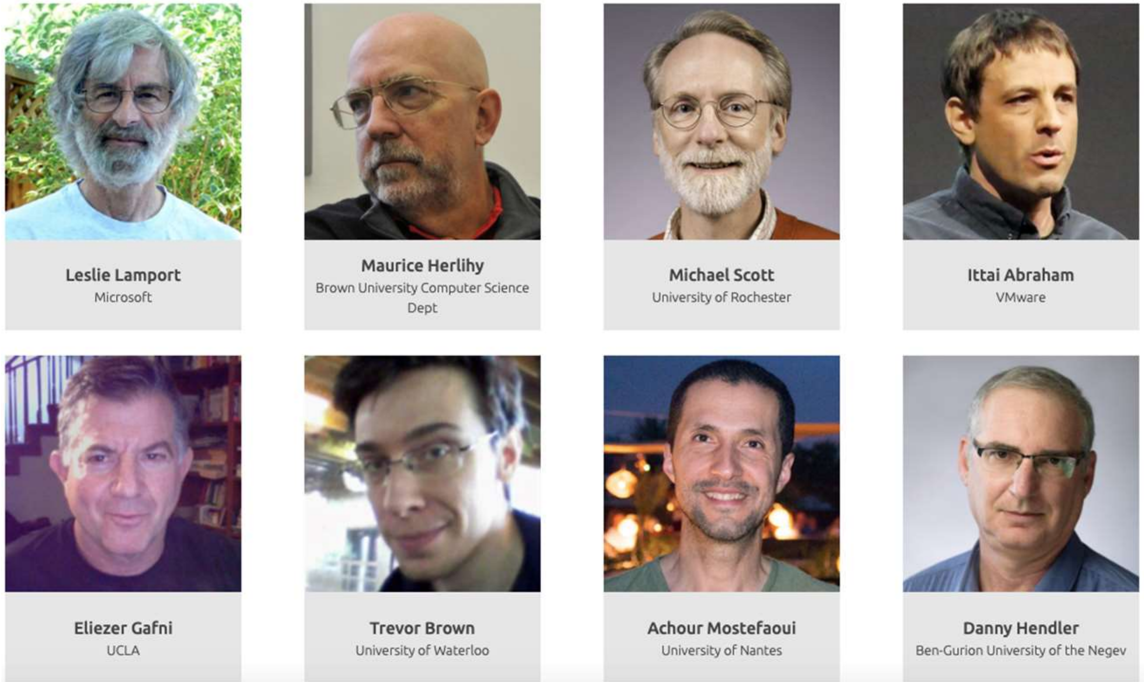
THE SECOND SUMMER SCHOOL ON PRACTICE AND THEORY OF DISTRIBUTED COMPUTING

July 8-12, 2019, St Petersburg, Russia



Algorithmic basics of blockchains

Concurrent data structures

Distributed computability

State-machine replication and Paxos

Byzantine fault-tolerance

https://sptdc.ru/en/

The Consensus Number of a Cryptocurrency

To appear at PODC 2019

Joint work with Rachid Guerraoui, Matteo Monti, Matej Pavlovic, and Adi Seredinschi

Bitcoin: A Peer-to-Peer Electronic Cash System

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Abstract. A purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution. Digital signatures provide part of the solution, but the main benefits are lost if a trusted third party is still required to prevent double-spending. We propose a solution to the double-spending problem using a peer-to-peer network.

...

The only way to confirm the absence of a transaction is to be aware of all transactions. In the mint based model, the mint was aware of all transactions and decided which arrived first. To accomplish this without a trusted party, transactions must be publicly announced [1], and we need a system for participants to agree on a single history of the order in which they were received.

Enhancing Bitcoin Security and Performance with Strong Consistency via Collective Signing

Eleftherios Kokoris-Kogias, Philipp Jovanovic, Nicolas Gailly, Ismail Khoffi, Linus Gasser, and Bryan Ford
EPFL

Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains

Elli Androulaki
Artem Barger
Vita Bortnikov
IBM

Christian Cachin
Konstantinos Christidis
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Manish Sethi
Gari Singh
Keith Smith
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Chrysoula Stathakopoulou
Marko Vukolić
Sharon Weed Cocco
Jason Yellick
IBM

Thunderella: Blockchains with Optimistic Instant Confirmation

SBFT: a Scalable Decentralized Trust Infrastructure for Blockchains

Guy Golan Gueta (VMware Research)
Shelly Grossman (TAU)
Michael K. Reiter (UNC-Chapel Hill)
Dahlia Malkhi (VMware Research)
Orr Tamir (TAU)
Ittai Abraham (VMware Research)
Benny Pinkas (BIU)
Dragos-Adrian Seredinschi (EPFL)
Alin Tomescu (MIT)

Algorand: Scaling Byzantine Agreements for Cryptocurrencies

Yossi Gilad, Rotem Hemo, Silvio Micali, Georgios Vlachos, Nickolai Zeldovich
MIT CSAIL

Hot-Stuff the Linear, Optimal-Resilience, One-Message BFT Devil

Ittai Abraham, Guy Gueta, Dahlia Malkhi
VMware Research

March 15, 2018

FruitChains: A Fair Blockchain

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May 5, 2017

Hybrid Consensus: Efficient Consensus in the Permissionless Model

Rafael Pass and Elaine Shi

CornellTech, Cornell, Initiative for CryptoCurrency and Contracts (IC3)*


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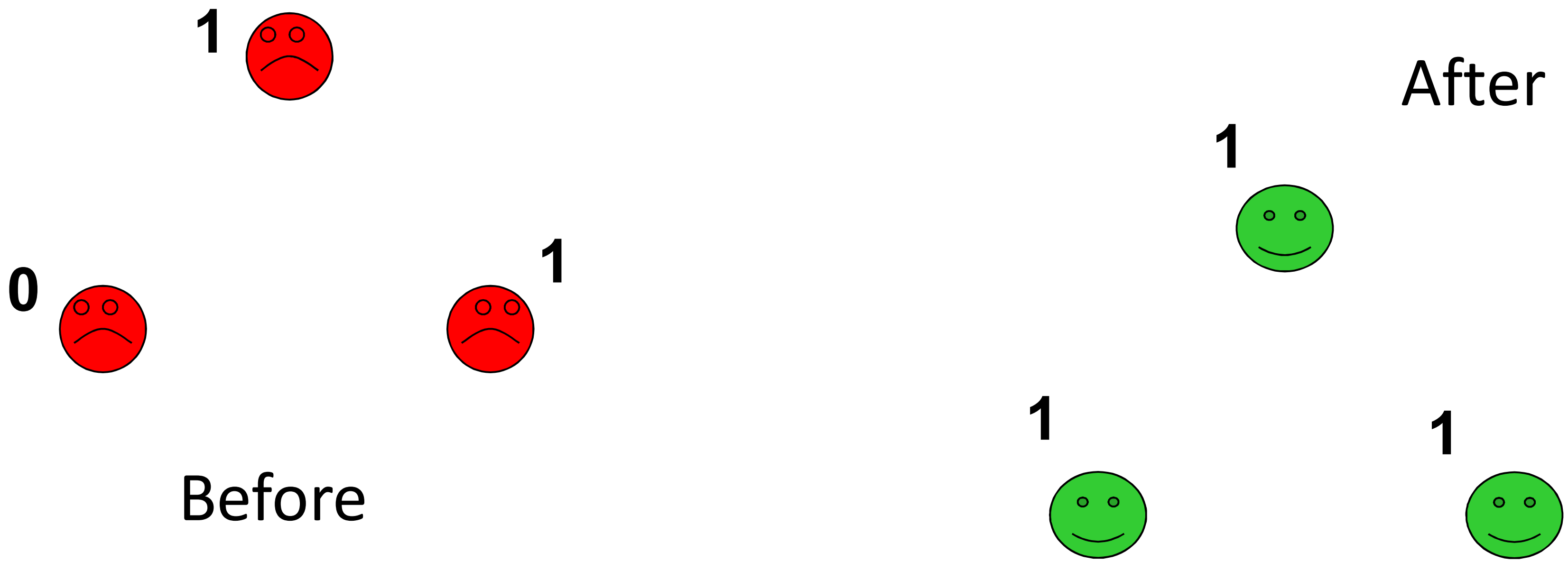
This talk

Cryptocurrency does not require consensus

- Consensus number of the asset transfer data type:
  - ✓k-owned (smart contracts with k parties) – k
- Asynchronous asset transfer algorithm
  - ✓1-owned: secure broadcast
  - ✓k-owned: k-consensus + secure broadcast

Consensus

Processes *propose* values and must *agree* on a common decision value so that the decided value is a proposed value of some process



But why consensus is interesting?

Because it is universal!

- If we can solve consensus among N processes, then we can *implement* any object shared by N processes
- A key to implement a generic fault-tolerant service (replicated state machine or blockchain)

Is consensus necessary for a cryptocurrency?

What is a “cryptocurrency”?

State:

- *P* - set of processes
- *A* - set of *accounts*
- μ: $A \rightarrow 2^P$ - *ownership map* (single owner if $A \rightarrow P$)
- β: $A \rightarrow \mathbf{N}$ – balance map (β_0 – initial balances)

Interface:

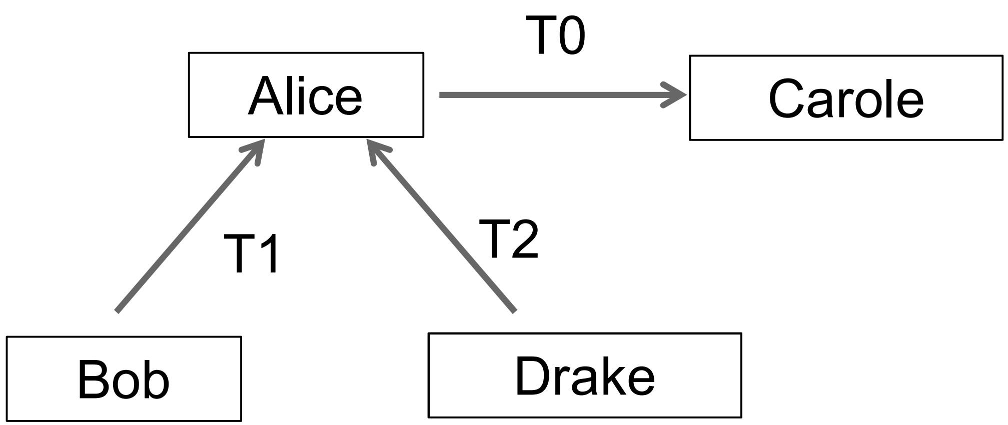
- *transfer*(a,b,x) – called by an owner of a, returns a boolean (success or failure)
- *read*(a) – returns the balance

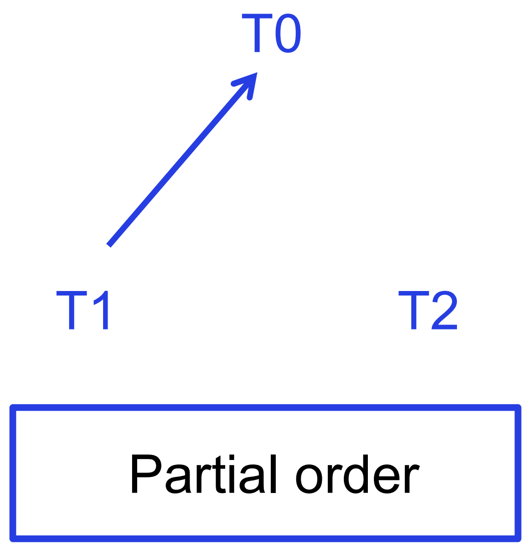
We call it asset transfer data type

Commutativity and causality

- T0: $100 from Alice to Carole
- T1: $100 from Bob to Alice
- T2: $100 from Drake to Alice

T0 causally depends on T1 (not enough funds otherwise)
T1 and T2 commute (T0 succeeds regardless of the order)





Consensus number

An object O has consensus number k if

- k-process consensus can be solved using registers and any number of copies of O but (k+1)-consensus cannot

(k is the maximal number of processes that can be synchronized using copies of O and registers)

Consensus hierarchy:

- cons(read-write register)=1
- cons(T&S)=cons(queue)=2
- …
- cons(CAS)=∞

Consensus number of asset transfer

Upon $transfer(a, b, x)$

$S := AS.snapshot()$

if $p \notin \mu(a) \vee balance(a, S) < x$ **then**

  return $false$

$ops_p := ops_p \cup \{(a, b, x)\}$

$AS.update(ops_p)$

return $true$

Upon $read(a)$

$S := AS.snapshot()$

return $balance(a, S)$

Single-owner: 1

- use atomic-snapshot memory to exchange the account balance

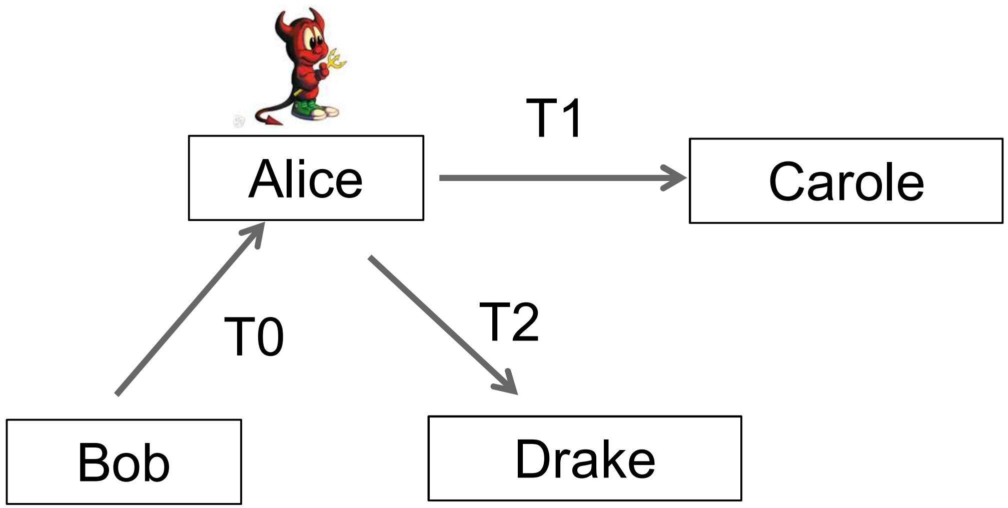
k-owner (up to k can debit an account): k

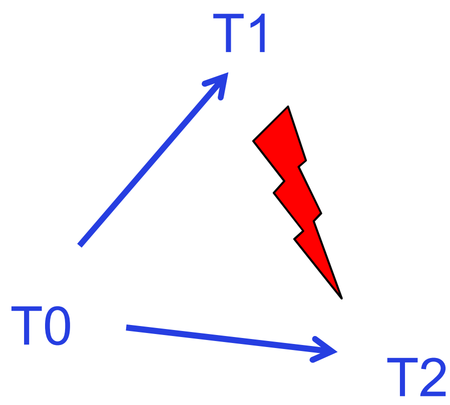
- account owners use k-consensus to agree on the per-account order of debit operations
- A single k-owned account solves k-consensus

What about double-pending?

- T0: $100 from Bob to Alice
- T1: $100 from Alice to Carole
- T2: $100 from Alice to Drake

Alice’s initial balance is 0, but it claims to both beneficiaries to have received money from Bob



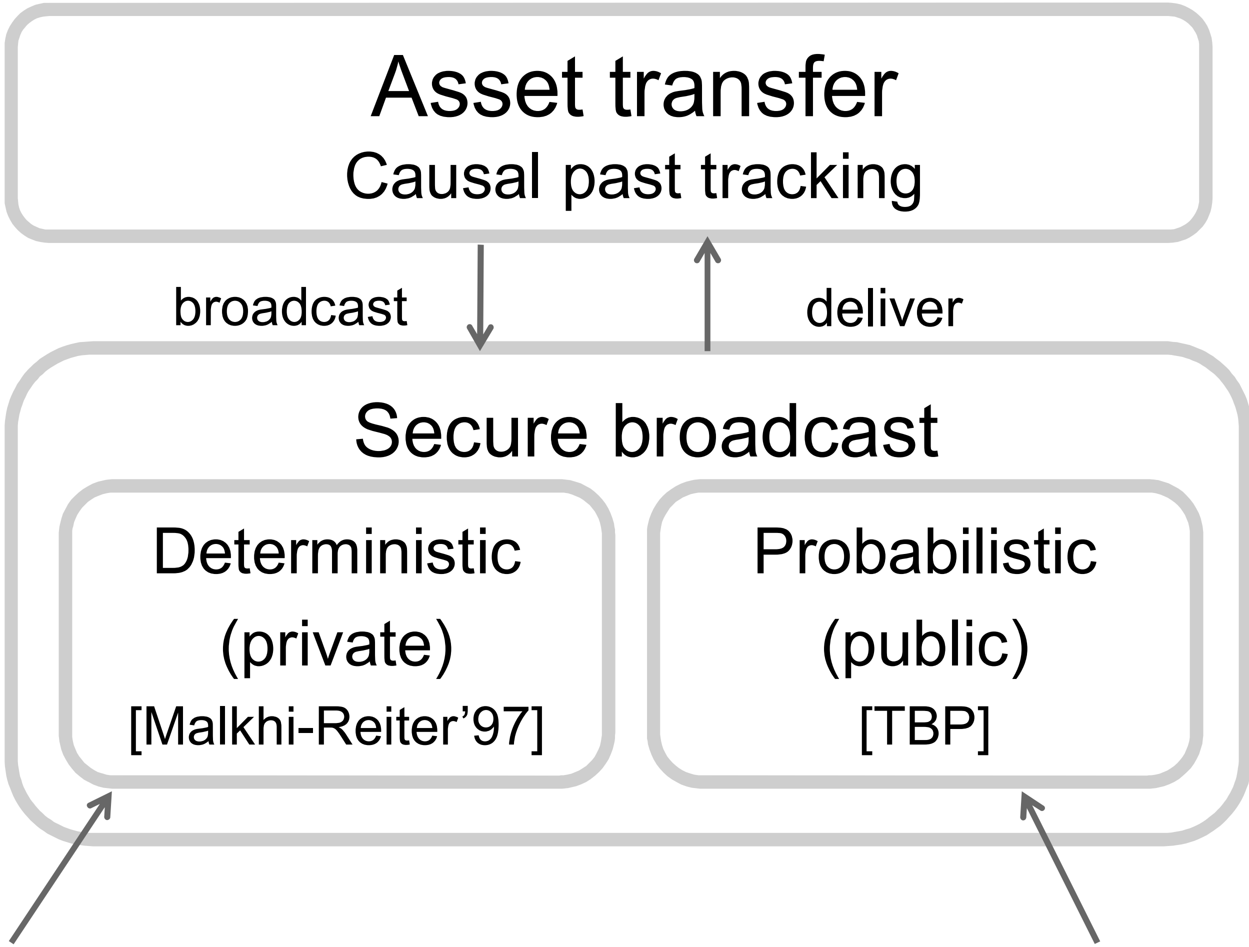


Asset transfer implementation

Message-passing, Byzantine failures

- Each transfer is equipped with it causal past (a set of incoming transactions)
- Make sure that a faulty account holder cannot lie about its causal past
- Secure broadcast [Bracha, 1987, Malkhi-Reiter, 1997]
  - ✓Source-order: messages by the same source are delivered in the same order

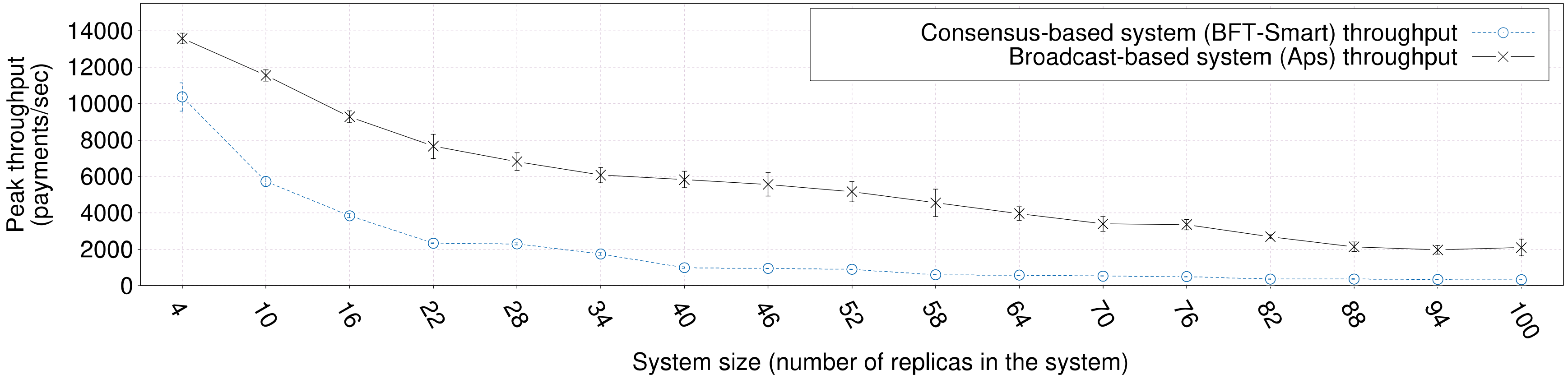
Modular approach: private and public

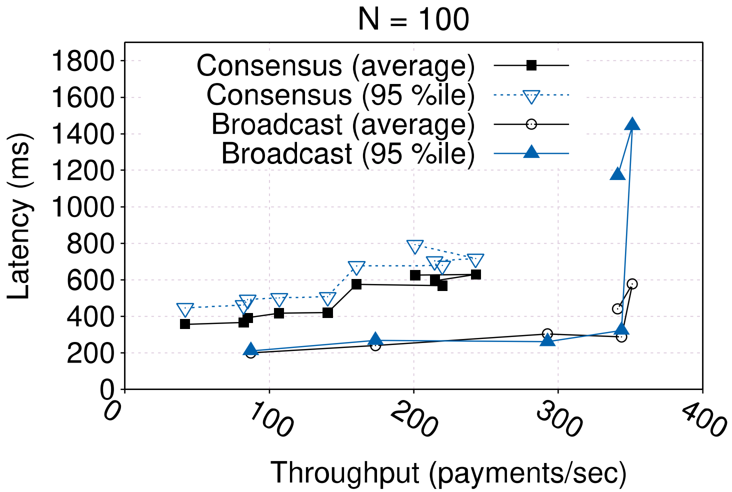


Intuition: deliver only if accepted by a Byzantine quorum (of 2f+1)

Intuition: deliver only if enough sample members are "ready"

Performance





Performance wrt BFT-Smart:

- Throughput 1,5-6x higher
- Latency 2x lower

Take-aways

- Asset transfers do not always require total order
  - ✓Source order is sufficient for consistency
  - ✓(Asynchronous) secure broadcast
- Can be generalized to (limited-scope) ”smart contracts”
  - ✓only account owners need consensus, but still no global total order
- Coming: probabilistic and Sybill-tolerant secure broadcast can be implemented (coming)
  - ✓Permissionless asset transfer

Thank you!

Implementing asset transfer

To perform a (successful) transfer:

- (securely) broadcast together with dependencies (the set of previously received and issued transfers) that justify it
- A delivered transfer is validated and accepted if:
  - ✓the transfer is issued by an owner
  - ✓the balance (based on declared dependencies) is sufficient
  - ✓ every its dependency transfer is validated (recursively)

Broadcasting and delivering

```
operation transfer(a, b, x) where a = p
  if balance(a, hist[p] ∪ deps) < x then
    return false
  broadcast([(a, b, x, seq[p] + 1), deps])
  deps := ∅

{ Secure broadcast callback }
upon deliver(q, m)          { Executed when p delivers message m from process q }
  let m be [(q, d, y, s), h]
  if s = rec[q] + 1 then
    rec[q] := rec[q] + 1
    toValidate := toValidate ∪ {(q, m)}
```

Validating transfers

upon $(q, \lfloor t, h \rfloor) \in \mathit{toValidate} \;\wedge\; \mathit{Valid}(q, t, h)$ $\quad$ { *Executed when a transfer delivered from q becomes v*
$\quad$ $\mathit{hist}[q] := \mathit{hist}[q] \cup h \cup \{t\}$ $\quad$ { *Update the history for the outgoing account* }
$\quad$ let t be (c, d, y, s)
$\quad\quad$ $\mathit{seq}[q] := s$
$\quad\quad$ **if** $d = p$ **then**
$\quad\quad\quad$ $\mathit{deps} := \mathit{deps} \cup \{(c, d, y, s)\}$ $\quad$ { *This transfer is incoming to account of local process p* }
$\quad\quad$ **if** $c = p$ **then**
$\quad\quad\quad$ **return** *true* $\quad$ { *This transfer is outgoing from account of local process p* }

function $\mathit{Valid}(q, t, h)$
$\quad$ let t be (c, d, y, s)
$\quad$ **return** $(q = c)$
$\quad\quad\quad$ **and** $(s = \mathit{seq}[q] + 1)$
$\quad\quad\quad$ **and** $(\forall (a, b, x, r) \in h : (a, b, x, r) \in \mathit{hist}[a])$
$\quad\quad\quad$ **and** $(\mathit{balance}(c, \mathit{hist}[q] \cup h) \geq y)$

Also, extended to the “k-owner” case

Quorums for samples

Needed: a Syblil-resistant sampling mechanism

- Every correct node maintains a sample of the system with a constant expected fraction of faulty nodes

"Proof-of-bandwidth": trust more to those who talk to you more

Brahms: Byzantine Resilient Random Membership Sampling [Bortnikov et al., 2010]

Gossip-based broadcast

- The idea: deliver once heard « enough » acks (e.g., a sample has confirmed)
- Analyze the probability
- Iterative construction:
  - ✓Probabilistic broadcast (validity+totality)=>
  - ✓Probabilistic consistent broadcast (consistency)=>
  - ✓Probabilistic secure broadcast (validity, totality, consistency)

ε-secure probabilistic broadcast

For any $\epsilon \in [0,1]$, we say that probabilistic broadcast is ϵ-secure if:

1. **No duplication**: No correct process delivers more than one message.
2. **Integrity**: If a correct process delivers a message m, and σ is correct, then m was previously broadcast by σ.
3. ϵ-**Validity**: If σ is correct, and σ broadcasts a message m, then σ eventually delivers m with probability at least $(1-\epsilon)$.
4. ϵ-**Totality**: If a correct process delivers a message, then every correct process eventually delivers a message with probability at least $(1-\epsilon)$.

- « Erdös-Rényi » gossip: to broadcast - send m to every member of the sample, once received m – deliver and send to the sample

ε-secure consistent broadcast

For any $\epsilon \in [0,1]$, we say that probabilistic consistent broadcast is ϵ-secure if:

1. **No duplication**: No correct process delivers more than one message.
2. **Integrity**: If a correct process delivers a message m, and σ is correct, then m was previously broadcast by σ.
3. ϵ-**Total validity**: If σ is correct, and σ broadcasts a message m, every correct process eventually delivers m with probability at least $(1-\epsilon)$.
4. ϵ-**Consistency**: Every correct process that delivers a message delivers the same message with probability at least $(1-\epsilon)$.

- Run ρ-secure probabilistic broadcast of m and wait until enough processes in « echo sample » deliver m