Agreement in Fault Tolerant Distributed Systems

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Distributed Agreement

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- Agreement requirements can be more or less stringent: one may need to agree on a unique leader, whether to commit or abort a distributed transaction, on the delivery order for a set of messages, etc.
- While on a fault-free system agreement can be easily reached, in the presence of faults and depending on the assumed model, reaching agreement can be very hard or even impossible.

Forms of Agreement

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- Non-blocking Atomic Commitment

[Jim Gray, Notes on Database Operating Systems, LNCS 60, 1978]

[D. Skeen, NonBlocking Commit Protocols, 1981]

- Leader Election

[L.Sabel & K. Marzullo, Election Vs. Consensus in Asynchronous Systems, 1995]

- Consensus

[M. Fischer, N. Lynch, M. Paterson. Impossibility of Distributed Consensus with One Faulty Process, 1985]

- k-Set Agreement

[S. Chaudhuri, More Choices Allow More Faults: Set Consensus Problems in Totally Asynchronous Systems, 1993]

- Atomic Broadcast, Group Membership, ...

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Validity: If any process votes no then abort should be decided

Uniform Agreement: No process decides differently

[P. A. Bernstein, V. Hadzilacos, N. Goodman, Concurrency Control and Recovery, 1987]

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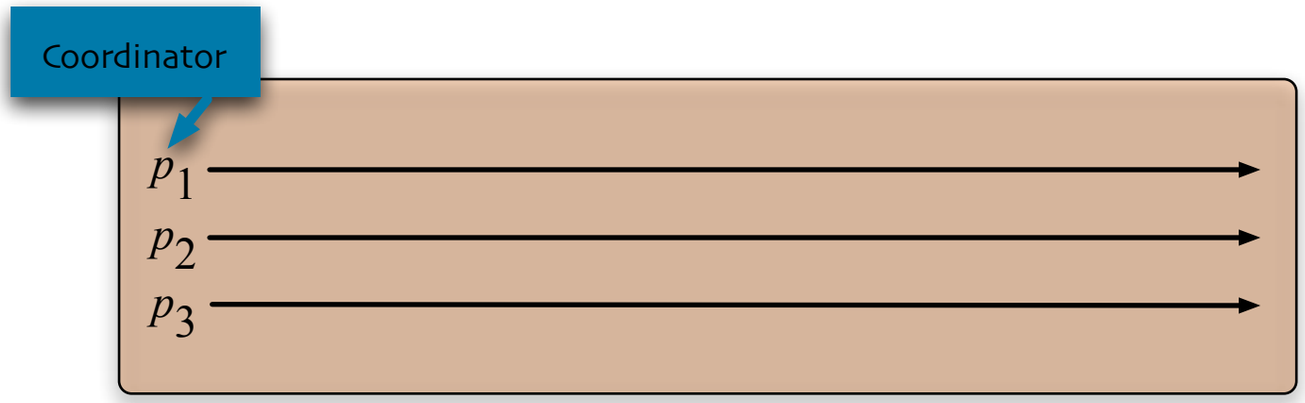

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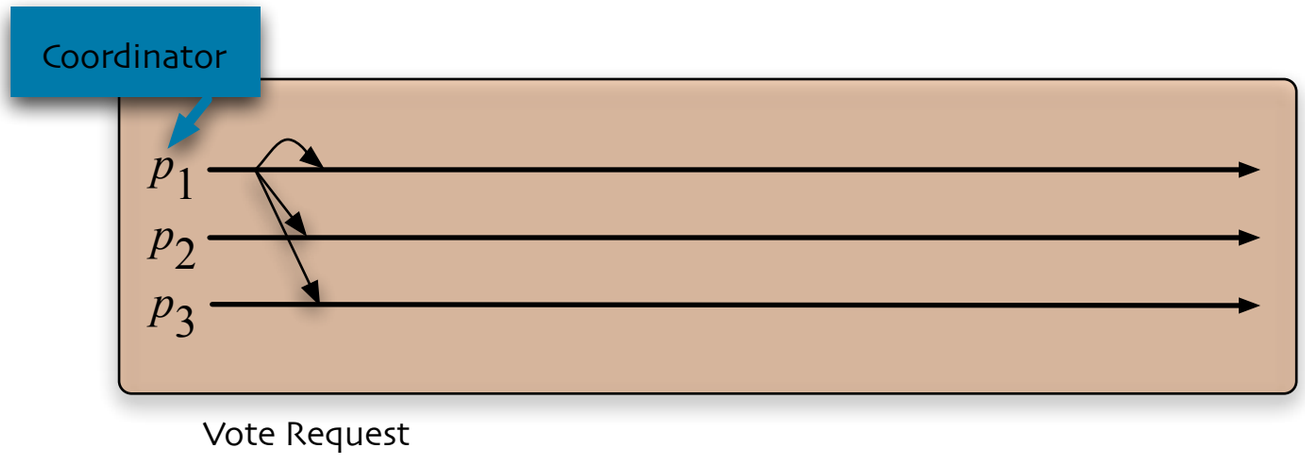

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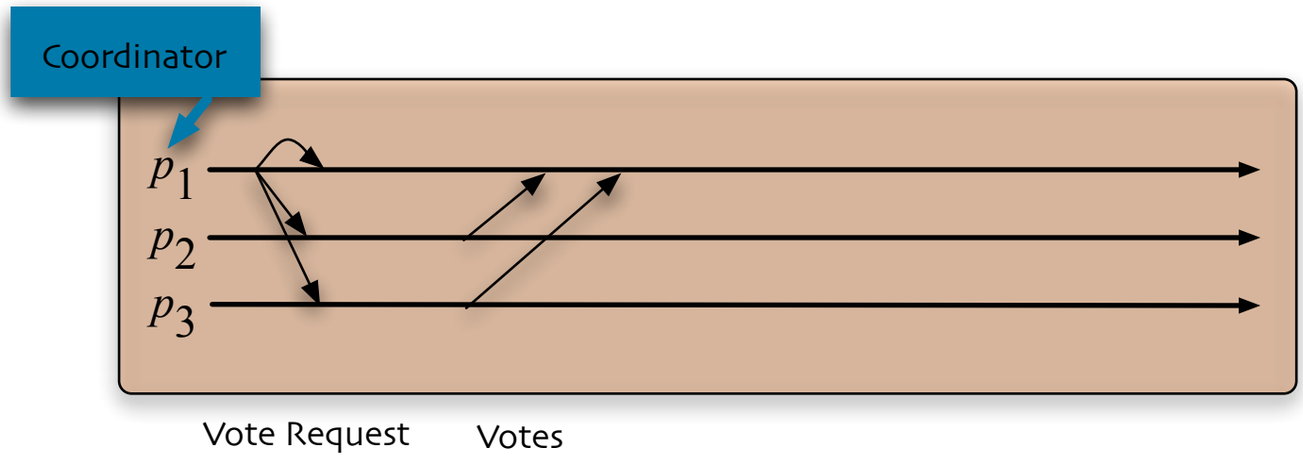

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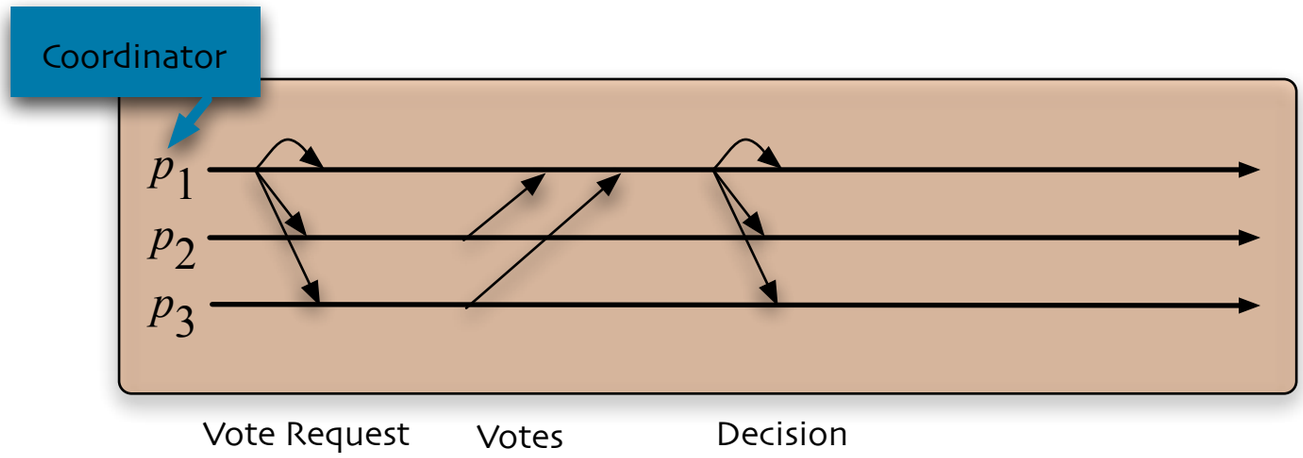

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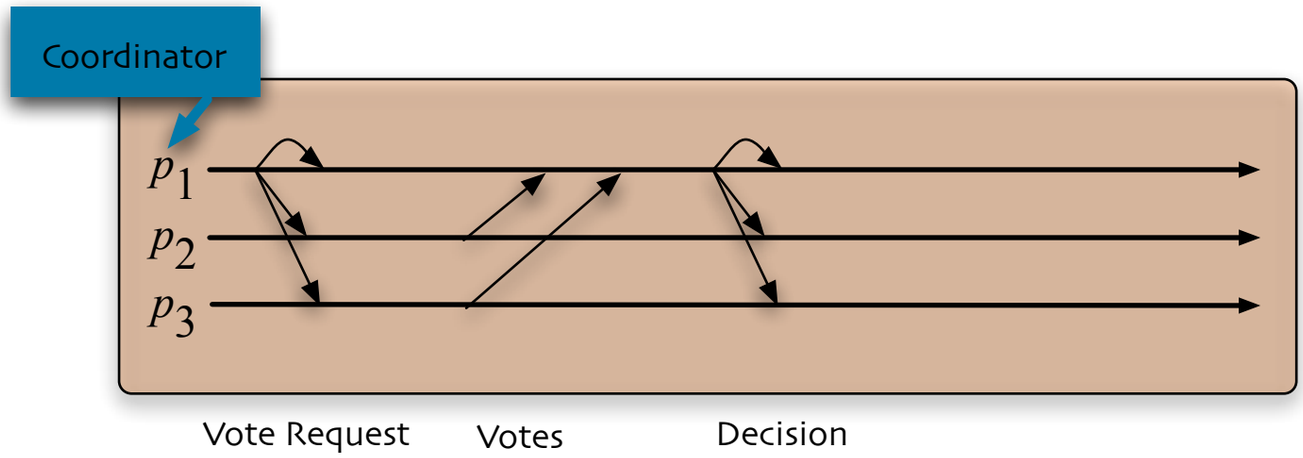

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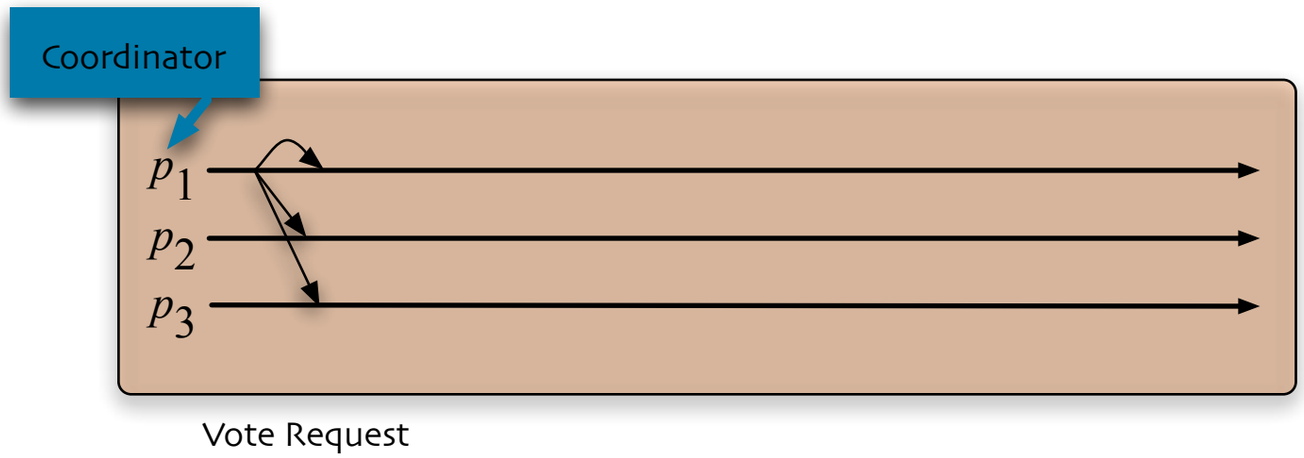

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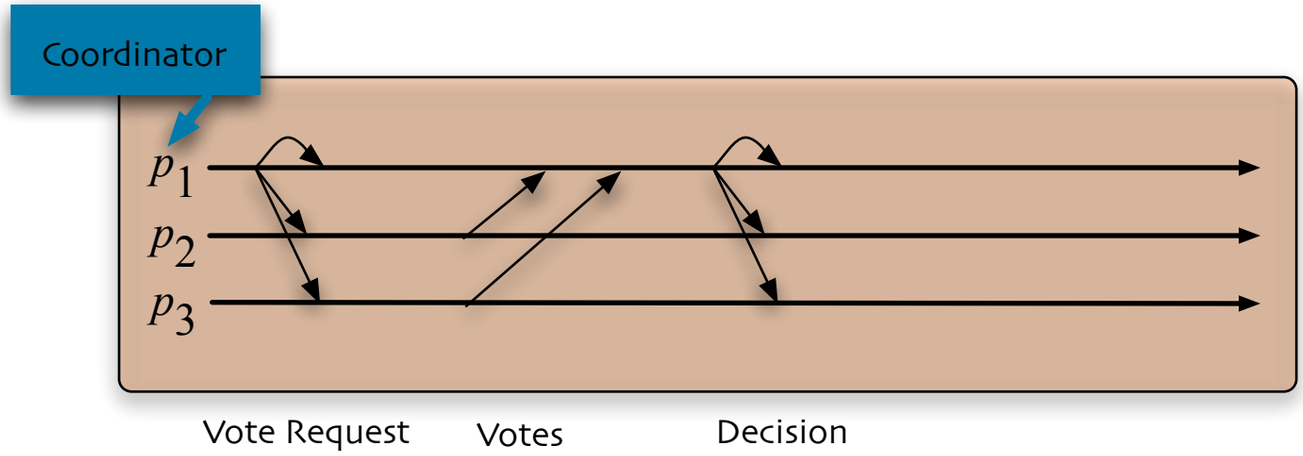

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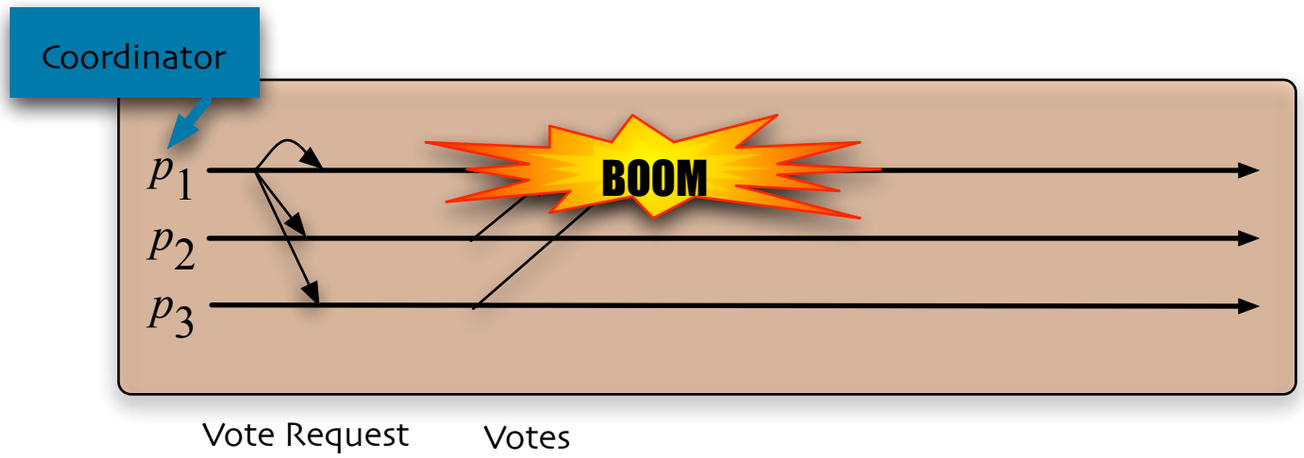

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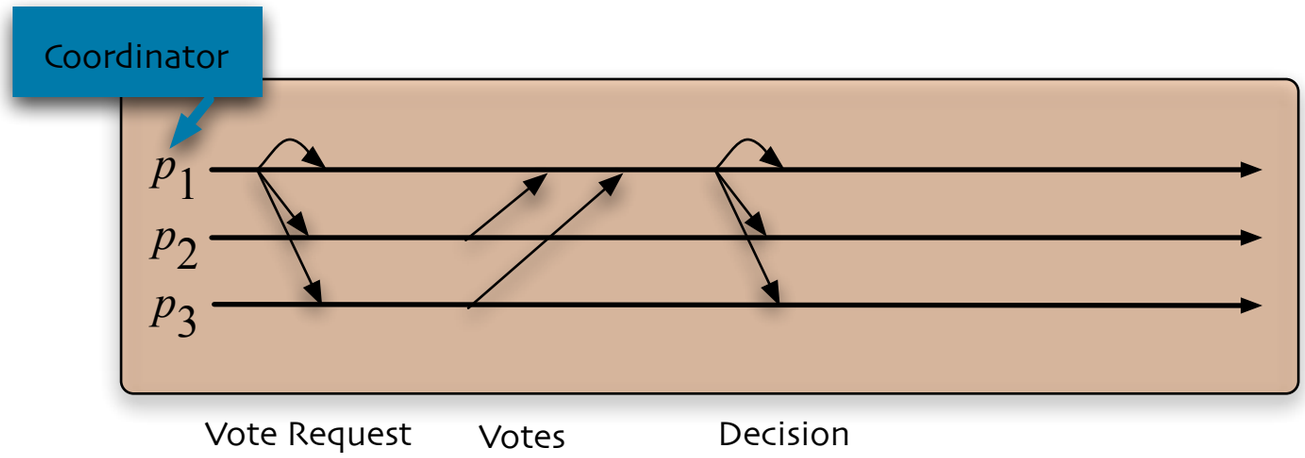

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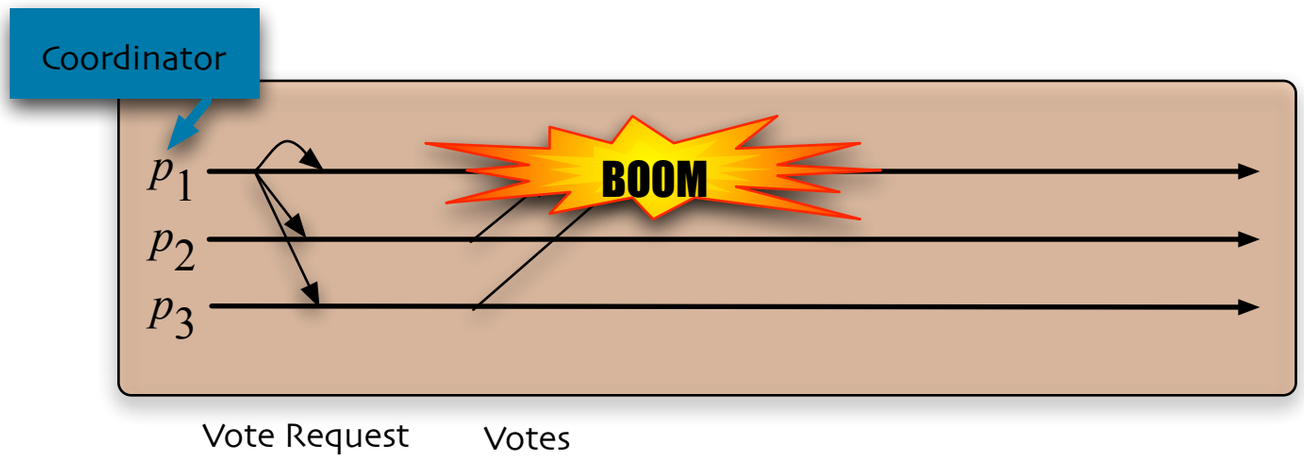

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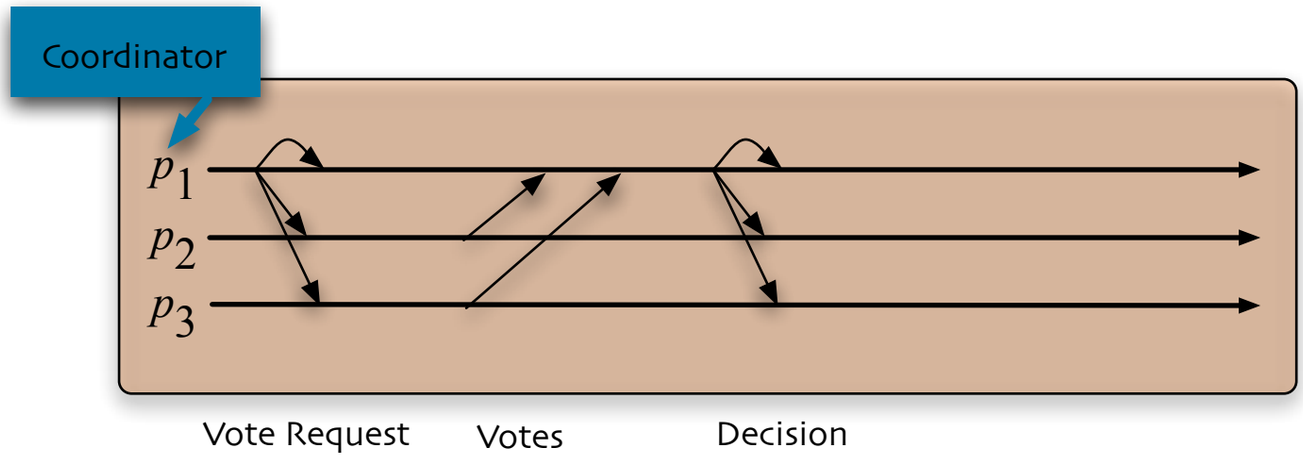

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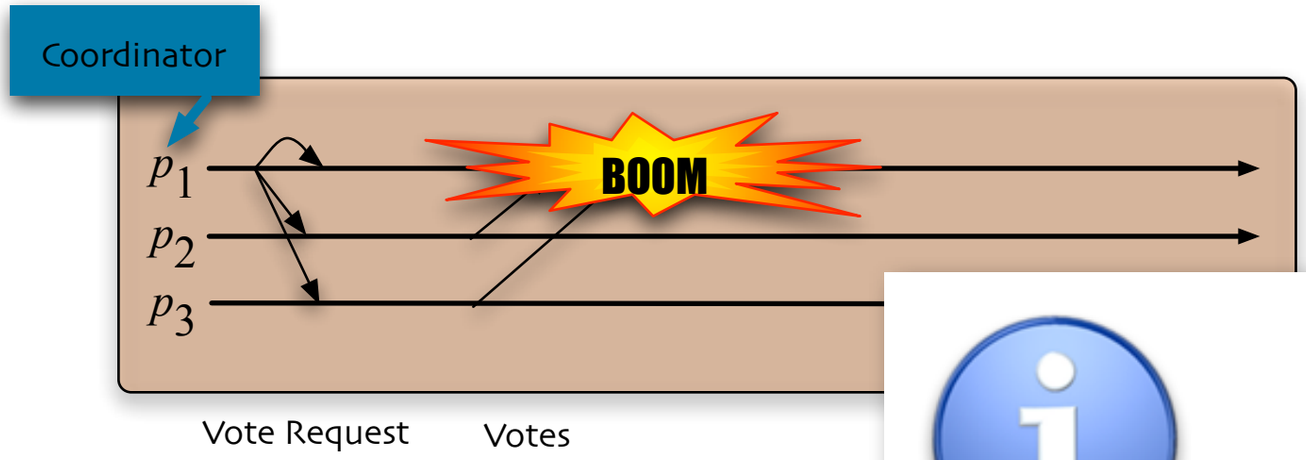

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OK
in Crash-Recover model

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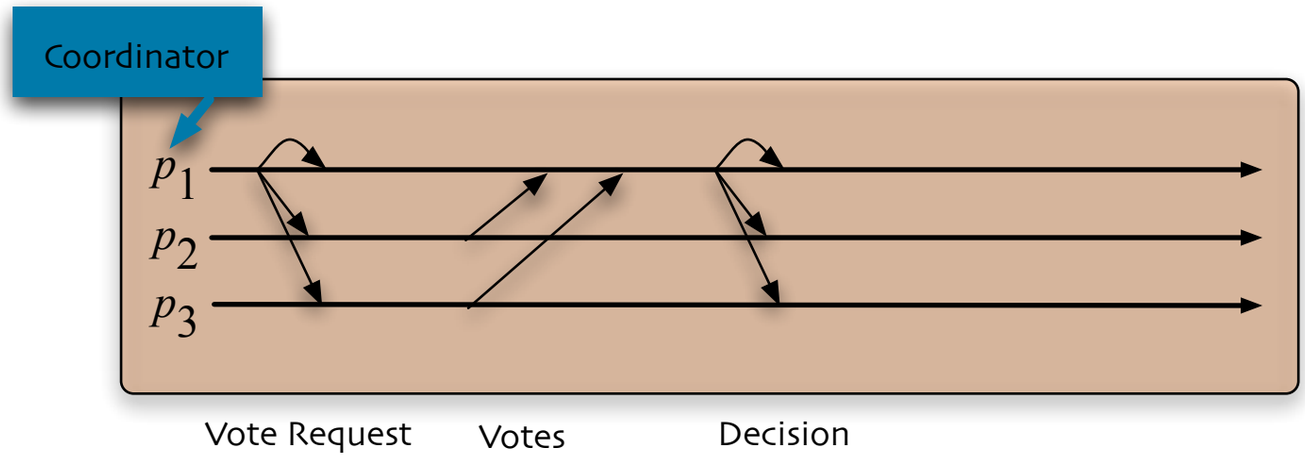

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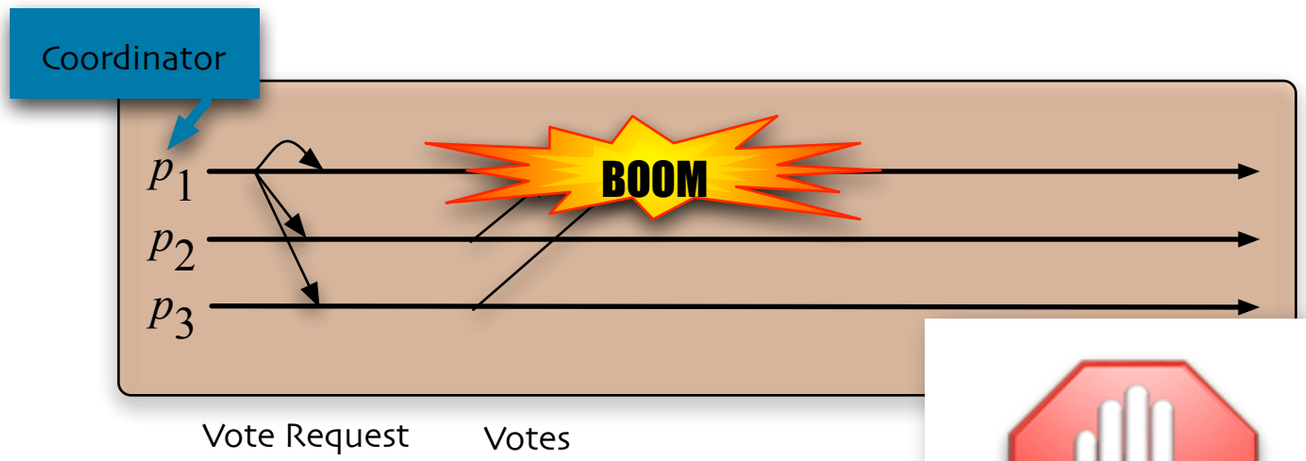

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Blocking
in Fail-Stop model

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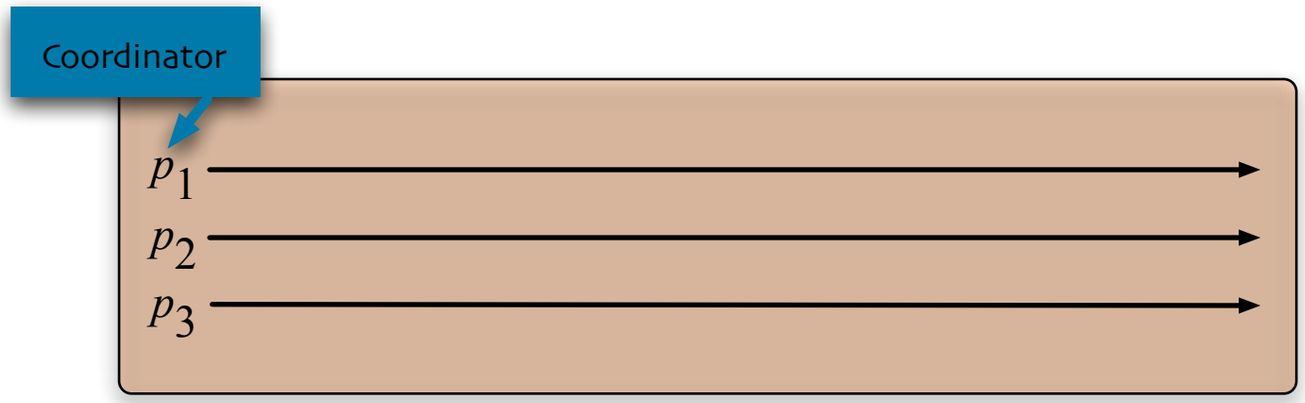

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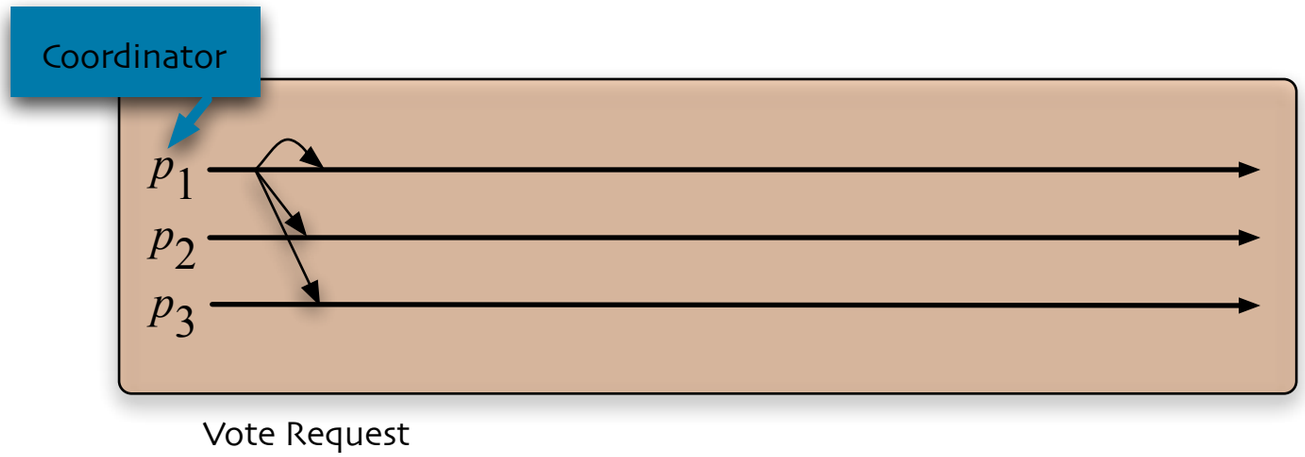

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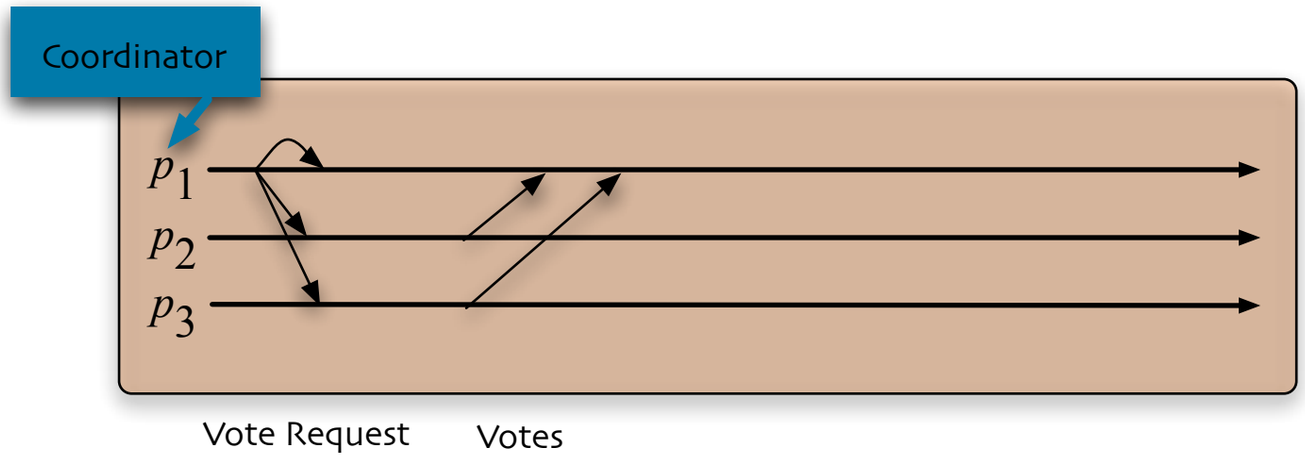

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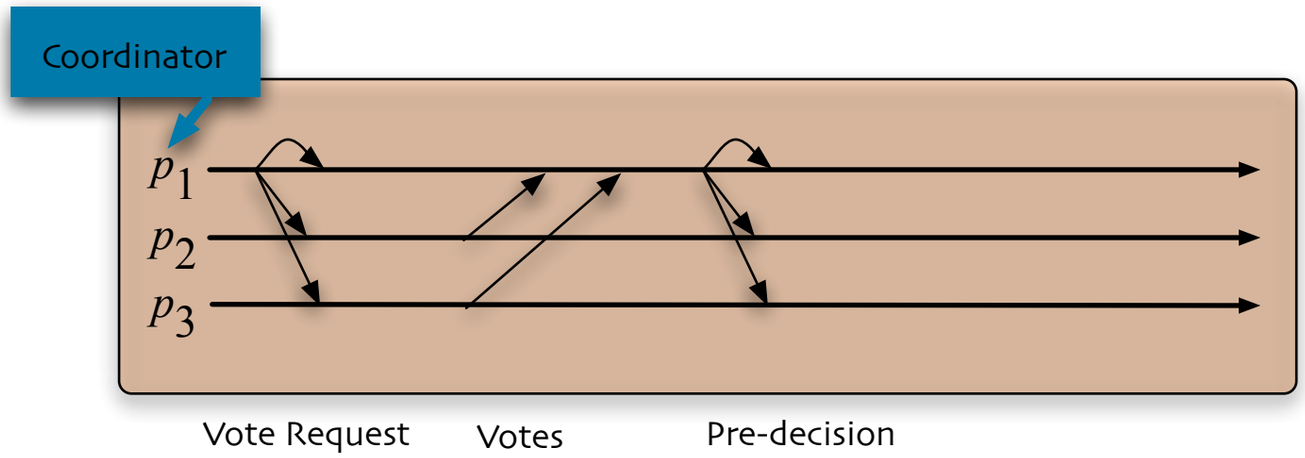

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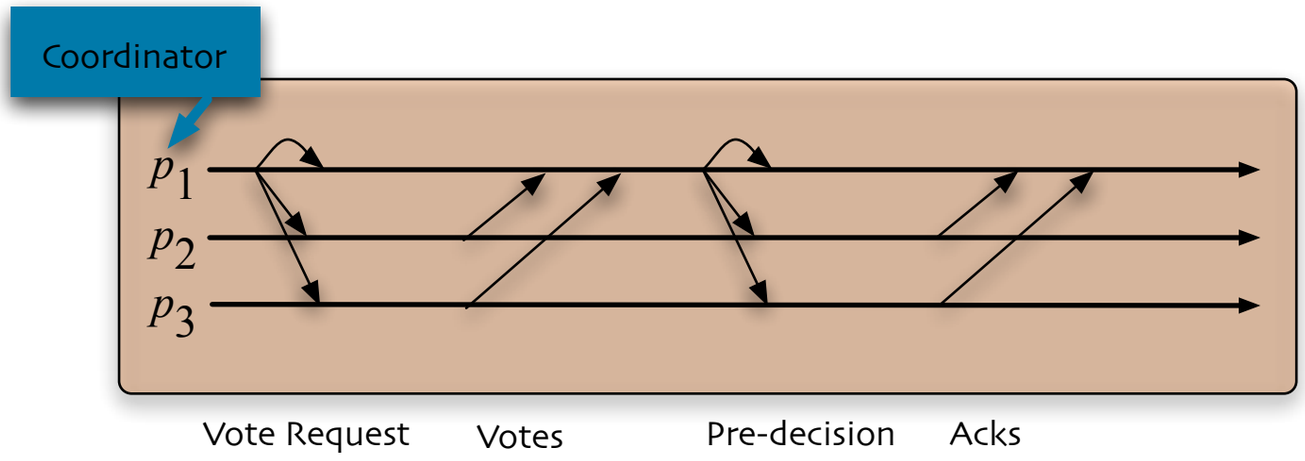

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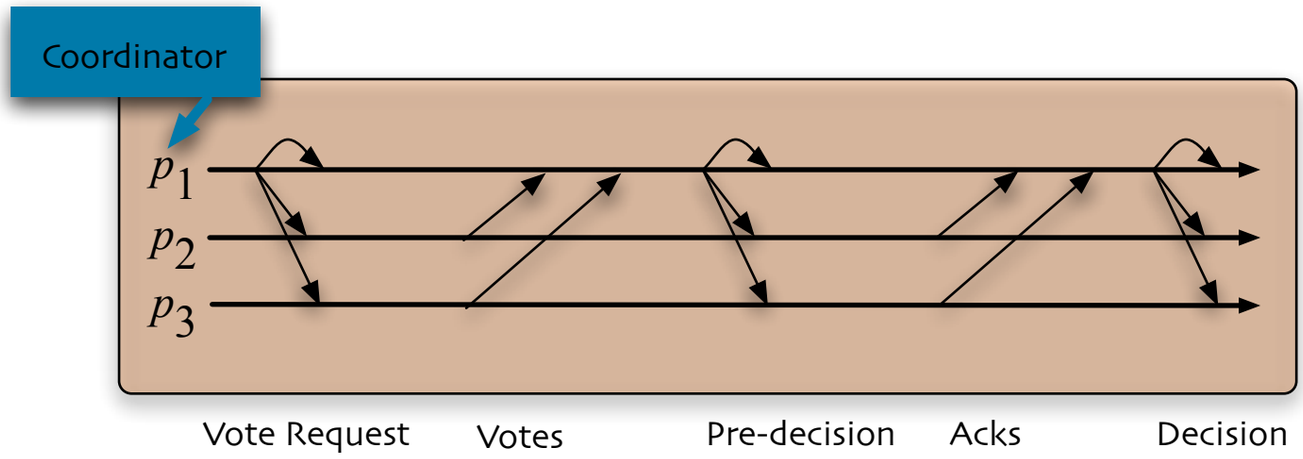

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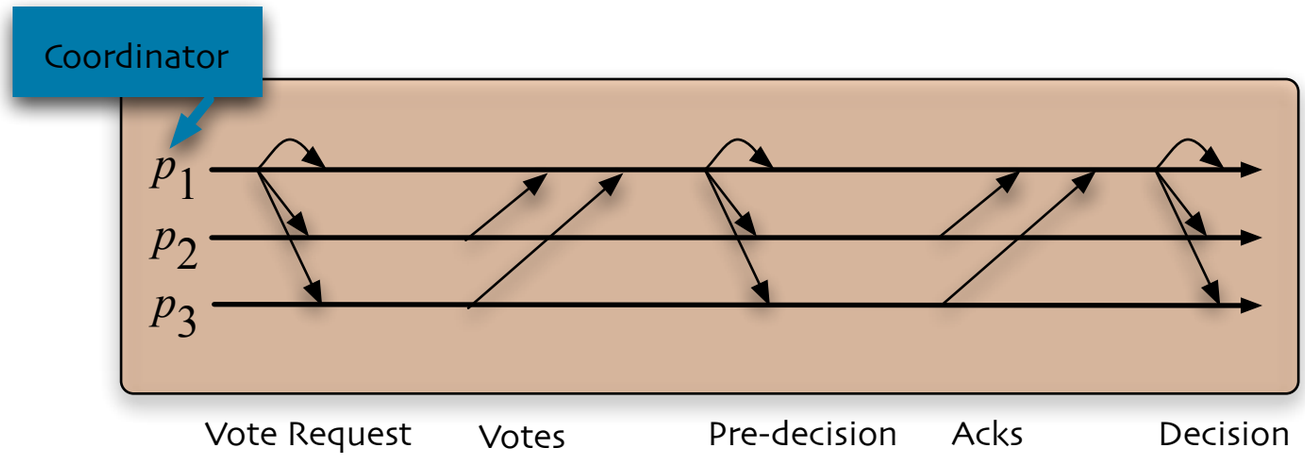

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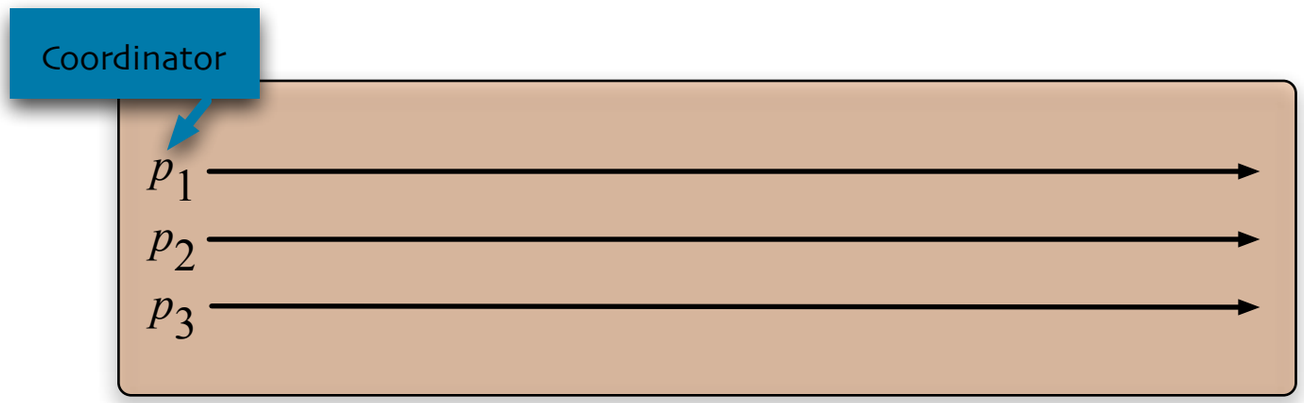

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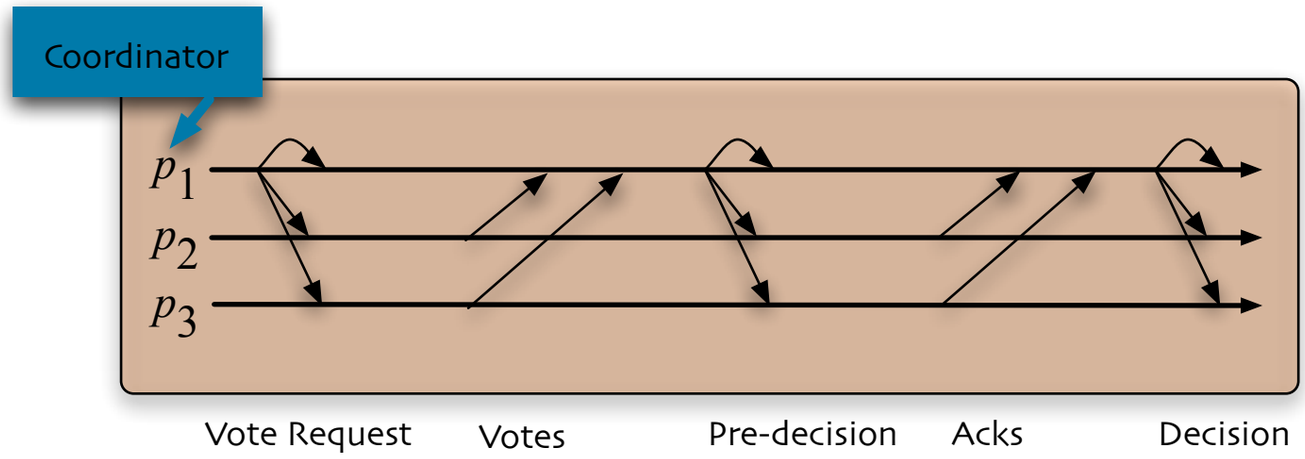

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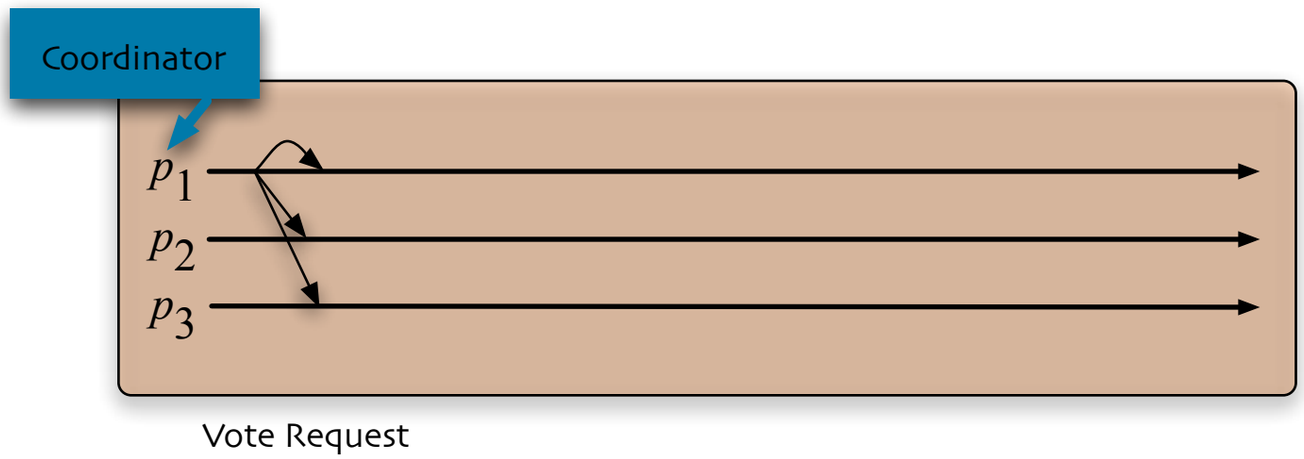

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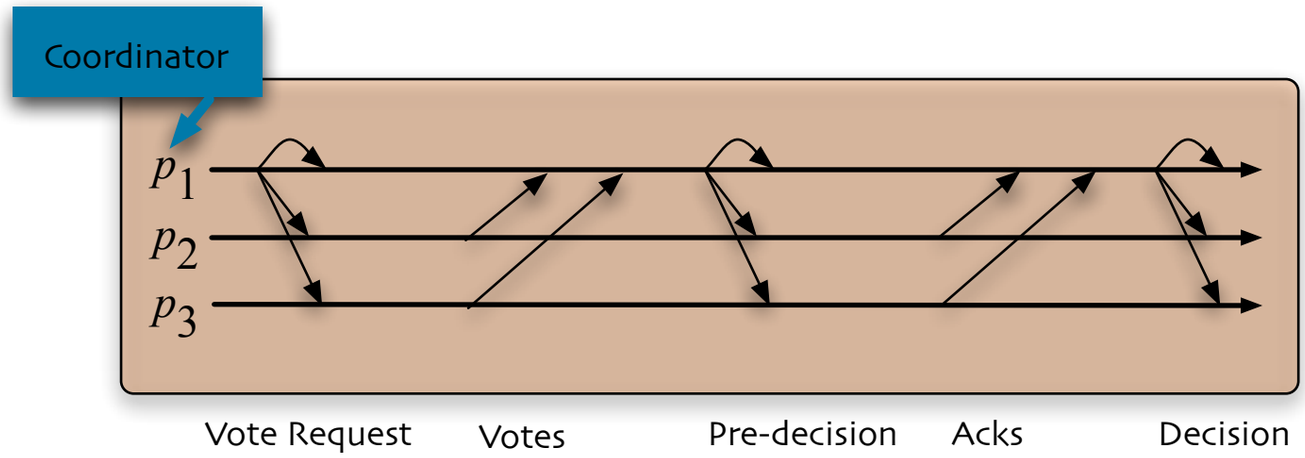

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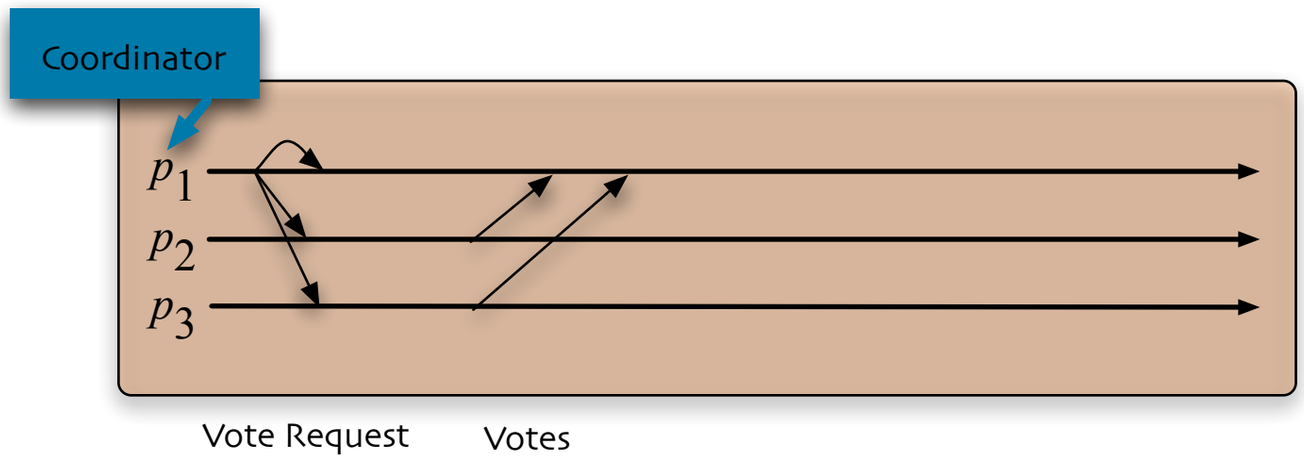

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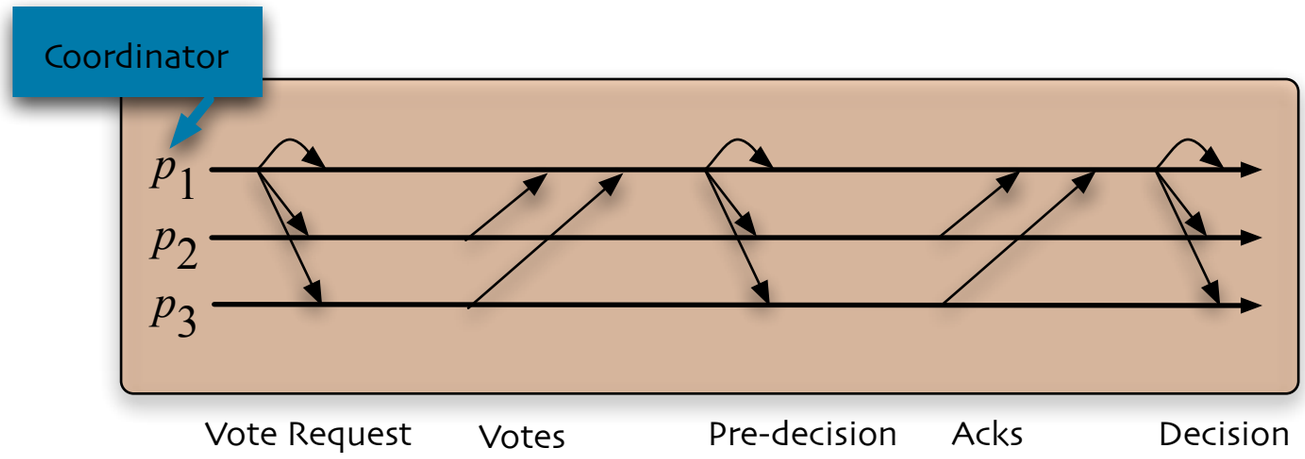

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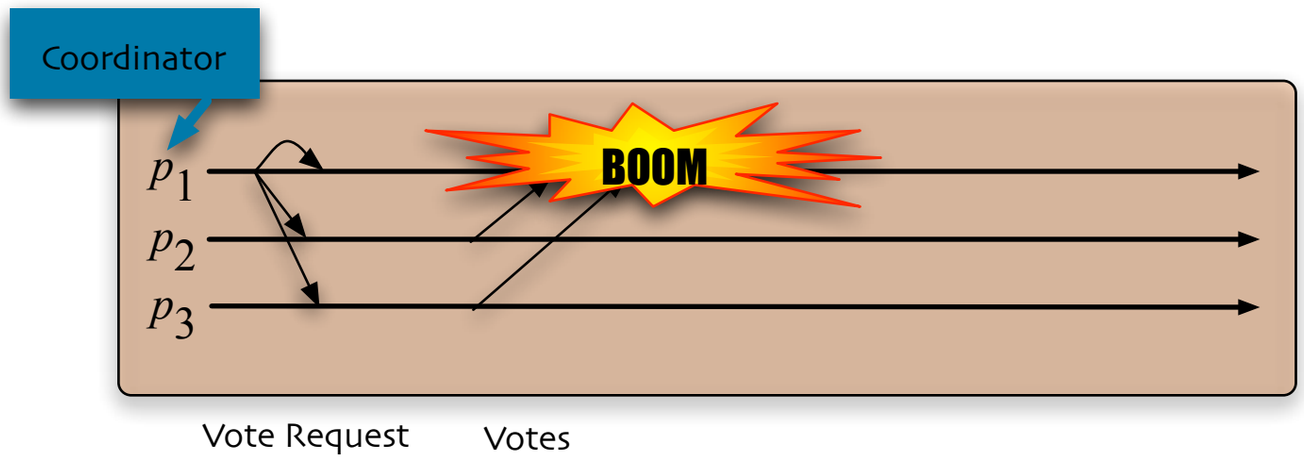

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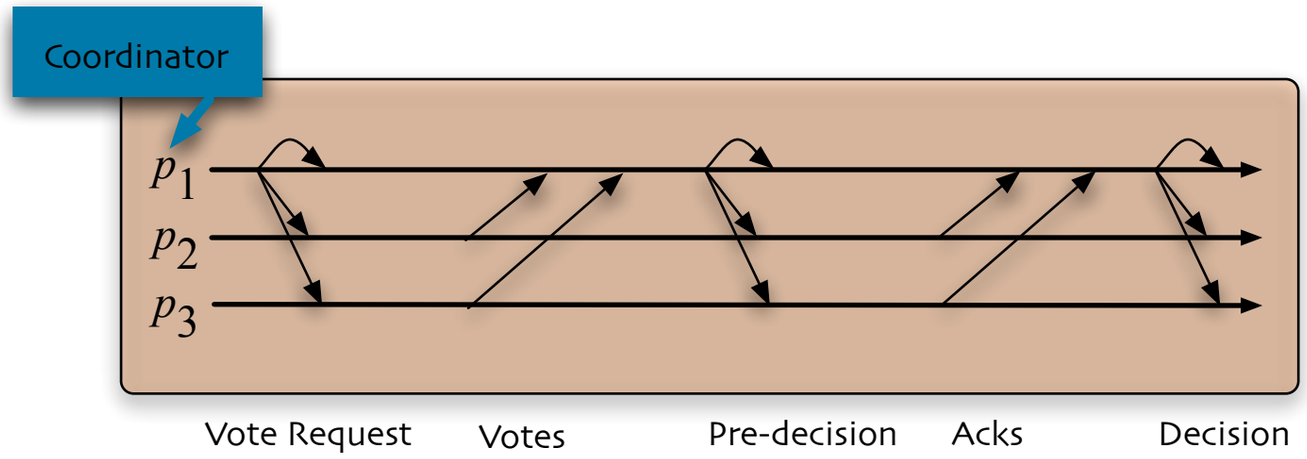

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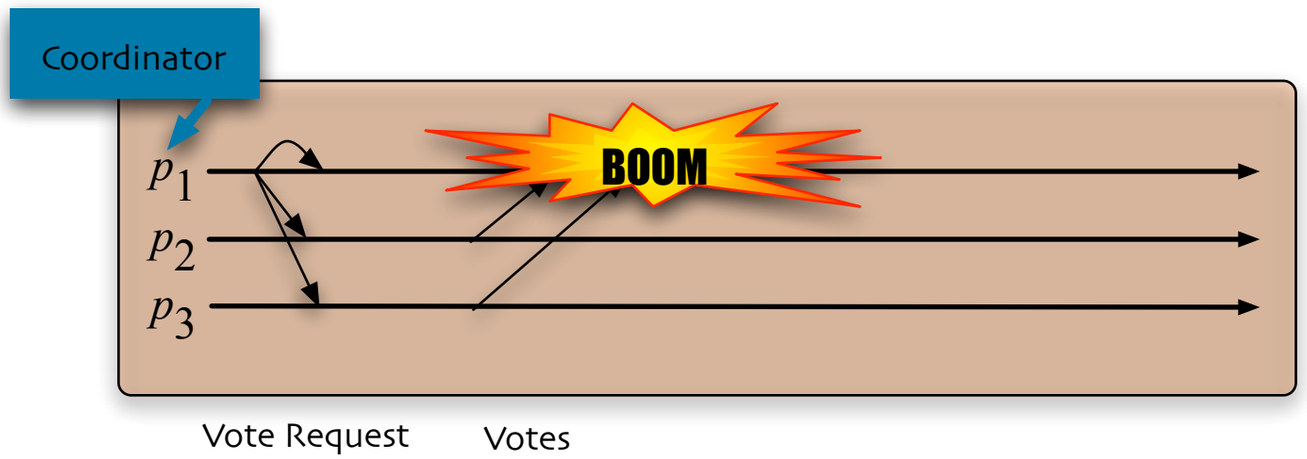

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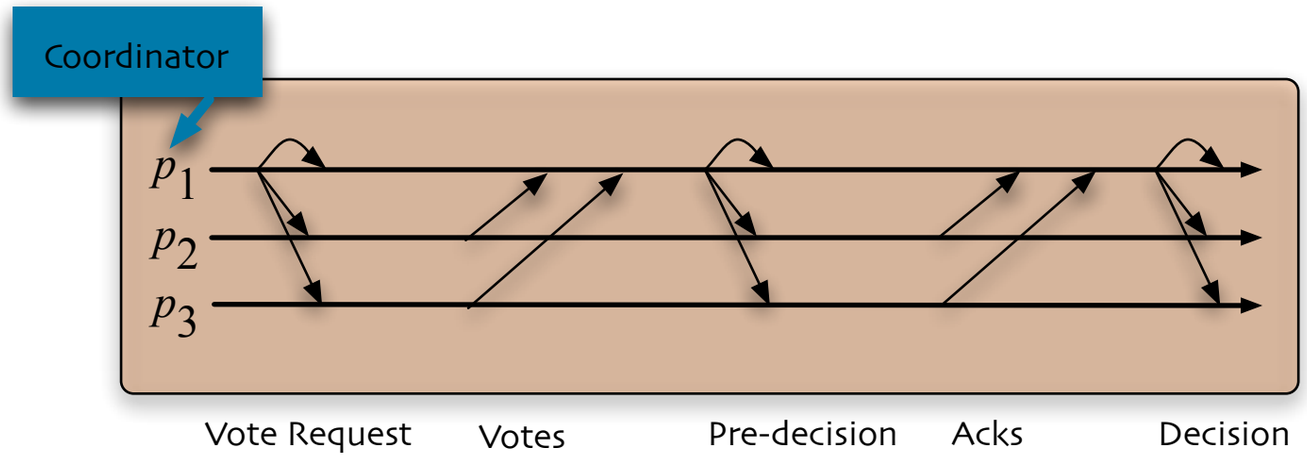

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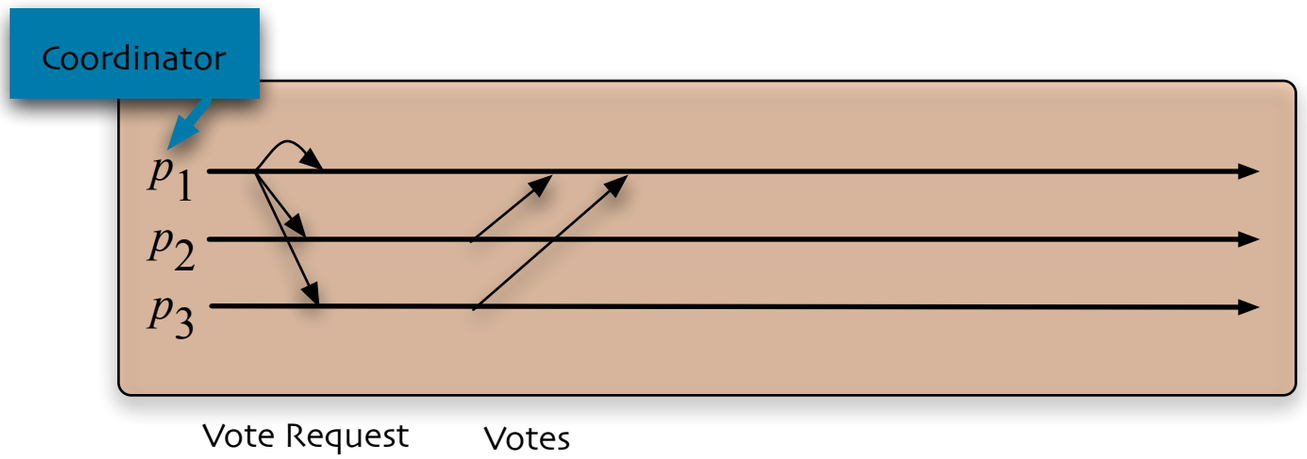

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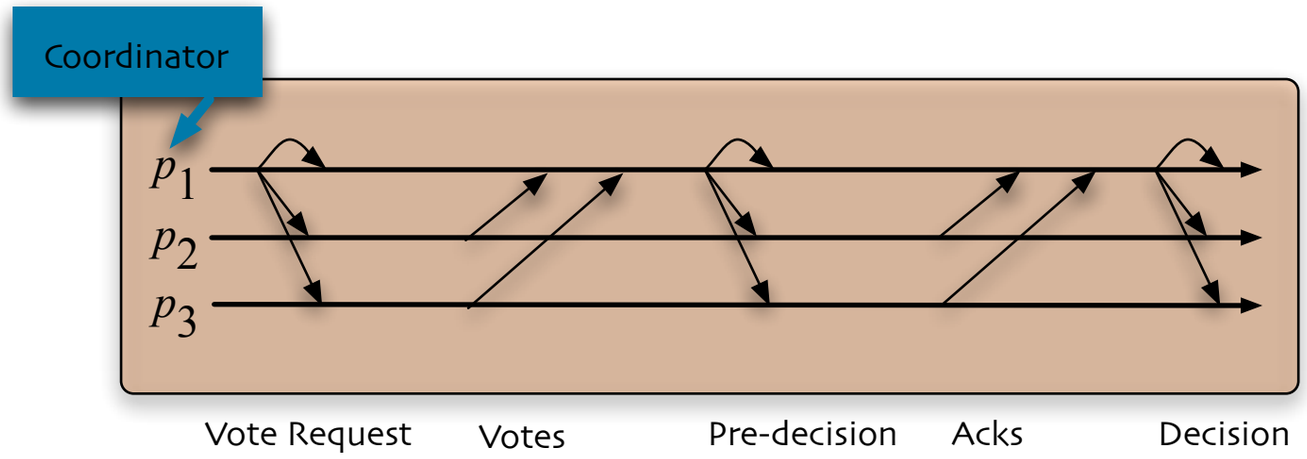

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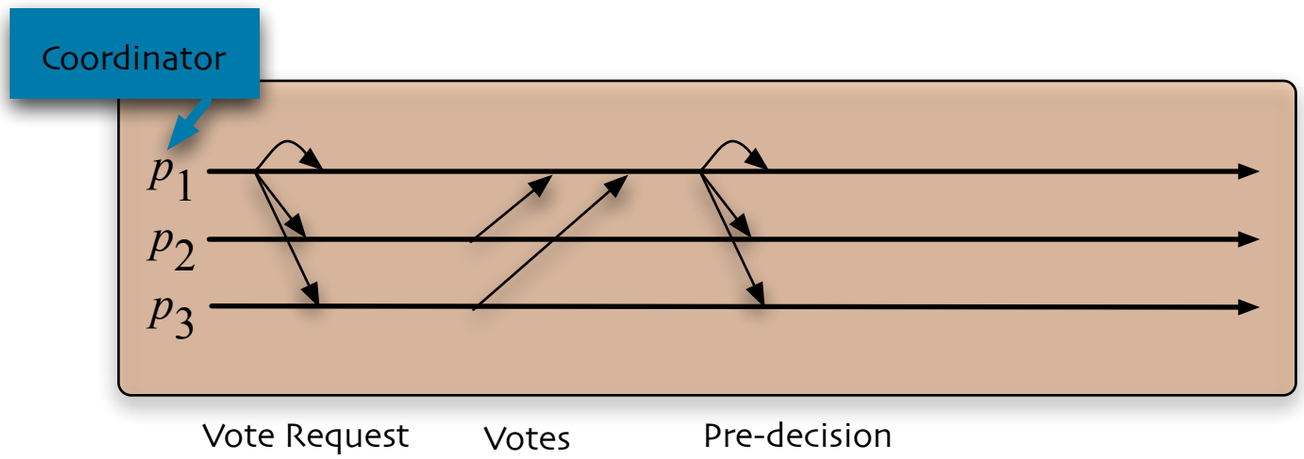

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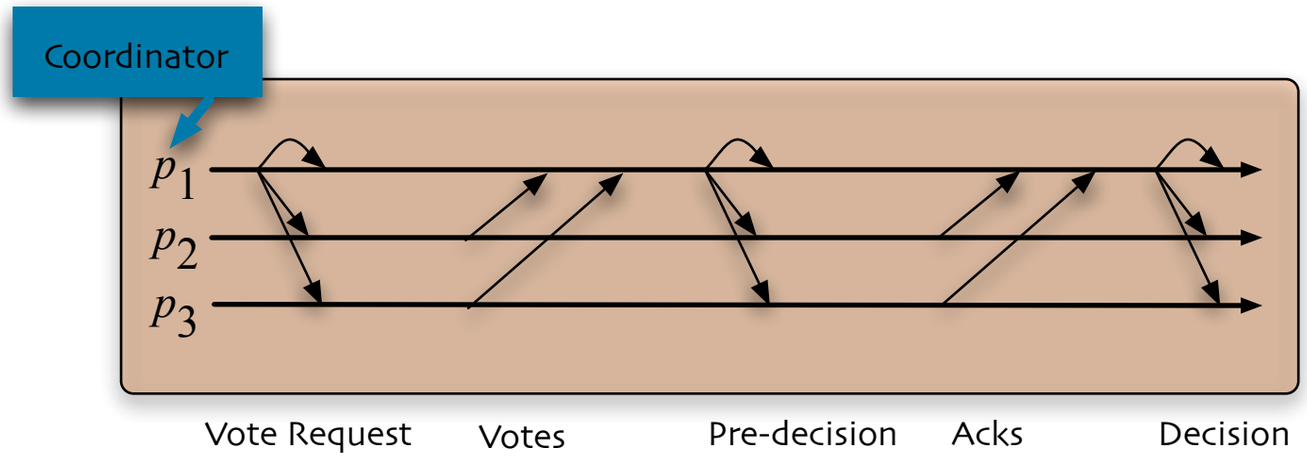

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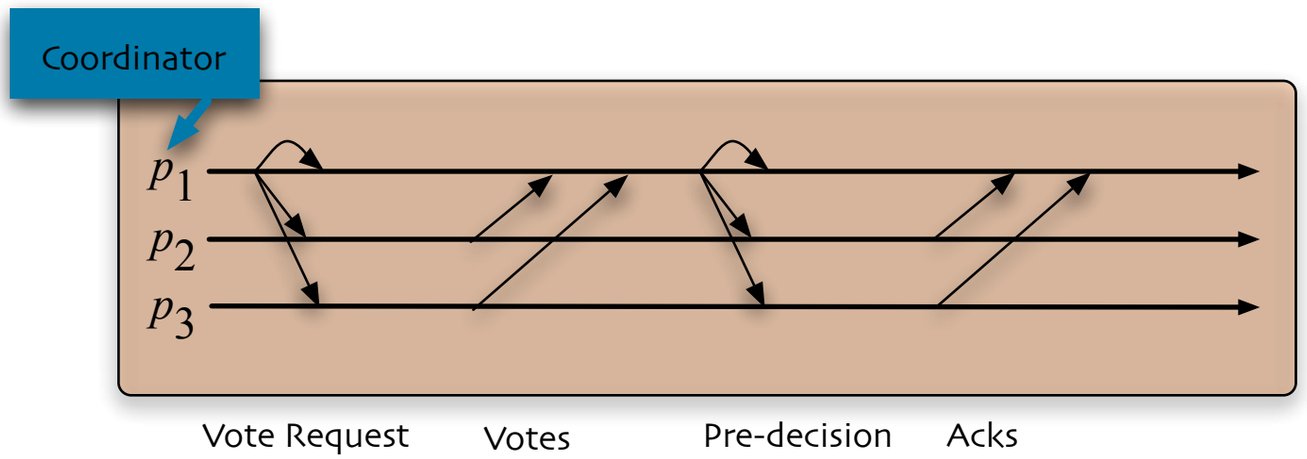

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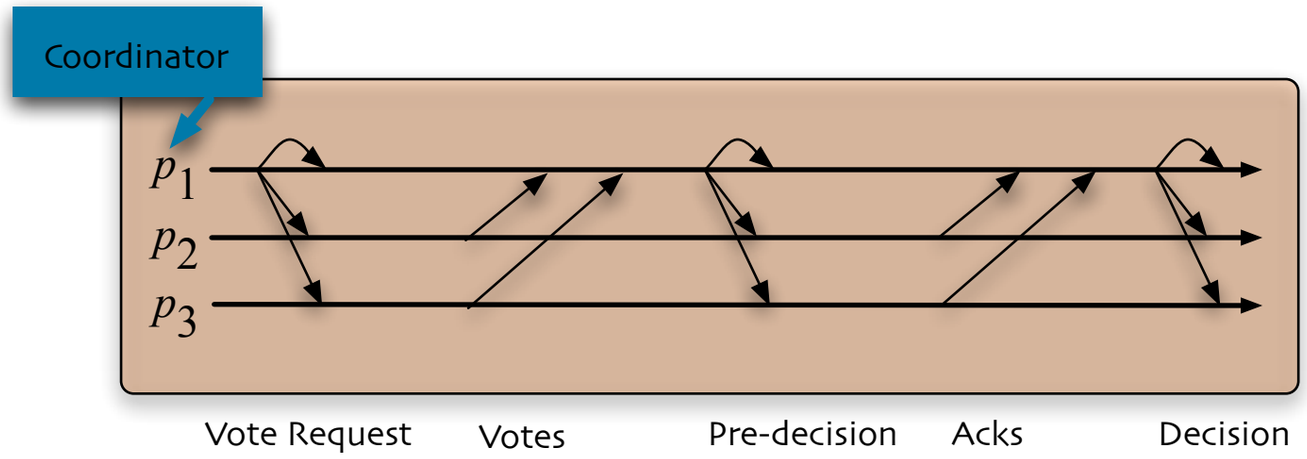

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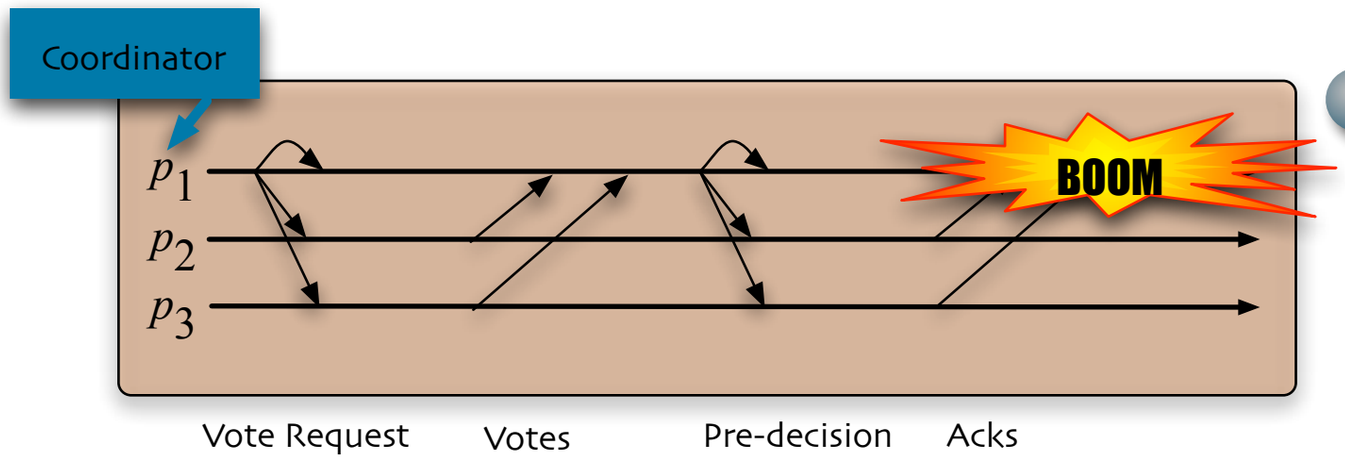

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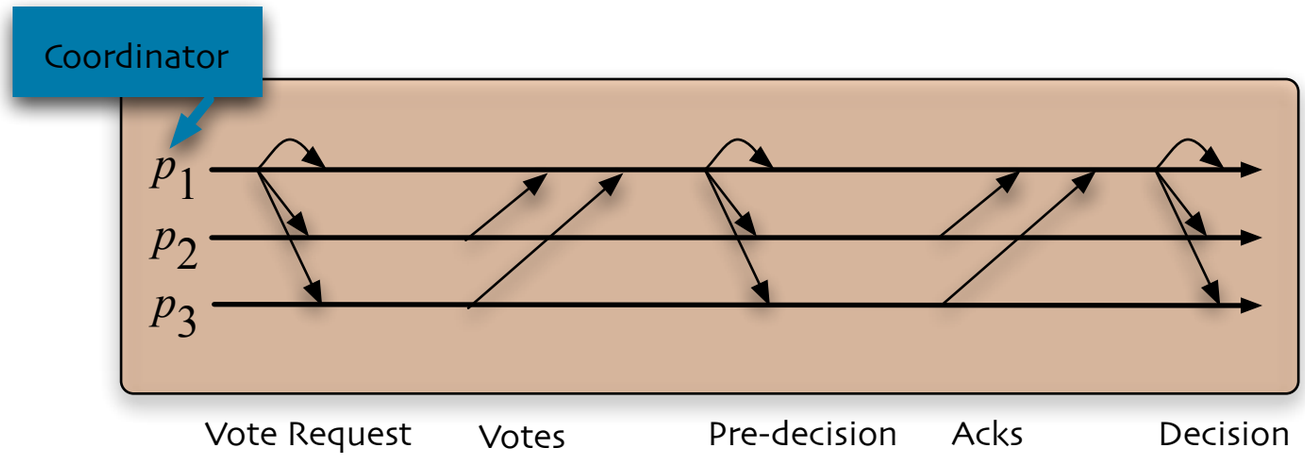

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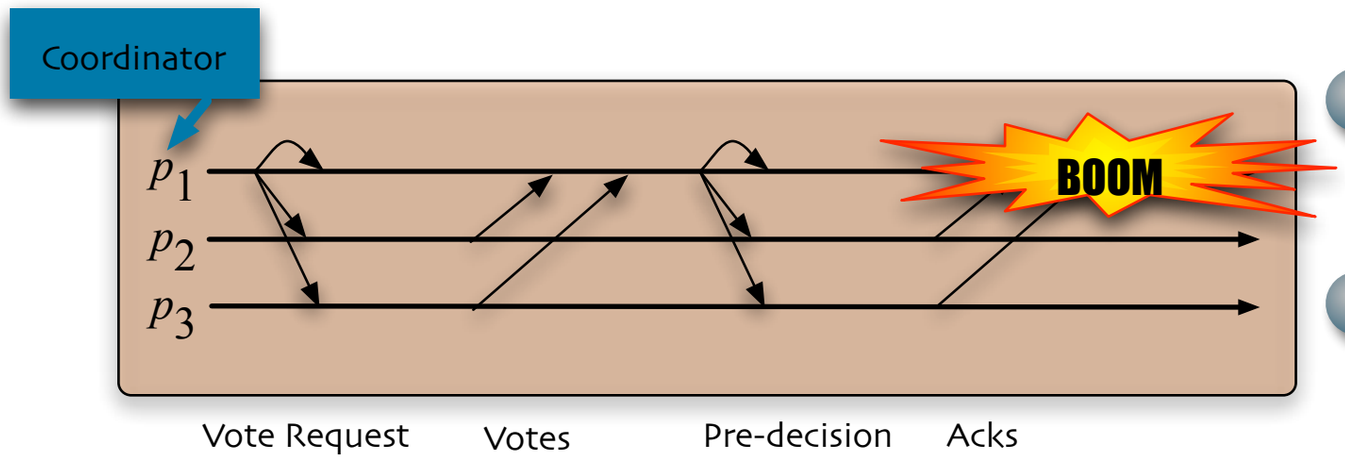

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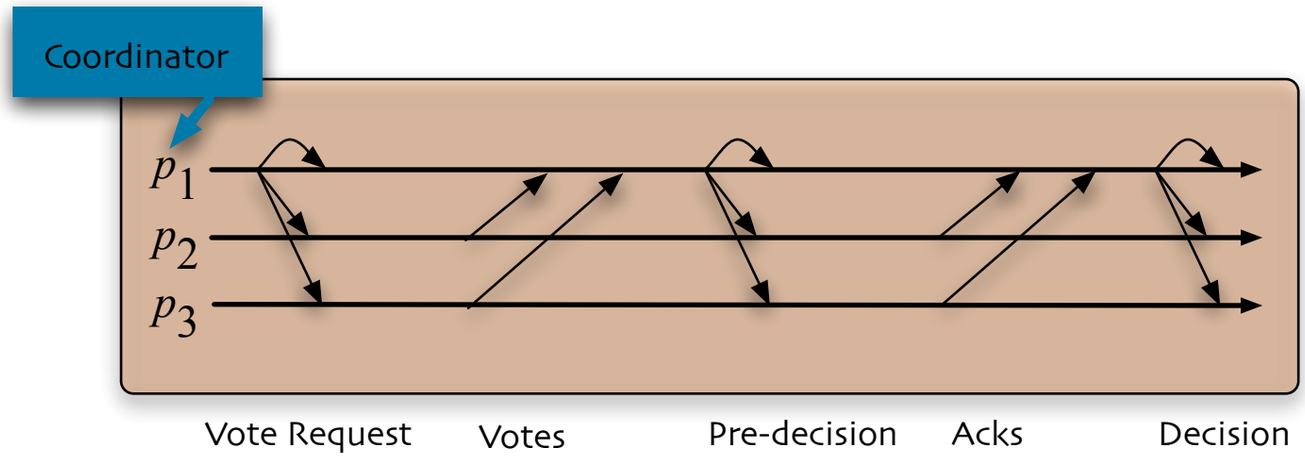

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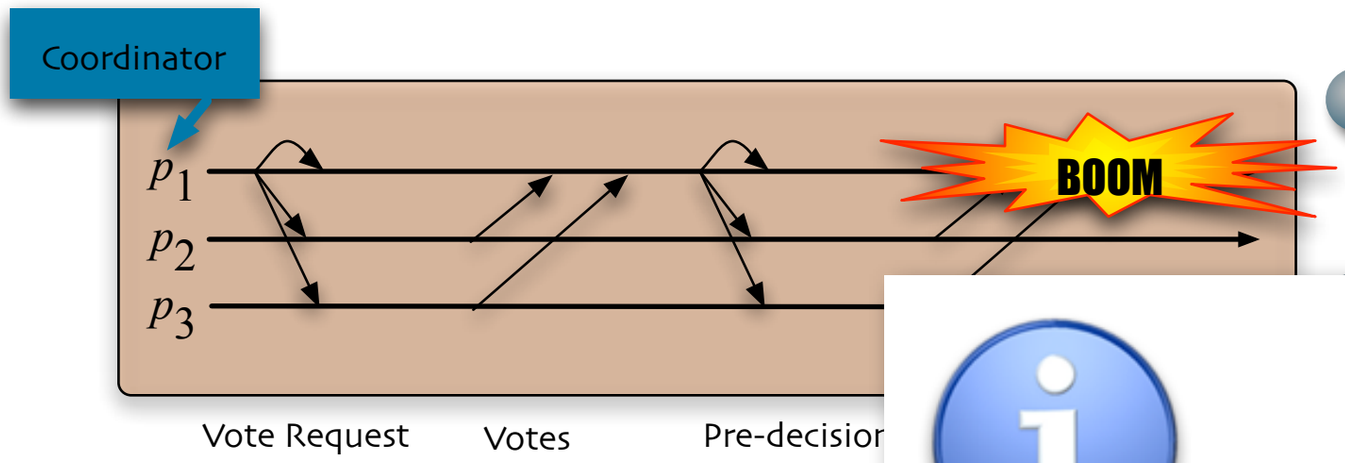

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OK
in Fail-Stop model

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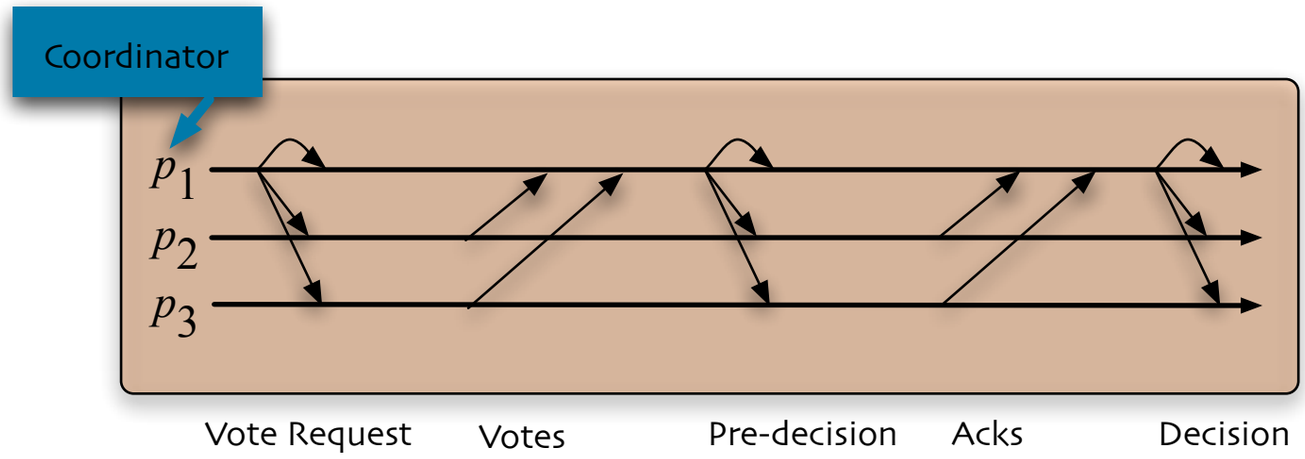

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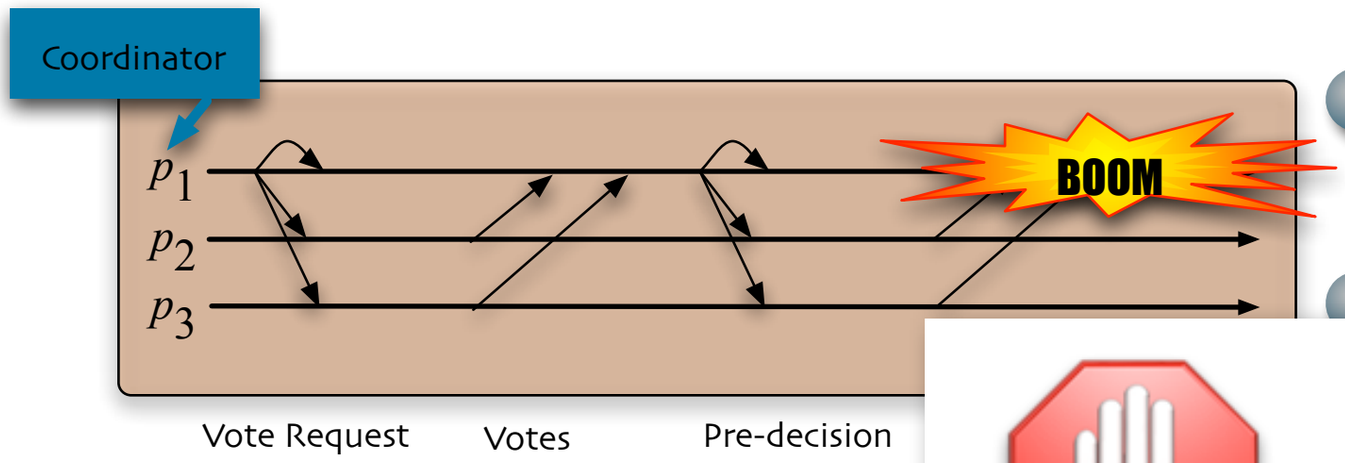

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Non terminating
in Crash-Stop model

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> Non-triviality: If all processes vote yes and no participant is ever suspected of failure then commit should be decided

[R. Guerraoui, Revisiting the relationship between non-blocking atomic commitment and consensus problems, 1995]

Consensus

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- The Consensus problem is usually seen as an abstraction of most distributed agreement problems

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- However, Consensus can be very hard to solve if one cannot accurately detect the failure of the processes

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When we cannot: FLP impossibility result

- "Impossibility of Distributed Consensus with One Faulty Process", Fischer, Lynch and Patterson in 1985:
  - In a "pure" asynchronous system (even) with reliable communication channels,
  - When (at least) some process may fail by crashing, forever ceasing its computation,
  - No deterministic algorithm can solve consensus
- Isn't such a result so counterintuitive?!

When we cannot: FLP impossibility result

- Consider an asynchronous system model, a finite set of processes P completely connected by reliable channels
- A process p is modeled through an input register ip, an output register op and an unbounded amount of internal storage. A configuration of the system consists of the internal state of each process, together with the contents of the message buffer.
- Processes take deterministic events (p, m) determined by the messages they receive. A schedule from a configuration C is a finite or infinite sequence of events that can be applied, in turn, starting from C.

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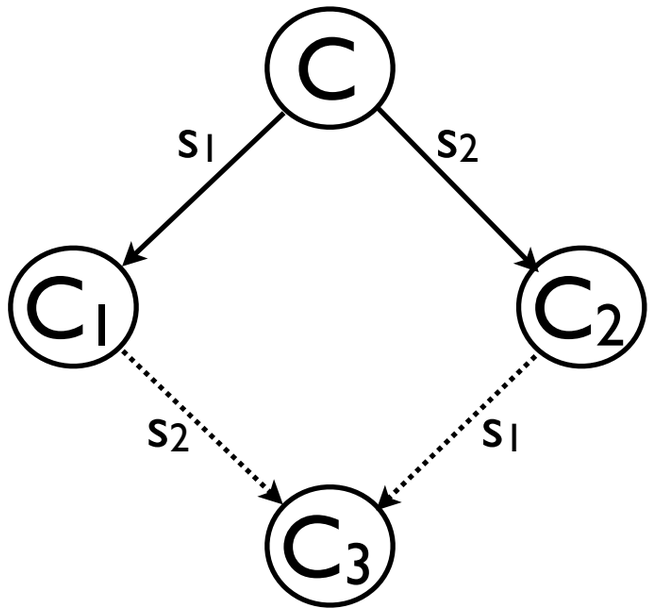

- Suppose that from some configuration C, the schedules s1, s2 lead to configurations C1, C2, respectively. If the sets of processes taking steps in s1 and s2, respectively, are disjoint, then s2 can be applied to C1 and s1 can be applied to C2, and both lead to the same configuration C3.

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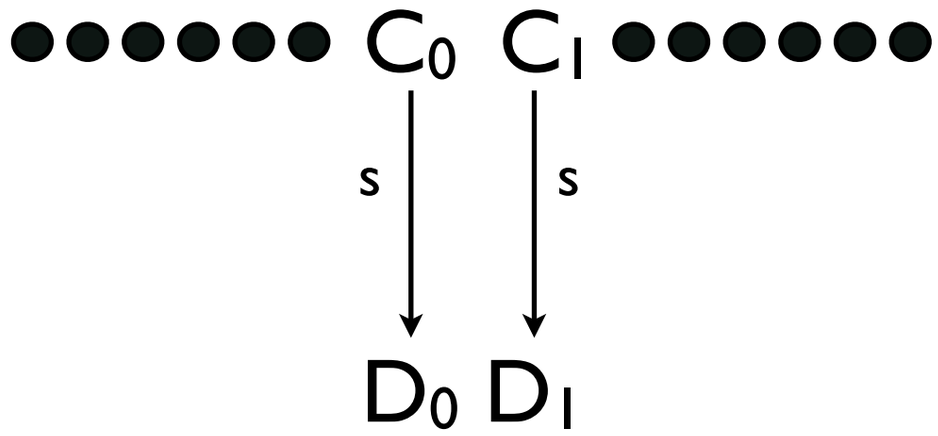

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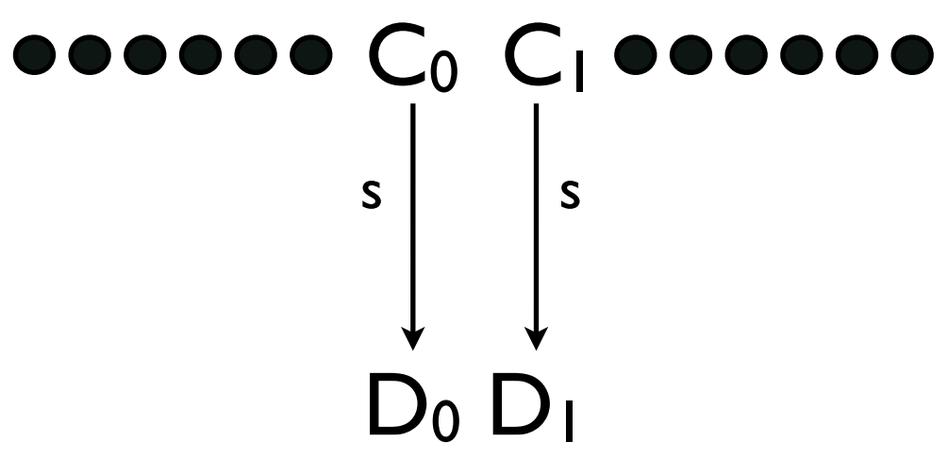

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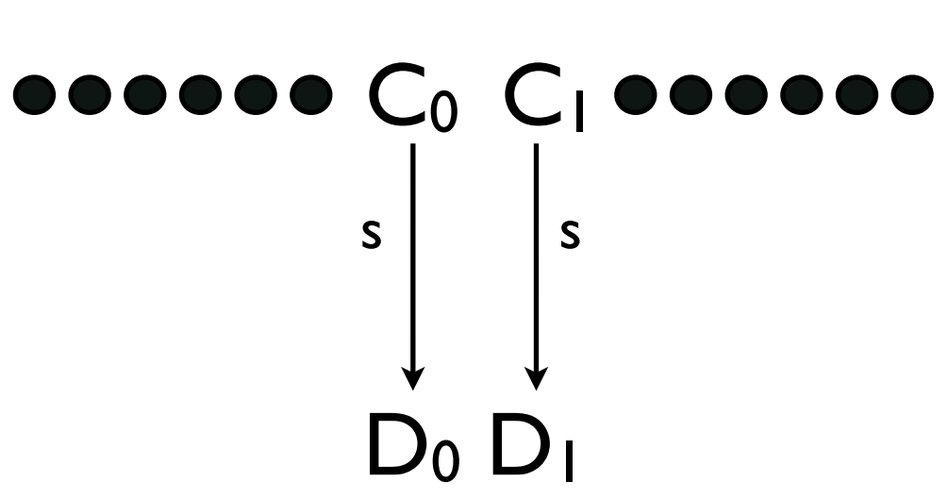

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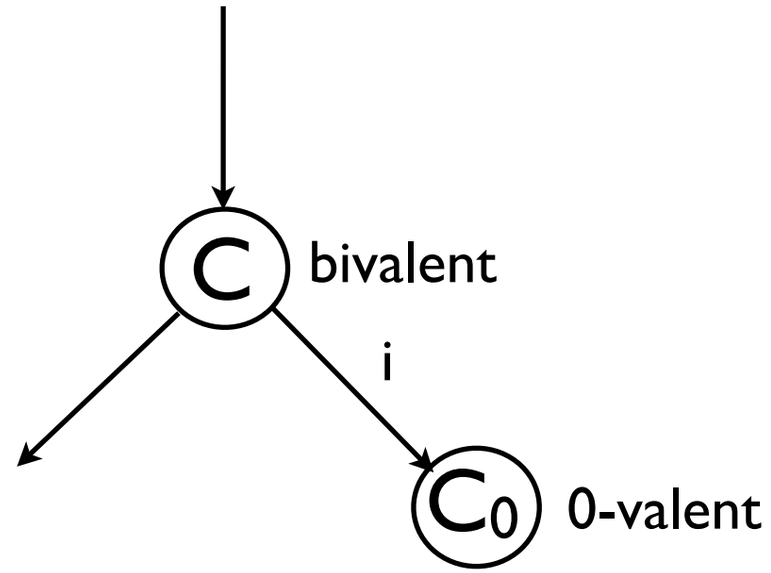
- S is a deciding schedule applicable both to C0 and to C1
- The decision at D0 and D1 must be the same. This implies that either C0 or C1 is bivalent!

When we cannot: FLP impossibility result

- Any deciding schedule eventually forks a bivalent into a univalent configuration:



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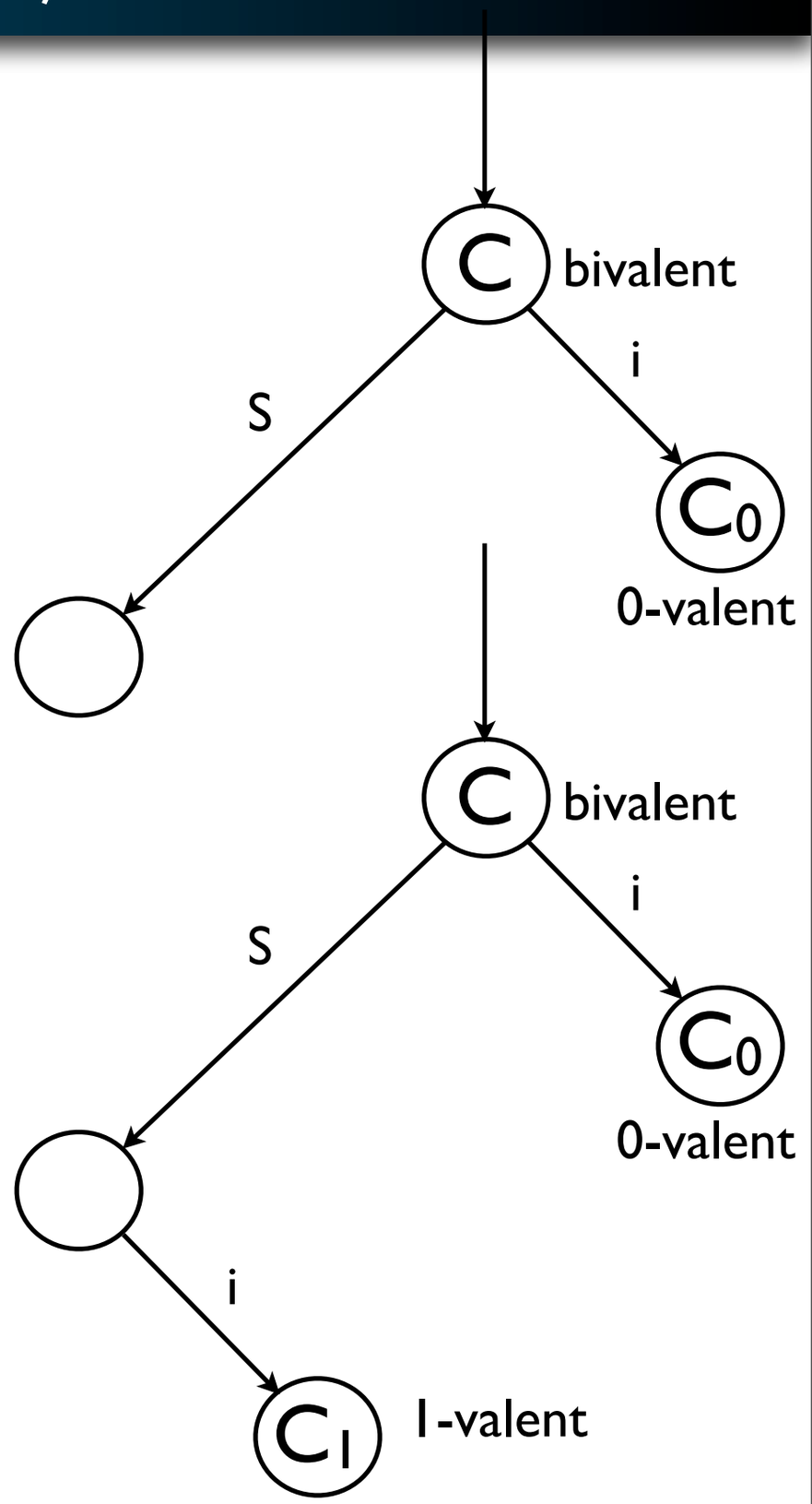

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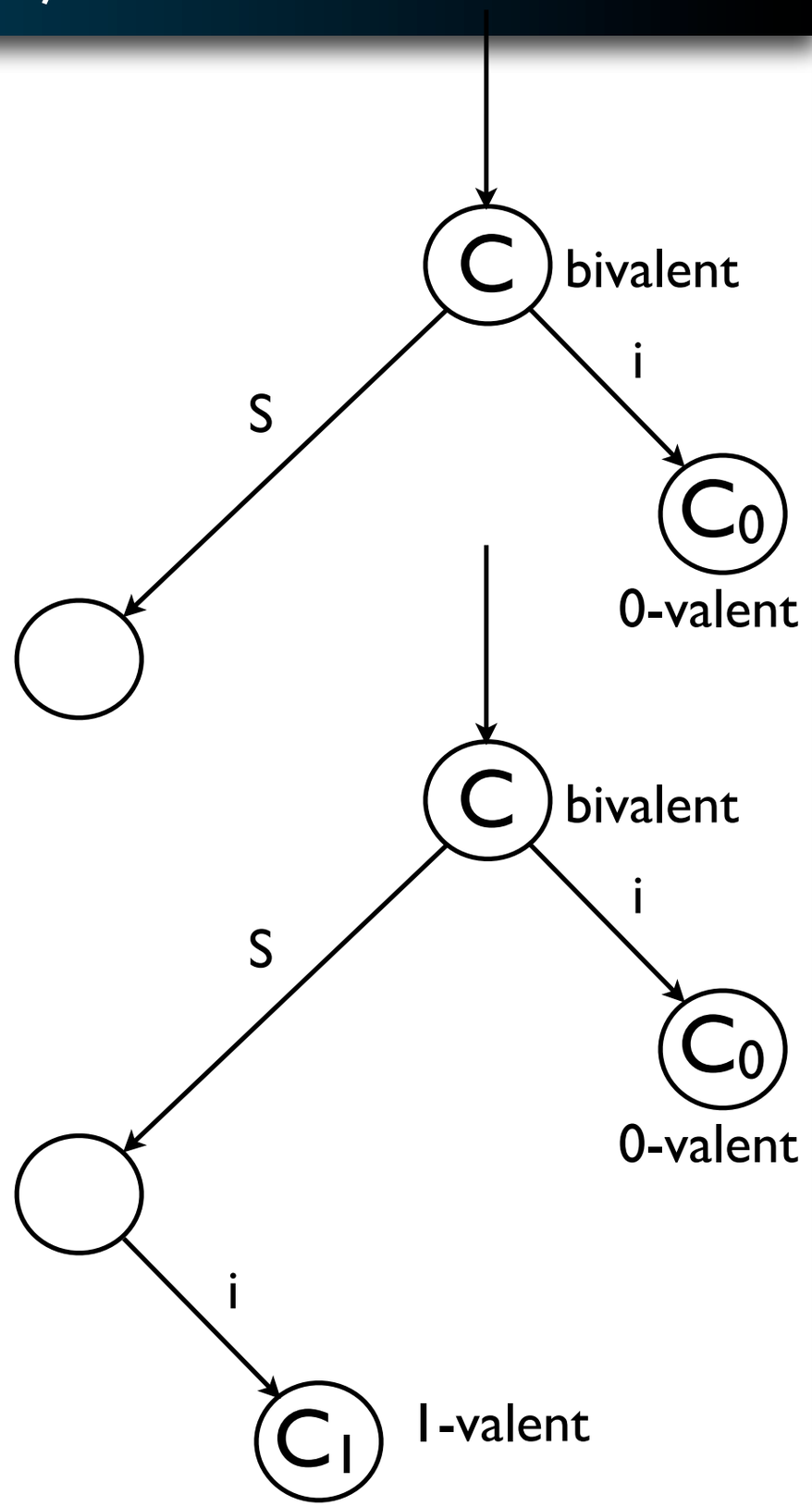

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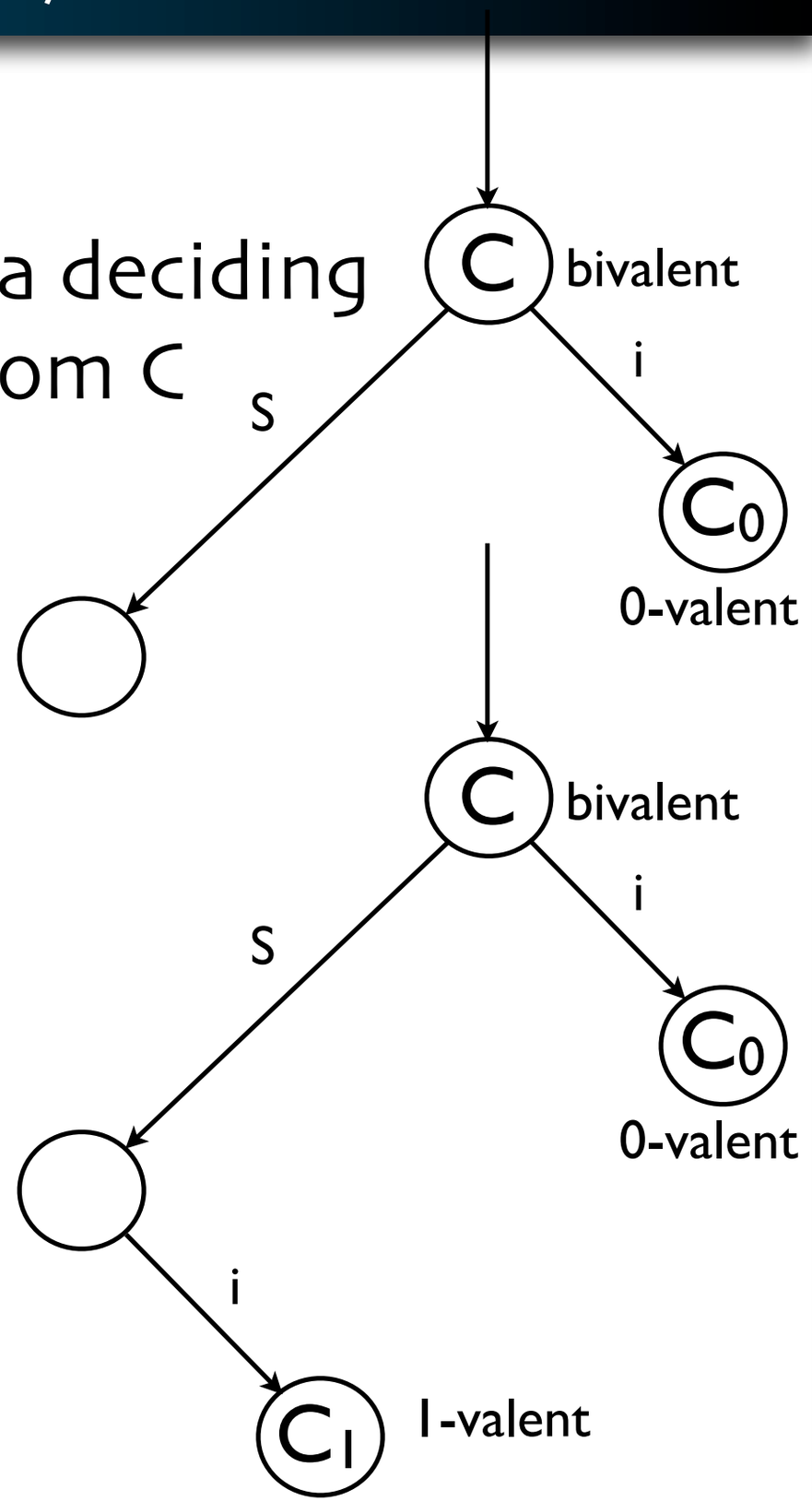

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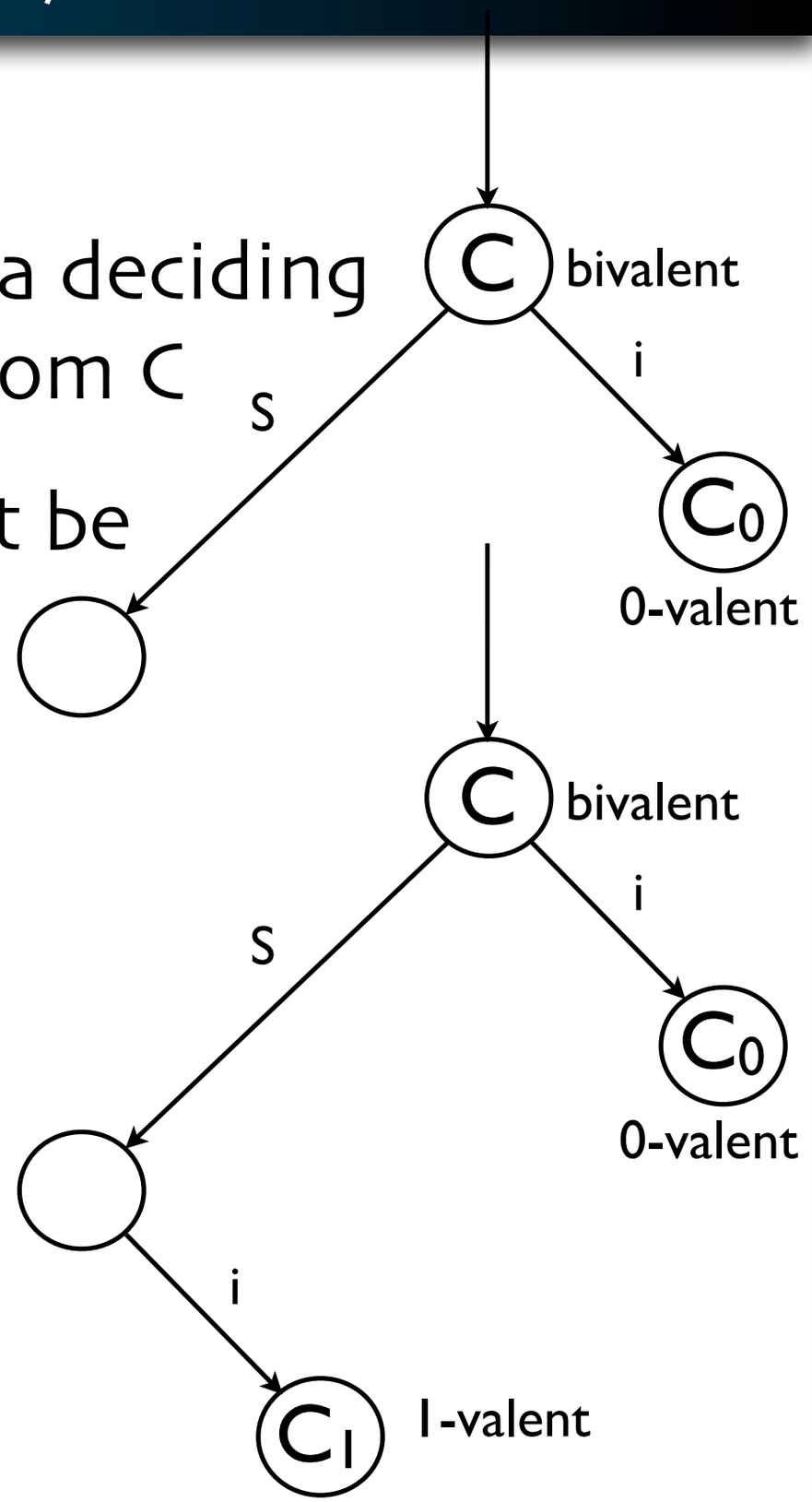

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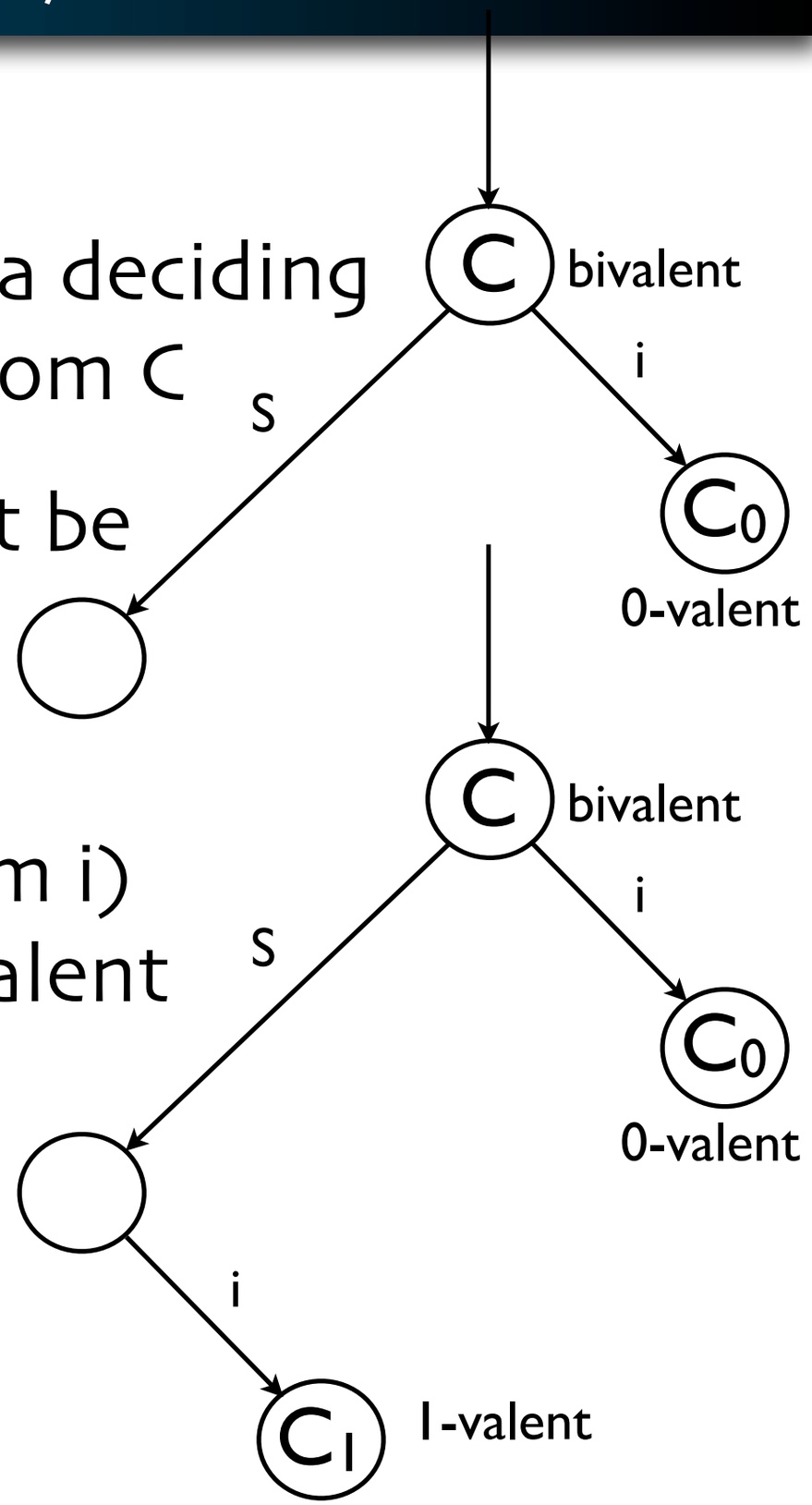
- Since C is bivalent there must be some schedule S (without steps from i) after which applying i leads to a 1-valent configuration (a "Hook"). But since S can be applied do C_0 this leads to a contradiction!



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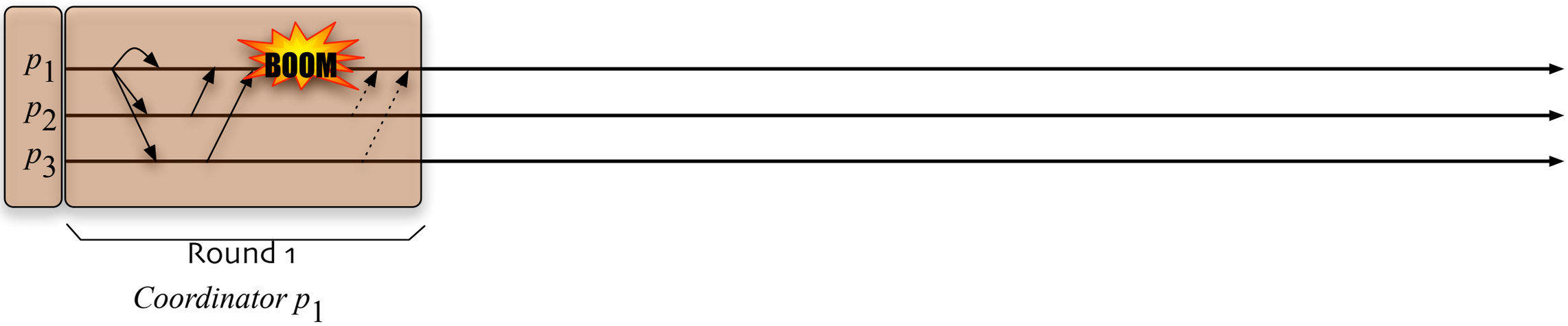

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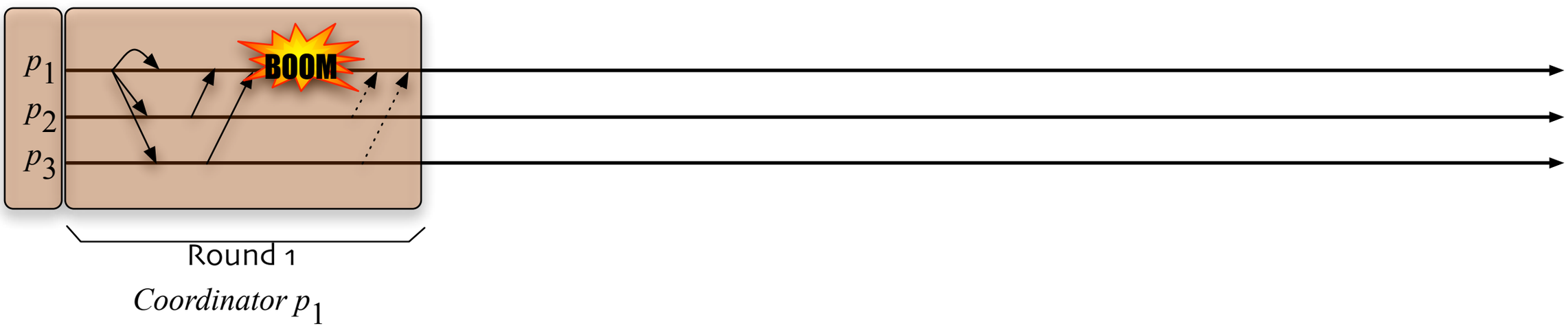

Participants suspect the coordinator.

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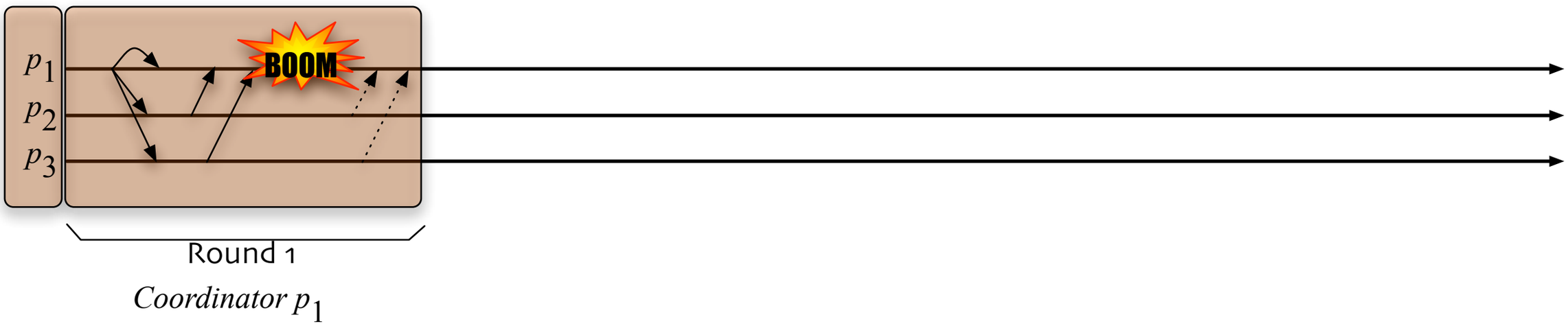

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Conundrum: shall I stay or shall I go?

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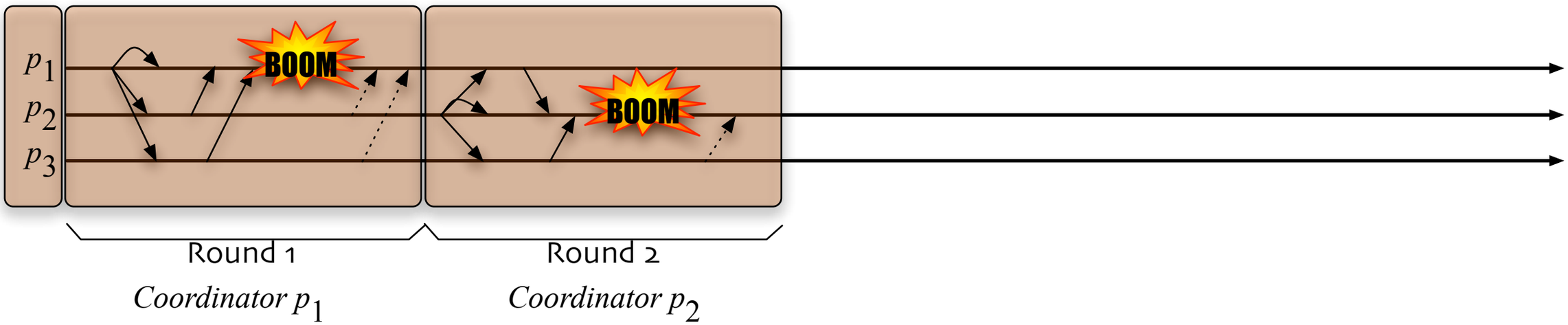

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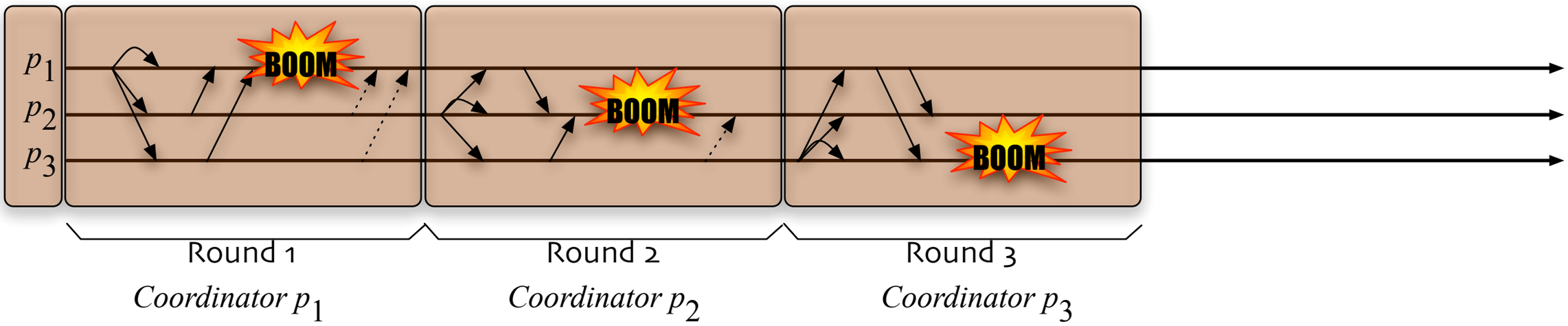

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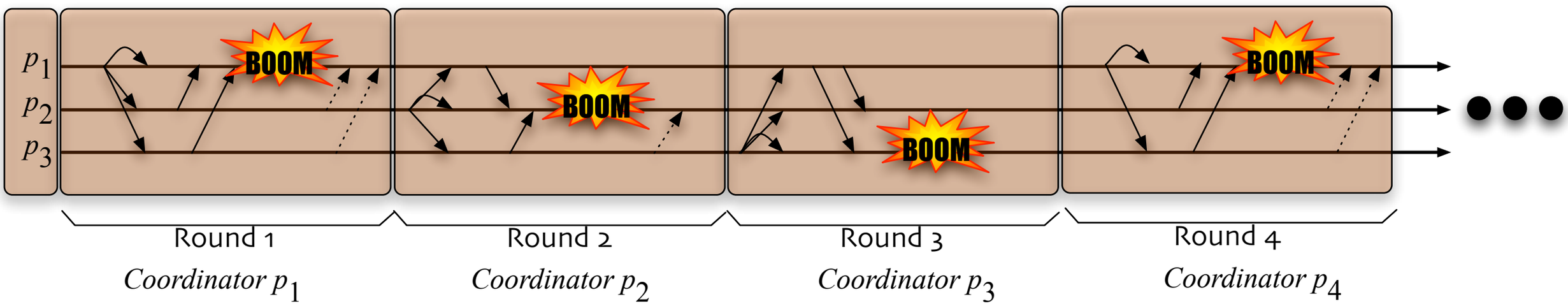

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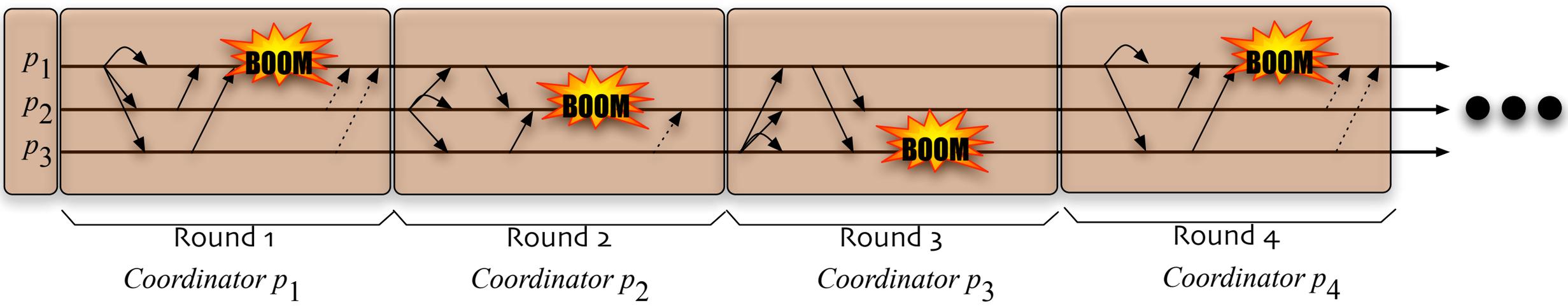

- ... ending up with the Chandra & Toueg's algorithm which is based on a Failure Detector Oracle

Unreliable failure detectors for reliable distributed systems, T. Chandra and S. Toueg, JACM, 1996

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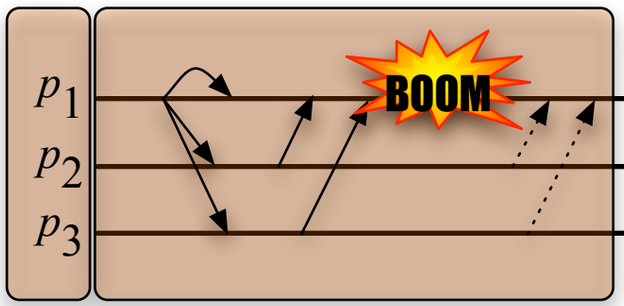

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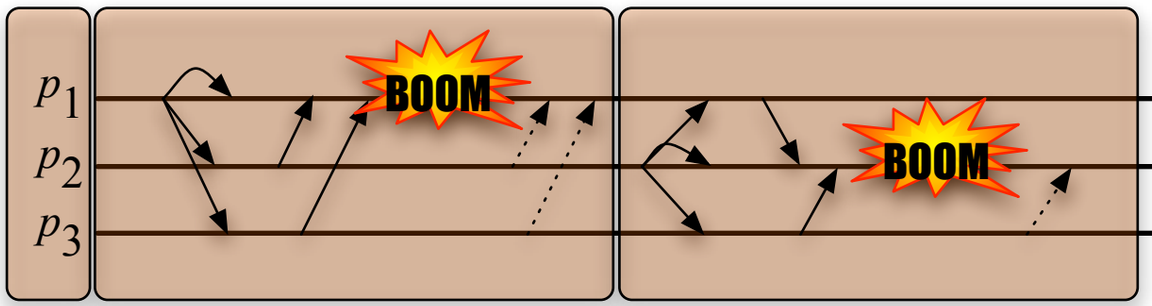

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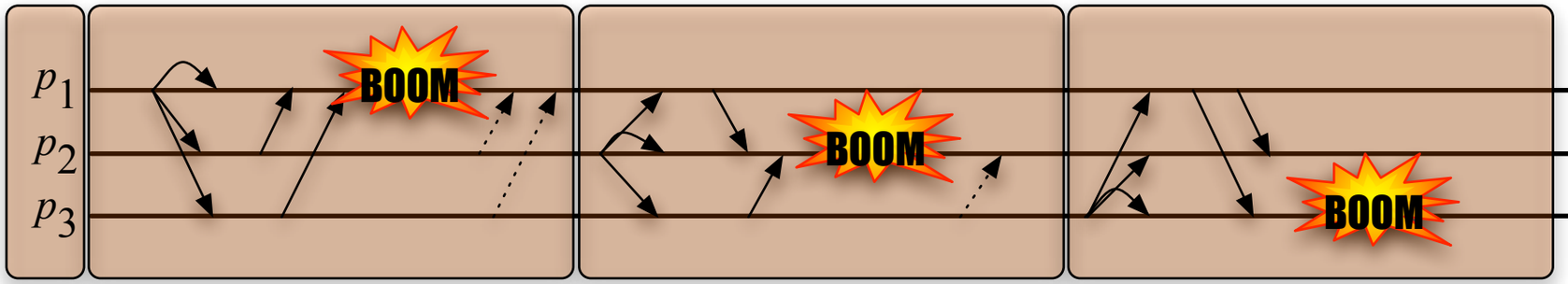

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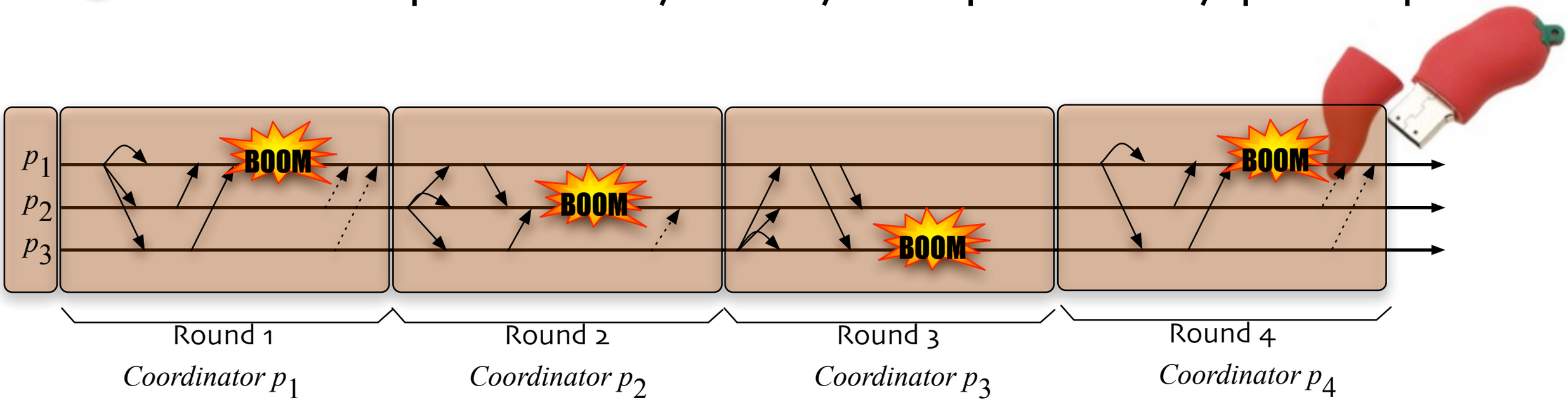

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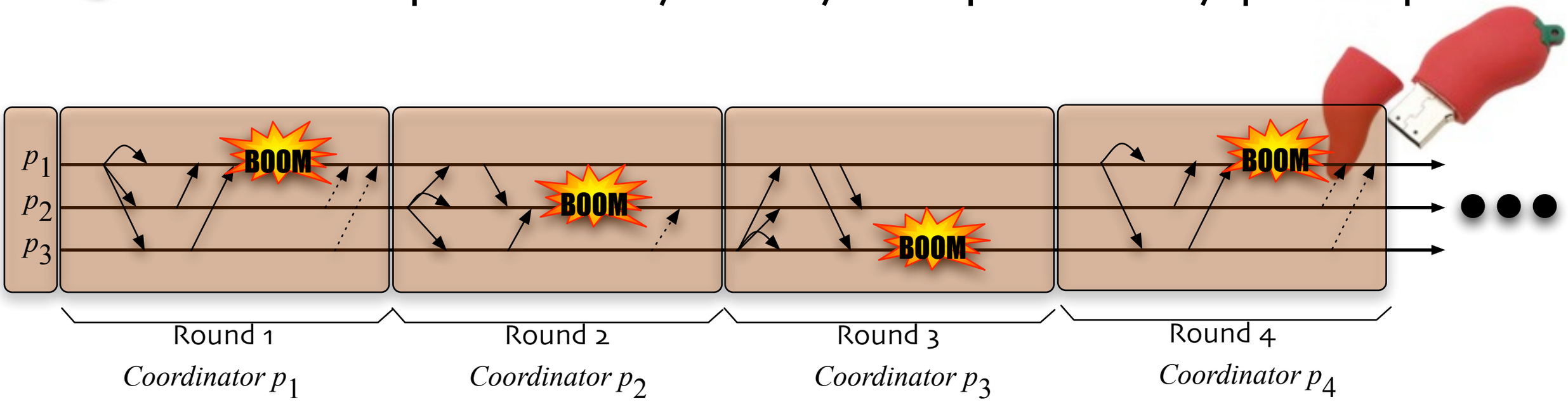

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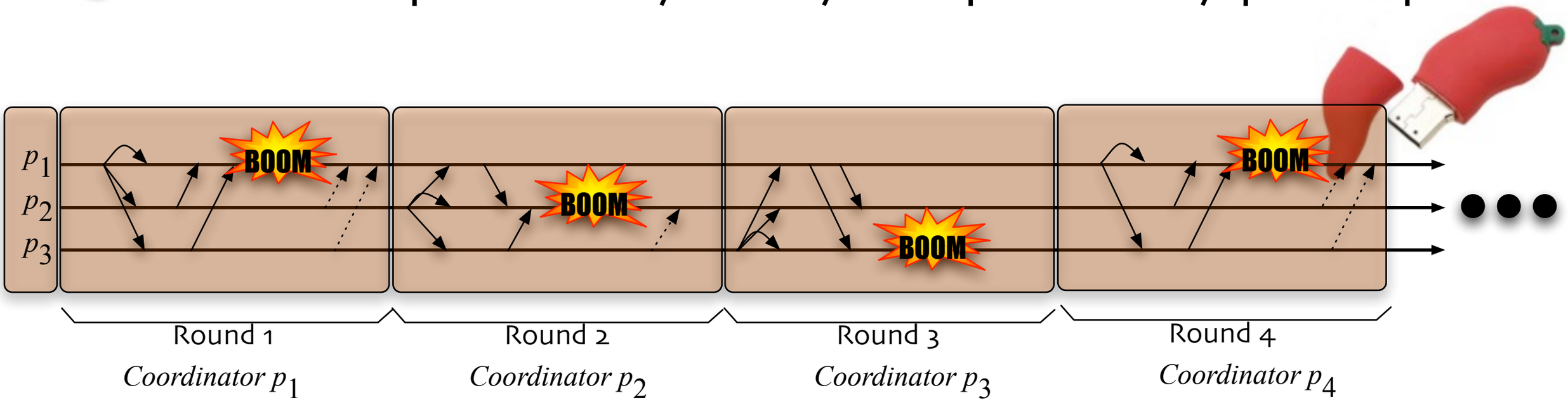

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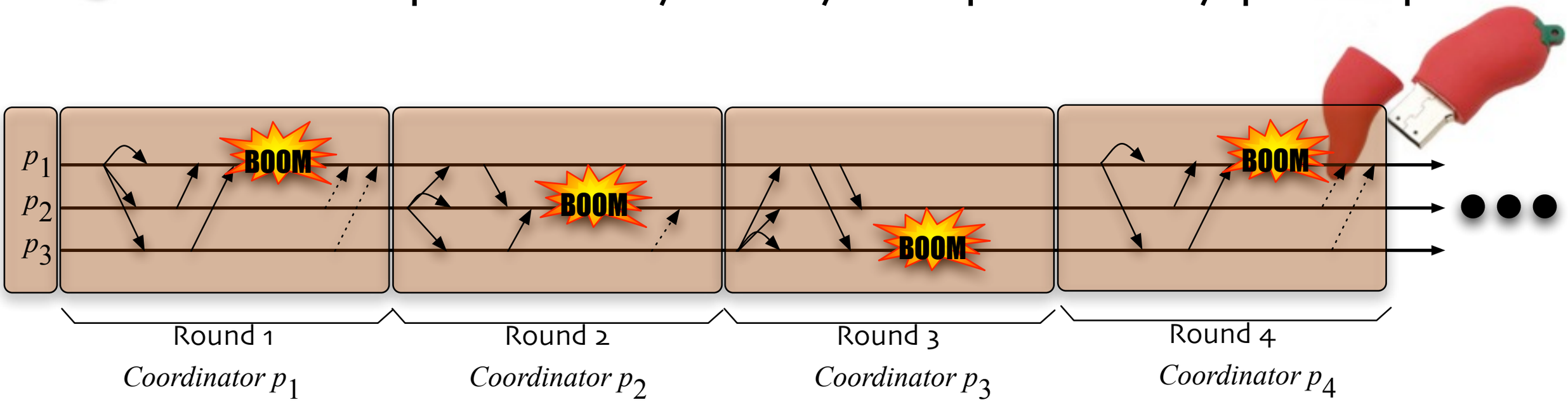

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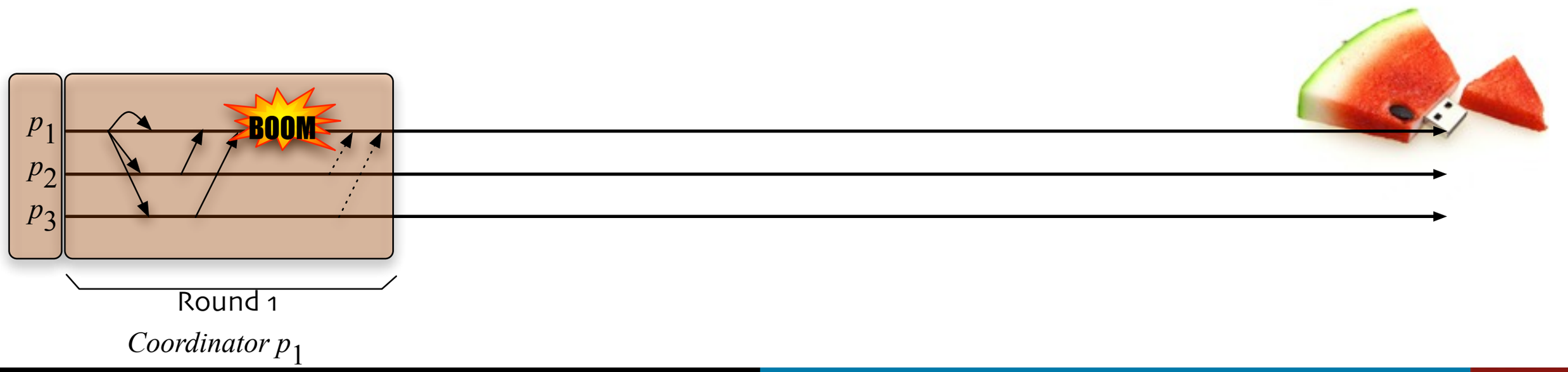

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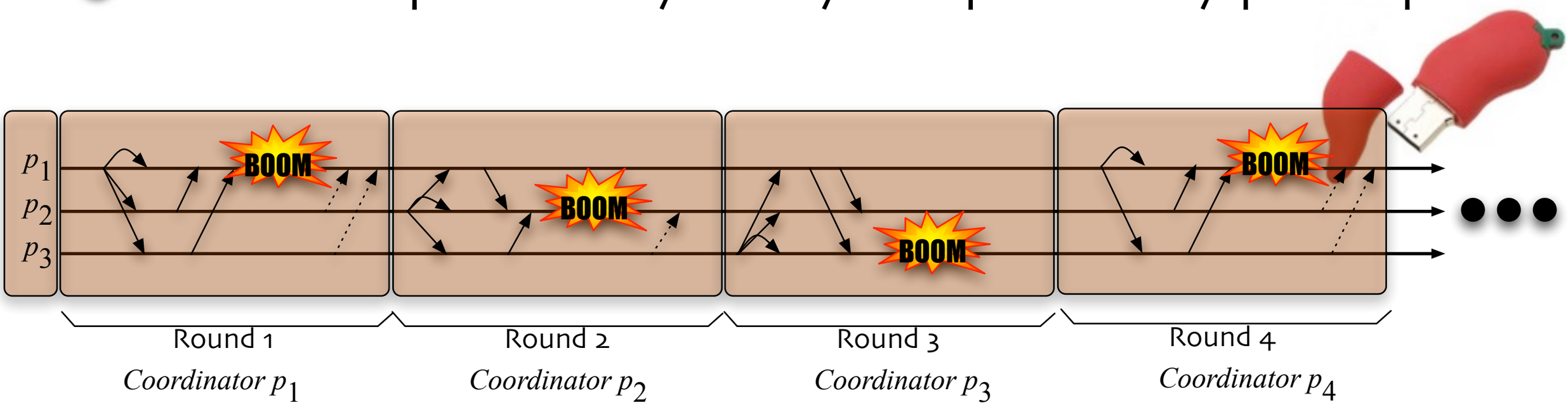

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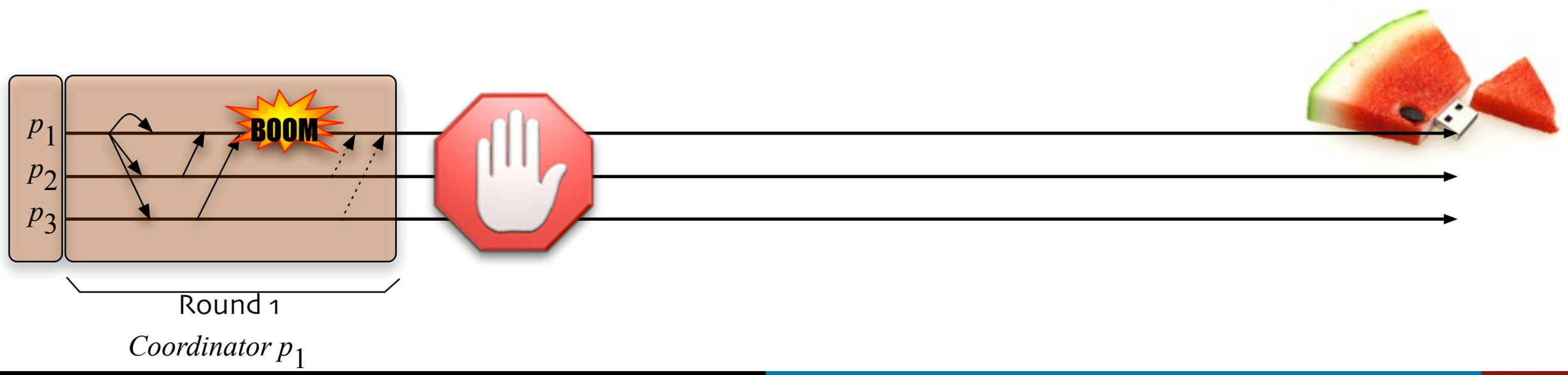

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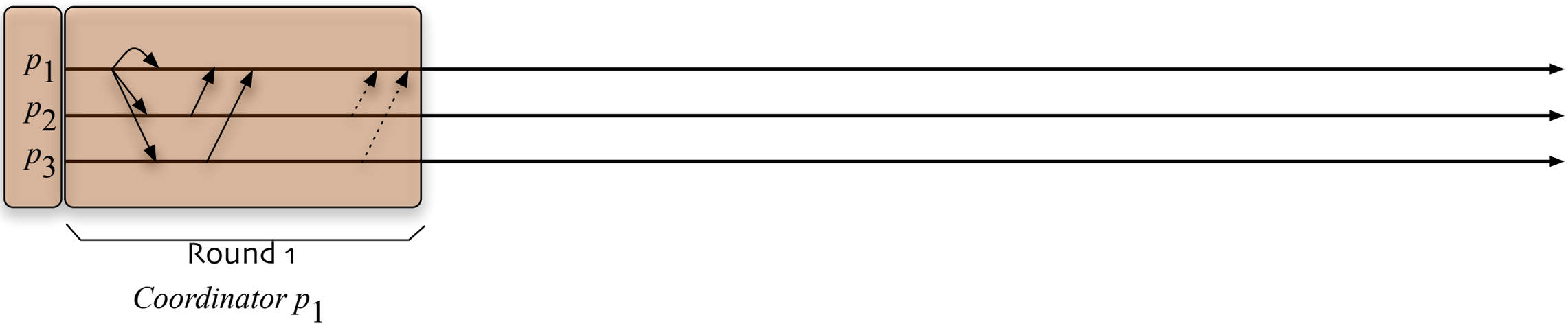

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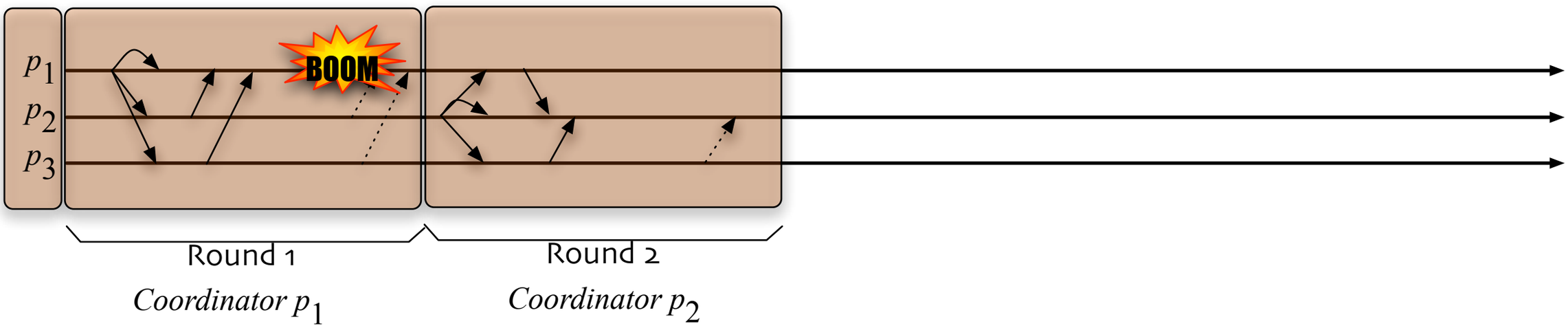

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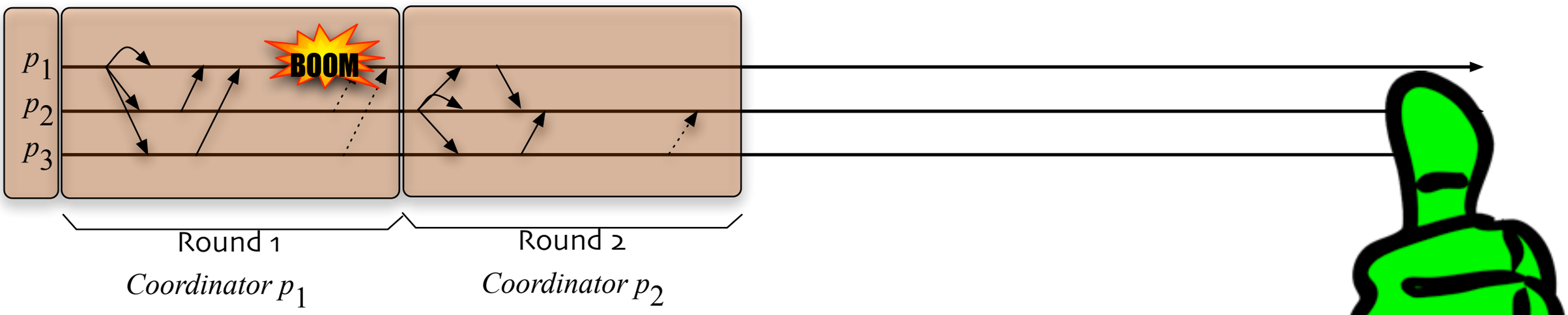

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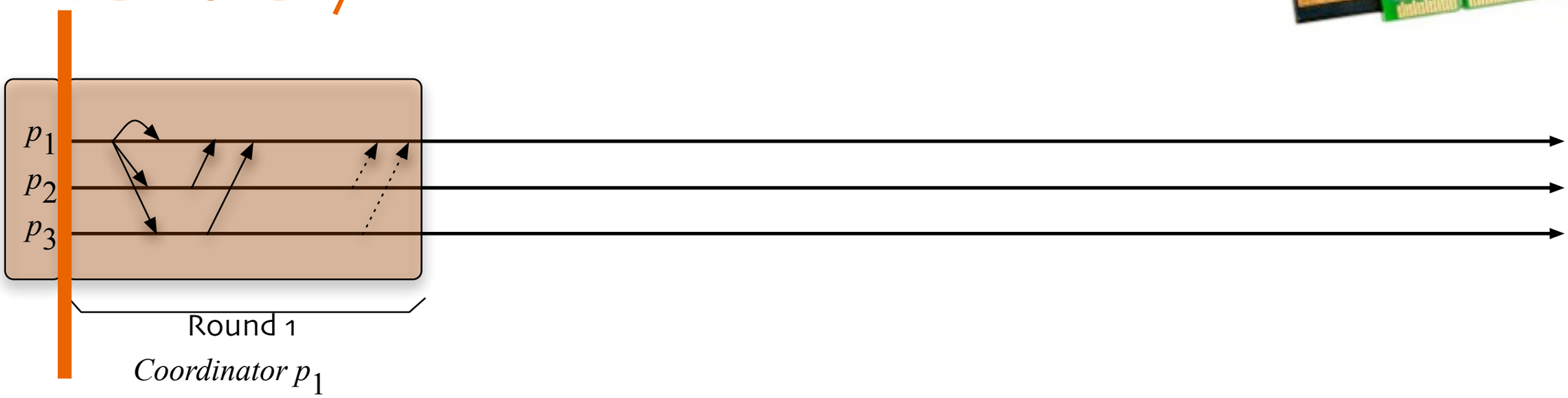

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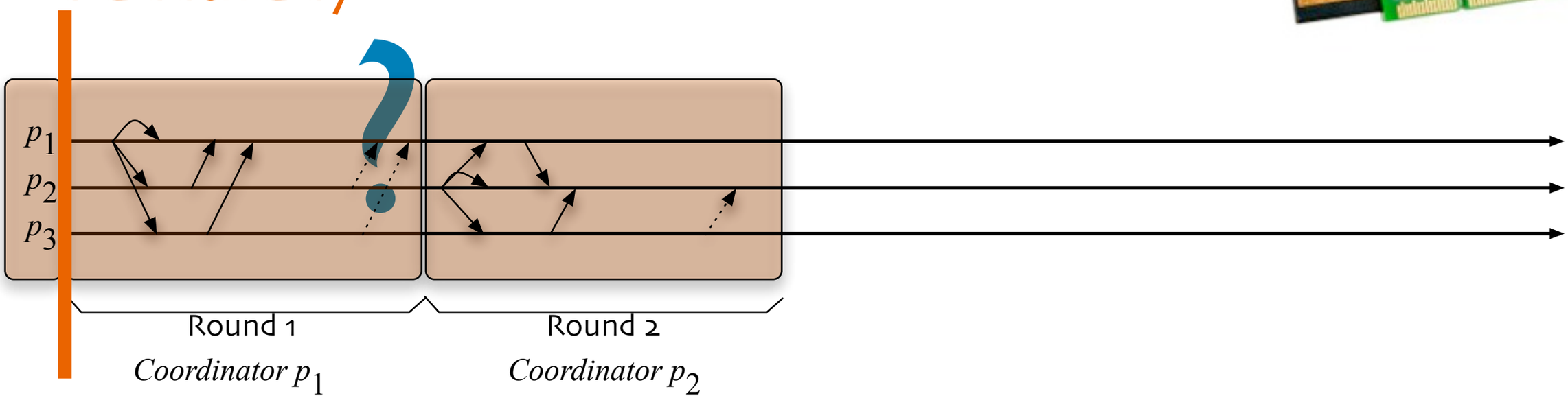

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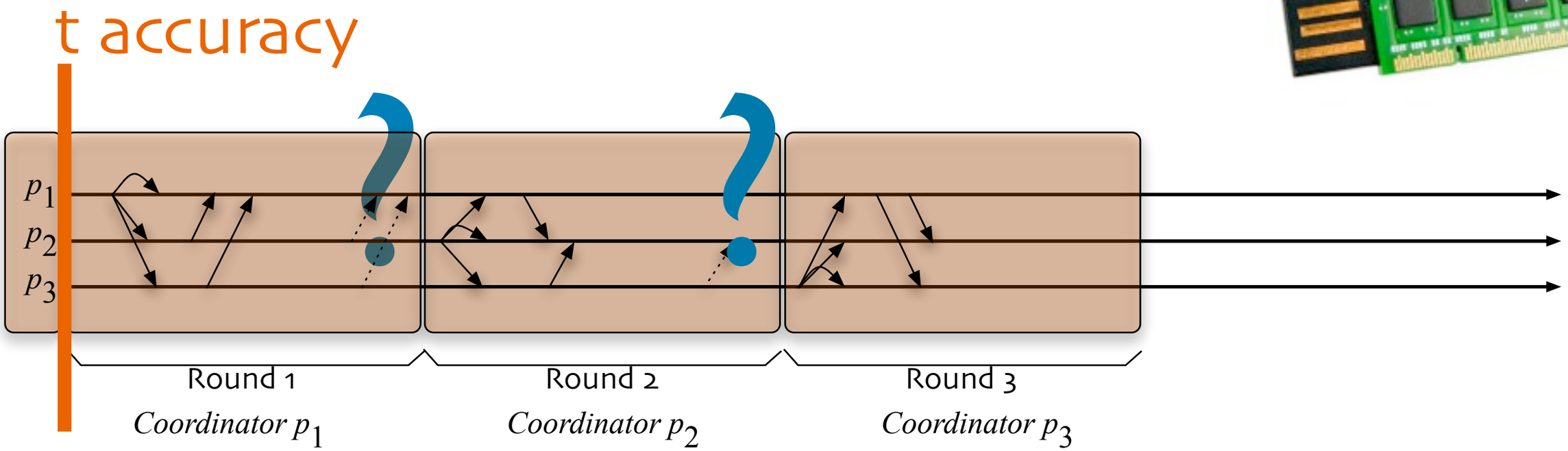

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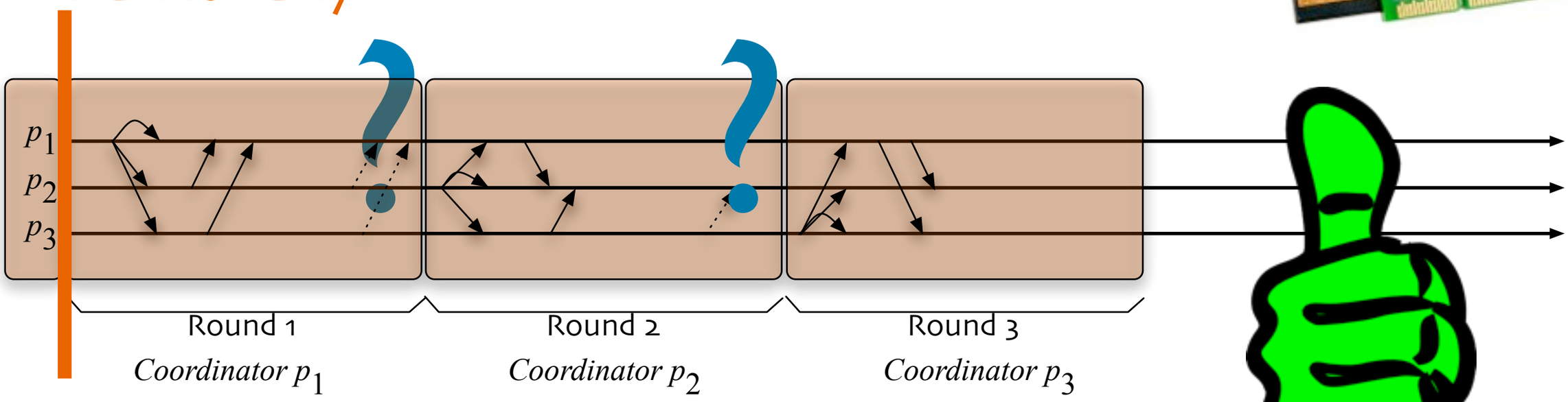

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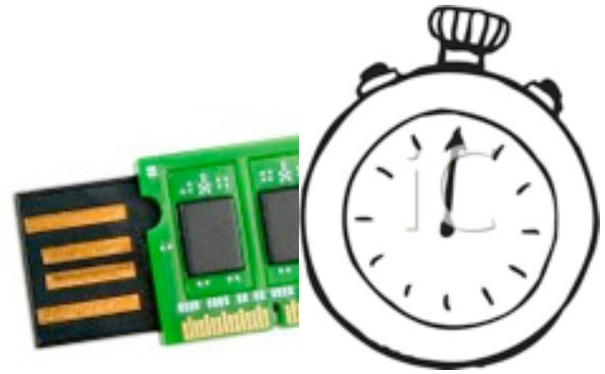

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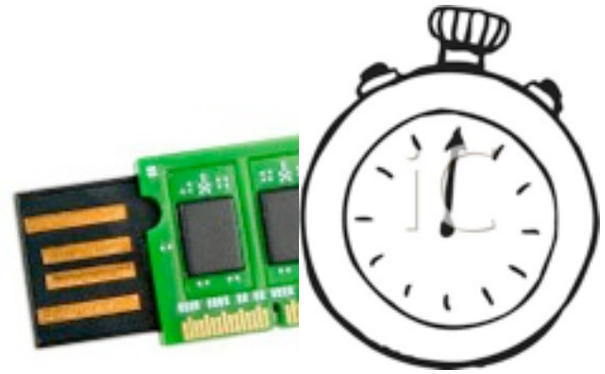

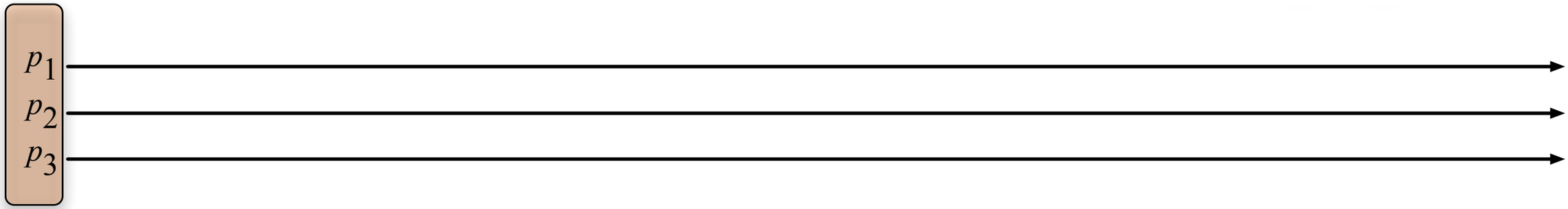

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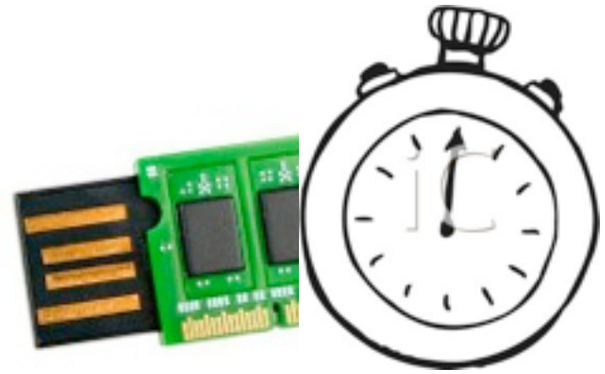

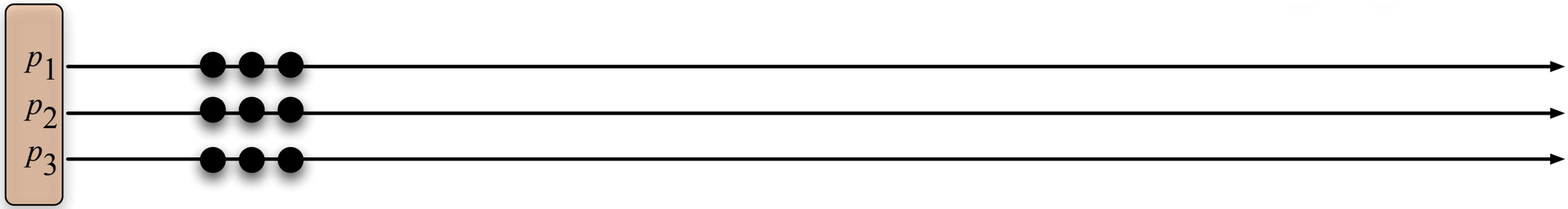

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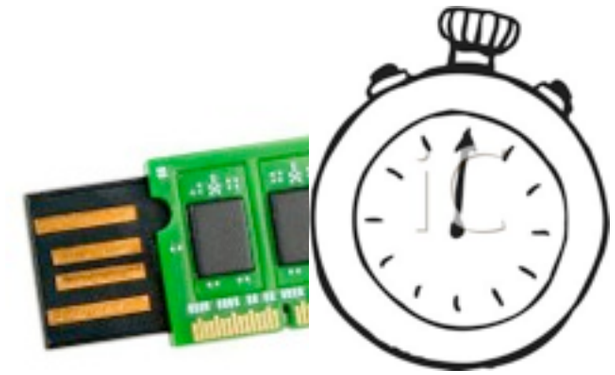

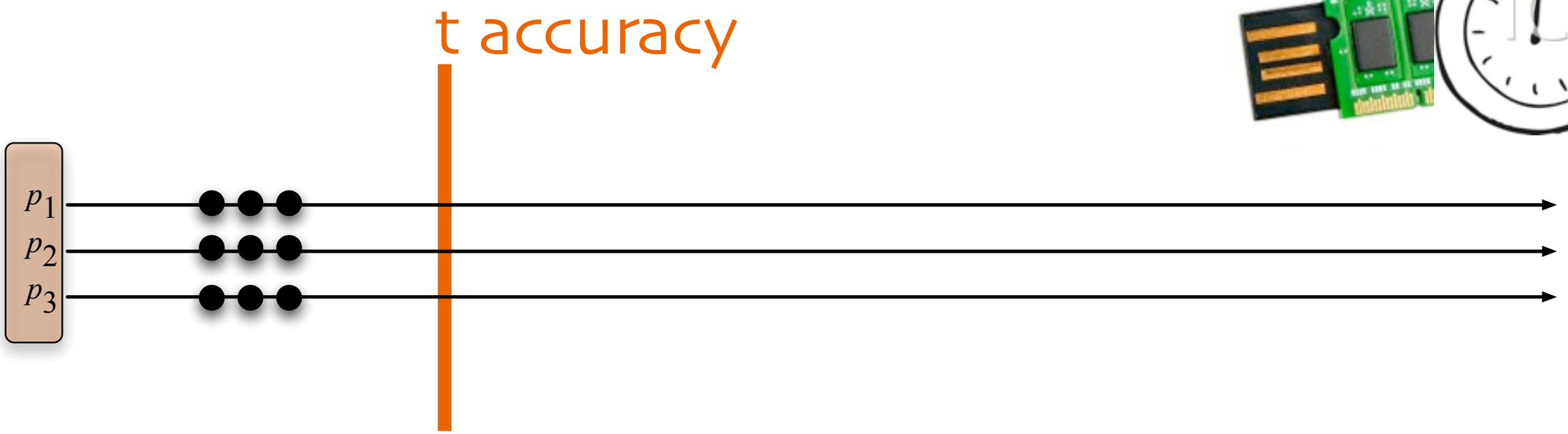

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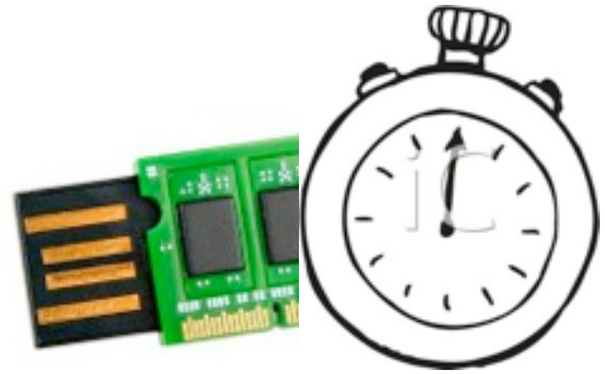

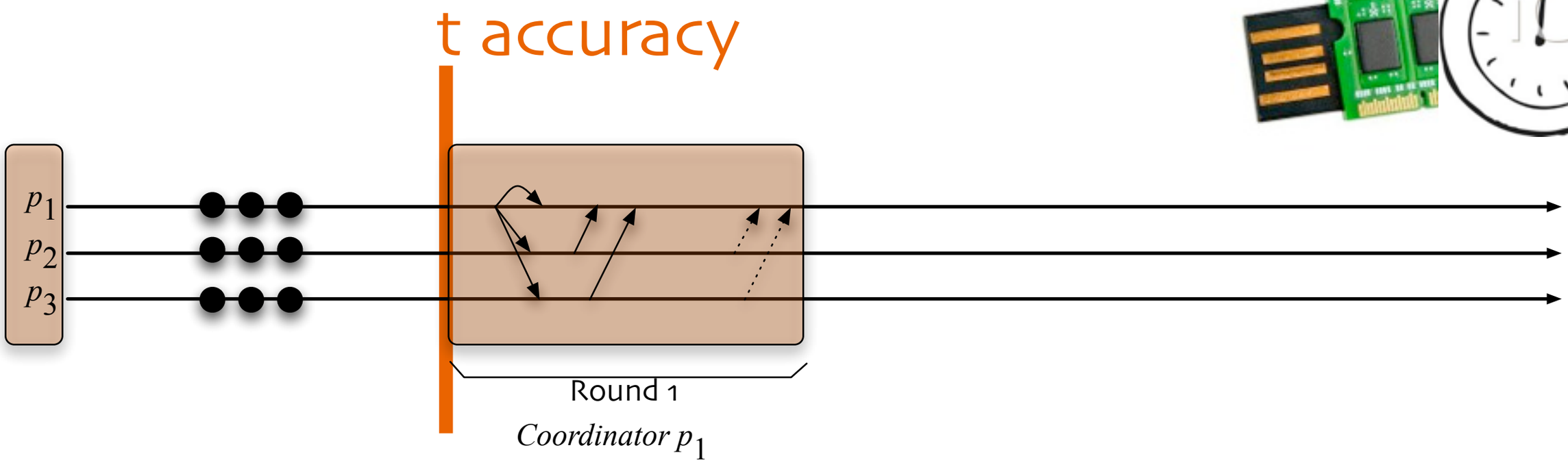

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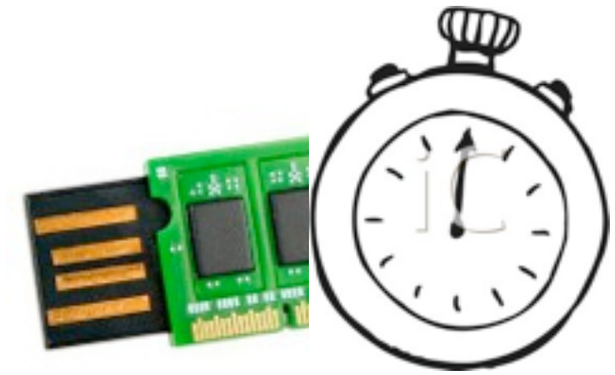

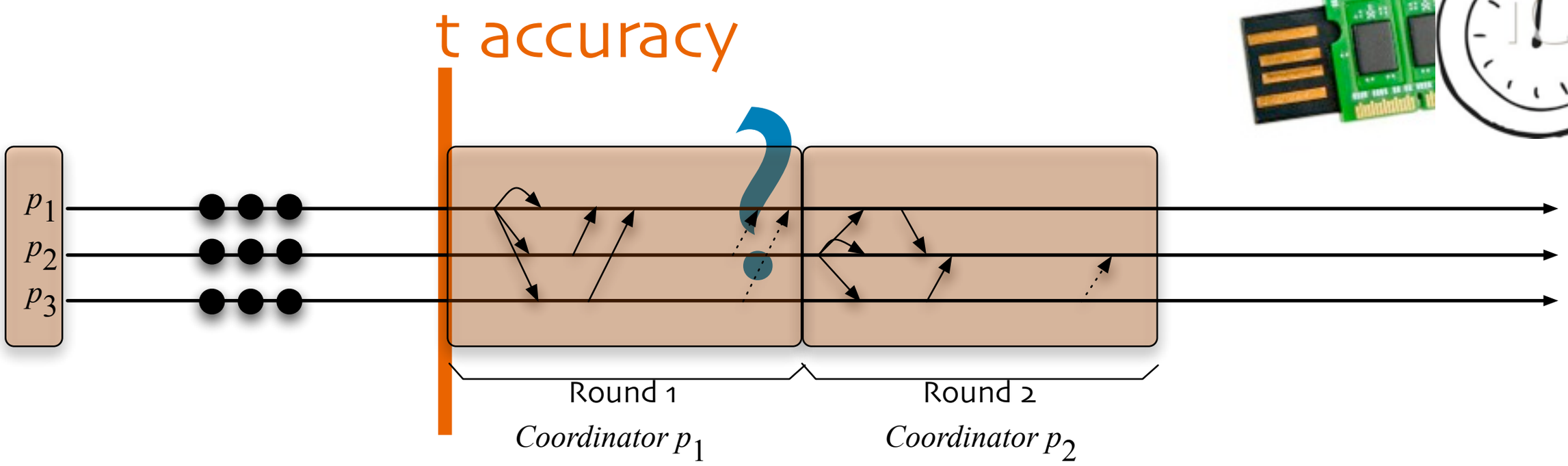

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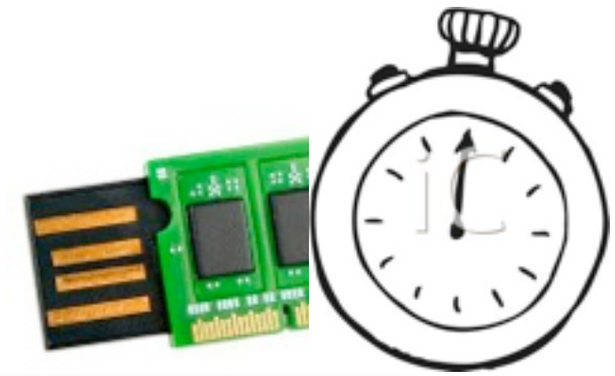

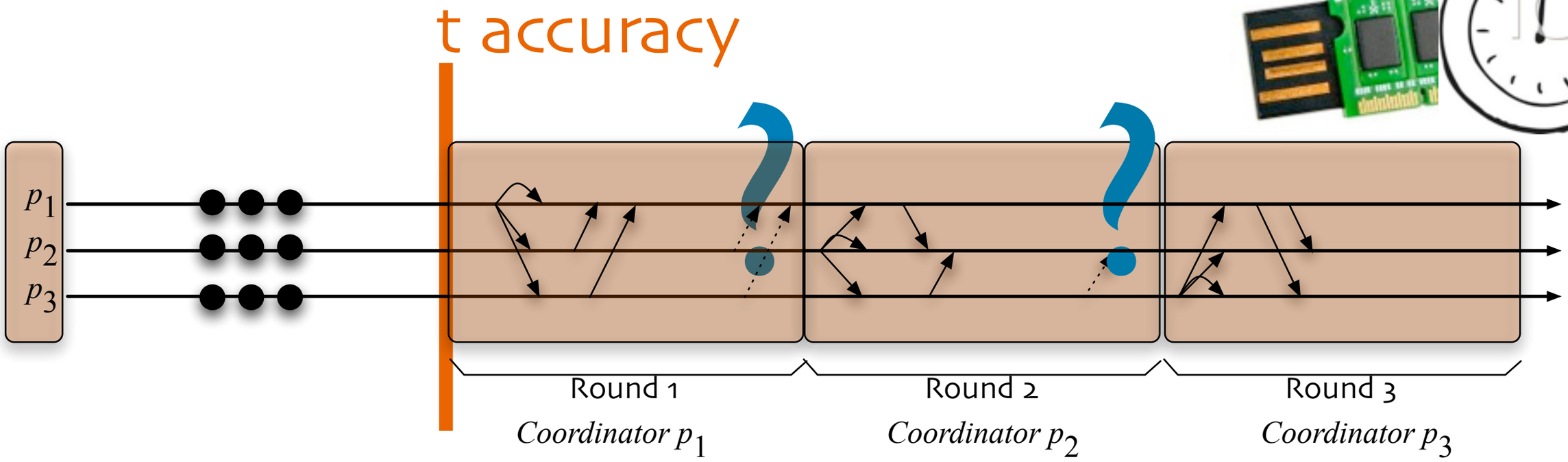

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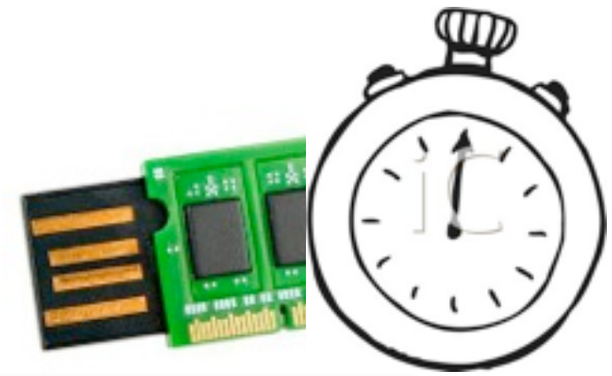

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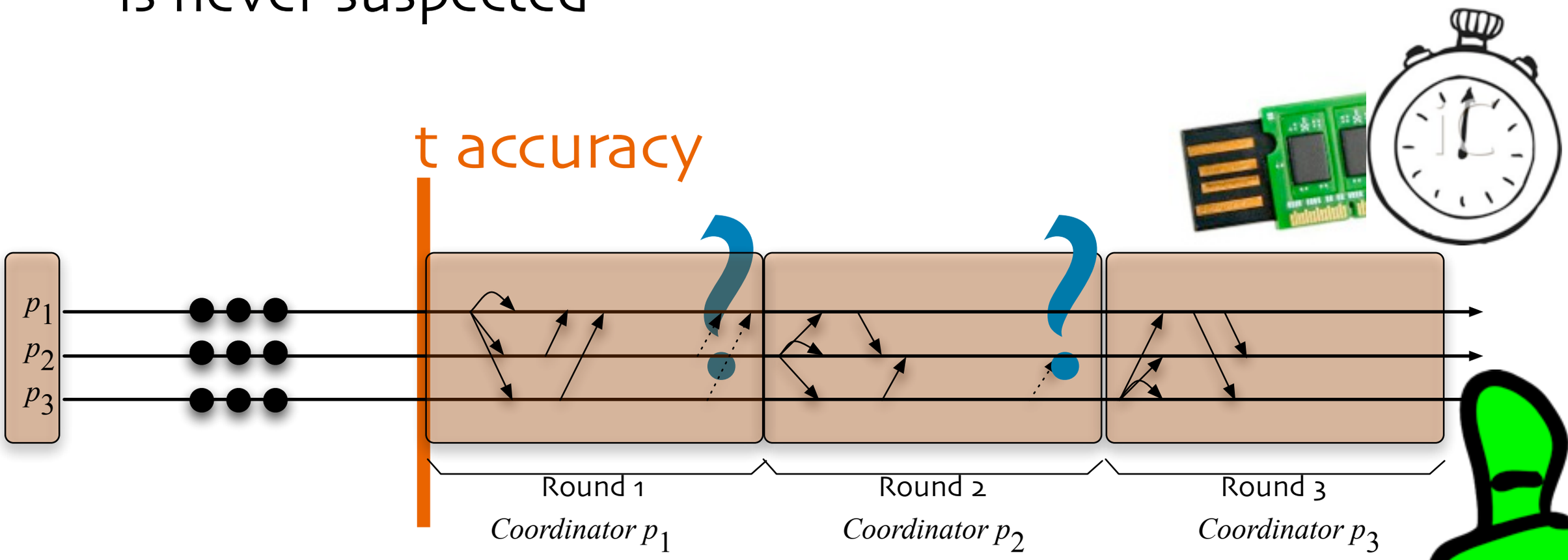
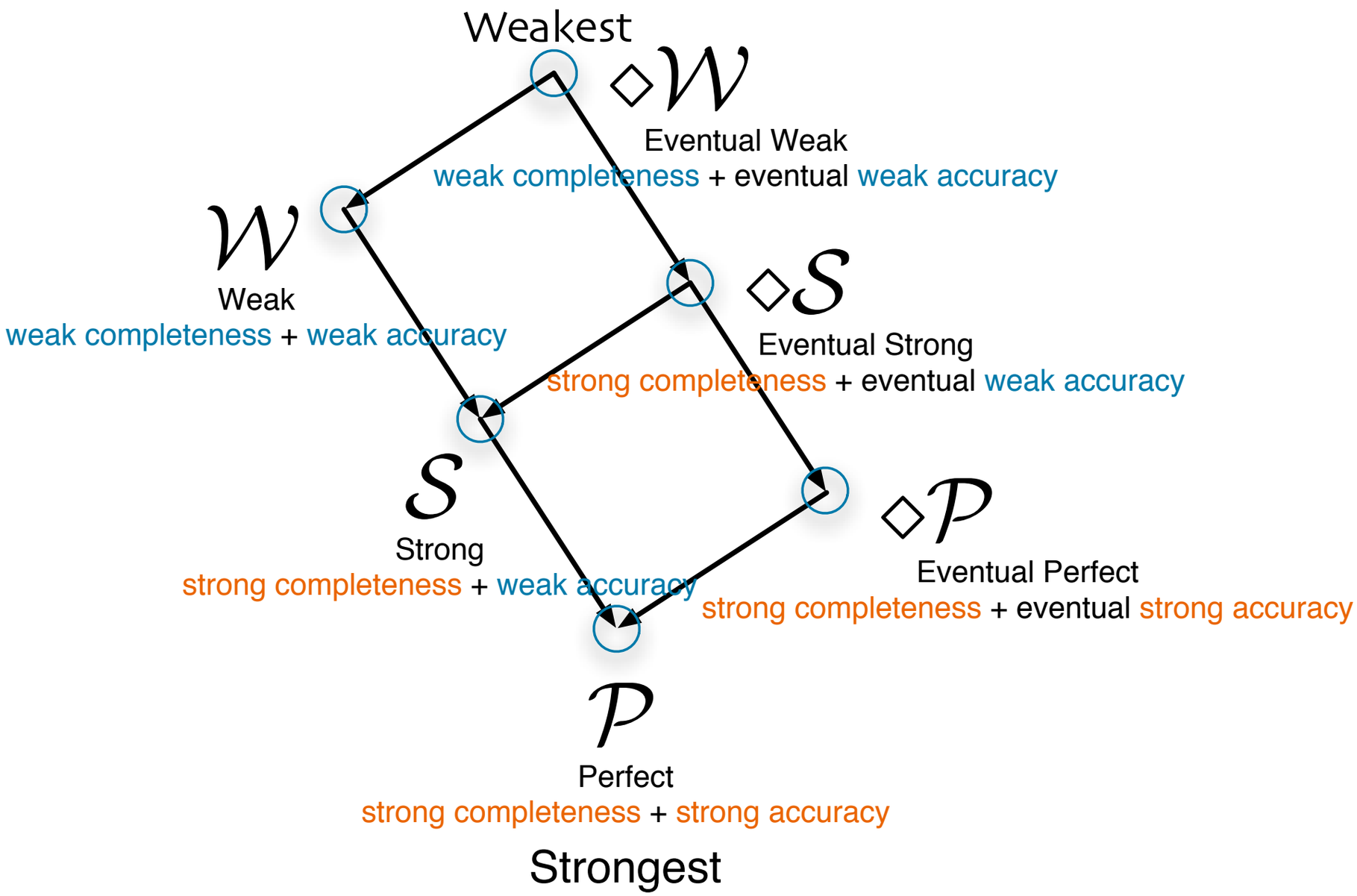


- Why is Strong Completeness required?

A lattice of failure detector classes



[V. Hadzilacos, S. Toueg and T. Chandra, The weakest failure detector for solving consensus, 1996.]

Consensus

Chandra & Toueg Algorithm

procedure $propose(v_p)$
  $estimate_p \leftarrow v_p$ $\{estimate_p \text{ is } p\text{'s estimate of the decision value}\}$
  $state_p \leftarrow undecided$
  $r_p \leftarrow 0$ $\{r_p \text{ is } p\text{'s current round number}\}$
  $ts_p \leftarrow 0$ $\{ts_p \text{ is the last round in which } p \text{ updated } estimate_p, \text{ initially } 0\}$

  $\{Rotate\ through\ coordinators\ until\ decision\ is\ reached\}$

  while $state_p = undecided$
    $r_p \leftarrow r_p + 1$
    $c_p \leftarrow (r_p \bmod n) + 1$ $\{c_p \text{ is the current coordinator}\}$

Consensus

Chandra & Toueg Algorithm

Phase 1: {*All processes p send* $estimate_p$ *to the current coordinator*}
send $(p, r_p, estimate_p, ts_p)$ to c_p

Phase 2: {*The current coordinator gathers* $\lceil \frac{(n+1)}{2} \rceil$ *estimates and proposes a new estimate*}
if $p = c_p$ **then**
wait until [for $\lceil \frac{(n+1)}{2} \rceil$ processes q : received $(q, r_p, estimate_q, ts_q)$ from q]
$msgs_p[r_p] \leftarrow \{(q, r_p, estimate_q, ts_q) \mid p$ received $(q, r_p, estimate_q, ts_q)$ from $q\}$
$t \leftarrow$ largest ts_q such that $(q, r_p, estimate_q, ts_q) \in msgs_p[r_p]$
$estimate_p \leftarrow$ select one $estimate_q$ such that $(q, r_p, estimate_q, t) \in msgs_p[r_p]$
send $(p, r_p, estimate_p)$ to all

Consensus

Chandra & Toueg Algorithm

Phase 3: $\{$*All processes wait for the new estimate proposed by the current coordinator*$\}$

wait until [received $(c_p, r_p, estimate_{c_p})$ from c_p **or** $c_p \in \mathcal{D}_p$]$\{$*Query the failure detector*$\}$

if [received $(c_p, r_p, estimate_{c_p})$ from c_p] **then** $\{p$ *received* $estimate_{c_p}$ *from* $c_p\}$

$estimate_p \leftarrow estimate_{c_p}$

$ts_p \leftarrow r_p$

send (p, r_p, ack) to c_p

else send $(p, r_p, nack)$ to c_p $\{p$ *suspects that* c_p *crashed*$\}$

Phase 4: $\left\{ \begin{array}{l} \textit{The current coordinator waits for } \lceil \frac{(n+1)}{2} \rceil \textit{ replies. If they indicate that } \lceil \frac{(n+1)}{2} \rceil \\ \textit{processes adopted its estimate, the coordinator R-broadcasts a decide message} \end{array} \right\}$

if $p = c_p$ **then**

wait until [for $\lceil \frac{(n+1)}{2} \rceil$ processes q : received (q, r_p, ack) **or** $(q, r_p, nack)$]

if [for $\lceil \frac{(n+1)}{2} \rceil$ processes q : received (q, r_p, ack)] **then**

$R\text{-}broadcast(p, r_p, estimate_p, decide)$

Consensus

Chandra & Toueg Algorithm

$\{If\ p\ R\text{-}delivers\ a\ decide\ message,\ p\ decides\ accordingly\}$

when $R\text{-}deliver(q, r_q, estimate_q, decide)$
  if $state_p = undecided$ **then**
    $decide(estimate_q)$
    $state_p \leftarrow decided$

Discussion on Failure Detection

- How are these 'USB FD modules' implemented?
- Can the model be asynchronous?
- What if the model is not asynchrnous?
  - Timed-asynchronous

    [F. Cristian and C. Fetzer, The Timed Asynchronous Distributed System Model, 1999]
  - Quasi-synchronous, wormholes

    [P. Veríssimo and C. Almeida, Quasi-synchronism: a step away from the traditional fault-tolerant real-time system models, 1995]
  - Synchronous

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