Distributed Systems

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Failure Detectors

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Failure Detector

- **Failure detector** is an application that is responsible for detection of node failures or crashes in a distributed system.
- A **failure detector** is a distributed oracle that provides hints about the operational status of other processes

Why Failure Detectors

- The design and verification of ***fault- tolerant*** distributed system is a difficult problem.
- The ***detection of process failures*** is a crucial problem, system designers have to cope with in order to build fault tolerant distributed platforms

Synchronous Vs Asynchronous

- A distributed system is synchronous if:
  - there is a known upper bound on the transmission delay of messages
  - there is a known upper bound on the processing time of a piece of code
- A distributed system is asynchronous if:
  - there is no bound on the transmission delay of messages
  - there is no bound on the processing time of a piece of code

Why Failure Detectors cont…

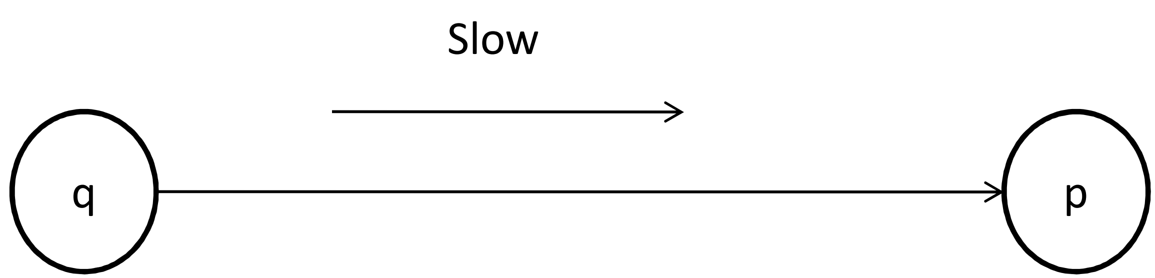
- **To stop waiting or not to stop waiting?**
- Unfortunately, it is impossible to distinguish with certainty a ***crashed process from a very slow process*** in a purely asynchronous distributed system.
- Look at two major problems
  - Consensus
  - Atomic Broadcast

Liveness & Safety

- The problem can be defined with a **safety** and a **liveness** property.
- The safety property stipulates that ***"nothing bad ever happens"***
- The liveness property stipulates that ***"something good eventually happens"***

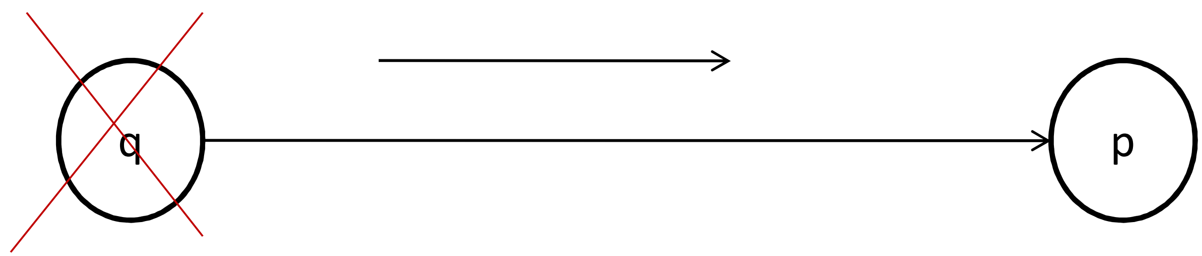
‘q’ not crashed

- The message from *q to p is only* very slow.
- Assuming that ‘q’ has crashed will violate the **safety** property



‘q’ has crashed

- To prevent the bad previous scenario from occurring, p must wait until it gets q’s message.
- It is easy to see that p will wait forever, and the **liveness** property of the application will never be satisfied



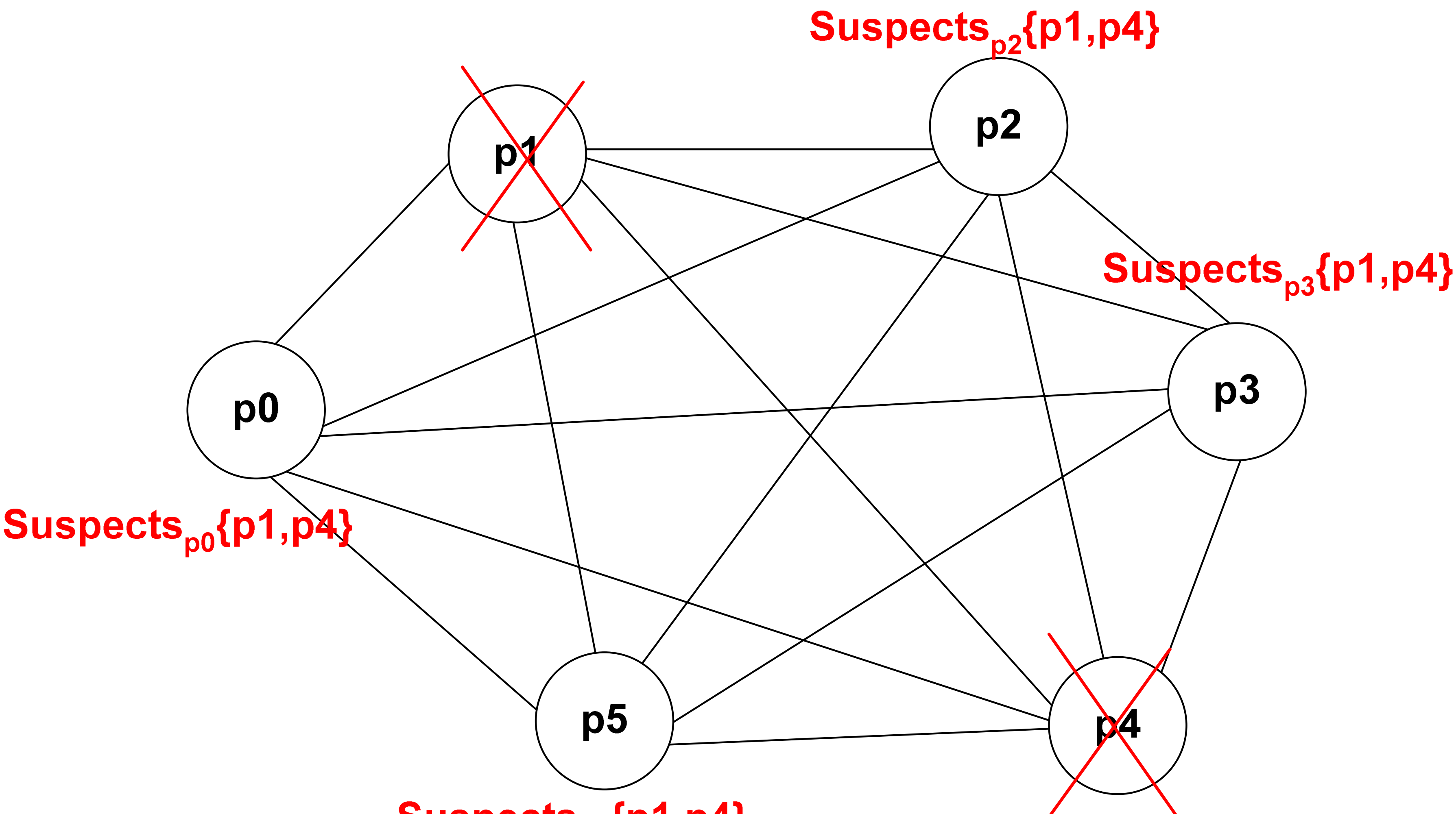
Characterizing Failure Detectors

- Completeness
  - Suspect every process that actually crashes
- Accuracy
  - Limit the number of correct processes that are suspected

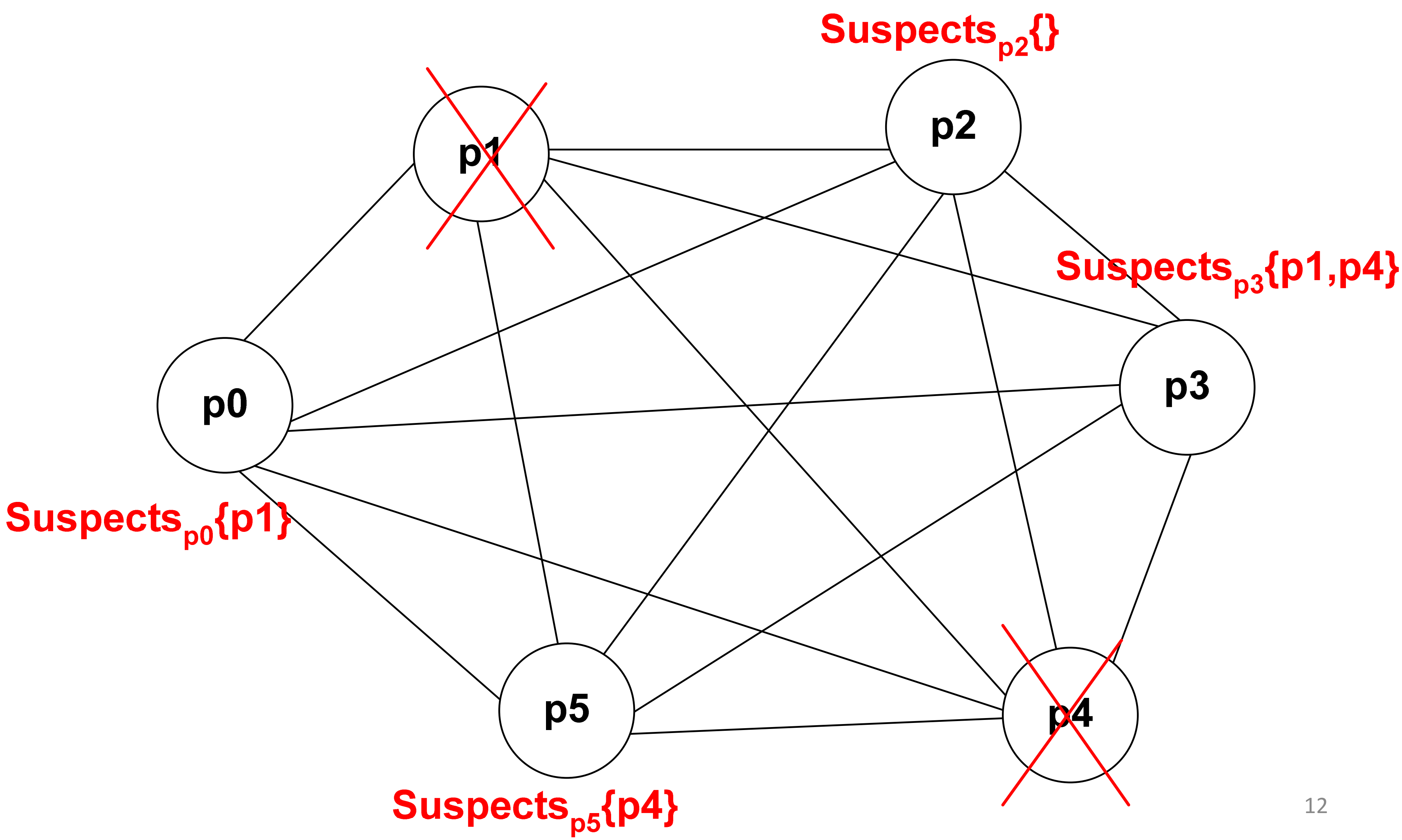
Completeness

- Strong Completeness
  - Eventually, every crashed process is permanently suspected by *every* correct process
- Weak Completeness
  - Eventually, every crashed process is permanently suspected by *some* correct process

Strong Completeness



Weak Completeness



Accuracy

- Strong Accuracy
  - A process is *never* suspected before it crashes by any correct process
- Weak Accuracy
  - Some correct process *never* suspected by any correct process

Perpetual Accuracy!

As these properties hold all the times

Eventual Accuracy

- Eventual Strong Accuracy
  - After a time, correct processes do not suspect correct processes
- Eventual Weak Accuracy
  - After a time, *some* correct process is not suspected by any correct process

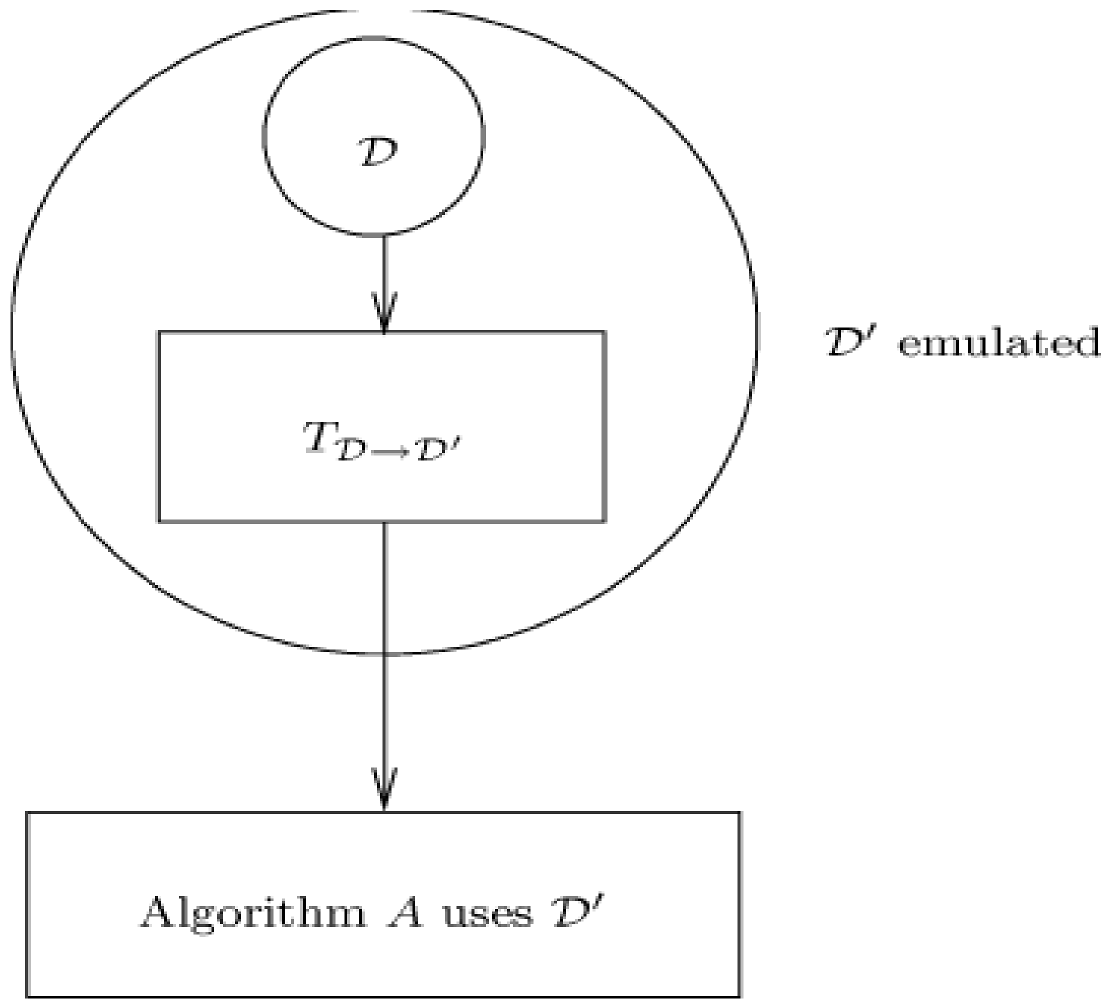
Failure Detector Classes

Completeness	Accuracy			
	Strong	**Weak**	**Eventual Strong**	**Eventual Weak**
Strong	Perfect $\mathcal{P}$	Strong $\mathcal{S}$	Eventually Perfect $\diamond \mathcal{P}$	Eventually Strong $\diamond \mathcal{S}$
Weak	$\mathcal{V}$	Weak $\mathcal{W}$	$\diamond \mathcal{V}$	Eventually Weak $\diamond \mathcal{W}$

Reducibility

- A Failure detector D is reducible to another failure detector D’ if there exist a reduction algorithm $T_{D \rightarrow D'}$ that transforms D to D’.
- Then
  - D’ is Weaker than D (i.e) D $\sqsubseteq$ D’
- If D $\sqsubseteq$ D’ and D’ $\sqsubseteq$ D then D and D’ are ***equivalent*** (i.e) D ≡ D’
- Suppose a given algorithm ‘A’ requires failure detector D’, but only D is available.

Example



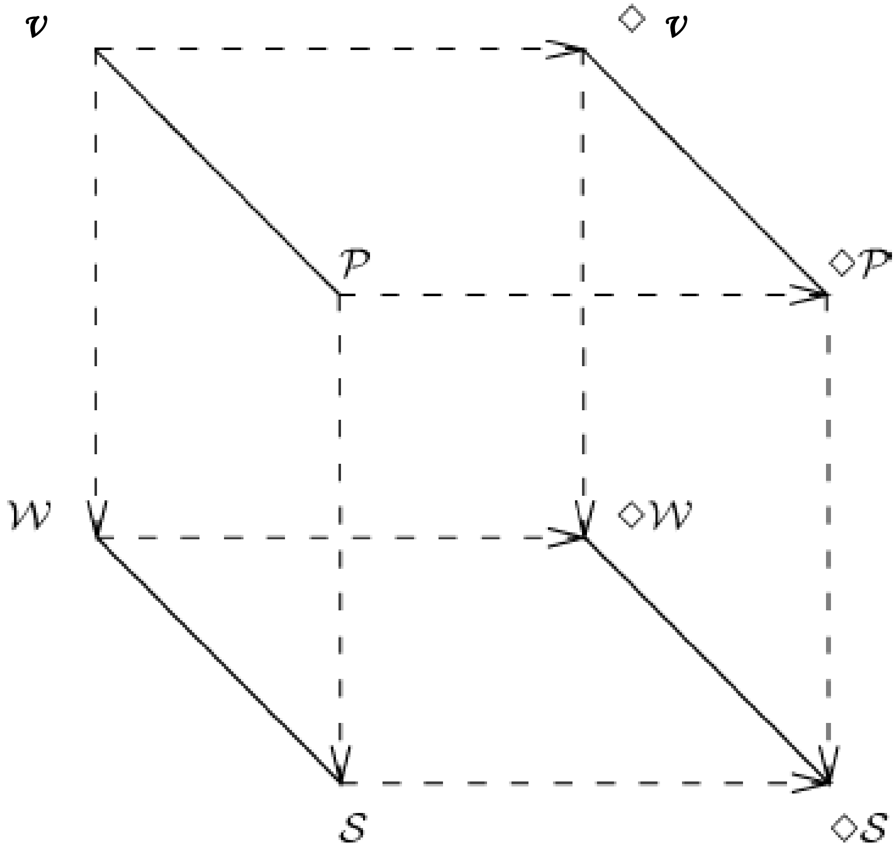
$\mathcal{D}$
$T_{\mathcal{D}\to\mathcal{D}'}$
$\mathcal{D}'$ emulated
Algorithm A uses $\mathcal{D}'$

Reducibility of FD

- $\mathcal{P} \sqsubseteq \mathcal{Q}$; $\mathcal{S} \sqsubseteq \mathcal{W}$; $\diamond\mathcal{P} \sqsubseteq \diamond\mathcal{Q}$; $\diamond\mathcal{S} \sqsubseteq \diamond\mathcal{W}$
- $\mathcal{Q} \sqsubseteq \mathcal{P}$; $\mathcal{W} \sqsubseteq \mathcal{S}$; $\diamond\mathcal{Q} \sqsubseteq \diamond\mathcal{P}$; $\diamond\mathcal{W} \sqsubseteq \diamond\mathcal{S}$
- $\mathcal{P} \equiv \mathcal{Q}$; $\mathcal{S} \equiv \mathcal{W}$; $\diamond\mathcal{P} \equiv \diamond\mathcal{Q}$; $\diamond\mathcal{S} \equiv \diamond\mathcal{W}$

- Hence if we solve a problem for four failure detectors with strong completeness, the problem is automatically solved for the remaining four failure detectors.

Comparing Failure detectors by Reducibility



C - - - -> C': C' is strictly weaker than C

C ——— C': C is equivalent to C'

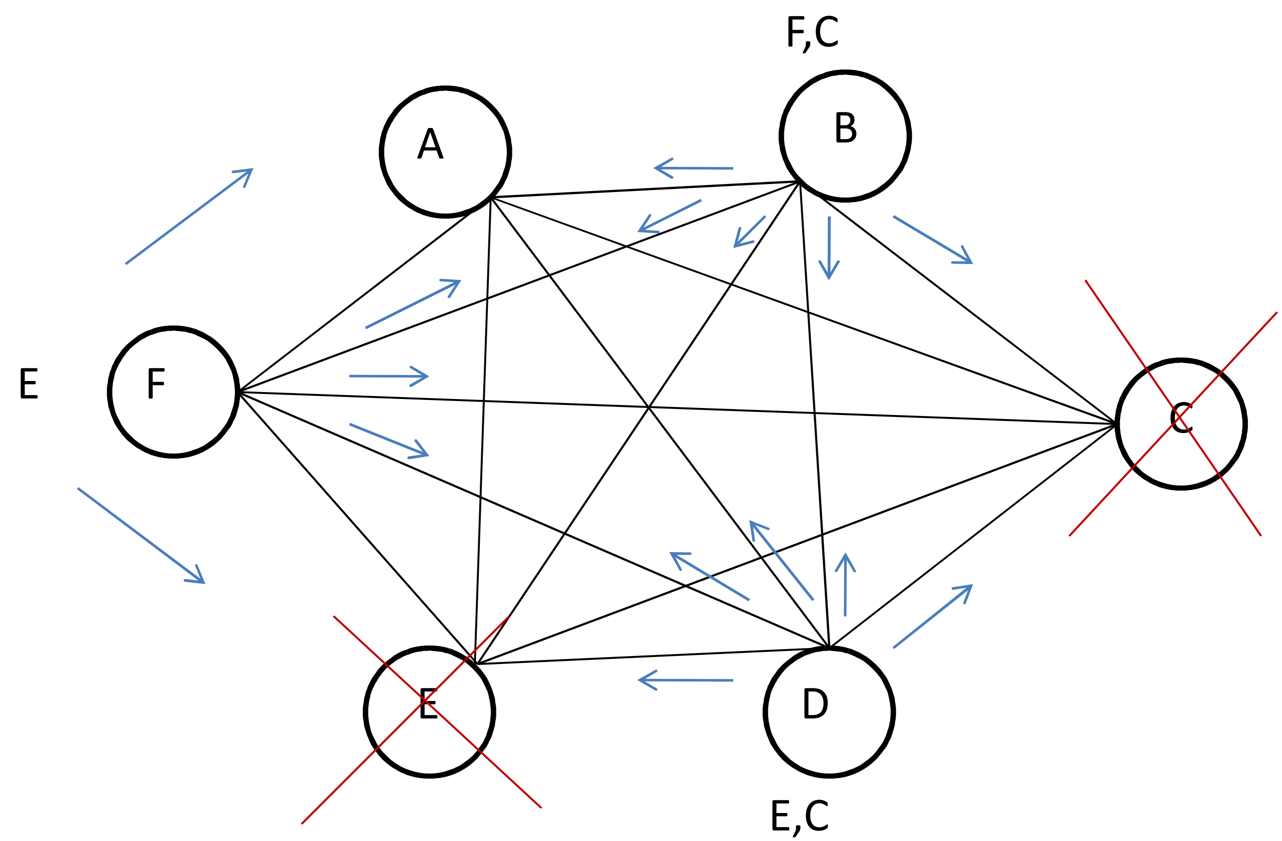
Failure Detectors : Reducibility

- Two failure detectors are equivalent if they are reducible to each other.
- Failure detector with weak completeness is equivalent to corresponding failure detector with strong completeness.
- $\mathcal{P} \equiv \mathcal{V}$; $\Diamond\mathcal{P} \equiv \Diamond\mathcal{V}$; $\mathcal{S} \equiv \mathcal{W}$; $\Diamond\mathcal{S} \equiv \Diamond\mathcal{W}$
- Solving a problem for the four failure detectors with strong completeness, automatically solves for the remaining four failure detectors.

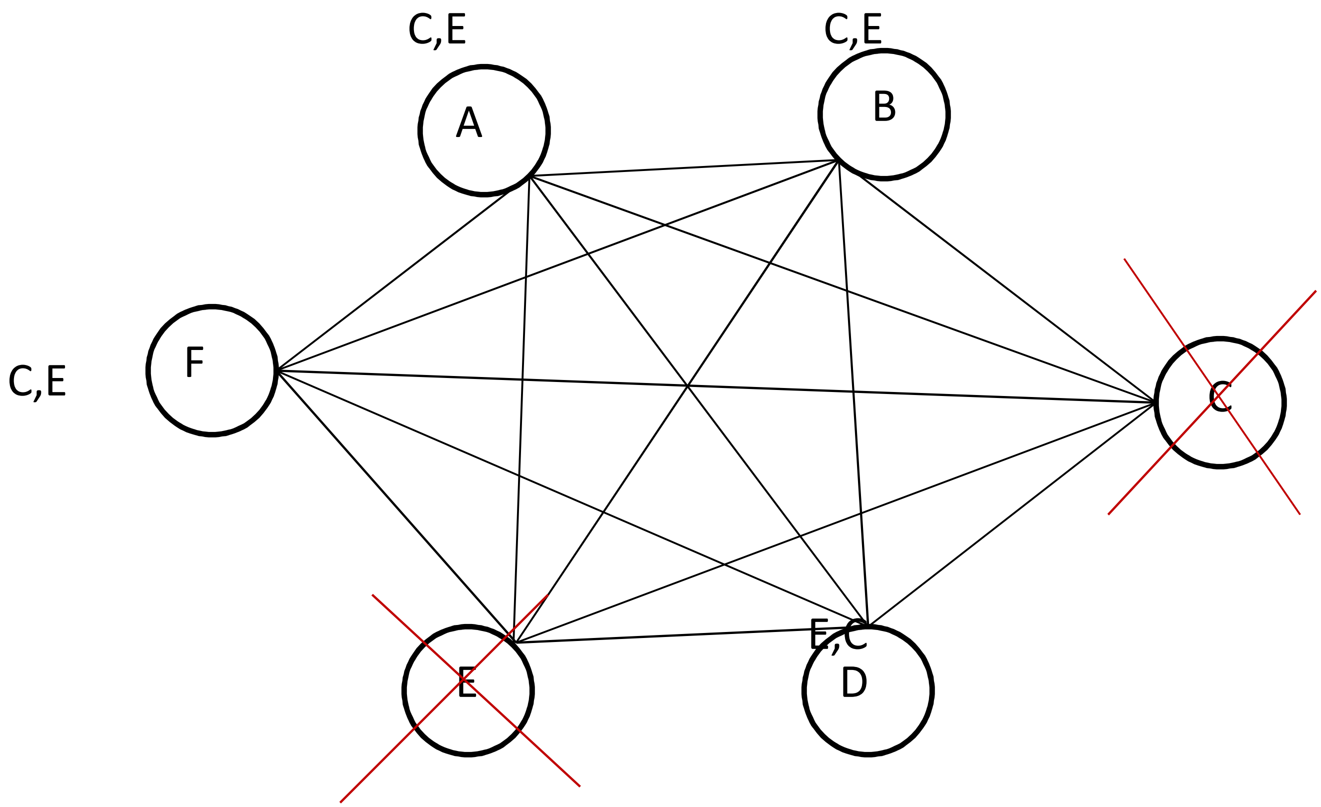
Weak to Strong Completeness

- Every process p executes the following:
- Output $_p$ ← Null
- cobegin
  - //Task 1: repeat forever
    - suspects $_p$ ← D $_p$ {p queries its local failure detector module D $_p$}
    - *send(p, suspects $_p$) to all other processes.*
  - //Task 2: when receive (q, suspects $_q$) for a process q
    - output $_p$ ← output $_p$ U suspects $_q$ – *{q} {output $_p$ emulates E $_p$}*
- coend

Weak to Strong Completeness



Weak to Strong Completeness



The consensus problem

- **Termination** : Every correct process eventually decides some value.
- **Uniform integrity :** Every process decides at most once.
- **Agreement :** No two correct processes decide differently.
- **Uniform validity :** If a process decides a value v, then some process proposed v.
- It is widely known that the consensus cannot be solved in ***asynchronous systems in the presence of even a single crash failure***

Solutions to the consensus problem

- $\mathcal{P} \equiv \mathcal{V}$; $\diamond\mathcal{P} \equiv \diamond\mathcal{V}$; $\mathcal{S} \equiv \mathcal{W}$; $\diamond\mathcal{S} \equiv \diamond\mathcal{W}$
- Solving a problem for the four failure detectors with strong completeness, automatically solves for the remaining four failure detectors
- Since $\mathcal{P}$ is reducible to $\mathcal{S}$ and $\diamond\mathcal{P}$ is reducible to $\diamond\mathcal{S}$.
- The algorithm for solving consensus using $\mathcal{S}$ also solve consensus using $\mathcal{P}$.
- The algorithm for solving consensus using $\diamond\mathcal{S}$ also solve consensus using $\diamond\mathcal{P}$.

Consensus using $\mathcal{S}$

Every process p executes the following:

procedure *propose*(v_p)

$V_p \leftarrow \langle \bot, \bot, \ldots, \bot \rangle$ {*p's estimate of the proposed values*}

$V_p[p] \leftarrow v_p$

$\Delta_p \leftarrow V_p$

Phase 1: $\{$*asynchronous rounds* r_p, $1 \le r_p \le n-1\}$

for $r_p \leftarrow 1$ to $n-1$

send (r_p, Δ_p, p) to all

wait until $[\forall q:$ received (r_p, Δ_q, q) **or** $q \in \mathcal{D}_p]$ {*query the failure detector*}

$msgs_p[r_p] \leftarrow \{(r_p, \Delta_q, q) \mid \text{received } (r_p, \Delta_q, q)\}$

$\Delta_p \leftarrow \langle \bot, \bot, \ldots, \bot \rangle$

for $k \leftarrow 1$ to n

if $V_p[k] = \bot$ and $\exists(r_p, \Delta_q, q) \in msgs_p[r_p]$ with $\Delta_q[k] \neq \bot$ then

$V_p[k] \leftarrow \Delta_q[k]$

$\Delta_p[k] \leftarrow \Delta_q[k]$

Phase 2: send V_p to all

wait until $[\forall q:$ received V_q or $q \in \mathcal{D}_p]$ $\{$*query the failure detector*$\}$

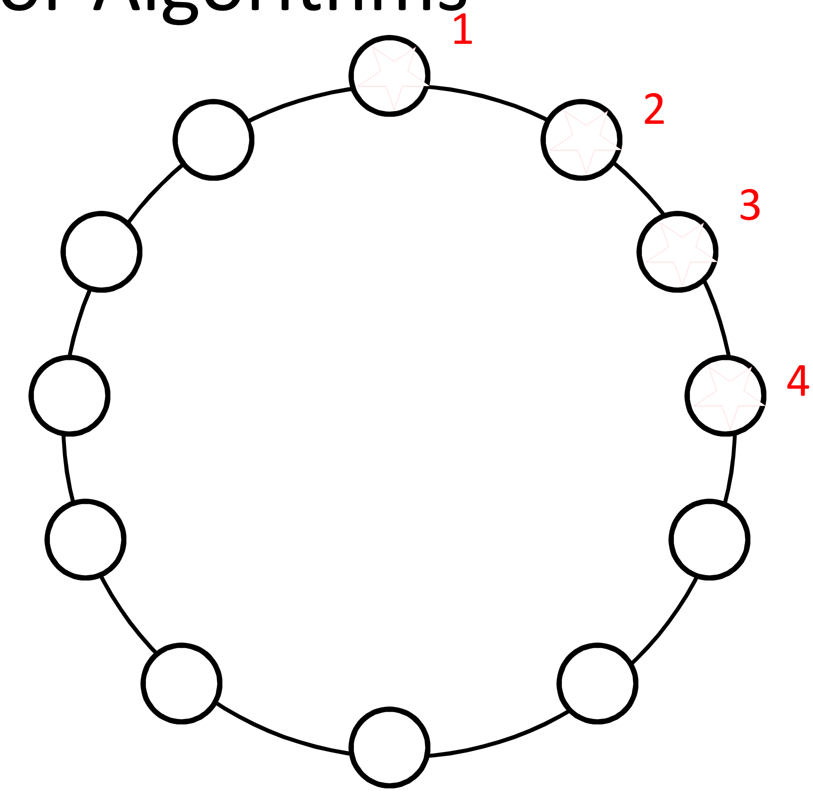
$lastmsgs_p \leftarrow \{V_q \mid \text{received } V_q\}$

for $k \leftarrow 1$ to n

if $\exists V_q \in lastmsgs_p$ with $V_q[k] = \bot$ then $V_p[k] \leftarrow \bot$

Phase 3: *decide*(first non-$\bot$ component of V_p)

Solving Consensus using ◇S : Rotating Coordinator Algorithms



Work for up to f < n/2 crashes

- Processes are numbered 1, 2, …, n
- They execute asynchronous *rounds*

- In round r , the *coordinator* is process (r mod n) + 1

- In round r , the coordinator:
  - tries to impose its estimate as the consensus value
  - succeeds if does not crash and it is not suspected by ◇S

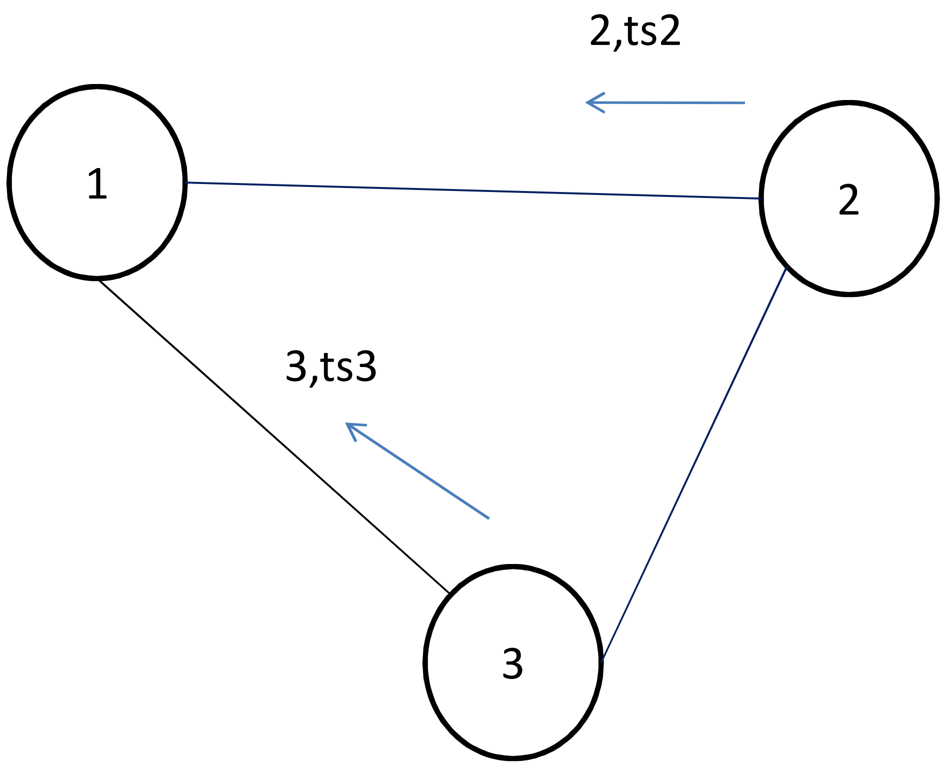
Consensus using $\diamond \mathcal{S}$

- The algorithm goes through
  - three Asynchronous stages
    - Each stage has several asynchronous rounds
      - Each round has 2 tasks
        - » Task 1
          - Four asynchronous phases
        - » Task 2
- In the first stage, several decision values are proposed
- In second stage, a value gets locked: no other decision value is possible
- In the third and final stage, the processes decide on the locked value and consensus is reached.

Consensus using $\diamond\mathcal{S}$

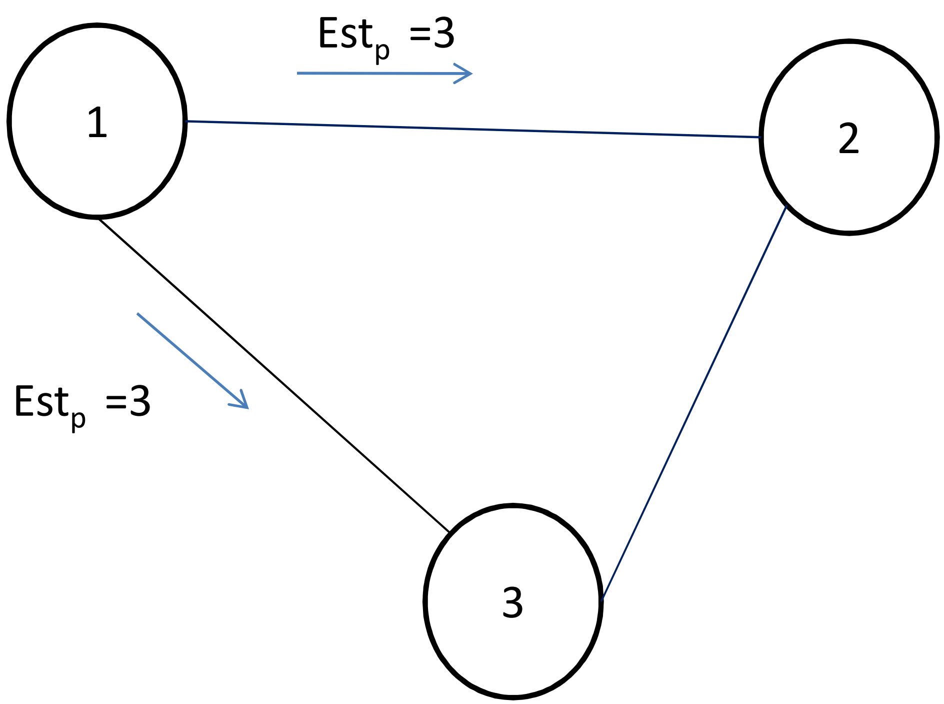
- Task 1
  - Phase1
    - Every process ‘p’ sends
      - Current estimate to coordinator C_p
      - Round number ts_p
  - Phase 2
    - C_p gathers $\lceil (n+1)/2 \rceil$ estimates
    - Selects one with largest time stamp $estimate_p$
    - Send the new estimate to all processes
  - Phase 3
    - Each process ‘p’
      - May receive $estimate_p$
        - » Send an ack to C_p
      - May not receive $estimate_p$
        - » Send an nack to C_p (suspecting C_p has crashed)
  - Phase 4
    - Waits for $\lceil (n+1)/2 \rceil$ (acks or nacks)
      - If all are acks then $estimate_p$ is locked
      - C_p broadcasts the decided value $estimate_p$
- Task 2
  - If a process ‘p’ receives a broadcast on decided value and has not already decided
    - Accepts the value

Consensus using $\diamond\mathcal{S}$

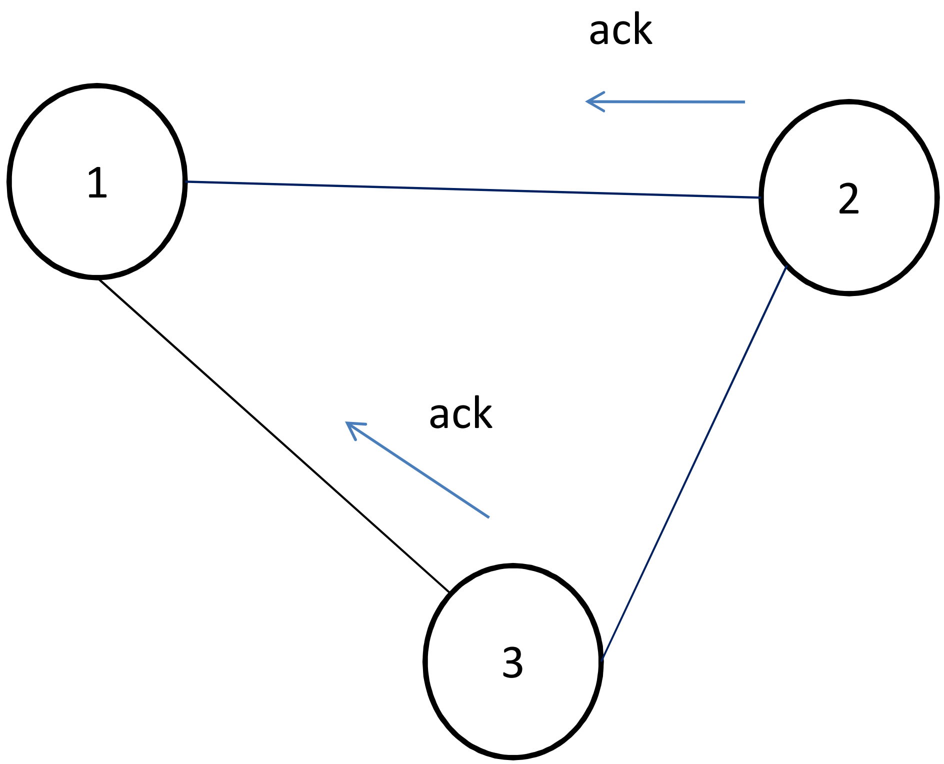


Let ts2 < ts1 < ts3

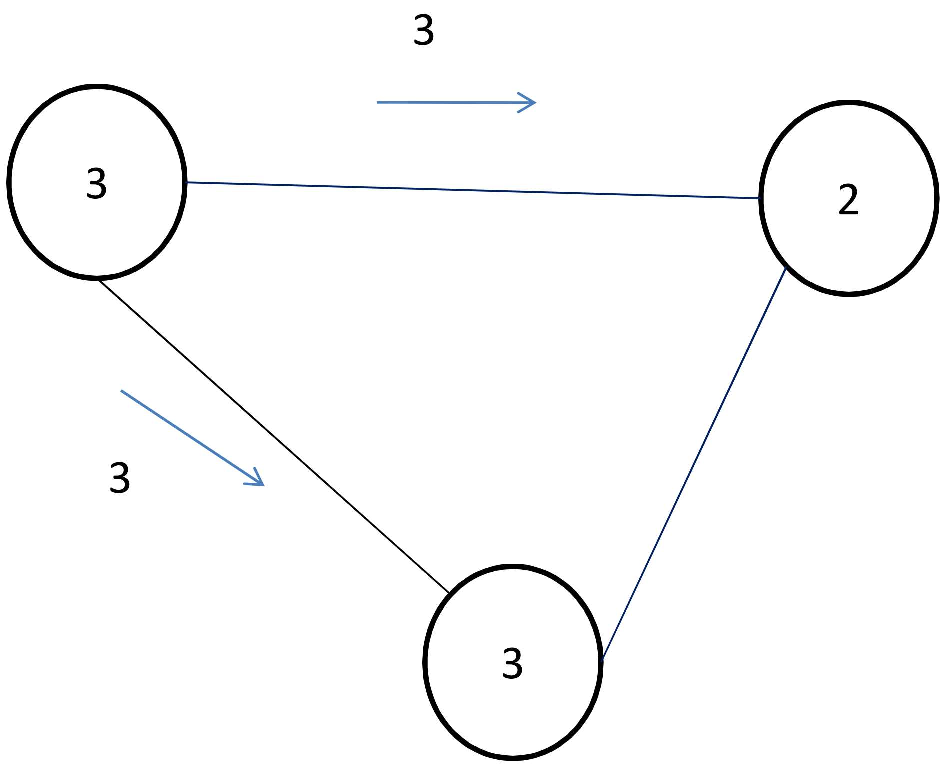
Consensus using $\diamond\mathcal{S}$



Consensus using $\diamond\mathcal{S}$

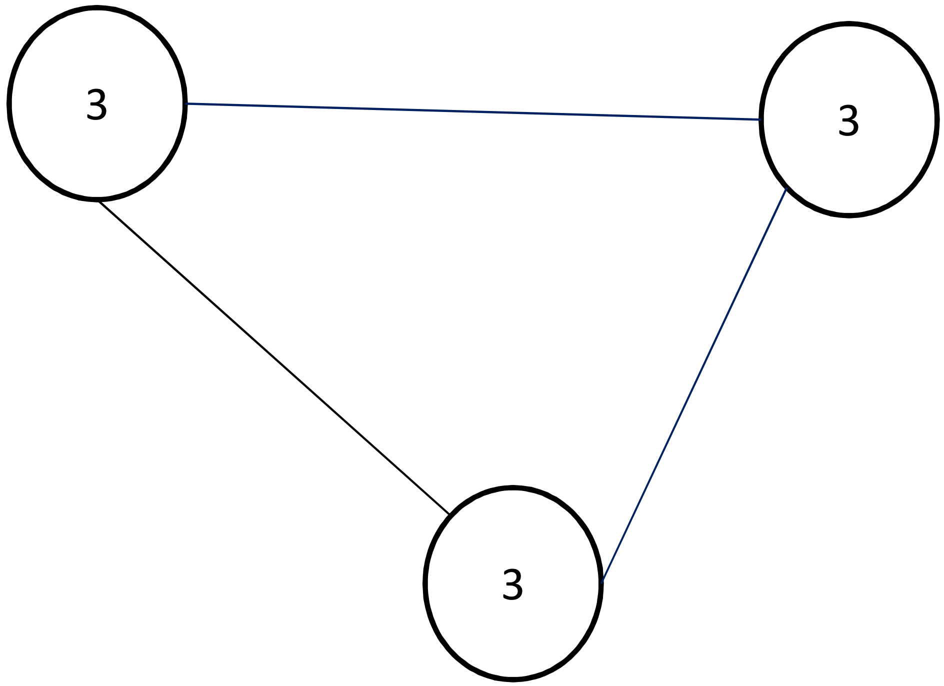


Consensus using $\diamond\mathcal{S}$



Locks 3 and broad casts

Consensus using $\diamond\mathcal{S}$



Locks 3 and broad casts

Consensus using $\diamond\mathcal{S}$

Every process p executes the following:

procedure $propose(v_p)$

$estimate_p \leftarrow v_p$ $\{estimate_p$ *is p's estimate of the decision value*$\}$

$state_p \leftarrow undecided$

$r_p \leftarrow 0$ $\{r_p$ *is p's current round number*$\}$

$ts_p \leftarrow 0$ $\{ts_p$ *is the last round in which p updated* $estimate_p$, *initially 0*$\}$

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

while $state_p = undecided$

$r_p \leftarrow r_p + 1$

$c_p \leftarrow (r_p \bmod n) + 1$ $\{c_p$ *is the current coordinator*$\}$

Phase 1: $\{$*All processes p send* $estimate_p$ *to the current coordinator*$\}$

send $(p, r_p, estimate_p, ts_p)$ to c_p

Consensus using $\diamond\mathcal{S}$ *cont…*

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

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*}

Consensus using $\diamond S$ *cont…*

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**

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

{*If p R-delivers a decide message, p decides accordingly*}

when $R\text{-}deliver(q, r_q, estimate_q, decide)$

  if $state_p = undecided$ **then**

    $decide(estimate_q)$

    $state_p \leftarrow decided$

Atomic Broadcast

- Informally, atomic broadcast requires that all correct processes deliver the same set of messages in the same order (i.e., deliver the same sequence of messages).
- Formally atomic broadcast can be defined as a reliable broadcast with the total order property
- Chandra and Toueg showed that the result of consensus can be used to solve the problem of atomic broad cast.

- **Reliable Broadcast**
  - **Validity** : If the sender of a broadcast message m is non-faulty, then all correct processes eventually deliver m.
  - **Agreement :** If a correct process delivers a message m, then all correct processes deliver m.
  - **Integrity :** Each correct process delivers a message at most once.
- **Total Order**
  - If two correct processes p and q deliver two messages m and m’, then p delivers m before m’ if and only if q delivers m before m’.

Reliable Broadcast

Every process p executes the following:

To execute R-broadcast(m):
    send m to all (including p)

R-deliver(m) *occurs as follows*:
    when receive m for the first time
        if $sender(m) \neq p$ **then** send m to all
        R-deliver(m)

Atomic Broadcast

- The algorithm consists of three tasks :
- **Task 1 :**
  - when a process p wants to A-broadcast a message m, it *R_broadcasts m.*
- **Task 2 :**
  - a message m is added to set R_delivered$_p$ when process p *R_delivers it.*
- **Task 3 :**
  - when a process p *A_delivers a message m, it adds m to set* A_delivered$_p$.
  - Process p periodically checks whether A_undelivered$_p$ contains messages. If it contains messages, p enters its next execution of consensus, say the kth one, and proposes A_undelivered$_p$ as the next batch of messages to be *A_delivered.*

Atomic Broadcast

Every process p executes the following:

Initialisation:

$R\_delivered \leftarrow \emptyset$
$A\_delivered \leftarrow \emptyset$
$k \leftarrow 0$

To execute *A-broadcast*(m): { *Task 1* }

R-broadcast(m)

A-deliver$(-)$ occurs as follows:

when *R-deliver*(m) { *Task 2* }
$R\_delivered \leftarrow R\_delivered \cup \{m\}$

when $R\_delivered - A\_delivered \neq \emptyset$ { *Task 3* }
$k \leftarrow k + 1$
$A\_undelivered \leftarrow R\_delivered - A\_delivered$
propose$(k, A\_undelivered)$
wait until *decide*$(k, msgSet^k)$
$A\_deliver^k \leftarrow msgSet^k - A\_delivered$
atomically deliver all messages in $A\_deliver^k$ in some deterministic order
$A\_delivered \leftarrow A\_delivered \cup A\_deliver^k$

Implementation of failure detector

- **Task 1 :** Each process *p periodically sends a "p-is-alive" message to* all other processes. This is like a heart-beat message that informs other processes that process p is alive.
- **Task 2 :** If a process p does not receive a "q-is-alive" message from a process q within p(q) time units on its clock, then p adds q to its set of suspects if q is not already in the suspect list of p.
- **Task 3 :** When a process delivers a message from a suspected process, it corrects its error about the suspected process and increases its timeout for that process.
  – If process p receives "q-is-alive" message from a process q that it currently suspects, p knows that its previous timeout on q was premature – p removes q from its set of suspects and increases its timeout period for process q, p(q).

Implementation of failure detector

Every process p executes the following:

$output_p \leftarrow \emptyset$
for all $q \in \Pi$ {$\Delta_p(q)$ *denotes the duration of p's time-out interval for q*}
    $\Delta_p(q) \leftarrow$ default time-out interval

cobegin
|| *Task 1:* **repeat periodically**
    send "p-is-alive" to all

|| *Task 2:* **repeat periodically**
    for all $q \in \Pi$
        if $q \notin output_p$ and
            p did not receive "q-is-alive" during the last $\Delta_p(q)$ ticks of p's clock
            $output_p \leftarrow output_p \cup \{q\}$ {*p times-out on q: it now suspects q has crashed*}

|| *Task 3:* **when** receive "q-is-alive" for some q
    if $q \in output_p$ {*p knows that it prematurely timed-out on q*}
        $output_p \leftarrow output_p - \{q\}$ {*1. p repents on q, and*}
        $\Delta_p(q) \leftarrow \Delta_p(q) + 1$ {*2. p increases its time-out period for q*}
coend

Fig. 10. A time-out based implementation of $\mathcal{D} \in \diamond\mathcal{P}$ in models of partial synchrony.

Lazy failure detection protocol

- A relatively simple protocol that allows a process to “monitor” another process, and consequently to detect its crash.
- This protocol enjoys the nice property to rely as much as possible on application messages to do this monitoring.
- The cost associated with the implementation of a failure detector incurs only when the failure detector is used (hence, it is called a lazy failure detector).
- Each process pi has a local hardware clock hc_i that strictly monotonically increases.
- The local clocks are not required to be synchronized
- Every pair of processes is connected by a channel and they communicate by sending and receiving messages through channels.
- Channels are not required to be FIFO

Lazy failure detection protocol

```
when SEND M to p_j is invoked:
   m.content ← M; m.st ← hc_i;
   pending_msg_st_i[j] ← pending_msg_st_i[j] ∪ {m.st}
   send appl(m) to p_i

when type(m) is received from p_j:
   case type=appl  then transmit M = m.content to the upper layer; % RECEIVE M %
                        send ack(m) to p_j % m.st keeps its value %
        type=ack   then rt ← hc_i;
                        max_rtd_i[j] ← max(max_rtd_i[j], rt − m.st);
                        pending_msg_st_i[j] ← pending_msg_st_i[j] − {m.st}
        type=ping  then send ack(m) to p_j % m.st keeps its value %
   endcase

when QUERY(j) is invoked:
   if pending_msg_st_i[j] = ∅ then create a control message m;
                                   m.content ← null; m.st ← hc_i;
                                   send ping(m) to p_j;
                                   pending_msg_st_i[j] ← {m.st};
                                   return (no_suspect)
                              else rt ← hc_i;
                                   if rt − min(pending_msg_st_i[j]) > max_rtd_i[j]
                                         then return (suspect)
                                         else return (no_suspect)
                                   endif
   endif
```

A short introduction to failure detectors for asynchronous Distributed Systems

Failure Detectors-Definition

Why use FD?

- Based on well defined set of Abstract concepts
- Not dependant on any particular implementation
- Layered approach favors design, proof and portability of protocol
- Helps to solve impossible time-free asynchronous distributed system problems like the Consensus problem.
- Eventually accurate failure detectors helps in designing indulgent algorithms.

Asynchronous System Models

Process model

- A process can fail by premature halting(crashing).
- A process is correct if it does not crash else it is faulty

Computation models

- **FLP** Crash-prone processes and reliable links
- **FLL** Crash-prone processes and fair lossy links

Asynchronous System Models

Communication model

Processes communicate and synchronize by exchanging messages through links.

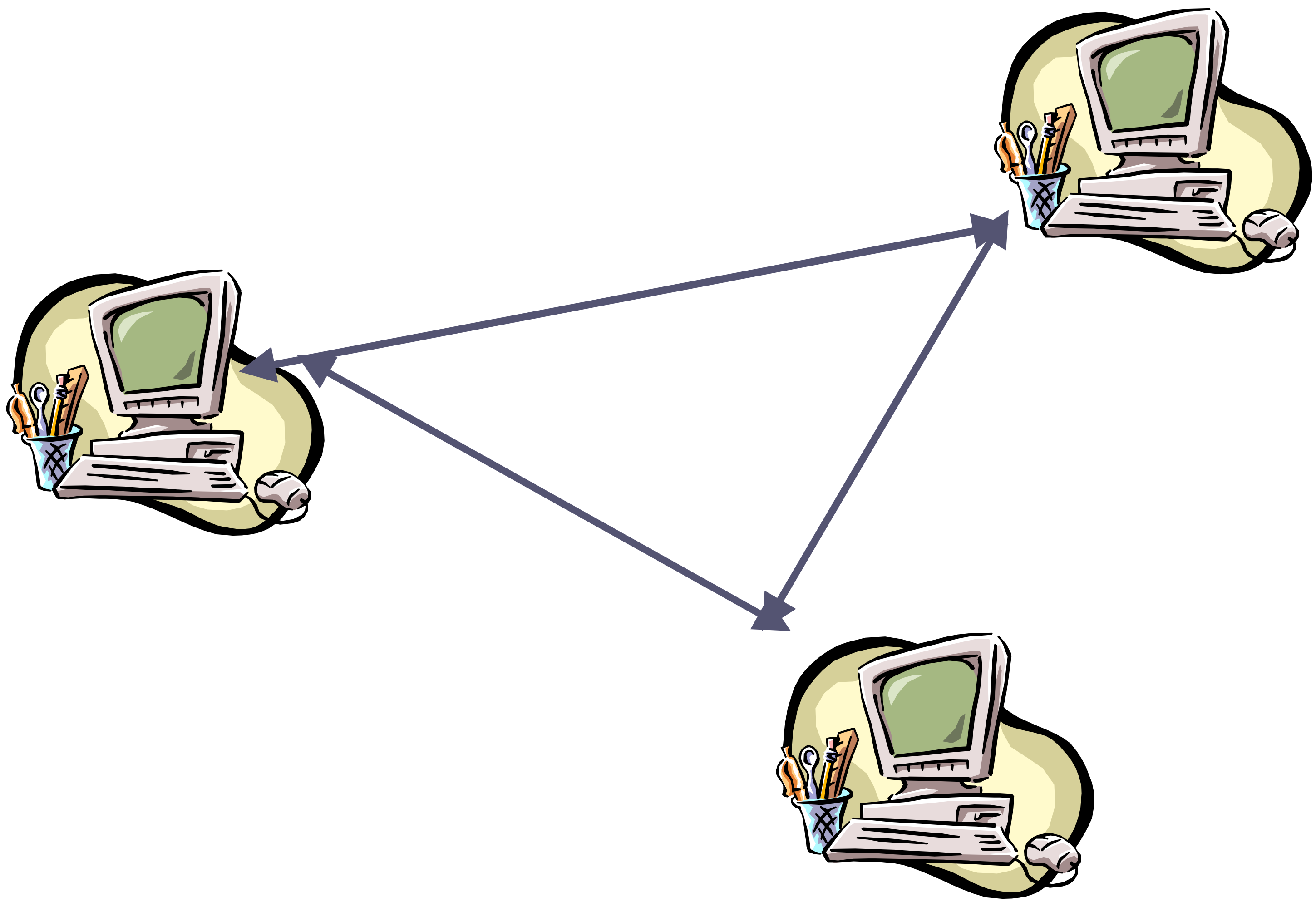
Reliable

- Does not create or duplicate messages
- Every message sent by Pi to Pj is eventually received by Pj

Fair lossy

- Does not create or duplicate messages
- Can lose message
- Can send infinite number of messages from one process to another

Consensus



Consensus

- All the processes, propose a initial value and they all have to agree upon some common value proposed

- Solving consensus is key to solving many problems in distributed computing (e.g., total order broadcast, atomic commit, terminating reliable broadcast)

Consensus definition

C-Validity: Any value decided is a value proposed

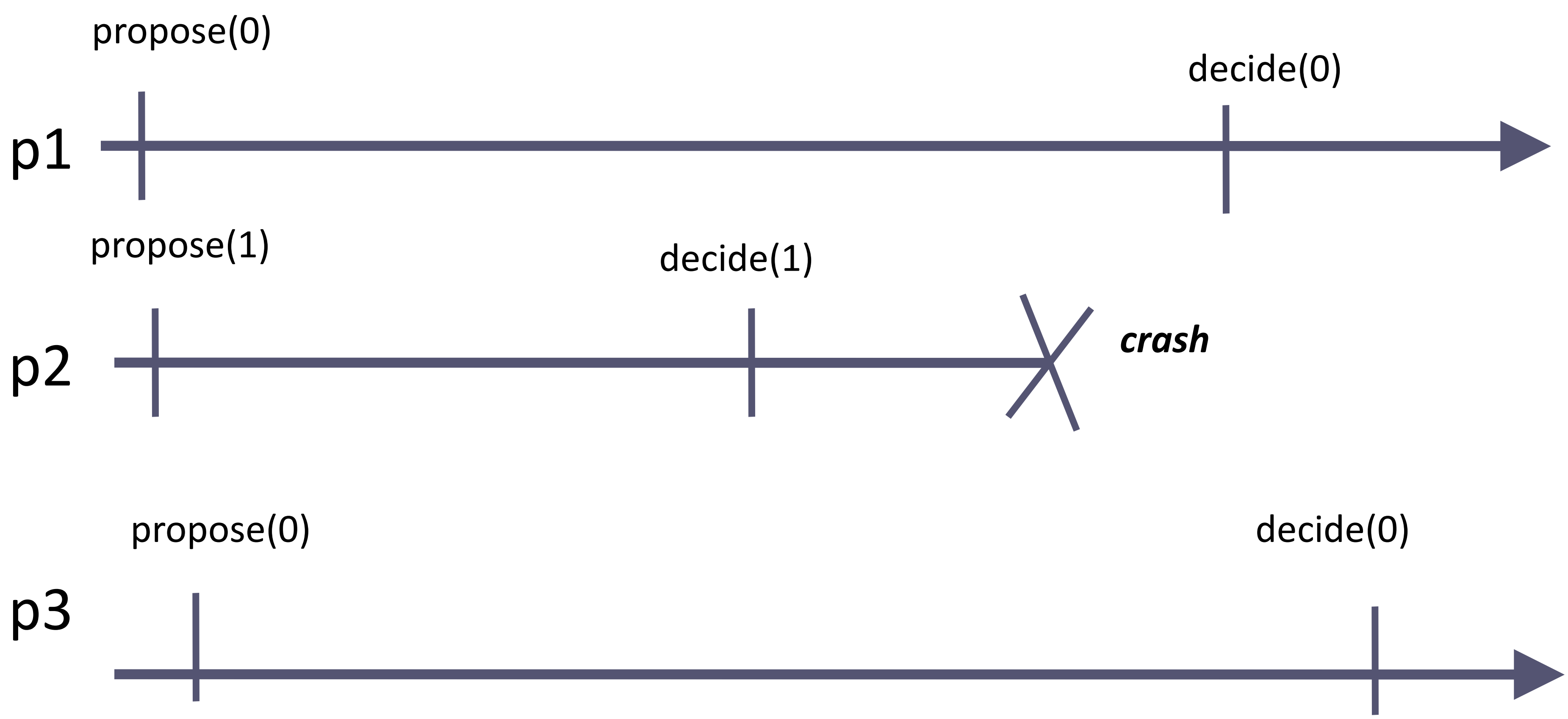
C-Agreement: No two correct processes decide differently

C-Termination: Every correct process eventually decides

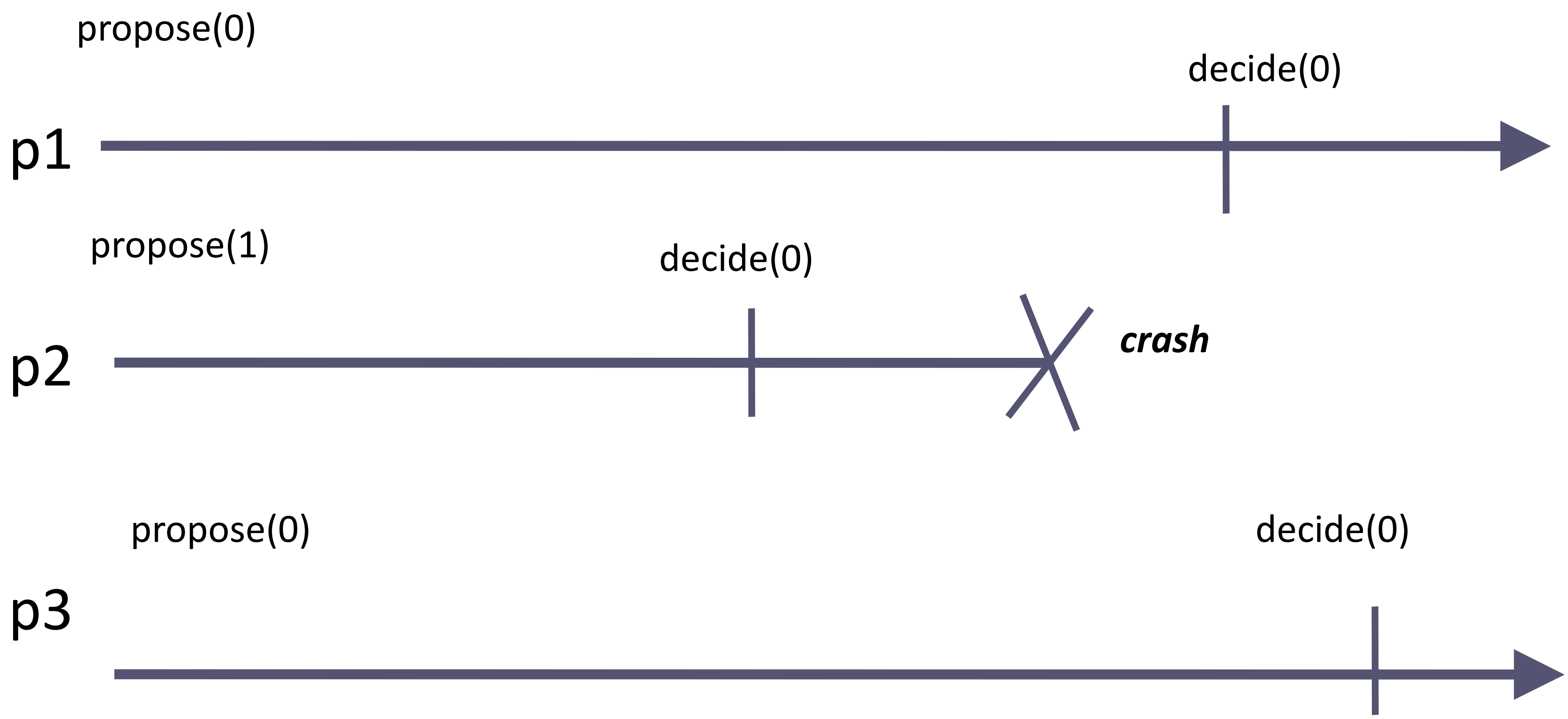
C-Integrity: No process decides twice

C- Uniform Agreement: No two (correct or not) processes decide differently

Consensus


propose(0)
decide(0)
p1
propose(1)
decide(1)
p2
crash
propose(0)
decide(0)
p3

Uniform Consensus



Eventually accurate failure detectors

- **Strong Completeness**

  Eventually, all processes that crash are suspected by every correct process

- **Eventually Weak Accuracy**

  There is a time after which some correct process is never suspected by the correct processes

◇ *S-based Consensus Protocol*

- FLP model
- Indulgent
  - Never violates consensus safety
  - Terminates when the sets contain correct values during a long enough period
- Requires majority of correct processes ($t<n/2$)
- Proceeds in asynchronous consecutive rounds
- Each round *r* is coordinated by process p_c such that, c=(r mod n) +1

Initialization

- v_i = *value* initially *proposed by* p_i.
- est_i = p_i*'s estimate of* the decision value.
- In round *r,* its coordinator p_c tries to impose its current estimate as the decision value.
- Algorithm runs in two phases.

Phase 1

- p_c sends est_c *to all the processes*
- *process* p_i *waits until it receives* p_c*'s estimate* or suspects it.
- Based on result of waiting, either

  $aux_i = v(=est_c)$

  or

  $aux_i = \bot$
- Due to the completeness property of the underlying failure detector no process can block forever

Phase 2

- All process exchange the values of their aux_i variables
- Due to the *"majority of correct processes"* assumption, no process can block forever
- Only two values can be exchanged: $v = est_c$ or $\perp$.
- Therefore,

  $rec_i = \{\{v\}, \{v, \perp\}, or\ \{\perp\}\}$
- Impossible for two sets rec_i and rec_j to be such that

  $rec_i = \{v\}$

  $rec_j = \{\perp\}$

Phase 2

$$\mathbf{rec_i = \{v\} \Rightarrow (\forall\, p_j : (rec_j = \{v\}) \vee (rec_j = \{v, \bot\}))}$$

$$\mathbf{rec_i = \{\bot\} \Rightarrow (\forall\, p_j : (rec_j = \{\bot\}) \vee (rec_j = \{v, \bot\})).}$$

$rec_i = \{v\}$

$est_i = v$.

To prevent possible deadlock situations, p_i broadcasts its decision value.

$rec_i = \{v, \bot\}$

$est_i = v$.

proceeds to the next round.

$rec_i = \{\bot\}$

p_i proceeds to the next round without modifying est_i.

A Simple *S-Based Consensus Protocol (t < n/2)*

Function Consensus(*v_i*)

Task *T1:*

(1) *$r_i \leftarrow 0$; $est_i \leftarrow v_i$;*

(2) **while *true do***

(3) *$c \leftarrow (r_i \bmod n) + 1$; $r_i \leftarrow r_i + 1$; % $1 \leq r_i < +\infty$ %*

————————— Phase 1 of round *r: from pc to all* ——————————

(4) **if (*$i = c$) then broadcast phase1(r_i, est_i) endif;***

(5) **wait until (phase1(*$ri_,$ v) has been received from $p_c \vee c \in suspected_i$);***

(6) **if (phase1(*r_i, v) received from p_c) then $aux_i \leftarrow v$ else $aux_i \leftarrow \bot$ endif;***

————————— Phase 2 of round *r: from all to all* ——————————

(7) *broadcast phase2(r_i, aux_i);*

(8) **wait until (phase2 (*r_i, aux) msgs have been received from a majority of proc.);***

(9) **let *rec_i be the set of values received by p_i at line 8;***

% We have *$rec_i = \{v\}$, or $rec_i = \{v, \bot\}$, or $rec_i = \{\bot\}$ where $v = est_c$* %

(10) **case *reci = {v} then $est_i \leftarrow v$; broadcast decision(est_i); stop T1***

(11) *$rec_i = \{v, \bot\}$* ***then $est_i \leftarrow v$***

(12) *$rec_i = \{\bot\}$* ***then skip***

(13) **endcase**

(14) **endwhile**

Task *T2: when decision(est) is received: broadcast decision(est_i); return(est)*

Findings

- The strong completeness property is used to show that the protocol never blocks.
- The eventual weak accuracy property is used to ensure termination.
- The majority of correct processes is used to prove consensus agreement.

Interactive consistency

- Harder than consensus problem
- Process has to agree on a vector of values!

Termination

Every correct process eventually decides on a vector

Validity

Any decided vector D is such that $D[i] \in \{v_i, \perp\}$, and is v_i if p_i does not crash

Agreement:

No two processes decide differently

Perfect failure detectors

- Requires perfect failure detectors

Strong Completeness

- Every process that crashes is eventually permanently suspected

Strong Accuracy

- No process is suspected before it crashes

Perfect failure detector

init: ***$suspected_i \leftarrow \emptyset$; $seq_i \leftarrow 0$***

task ***T1: while true do***

$seq_i \leftarrow seq_i + 1$; % IC instance number %

$D_i \leftarrow$ IC Protocol(seq_i, v_i); % $v_i = \perp$ %

$suspected_i \leftarrow \{j \mid D_i[j] = \perp\}$

enddo

task ***T2: when p_i issues QUERY:***

return($suspected_i$)

Non-Blocking Atomic Commit Problem (NBAC)

- Yet another agreement problem in the world of distributed computing
- Each process cast their votes (yes or no).
- Non-crashed process decide on single value (*commit* or *abort*)

Properties

The problem is defined by following properties

NBAC - Termination → Every correct process eventually decides.

NBAC - Validity → A decided value is either commit or abort. Moreover:

- **NBAC - Justification** → If process decides commit, all process have voted yes.
- **NBAC - Obligation** → If all process vote yes and there is no crash, then the decision value is commit

NBAC - Obligation → No two process decide differently.

Continued

- Justification property relates commit decision to yes.
- Obligation property eliminates trivial solution of all process opting abort.
    - *"good" run* – all process wants to commit and the environment is free of crashes.
- Process crashes are explicit in NBAC compared consensus.

Appropriate Failure Detector

Why appropriate failure detector?

- To solve NBAC in the FLP model

Timeless failure detectors – No information (sense of time) when failure occurred.

Anonymously Perfect Failure Detectors

P and ◇S - timeless failure detectors.

To address this problem, class ?P anonymous perfect failure detector introduced.

- **Anonymous completeness**: If a crash occurs, eventually every correct process is permanently informed that some crash occurred.
- **Anonymous accuracy**: No crash is detected unless some process crashed.

Class ?P + ◇S - weakest class to solve NBAC, assuming a majority of correct process. The following protocol converts NBAC to consensus and subsequently uses subroutine consensus protocol.

Simple ?P + ◇S-Based NBAC protocol (t < n/2)

Function Nbac($vote_i$)

broadcast MY_VOTE($vote_i$);

wait until (MY_VOTE($vote_j$) has been received from each process $\vee$ ap_flag$_i$);

if (a vote yes has been received from each of the n processes)

then $output_i \leftarrow$ Consensus(commit)

else $output_i \leftarrow$ Consensus(abort)

endif;

return($output_i$)

Quiescence Problem

- Consider processes p_i and p_j that do not crash connected by fair lossy link, a basic communication problem is to build a reliable link on top of fair lossy link.

- Protocol used (including TCP) are quiescent - no message transfer after some time. (communication ceases)

- What if process p_j crashes?
- How to solve quiescent communication problem?
  - *Heartbeat failure* detectors

Heartbeat Failure Detector

- Failure detector outputs an array HB_i [1 ..n] – non decreasing counter at each process which satisfies……
  - **HB-completeness:** If p_j crashes, then *HBi*[j] stops increasing.
  - **HB-accuracy:** If p_j is correct, then HB_i[j] never stops increasing.

- Easy implementation but it is not quiescent.
- Allows the non-quiescent part of communication protocol to be isolated.
- Favors design modularity and eases correctness proof.

- "service" can be extended to upper layer applications.

Quiescent Implementation

Sender p_i:

when SEND(m) TO p_j **is invoked**:

$seq_i \leftarrow seq_i + 1$;

fork task *repeat_send(m,*seq_i)

task *repeat_send(m,*seq_i)

prev_hb $\leftarrow$ 1;

repeat periodically *hb* $\leftarrow$ HB_i[j];

if (*prev_hb* < *hb*) **then** send *msg*(m,*seq*) to p_j;

prev_hb $\leftarrow$ *hb*

endif

until (*ack(m,seq) is received*)

Receiver p_j:

when msg(m,*seq*) is received from p_i:

if (first reception of *msg*(m,*seq*)) **then** *m* is RECEIVED **endif**;

send ack(m,seq) to p_i

Failure Detectors in Synchronous Systems

Synchronous System Model

- Synchronous systems – characterized by time bound to receive & send message.
- Local computations take no time & transfer delays bounded by D.
  - Message sent at time 't' is not received after t+D (D-timeliness)
  - Links are reliable (no duplication, losses)
  - Process have access to common clock.

Consider p_i sends message to p_j & p_k , D-timeliness and no-loss properties gives rise to following scenarios…

- P_i crashes at time t, no message sent
- P_i crashes at time t, p_j receives while p_k doesn't by t + D, vice versa.
- P_i doesn't crash, p_j & p_k receives message by t + D

Fast Failure Detectors

- Fast failure detector provides processes with following properties (d < D)
  - **d – Timely completeness**: If a process p_j crashes at time t, then, by time t + d, every alive process suspects it permanently.
  - **Strong accuracy**: No process is suspected before it crashes.
- Implemented with specialized hardware, also attains time complexity lower bounds << pure synchronous system.
- Protocol described in the following slide illustrates early deciding property, reducing time complexity to D +*f*d (*f* – actual number of process crashes)

- Snapshot of the Synchronous Consensus with Fast Failure Detector implementation is illustrated as follows…

Fast Failure Detector Implementation

init $est_i \leftarrow v_i; max_i \leftarrow 0$

when *(est,j)* is *received*:

if ($j > max_i$) **then** $est_i \leftarrow est; max_i \leftarrow j$ **endif**

at time $(i\text{-}1)d$ **do**

if ($\{p_1,p_2,\ldots,p_{i-1}\} \subseteq suspected_i$) **then** *broadcast* (est_i,i) **endif**

at time ($j\text{-}1)d + D$ **for every** $1 \leq j \leq n$ **do**

if (($p_j \notin suspected_i$) $\wedge$ (p_i has not yet decided)) **then** return (est_i)

endif

Thank You