Integrity and Consistency for Untrusted Services

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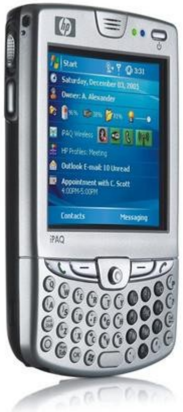
Joint work with Alex Shraer, Idit Keidar and many others.

22 June 2011

Where is my data?

amazon webservices™

Google



IBM

1986

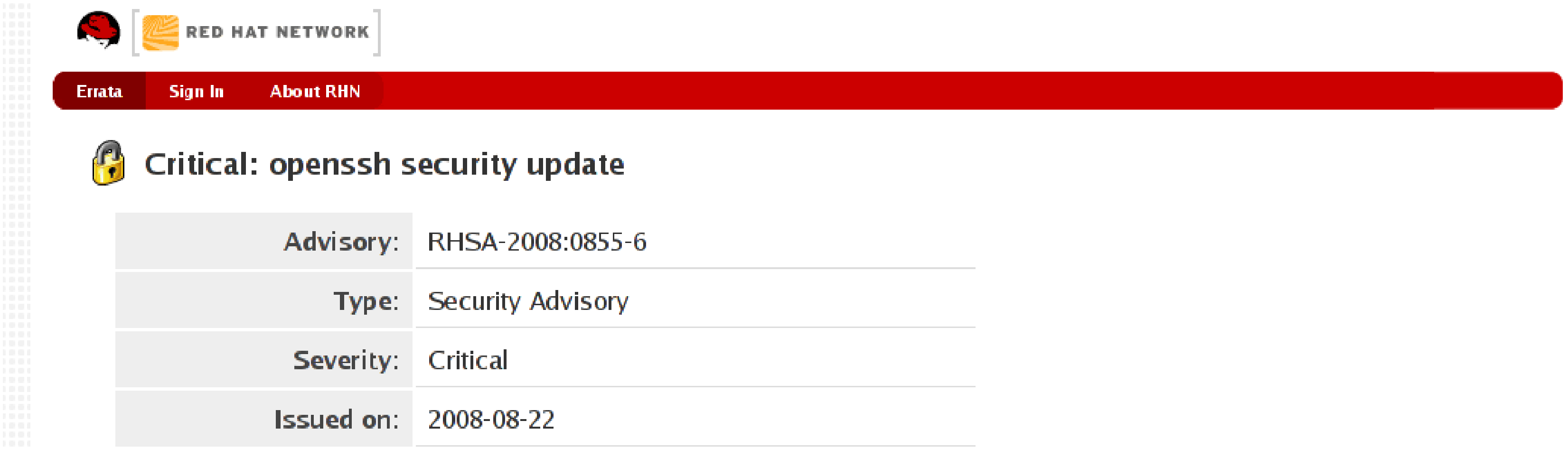
2011

Who runs my computation?

1986

2011

Remote storage - secure?



Critical: openssh security update

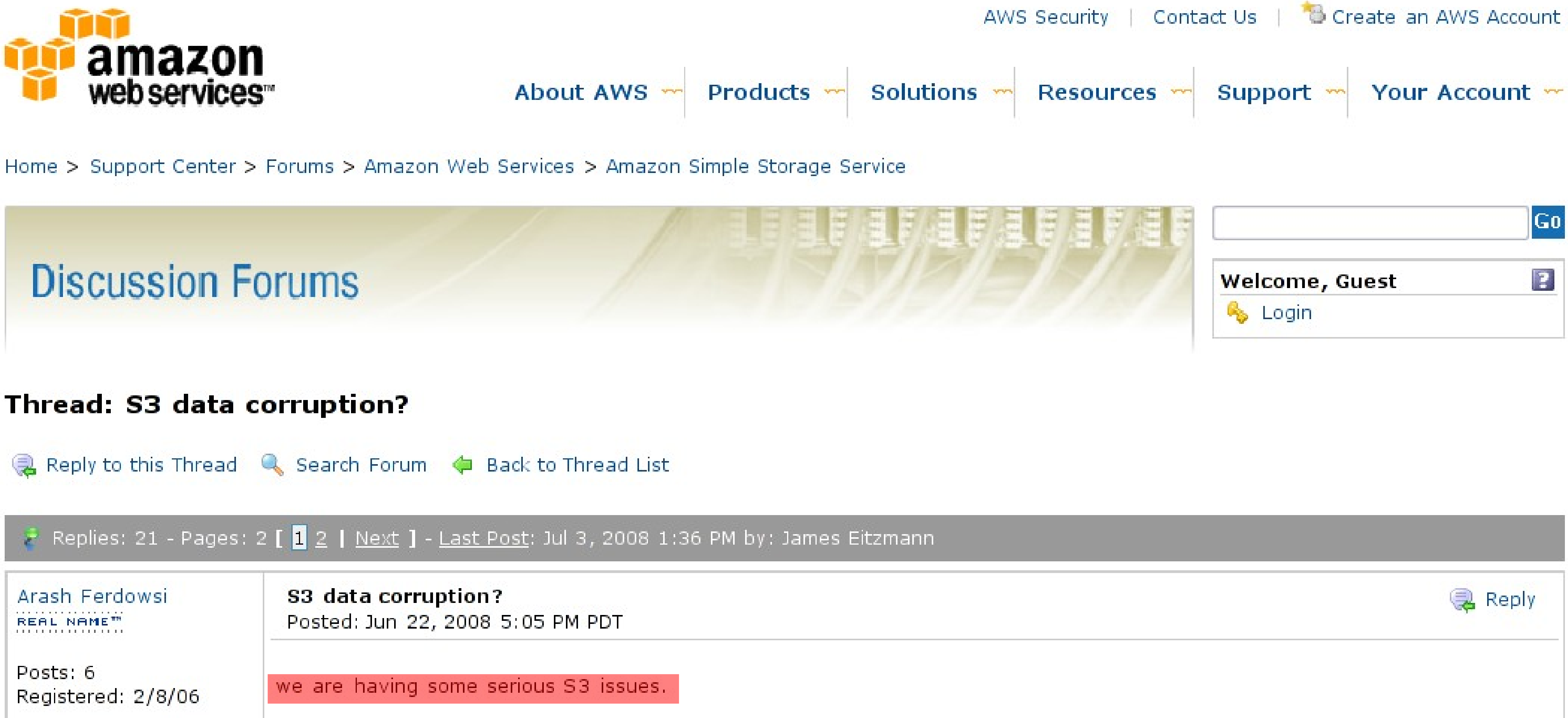
Advisory:	RHSA-2008:0855-6
Type:	Security Advisory
Severity:	Critical
Issued on:	2008-08-22

- Red Hat's servers were corrupted in Aug. '08
  - Package-signing key potentially exposed
  - Was source or binary content modified?
  - Red Hat stated in RHSA-2008:0855-6:

> … we remain highly confident that our systems and processes prevented the intrusion from compromising RHN or the content distributed via RHN and accordingly believe that customers who keep their systems updated using Red Hat Network are not at risk.

Remote storage - correct?

- Amazon S3 silently corrupted data (20-Jun-08)
  - Cause was later traced to a defective router



Thread: S3 data corruption?

Replies: 21 - Pages: 2 [1 2 | Next] - Last Post: Jul 3, 2008 1:36 PM by: James Eitzmann

Arash Ferdowsi

Posts: 6
Registered: 2/8/06

S3 data corruption?
Posted: Jun 22, 2008 5:05 PM PDT

we are having some serious S3 issues.

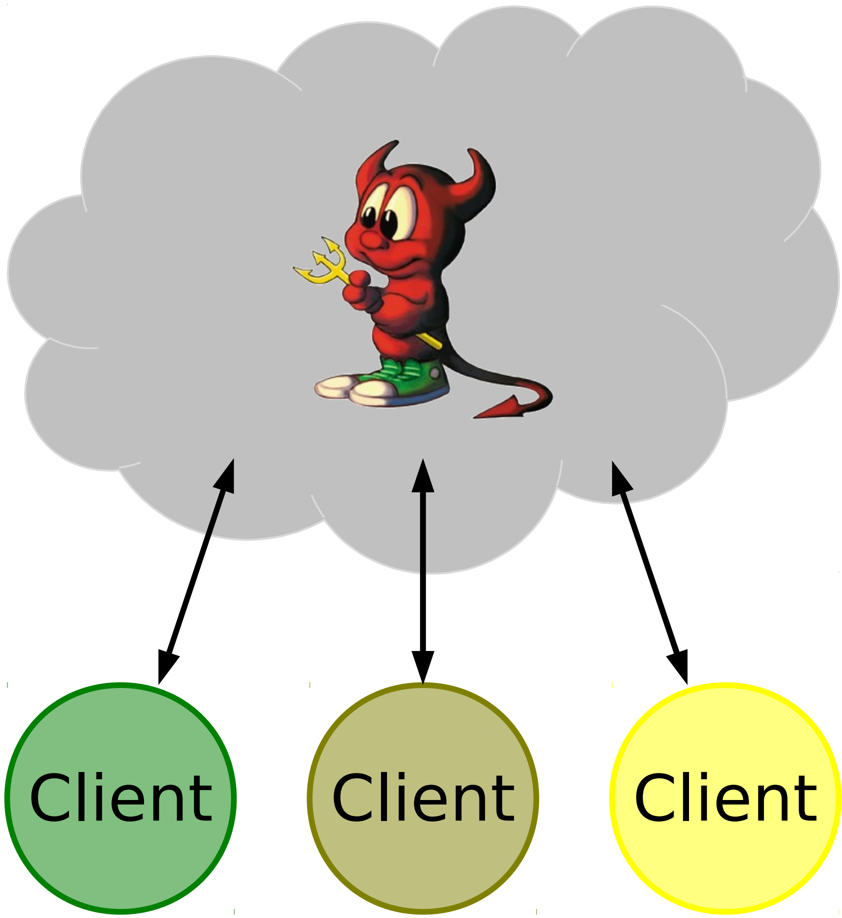
Remote services - secure?

- City of Los Angeles moves 30'000 employees from desktops to the cloud (Google Apps)
- But:

> The Los Angeles police department (LAPD) is not ready to embrace the migration due to concerns with lags in e-mail delivery, and continued anxiety over the security of data entrusted to Google.
>
> "Google Apps Project Delays Highlight Cloud Security Concerns" [PCWorld, 26 Jul. 2010]

- Google installs a dedicated "Government Cloud" for U.S. federal/state/local customers

System model



- Server S
  - Normally correct
  - Sometimes faulty (untrusted, Byzantine)
- Clients: $C_1 \dots C_n$
  - Correct, may crash
  - Run operations on server
  - Disconnected
  - Small trusted memory
- Asynchronous

Security issues

- Confidentiality
  - Expose stored data
  - Leak program code
  - Privacy of personally identifiable data

    → No concern here

- Integrity
  - Modify stored data
  - Computation returns incorrect results
  - Responses to clients not consistent

    → Focus of this work

Part 1: Storage

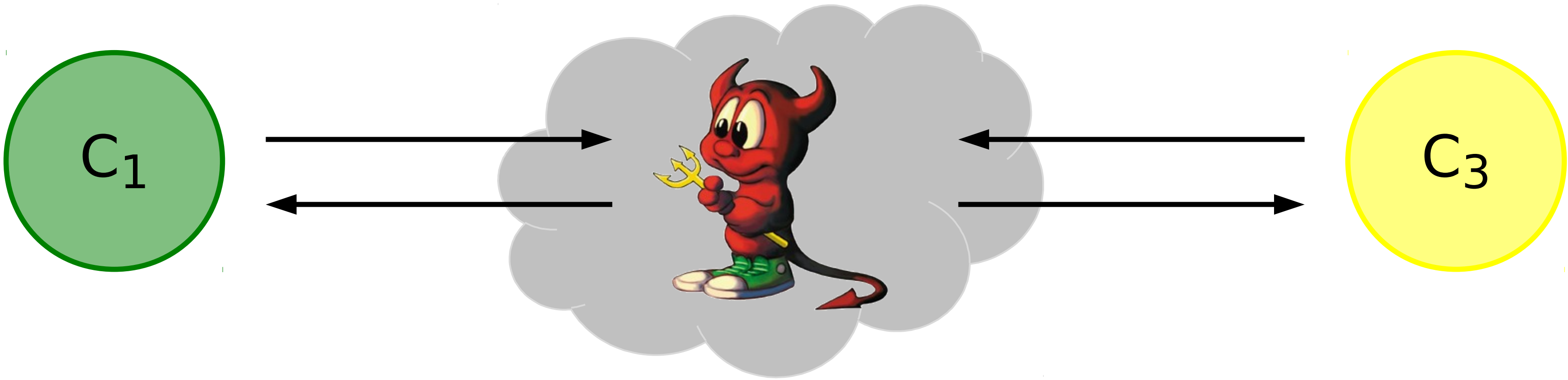
Storage model

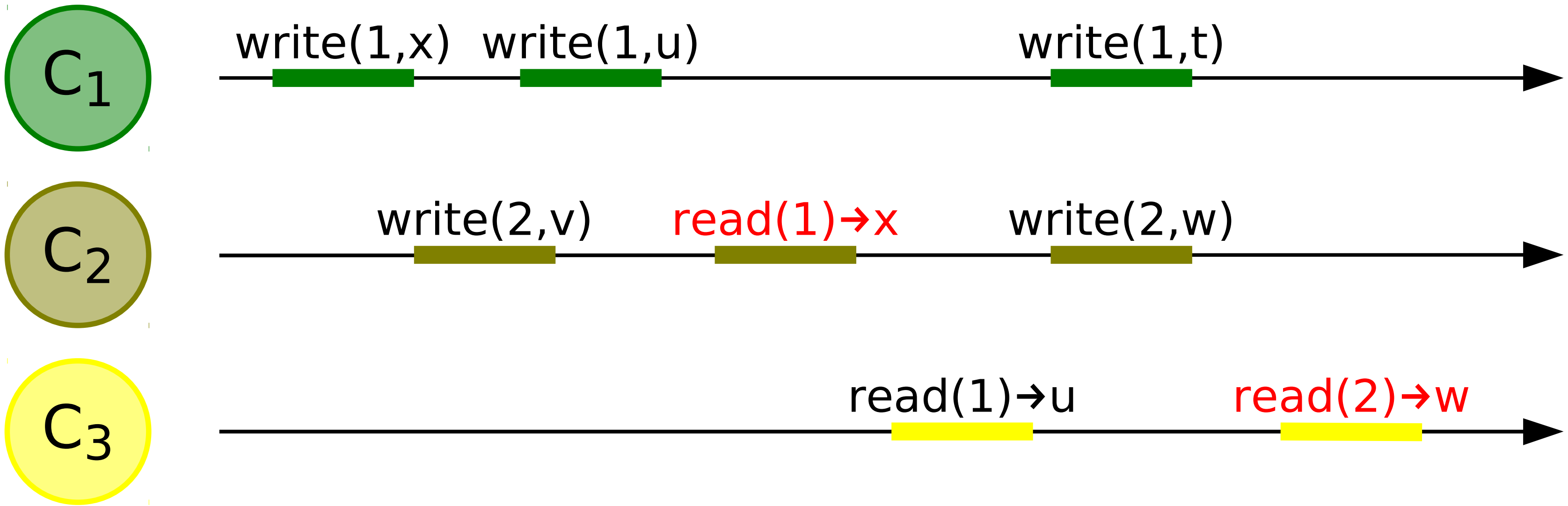
- Functionality MEM
  - Array of registers $x_1 \ldots x_n$
  - Two operations
    - $\text{read}(i) \rightarrow x_i$ returns x_i
    - $\text{write}(i,x) \rightarrow \text{ok}$ updates x_i to new value x
- Operations should be atomic
- Abstraction of shared memory
- Previous work on forking consistency conditions only considered MEM
[MS02] [LKMS04] [CSS07] [CKS09] ...

Untrusted storage

- Clients interact with service through operations to read/write data
- Clients may digitally sign their write requests
  - → Server cannot forge read values
  - → But answer with outdated values ("replay attack")
  - → But send different values to different clients (violates consistency)

The problem


C_1
C_3


C_1
write(1,x)
write(1,u)
write(1,t)
C_2
write(2,v)
read(1)→x
write(2,w)
C_3
read(1)→u
read(2)→w

Solution: Fork-linearizability

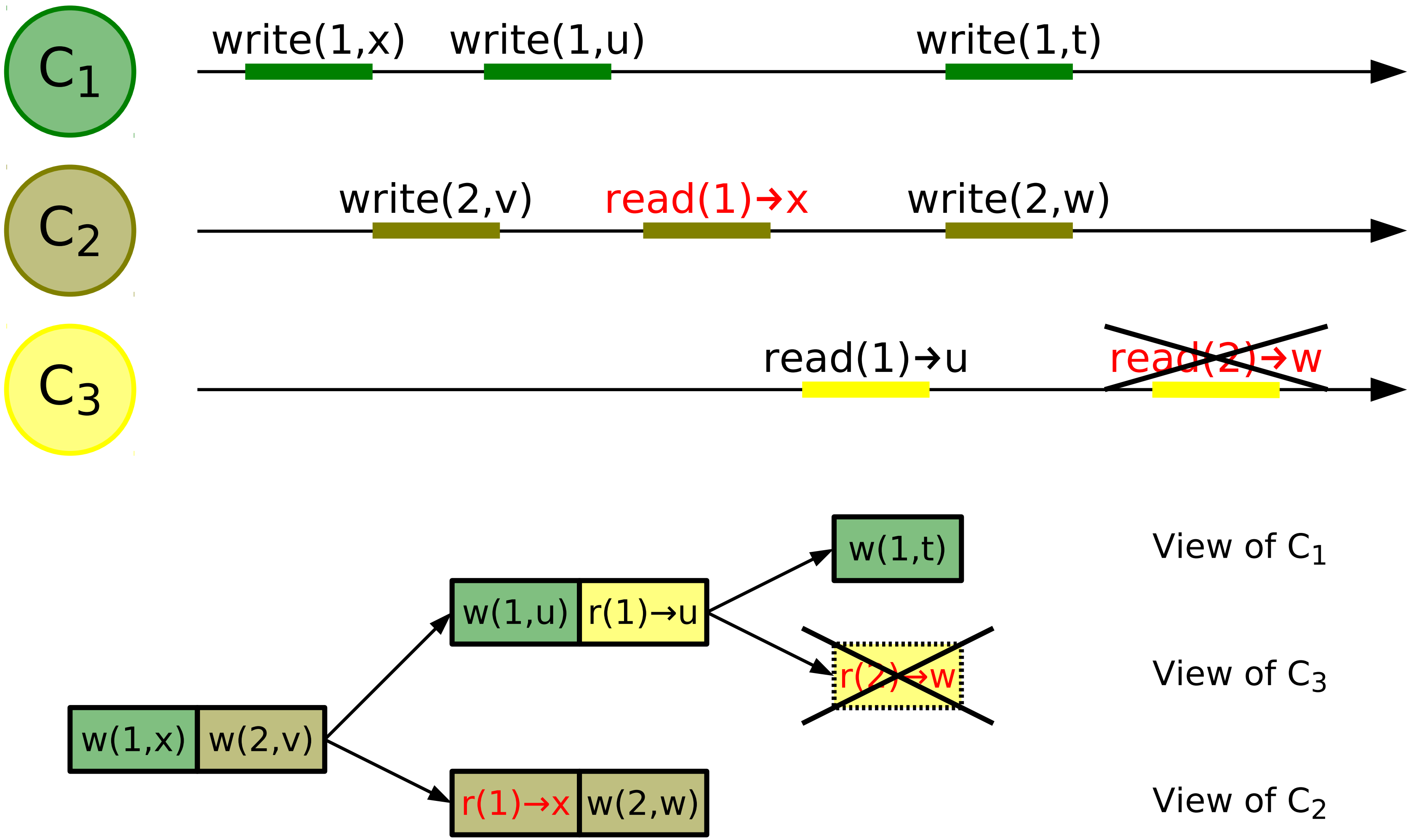
- Server may present different views to clients
  - "Fork" their views of history
  - Clients cannot prevent this

- Fork linearizability [MS02]
  - If server forks the views of two clients once, then
    → their views are forked ever after
    → they never again see each others updates

- Every inconsistency results in a fork
  - Not possible to cover up

- Forks can be detected on separate channel
  - Best achievable guarantee with faulty server

Fork-linearizability graphically



C_1 write(1,x) write(1,u) write(1,t)

C_2 write(2,v) read(1)→x write(2,w)

C_3 read(1)→u ~~read(2)→w~~

w(1,x) w(2,v)

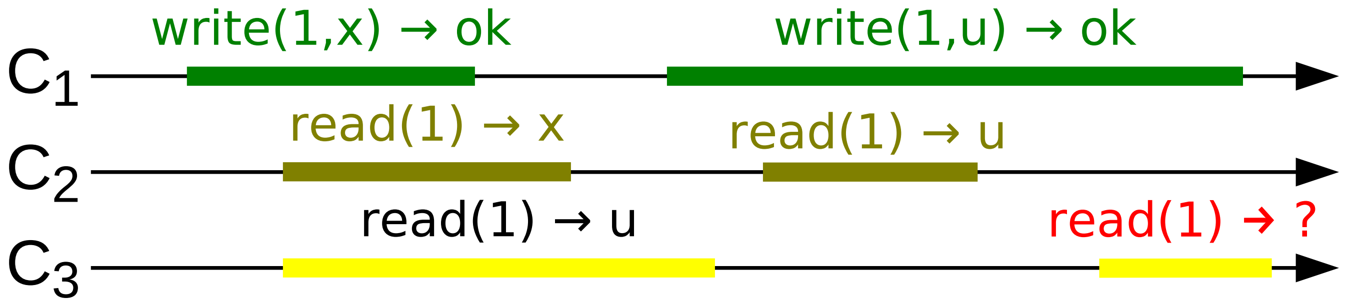
w(1,u) r(1)→u

w(1,t) View of C_1

~~r(2)→w~~ View of C_3

r(1)→x w(2,w) View of C_2

Background: Semantics of concurrent operations

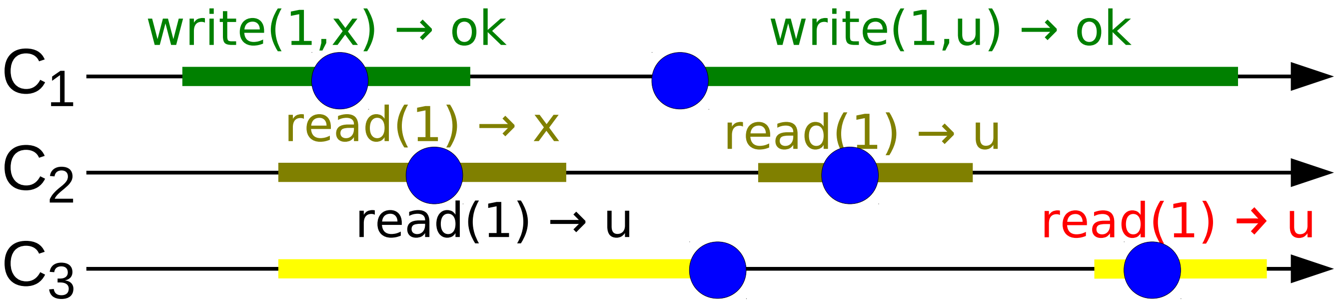


Safe: Every *read* not concurrent with a *write* returns the most recently *written* value.

(Regular: *Safe* & any *read* concurrent with a *write* returns either the most recently *written* value or the concurrently *written* value: C_3 may read x or u.)

Atomic: *Regular* & all *read* and *write* operations are linearizable: C_3 must read u.

Linearizability example



- Every operations appears to execute atomically at its linearization point ● which lies in real time between invocation and response

Linearizability formally

A history σ is linearizable (w.r.t. F)

$\Leftrightarrow$ $\exists$ permutation π of σ such that:

- π is sequential and follows specification (of F);
- $\forall i$ all operations of C_i are in σ ;
- π preserves real-time order of σ.

Fork-linearizability formally

A history σ is fork-linearizable

$\Leftrightarrow$ $\forall i \; \exists$ subset $\sigma_i \subseteq \sigma$ and permutation π_i of σ_i s.t.

- All operations of C_i are in σ_i ;
- π_i is sequential and follows specification;
- If $o \in \pi_i \cap \pi_j$, then $\pi_i = \pi_j$ up to o;
- π_i preserves real-time order of σ_i.

Fork-linearizable Byzantine emulations

- Protocol P emulates functionality F on a Byzantine server S with fork-linearizability, whenever
  - If S correct, then history of every (...) execution of P is linearizable w.r.t. F;
  - The history of every (...) execution of P is fork-linearizable w.r.t. F.

[CSS07]

A trivial protocol

- Fork-linearizable Byzantine emulation
- Idea [MS02]: sign the complete history
  - Server sends history with all signatures
  - Client verifies all operations and signatures
  - Client adds its operation and signs new history
- Impractical since messages and history grow with system age

Fork-linearizable storage (1)

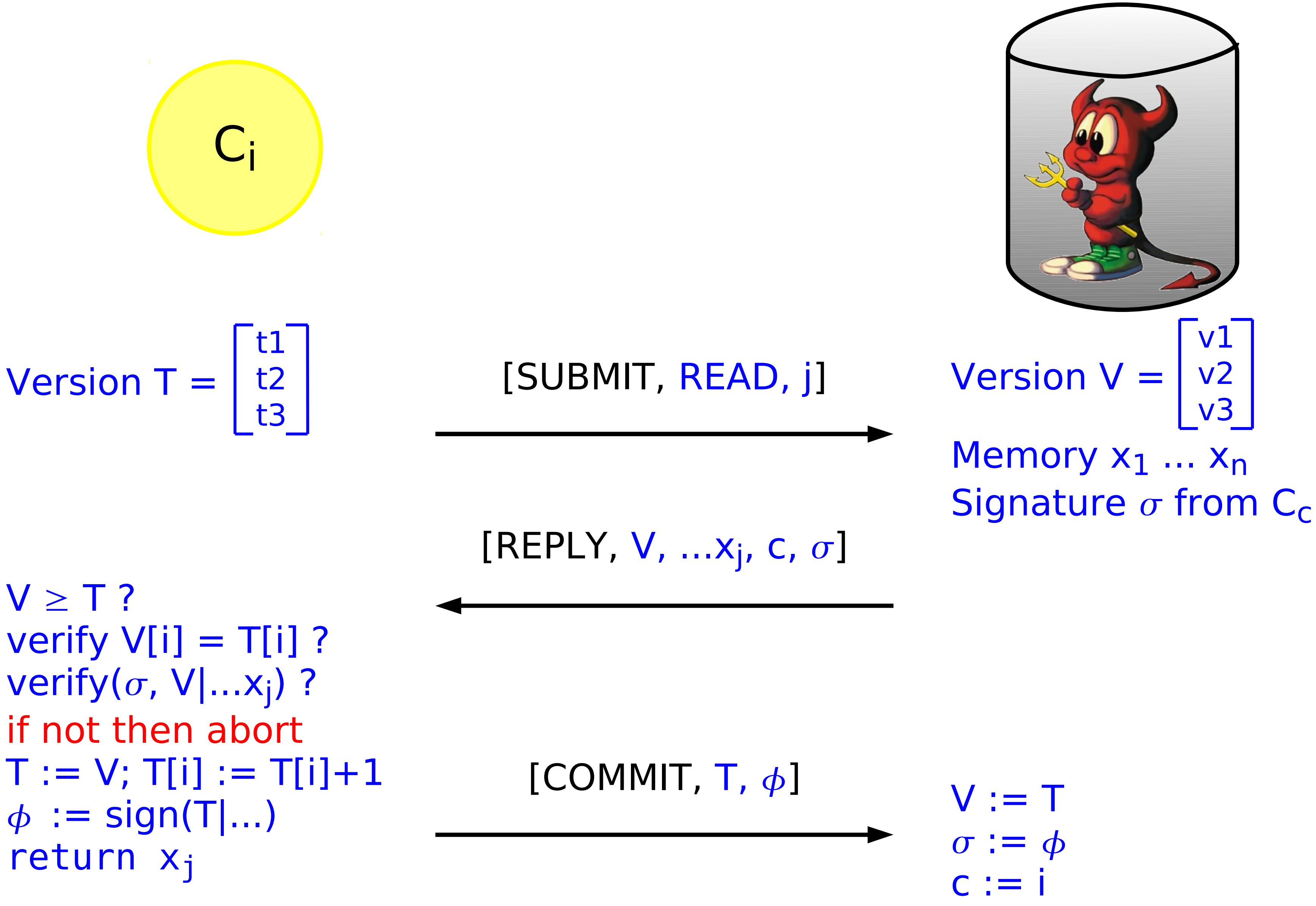
- Client C_i
  - Stores timestamp t_i and
  - Version (vector of timestamps) T, where $T[i] = t_i$
  - Increments t_i and updates T at every operation

- Versions order operations
  - After every operation, client signs new timestamp, version, and data

$$V = \begin{bmatrix} v1 \\ v2 \\ v3 \end{bmatrix}$$

- Verification with version T of last operation
  - Version V of next operation must be $V \geq T$
  - Signatures must verify

Fork-linearizable storage (2)



C_i

Version $T = \begin{bmatrix} t1 \\ t2 \\ t3 \end{bmatrix}$

[SUBMIT, READ, j] →

Version $V = \begin{bmatrix} v1 \\ v2 \\ v3 \end{bmatrix}$

Memory $x_1 \ldots x_n$

Signature σ from C_c

← [REPLY, V, $\ldots x_j$, c, σ]

$V \geq T$?

verify $V[i] = T[i]$?

verify(σ, $V|\ldots x_j$) ?

if not then abort

$T := V$; $T[i] := T[i]+1$

$\phi := \text{sign}(T|\ldots)$

return x_j

[COMMIT, T, ϕ] →

$V := T$

$\sigma := \phi$

$c := i$

Fork-linearizable storage (3)

- If clients are forked, they sign and store incomparable versions

$$\begin{bmatrix} u \\ v \\ w+1 \end{bmatrix} \quad ? \quad \begin{bmatrix} u \\ v+1 \\ w \end{bmatrix}$$

- Signatures prevent server from other manipulations
  - Protocol uses O(n) memory for emulating fork-linearizable shared memory on Byzantine server
- Increasing concurrency?
  - Here, clients proceed in lock-step mode
  - Yes, but see papers...

Fork-linearizability benefits

- Client C_i writes many values u, v, w, x ...
- Without protection, faulty S may return any of those values to a reader C_i
- With fork-linearizable emulation
  - C_i writes z and tells C_j out-of-band
  - C_i reads r from location i
    - if $r = z$, then all values read so far were correct
    - if $r \neq z$, then S is faulty
  - Out-of-band might be only synchronized clocks

Storage systems providing fork-linearizability

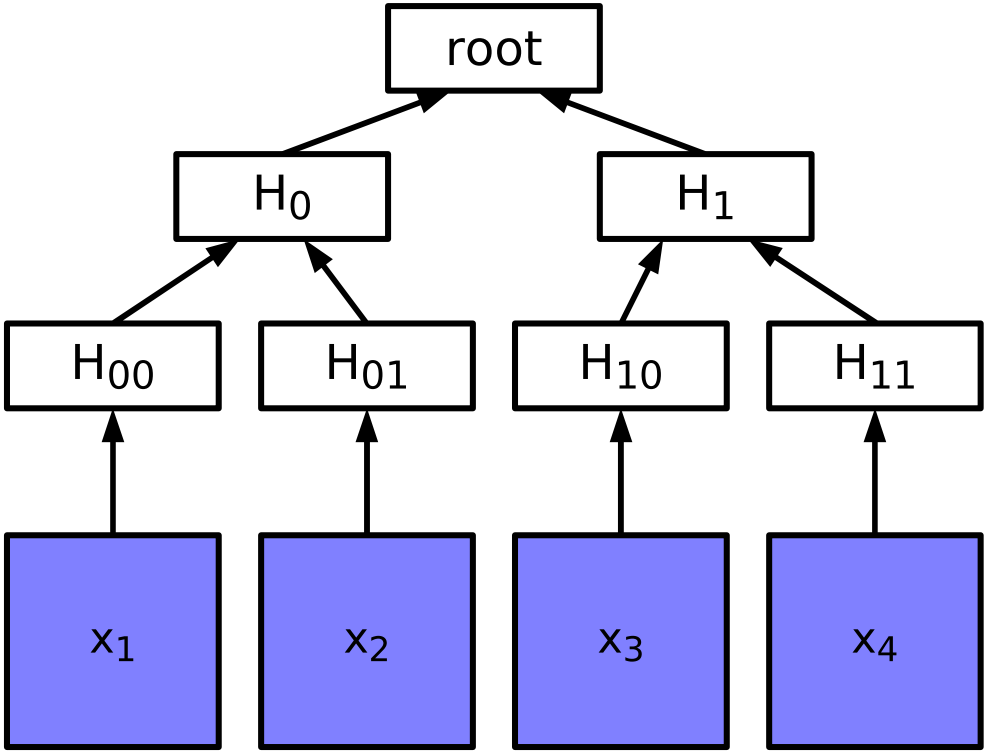
SUNDR [LKMS04] Secure untrusted data repository

- NFS network file system API
- Extensions to NFS server and NFS client
- Hash tree over all files owned by every user

CSVN [CG09] Integrity-protecting Subversion revision-control system

- SVN operations are verified
- Hash tree over file repository
- Based on fork-linearizable storage protocol [CSS07]

Hash trees for integrity checking (Merkle)



- Parent node is hash of its children
- Root hash value commits all data blocks
  - Root hash in trusted memory
  - Tree is on extra untrusted storage
- To verify x_i, recompute path from x_i to root with sibling nodes and compare to trusted root hash
- To update x_i, recompute new root and nodes along path from x_i to root

Read & write operations in O(log n) work
- hash operations
- extra storage accesses

Forking consistency is blocking

- All fork-linearizable emulations of storage have executions with a correct S, where C_i must wait for C_j [CSS07].

- Also fork-sequentially consistent storage emulation protocols [OR06] are blocking.

- Also fork-*-linearizable storage emulation protocols [LM07] are blocking.

→ Weak forklinearizability allows wait-free emulations [CKS09]

Part 2: General services

From storage to any service

- Server provides any deterministic functionality F

- F is a state machine: $F(s,o) \rightarrow (s',r)$
  - State s
  - Operation o
  - New state s'
  - Result r

- Previous work on forking consistency conditions only considers MEM function [MS02] [LKMS04] [CSS07] [CKS09] ...

Background:
Authenticated data structures

- Server stores (large) state s of DB (read-only)
- Client has (short) trusted authenticator a

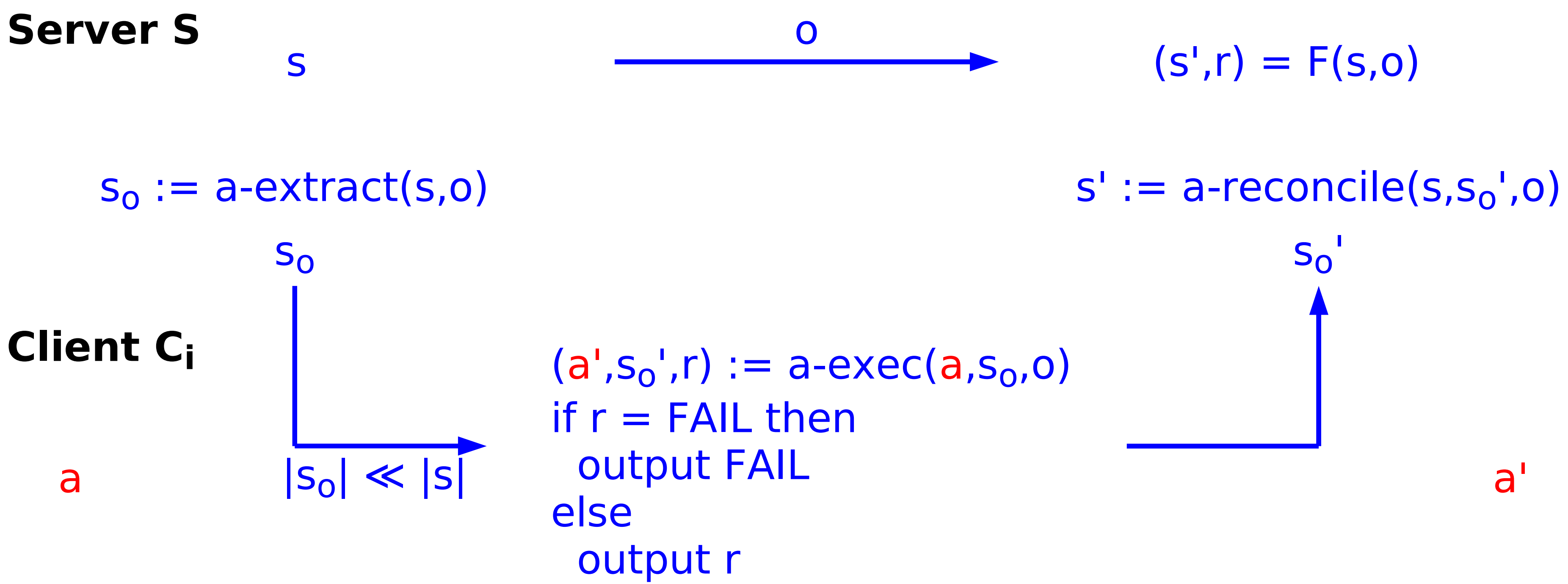
- Syntax
  - Client sends query q to S
  - S sends result r := DB(s,q)
  - Client runs algorithm verify(a,q,r) → OK / FAIL

- Correctness & security
  - If a is correct authenticator for s and DB(s,q)=r then
    verify(a,q,r) → OK
  - No faulty S can forge q* and r*≠DB(s,q*) with
    verify(a,q*,r*) → OK

Authenticated separated exec.

- Generalizes authenticated data structures
  - Client maintains authenticator a in trusted memory

- Execution separated between S and C_i



Server S

s

o

(s',r) = F(s,o)

s_o := a-extract(s,o)

s' := a-reconcile(s,s_o',o)

s_o

s_o'

Client C_i

```
(a',s_o',r) := a-exec(a,s_o,o)
if r = FAIL then
  output FAIL
else
  output r
```

a

$|s_o| \ll |s|$

a'

Properties of authenticated separated execution

- Correctness
  - Result computed by separated execution of operation o under F on state s is equal to $F(s,o)$
  - Size of s_o and s_o' is much smaller than size of s
- Security
  - Given proper authenticator a for state s, then for any o^* and s^*_o (forged by faulty S):

    $a\text{-exec}(a,s^*_o,o^*) \rightarrow \text{FAIL}$ or $a\text{-exec}(a,s^*_o,o^*) \rightarrow r$ with $r=F(s,o)$
  - I.e., client detects modification or gets correct result

Fork-linearizable service impl.

C_i

Version T

[SUBMIT, o] →

Version V
State s
Authenticator a
Signature σ from C_c

[REPLY, V, a, s_o, c, σ] ←

s_o := a-extract(s,o)

V $\geq$ T ?
verify V[i] = T[i] ?
verify(σ, V|a) ?
if not then abort
(a',s_o',r) := a-exec(a,s_o,o)
if r = FAIL then abort
T := V; T[i] := T[i]+1
ϕ:= sign(T|a')

[COMMIT, T, a', s_o', ϕ] →

s := a-reconcile(s, s_o', o)
V := T
a := a'; σ := ϕ; c := i

Protocol properties

- If server correct, then linearizable
  - Correct server schedules operations as they arrive
- With faulty server, still fork-linearizable w.r.t. F
  - From properties of versions and authenticated execution scheme
- Complexity
  - Three messages
  - Message size O(n), with n clients

Insight

- New protocol extends all existing protocols for untrusted storage
- Generalizes untrusted remote execution protocols for other (limited) functions
- Relevant for applications run in "clouds"

Related work

[WSS09] Blind Stone Tablet

- Run relational database on untrusted server

[FZFF10] SPORC: Group collaboration on ...

- Shared editor for working on documents in cloud
- Operational transforms let operations commute

[MSLCADW10] Depot: Cloud storage

- Respects fork-causality consistency notion

Conclusion

- Remote checking for applications in cloud
- Target is collaboration among group of mutually trusting clients
- Fork-linearizable service execution protocol
  - In normal case, linearizable and “blocking”
  - In failure case, respects fork-linearizability
- Ongoing and future work on extending the protocol to avoid “blocking”

References

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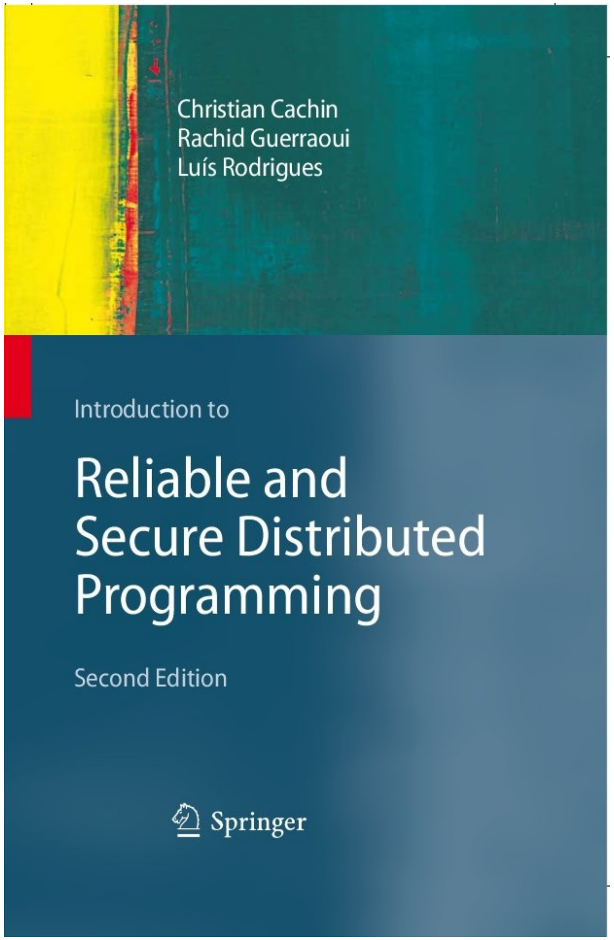

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Introduction to

Reliable and Secure Distributed Programming

Second Edition

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- C. Cachin, R. Guerraoui, L. Rodrigues
- 2nd ed. of Introduction to Reliable Distributed Programming
- Springer, 2011

Web: www.distributedprogramming.net

Backup

Emulating fork-linearizable memory requires waiting

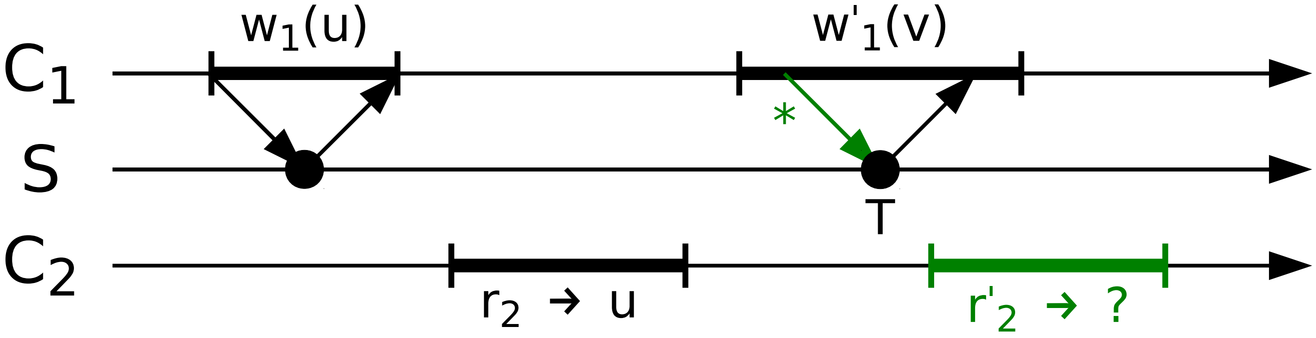
Theorem: Every protocol has executions with a correct server where a client C_i must wait for some client C_j.

Proof sketch:

- Protocol with only 1 round of messages
- Assume such a protocol exists
- Construct an execution that is not fork-linearizable, but looks like one that is to every client

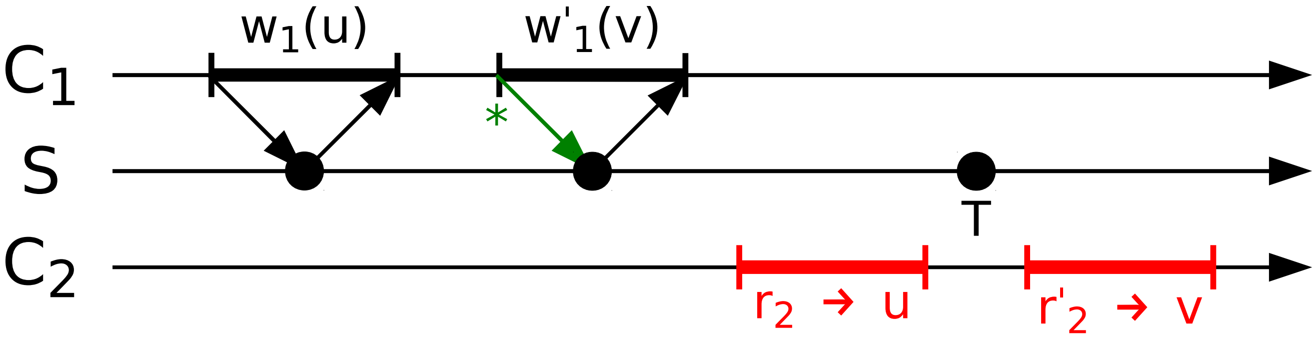
Proof for 1-round protocols

Correct S:



- → Msg. * is oblivious of r_2
- → r'_2 must return v

Faulty S:



- → S reorders w'_1 and r_2, as msg. * is oblivious of r_2
- → If S forges same state at T as before, r'_2 returns v
- → History is not fork-linearizable