# The weakest failure detectors to solve certain fundamental problems in distributed computing

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# Contribution

The weakest failure detectors for:

- Implementing an atomic register
- Solving consensus
- Solving *quittable* consensus (QC)
- Solving non-blocking atomic commit (NBAC)

in distributed message-passing systems,

for all environments !

# Some related work

- Implementing registers with a majority of correct processes [ABD95]
- The weakest failure detector for consensus with a majority of correct processes [CHT96]
- Implementing registers and solving consensus in other environments [DFG02]
- NBAC with failure detectors [FRT99,Gue02,GK02]

# Roadmap

1. Model: asynchronous system with failure detectors
2. Implementing a register
3. Solving consensus
4. Solving QC
5. Solving NBAC

# Asynchronous message-passing system

- Communication by message-passing through reliable channels
- Processes can fail only by crashing
  Correct processes never crash

- In such a system:
  - ✓ Register can be implemented if and only if a majority of processes are correct [ABD95]
  - ✓ (Weak) consensus is not solvable if at least one process can crash [FLP85]

# Environments

An environment E specifies *when* and *where* failures might occur

Examples:

- Majority of processes are correct
- At most one process crash

# Failure detectors [CT96, CHT96]

Each process has a failure detector module that provides some (maybe incomplete and inaccurate) information about failures

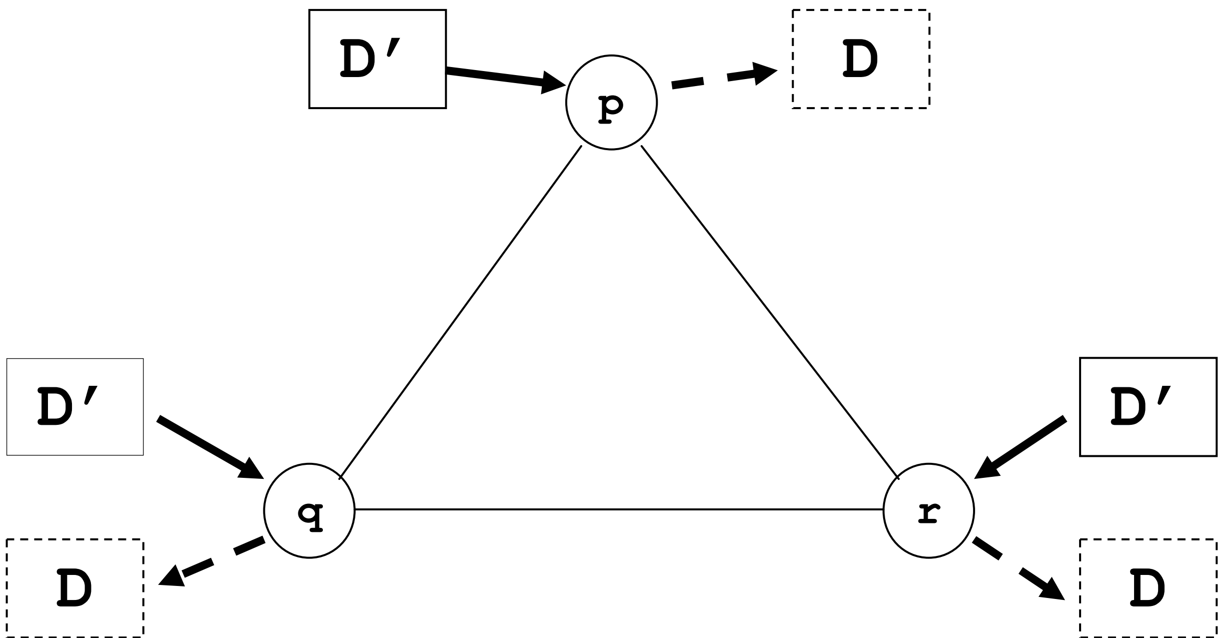
*Failure signal* failure detector FS: at each process, FS outputs green or red.

- If red is output, then a failure previously occurred.
- If a failure occurs, then eventually red is output at all correct processes.

# The weakest failure detector

D is *the weakest failure detector to solve problem* P *in an environment* E if and only if:

- ✓D is sufficient for P in E: D can be used to solve P in E
- ✓D is necessary for P in E: D can be extracted from *any* failure detector D' that can be used to solve P in E



# Roadmap

1. Model: asynchronous system with failure detectors
2. *Implementing a register*
3. Solving consensus
4. Solving QC
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# Problem: implementing a register

- An atomic register is an object accessed through *reads* and *writes*
- The *write(v)* stores *v* at the register and returns *ok*
- The *read* returns the last value written at the register

# *Quorum* failure detector Σ

At each process, Σ outputs a set of processes

- Any two sets (output at any times and at any processes) intersect.
- Eventually every set contains only correct processes.

# Σ is sufficient to implement registers

- Adapt the “correct majority-based” algorithm of [ABD95] to implement (1 reader, 1 writer) atomic register using Σ:

  Substitute

  *« process p waits until a majority of processes reply »*

  with

  *« process p waits until all processes in Σ reply »*

# Σ is necessary to implement registers

Let A be any implementation of registers that uses some failure detector D.

Must show that we can extract Σ from D.

- Each write operation involves a set of "participants": the processes that help the operation take effect (w.r.t. A and D)

*Fact: the set of participants includes at least one correct process*

# Extraction algorithm

Every process p periodically:

- writes in its register the participant sets of its previous writes
- reads participant sets of other processes
- outputs
  - ✓the participant set of its *previous* write, and
  - ✓for every known participant set S, one *live* process in S

*All output sets intersect and eventually contain only correct processes*

# Registers: the weakest failure detector

- $\Sigma$ is the weakest failure detector to implement atomic registers, in any environment

# Roadmap

1. Model: asynchronous system with failure detectors
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# *Leader* failure detector $\Omega$ [CHT96]

Outputs the id of a process. Eventually, the id of the same correct process is output at all correct processes.

# Consensus $\Leftrightarrow$ registers + $\Omega$

- $\Omega$ can be used to solve consensus with registers, in *any* environment [LH94]
- Consensus => Registers: any consensus algorithm can be used to implement registers, in *any* environment [Lam86,Sch90]
- Consensus => $\Omega$: $\Omega$ can be extracted from any failure detector D that solves consensus, in *any* environment [CHT96]

# Consensus: the weakest failure detector

- Consensus ⇔ registers + Ω (in any environment)
- Σ is the weakest FD to implement registers (in any environment)

Thus,

(Ω, Σ) is the weakest failure detector to solve consensus, in any environment

# Roadmap

1. Model: asynchronous system with failure detectors
2. Implementing a register
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# Quittable consensus (QC)

QC is like consensus except that

*if a failure occurs,* then processes can agree

- on the special value Q (« Quit »), *or*
- on one of the proposed values (as in consensus)

# Failure detector Ψ

- For some initial period of time Ψ outputs some predefined value T
- Eventually,
  - ✓Ψ behaves like (Ω,Σ), or
  - ✓(only if a failure occurs) Ψ behaves like FS (outputs red)

NB: If a failure occurs, Ψ can choose to behave like (Ω,Σ) or like FS (the choice is the same at all processes)

# Ψ is sufficient to solve QC

```
Propose(v)                          // v  in {0,1}
  wait until Ψ ≠ T
  if Ψ = red then return Q          // If Ψ behaves like FS

  d := ConsPropose(v)               // If Ψ behaves like (Ω,Σ)
                                    // run a consensus algorithm
  return d
```

# Ψ is necessary to solve QC

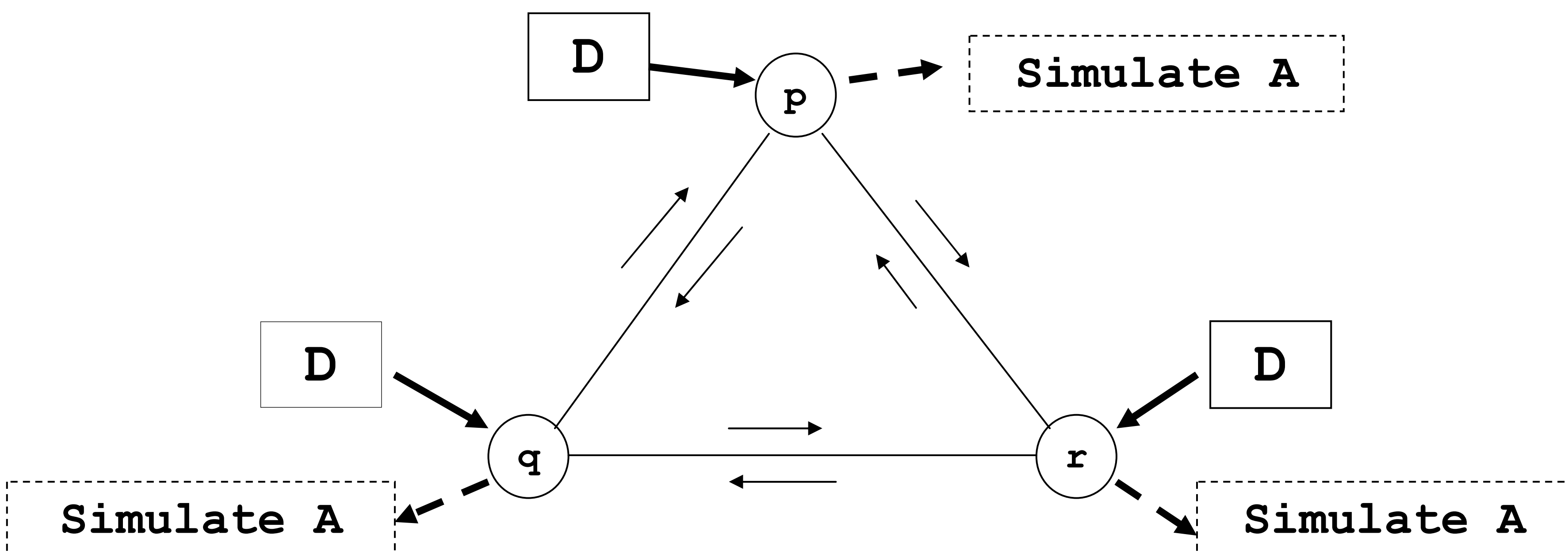
Let A be a QC algorithm that uses a failure detector D.

Must show that we can extract Ψ from A and D

# Simulating runs of A

Every process periodically samples D and exchanges its FD samples with other processes

=> using these FD samples, the process locally simulates runs of A [CHT96]

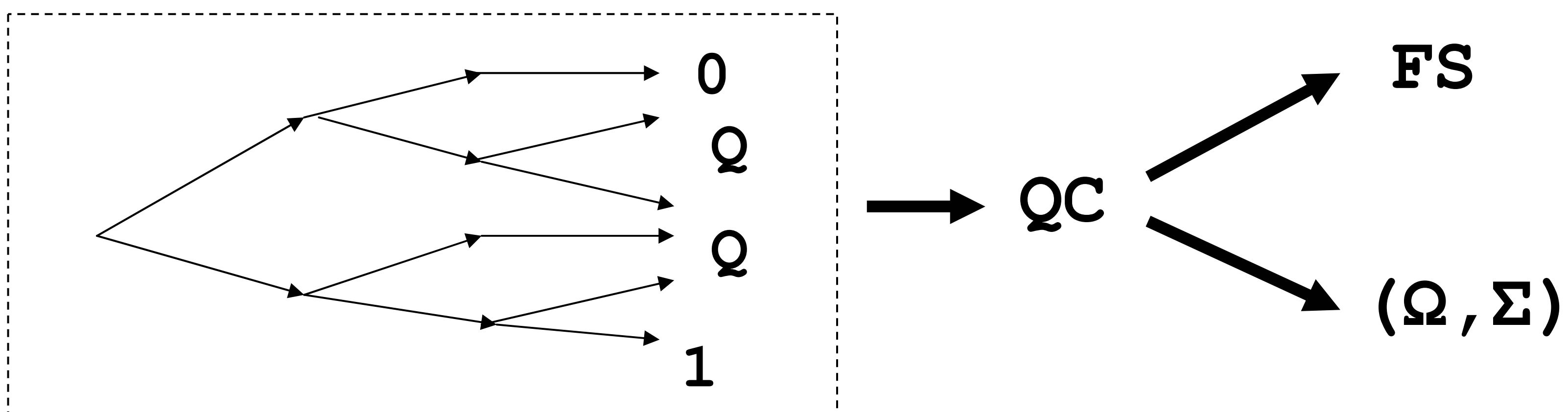


# Extracting Ψ

If there are “enough” simulated runs of A in which non-Q values are decided, then it is possible to extract (Ω,Σ).

Otherwise, it is possible to extract FS.

Processes use the QC algorithm A to agree on which failure detector to extract.



# QC: the weakest failure detector

$\Psi$ is the weakest failure detector to solve QC, in any environment

# Roadmap

1. Model: asynchronous system with failure detectors
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5. *Solving NBAC*

# NBAC

A set of processes need to agree on whether to commit or to abort a transaction.

Initially, each process votes Yes (“I want to commit”) or No (“We must abort”)

Eventually, processes must reach a common decision (Commit or Abort):

- Commit is decided => all processes voted Yes
- Abort is decided => some process voted No or a failure previously occurred

# NBAC ⇔ QC + FS

- QC+FS => NBAC:
  given (a) any algorithm for QC and (b) FS, we can solve NBAC
- NBAC => QC:
  Any algorithm for NBAC can be used to solve QC
- NBAC => FS:
  Any algorithm for NBAC can be used to extract FS

# NBAC: the weakest failure detector

- NBAC ⇔ QC + FS (in any environment)
- Ψ is the weakest FD to solve QC (in any environment)

Thus,

(Ψ,FS) is the weakest failure detector to solve NBAC, in any environment

# The original results

- *C. Delporte-Gallet, H. Fauconnier and R. Guerraoui*

  Shared memory vs. message-passing

  *Technical report IC/2003/77, EPFL, 2003*

- *R. Guerraoui, V. Hadzilacos, P. Kouznetsov and S. Toueg*

  The weakest failure detectors for quittable consensus and non-blocking atomic commit

  *Technical repport, LPD, EPFL, 2004*

Thank you!

# Quittable consensus (QC)

propose(v) (v in {0,1}) returns a value in {0,1,Q}
(Q stands for « quit »)

- Agreement: no two processes return different values
- Termination: every correct process eventually returns a value
- Validity: only a value v in {0,1,Q} can be returned
  - ✓ If v in {0,1}, then some process previously proposed v
  - ✓ If v=Q, then a failure previously occurred

# Emulating Σ: the reduction algorithm

Periodically (round k):

Pi(k) := set of participants of write k by process i

Ei := {Pi(j)} j≤k

write(Ei) to register Ri

Ei := Ei U Pi(k)

send (k,?) to all

wait until, for every j, received (k,ack) from every X read in register Rj

current output of Σ := set of all processes sent (ack,k) U Pi(k-1)

# Emulating Σ: the proof intuition

- For any round k, process i stores all Pi(k’) (k’<k) in Ri and includes Pi(k-1) to its emulated set Σi

  =>

  Any process j that reads Ri afterwards will include at least one process from Pi(k-1) to its emulated set Σj

  =>

  Every two emulated sets intersect

- Eventually, only correct processes send acks

  =>

  Eventually, the emulation set includes only correct processes

# NBAC

Propose(v) (v in {Yes,No}) returns a value in {Commit,Abort}

- Agreement: no two processes return different values
- Termination: every correct process eventually returns a value
- Validity: a value in {Commit,Abort} is returned
  - ✓If Commit is returned, then every process voted Yes
  - ✓If Abort is returned, then some process voted no or a failure previously occurred

# NBAC using QC and FS

```
send v to all
wait until received all votes or FS outputs red
                        \\ wait until all votes received or
                        \\ a failure occurs
if all votes are received and are Yes  then
   proposal := 1    \\ propose to commit
else
   proposal := 0    \\ propose to abort
if QC.Propose(proposal) returns 1 then
            return Commit
else
            return Abort
```