From Reliable to Secure Distributed Programming

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Tutorial at DISC 2011

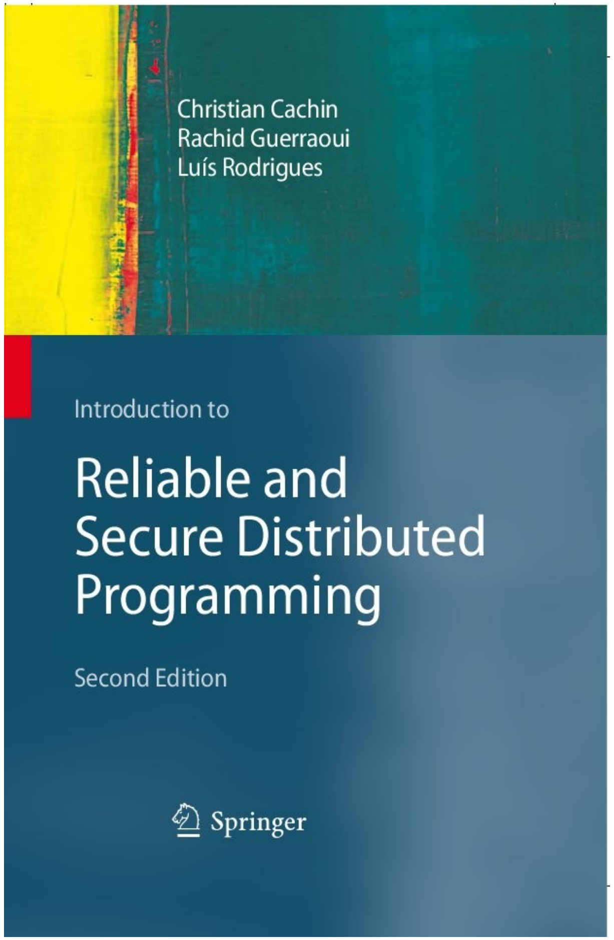
A play in three acts

- Abstractions and protocols for
  - Reliable broadcast
  - Shared memory
  - Consensus

- In asynchronous distributed systems

- With processes subject to
  - Crash failures
  - Malicious attacks / Byzantine failures

Motivation



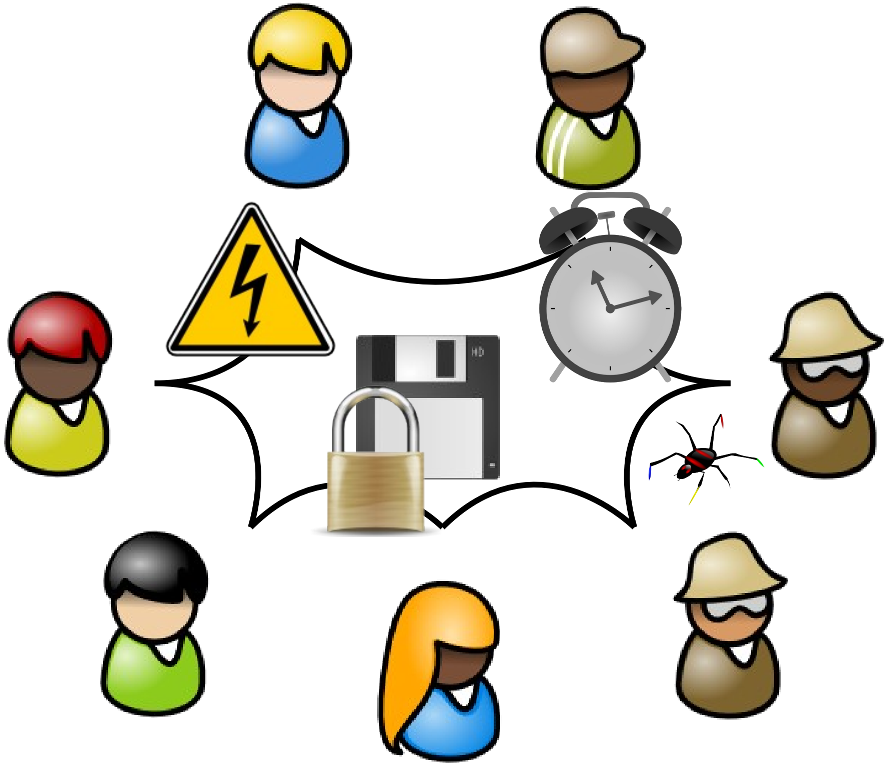
Introduction to Reliable <u>and Secure</u> Distributed Programming

- C. Cachin, R. Guerraoui, L. Rodrigues
- 2nd ed. of "Introduction to Reliable Distributed Programming" (Springer, 2011)
- <u>The new content covers Byzantine failures</u>

Web: www.distributedprogramming.net

Distributed systems

- Basic abstractions
  - Processes
  - Links
  - Timing models
  - Cryptography



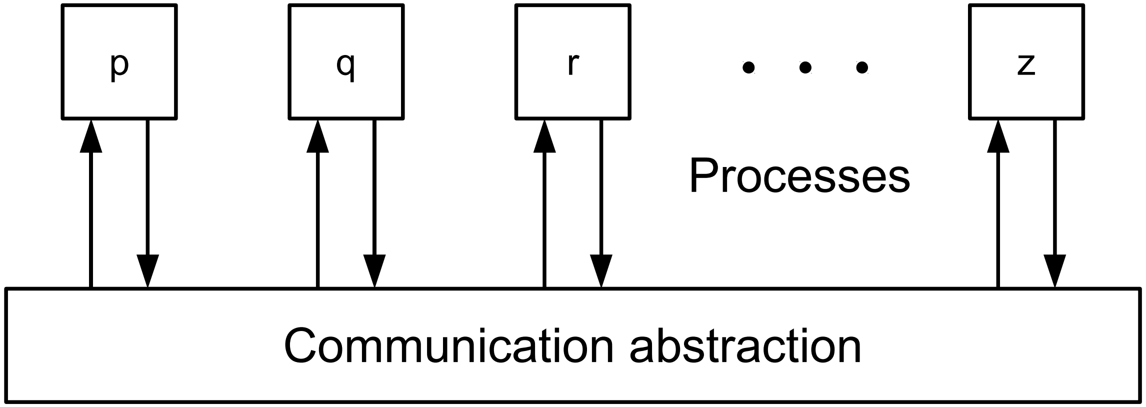
Prologue

Models and assumptions

Programming abstractions

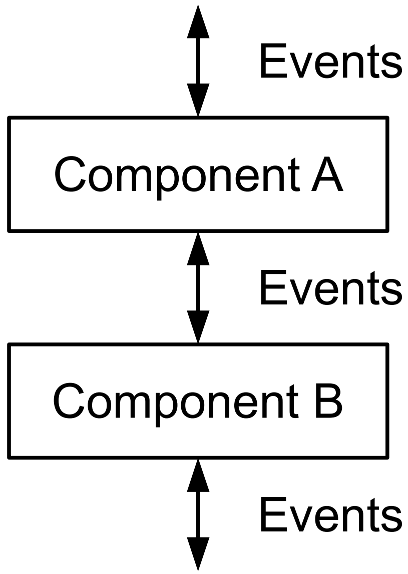
- Sequential programming
  - Array, record, list ...
- Concurrent programming
  - Thread, semaphore, monitor ...
- Distributed programming
  - Reliable broadcast
  - Shared memory
  - Consensus
  - Atomic commit
  - ...

Distributed programming abstractions



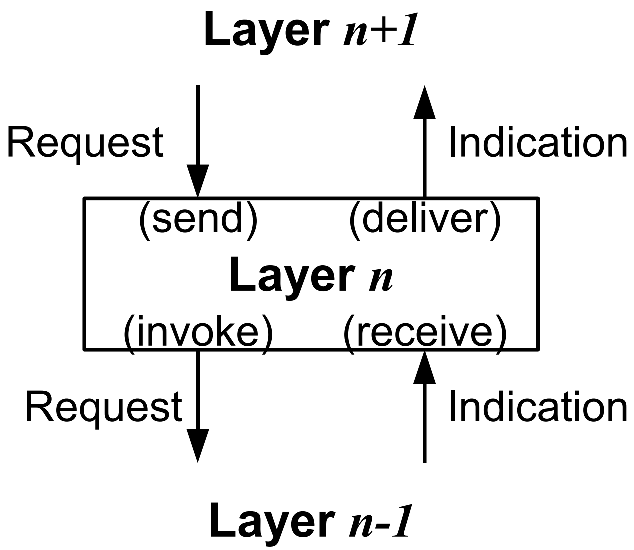
- Coordination among N identical processes
  - Processes are also called replicas
- Processes jointly implement application
  - Need coordination

Layered modular architecture



- Every process consists of modules
  - Modules may exist in multiple instances
  - Every instance has a unique identifier
- Modules communicate through events

Programming with events



- Modules are arranged in layers of a stack
- Asynchronous events represent communi-cation or control flow
  - Request events flow downward
  - Indication events flow upward

Processes

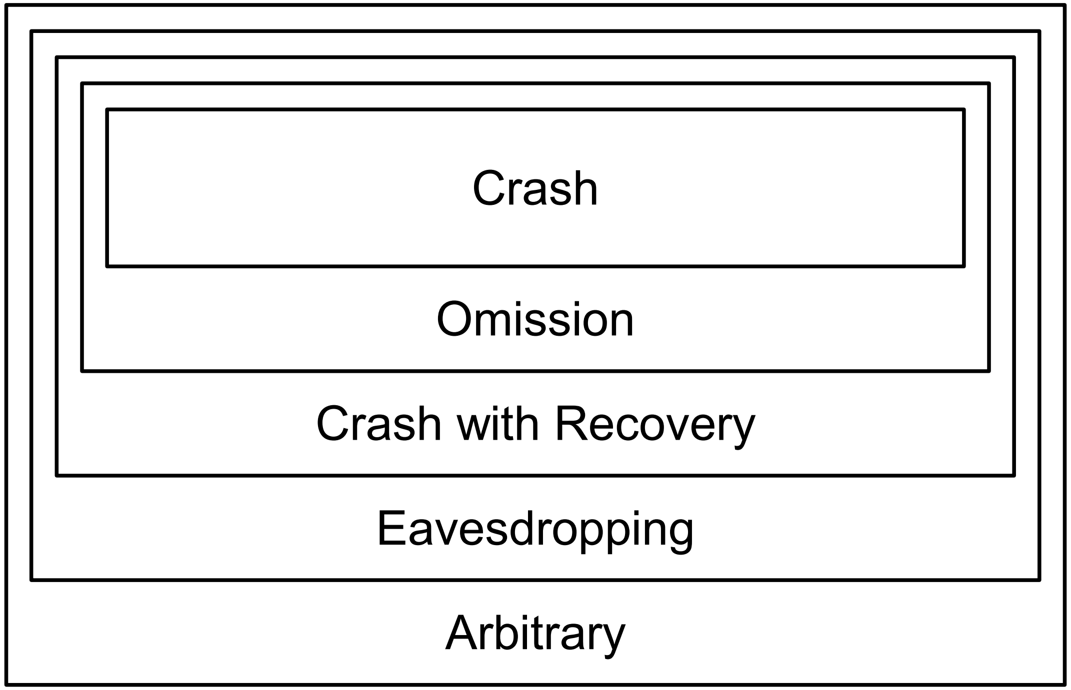
- System with N processes Π = {p, q, r ...}
- Processes know each other
- Every process consists of a set of modules and interacts through events
- Reactive programming model

upon event <mod, Event | att$_1$, att$_2$ ...> **do**

    do something;

    trigger <mod', Event' | att'$_1$, att'$_2$ ...>;

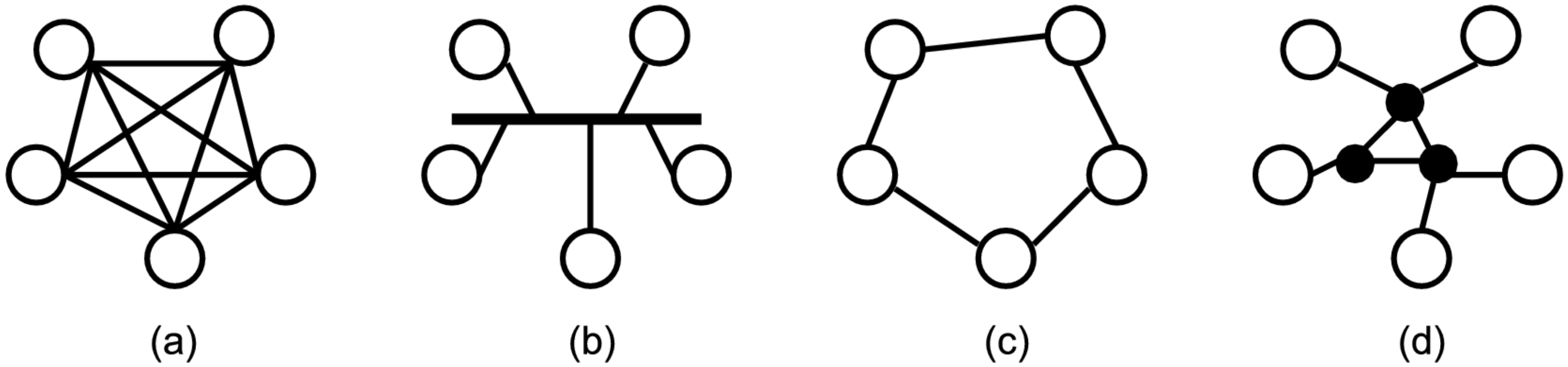
Process failures



- In this tutorial, we consider only:
  - Crash failures
    - Failed process stops executing steps
  - Arbitrary or "Byzantine" failures
    - Failed process behaves arbitrarily and adversarially
    - May not break cryptographic primitives

Links

- Logically every process may communicate with every other process: (a)
- Physical implementation may differ: (b)-(d)



Perfect Point-to-point Links (pl)

- Events
  - Request <pl, Send | q, m>
    - Sends a message m to process q
  - Indication <pl, Deliver | p, m>
    - Delivers a message m from sender p
- Properties
  - PL1 (Reliability): If a correct sendsmessage m to correct q, then q eventually delivers m.
  - PL2 (No duplication): No message is delivered more than once.
  - PL3 (No creation): If a process delivers a message m with sender s, then s has sent m.

Time

- Most algorithms shown here are asynchronous
  - No bounds on message transmission time or process execution time
- Some algorithms use an abstraction of time
  - Failure detector
  - Leadership detector

Cryptographic primitives

- Dual goals of cryptography
- Confidentiality (encryption, not relevant here)
- Integrity
  - Hash functions
  - Message authentication codes (MAC)
  - Digital signatures

Hash functions

- Cryptographic hash function H maps inputs of arbitrary length to a short unique tag

- Collision-freeness: No process can find distinct values x and x' such that H(x) = H(x')

- Formally, implemented by a distributed oracle
  - Maintains list L of inputs given to H so far
  - **upon** invocation H(x)
    - **if** $x \in L$, **then** append x to L
    - **return** index of x in L

  - Practical hash functions have more properties not modeled here

Message-authentication codes

- A MAC authenticates data between two processes (messages from sender to receiver)

- Formally, given by a distributed oracle
  - Maintains set A of strings authenticated so far
  - **upon** invocation authenticate(p, q, m) // only by p
    - pick authenticator a, add (p,q,m,a) to A
    - **return** a
  - **upon** invocation verifyauth(q, p, m, a) // only by q
    - **if** (p,q,m,a) $\in$ A **then**
      - **return** TRUE
    - **else**
      - **return** FALSE

  - Implemented with shared secret key and hash functions

Digital signatures

- A digital signature scheme authenticates data with public verification

- Formally, given by a distributed oracle
  - Maintains set S of strings signed so far
  - **upon** invocation sign(p, m) // only by p
    - pick signature s, add (p,m,s) to S
    - **return** s
  - **upon** invocation verifysig(q, m, s) // by anyone
    - **if** (q,m,s) $\in$ S **then**
      - **return** TRUE
    - **else**
      - **return** FALSE

  - Implemented from public-key cryptosystems
  - Authenticity can be relayed by untrusted process

Act I

Reliable broadcast

Broadcast

- Broadcast is a basic primitive to disseminate information
  - Processes in the group send messages
  - All processes should receive or "deliver" the messages

- Reliable broadcast
  - Guarantees that messages are delivered to all processes consistently
  - Agreement on the delivered messages
  - No ordering among delivered messages

Best-Effort Broadcast (beb)

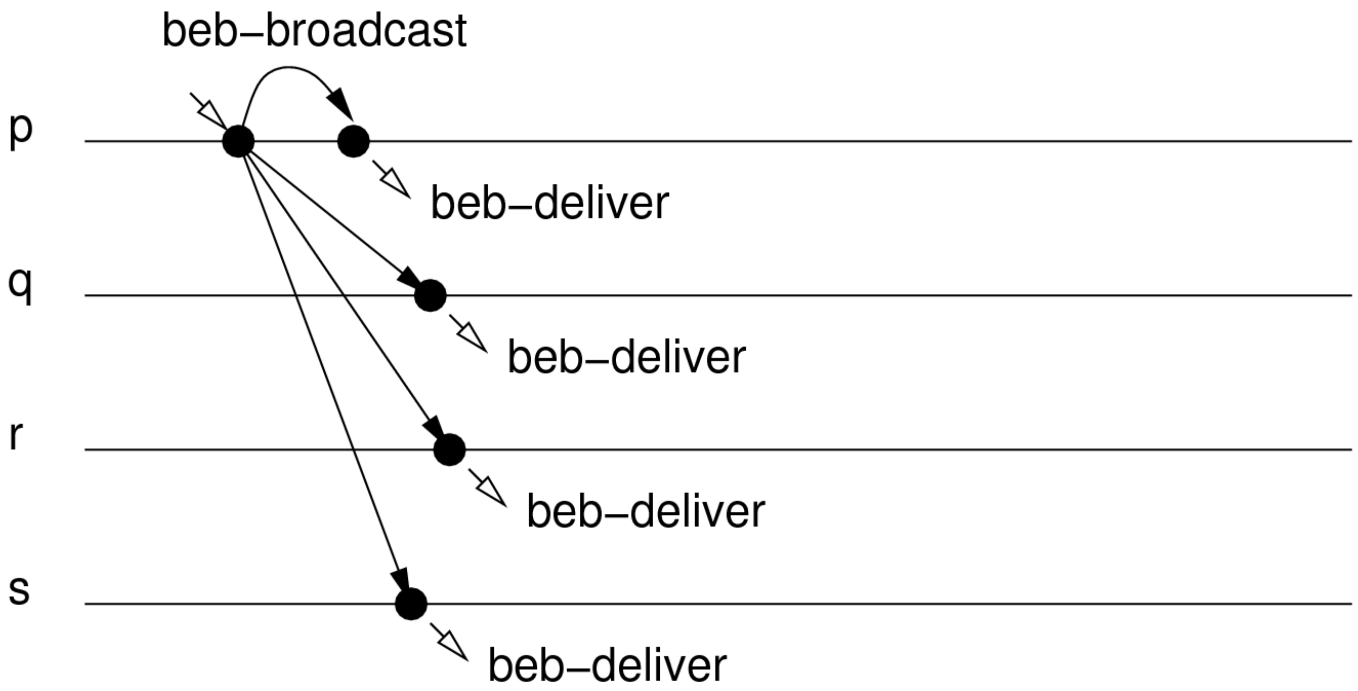
- Events
  - Request <beb, Broadcast | m>
    - Broadcasts a message m to all processes
  - Indication <beb, Deliver | p, m>
    - Delivers a message m from sender p

- Properties
  - BEB1 (Validity): If a correct process broadcasts m, then every correct process eventually delivers m.
  - BEB2 (No duplication): No message is delivered more than once.
  - BEB3 (No creation): If a process delivers a message m with sender s, then s has broadcast m.

- Offers no "reliability" when a process fails

Best-effort broadcast protocol

- Sender sends message m to all processes over point-to-point links
- Not reliable



Uniform Reliable Broadcast (urb)

- Events
  - Request <urb, Broadcast | m>
    - Broadcasts a message m to all processes
  - Indication <urb, Deliver | p, m>
    - Delivers a message m from sender p

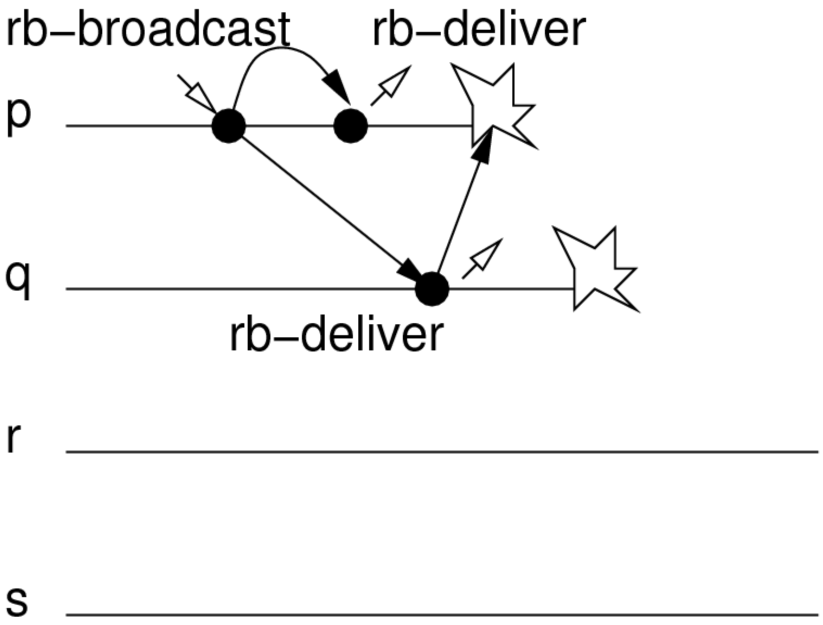
- Properties
  - RB1 (Validity) = BEB1
  - RB2 (No duplication) = BEB2
  - RB3 (No creation) = BEB3
  - RB4 (Uniform agreement): If some process* delivers a message m, then every correct process eventually delivers m.

    * whether process is correct or faulty!

Why uniform agreement?

- A process p delivers a message m and crashes later; still every correct process must deliver m.
- A regular reliable broadcast requires this only when p is correct (= never fails).
- When p may influence application or environment before it crashes, other processes will also deliver message, consistent with p.

Regular reliable broadcast



- Example of reliable but non-uniform execution
- Process p delivers m
- No other process delivers m

Majority-Ack Uniform Reliable Broadcast

Implements urb, uses beb (N>2f)

delivered := ∅; pending := ∅; ∀m : ack[m] := ∅

upon <urb, Broadcast | m> **do**
    pending := pending ∪ {(self,m)}
    for q∈∏ **do trigger** <beb, Broadcast | [DATA, self, m]>

upon <beb, Deliver | p, [DATA, s, m]> **do**
    ack[m] := ack[m] ∪ {p}
    if (s,m) ∉ pending **then**
        pending := pending ∪ {(s,m)}
        for q∈∏ **do**
            trigger <beb, Broadcast | [DATA, Self, m]>
...

Majority-Ack Uniform Reliable Broadcast

...
upon ∃ (s,m) ∈ pending : m ∉ delivered ∧ #ack[m] > N/2 **do**
    trigger <urb, Deliver | s, m>

- Delivers message m only after m has been relayed by a majority of processes

- Every majority contains at least one correct process

Byzantine reliable broadcasts

- Almost the same primitive: needs to reach agreement on delivered messages
- Byzantine sender may cause processes to deliver different message content for the "same" message
- How to identify a message?

Messages not self-explaining

- Important change from model with crashes
  - With crash failures, a reliable broadcast module delivers many messages
    - Messages are unique and identified only by their content
  - With Byzantine processes, this is problematic
    - Since messages are not ordered, and Byz. sender may send any message, application may become confused
    - Ex.: application broadcasts message [l,m], containing a payload m and a label l; faulty sender may cause p to deliver [l,m] first and q to deliver [l,m'] first, with m≠m'
- A Byzantine reliable broadcast instance
  - Corresponds to one delivered message
  - A priori declares a sender process for the instance

Authenticated communi-cation primitives

- Recall modules in model with crash failures
  - Perfect Links (pl)
  - Best-effort Broadcast (beb) modules
- Authenticated versions can be defined that tolerate network subject to attacks
  - Authenticated Perfect Links (al)
  - Authenticated Best-effort Broadcast (abeb)

  - Implemented using cryptographic authentication (MACs or digital signatures)

Byzantine broadcast variants

- Byzantine consistent broadcast
- Byzantine reliable broadcast

Byzantine Consistent Bc. (bcb)

- Events
  - Request <bcb, Broadcast | m>
    - Broadcasts a message m to all processes
  - Indication <bcb, Deliver | p, m>
    - Delivers a message m from sender p

- Properties
  - BCB1 (Validity) = BEB1
  - BCB2 (No duplication): Every correct process delivers at most one message
  - BCB3 (Integrity): If a correct process delivers m with sender p, and p correct, then p has broadcast m. (...)

Byzantine Consistent Bc. (bcb) (cont.)

- (...) Properties
  - BCB4 (Consistency): If a correct process delivers message m and another correct process delivers message m', then m=m'.

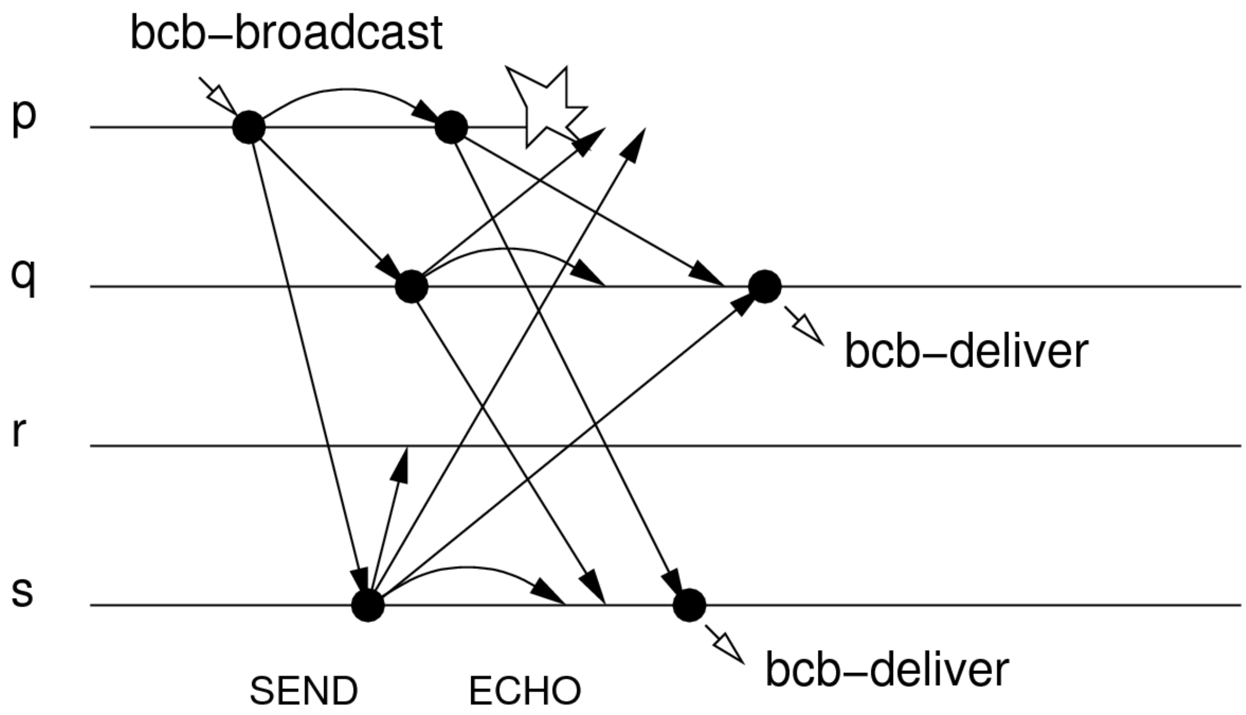
- Note: some correct process may not deliver any message (agreement is not needed)

Auth. Echo Broadcast

Implements bcb, uses abeb, with sender s (N>3f) [ST87]

```
upon <bcb, Broadcast | m> do
    trigger <abeb, Broadcast | [SEND, m]>

upon <abeb, Deliver | s, [SEND, m]> do
    trigger <abeb, Broadcast | [ECHO, m]>

upon <abeb, Deliver | p, [ECHO, m]> do
    echo[p] := m
    if ∃m : #{p | echo[p]=m} > (N+f)/2 then
        trigger <bcb, Deliver | s, m>

// code to prevent duplicate execution is omitted
```

Example



- Faulty sender p
- Processes q and s bcb-deliver the message
- Process r does not deliver any message
- $O(n^2)$ messages; $O(n^2 |m|)$ communication

Using Byzantine quorums

- System of $N > 3f$ processes, f are faulty
- Every subset with size strictly larger than $(N+f)/2$ processes is a Byzantine quorum (B.Q.)
  - Every B.Q. has more than $(N-f)/2$ correct processes
  - Two distinct B.Q. together contain more than $N-f$ correct pr.
  - Thus, every two B.Q. overlap in some correct pr.
    - This correct process has abeb-broadcast the same message [ECHO, m] to all processes
- The collection of all Byzantine quorums is a quorum system

Byzantine Reliable Bc. (brb)

- Events
  - Request <brb, Broadcast | m>
  - Indication <brb, Deliver | p, m>
- Properties
  - BRB1 (Validity) = BCB1
  - BRB2 (No duplication) = BCB2
  - BRB3 (Integrity) = BCB3
  - BRB4 (Consistency) = BCB4
  - BRB5 (Totality): If some correct process delivers a message, then every correct process eventually delivers a message
- Either all or none of the correct processes deliver the message

Auth. Double-Echo Broadcast

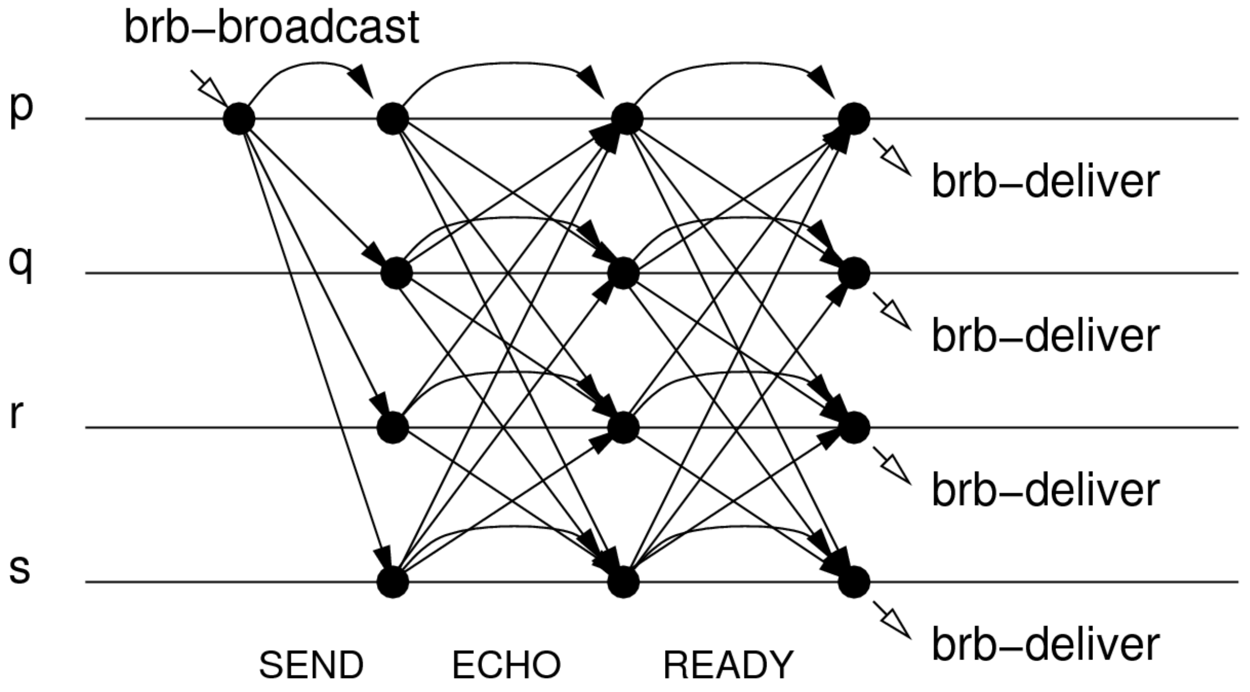
Implements brb, uses abeb, with sender s (N>3f) [Bra87]

```
sentready := FALSE

upon <brb, Broadcast | m> do
    trigger <abeb, Broadcast | [SEND, m]>

upon <abeb, Deliver | s, [SEND, m]> do
    trigger <abeb, Broadcast | [ECHO, m]>

upon <abeb, Deliver | p, [ECHO, m]> do
    echo[p] := m
    if ∃m : #{p | echo[p]=m} > (N+f)/2  ∧ ¬sentready then
        sentready := TRUE
        trigger <abeb, Broadcast | [READY, m]>
...
```

Auth. Double-Echo Broadcast

```
...
upon <abeb, Deliver | p, [READY, m]> do
    ready[p] := m
    if ∃m : #{p | ready[p]=m} > f ∧ ¬sentready then
        // amplification of READY messages
        sentready := TRUE
        trigger <abeb, Broadcast | [READY, m]>
    else if ∃m : #{p | ready[p]=m} > (N+f)/2 then
        trigger <brb, Deliver| s, m>

// again, some code to prevent duplicate execution is omitted
```

Example



- Amplification from f+1 to 2f+1 READY messages ensures totality
  - All or none of the correct processes deliver message
- $O(n^2)$ messages; $O(n^2 |m|)$ communication

Byzantine Broadcast Channel

- Combines many one-message broadcast instances
- Every message delivered together with a unique label
  - Consistency and totality hold for each label
- Implemented from multiple "parallel" instances of Byzantine broadcasts
- Two variants
  - Consistent Channel
  - Reliable Channel

Act II

Shared memory

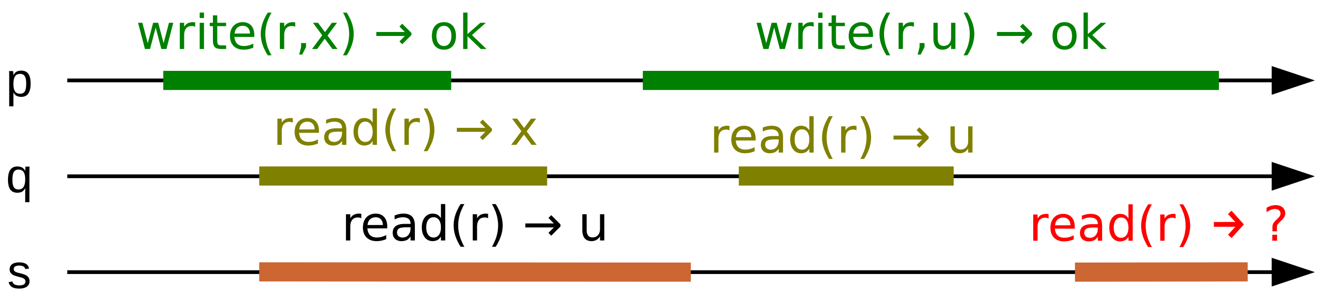
Operations on shared memory

- Memory abstraction is a register
- Two operations: read and write
- Operations restricted to certain processes
  - 1 writer or N writers
  - 1 reader or N readers
  - (W,R)-register has W writers and R readers

Concurrent operations

- Operations take time, defined by two events at a process: invocation and completion
- Write(r, v) → ok
  - Writes value v to register instance r
- Read(r) → v
  - Reads from register instance r and returns value v
- Operation o precedes o' whenever completion of o occurs before invocation of o'
- Otherwise, o and o' are concurrent

Semantics of memory ops.

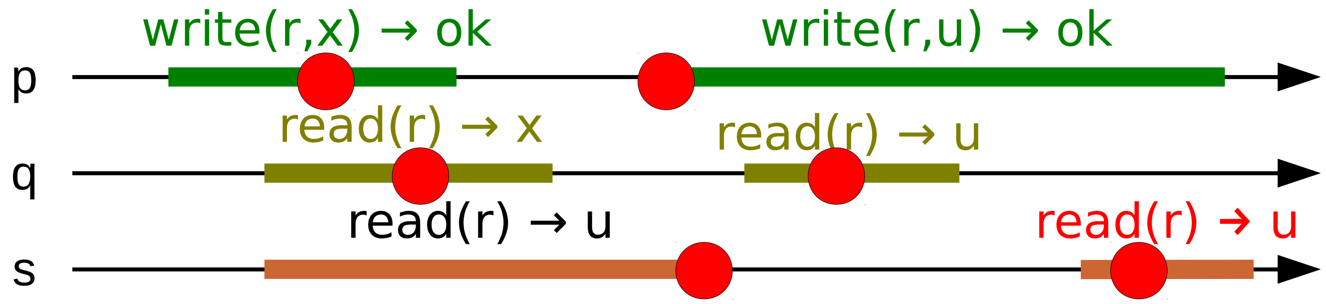


Safe: Every read not concurrent with a write returns the most recently *written* value.

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

Atomic: *Regular* & all read and write operations occur atomically (= linearizable): process s must read u.

Linearizability



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

(1,N) Regular Register (onrr)

- Events
  - Request <onrr, Read>
    - Invokes a read operation on the register
  - Request <onrr, Write | v>
    - Invokes a write operation with value v
  - Indication <onrr, ReadReturn | v>
    - Completes a read operation, returning value v
  - Indication <onrr, WriteReturn>
    - Completes a write operation

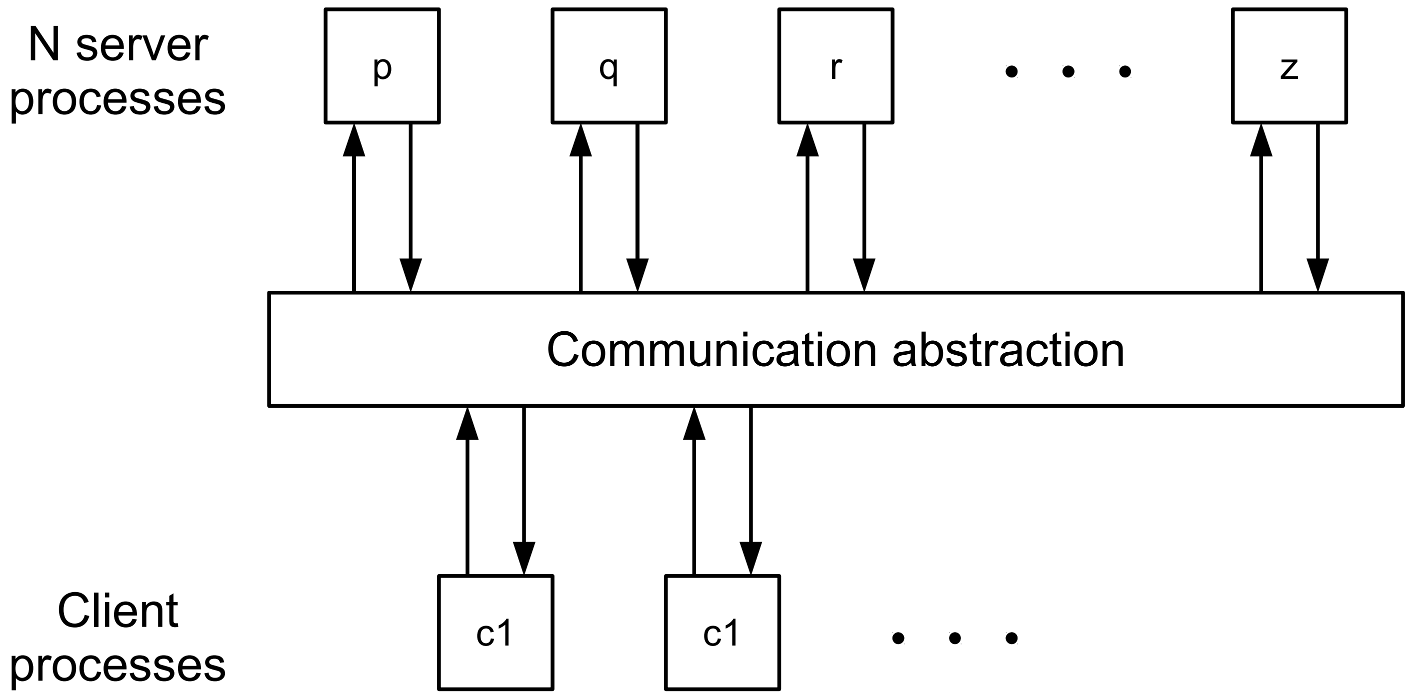
- Properties
  - ONRR1 (Liveness): If a correct process invokes an operation, then the operation eventually completes.
  - ONRR1 (Validity): A read returns the last value written or the* value written concurrently.

    *Only one process can possibly write.

Implementations of registers

- From other (simpler, unreliable) registers
  - Multi-valued from binary registers
  - (1,N) from (1,1) registers
  - Regular registers from safe registers
  - Atomic registers from regular registers
  - ...
- From replicated (unreliable) processes
  - Considered here
  - Replica processes may fail
    - Crash failures
    - Byzantine failures

Client-server model



- Clients and servers are usually separate
- For simplicity, we model them all as one group of N processes
  - Processes have dual role as clients and servers

Majority-Voting Reg. Register

Implements onrr, uses pl, beb (N > 2f)

```
(ts,val) := (0,⊥); wts := 0; rid := 0

upon <onrr, Write | v> do
    wts := wts + 1
    acklist := [⊥]^N
    trigger <beb, Broadcast | [WRITE, wts, v]>

upon <beb, Deliver | p, [WRITE, ts', v']> do
    if ts' > ts then
        (ts, val) := (ts', v')
    trigger <pl, Send | p, [ACK, ts']>

upon <pl, Deliver | q, [ACK, wts]> do
    acklist[q] := 1
    if #(acklist) > N/2 then
        trigger <onrr, WriteReturn>
...
```

Majority-Voting Reg. Register

```
...
upon <onrr, Read> do
    rid := rid + 1
    readlist := [⊥]^N
    trigger <beb, Broadcast | [READ, rid]>

upon <beb, Deliver | p, [READ, r]> do
    trigger <pl, Send | p, [VALUE, r, ts, val]>

upon <pl, Deliver | q, [VALUE, rid, ts', v']> do
    readlist[q] := (ts', v')
    if #(readlist) > N/2 then
        v := highestval(readlist)            // value with highest ts
        trigger <onrr, ReadReturn | v>
```

- Validity: every two operations access one common correct process

Registers in Byzantine model

- Up to f processes may be (Byzantine) faulty, including reader
- Writer process is always correct
- Specification of
  - (1,N) safe Byzantine register (bonsr) and
  - (1,N) regular Byzantine register (bonrr)

  directly follows from (1,N) regular register

Implementations

- Algorithms must eliminate wrong values returned by Byzantine processes

- Two approaches for elimination
  - Masking by sufficiently many correct values
    - → Alg. "Masking Quorum" for Byzantine safe register
  - Authentication of correct values with digital signatures
    - → Alg. "Authenticated-Data" for Byzantine regular register

Byzantine Masking Quorum

Implements bonsr, uses al, abeb ($N > 4f$), writer is w

```
(ts,val) := (0,⊥); wts := 0; rid := 0        // Differences are in this color

upon <bonsr, Write | v> do
    wts := wts + 1
    acklist := [⊥]^N
    trigger <abeb, Broadcast | [WRITE, wts, v]>

upon <abeb, Deliver | w, [WRITE, ts', v']> do
    if ts' > ts then
        (ts, val) := (ts', v')
    trigger <al, Send | w, [ACK, ts']>

upon <al, Deliver | q, [ACK, wts]> do
    acklist[q] := 1
    if #(acklist) > (N+2f)/2 then
        trigger <bonsr, WriteReturn>
...
```

Byzantine Masking Quorum

```
...
upon <bonsr, Read> do
    rid := rid + 1
    readlist := [⊥]^N
    trigger <abeb, Broadcast | [READ, rid]>

upon <abeb, Deliver | p, [READ, r]> do
    trigger <al, Send | p, [VALUE, r, ts, val]>

upon <al, Deliver | q, [VALUE, rid, ts', v']> do
    readlist[q] := (ts', v')
    if #(readlist) > (N+2f)/2 then
        v := byz-highestval(readlist)        // filter and extract value
        trigger <bonsrr, ReadReturn | v>
```

- byz-highestval()
  - eliminates all values occurring f or fewer times
  - returns survivor value with highest timestamp -- or -- special value ⊥ if no such value exists

Comments

- Alg. Byzantine Masking Quorum may return ⊥
  - Implements safe register on domain with {⊥}

- Without concurrent write operation
  - Last write op. has touched more than (N+2f)/2 pr.
    - Among them, more than (N+2f)/2 - f are correct
    - Less than (N-2f)/2 correct processes are untouched
  - Read op. obtains value from more than (N+2f)/2 pr.
    - Up to f may be from Byzantine pr.
    - Less than (N-2f)/2 are from untouched correct pr.
    - Strictly more than f are from correct pr. and contain last-written timestamp/value pair

Auth.-Data Byzantine Quorum

Implements bonrr, uses al, abeb, signatures ($N > 3f$), writer is w

(ts,val, s) := (0,⊥,⊥); wts := 0; rid := 0 // Differences are in this color

```
upon <bonrr, Write | v> do
    wts := wts + 1; s := sign(w, WRITE||w||wts||v)
    acklist := [⊥]^N
    trigger <abeb, Broadcast | [WRITE, wts, v, s]>

upon <abeb, Deliver | w, [WRITE, ts', v', s']> do
    if ts' > ts then
        (ts, val, s) := (ts', v', s')
    trigger <al, Send | w, [ACK, ts']>

upon <al, Deliver | q, [ACK, wts]> do
    acklist[q] := 1
    if #(acklist) > (N+f)/2 then
        trigger <bonsr, WriteReturn>
...
```

Auth.-Data Byzantine Quorum

```
...
upon <bonrr, Read> do
    rid := rid + 1
    readlist := [⊥]^N
    trigger <abeb, Broadcast | [READ, rid]>

upon <abeb, Deliver | p, [READ, r]> do
    trigger <al, Send | p, [VALUE, r, ts, val, s]>

upon <al, Deliver | q, [VALUE, rid, ts', v', s']> do
    if verifysig(w, WRITE||w||ts'||v', s') then
        readlist[q] := (ts', v')
        if #(readlist) > (N+f)/2 then
            v := highestval(readlist)          // value with highest ts
            trigger <bonrr, ReadReturn | v>
```

Comments

- Alg. Authenticated-Data Byz. Quorum uses
  - Digital signatures issued by writer
  - Byzantine quorums

- Otherwise, exactly the same as the Majority Quorum algorithm
  - Signatures authenticate the value
  - Signatures bind value to timestamp

Act III

Consensus

Consensus

- Processes propose values and have to agree on one decision value among the proposed values

- Consensus is a key abstraction for solving many other problems in fault-tolerant distributed systems
  - Total-order broadcast
  - Non-blocking atomic commit
  - Replicated services
  - ...

Uniform Consensus (uc)

- Events
  - Request <uc, Propose | v>
    - Proposes value v for consensus
  - Indication <uc, Decide | v>
    - Outputs a decided value v of consensus

- Properties
  - UC1 (Termination): Every correct process eventually decides.
  - UC2 (Validity): Any decided value has been proposed by some process.
  - UC3 (Integrity): No process decides twice.
  - UC4 (Uniform Agreement): No two processes* decide differently.

  * whether correct or faulty

Weak Byzantine Consensus (wbc)

- Events
  - Request <wbc, Propose | v>
    - Proposes value v for consensus
  - Indication <wbc, Decide | v>
    - Outputs a decided value v of consensus

- Properties
  - WBC1 (Termination) = UC1
  - WBC2 (Weak Validity): Suppose all processes are correct: if all propose v, then a process may only decide v; if a process decides v, then v was proposed by some process.
  - WBC3 (Integrity): No correct process decides twice.
  - WBC4 (Agreement): No two correct processes decide differently.

Implementing consensus

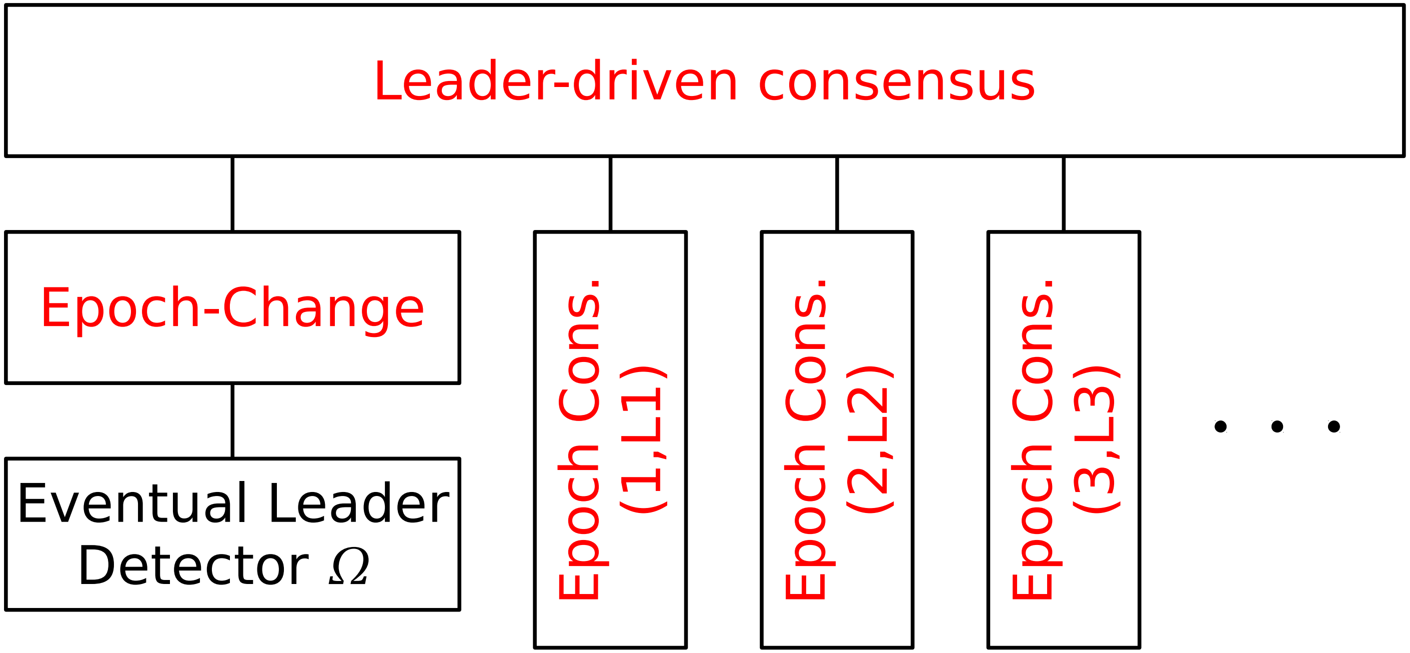
- In asynchronous system with processes prone to crash and Byzantine failures, deterministic algorithms cannot implement consensus [FLP].
- We use a timing assumption, encapsulated as a leader detection oracle Ω
  - Ω periodically designates a trusted leader
  - Ω is not perfect, may make mistakes
- Variations of Ω can be implemented in partially synchronous systems
  - With crash or Byzantine failures

Leader-driven consensus

- Most important paradigm for efficient implementations of consensus
- Introduced in
  - Viewstamped replication [OL88]
  - Paxos [L96]
  - PBFT [CL02]

    (these formulate it as total-order broadcast)
- Used in many cloud-serving platforms today
- Modular presentation of consensus algorithm in 3 steps

Leader-driven consensus



- Leader-driven consensus invokes
  - One instance of Epoch-Change (invokes Omega)
  - Multiple instances of Epoch Consensus
    - Identified by the epoch number and a designated leader

Preview - Step 1

- Define abstract primitives for
  - Epoch-Change
  - Epoch Consensus
- Abstractions are valid in both models
- Leader-driven algorithm for Uniform Consensus (crash faults) and Weak Byzantine Consensus (Byzantine faults)
  - Using Epoch-Change and Epoch Consensus abstractions

Preview - Step 2

- Instantiate primitives in model with crash failures
  - According to Viewstamped Replication/Paxos

- Implement Epoch-Change

- Implement Epoch Consensus

Preview - Step 3

- Instantiate primitives in model with Byzantine failures
  - According to PBFT
- Implement Epoch-Change
- Implement Epoch Consensus

Step 1

Implement consensus using leader-driven algorithm

Eventual Leader Detector (Ω)

- Events
  - Indication <Ω, Trust | p>
    - Indicates that process p is trusted to be leader
- Properties
  - ELD1 (Eventual accuracy): Eventually every correct process trusts some correct process.
  - ELD2 (Eventual agreement): Eventually no two correct processes trust a different process.
- The trusted leader may change over time, different leaders may be elected, only eventually every process follows a "good" leader.

Epoch-Change (ec)

- Events
  - Request <ec, StartEpoch | ts, L>
    - Starts epoch (ts,L), timestamp ts and leader L

- Properties
  - EC1 (Monotonicity): If a correct process starts epoch (ts,L) and later starts epoch (ts',L'), then ts' > ts.
  - EC2 (Consistency): If a correct process starts epoch (ts,L) and another correct process starts epoch (ts,L'), then L = L'.
  - EC3 (Eventual Leadership): Eventually every correct process starts no further epoch; moreover, every correct process starts the same last epoch (ts,L), where L is a correct process.

Epoch Consensus (ep)

- Associated with timestamp ts and leader L (globally known)

- Events
  - Request <ep, Propose | v>
    - Proposes v for epoch consensus (executed by leader only)
  - Request <ep, Abort>
    - Aborts this epoch consensus
  - Indication <ep, Decide | v>
    - Outputs decided value v for epoch consensus
  - Indication <ep, Aborted | s>
    - Signals that this epoch consensus has completed the abort and returns state s

Epoch Consensus (ep)

- Properties
  - EP1 (Validity): If a correct process ep-decides v, then v was proposed by the leader of some epoch consensus (ts',L) with ts' ≤ ts.
  - EP2 (Uniform Agreement): No two [correct*] processes ep-decide differently.
  - EP3 (Integrity): A correct process ep-decides at most once.
  - EP4 (Lock-in): If a process ep-decides v in epoch ts' < ts, no process ep-decides a value different from v.
  - EP5 (Termination): If the leader L is correct, has ep-proposed a value and no process aborts, then every correct process eventually ep-decides.

  (...)   * for Byzantine epoch consensus

Epoch Consensus (ep)

- (...) Properties
  - EP6 (Abort behavior): When a correct process aborts, then it eventually completes the abort; plus, a correct process completes an aborts only if it has been aborted before.

- Every process must run a well-formed sequence of epoch consensus instances:
  - Only one instance of epoch consensus at a time
  - Associated timestamps monotonically increasing
  - Give state from previous (aborted) instance to next instance

Leader-driven consensus impl.

Implements c* (either uc or wbc), uses ec, ep (multiple instances)

val := ⊥; proposed := FALSE; decided := FALSE
(ets,L) := (0,L_0); (newts,newL) := (0,⊥)
Init. Epoch Consensus inst. ep.0 with timestamp 0 and leader L_0

upon <c*, Propose | v> **do**
    val := v

upon <ec, StartEpoch | newts', newL'> **do**
    (newts,newL) := (newts',newL')
    trigger <ep.ets, Abort>

upon <ep.ets, Aborted | s> **do**
    (ets,L) := (newts,newL)
    proposed := FALSE
    Init. Epoch Consensus inst. ep.ets with timestamp ets, leader L,
        and state s

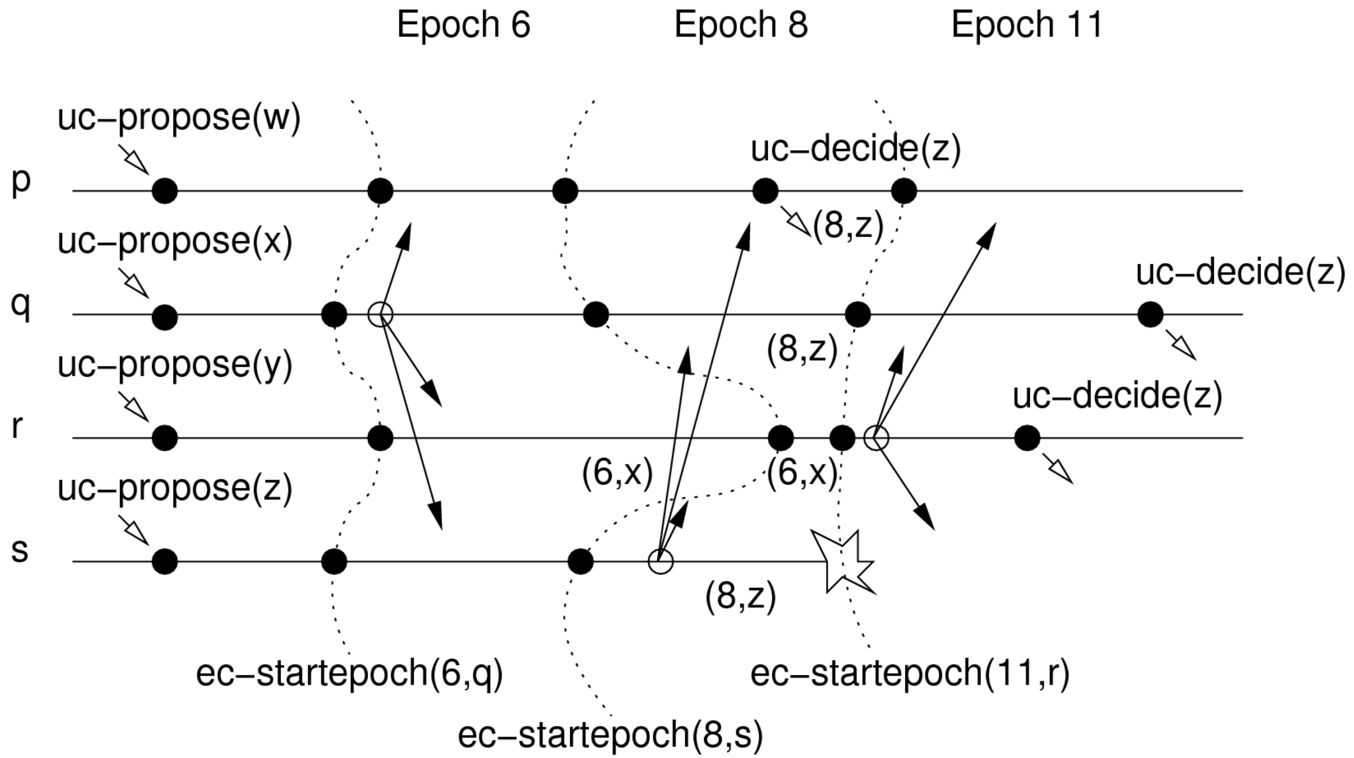
Leader-driven consensus impl.

(...)

upon L = self ∧ val ≠ ⊥ ∧ ¬proposed **do**
    proposed := TRUE
    trigger <ep.ets, Propose | val>

upon <ep.ets, Decide | v> **do**
    if ¬decided **then**
        decided := TRUE
        trigger <c*, Decide | v>

Ex.



- Every process (p, q, r, s) uc-proposes a value
- Epoch 6 has leader q
  - q ep-proposes y, but only r receives it before epoch aborts
  - r now has state (6,x)
- Epoch 8 has leader s
  - s ep-proposes z, proc. p, q, s receive it
  - only p ep-decides(z); then s crashes
- Epoch 11 has leader r, and ep-decides(z)

Correctness

- Termination (UC1 / WBC1)
  - From EC3 (eventual leadership), EP5 (termination) and algorithm
- Validity (UC2) / Weak Validity (WBC2)
  - From EP1 (validity) and algorithm
- Integrity (UC3)
  - Immediate from algorithm
- Uniform Agreement (UC4 / WBC4)
  - From algorithm and EP2 (agreement) and EP4 (lock-in)

Step 2

Implement epoch-change and epoch consensus in crash-failure model

Implementing epoch-change

- Use eventual leader detector (Ω)

- Maintain current trusted leader and timestamp

- When Ω indicates a different leader is trusted
  - Increment timestamp
  - Broadcast a NEWEPOCH message (with leader and timestamp)

- When delivering a NEWEPOCH message
  - Trigger start of new epoch

(Only a sketch; details omitted)

Implementing epoch consensus

- Read/write epoch consensus algorithm
  - Analogous to replicated implementation of a shared single-writer register
- State consists of a timestamp/value pair
- Leader reads state and looks for a value
  - Chooses value with highest timestamp
  - If no value found, takes value from its ep-proposal
  - Writes the chosen value
- Decide once a quorum of processes (> N/2) accept the written value

Read/write epoch consensus

Implements ep, uses pl, beb (N > 2f), with ts. ets and leader L

upon <ep, Init | (valts,val)> **do**
tmpval := ⊥; states := $[\perp]^N$; accepted := 0

upon <ep, Propose | v> **do**
tmpval := v
trigger <beb, Broadcast | [READ]>

upon <beb, Deliver | L, [READ]> **do**
trigger <pl, Send | L, [STATE, valts, val]>

upon <pl, Deliver | q, [STATE, ts, v]> **do**
states[q] := (ts,v)

upon #(states) > N/2 **do**
(ts,v) := highest(states); states := $[\perp]^N$
if v ≠ ⊥ **then** tmpval := v
trigger <beb, Broadcast | [WRITE, tmpval]>

Read/write epoch consensus

(...)

```
upon <beb, Deliver | L, [WRITE, v]> do
    (valts,val) := (ets,v)
    trigger <pl, Send | L, [ACCEPT]>

upon <pl, Deliver | q, [ACCEPT]> do
    accepted := accepted + 1

upon accepted > N/2 do
    accepted := 0
    trigger <beb, Broadcast | [DECIDED, tmpval]>

upon <pl, Deliver | L, [DECIDED, v]> do
    trigger <ep, Decide | v>

upon <ep, Abort> do
    trigger <ep, Aborted | (valts,val)>
```

Correctness (1)

- Validity (EP1)
  - The ep-decided value was written by L
  - If any STATE msg. contains a value, L writes this
    - This value has been written by some leader
  - Otherwise, L writes its own ep-proposed value
- Uniform Agreement (EP2)
  - Immediate from DECIDED msg. in algorithm
- Integrity (EP3)
  - Immediate from algorithm
- Lock-in (EP4)
  - A write-quorum ($> N/2$) stored v before sending the ACCEPT msg. in previous epoch $ts' < ts$
  - Processes passed it in state to subsequent epochs
  - Then, L reads v from at least one STATE msg. in read-quorum ($> N/2$)

Correctness (2)

- Termination (EP5)
  - If leader L is correct, then every process ep-decides
- Abort behavior (EP6)
  - Immediate from algorithm

Step 3

Implement epoch-change and epoch consensus in Byzantine-failure model

Implementing Byzantine epoch-change

- Use Byzantine eventual leader detector (bld)
  - bld allows application to complain when no progress
- Maintain current trusted leader and timestamp
- When bld indicates a different leader is trusted
  - Increment timestamp
  - Derive leader from timestamp (deterministically)
  - Broadcast a NEWEPOCH message (with timestamp)
- When delivering $> f$ NEWEPOCH messages
  - Trigger start of new epoch

(Only a sketch; details omitted)

Implementing Byzantine epoch consensus (1)

- Byzantine read/write epoch consensus alg.
  - Analogous to replicated implementation of a Byz. shared single-writer register

- State consists of timestamp/value pair and set of "previously" written values

- Leader should read state of all processes and determine value to write
  - But cannot trust single leader
  - Thus, all processes read state and determine value
    - Encapsulated by a conditional collect primitive

(...)

Implementing Byzantine epoch consensus (2)

- Processes choose value with highest timestamp
  - If no value found, only then leader is free to take the value from its ep-proposal
- All processes write the chosen value
  - Broadcast WRITE message to all
- When receiving WRITE msg. with value v from > (N+f)/2 processes, then store v
  - Broadcast ACCEPT msg. message to all
- When receiving ACCEPT msg. with v from > (N+f)/2 processes, then ep-decide

Conditional Collect (cc)

- Parameterized by a predicate C and leader L
  - Leader L will also be the leader of the epoch

- Events
  - Request <cc, Input | m>
    - Inputs message m
  - Indication <cc, Collected | M>
    - Outputs vector M of collected messages or UNDEFINED

- Properties
  - CC1 (Consistency): If L is correct, every correct pr. collects the same M, which contains at least N-f messages different from UNDEFINED.
  - CC2 (Integrity): If a correct pr. collects M with M[p] ≠ UNDEFINED and p is correct, then p has input m. (...)

Conditional Collect (cc)

- (... Properties)
  - CC3 (Termination): If L is correct and all correct pr. input messages such that they satisfy C, then every correct process eventually collects M s.t. C(M).

- Note
  - Every process inputs a message
  - Output is vector of such messages, one per process
  - If L correct, then output M satisfies the predicate
    - Otherwise, may not terminate

Byz. read/write epoch cons. (1)

Implements ep, uses al, abeb, cc (N > 3f), with ts. ets and leader L

upon <ep, Init | (valts,val,ws)> **do**
    written := $[\bot]^N$; accepted := $[\bot]^N$

upon <ep, Propose | v> **do**
    if val = ⊥ **then** val := v
    trigger <abeb, Broadcast | [READ]>

upon <abeb, Deliver | L, [READ]> **do**
    trigger <cc, Input | [STATE, valts, val, ws]>

upon <cc, Collected | S> **do**
    // note, for all p : S[p] = [STATE, ts, v, ws] or UNDEFINED
    tmpval := ⊥
    if ∃ts ≥ 0, v ≠ ⊥ from S : binds(ts,v,S) **then** tmpval := v
    else if ∃v ≠ ⊥ : unbound(S) ∧ v ∈ S[L] **then** tmpval := v
    if tmpval = ⊥ **then** halt
    (...)

Byz. read/write epoch cons. (2)

```
(... upon <cc, Collected | S> do)
    if ∃ts : (ts,tmpval) ∈ ws then ws := ws \ {(ts,tmpval)}
    ws := ws ∪ {(ets,tmpval)}
    trigger <abeb, Broadcast | [WRITE, tmpval]>

upon <abeb, Deliver | p, [WRITE, v]> do
    written[p] := v
    if ∃v : #{p|written[p]=v} > (N+f)/2 then
        (valts,val) := (ets,v)
        written := [⊥]^N
        trigger <abeb, Broadcast | [ACCEPT, val]>

upon <abeb, Deliver | q, [ACCEPT, v]> do
    accepted[p] := v
    if ∃v : #{p|accepted[p]=v} > (N+f)/2 then
        written := [⊥]^N
        trigger <ep, Decide | v>
```

Byz. read/write epoch cons. (3)

- Predicate binds(ts,v,S):
  - Whether (ts,v) is confirmed by $> (N+f)/2$ entries in S to be value associated to highest timestamp, and
  - Value v has not been invented out of thin air
    - Hence, processes write this value again
- Predicate unbound(S):
  - Evidence that no value can be bound by S
    - Hence, processes write value of the leader
- Predicate sound(S) for cc:
  - $\exists$(ts,v) such that binds(ts,v,S) $\vee$ unbound(S)

Correctness (1)

- Validity (EP1)
  - The ep-decided value v was written in the epoch
  - Either collected vector S satisfies bound(ts,v,S)
    - Then v has been written in an "earlier" epoch
  - Otherwise, take ep-proposed value of L
- Uniform Agreement (EP2)
  - Immediate from quorum of ACCEPT msgs.
- Integrity (EP3)
  - Immediate from algorithm
- Lock-in (EP4)
  - A write-quorum ($> (N+f)/2$) stored v before sending an ACCEPT msg. in previous epoch $ts' < ts$
  - Processes passed it in state to subsequent epochs
  - Then, conditional collect determines from STATE msgs. in a quorum ($> (N+f)/2$) that such v exists

Correctness (2)

- Termination (EP5)
  - If leader L is correct, then every process ep-decides
    - Given termination of conditional collect (CC3)
    - Same as termination of Byz. reliable broadcast
- Abort behavior (EP6)
  - Immediate from algorithm (omitted)

Summary

- Same leader-driven consensus algorithm with crash failures and Byzantine failures
  - Using abstract primitives of epoch-change and epoch consensus
- Primitives implemented in crash model
  - Paxos consensus algorithm
- Primitives implemented in Byzantine model
  - PBFT consensus algorithm

Coda

Wrap-up

- Distributed programming defines abstractions of
  - Reliable broadcast
  - Shared memory
  - Consensus
- Implementations in distributed systems
- By group of processes, which are subject to
  - Crash failures
  - Attacks/Byzantine failures

For everything else, see the book.

www.distributedprogramming.net