Advanced Course
Distributed Systems

Failure Detectors

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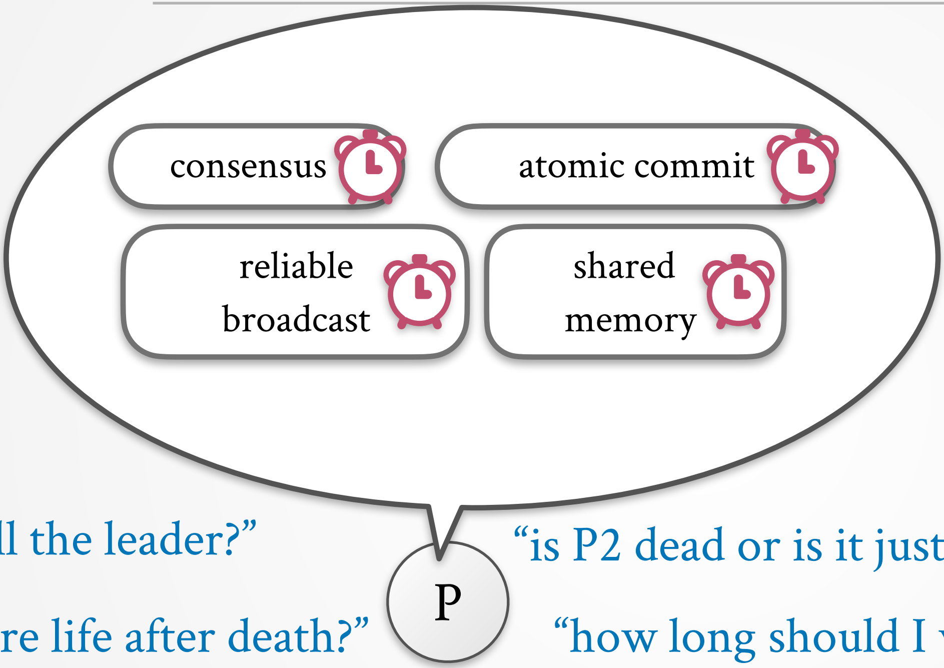
Course Topics

- Intro to Distributed Systems
- Basic Abstractions and Failure Detectors
- Reliable and Causal Order Broadcast
- Distributed Shared Memory
- Consensus (Paxos, Raft, etc.)
- Dynamic Reconfiguration
- Time Abstractions and Interval Clocks (Spanner etc.)
- Consistent Snapshotting (Stream Data Management)
- Distributed ACID Transactions (Cloud DBs)

Motivation



- Protocols in synchronous/ eventually synchronous models require heavy use of **timers** (Tideous).

"is P3 still the leader?"

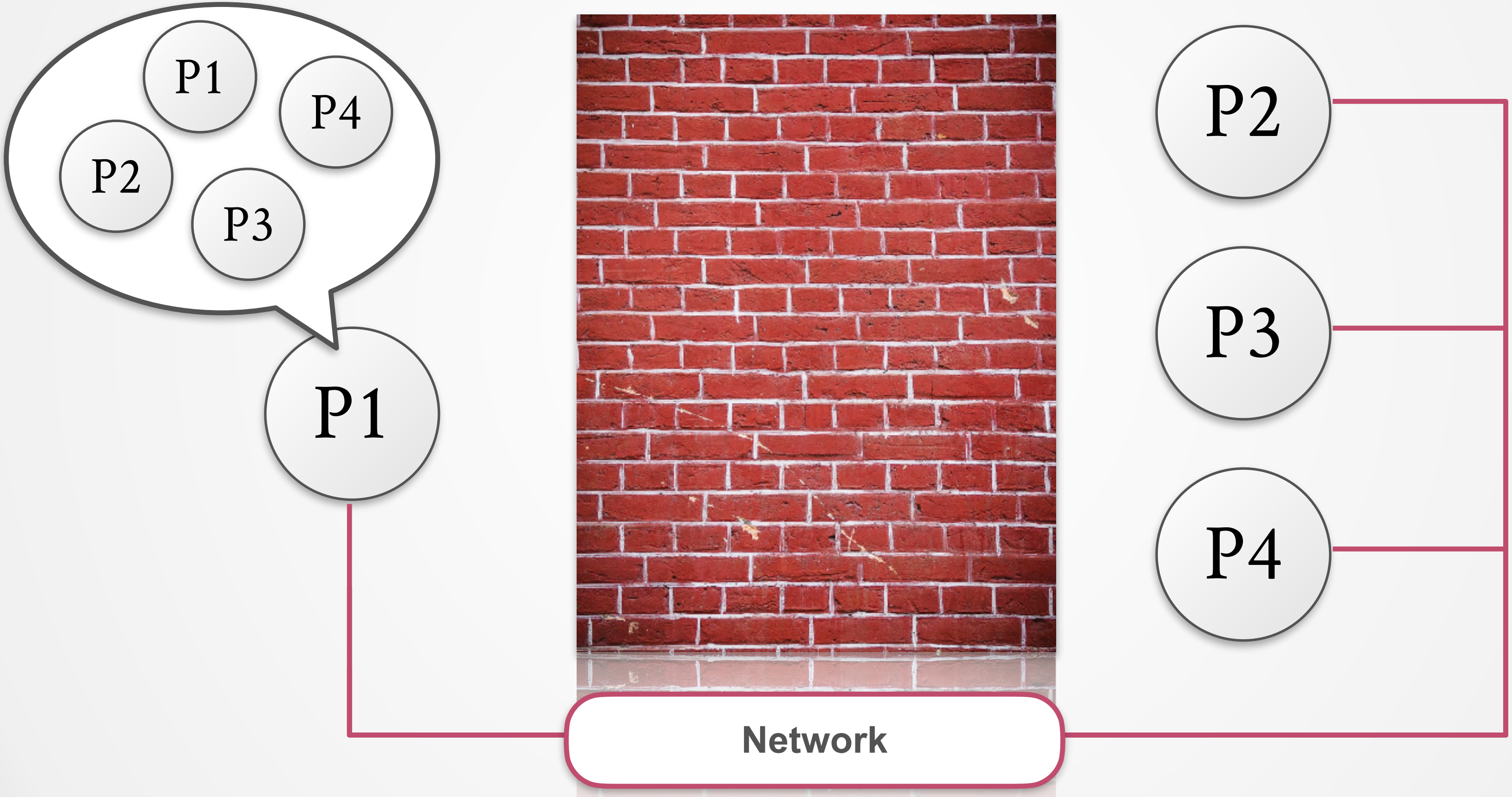
"is P2 dead or is it just too slow?"

"is there life after death?"

"how long should I wait to get response?"

- Time-related questions need to be <u>abstracted</u>..somehow

THE PROBLEM



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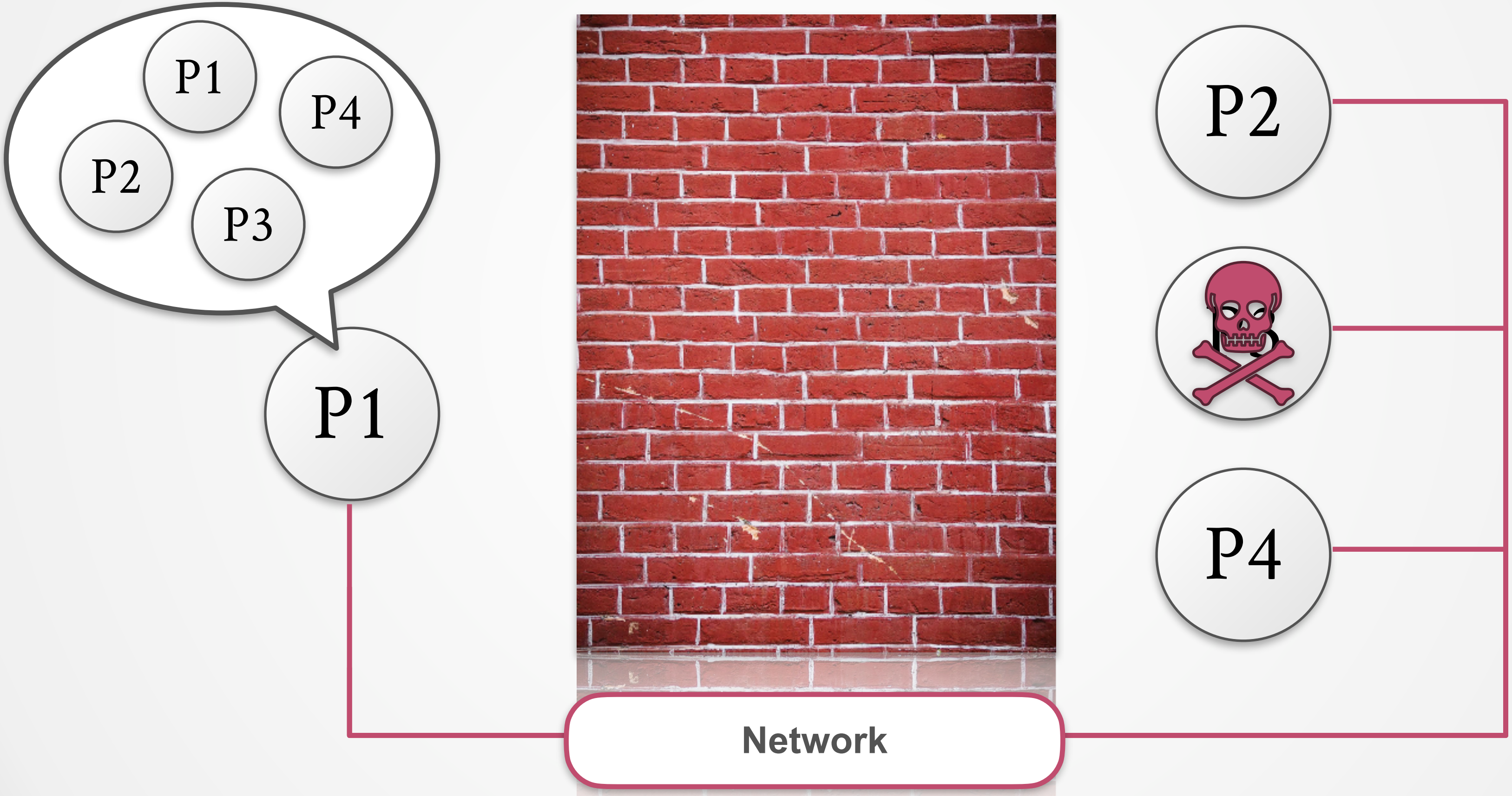

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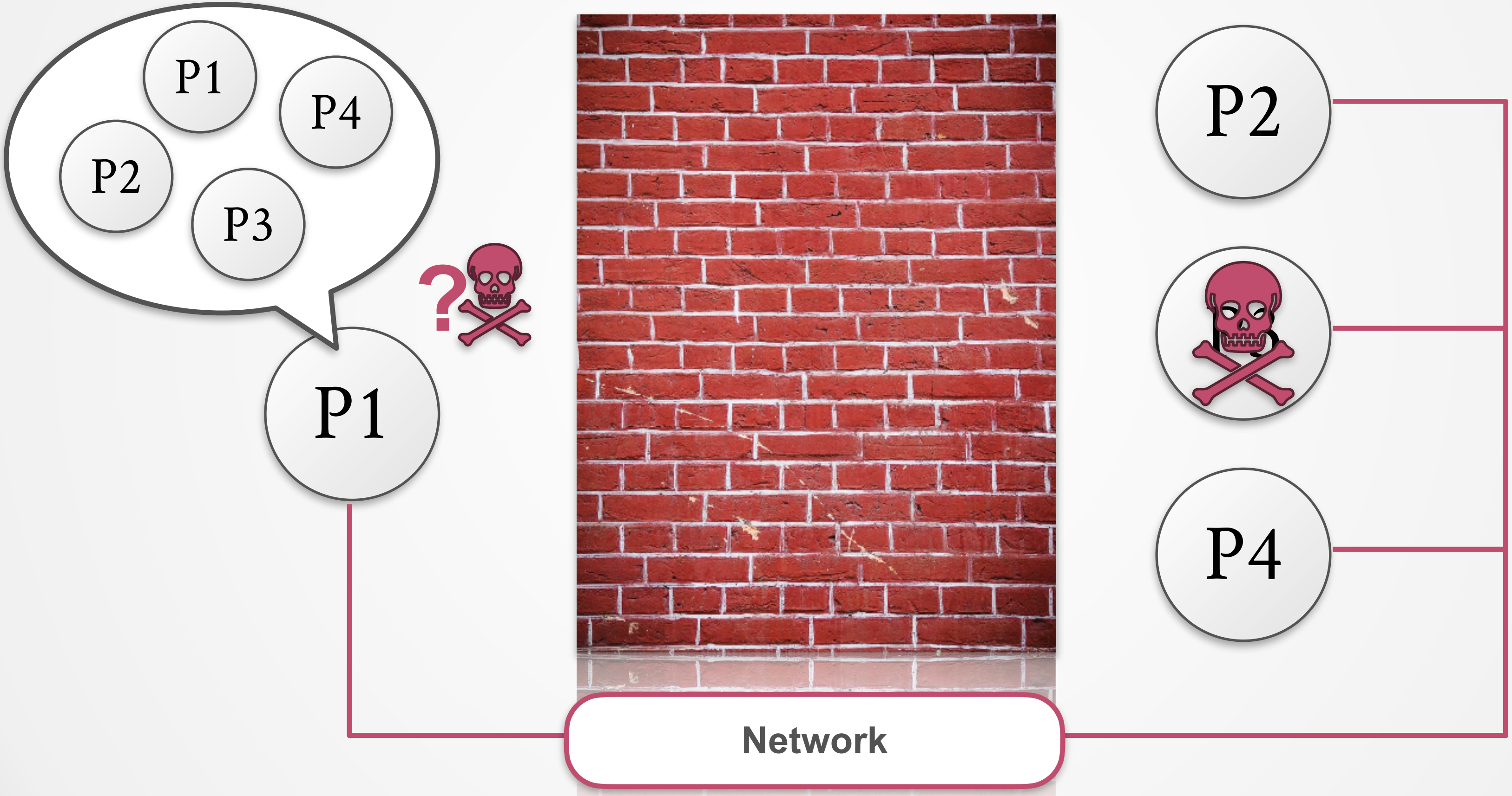

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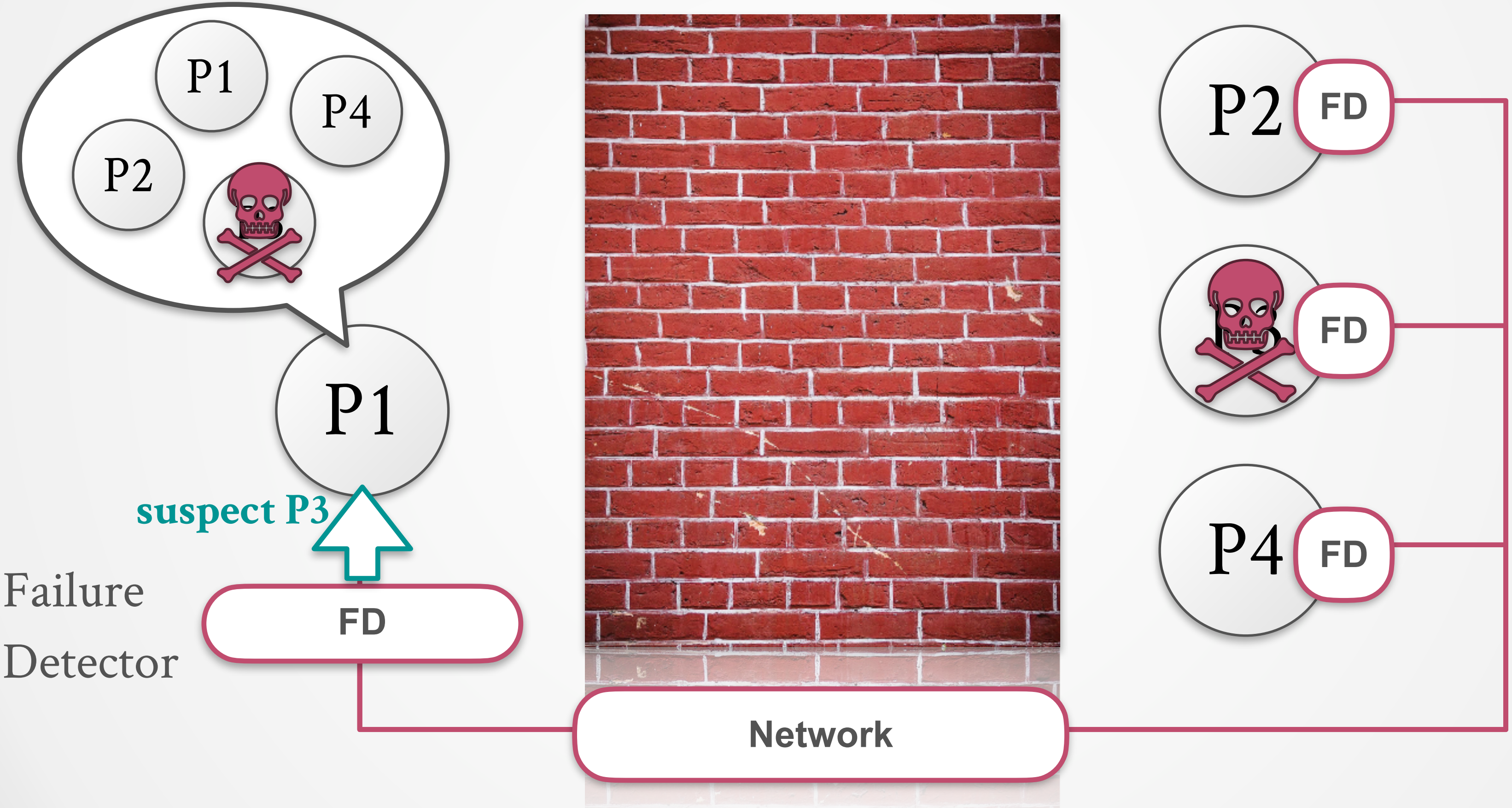
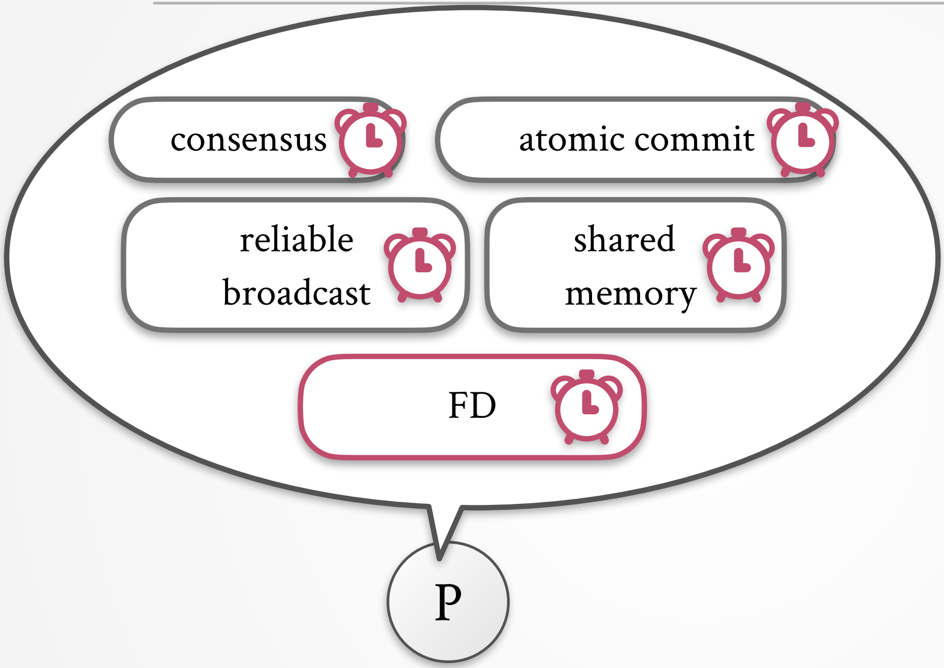


P1
P4
P2
P1
suspect P3
Failure
Detector
FD
Network
P2
FD
FD
P4
FD

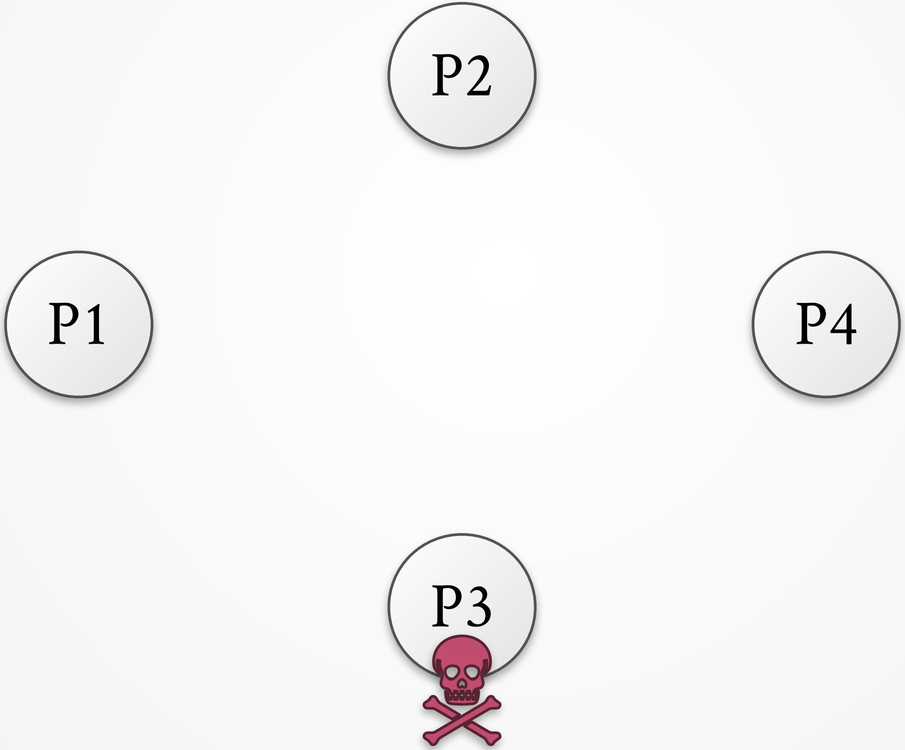
Motivation



- A Failure Detector can substitute timing assumptions.

- **Spoiler Alert**: The Accuracy of a FD relates to the strength of the underlying model.

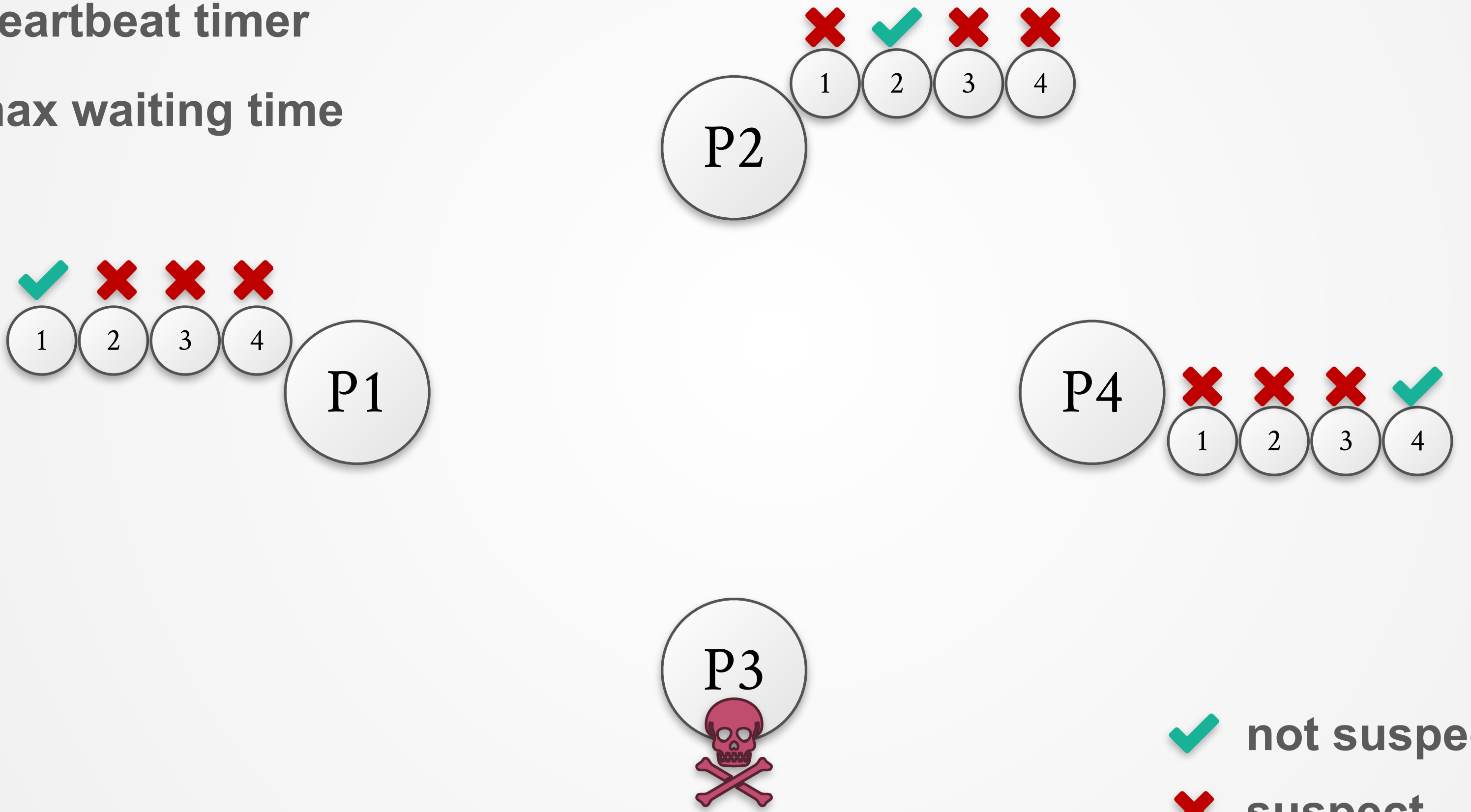
IDEA SKETCH



HEARTBEATS

= heartbeat timer

= max waiting time



not suspect

suspect

HEARTBEATS

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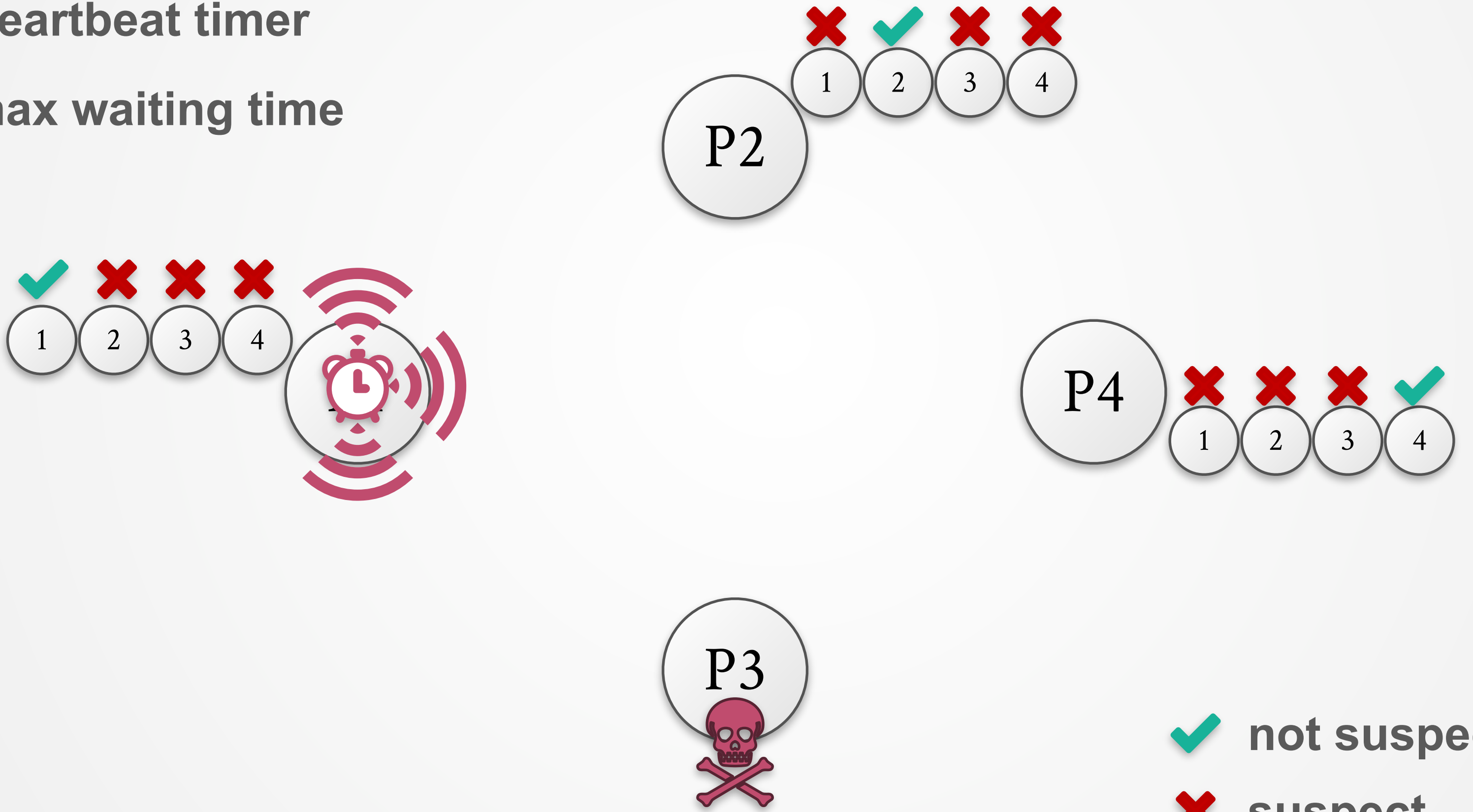

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Heartbeats

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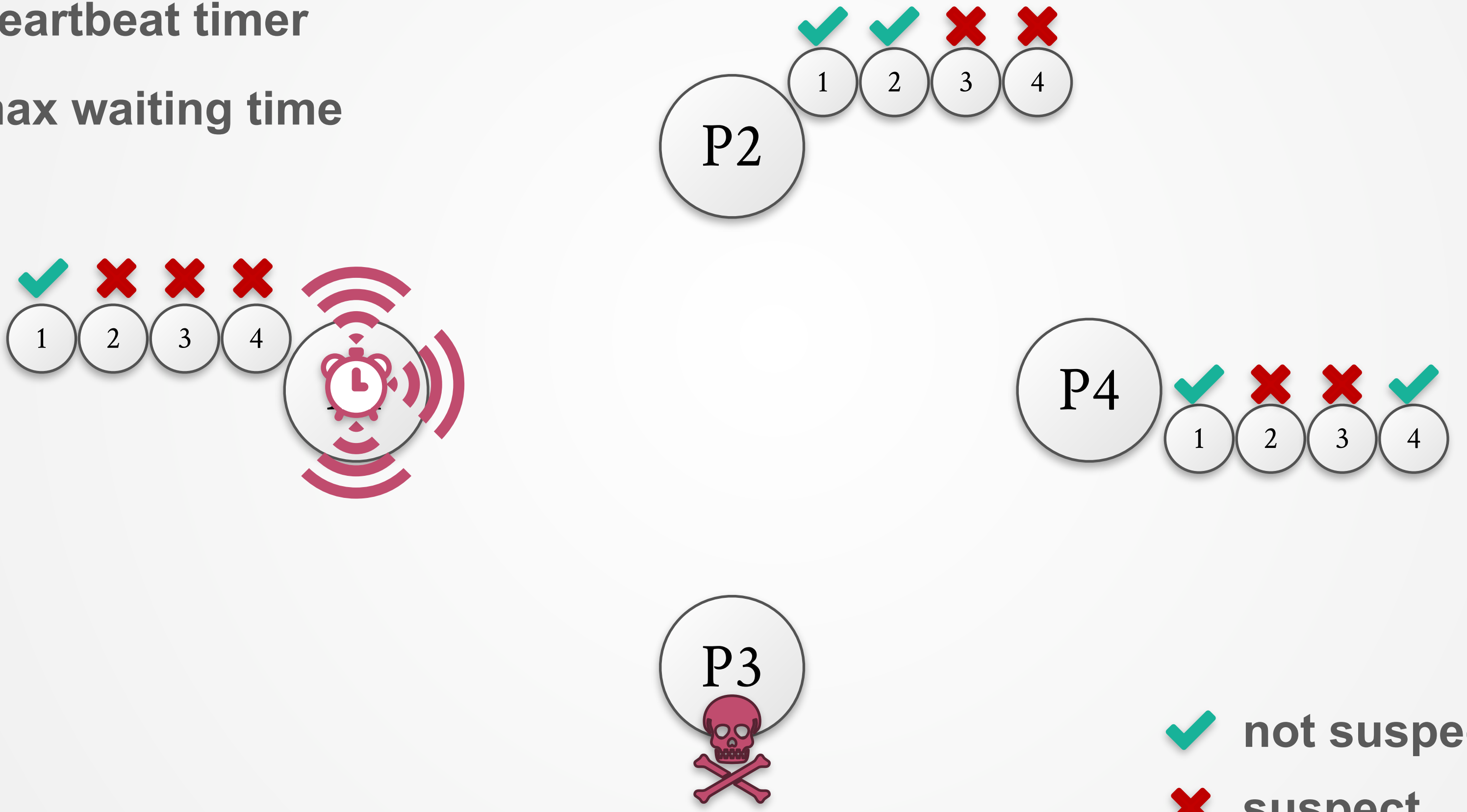

not suspect

suspect

HEARTBEATS

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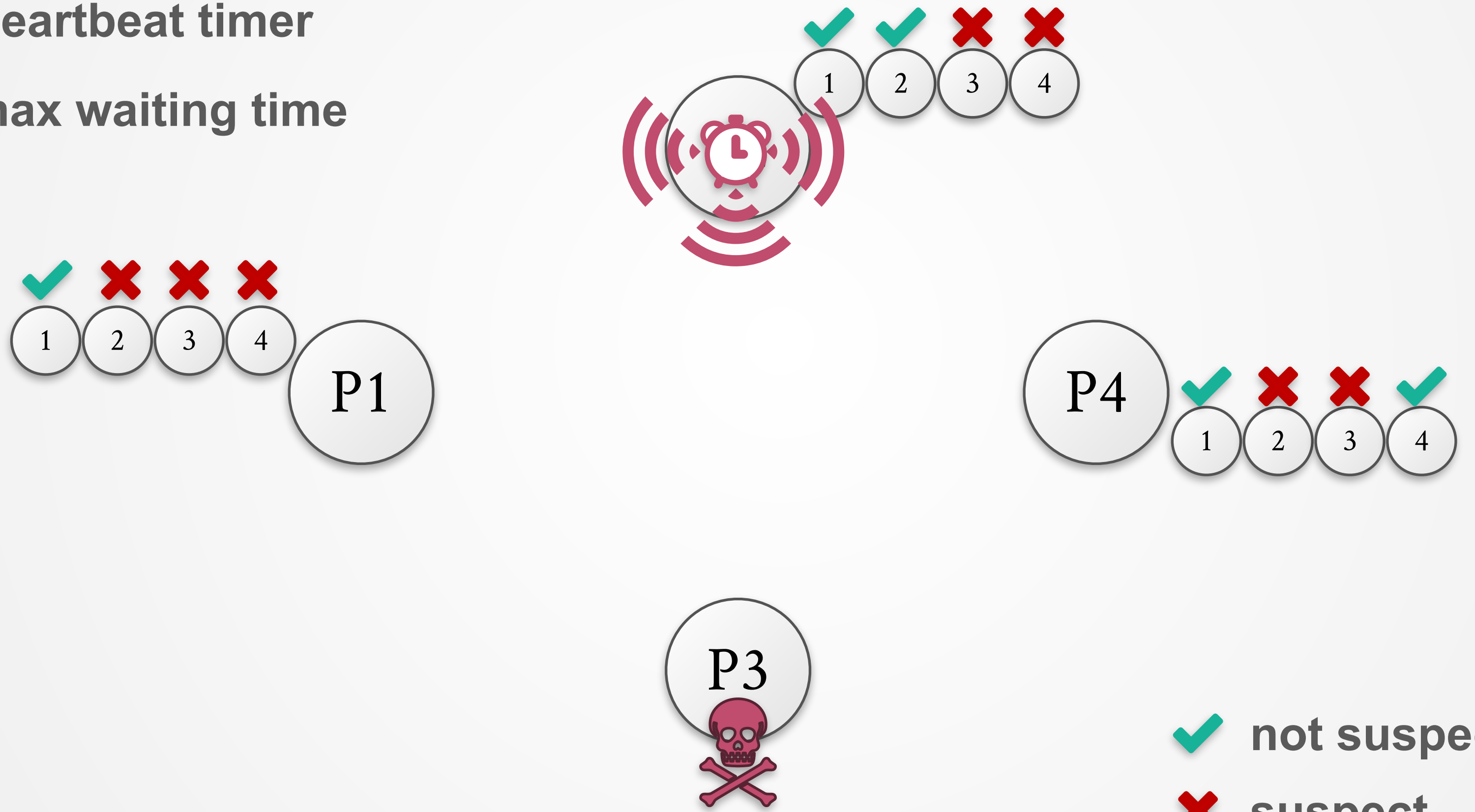

✔ not suspect

✖ suspect

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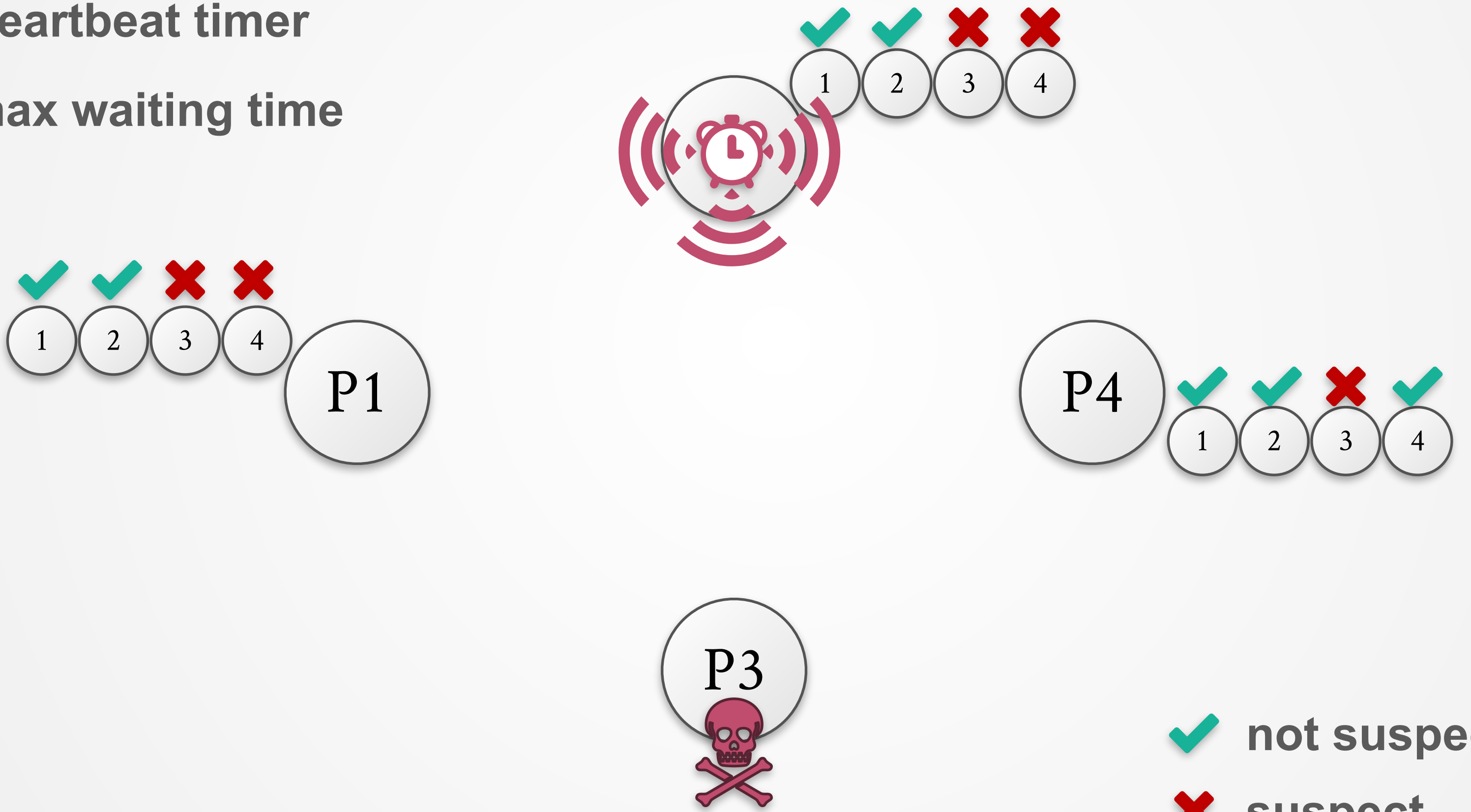

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suspect

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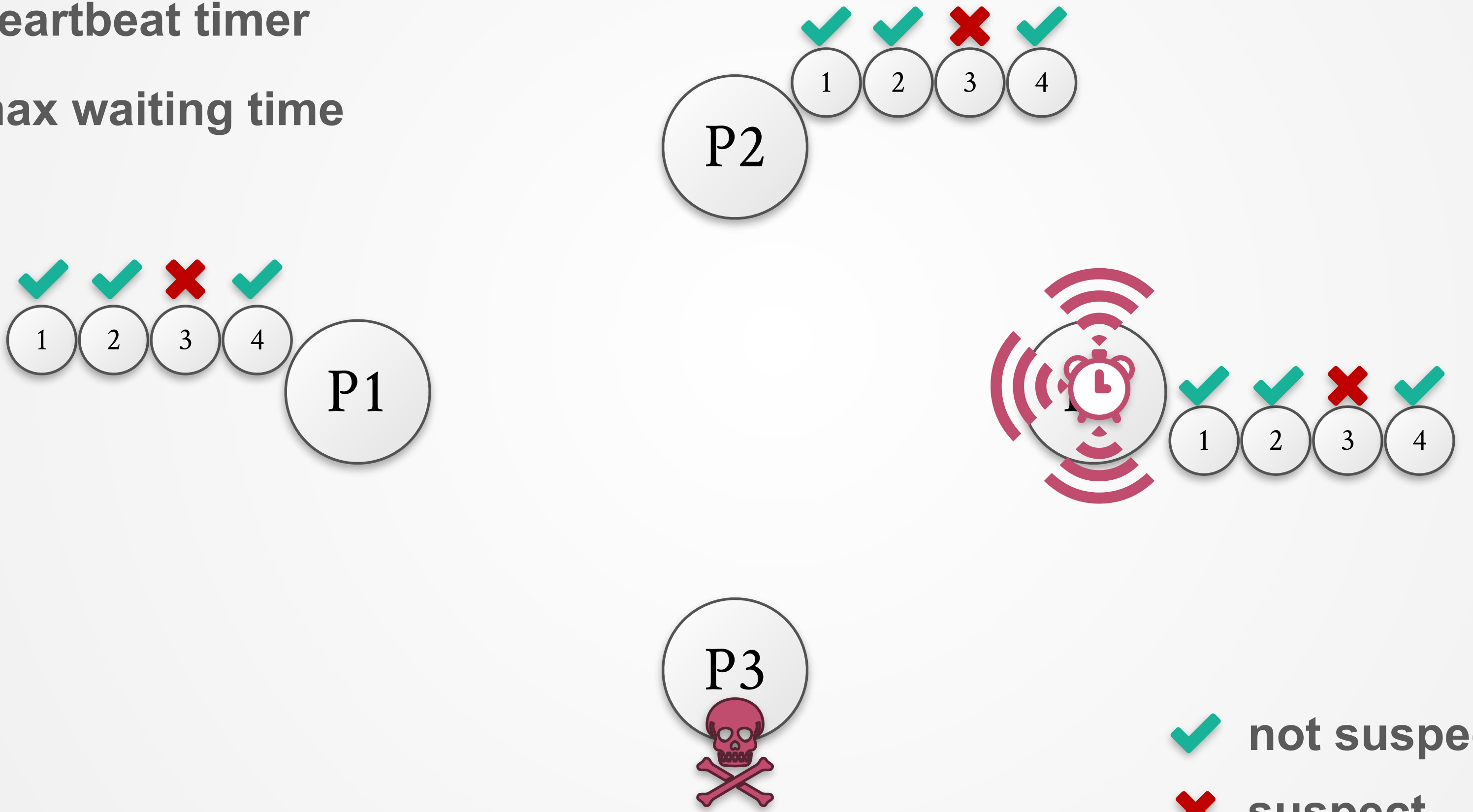

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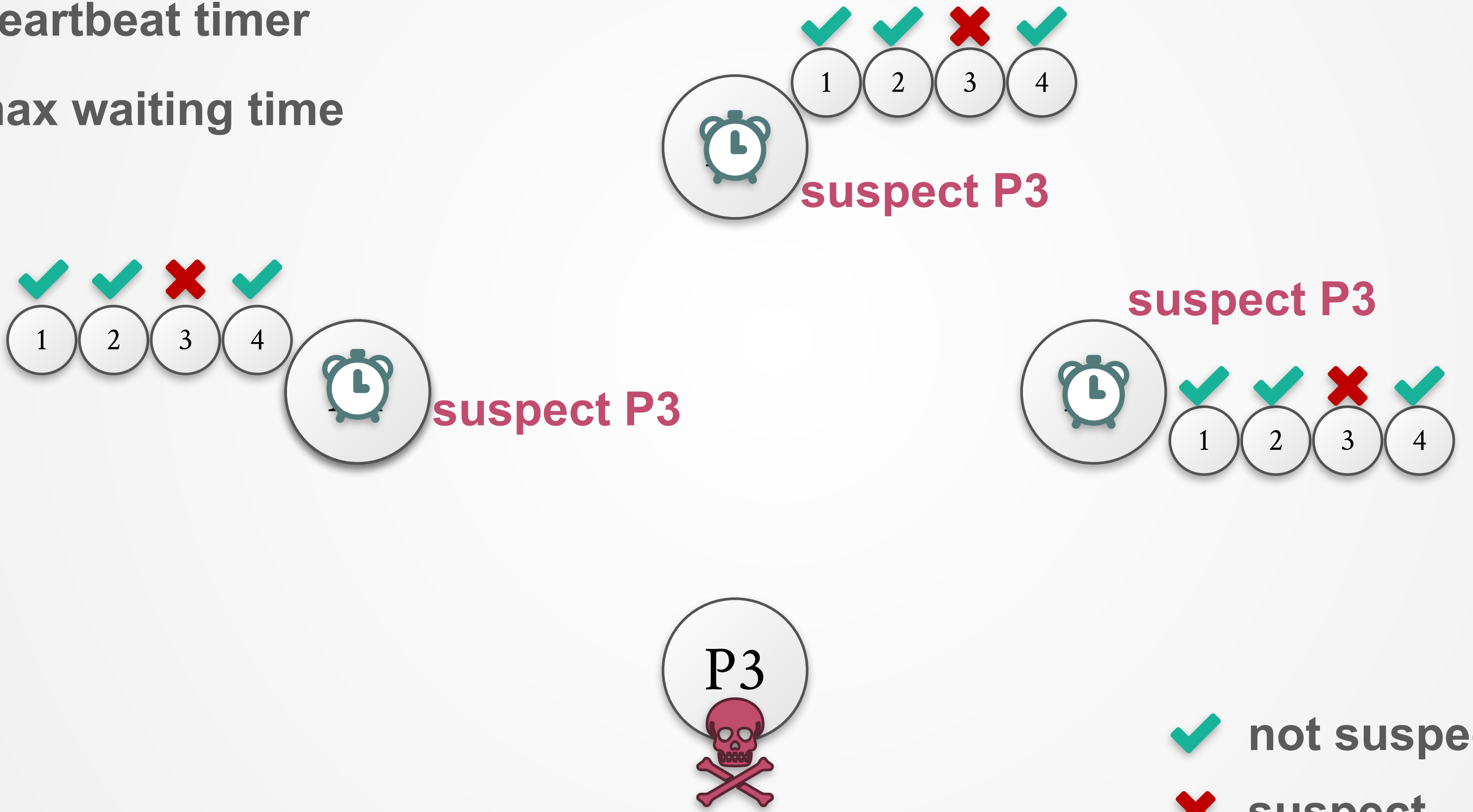


not suspect

suspect

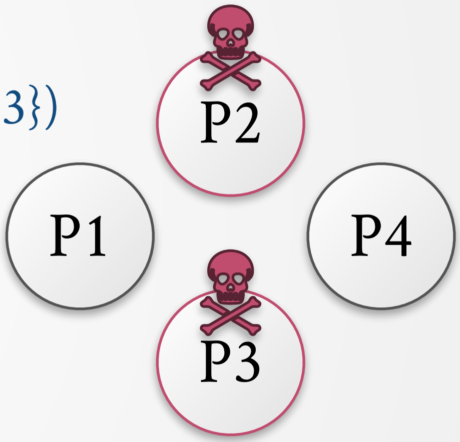
Implementation Idea

- Periodically exchange heartbeat messages
- Timeout based on worst case message round trip
  - If timeout, then suspect process
  - If received message from suspected node, revise suspicion and increase time-out

Completeness and Accuracy

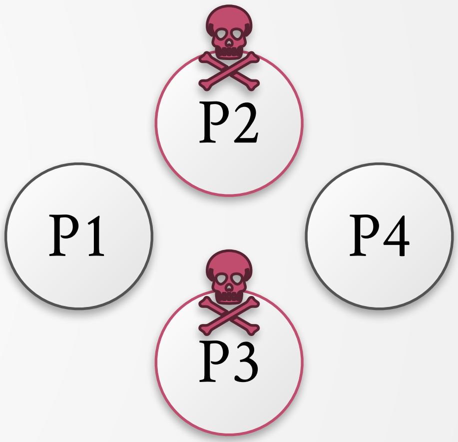
- Two important types of requirements

1. **Completeness**
    - No False-Negatives! (i.e., should suspect at least {P2,P3})
    - When do they have to be suspected?
2. **Accuracy**
    - No False-Positives! (i.e., should not suspect {P1,P4})
    - When are they allowed to be suspected?



Completeness and Accuracy

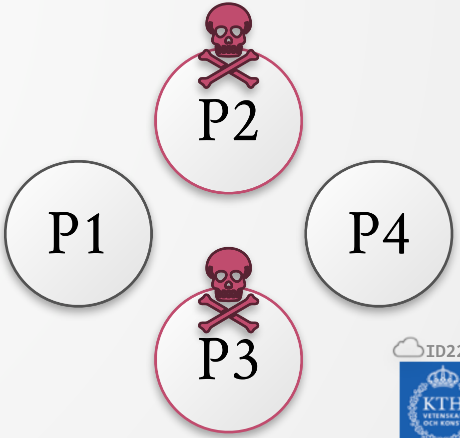
- Assume the **asynchronous** system model
  - Is it possible to achieve completeness?
    - Yep, suspect all processes (i.e., {P1, P2, P3, P4})
  - Is it possible to achieve accuracy?
    - Yep, suspect none (i.e., { })
  - How about achieving both?
    - NOPE!
- Failure detectors are feasible **only** in synchronous and partially synchronous systems



REQUIREMENTS: COMPLETENESS

- **Strong Completeness**
  - Every crashed process is eventually detected by all correct processes

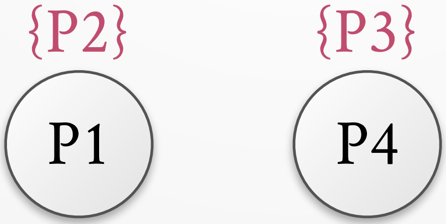
- There exists a time after which…all crashed processes are detected by all correct processes
  - We only study failure detectors with this property

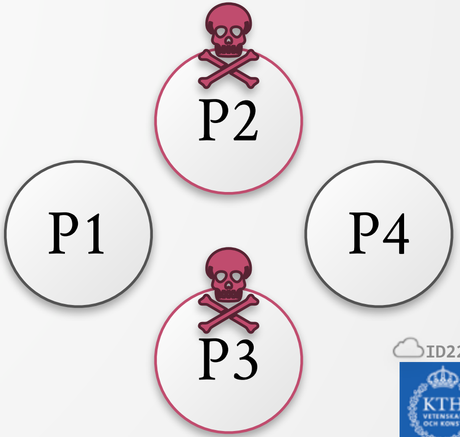


Requirements: Completeness

- **Weak Completeness**
  - Every crashed process is eventually detected by some correct process

- There exists a time after which…all crashed processes are detected by some correct processes
  - Possibly detected by different correct processes





REQUIREMENTS: ACCURACY

- **Strong Accuracy**
  - No correct process is ever suspected
- For all process p and q,
  - p does not suspect q, unless q has crashed
- Is it realistic? [d]
  - Strong assumption, requires synchrony
  - I.e. no premature timeouts

Requirements: Accuracy

- **Weak Accuracy**
  - There exists a correct process which is never suspected by any process
- There exists a correct node P
  - All nodes will never suspect P
- Still strong assumption
  - One node is always "well-connected"

Requirements: Accuracy

Eventual Strong Accuracy

After some finite time the FD provides strong accuracy

Eventual Weak Accuracy

After some finite time the detector provides weak accuracy

After some time, the requirements are fulfilled

Prior to that, any behaviour is possible!

Quite weak assumptions [d]

When can eventual weak accuracy be achieved?

Classes of Failure Detectors

The Practical FDs

Four detectors with strong completeness

- Perfect Detector (P)
  - Strong Accuracy
- Strong Detector (S)
  - Weak Accuracy

Synchronous Systems

- Eventually Perfect Detector (◊P)
  - Eventual Strong Accuracy
- Eventually Strong Detector (◊S)
  - Eventual Weak Accuracy

Partially Synchronous Systems

LESS INTERESTING FDS

Four detectors with weak completeness

- Detector Q
  - Strong Accuracy
- Weak Detector (W)
  - Weak Accuracy

Synchronous Systems

- Eventually Detector Q (◊Q)
  - Eventual Strong Accuracy
- Eventually Weak Detector (◊W)
  - Eventual Weak Accuracy

Partially Synchronous Systems

Perfect Failure Detector - P

INTERFACE OF PERFECT FAILURE DETECTOR

Module:

Name: PerfectFailureDetector, instance **P**

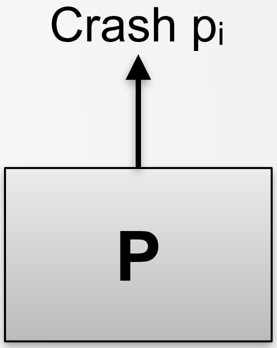
Events:

Indication (out): ⟨**P**, Crash | p_i⟩

Notifies that process p_i has crashed

Properties:

PFD1 (strong completeness)
PFD2 (strong accuracy)

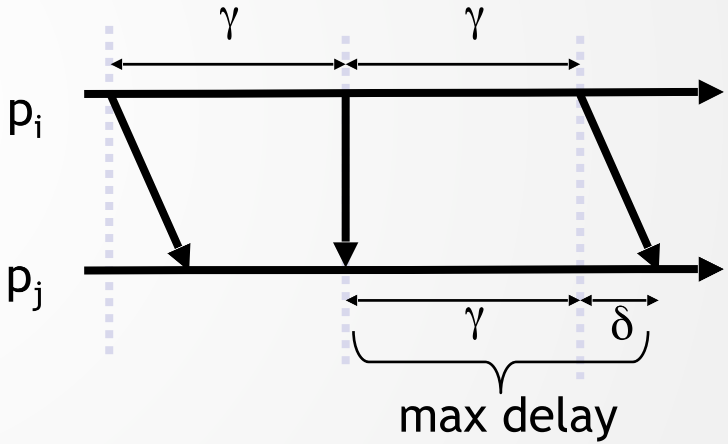


PROPERTIES OF P

- Properties:
  - *PFD1 (strong completeness)*
    - **Eventually every process that crashes is permanently detected by every correct process** (liveness)
  - *PFD2 (strong accuracy)*
    - If a node p is detected by any node, then p has crashed (safety)
- Safety or Liveness?

Implementing P in Synchrony

- Assume synchronous system
  - Max transmission delay between 0 and δ time units
- Each process every γ time units
  - Send <heartbeat> to all processes
- Each process waits $\gamma+\delta$ time units
  - If did not get <heartbeat> from p_i
    - Detect <crash | p_i>



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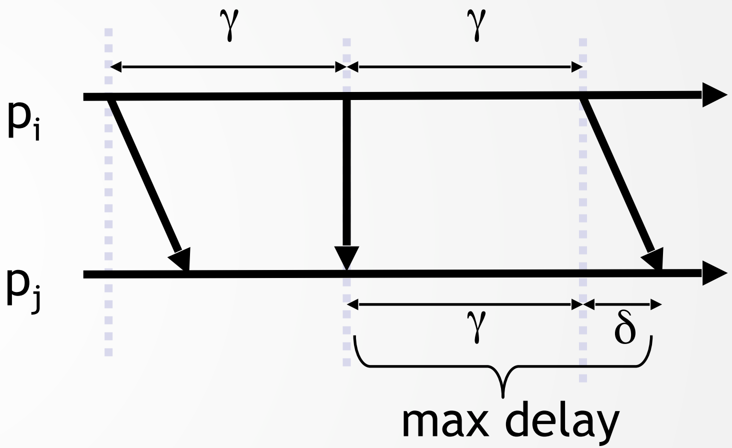
Correctness of P

PFD1 (strong completeness)

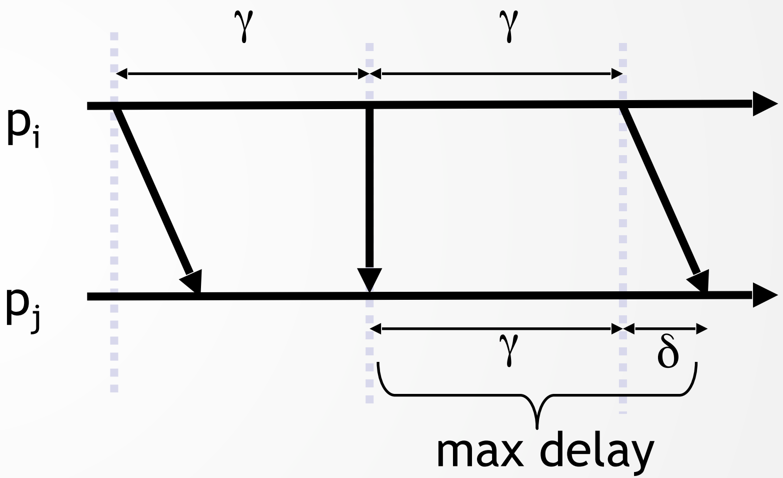
- A crashed process doesn't send <heartbeat>
- Eventually every process will notice the absence of <heartbeat>



Correctness of P

PFD2 (strong accuracy)

- Assuming local computation is negligible
- Maximum time between 2 heartbeats
    - $\gamma+\delta$ time units
- If alive, all process will receive hb in time
    - No inaccuracy



Eventually Perfect Failure Detector - $\Diamond P$

Interface of ◊P

Module:

Name: EventuallyPerfectFailureDetector, **instance** ◊P

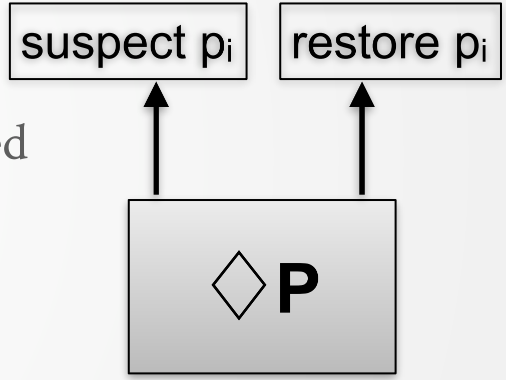
Events:

Indication: ⟨◊P, suspect | p_i⟩

Notifies that process p_i is suspected to have crashed

Indication: ⟨◊P, restore | p_i⟩

Notifies that process p_i is not suspected anymore



Properties:

PFD1 *(strong completeness)*

PFD2 *(eventual strong accuracy).* Eventually, no correct process is suspected by any correct process

Implementing $\Diamond P$

- Assume partially synchronous system
  - Eventually some bounds exists

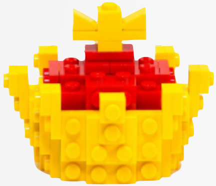
- Each process every γ time units
  - Send <heartbeat> to all processes

- Each process waits T time units
  - If did not get <heartbeat> from p_i
    - Indicate <suspect | p_i> if p_i is not in **suspected** set
    - Put p_i in **suspected** set

  - If get HB from p_i, and p_i is in **suspected**
    - Indicate <restore | p_i> and remove p_i from **suspected**
    - Increase timeout **T**

Correctness of ◇P

- ***EPFD1 (strong completeness)***
  - Same as before
- ***EPFD2 (eventual strong accuracy)***
  - Each time p is inaccurately suspected by a correct q
    - Timeout T is increased at q
    - Eventually system becomes synchronous, and T becomes larger than the unknown bound δ ($T>\gamma+\delta$)
    - q will receive HB on time, and never suspect p again



Leader Election

LEADER ELECTION VS FAILURE DETECTION

- Failure detection captures failure behaviour
  - Detect failed processes

- Leader election (LE) also captures failure behaviour
  - Detect correct processes (a single and same for all)

- Formally, leader election is a FD
  - Always suspects all processes except one (leader)
  - Ensures some properties regarding that process

LEADER ELECTION VS. FAILURE DETECTION

We will define two leader election abstractions and algorithms

- Leader election (LE) which "matches" P
- Eventual leader election (Ω) which "matches" $\diamond$P

Matching LE and P

P's properties

P always eventually detects failures (strong completeness)

P never suspects correct processes (strong accuracy)

Completeness of **LE**

Informally: eventually ditch failed leaders

Formally: eventually every correct process trusts some correct process

Accuracy of **LE**

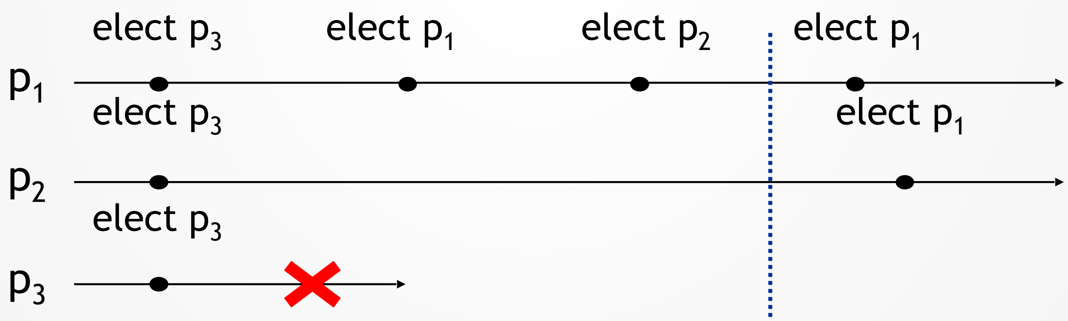
Informally: never ditch a correct leader

Formally: No two correct processes trust different correct nodes

- Is this really accuracy? [d]
- Yes! Assume two processes trust different correct processes
  - One of them must eventually switch, i.e. leaving a correct node

LE DESIRABLE PROPERTIES

- LE always eventually detects failures
  - Eventually every correct process trusts some correct node
- LE is always accurate
  - No two correct processes trust different correct processes
- But the above two permit the following



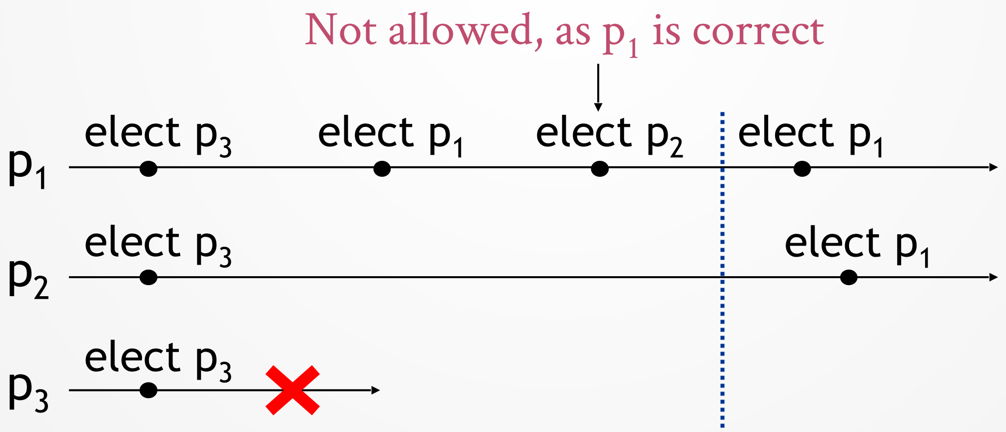
- But P_1 is "inaccurately" leaving a correct leader

LE DESIRABLE PROPERTIES

To avoid "inaccuracy" we add

Local Accuracy:

If a process is elected leader by p_i, all previously elected leaders by p_i have crashed



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Interface of Leader Election

Module:

Name: LeaderElection (le)

Events:

Indication: $\langle$leLeader | $p_i\rangle$

Indicate that leader is node p_i

Properties:

- ***LE1 (eventual completeness).*** Eventually every correct process trusts some correct process
- ***LE2 (agreement).*** No two correct processes trust different correct processes
- ***LE3 (local accuracy).*** If a process is elected leader by p_i, all previously elected leaders by p_i have crashed

Implementing LE

- Globally rank all processes

  E.g. rank ordering $rank(p_1)>rank(p_2)>rank(p_3)> \dots$

- maxrank(S)

  The process $p \in S$, with the largest rank

Implementing LE

LeaderElection, **instance** le

Uses:

PerfectFailureDetector, **instance P**

upon event $\langle$le, Init$\rangle$ **do**

suspected := $\emptyset$
leader := $\perp$

upon event $\langle$**P**, Crash | p$\rangle$ **do**

suspected := suspected $\cup$ {p}

upon leader $\neq$ maxrank($\Pi \setminus$ suspected) **do**

leader := maxrank($\Pi \setminus$ suspected)
trigger $\langle$le, Leader | leader$\rangle$

Eventual Leader Election - Ω

MATCHING Ω AND ◊P

◊P weakens P by only providing eventual accuracy

Weaken LE to Ω by only guaranteeing eventual agreement

LE Properties:

- ***LE1 (eventual completeness).*** Eventually every correct node trusts some correct node

eventual

- ***LE2 (agreement).*** No two correct nodes trust different correct nodes

- ~~***LE3 (local accuracy).*** If a node is elected leader by p_i, all previously elected leaders by p_i have crashed~~

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Interface of Eventual Leader Election

Module:

Name: EventualLeaderElection (Ω)

Events:

Indication (out): $\langle \Omega, \text{Trust} \mid p_i \rangle$

Notify that p_i is trusted to be leader

Properties:

ELD1 (eventual completeness). Eventually every correct node trusts some correct node

ELD2 (eventual agreement). Eventually no two correct nodes trust different correct node

Eventual Leader Detection Ω

In crash-stop process abstraction

Ω is obtained directly from ◊P

- Each process trusts the process with highest rank among all processes not suspected by ◊P
- Eventually, exactly one correct process will be trusted by all correct processes

IMPLEMENTING Ω

EventualLeaderElection, **instance** Ω

Uses: EventuallyPerfectFailureDetector, **instance** ◊**P**

upon event ⟨ Ω, Init⟩ **do**

  suspected := ∅; leader := ⊥

upon event ⟨◊**P**, Suspect |p⟩ **do**

  suspected := suspected ∪ {p}

upon event ⟨◊**P, **Restore | p⟩ **do**

  suspected := suspected \ {p}

upon leader ≠ maxrank(Π \ suspected) **do**

  leader := maxrank(Π \ suspected)

  trigger ⟨ Ω, Trust | leader⟩

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Ω for Crash Recovery

Can we elect a recovered process? [d]

Not if it keeps crash-recovering infinitely often!

Basic idea

Count number of times you've crashed (**epoch**)

Distribute your **epoch** periodically to all nodes

Elect leader with lowest **(epoch, rank(node))**

Implementation

Similar to ◊P and Ω for crash-stop

Piggyback **epoch** with heartbeats

Store **epoch**, upon recovery load **epoch** and increment

Reductions

REDUCTIONS

We say $X \preccurlyeq Y$ if

- X can be solved given a solution of Y
- Read X is reducible to Y
- Informally, problem X is easier or as hard as Y

PREORDERS, PARTIAL ORDERS…

- A relation $\preccurlyeq$ is a preorder on a set A if for any x,y,z in A
  - $x \preccurlyeq x$ (reflexivity)
  - $x \preccurlyeq y$ and $y \preccurlyeq z$ implies $x \preccurlyeq z$ (transitivity)
- Difference between preorder and partial order
  - Partial order is a preorder with anti-symmetry
    - $x \preccurlyeq y$ and $y \preccurlyeq x$ implies $x = y$
- For preorder two different objects x and y can be symmetric
  - It is possible that $x \preccurlyeq y$ and $y \preccurlyeq x$ for two different x and y, $(x \neq y)$

Reducibility ≼ is a preorder

- ≼ is a preorder
  - Reflexivity. X≼X
    - X can be solved given a solution to X
  - Transitivity. X≼Y and Y≼Z implies X≼Z
    - Since Y≼Z, use implementation of Z to implement Y.
    - ….use that implementation of Y to implement X.
    - Hence we implemented X from Z's implementation

- ≼ is not anti-symmetric, thus not a partial order
  - Two different X and Y can be equivalent
    - Distinct problems X and Y can be solved from the other's solution

Shortcut definitions

- We write $X \simeq Y$ if
  - $X \preccurlyeq Y$ and $Y \preccurlyeq X$
  - Problem X is equivalent to Y

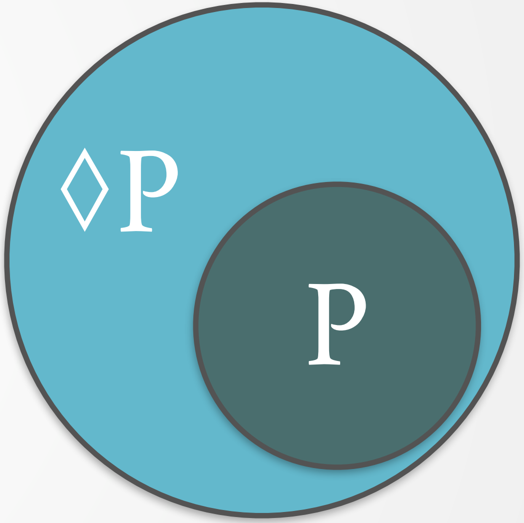
- We write $X \prec Y$ if
  - $X \preccurlyeq Y$ and not $X \simeq Y$
  - or equivalently, $X \preccurlyeq Y$ and not $Y \preccurlyeq X$

  - Problem X is strictly weaker than Y, or
  - Problem Y is strictly stronger than X

EXAMPLE

- It is true that ◊P≼P
  - Given P, we can implement ◊P
    - We just return P's suspicions.
    - P always satisfies ◊P's properties
- In fact, ◊P≺P in the asynchronous model
  - Because not P≼◊P is true
- Reductions common in computability theory
  - If X≼Y, and if we know X is impossible to solve
    - Then Y is impossible to solve too
  - If ◊P≼P, and some problem Z can be solved with ◊P
    - Then Z can also be solved with P

Possible Traces



Weakest FD for a problem?

- Often P is used to solve problem X
  - But P is not very practical (needs synchrony)
  - Is X a "practically" solvable problem?
    - Can we implement X with ◊P?
    - Sometimes a weaker FD than P will not solve X
      - Proven using reductions

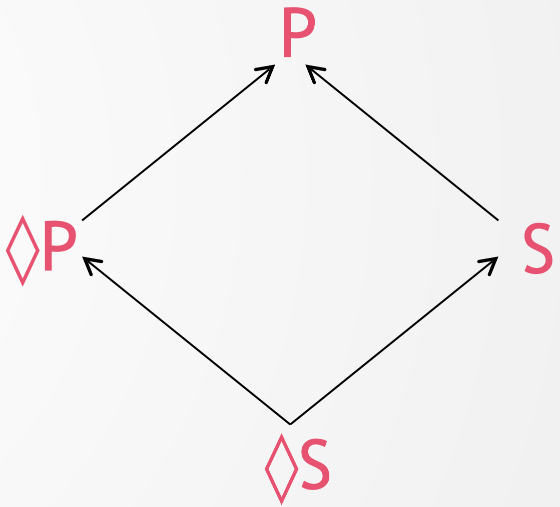
WEAKEST FD FOR A PROBLEM

- Common proof to show P is weakest FD for X
  - Prove that P≼X
  - I.e. P can be solved given X
- If P≼X then ◊P≺X
  - Because we know ◊P≺P and P≃X, i.e. ◊P≺P≃X
    - If we can solve X with ◊P, then
    - we can solve P with ◊P, which is a contradiction

How are the detectors related

TRIVIAL REDUCTIONS

- Strongly complete
  - ◊P≼P
    - P is always strongly accurate, thus also eventually strongly accurate
  - ◊S≼S
    - S is always weakly accurate, thus also eventually weakly accurate
  - S≼P
    - P is always strongly accurate, thus also always weakly accurate
  - ◊S≼◊P
    - ◊P is always eventually strongly accurate, thus also always eventually weakly accurate



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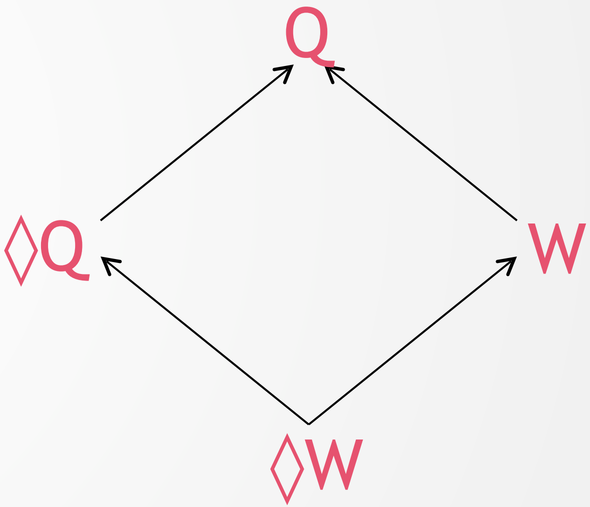
Trivial Reductions (2)

- Weakly complete
  - ◊Q≼Q
    - Q is always strongly accurate, thus also eventually strongly accurate
  - ◊W≼W
    - W is always weakly accurate, thus also eventually weakly accurate
  - W≼Q
    - Q is always strongly accurate, thus also always weakly accurate
  - ◊W≼◊Q
    - ◊Q is always eventually strongly accurate, thus also always eventually weakly accurate



Completeness "Irrelevant"

- Weak completeness trivially reducible to strong
- Strong completeness reducible to weak
  - i.e. can get strong completeness from weak
    - P≼Q, S≼W, ◊P≼◊Q, ◊S≼◊W,
  - They're equivalent!
    - P≃Q, S≃W, ◊P≃◊Q, ◊S≃◊W

Completeness \ Accuracy	Strong	Weak	Eventual Strong	Eventual Weak
Strong	P	S	◊P	◊S
Weak	Q	W	◊Q	◊W

Proving Irrelevance of Completeness

- Weak completeness ensures
  - every crash is eventually detected by some correct node
- Simple idea
  - Every process q broadcast suspicions **Susp** periodically
  - upon event receive <**S**,q>
    - Susp := (Susp ∪ S) — {q}
- Every crash is eventually detected by all correct p
  - Can this violate some accuracy properties?

also works like a heartbeat

Maintaining Accuracy

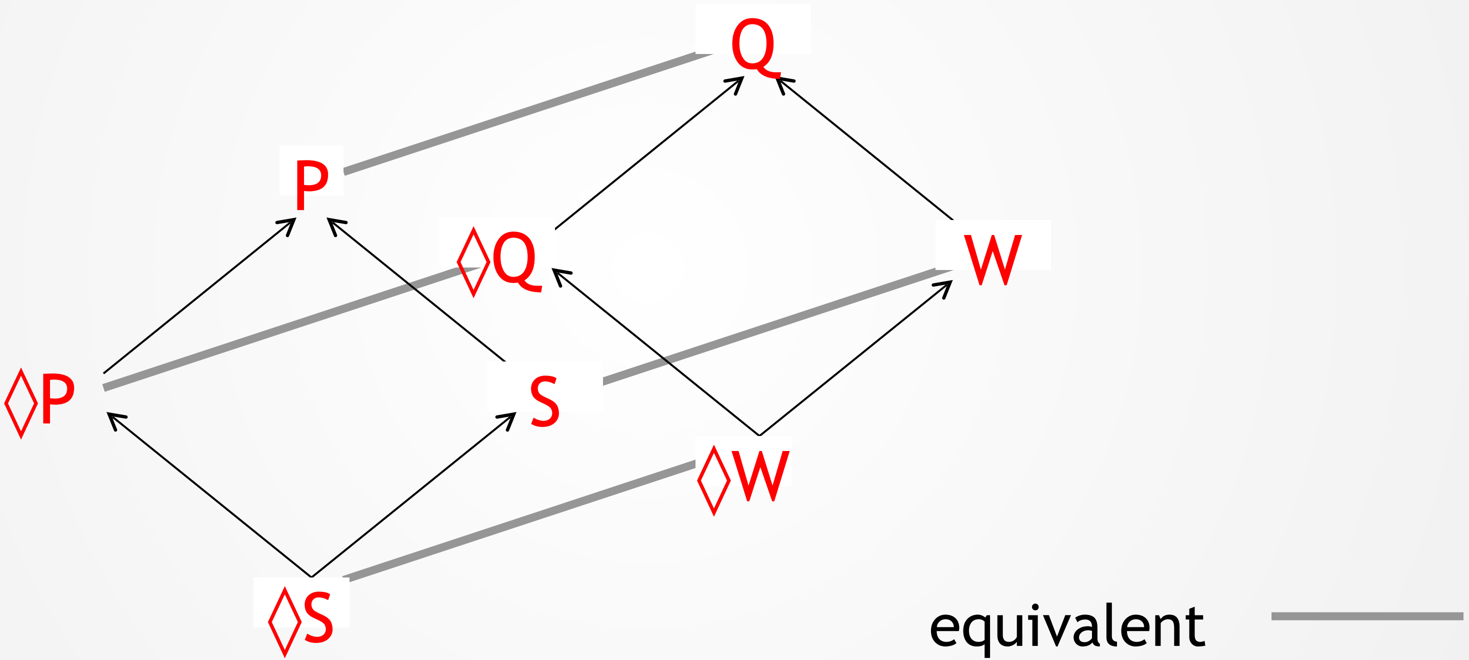
- Strong and Weak Accuracy aren't violated
- Strong accuracy
  - No one is ever inaccurate
  - Our reduction never spreads inaccurate suspicions
- Weak accuracy
  - Everyone is accurate about at least one process p
    - No one will spread inaccurate information about p

Maintaining Eventual Accuracy

- Eventual Strong and Eventual Weak Accuracy aren’t violated

- Proof is almost same as previous page
  - Eventually all faulty processes crash
  - Inaccurate suspicions undone
    - Will get heartbeat from correct nodes and revise (–{q})

RELATION BETWEEN FDS



Ω ALSO A FD

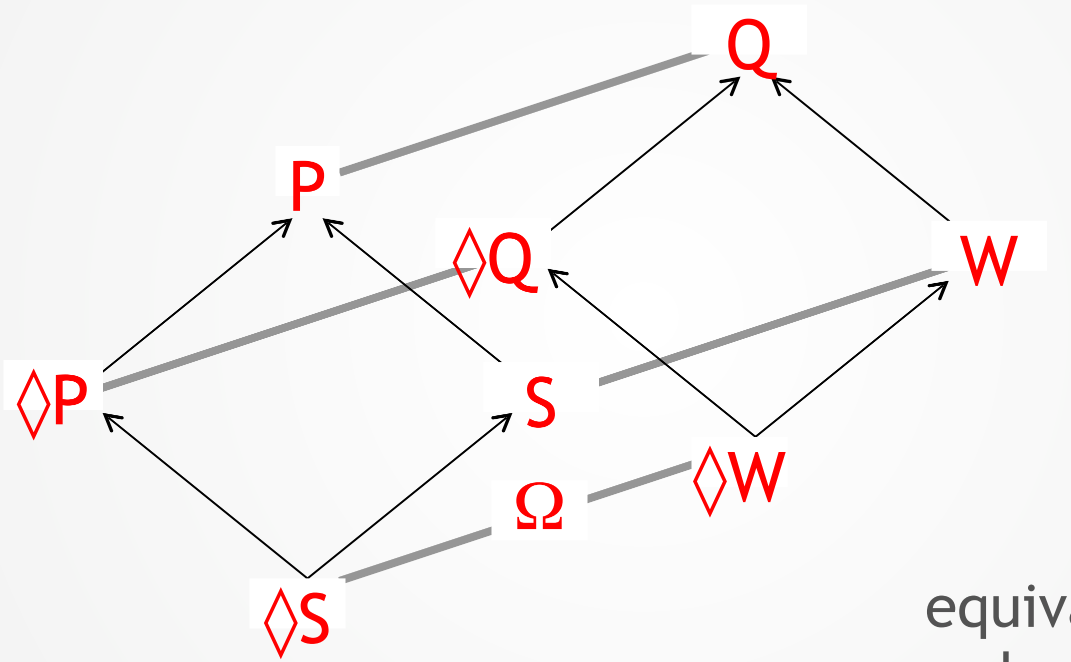
- Can we implement ◊S with Ω? [d]
  - I.e. is it true that ◊S≼Ω
  - Suspect all nodes except the leader given by Ω
    - Eventual Completeness
      - All nodes are suspected except the leader (which is correct)
    - Eventual Weak Accuracy
      - Eventually, one correct node (leader) is not suspected by anyone
  - Thus, ◊S≼Ω

Ω EQUIVALENT TO ◊S (AND ◊W)

- We showed $\Diamond S \preccurlyeq \Omega$, it turns out we also have $\Omega \preccurlyeq \Diamond S$
  - I.e. $\Omega \simeq \Diamond S$

- The famous CHT (Chandra, Hadzilocas, Toueg) result
  - If consensus implementable with detector D
    - Then Omega can be implemented using D
  - I.e. if Consensus$\preccurlyeq$D, then $\Omega \preccurlyeq$D
    - Since ◊S can be used to solve consensus, we have $\Omega \preccurlyeq$D
  - Implies ◊W is weakest detector to solve consensus

Relation between FDs (2)



equivalent
reducible to

Combining Abstractions

COMBINING ABSTRACTIONS

Fail-stop

Crash-stop process model
Perfect links + Perfect failure detector (P)

(synchronous)

Fail-silent

Crash-stop process model
Perfect links

(asynchronous)

Fail-noisy

Crash-stop process model
Perfect links + Eventually Perfect failure detector (◊P)

(partially synchronous)

Fail-recovery

Crash-recovery process model
Stubborn links + …

THE REST OF COURSE

- Assume crash-stop system with a perfect failure detector (fail-stop)
  - Give algorithms

- Try to make a weaker assumption
  - Revisit the algorithms