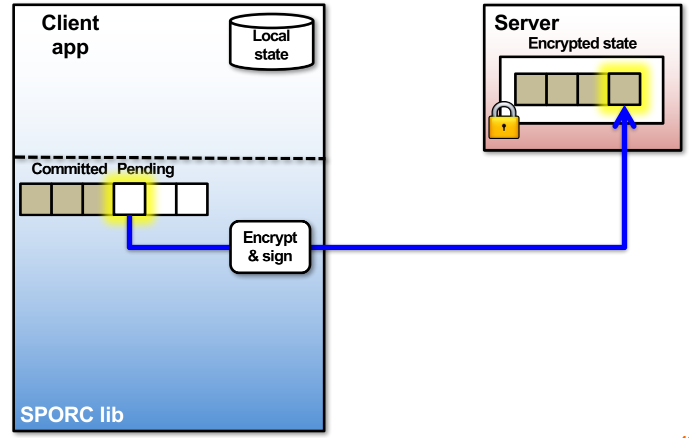
44

System design



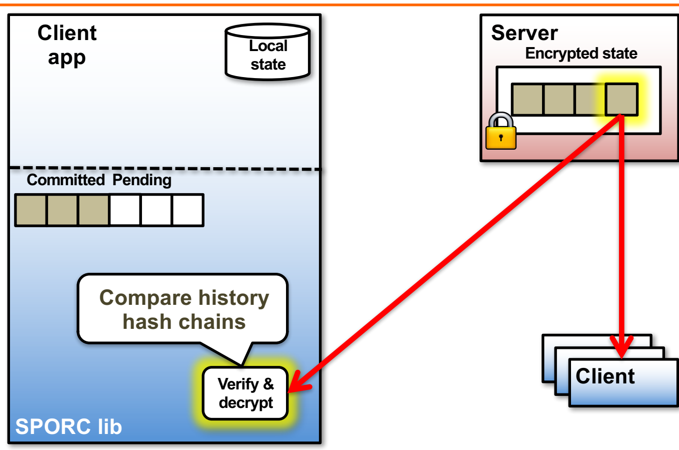
45

System design



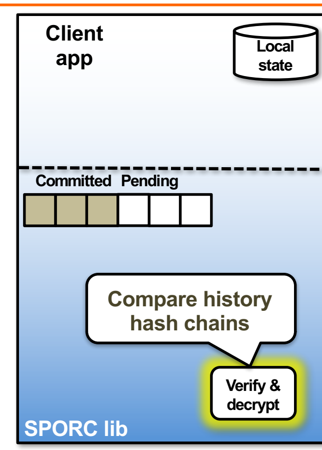
46

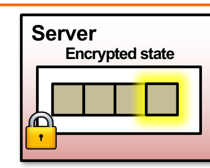
System design



47

System design

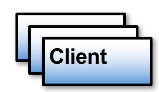




If op_k depends on op_i , it includes

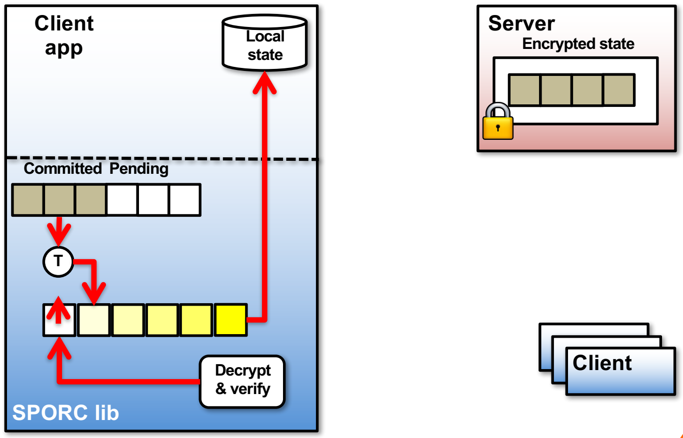
$$H(op_i \,||\, H(op_{i-1} \,||\, H(op_{i-2} \ldots))$$

Possible as ops sequentially ordered by server



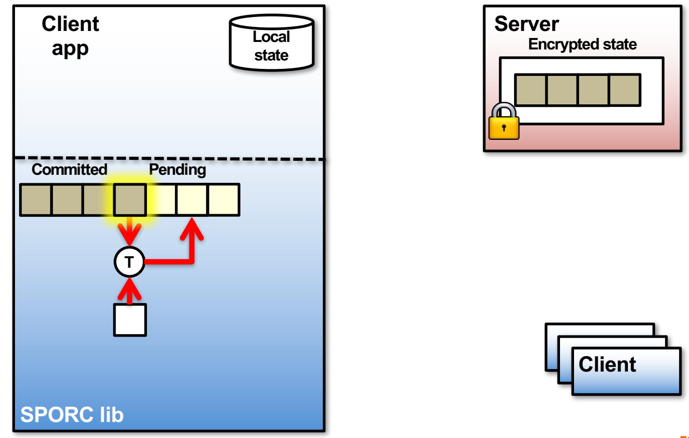
48

System design



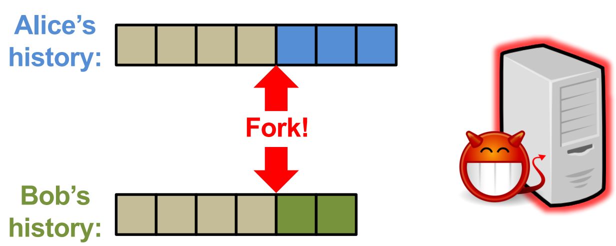
49

System design



50

Recovering from a fork



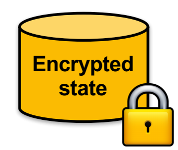
Can use OT to resolve malicious forks too

51

Access control

Challenges

- Server can't do it — it's untrusted!
- Preserving causality
- Concurrency makes it harder



Solutions

- Ops encrypted with symmetric key shared by clients
- ACL changes are ops too
- Concurrent ACL changes handled with barriers

52

Summary

- Concurrent operations in eventual-/casual-consistent systems introduce conflicts
  - OT provides general way to merge conflicting ops
  - Newer, more powerful techniques: CRDTs
- Collision resistance in cryptographic hashes can be leveraged to ensure data integrity
  - Used in variety of settings. Key idea in Bitcoin!

Monday lecture

Bitcoin and blockchains and consensus, oh my!