Consensus

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Consensus problems

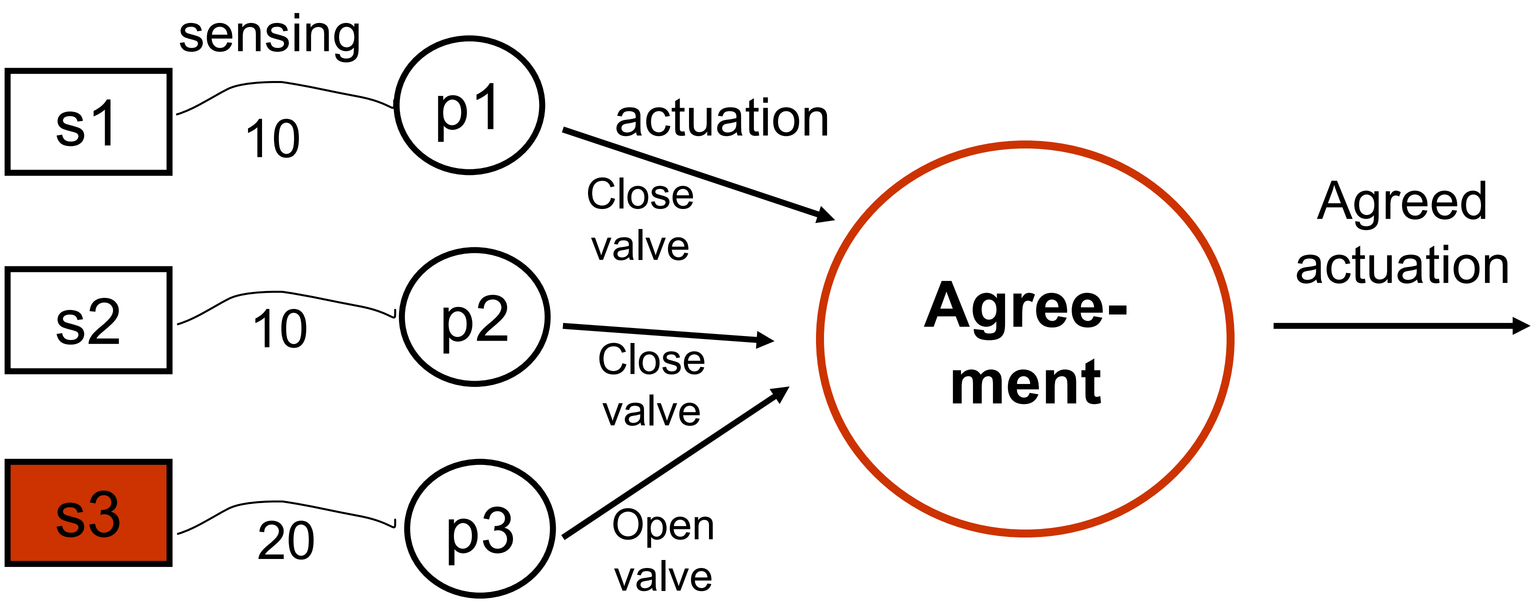
- Examples
  - Mutex: which process is granted access
  - Reliable and ordered Multicast
  - Election
  - Abort/proceed in space shuttle launch
  - Consistent credit/debit bank account
- Fault Tolerance
  - Crash
  - Byzantine
  - No message signing
    - Message signing limits the harm a faulty process can do
- Problems
  - Consensus
  - Byzantine generals
  - Interactive consistency

Redundancy

•Components (censors / memory / processors/processes) may fail

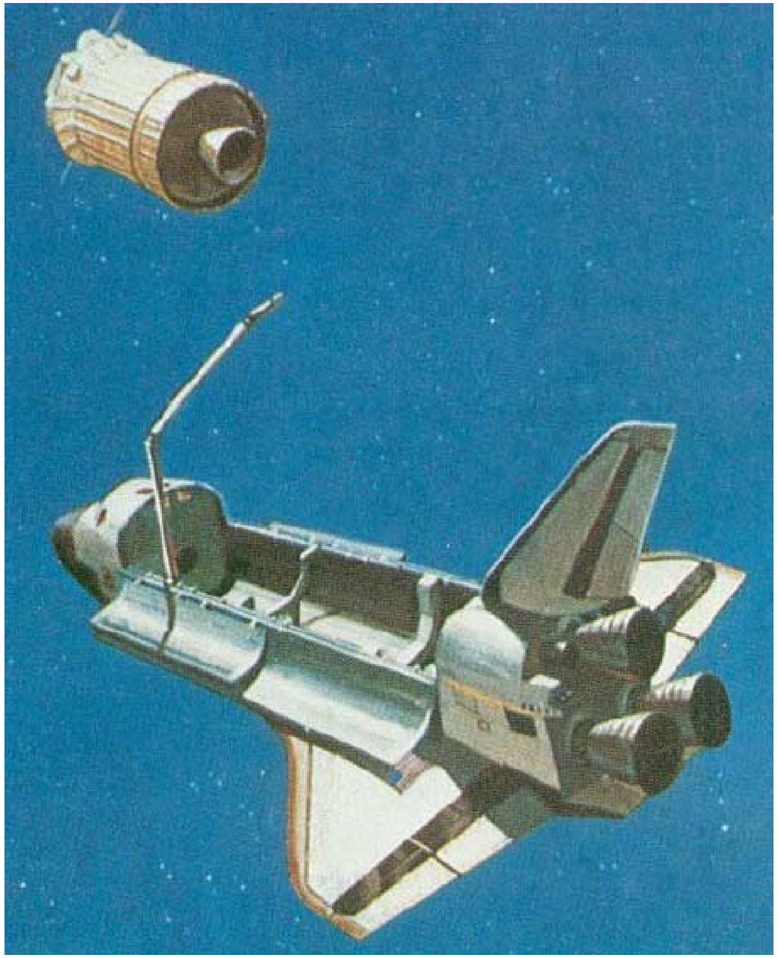
•Critical systems: space / aeronautics / nuclear

•Increase availabiliy ⇒ Dublicate components/functionality

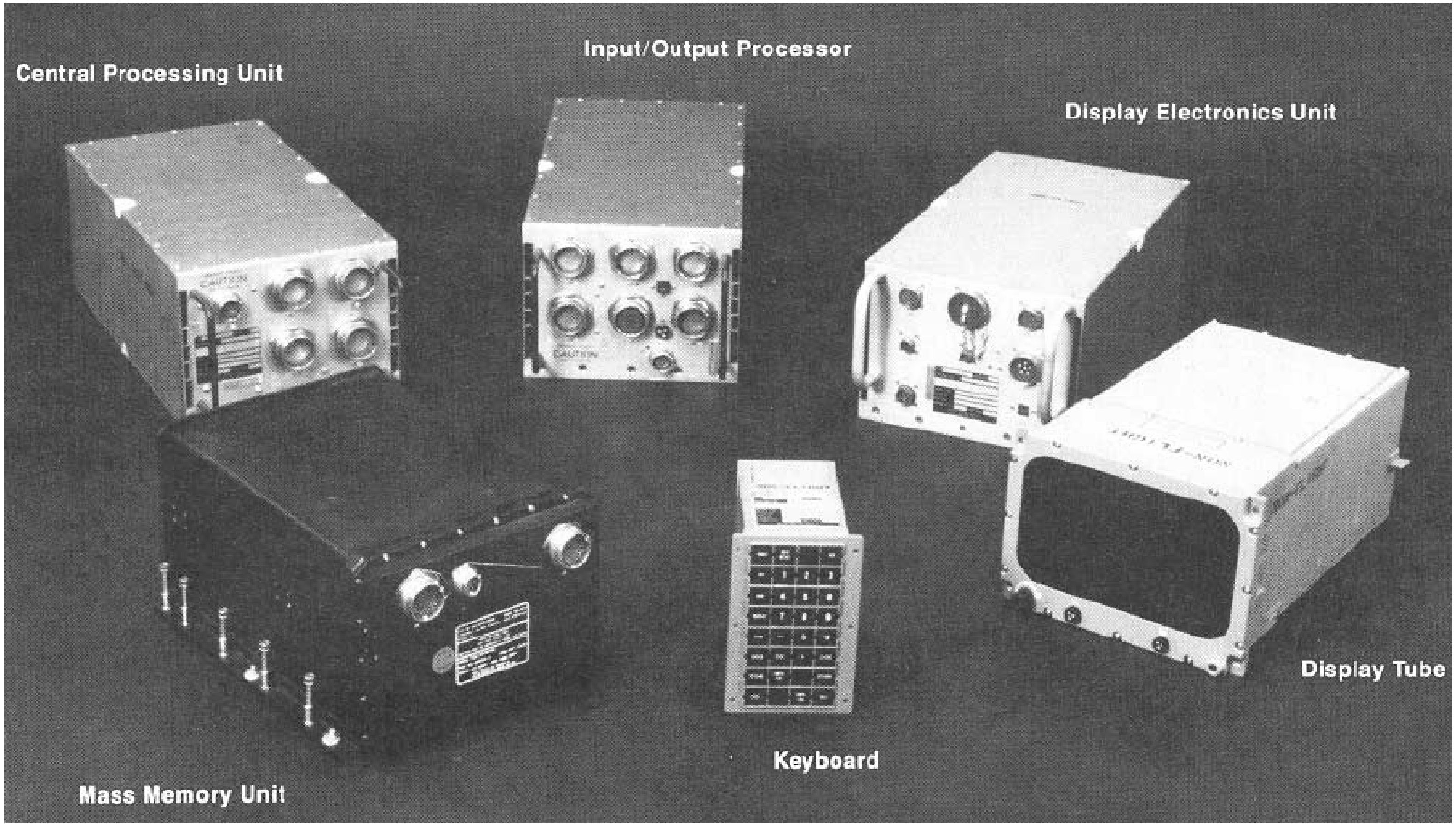


Example

- The PASS (Primary Avionics Software System) developed by IBM in 1981, was used in a space shuttle
  - Could have been done on one computer
  - But 4 separate processors were used for fault-tolerance
    - Voting on the outcome

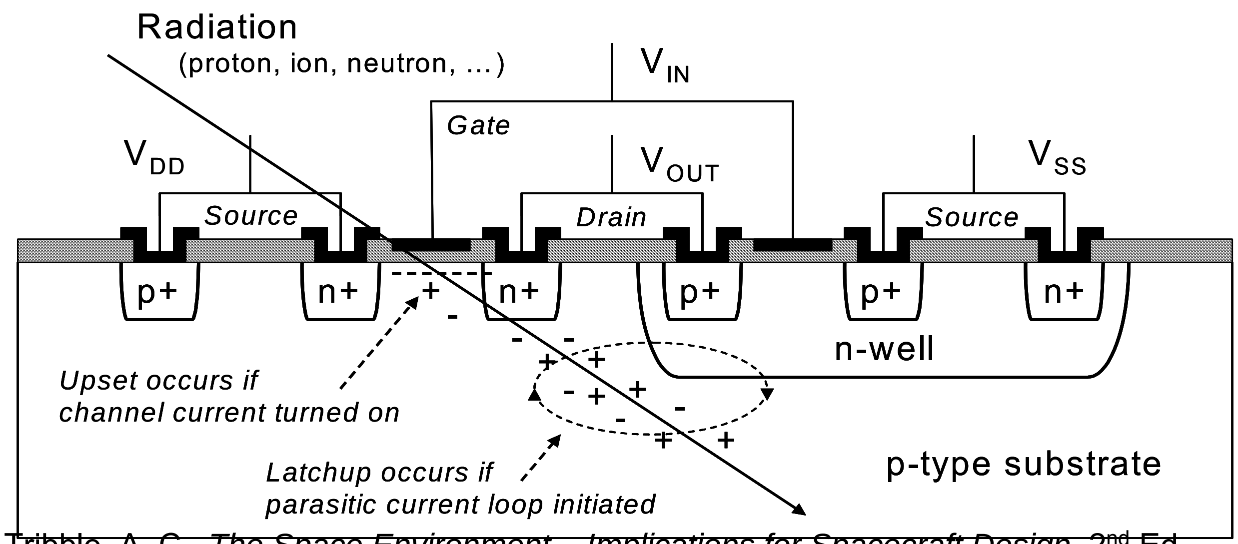


Space Shuttle DS hardware



Radiation

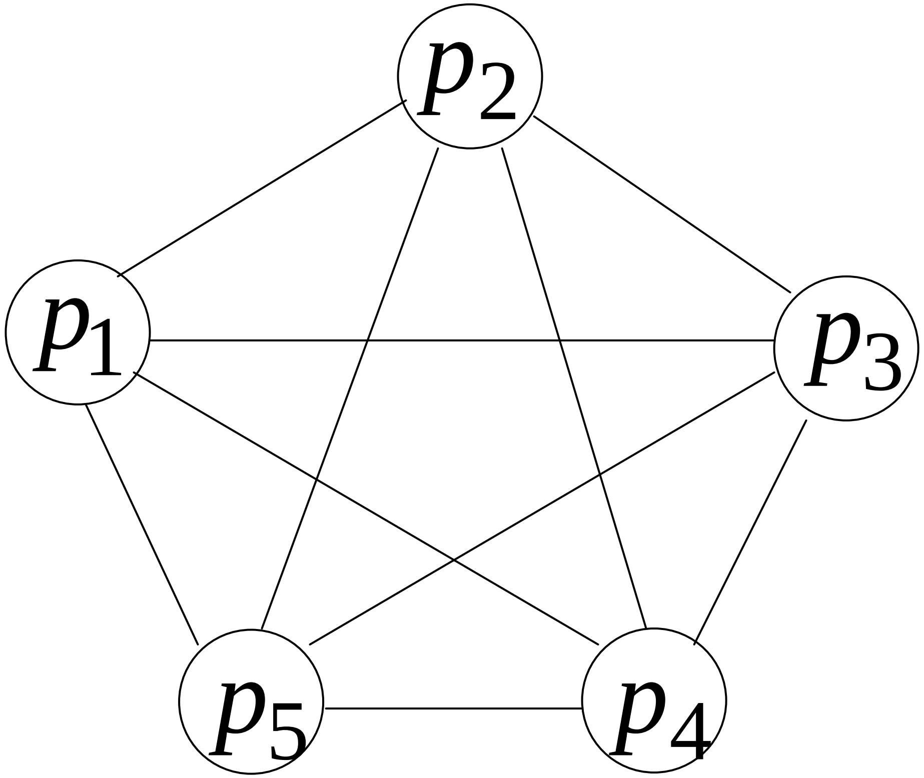
- The Natural (and Hostile) Radiation Environment Poses a Significant Threat to Many Electronic Devices
  - Single Event Upset (SEU), Single Event Latchup (SEL), …



Tribble, A. C., *The Space Environment – Implications for Spacecraft Design*, 2nd Ed., (Princeton, NJ: Princeton University Press, 2003).

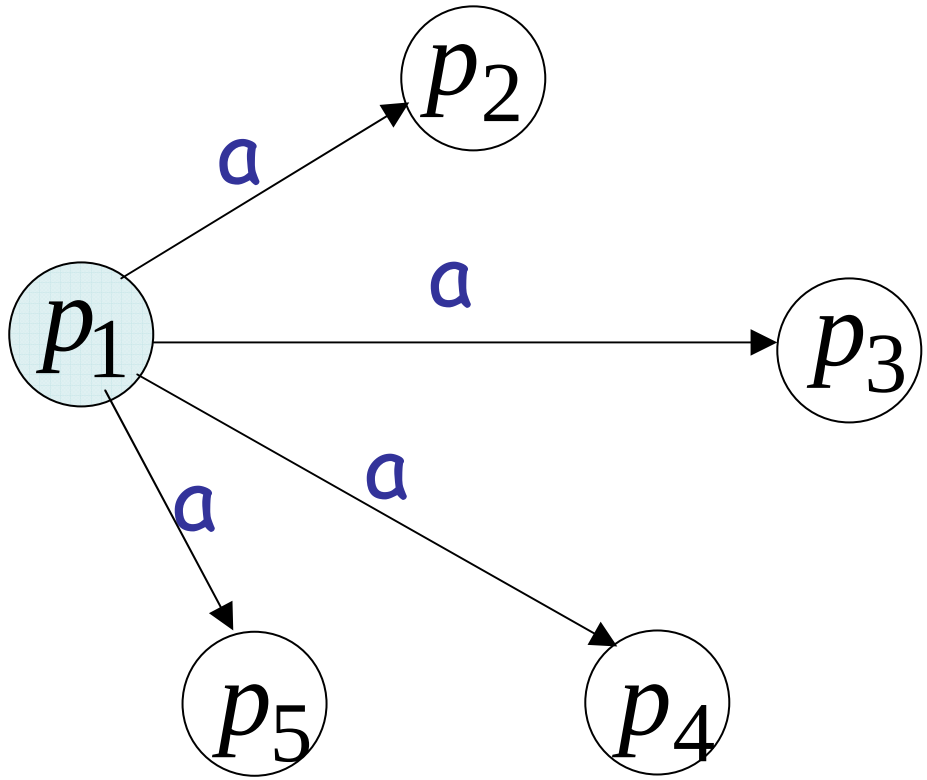
Consensus in a synchronous systems w. crash failures

Communication Model



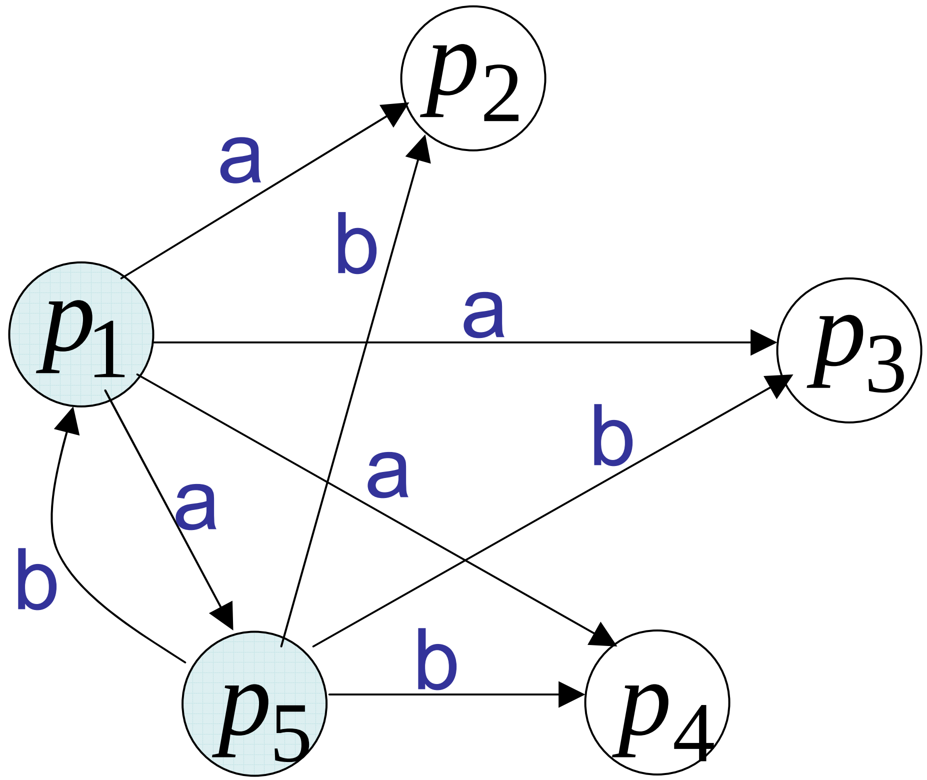
- Reliable point-to-point communication
- Pairwise channels (complete graph)
- Synchronous system

B-Multicast



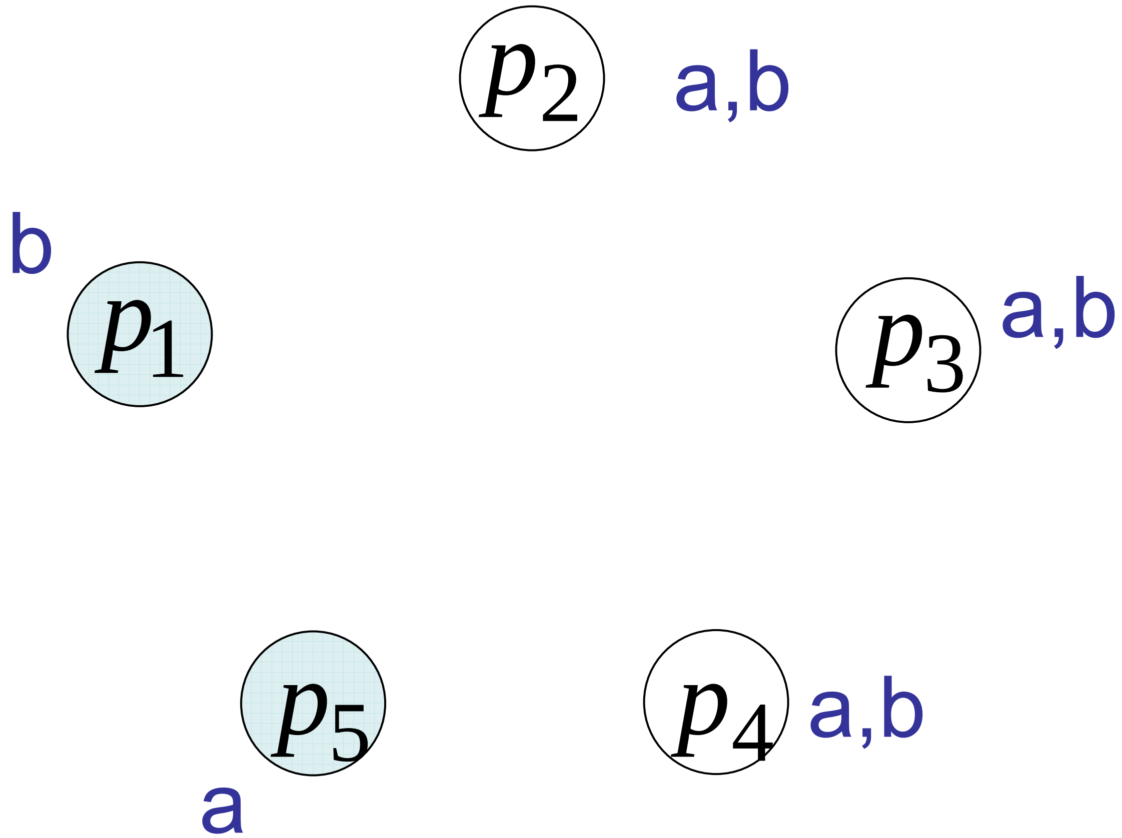
Send a message to all processors in one round

Concurrent Multicast

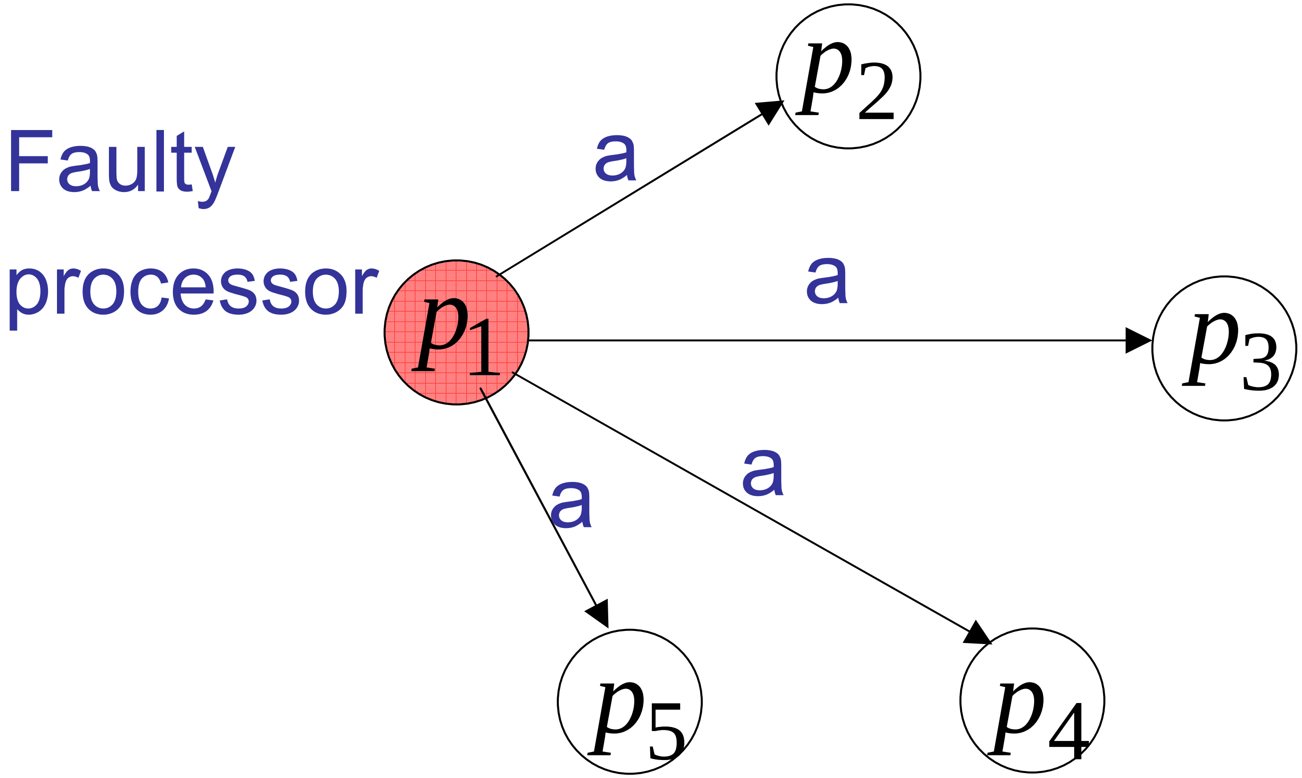


- More processes can multicast at the same round

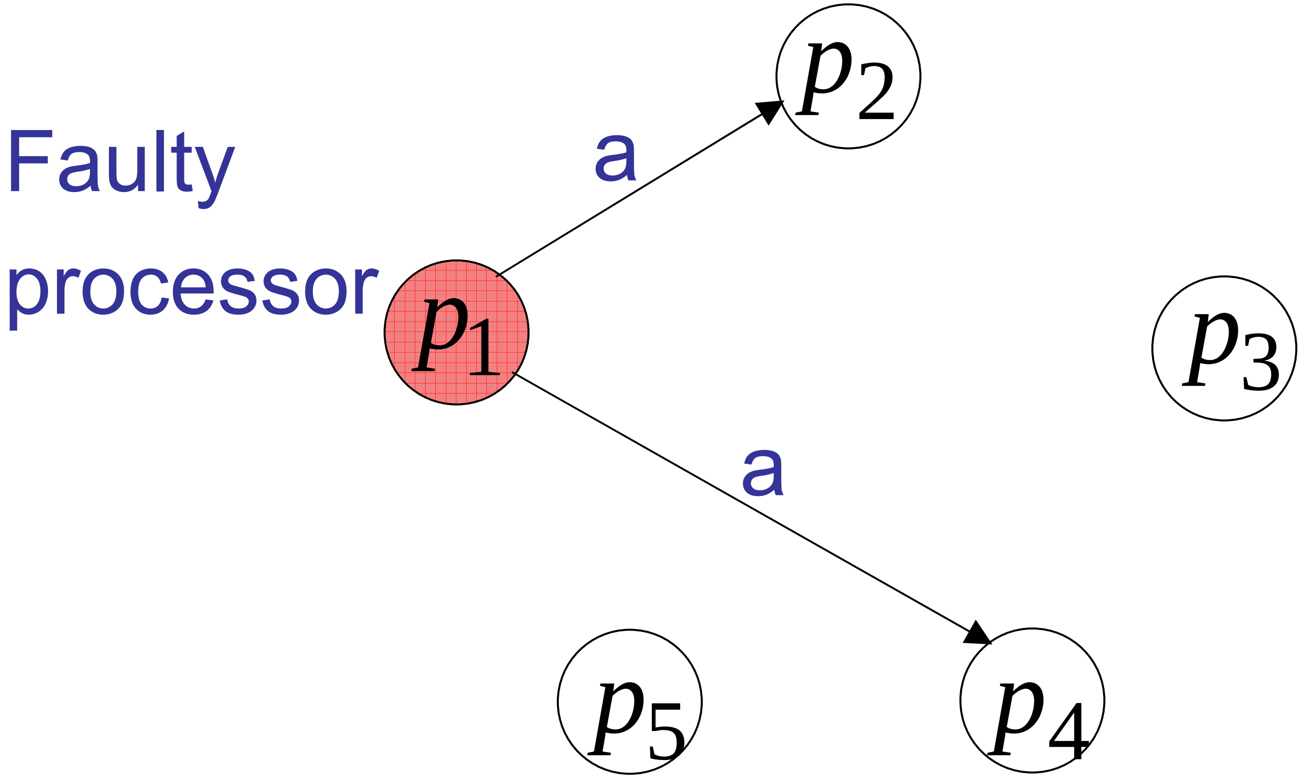
Concurrent Multicast



Crash Failures



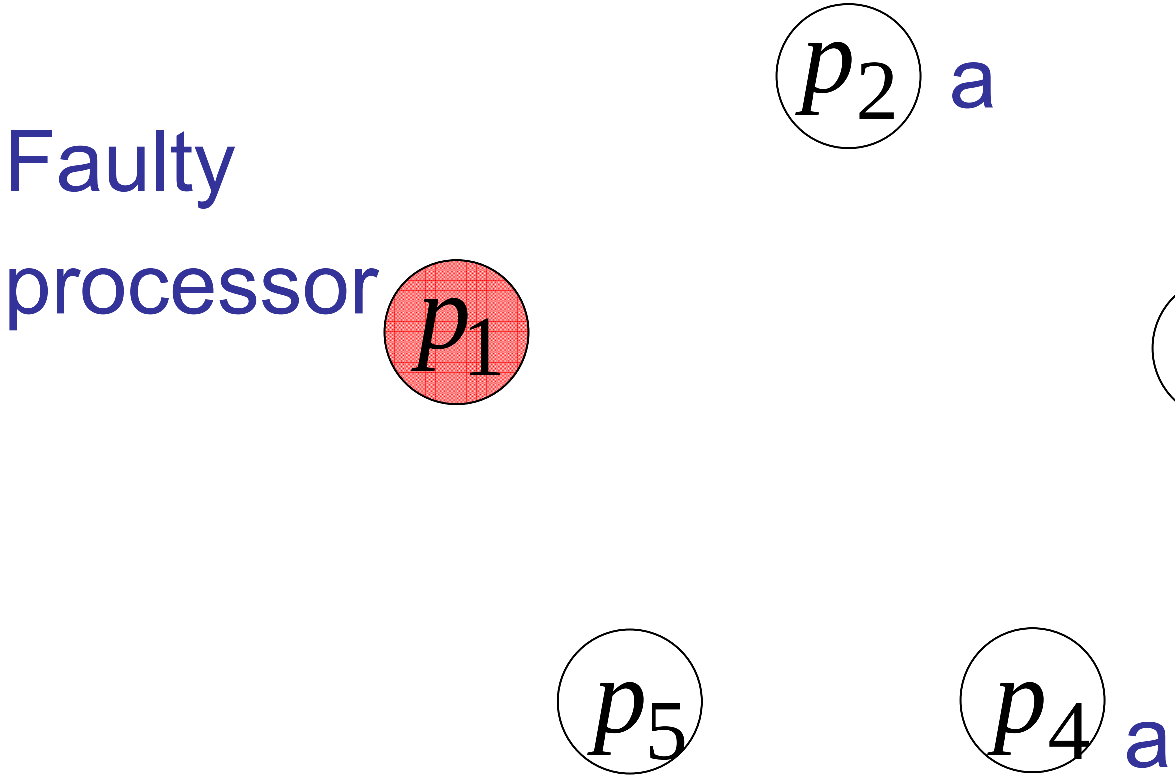
Un-reliable multicast



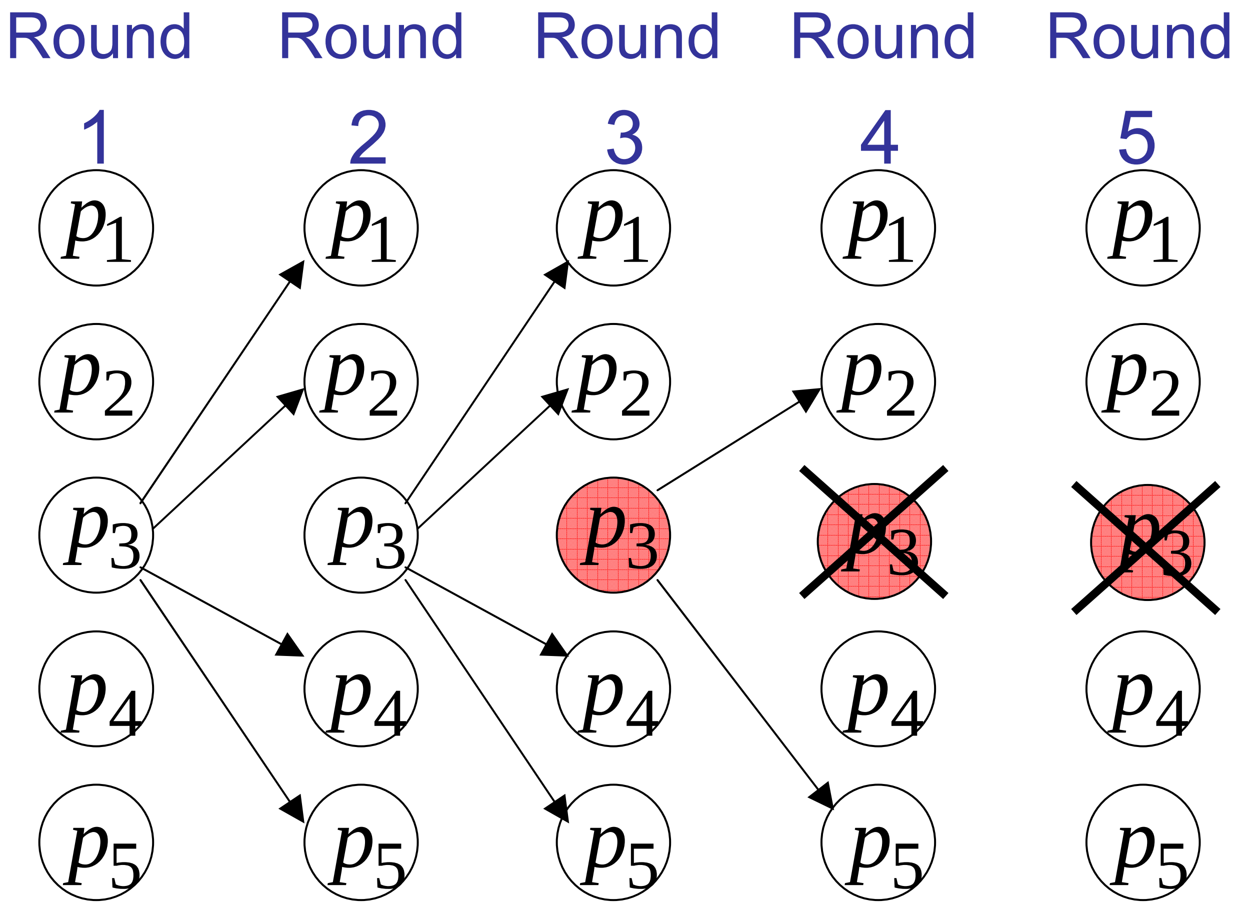
B-multicast is unreliable

- Some of the messages are never delivered, if sender crashes

Un-reliable multicast



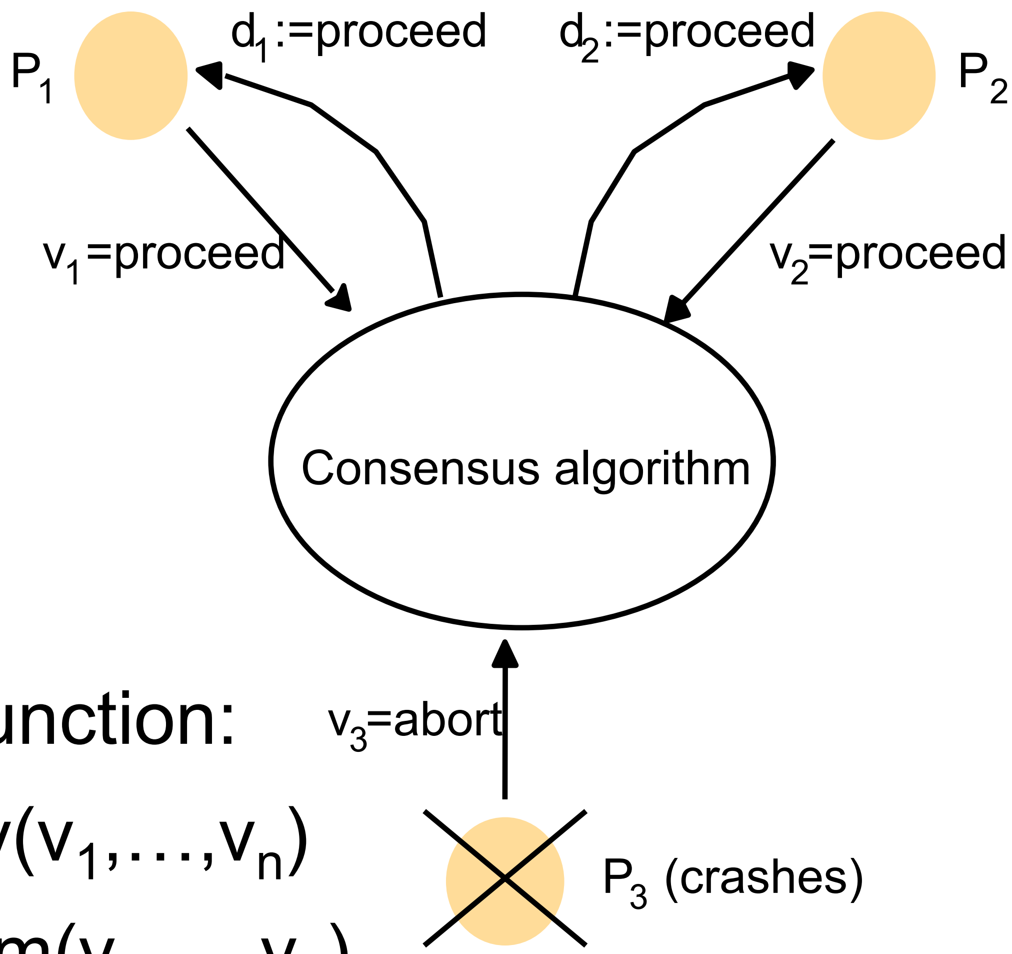
Crash-failures



Failure

After failure the process disappears from the network

Consensus for three processes



Selection function:

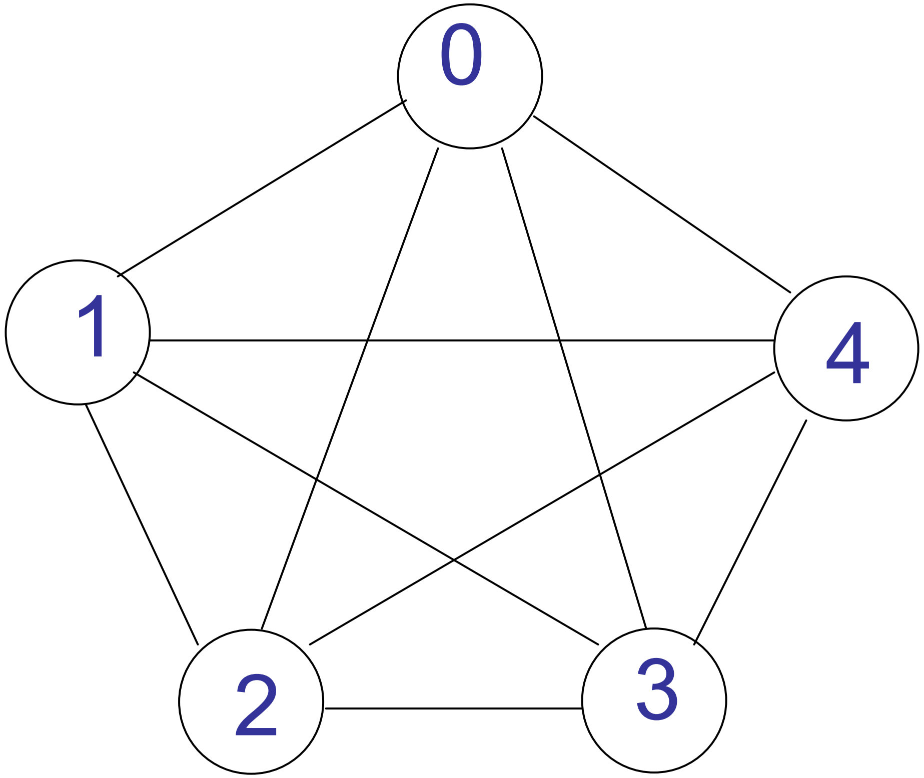
- d_i=majority(v_1,…,v_n)
- d_i=minimum(v_1,…,v_n)
- …

Consensus

- ***Termination:*** Eventually each correct process p_i sets its decision variable d_i.
- ***Agreement:*** The decision value of all correct processes is the same: if p_i and p_j are correct and have entered their *decided* state, then $d_i = d_j$ (for all $i,j \in 1..N$).
- ***Integrity:*** If the correct processes all proposed the same value, then any correct process in the *decided* state has chosen that value.

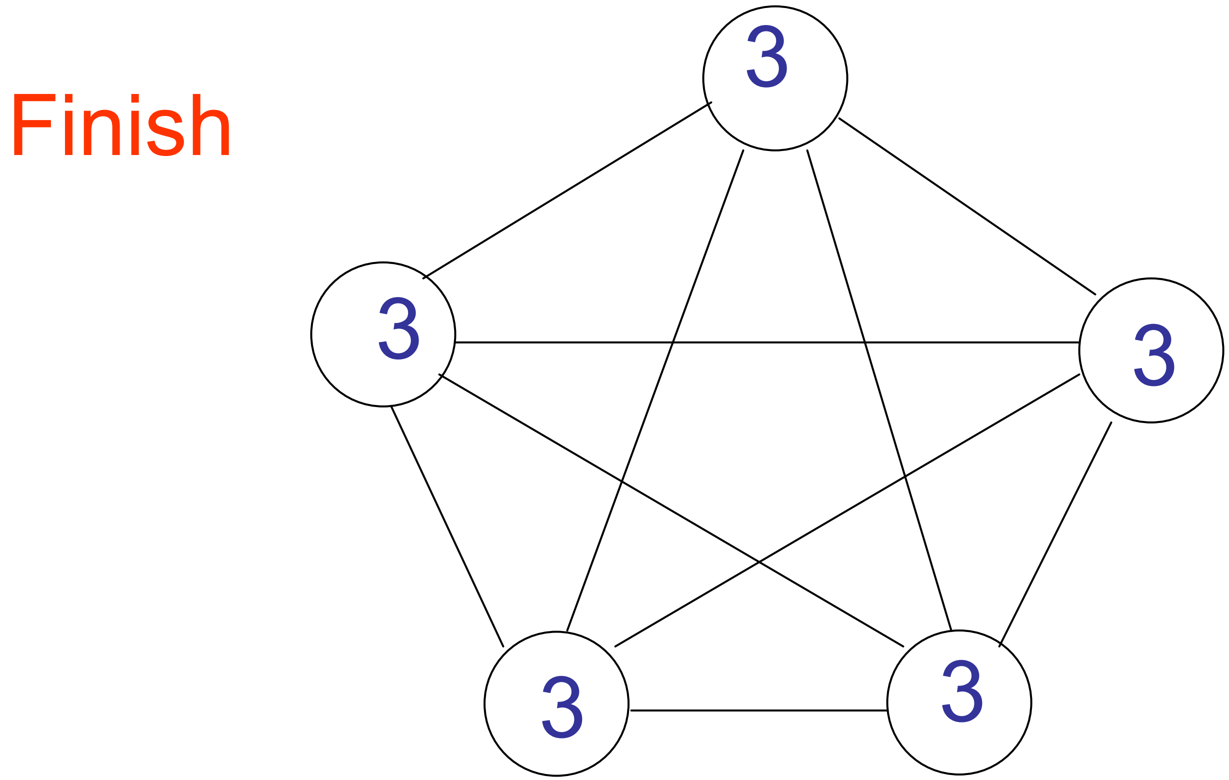
Consensus

Start



Everybody has an initial proposed value v_i

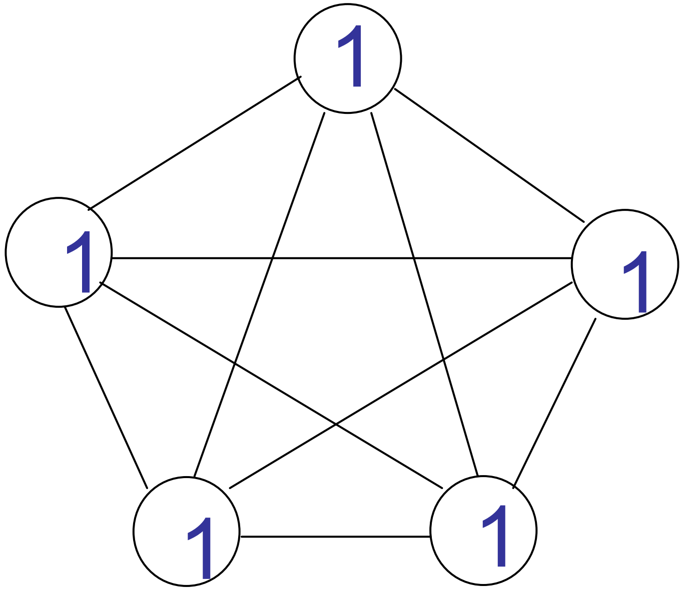
Consensus



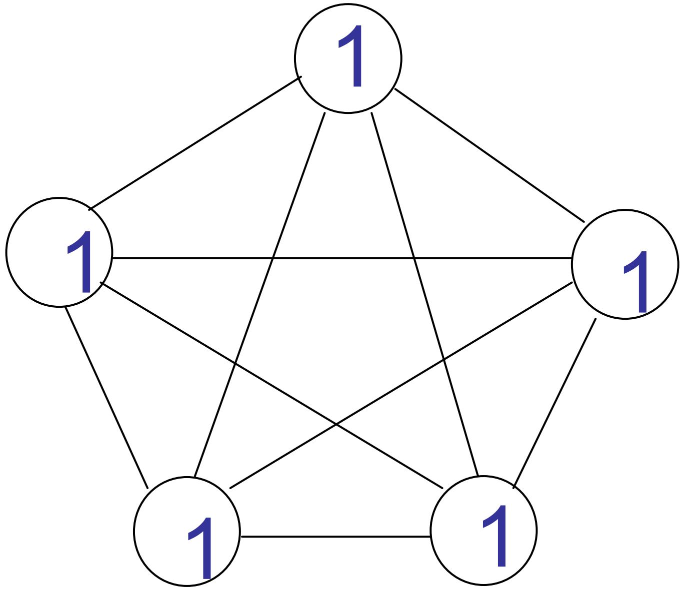
Agreement: Everybody decides on the same value: $d_i = d_j$ (for all $i,j \in 1..N$)

Consensus

Start



Finish



Integrity: If the correct processes all proposed the same value, then any correct process in the *decided* state has chosen that value

An Algorithm?

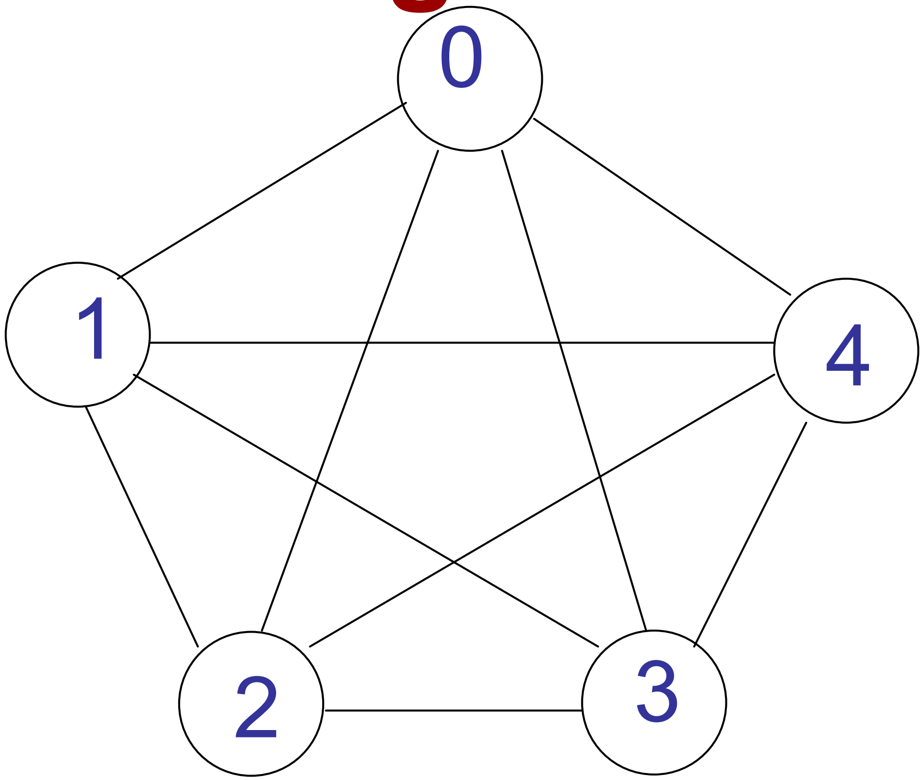
Each proces p_i:

1. B-multicast its value to all processes
2. Decide on the minimum

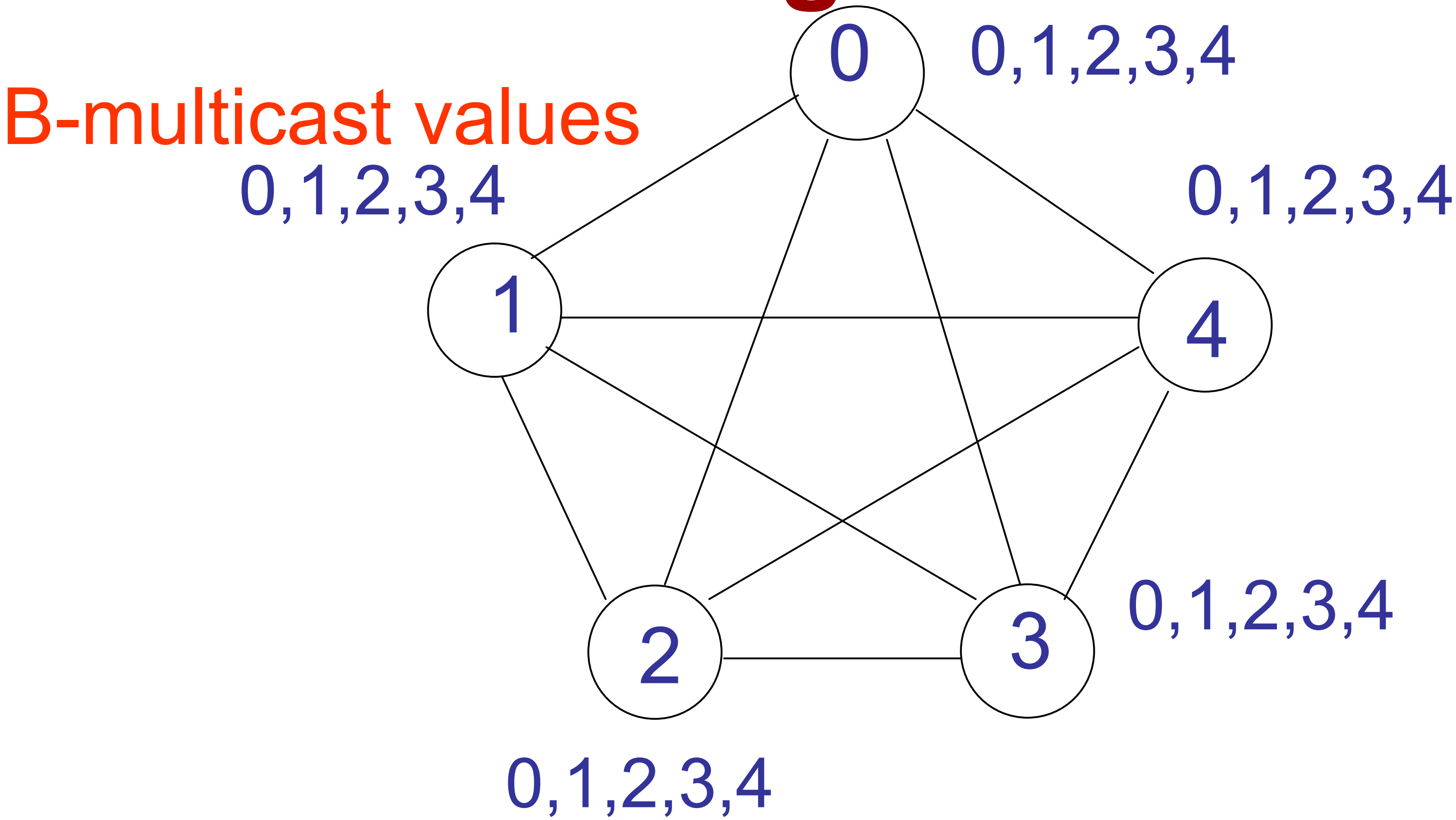
(only one round is needed)

An Algorithm?

Start

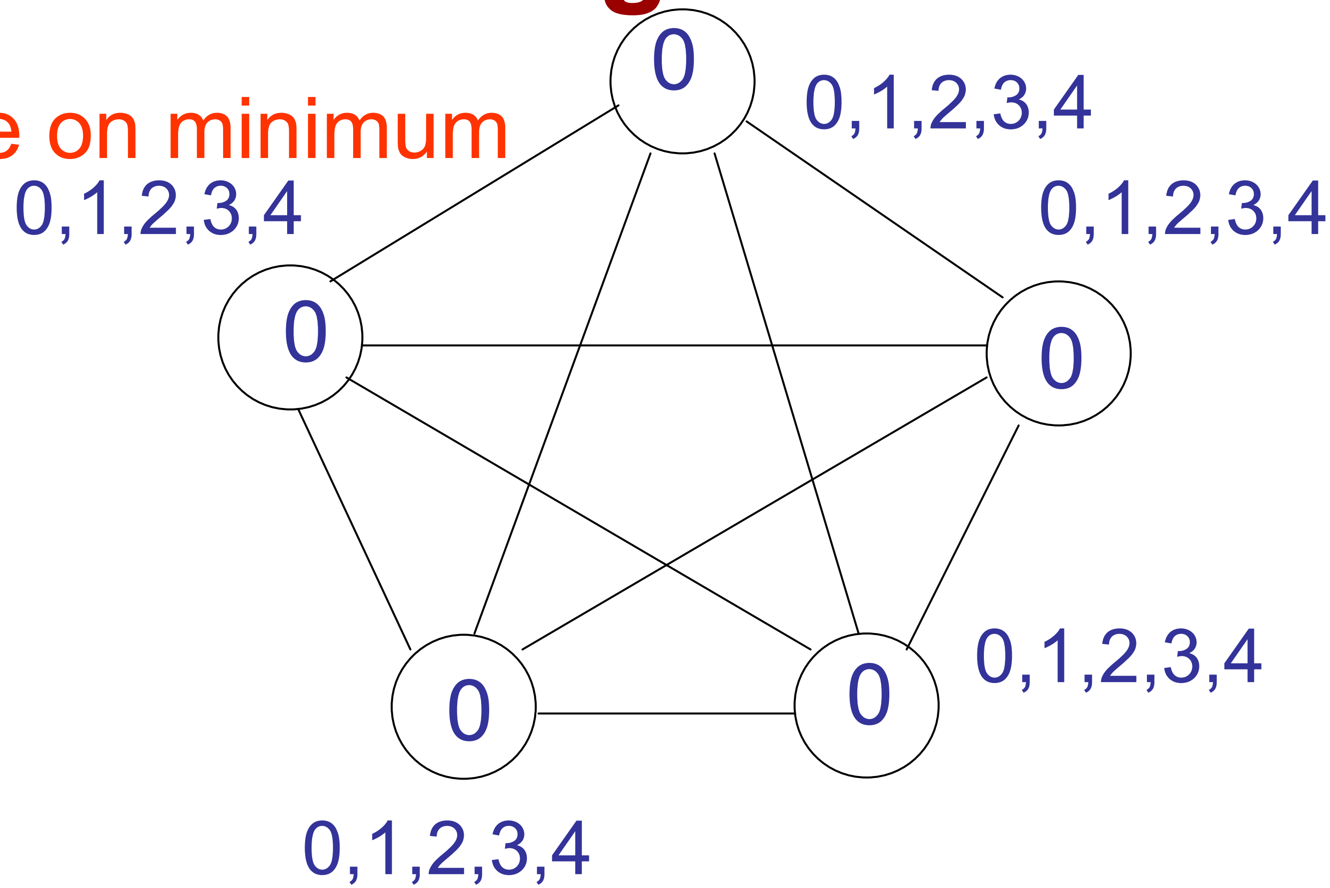


An Algorithm?



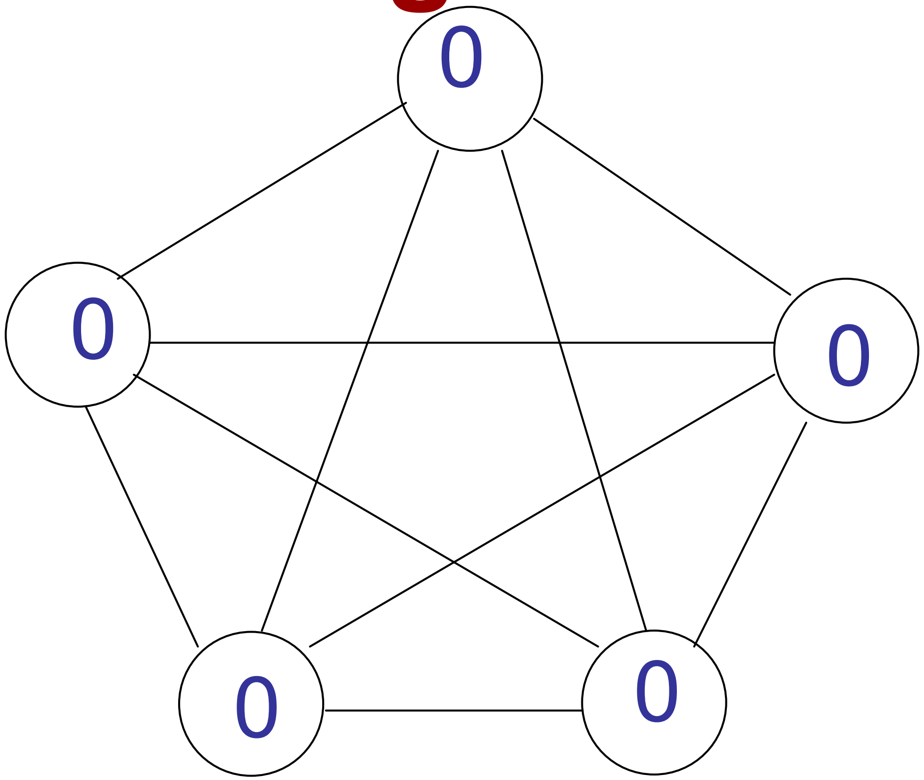
An Algorithm?

Decide on minimum



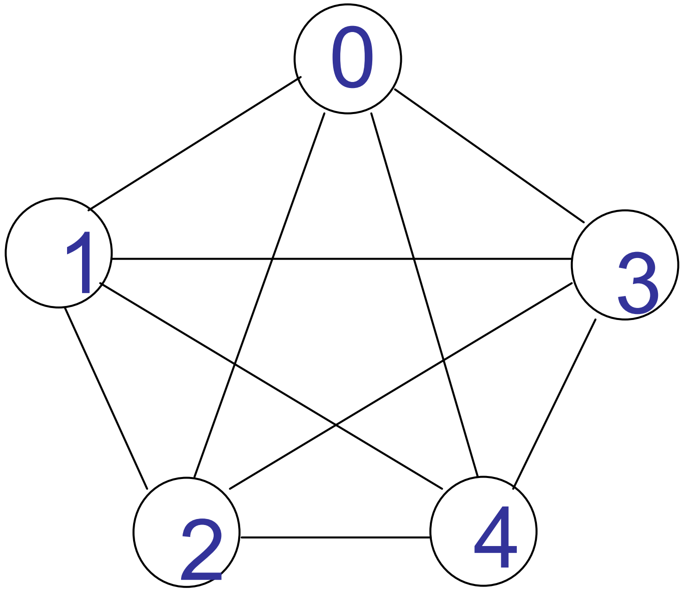
An Algorithm?

Finish

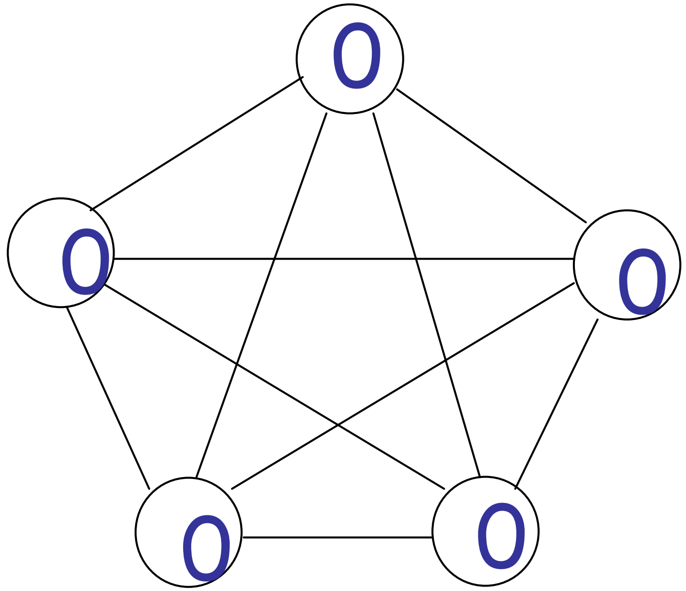


An Algorithm?

Start



Finish



Without Failures, this algorithm gives consensus

If everybody starts with the same initial value, everybody decides on that value (minimum)

Consensus w. Crash Failures

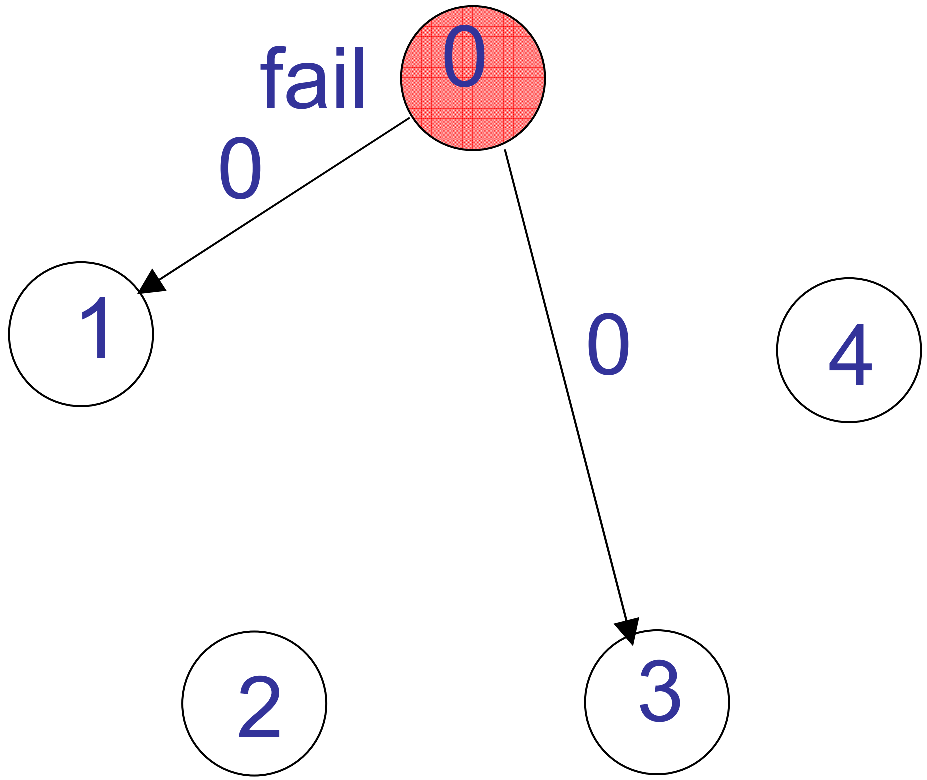
The simple algorithm doesn’t work

Each proces p_i :

1. B-multicast value to all processors
2. Decide on the minimum

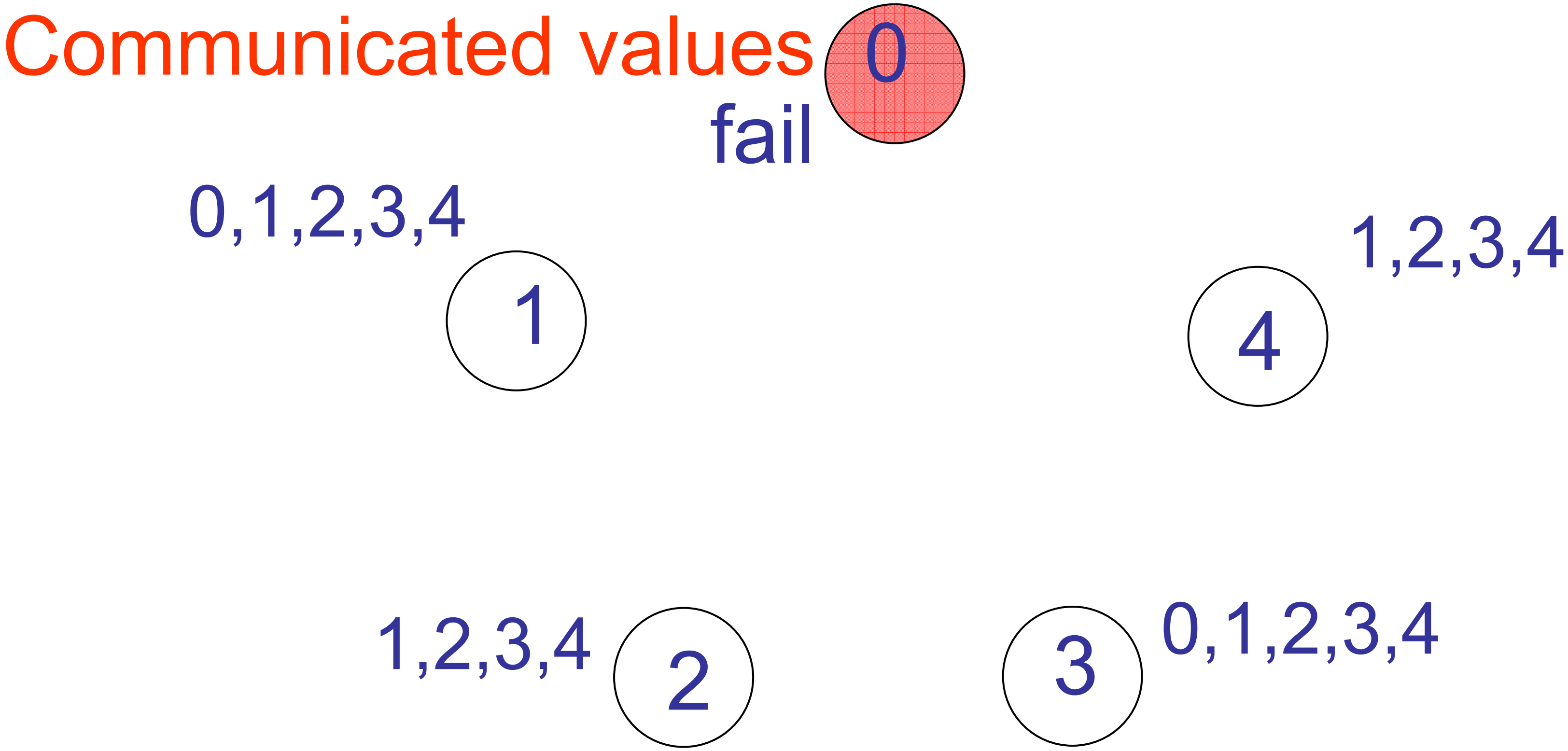
Consensus w. Crash Failures

Start



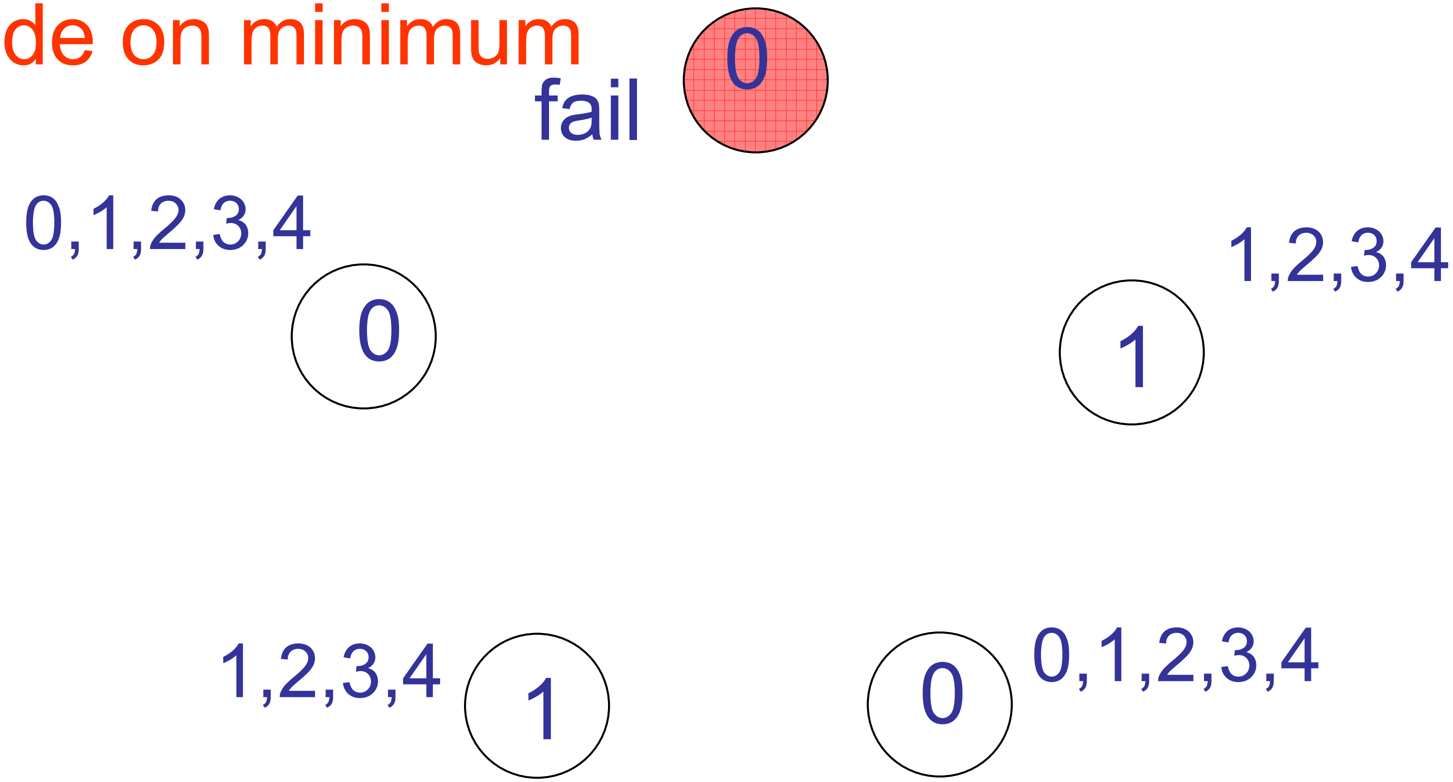
Not all processes receives the proposed value from the failed process

Consensus w. Crash Failures



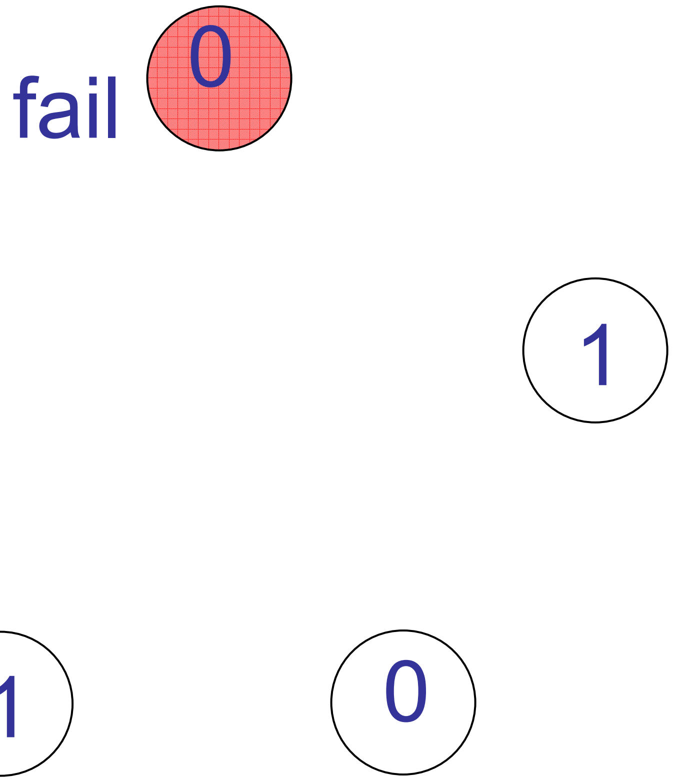
Consensus w. Crash Failures

Decide on minimum



Consensus w. Crash Failures

Finish



No Consensus!!!

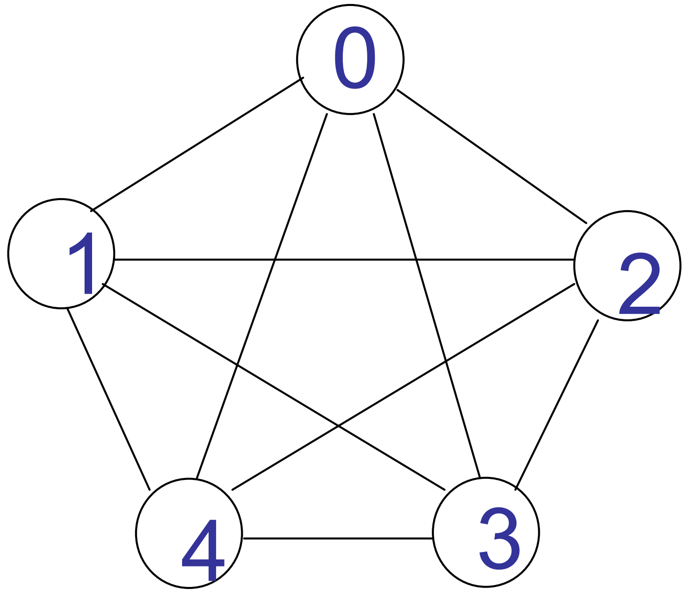
f-resiliency

- ***f-resilient consensus algorithm***
  - Guarentees consensus with up to f failed process

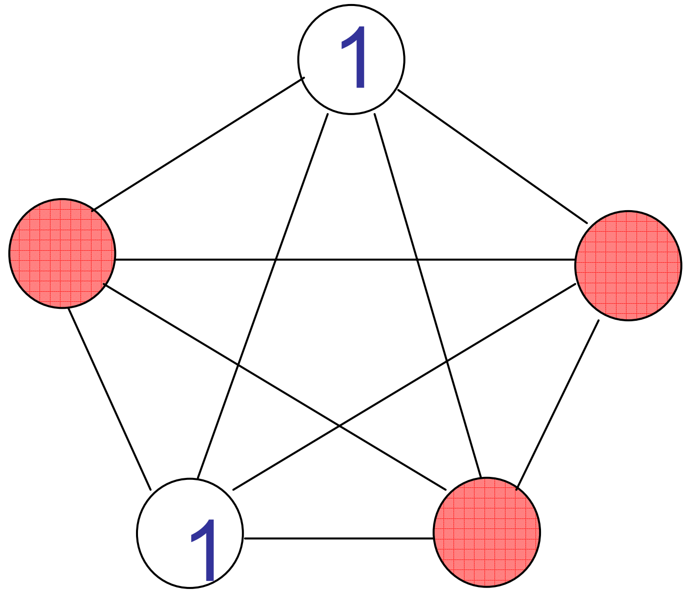
Example 3-resiliency

Example: The input and output of
a 3-resilient consensus algorithm

Start



Finish



An f-resilient algorithm

Round 1:

Each process B-multicast its value

Round 2 to round f+1:

B-multicast any new received values

End of round f+1:

Decide on the minimum value received

Consensus in a synchronous system

Algorithm for process $p_i \in g$; algorithm proceeds in $f + 1$ rounds

On initialization

$Values_i^1 := \{v_i\}$; $Values_i^0 = \{\}$;

In round r $(1 \leq r \leq f + 1)$

$B\text{-}multicast(g, Values_i^r - Values_i^{r-1})$; // Send only values that have not been sent

$Values_i^{r+1} := Values_i^r$;

while (in round r)

{

On B-deliver(V_j) *from some* p_j

$Values_i^{r-1} := Values_i^{r-1} \cup V_j$;

}

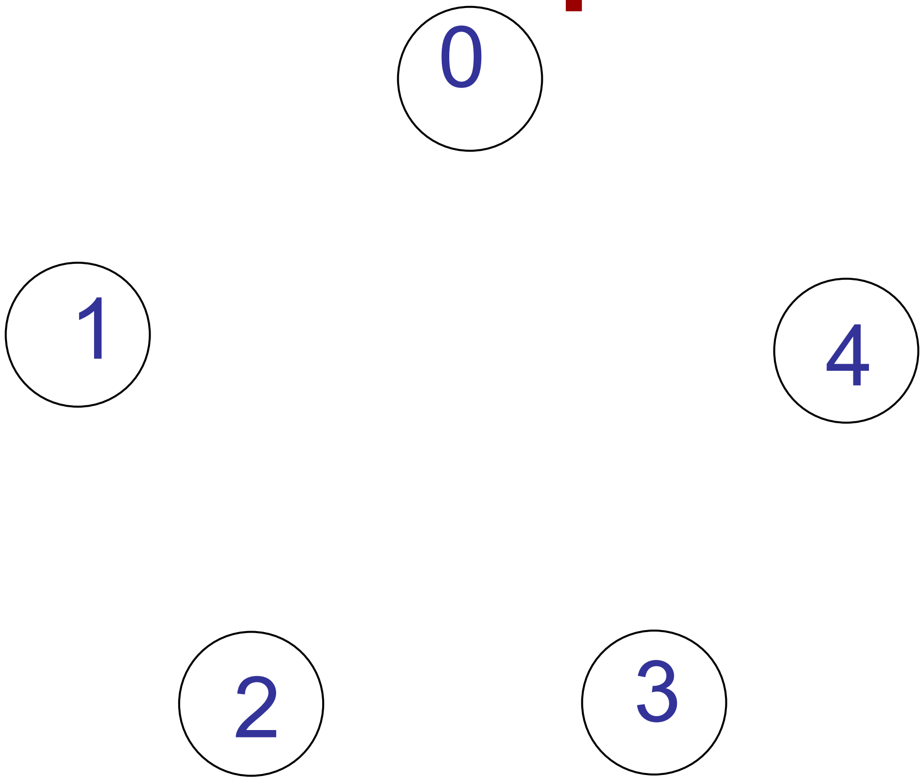
A round is completed in T secs ⇒ synchronous system

After $(f + 1)$ *rounds*

Assign $d_i = minimum(Values_i^{f-1})$;

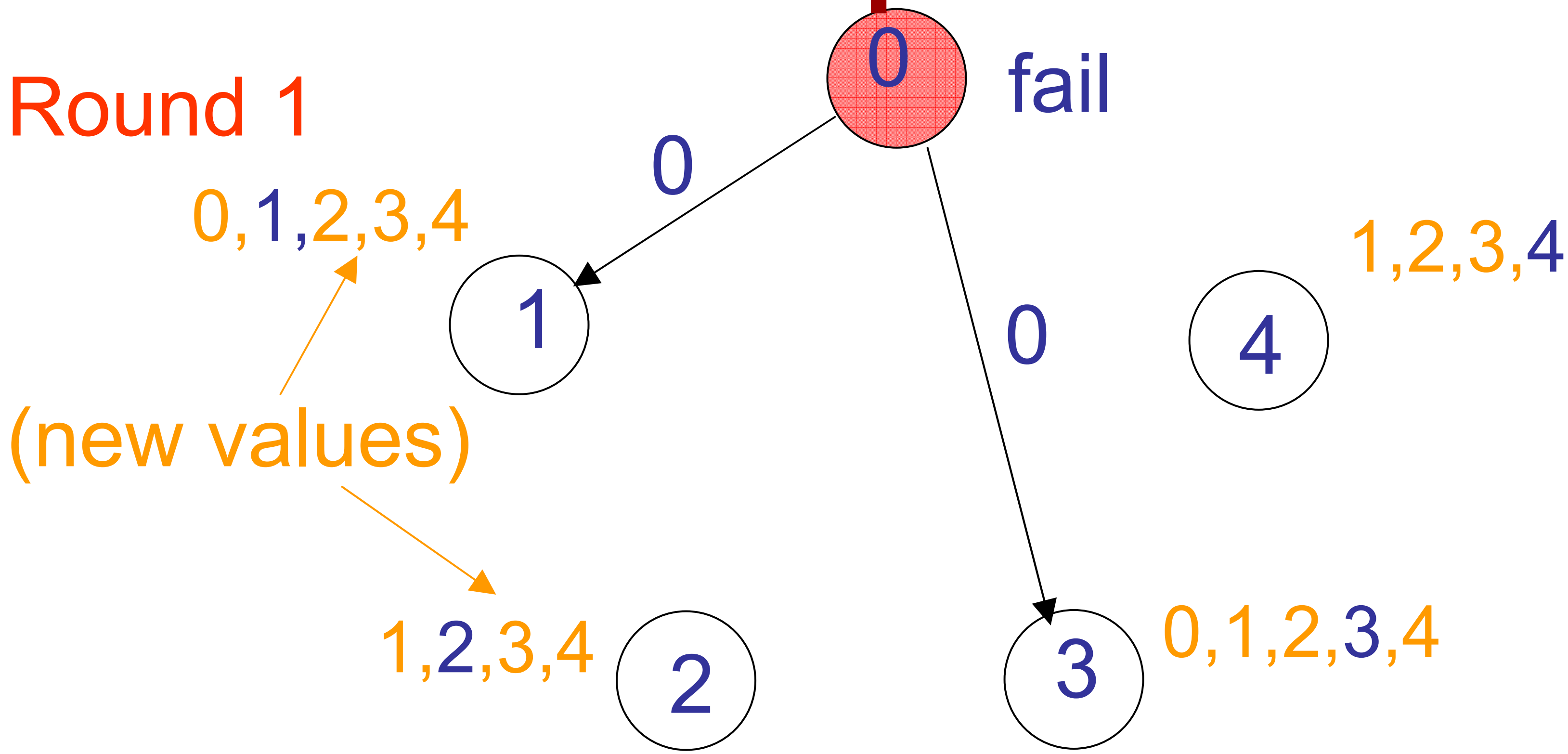
Example

Start



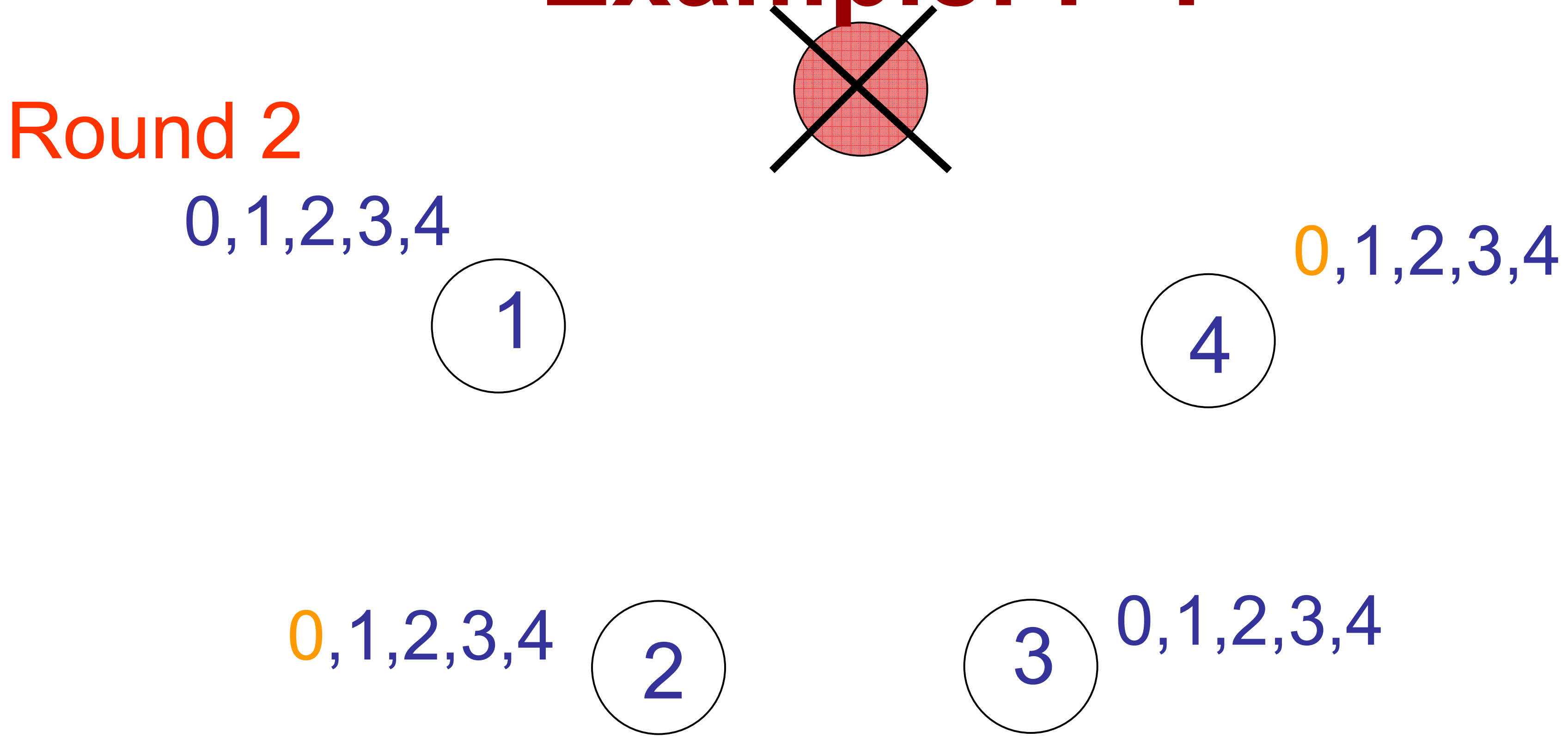
f=1 failures, f+1 = 2 rounds needed

Example: f=1



B-multicast all values to everybody

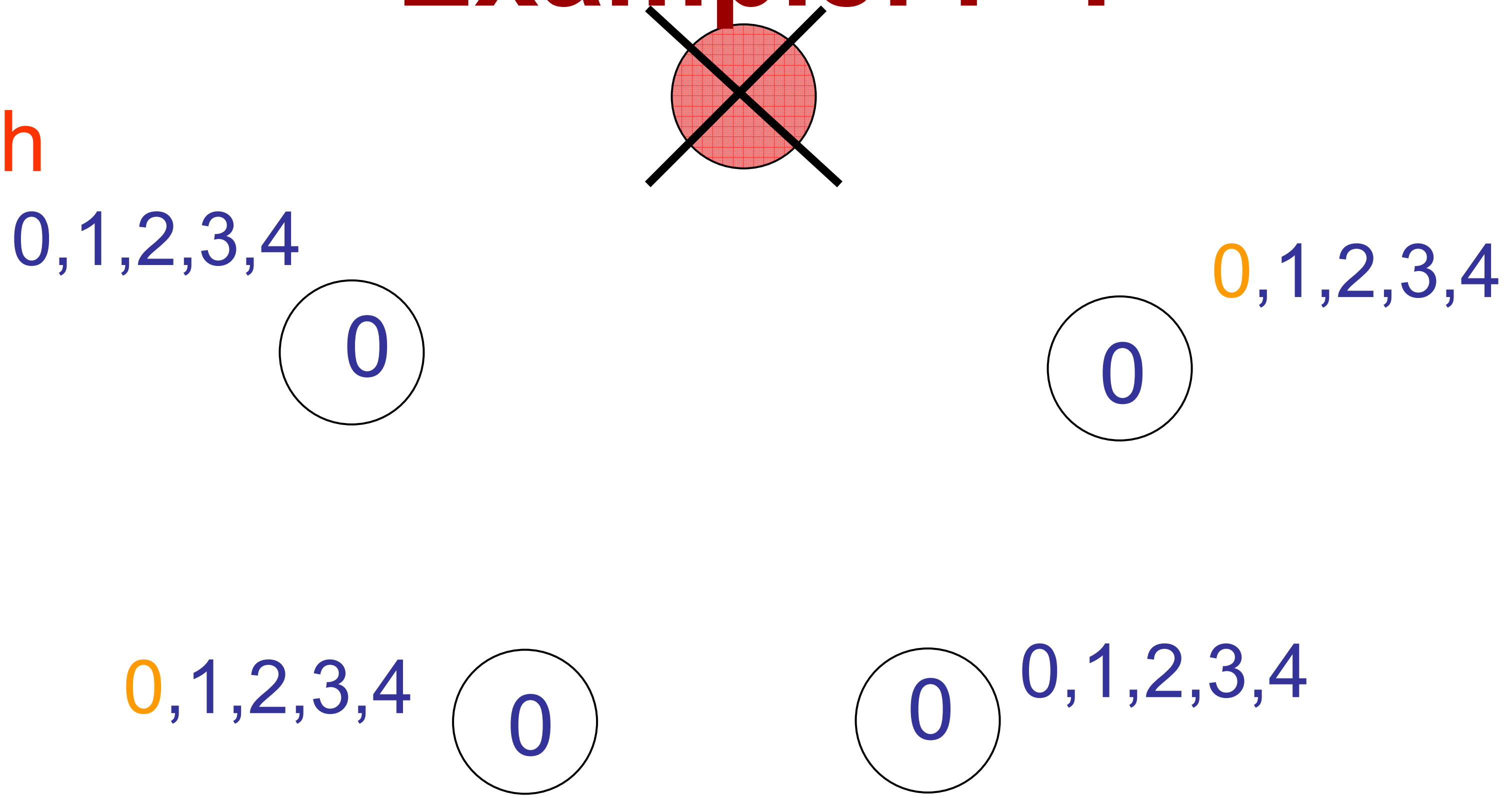
Example: f=1



B-multicast all new values to everybody

Example: f=1

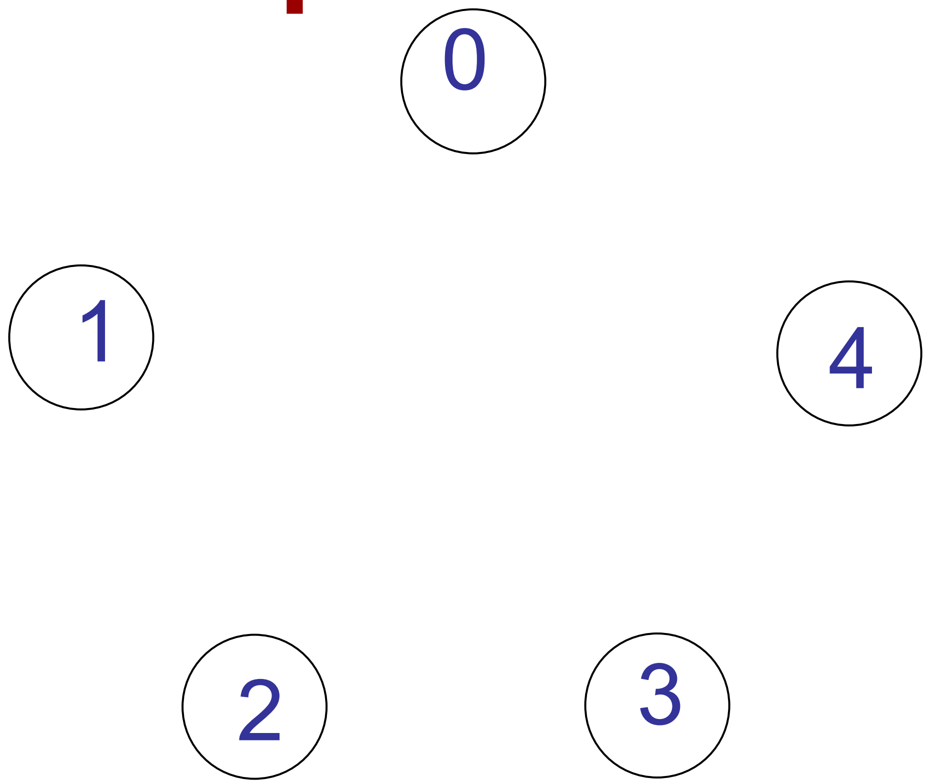
Finish



Decide on minimum value: forall i: d_i=0,

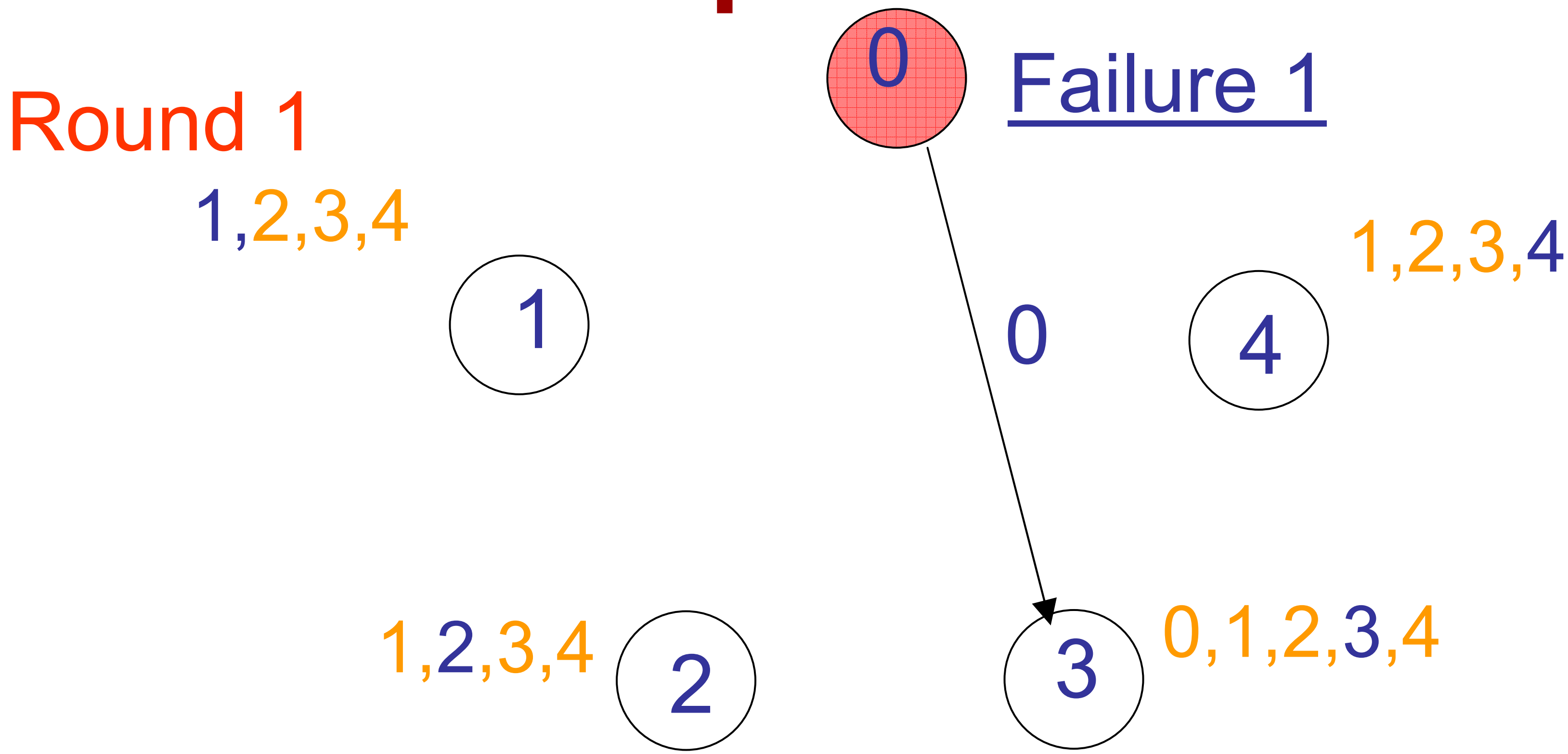
Example run 1: f=2

Start



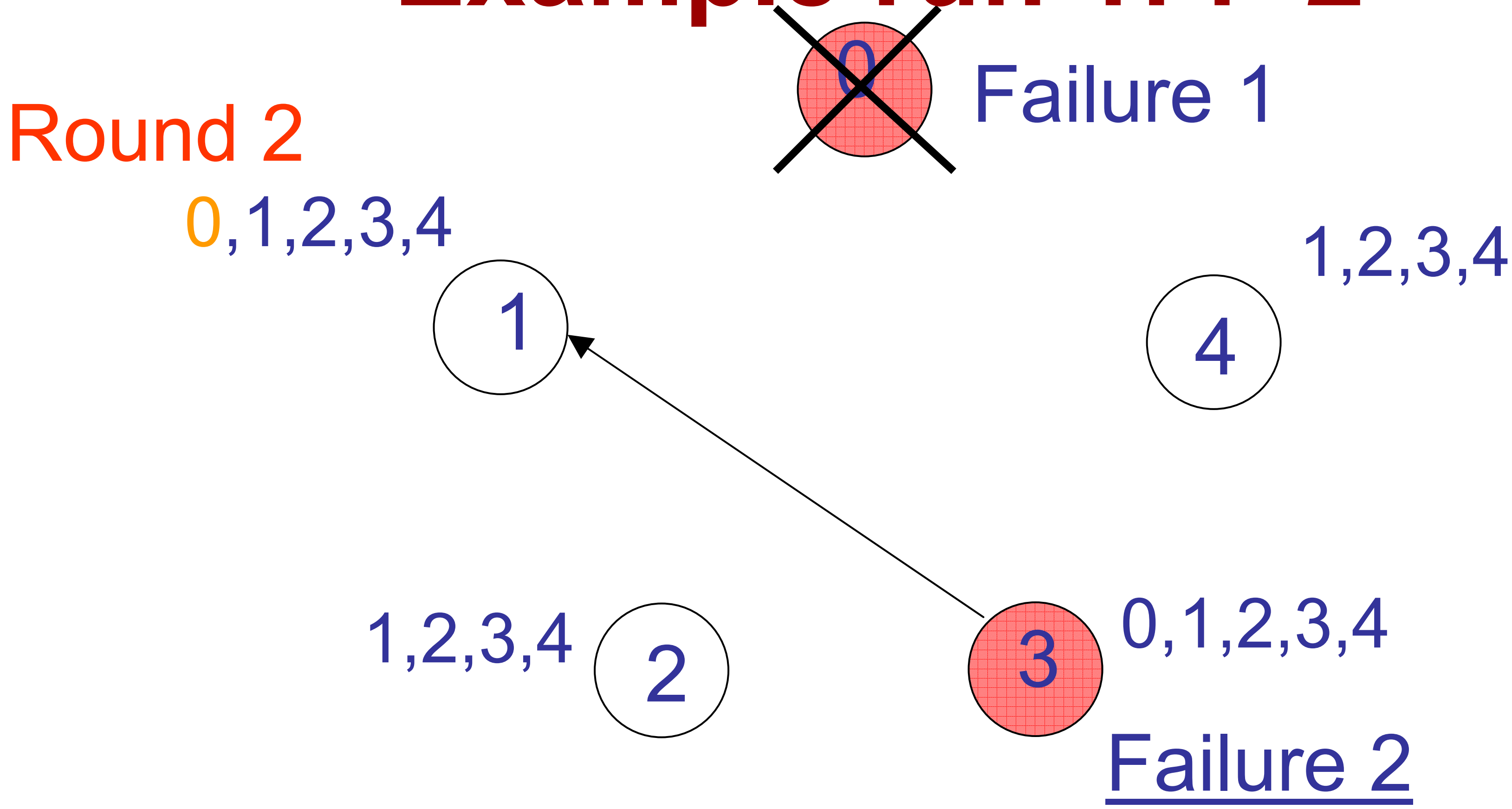
Example: f=2 failures, f+1 = 3 rounds needed

Example run 1: f=2



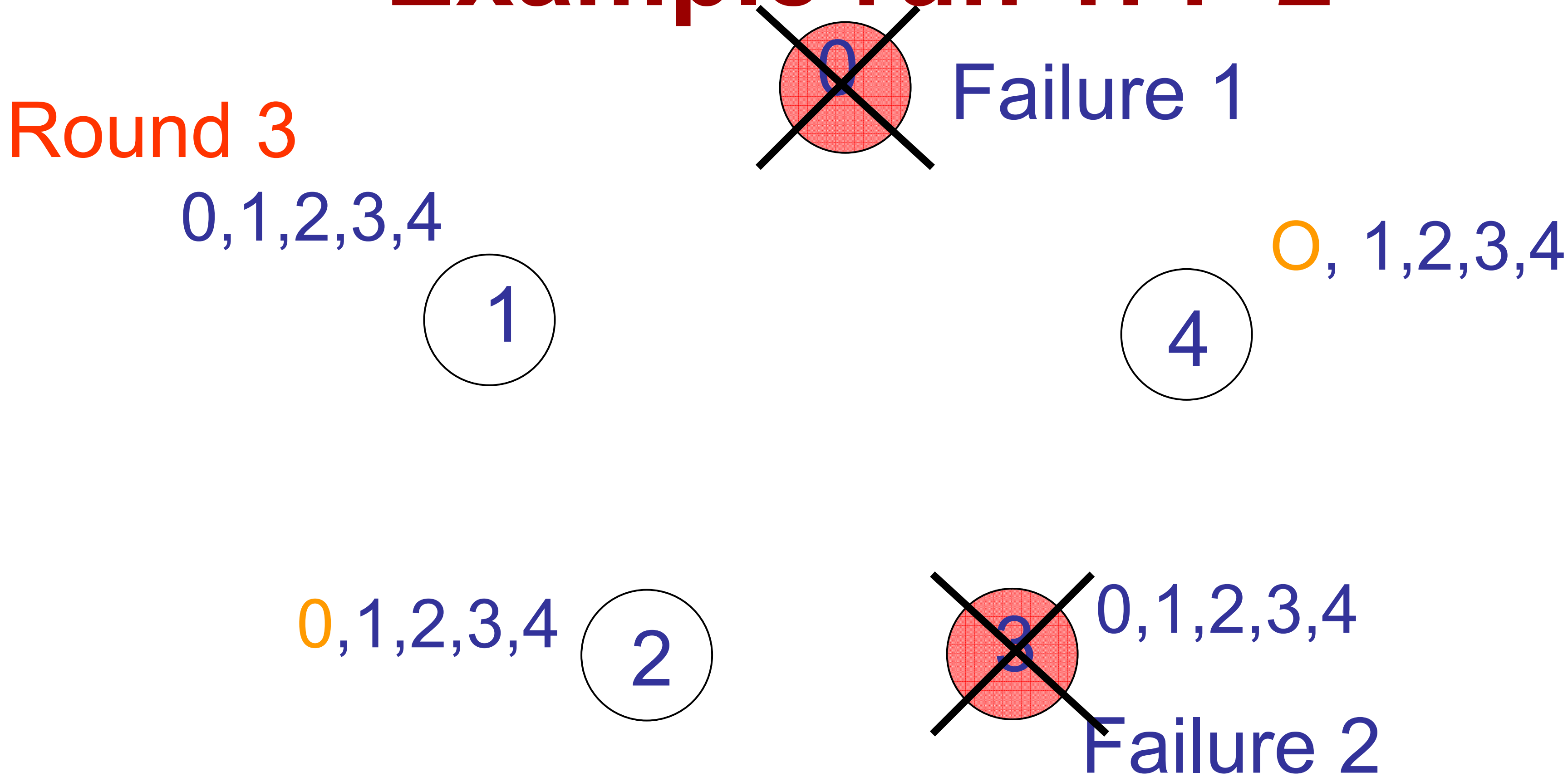
B-multicast all values to everybody

Example run 1: f=2



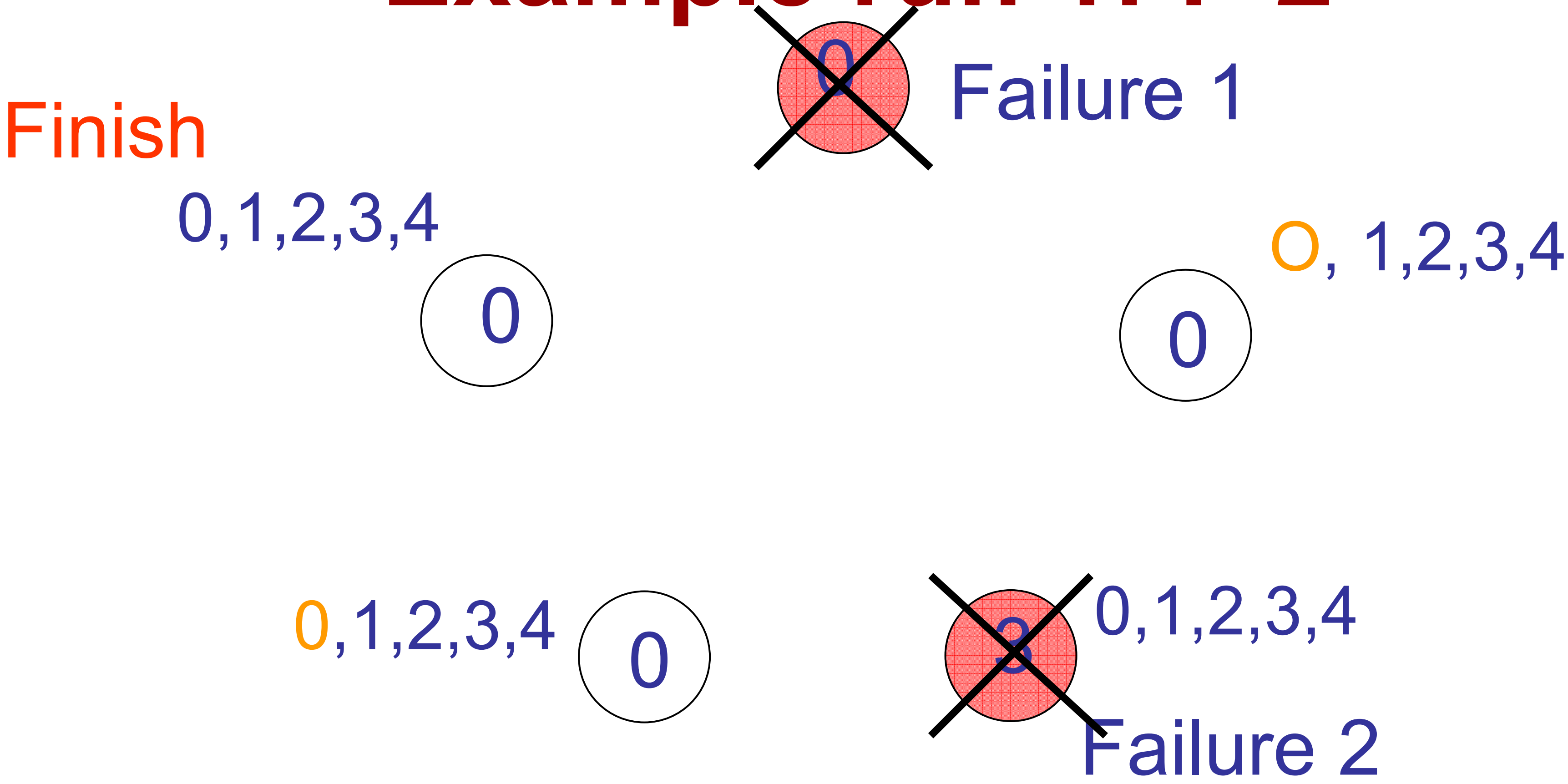
B-multicast new values to everybody

Example run 1: f=2



B-Multicast new values to everybody

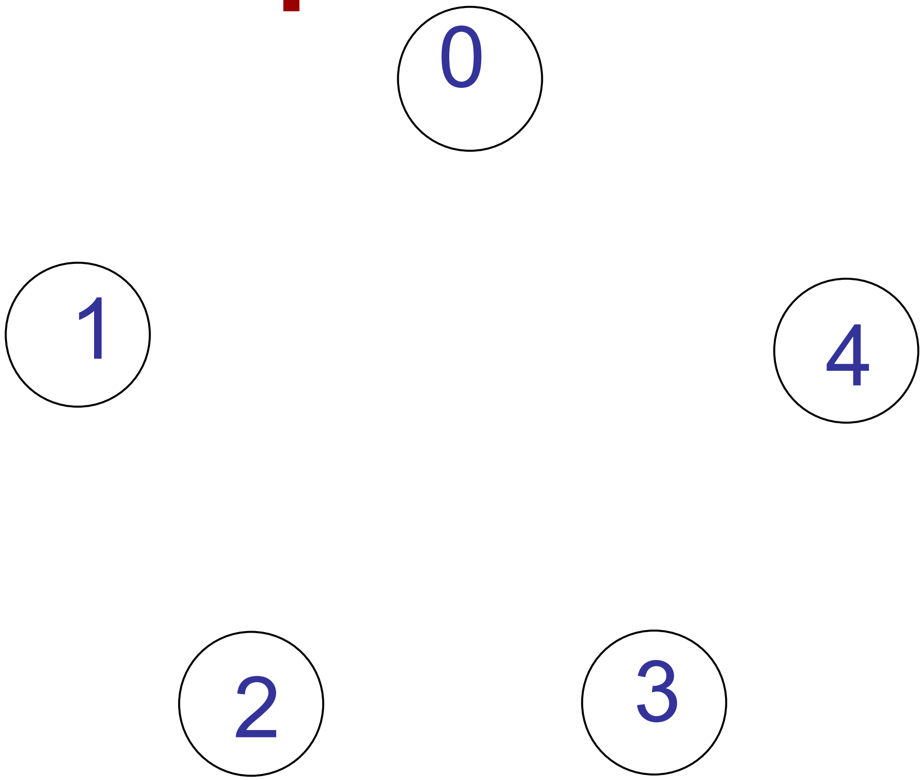
Example run 1: f=2



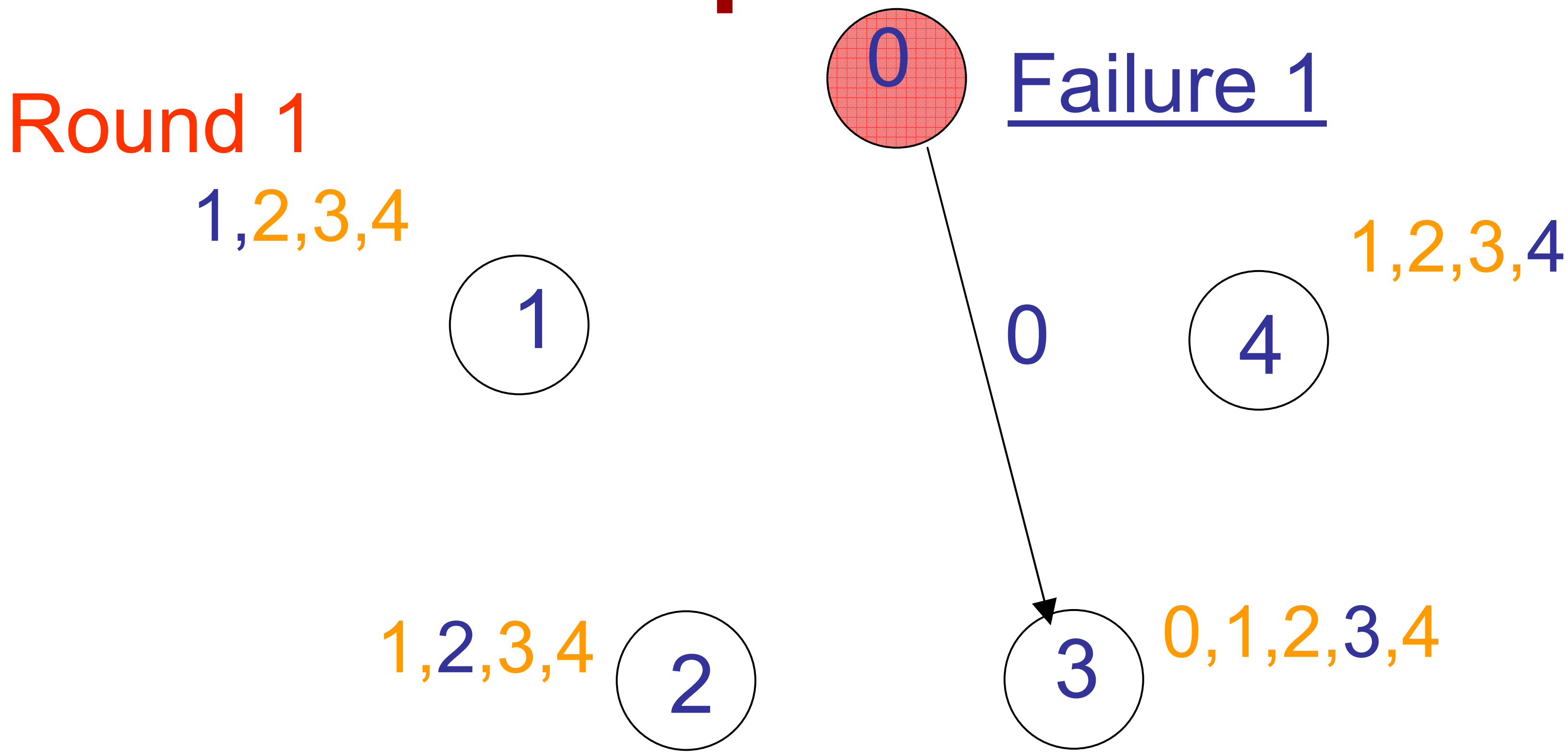
Decide on the minimum value

Example run 2: f=2

Start

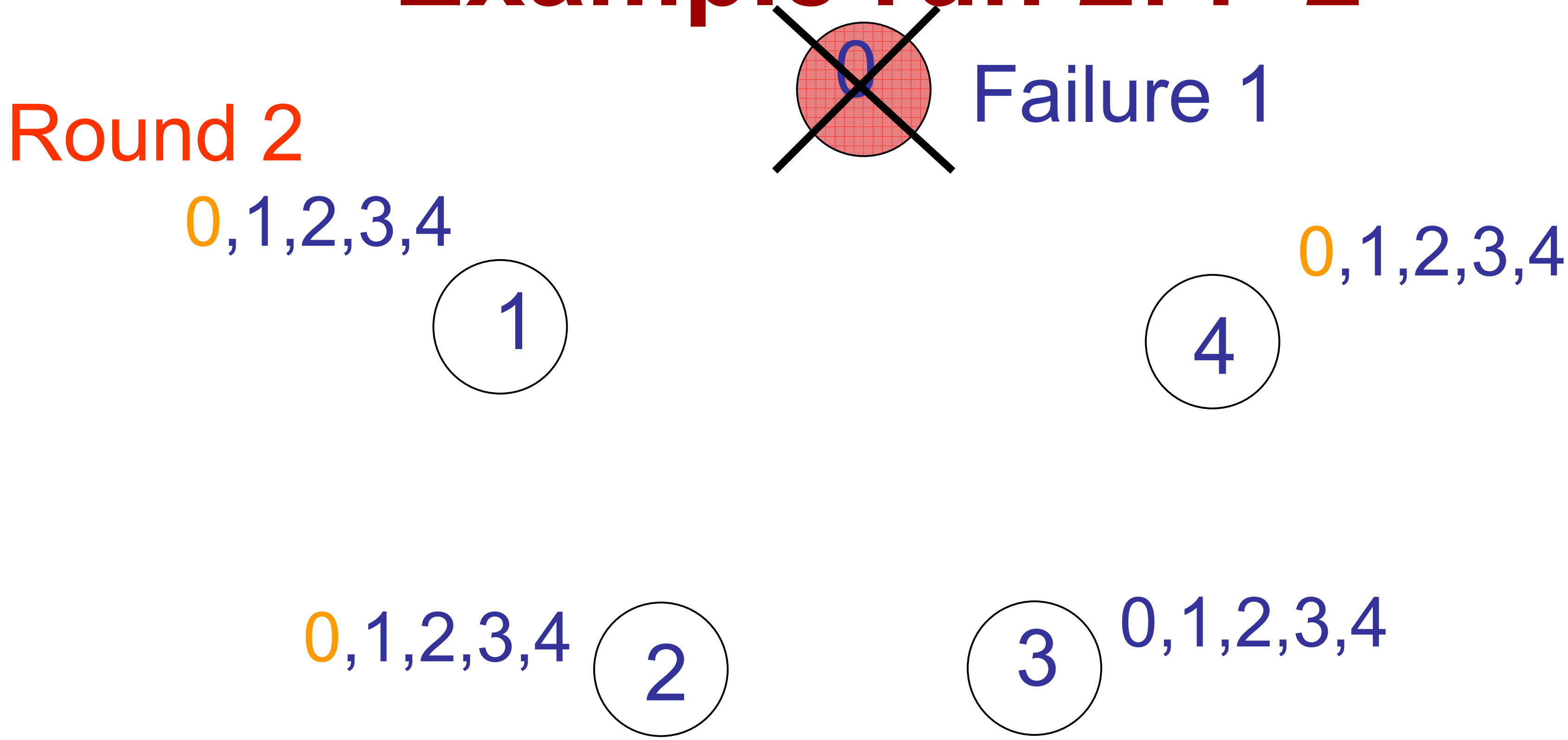


Example run 2: f=2



B-multicast all values to everybody

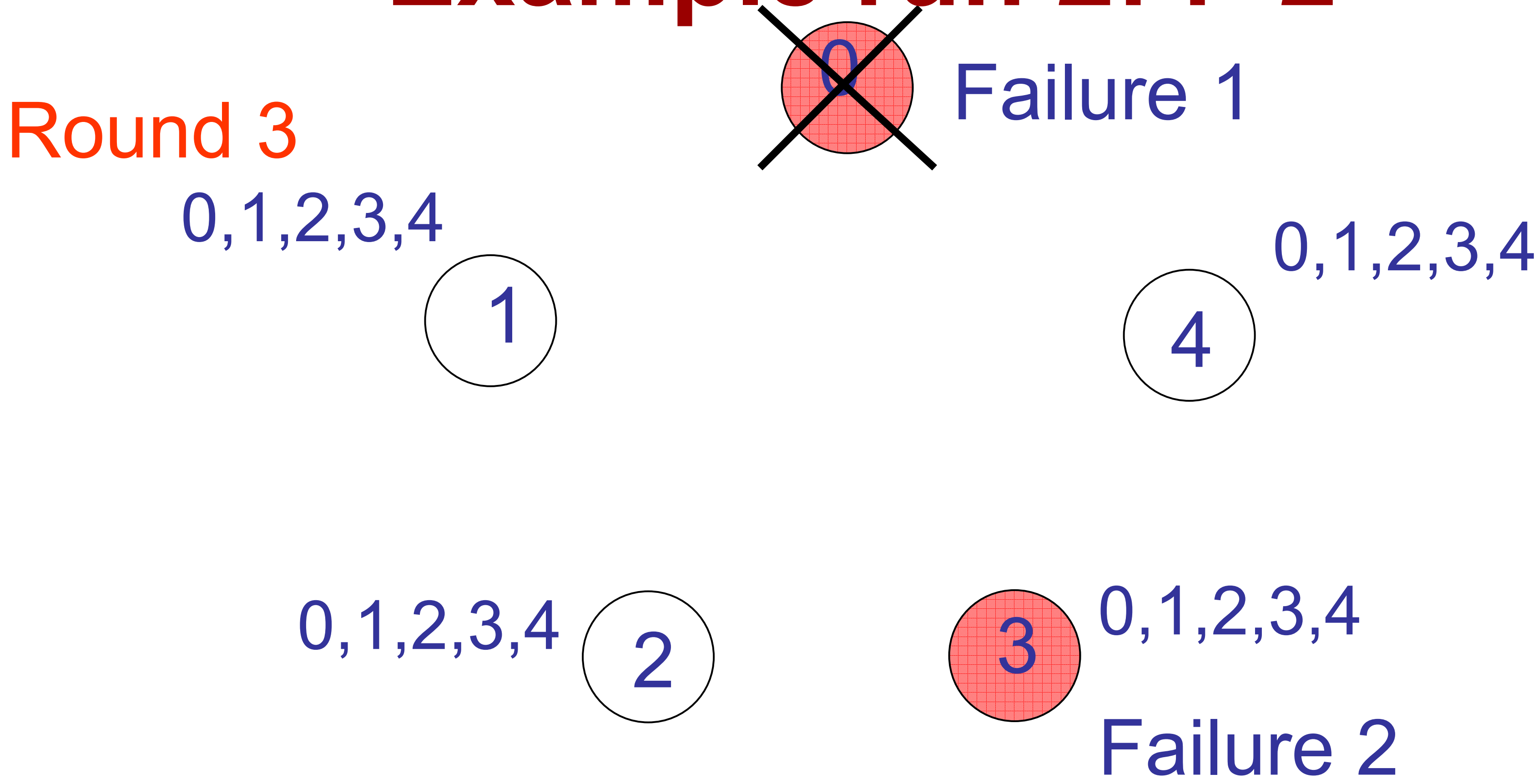
Example run 2: f=2



B-multicast new values to everybody

Remark: At the end of this round all processes know about all the other values

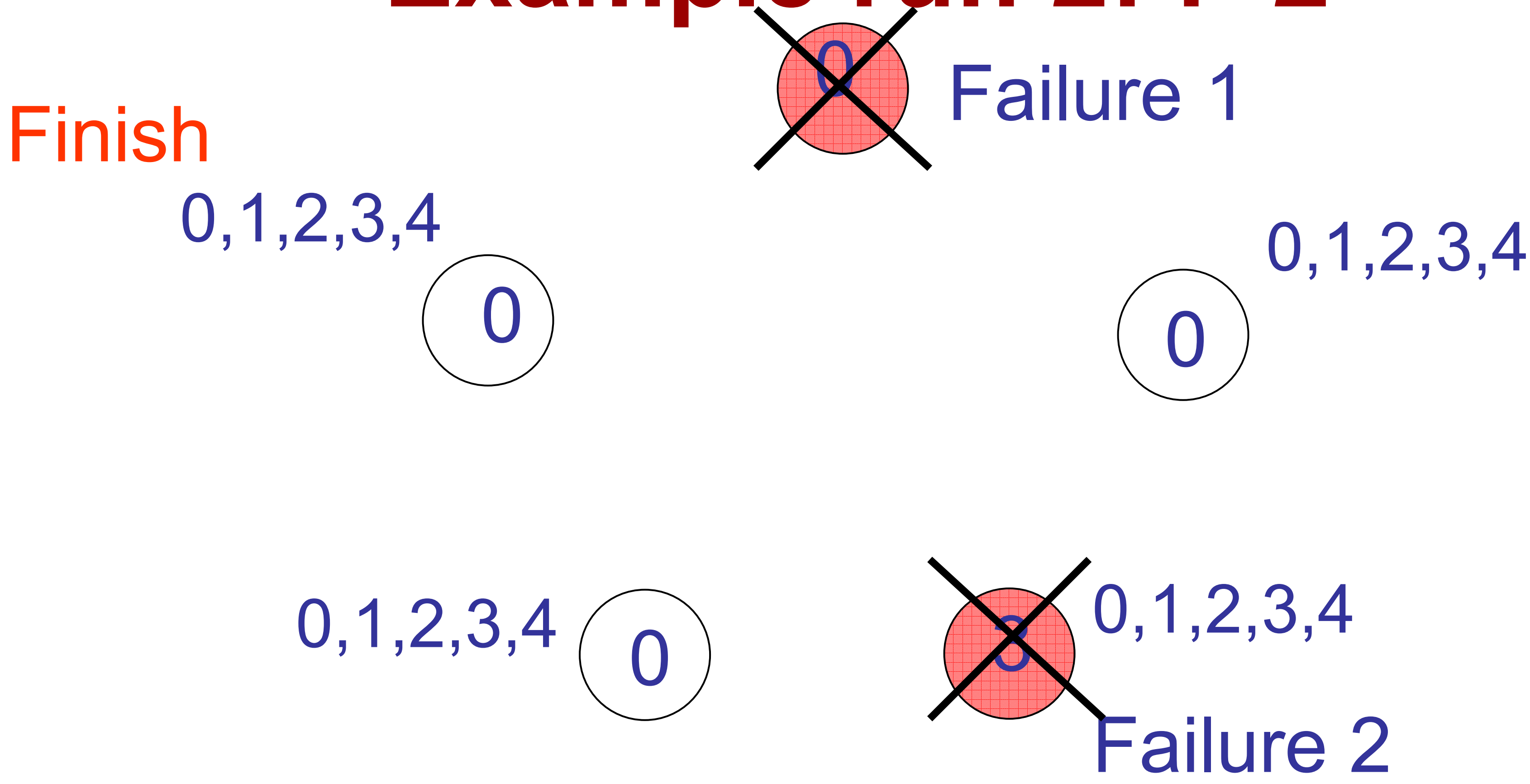
Example run 2: f=2



B-multicast new values to everybody

(no new values are learned in this round)

Example run 2: f=2



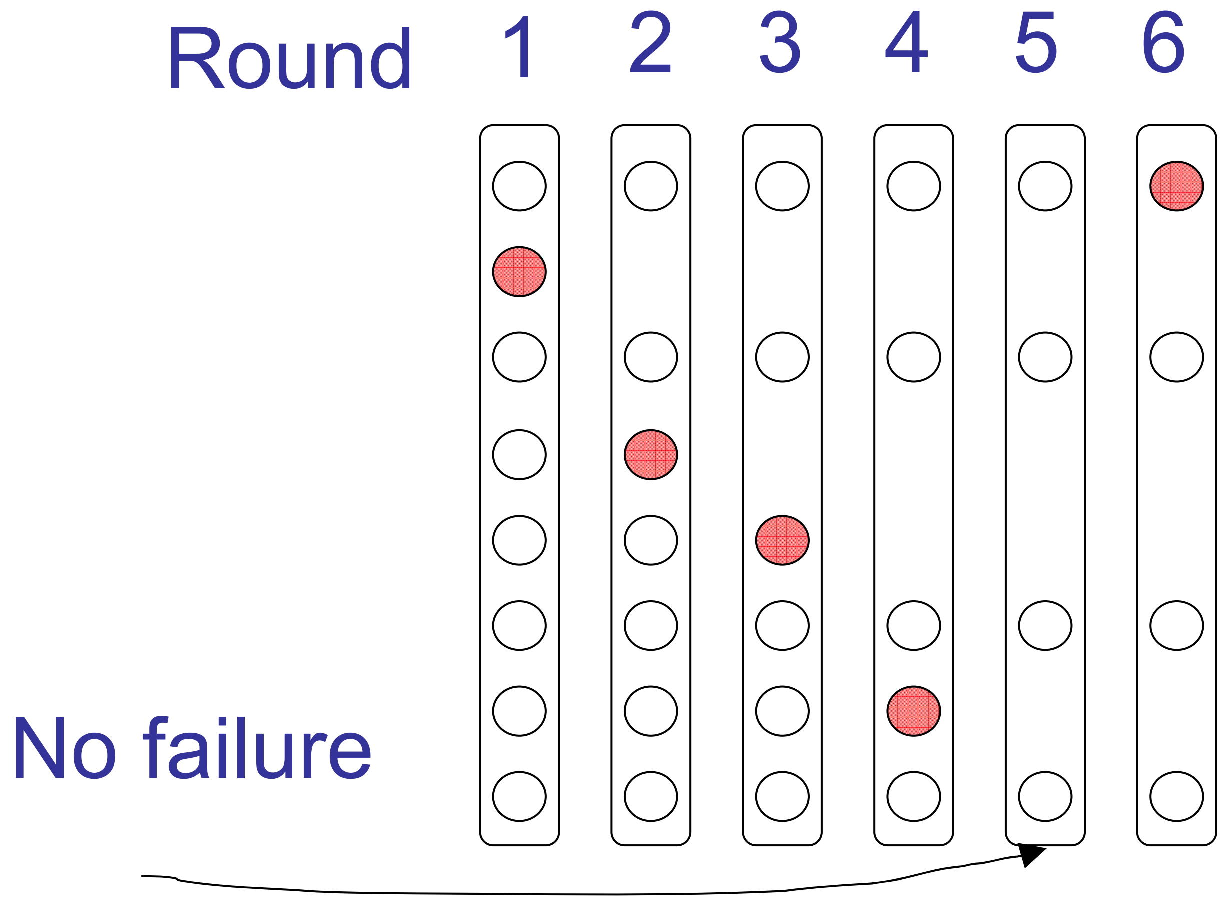
Decide on minimum value

Observation

Example:

5 failures,

6 rounds



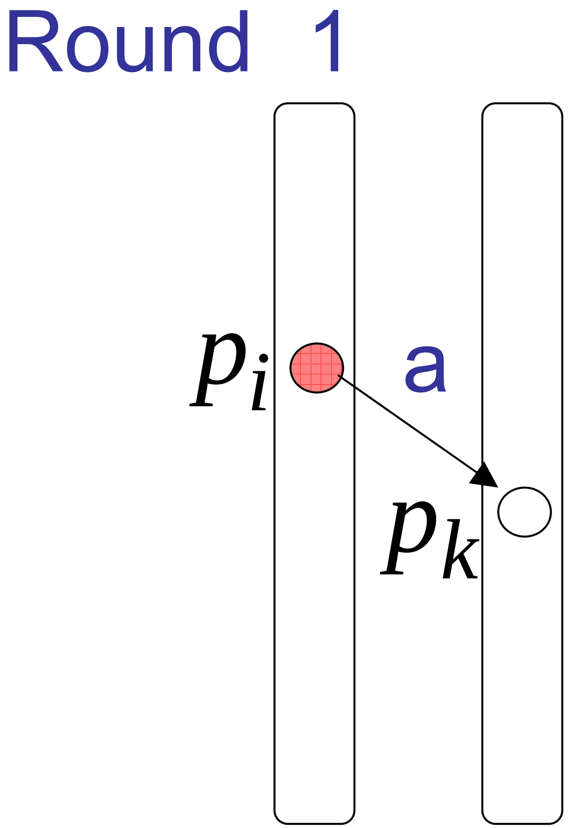
If there are f failures and f+1 rounds then there is a round with no failed process

Need for f+1Rounds

- At the end of the round with no failure:
  - Every (non faulty) process knows about all the values of all other participating processes
  - This knowledge doesn't change until the end of the algorithm
- Therefore, at the end of the round with no failure:

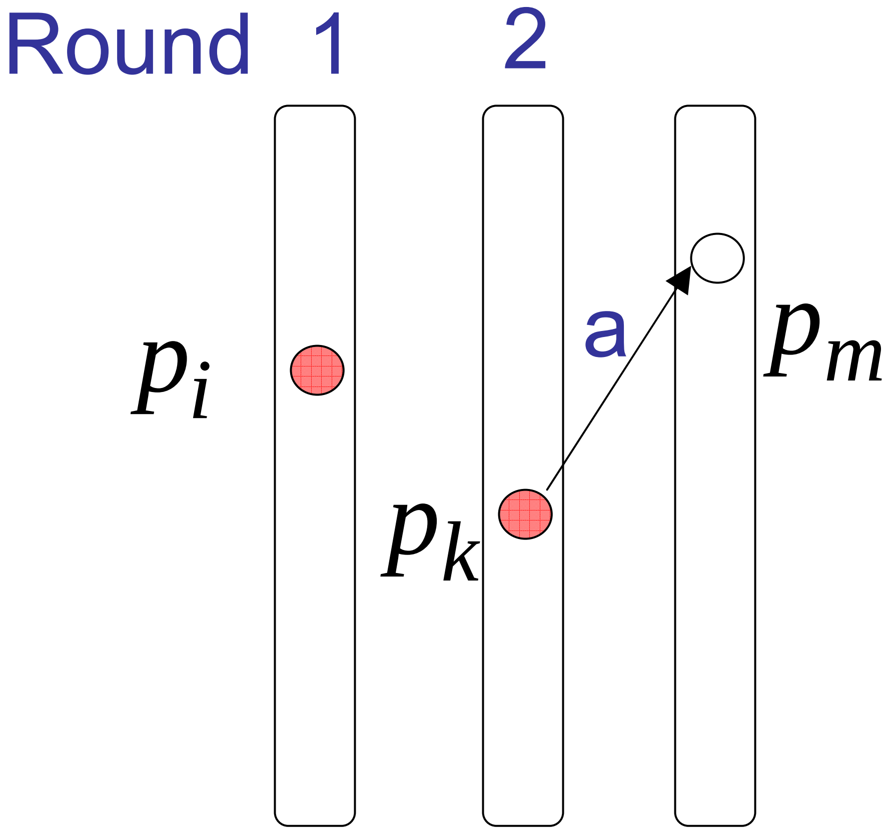
  everybody would decide the same value
- The exact position of this 'good' round is not known:
  - In worst-case we need f+1 rounds

Worst-case Scenario



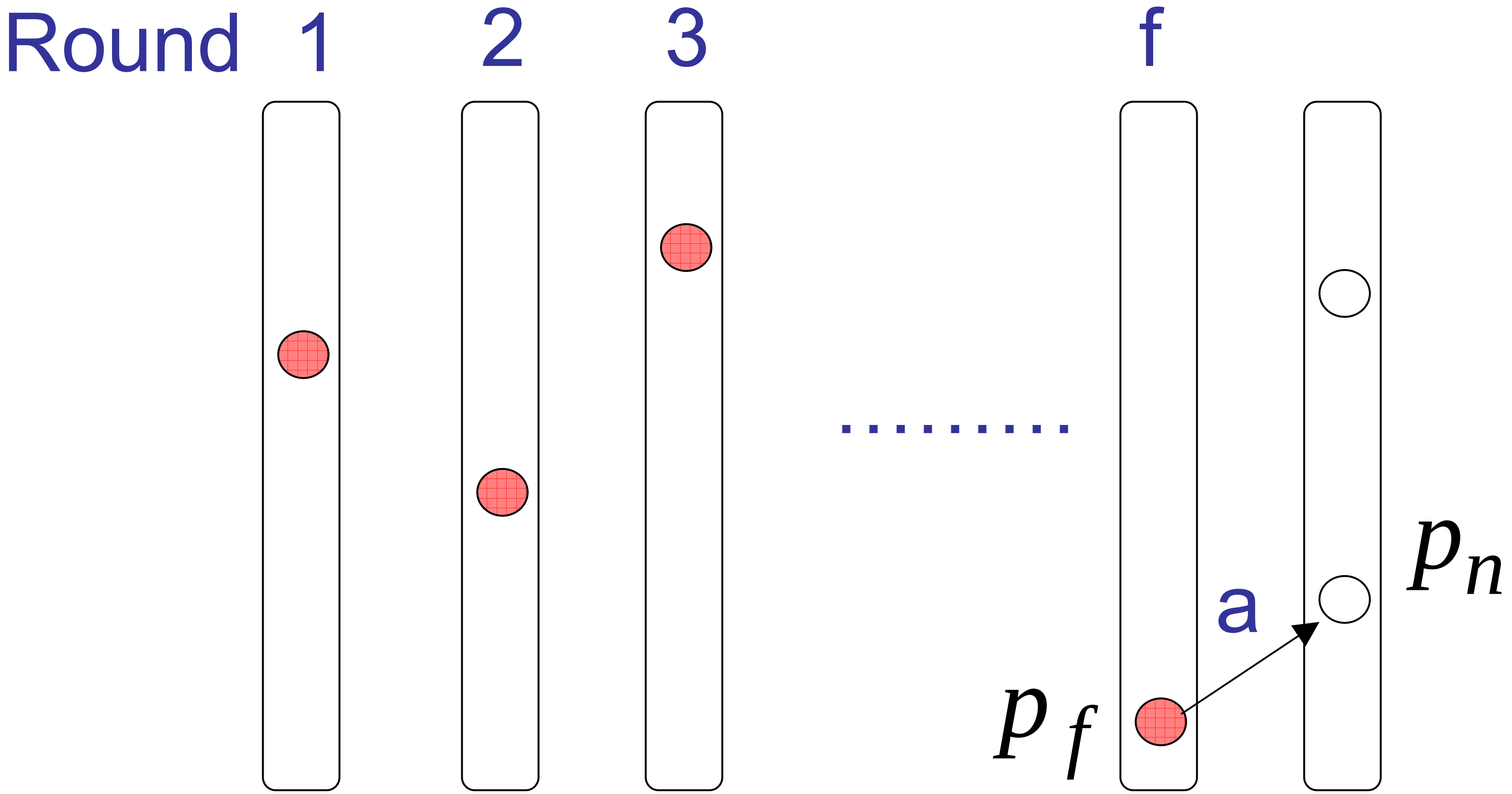
before process p_i fails, it sends its value ***a*** to only one process p_k

Worst-case Scenario



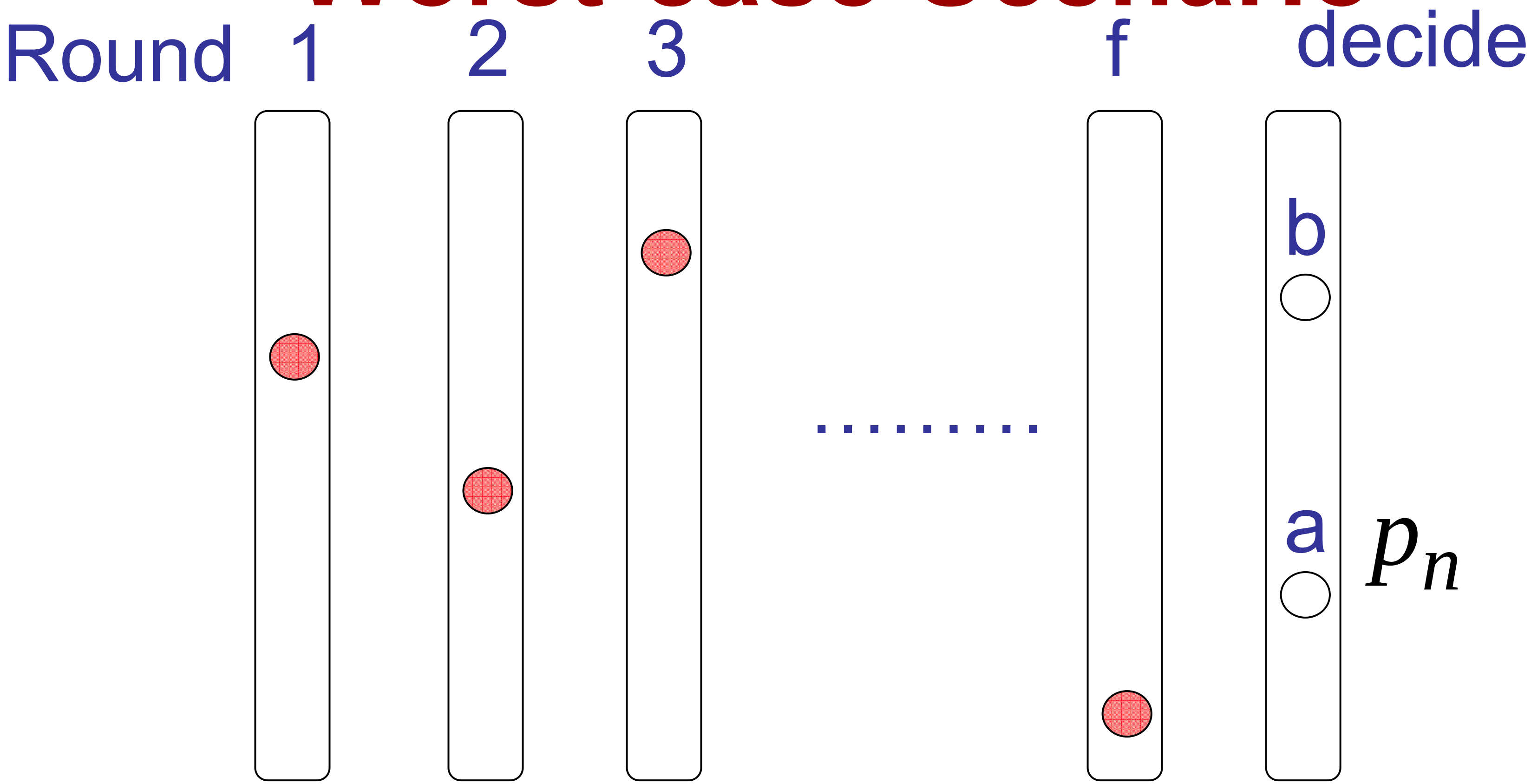
before process p_k fails, it sends value **a** to only one process p_m

Worst-case Scenario



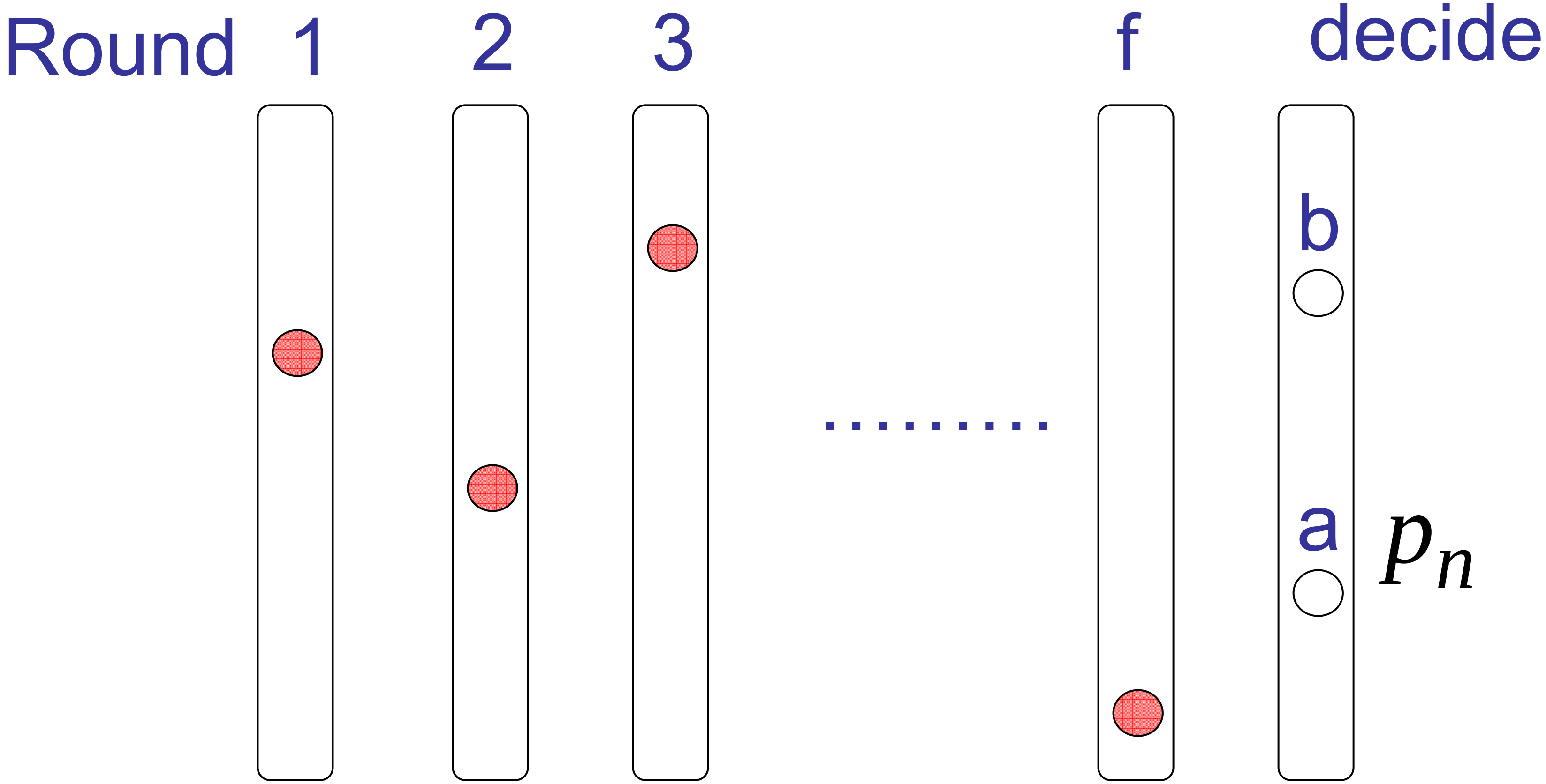
At the end of round **f** only one process p_n knows about value **a**

Worst-case Scenario



Process p_n may decide **a**, and all other processes may decide another value **(b)**

Worst-case Scenario



Therefore f rounds are not enough

At least f+1 rounds are needed

A Lower Bound

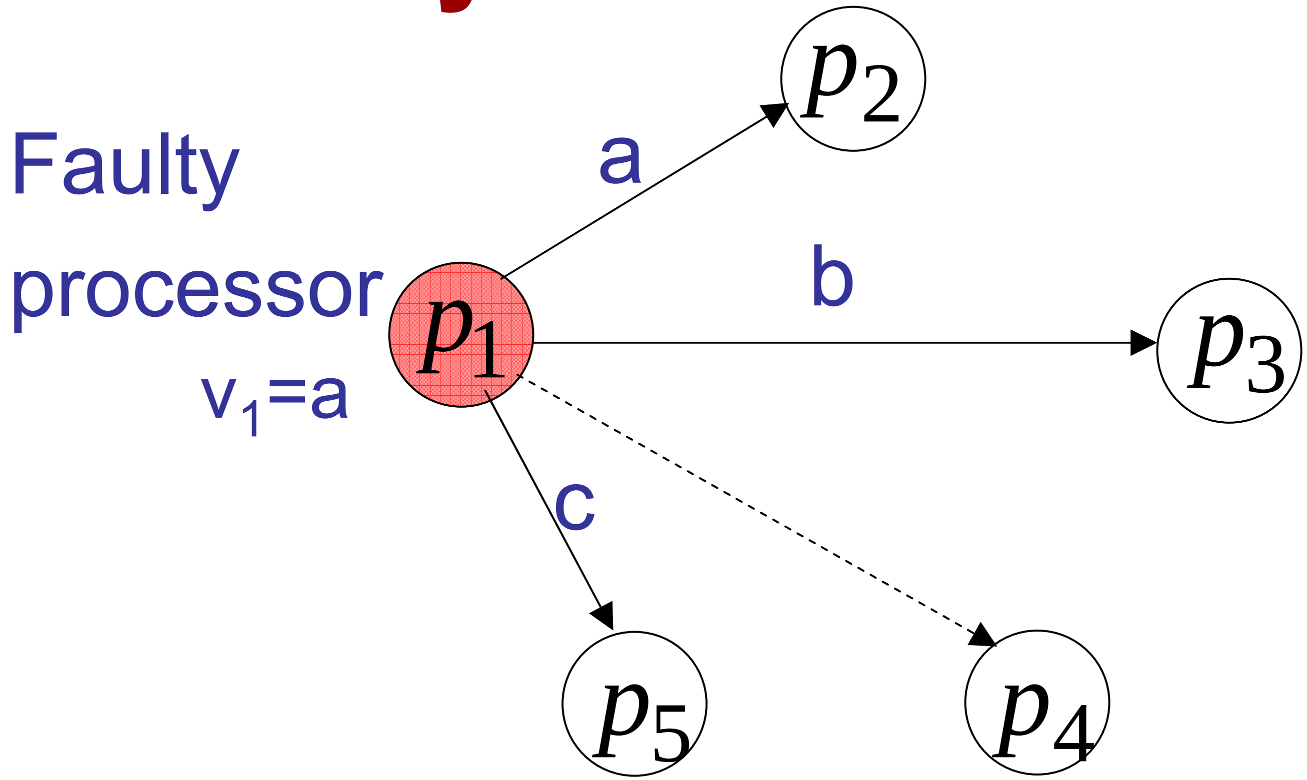
- Theorem
  - ***Any f-resilient consensus algorithm requires at least f+1 rounds***

Byzantine Failures

The Byzantine generals problem

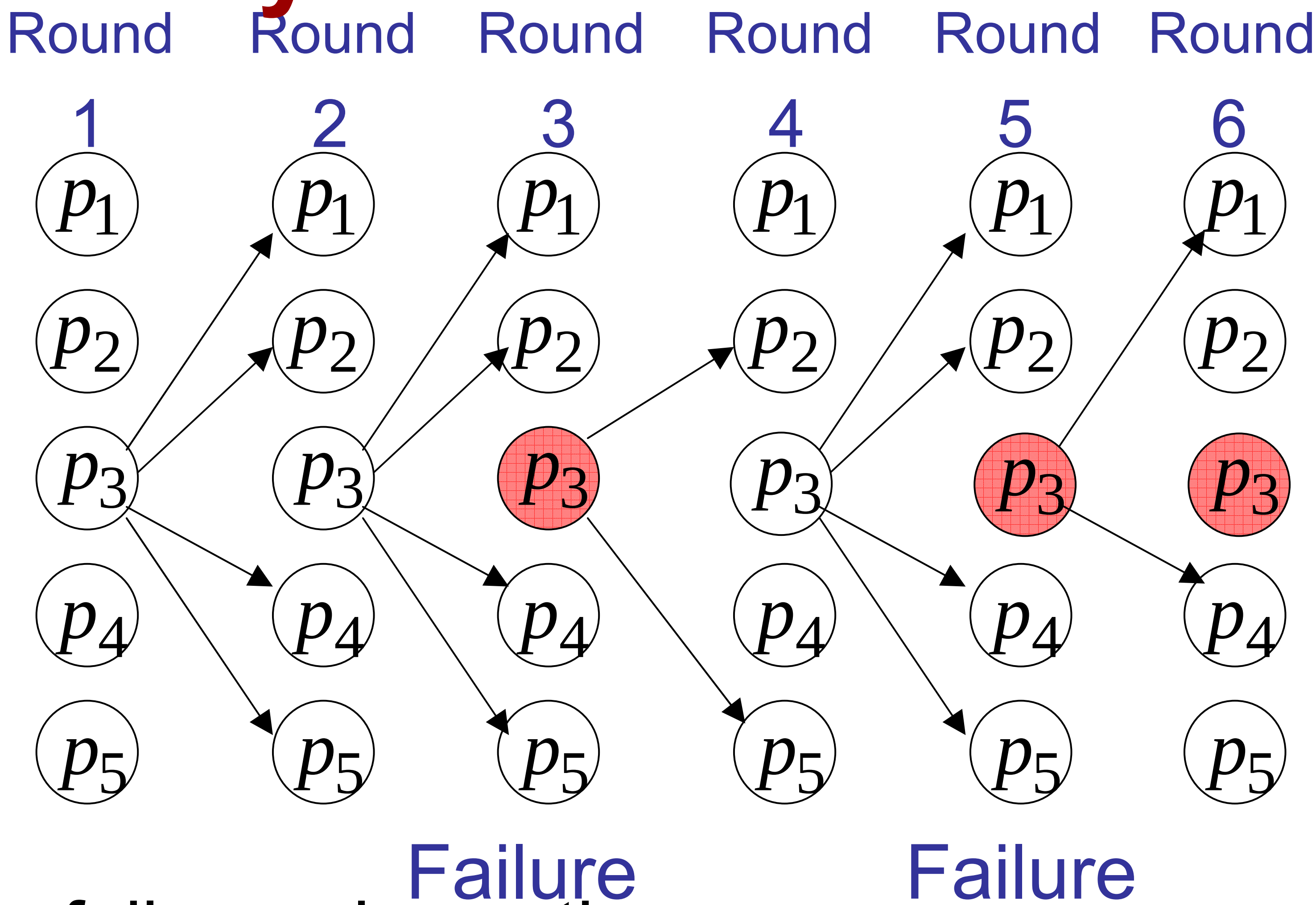
- Turkish invasion into Byzantium
  - Byzantine generals have to agree on attack or retreaval
  - The enemy works by corrupting the soldiers
  - Byzantine generals are notoriously treacherous ...
  - The loyal generals have to prevent traitors from spoiling a coordinated attack
  - Messengers are sent to each other camps
  - Orders are distributed by exchange of messages, corrupt soldiers violate protocol at will
  - But corrupt soldiers can’t intercept and modify messages between loyal troops
  - The gong sounds slowly: there is ample time for loyal soldiers to exchange messages (all to all)

Byzantine Failures



- Aka. Arbitrary Faults
  - Different processes receive different values
  - Ommision failures
  - Crash Failure

Byzantine Failures



After failure a byzantine process may continue functioning in the network

Byzantine Generals

- ***Termination:*** Eventually each correct process sets its decision variable.
- ***Agreement:*** The decision value of all correct process is the same: if p_i and p_j are correct and have entered their *decided* state, then $d_i = d_j$ (for all $i,j \in 1..N$).
- ***Integrity:*** If the *commander* is correct, then all correct processes decide on the value that the commander proposed.

A Theorem

- N processes must tolerate f-faults
- ***There is no f-resilient algorithm if $N \leq 3f$***
- ***Outline***

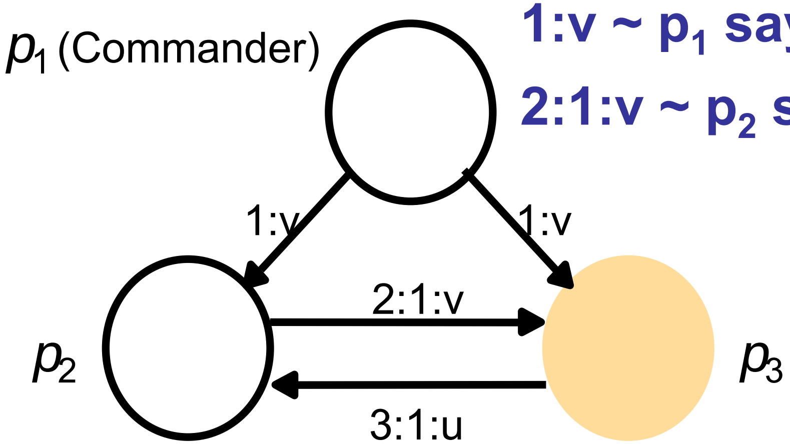
1. Impossibility with 3 processes case,
2. Impossibility if $N \leq 3f$
3. An algorithm for $N \geq 3f+1$ in synchronous systems
4. Impossibility of consensus in asynchronous systems

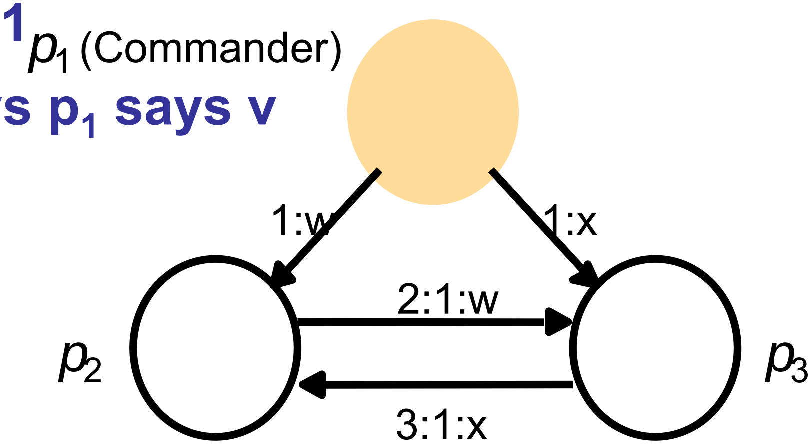
Impossibility of Three Byzantine Generals

Notation:

1:v ~ p_1 says 1

2:1:v ~ p_2 says p_1 says v

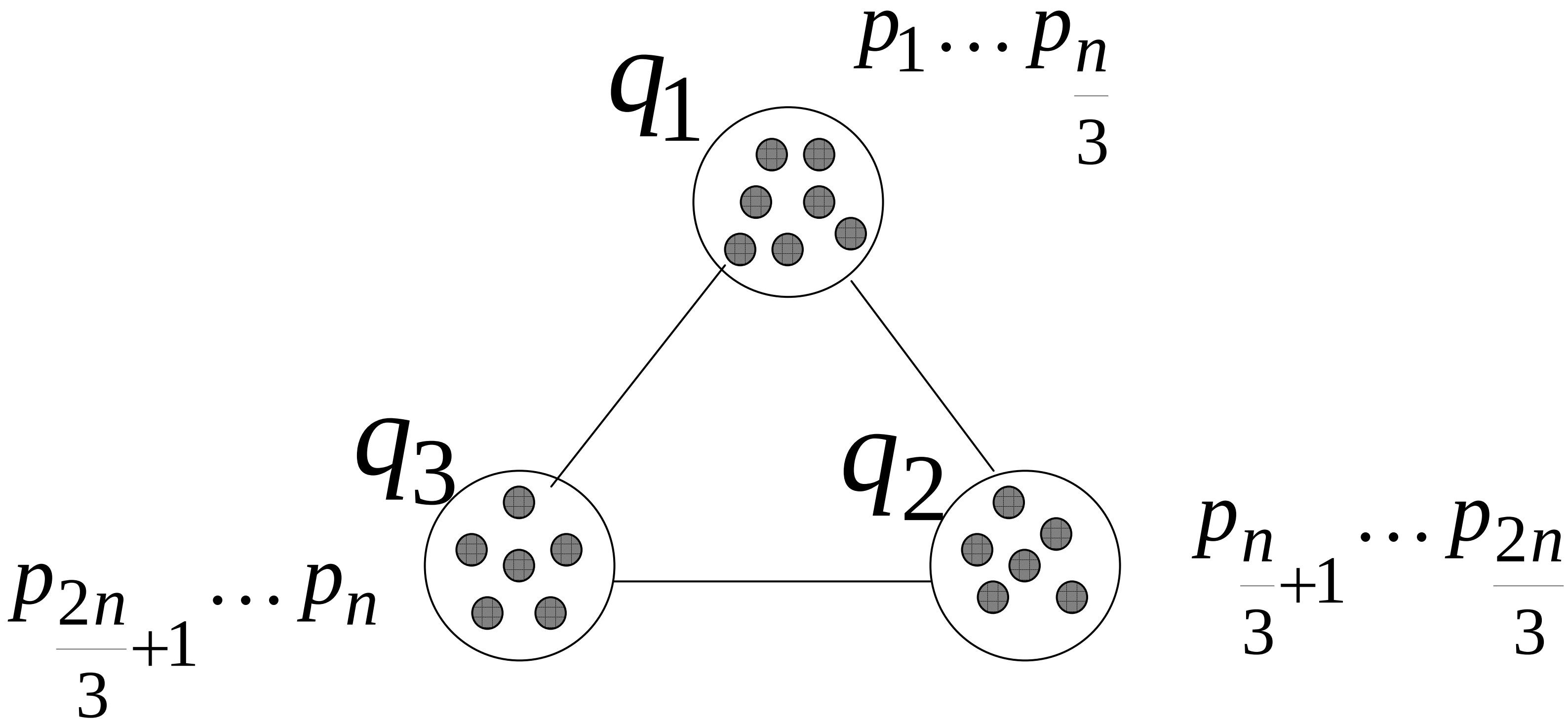




Faulty processes are shown shaded

1. Left: p_2 gets conflicting information. Which is correct?
2. If commander is correct p_2 and p_3 must decide ***v*** accordingly (integrity)
3. Right: Symmetrically, p_2 must decide ***w*** and p_3 must decide ***x***
4. An algorithm cannot distinguish scenarios: **No Agreement**

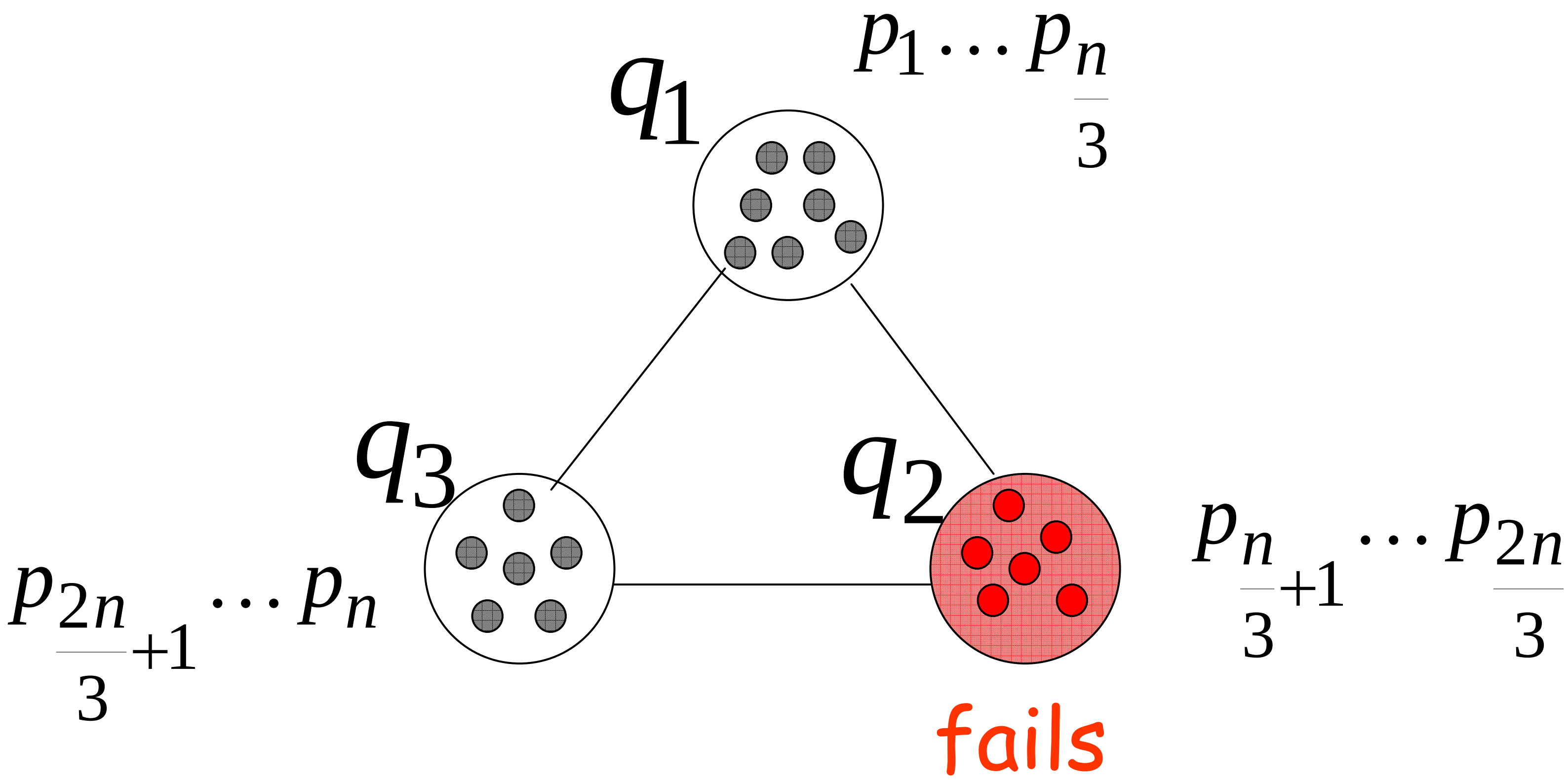
Impossibility of N≤3f Byzantine Generals



Reduction:

Each process q simulates N/3 processes using **algorithm X**

Impossibility of N≤3f Byzantine Generals

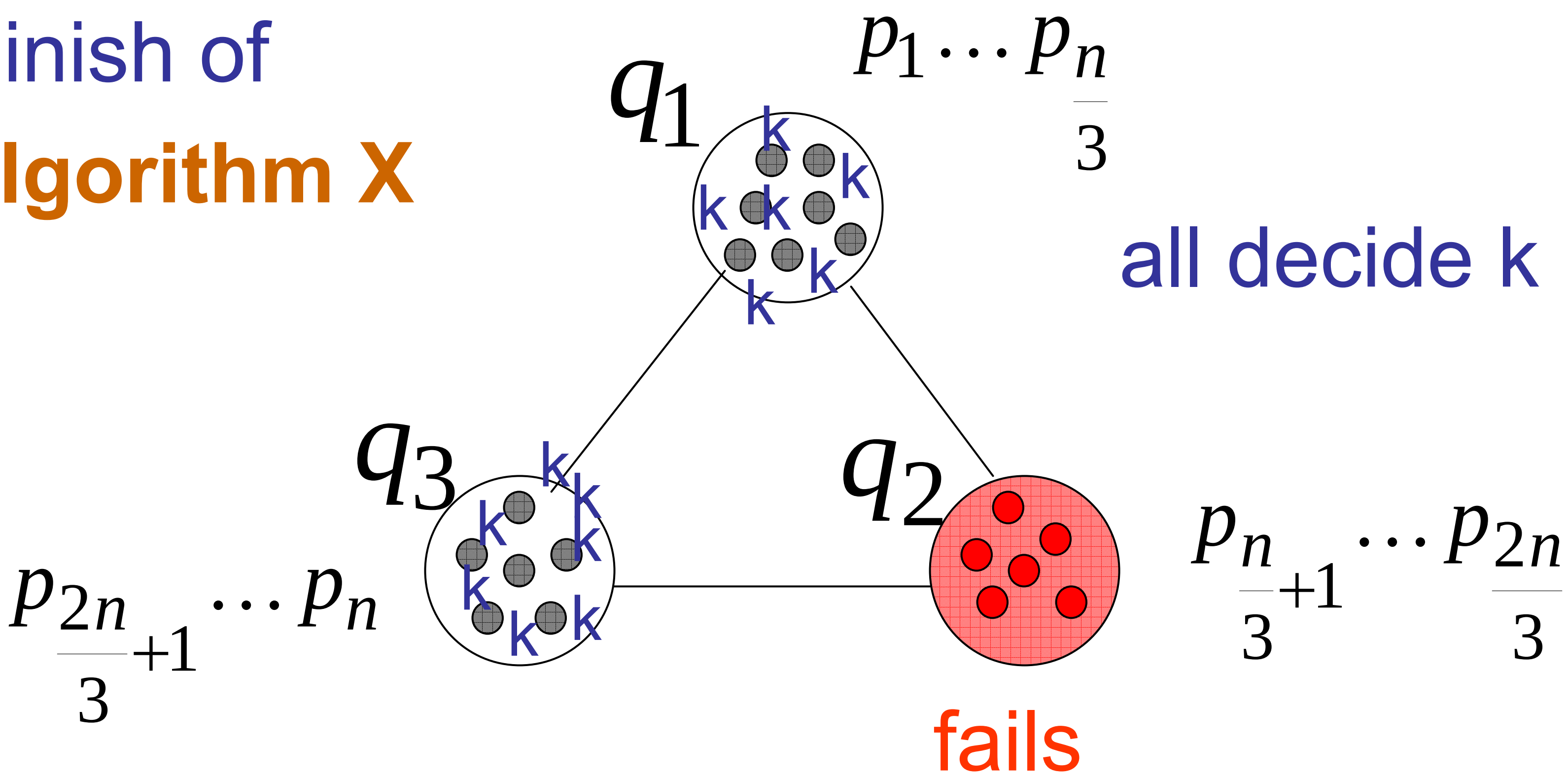


When a ‘q’ fails n/3 then processes fail too

Impossibility of N≤3f Byzantine Generals

Finish of

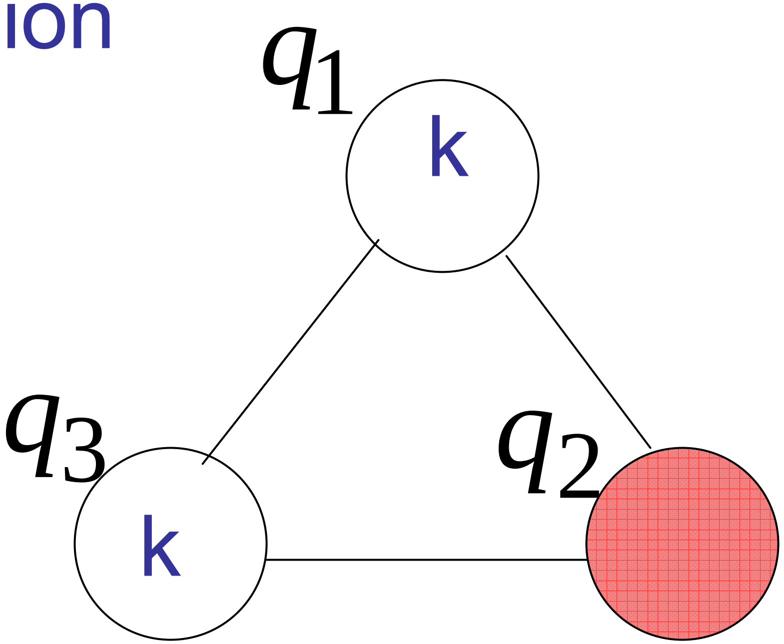
algorithm X



algorithm X tolerates n/3 failures

Impossibility of
N≤3f Byzantine Generals

Final decision

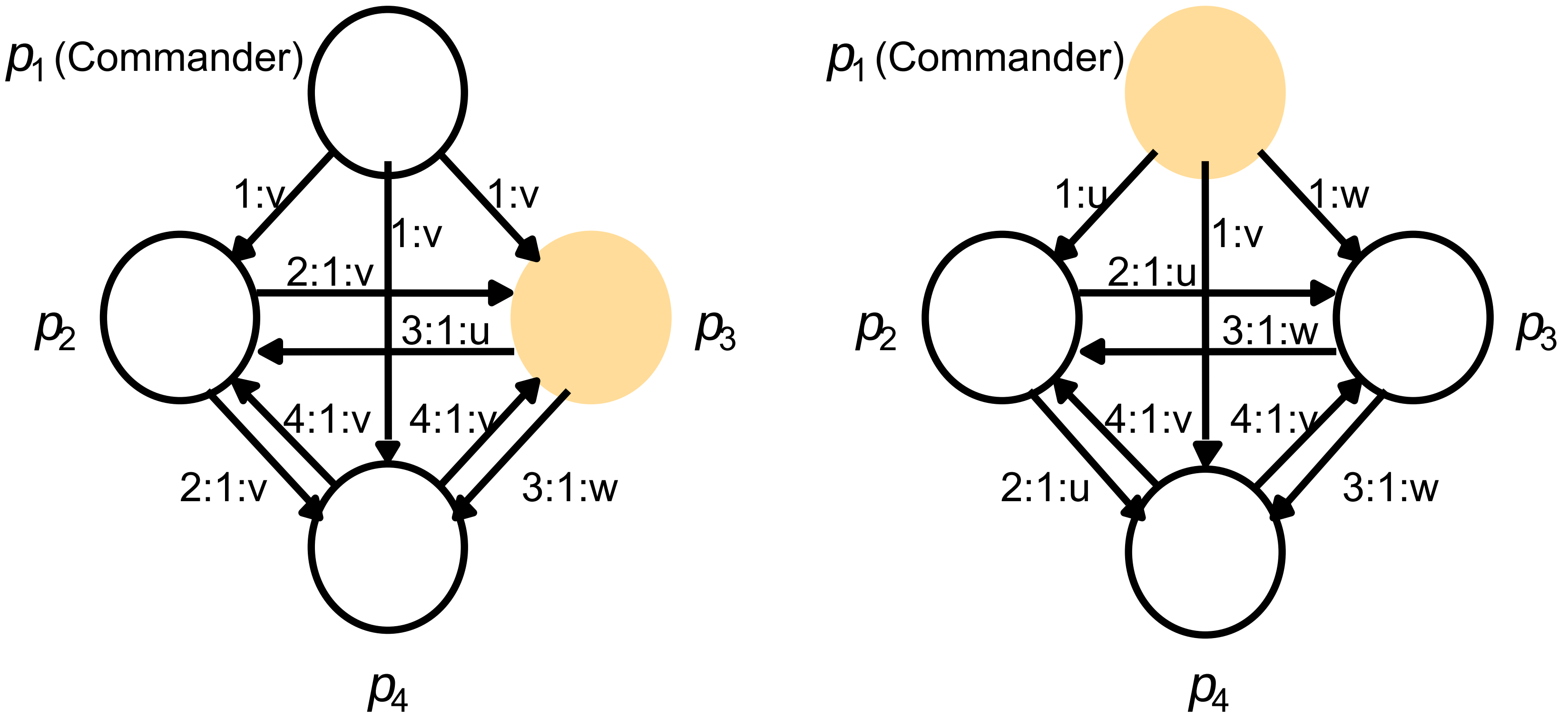


We reached consensus with 1 failure

Previously shown Impossible!!!

algorithm X cannot exist

Four byzantine generals



Faulty processes are shown shaded

p_2 and p_4 agrees:

d_2 =majority (v,v,u)=v

d_4 =majority (v,v,w)=v

p_2, p_3, and p_4 agrees:

d_2= d_2 = d_4 =majority (v,u,w)=$\perp$

$\Rightarrow$Use common default value

Cost of Byzantine Generals

- Requires *f*+1 rounds,
- Sends $O(n^{f+1})$ messages
- If we use digital signatures a solution exist with $O(n^2)$ messages (f+1 rounds)
  – False claims not possible:
  – If ”p says v” other processes can detect if ”q says p says w”
- Truely arbitrary failures are rare.

Impossibility of Consensus in *asynchronous* systems

- No algorithm exists to reach consensus
  - (Concensus may possibly (very often) be reached, but cannot always guaranteed)
  - Neither for crash or byzantine failues
- Eg. Two-army problem:
  - There is some program continutation that avoids consensus
- No guaranteed solution to
    - Byzantine generals problem
    - Interactive consistency
    - Totally ordered multicast
    - Reliable multicast

Two-Army Problem

The two-army problem:

1. Sparta and Carthage together can beat Bad guys but not individually. Therefore, they have to decide to attack at exactly the same time.
2. Sparta general sends a message to Carthage general to attack at noon
3. How does he know that Carthage general received the message?

Arbitrarily slow processes (or channels) are indistinguishable from crashed ones (omission)

Workarounds in an asynchronous system

- Masking faults:
  - restart crashed process and use persistent storage
  - Eg recovery files like in databases
- Use failure detectors:
  - make failure *fail-silent* by discarding messages
- Probabilistic algorithms:
  - conceal strategy for adversary

END