

# *Part 2: Fault-Tolerance*

*Distributed Systems 2013*



*Roger Wattenhofer*

# Overview Part 2

- **Lecture (Monday 9-11 & Friday 9-11, usually)**
  - It's all about fault-tolerance
  - First theory, in particular consensus, models, algorithms, and lower bounds
  - Then large-scale practice, fault-tolerant systems
  - Finally small-scale practice, programming, multi-core
- **Exercises (Monday 11-12 & Friday 11-12, sometimes)**
  - There will be paper exercises, without grades
  - Exercises don't have to be handed in...  
...but you are strongly encouraged to solve them!
  - But: There will be a creative task that gives exam points (10 or 20).
- **Personnel**
  - Roger Wattenhofer, Christian Decker, Michael König, Jara Uitto
  - [www.disco.ethz.ch](http://www.disco.ethz.ch)

# Why are we studying distributed systems?

- **First, and most importantly: The world is distributed!**
  - Companies with offices around the world
  - Computer networks, in particular the Internet
- **Performance**
  - Parallel high performance computing
  - Multi-core machines
- **Fault-Tolerance**
  - Availability
  - Reliability

## Book for Part 2

- Great book
- Goes beyond class
- Fully covers Chapter 3
- Does not cover everything we do (but also some parts of Chapters 1 & 2)
- Some pictures on slides are from Maurice Herlihy  
  
(Thanks, Maurice!)

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# THE ART *of* MULTIPROCESSOR PROGRAMMING

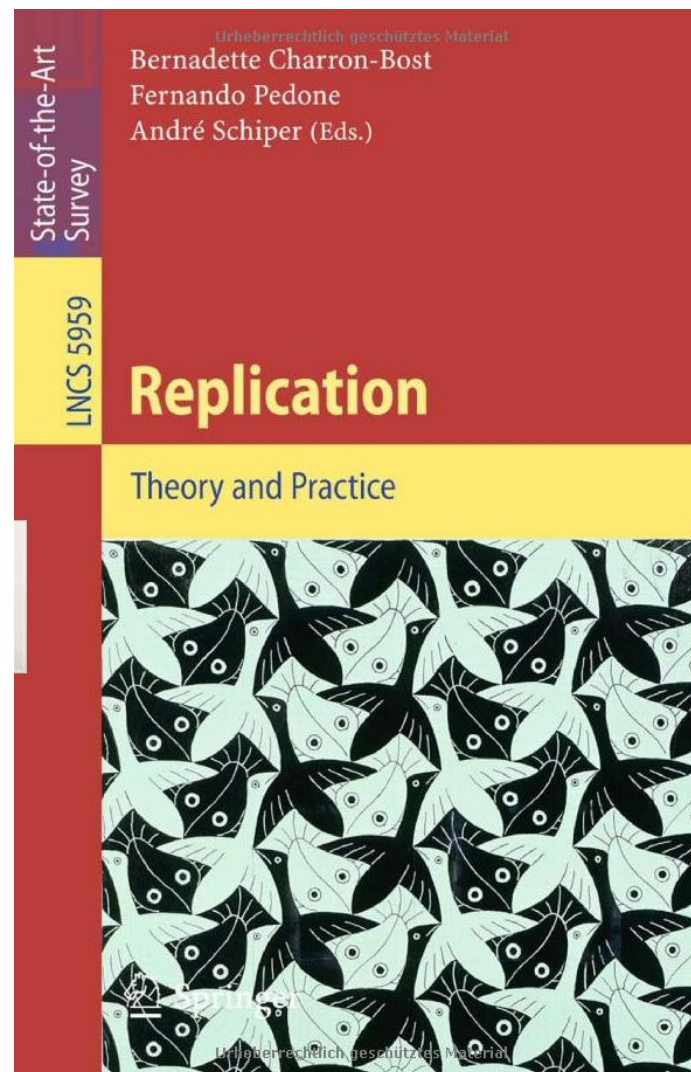
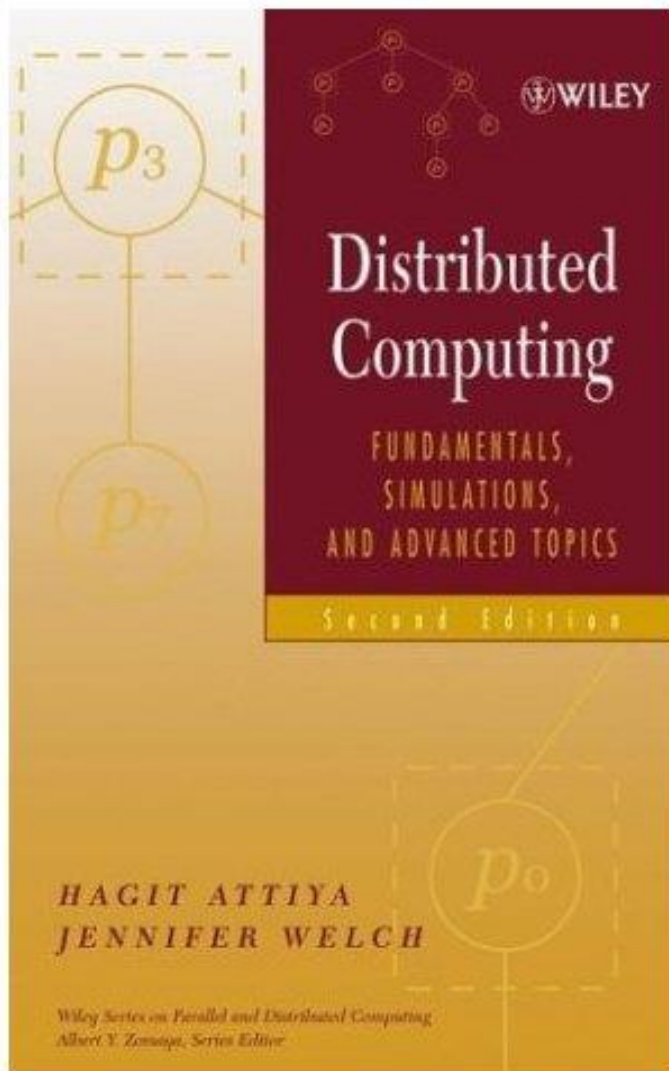


*Maurice Herlihy & Nir Shavit*  
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# Books for Chapters 1 & 2



# *Theory: Consensus*

*Part 2, Chapter 1*

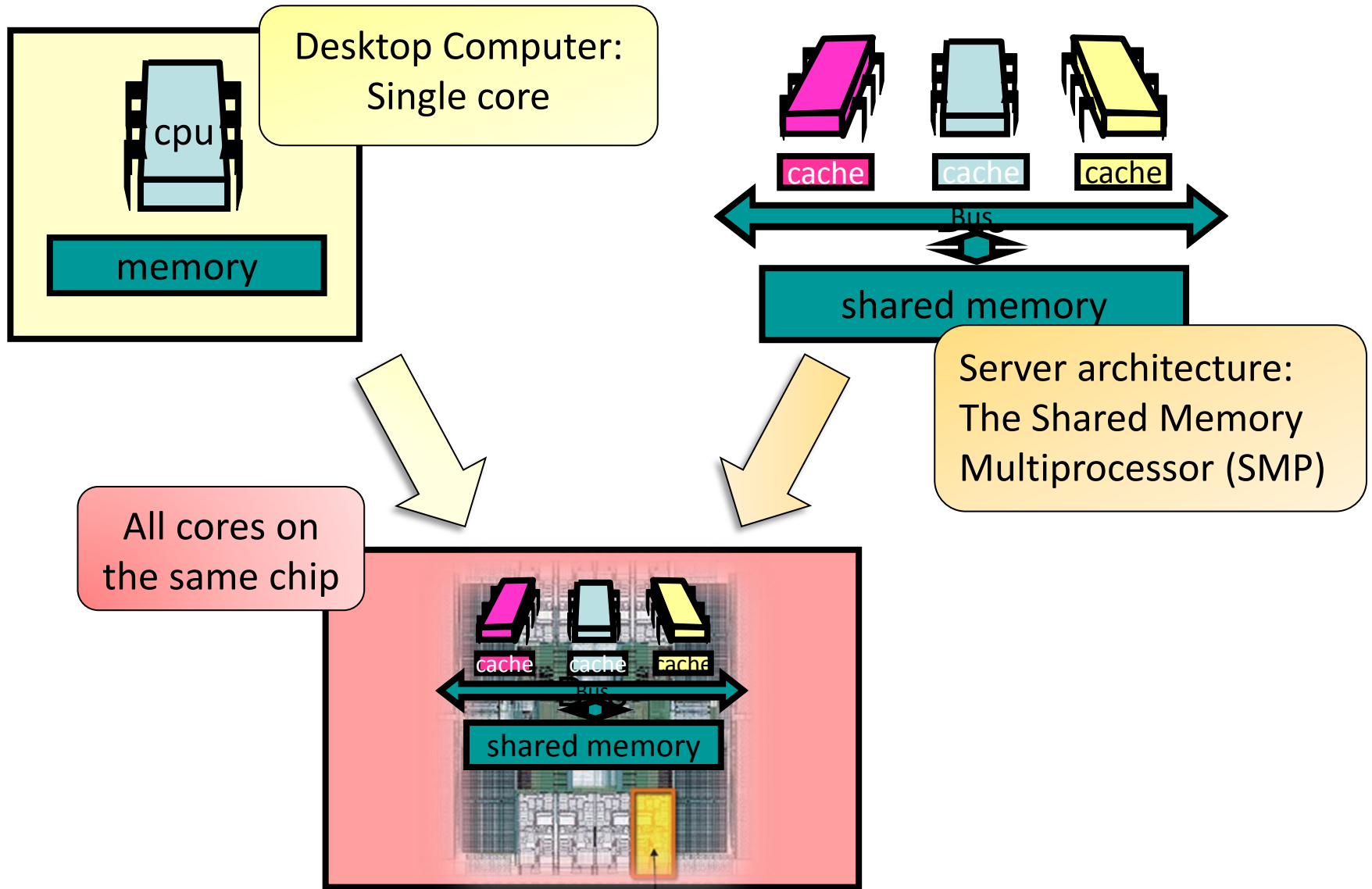


*Roger Wattenhofer*

# Overview

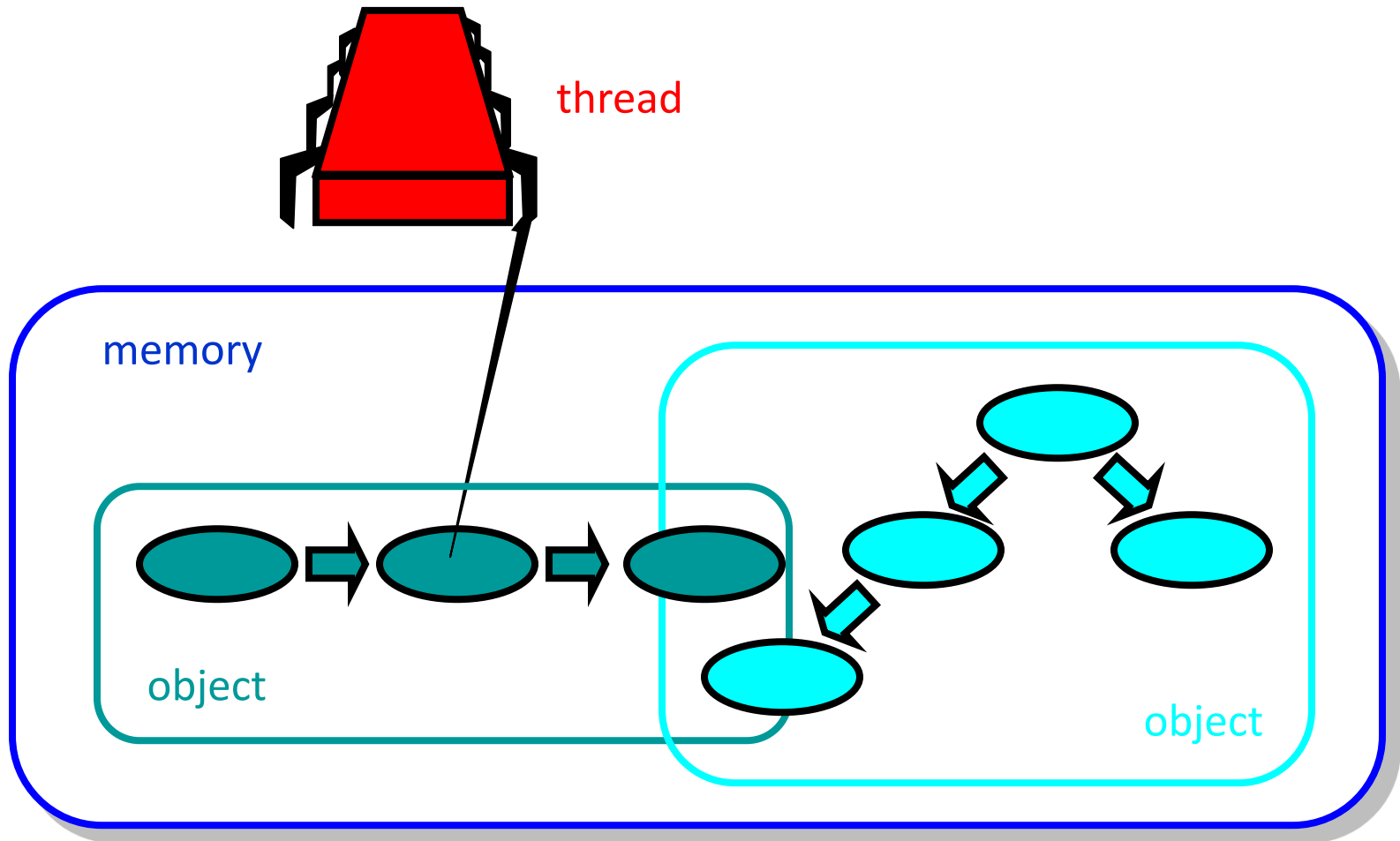
- Introduction
- Consensus #1: Shared Memory
- Consensus #2: Wait-free Shared Memory
- Consensus #3: Read-Modify-Write Shared Memory
- Consensus #4: Synchronous Systems
- Consensus #5: Byzantine Failures
- Consensus #6: A Simple Algorithm for Byzantine Agreement
- Consensus #7: The Queen Algorithm
- Consensus #8: The King Algorithm
- Consensus #9: Byzantine Agreement Using Authentication
- Consensus #10: A Randomized Algorithm
- Shared Coin

# Introduction: From Single-Core to Multicore Computers

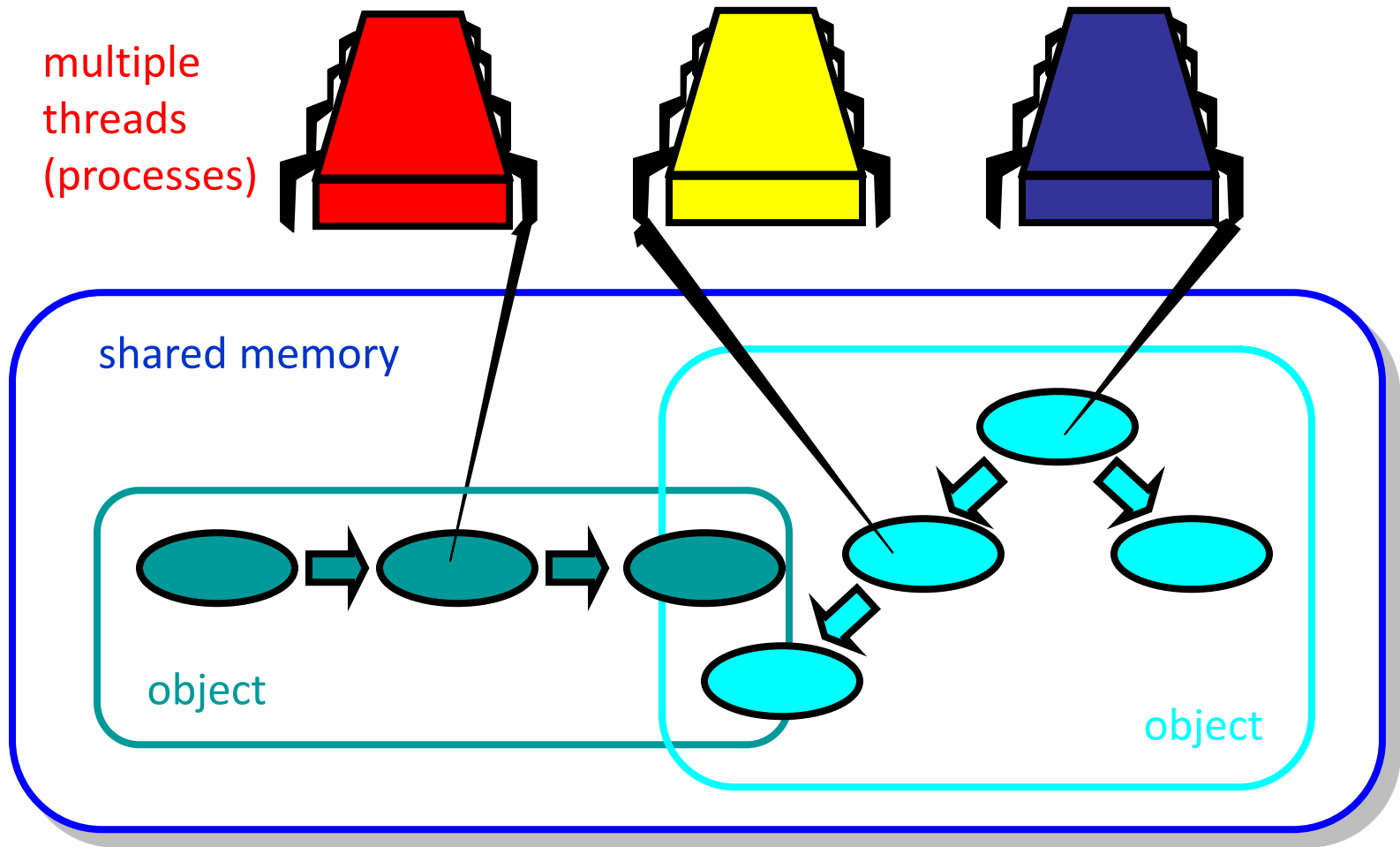




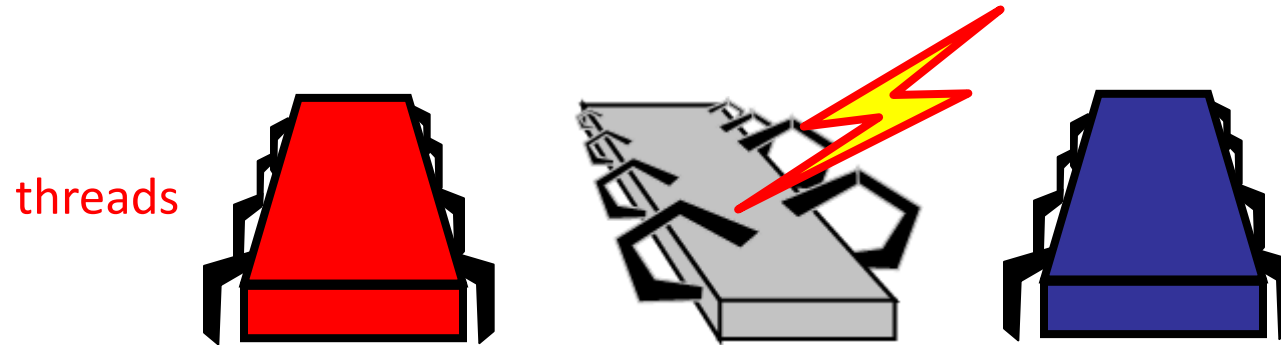
# Sequential Computation



# Concurrent Computation



# Fault Tolerance & Asynchrony



- Why fault-tolerance?
  - Even if processes do not die, there are “near-death experiences”
- Sudden unpredictable delays:
  - Cache misses (short)
  - Page faults (long)
  - Scheduling quantum used up (really long)

# Road Map

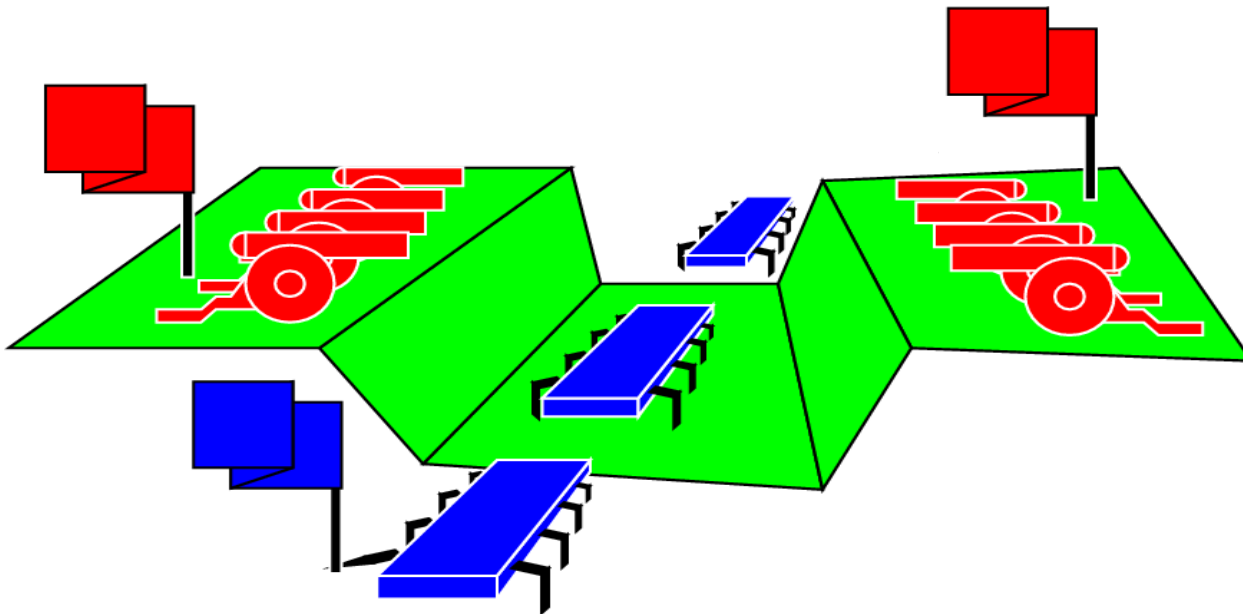
- In this first part, we are going to focus on **principles**
  - Start with idealized models
  - Look at a simplistic problem
  - Emphasize correctness over pragmatism
  - “Correctness may be theoretical, but incorrectness has practical impact”

I’m no theory weenie! Why all the theorems and proofs?

- Distributed systems are hard
  - Failures
  - Concurrency
- Easier to go from theory to practice than vice-versa

# The Two Generals

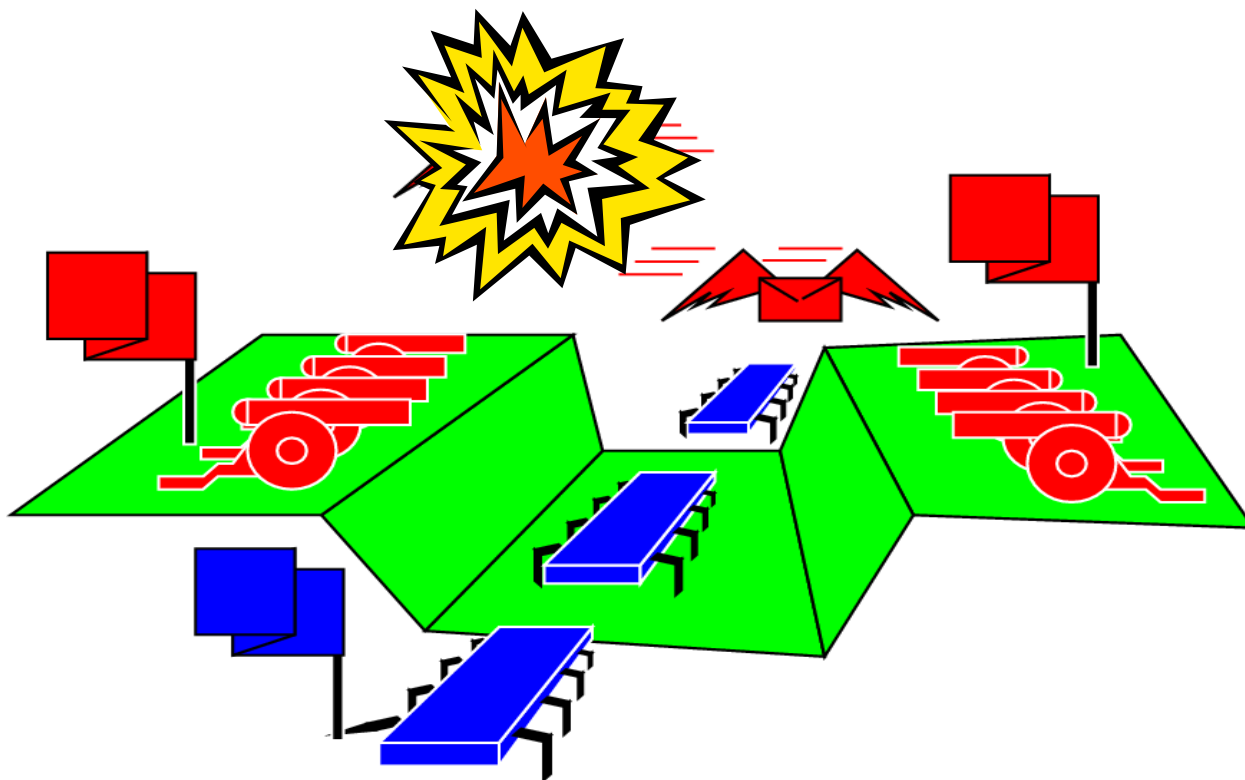
- Red army wins if both sides attack simultaneously
- Red army can communicate by sending messages...





# Problem: Unreliable Communication

- ... such as “let’s attack tomorrow at 6am” ...
- ... but messages do not always make it!
- Task: Design a “red army protocol” that works despite message failures!



# Real World Generals

Date: Wed, 11 Dec 2002 12:33:58 +0100

From: Friedemann Mattern <mattern@inf.ethz.ch>

To: Roger Wattenhofer <wattenhofer@inf.ethz.ch>

Subject: Vorlesung

Sie machen jetzt am Freitag, 08:15 die Vorlesung Verteilte Systeme, wie vereinbart. OK? (Ich bin jedenfalls am Freitag auch gar nicht da.) Ich uebernehme das dann wieder nach den Weihnachtsferien.

# Real World Generals

Date: Mi 11.12.2002 12:34

From: Roger Wattenhofer <wattenhofer@inf.ethz.ch>

To: Friedemann Mattern <mattern@inf.ethz.ch>

Subject: Re: Vorlesung

OK. Aber ich gehe nur, wenn sie diese Email nochmals  
bestaetigen... :-)

# Real World Generals

Date: Wed, 11 Dec 2002 12:53:37 +0100

From: Friedemann Mattern <mattern@inf.ethz.ch>

To: Roger Wattenhofer <wattenhofer@inf.ethz.ch>

Subject: Naechste Runde: Re: Vorlesung

Das dachte ich mir fast. Ich bin Praktiker und mache es schlauer: Ich gehe nicht, unabhaengig davon, ob Sie diese email bestaetigen (beziehungsweise rechtzeitig erhalten). (:-

# Real World Generals

Date: Mi 11.12.2002 13:01

From: Roger Wattenhofer <wattenhofer@inf.ethz.ch>

To: Friedemann Mattern <mattern@inf.ethz.ch>

Subject: Re: Naechste Runde: Re: Vorlesung ...

Ich glaube, jetzt sind wir so weit, dass ich diese Emails in der Vorlesung auflegen werde...



# Real World Generals

Date: Wed, 11 Dec 2002 18:55:08 +0100

From: Friedemann Mattern <mattern@inf.ethz.ch>

To: Roger Wattenhofer <wattenhofer@inf.ethz.ch>

Subject: Re: Naechste Runde: Re: Vorlesung ...

Kein Problem. (Hauptsache es kommt raus, dass der  
Prakiker am Ende der schlauere ist... Und der  
Theoretiker entweder heute noch auf das allerletzte  
Ack wartet oder wissend das das ja gar nicht gehen  
kann alles gleich von vornherein bleiben laesst...  
(:-))

# Theorem

Theorem

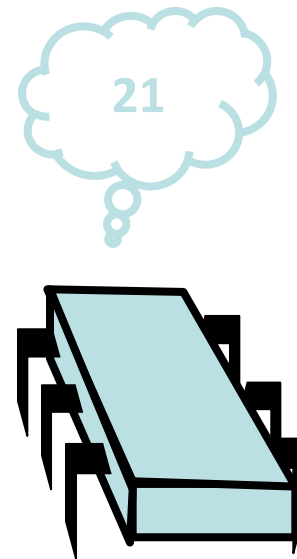
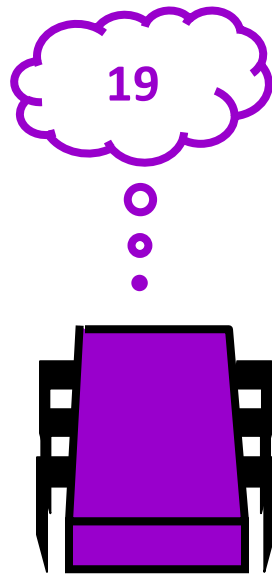
There is no non-trivial protocol that ensures that the red armies attack simultaneously

## Proof:

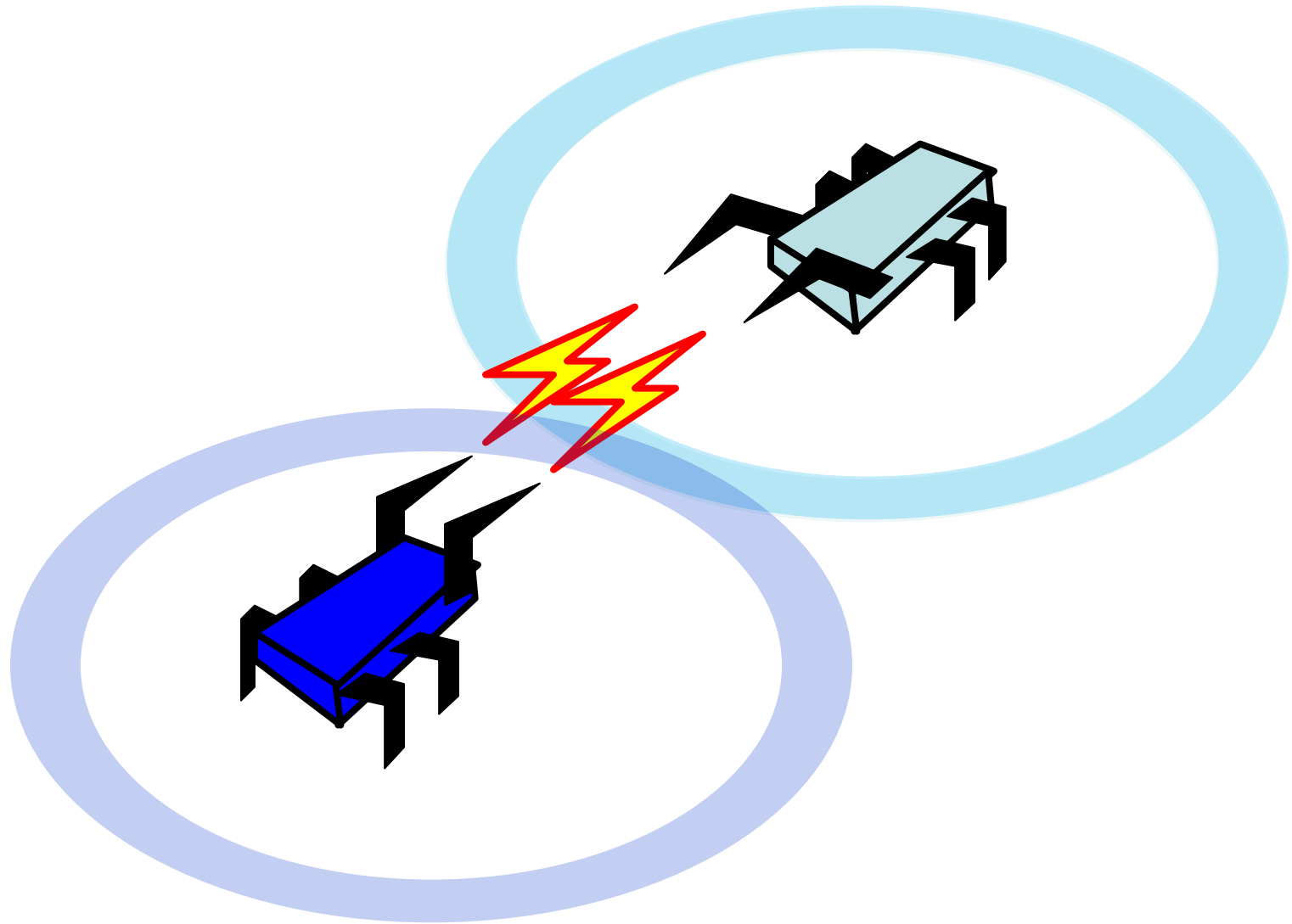
1. Consider the protocol that sends the fewest messages
2. It still works if the last message is lost
3. So just don't send it (messengers' union happy!)
4. But now we have a shorter protocol!
5. Contradicting #1

**Fundamental limitation:** We need an unbounded number of messages, otherwise it is possible that no attack takes place!

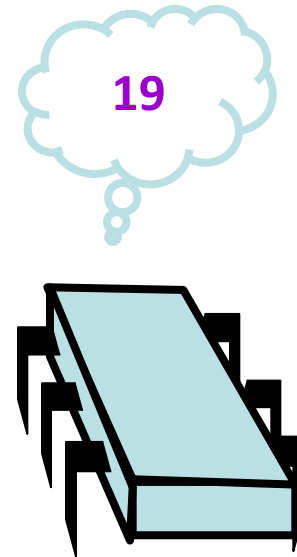
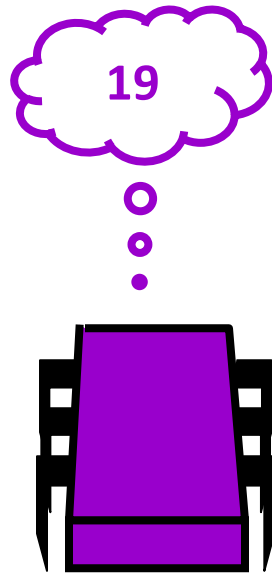
# Consensus Definition: Each Thread has a Private Input



# Consensus Definition: The Threads Communicate



# Consensus Definition: They Agree on Some Thread's Input





# Consensus is Important

- With consensus, you can implement anything you can imagine...
- Examples:
  - With consensus you can decide on a leader,
  - implement mutual exclusion,
  - or solve the two generals problem
  - and much more...
- We will see that in some models, consensus is possible, in some other models, it is not
- The goal is to learn whether for a given model consensus is possible or not ... and prove it!

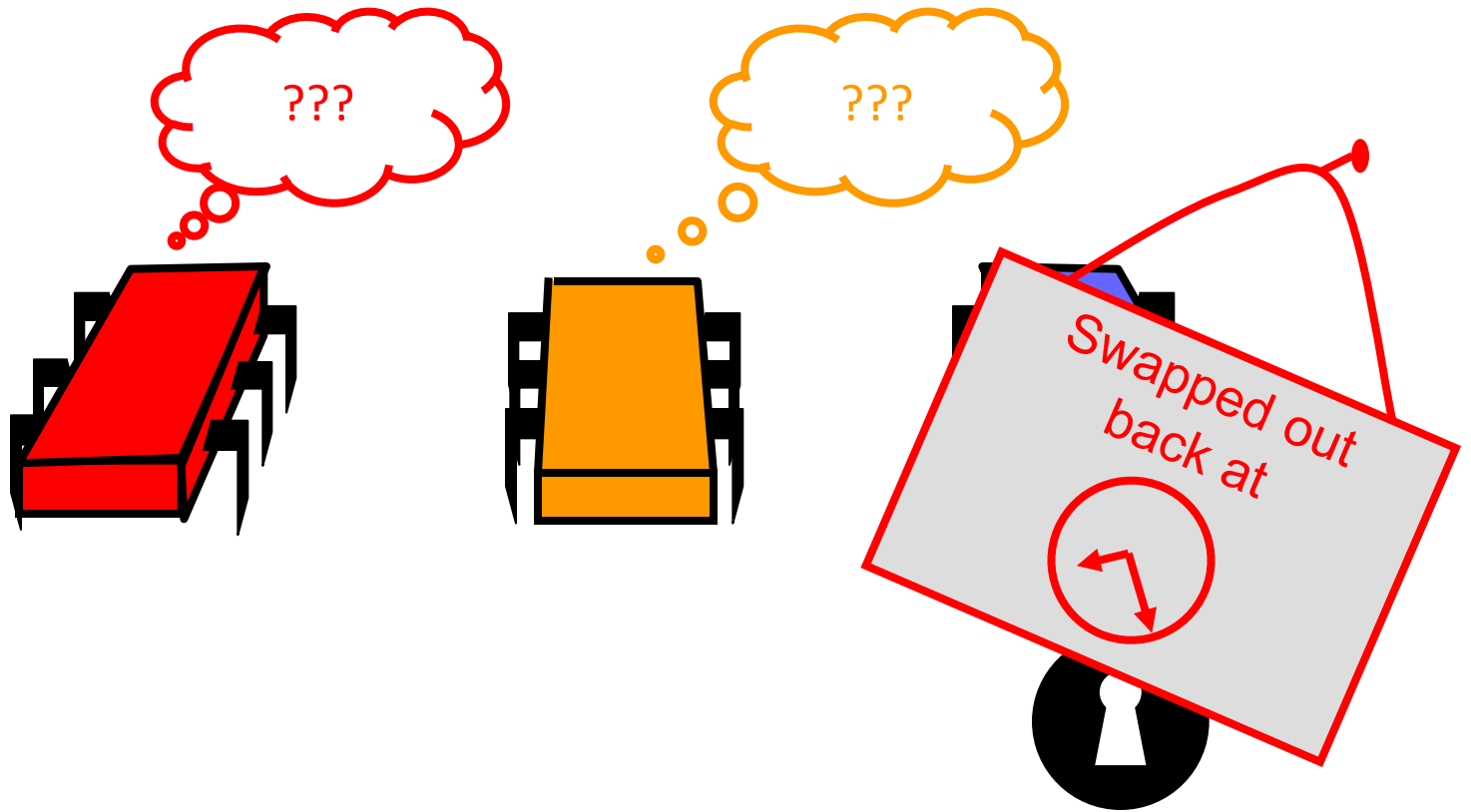
# Consensus #1: Shared Memory

- $n > 1$  processors
- Shared memory is memory that may be accessed simultaneously by multiple threads/processes.
- Processors can atomically *read* or *write* (not both) a shared memory cell

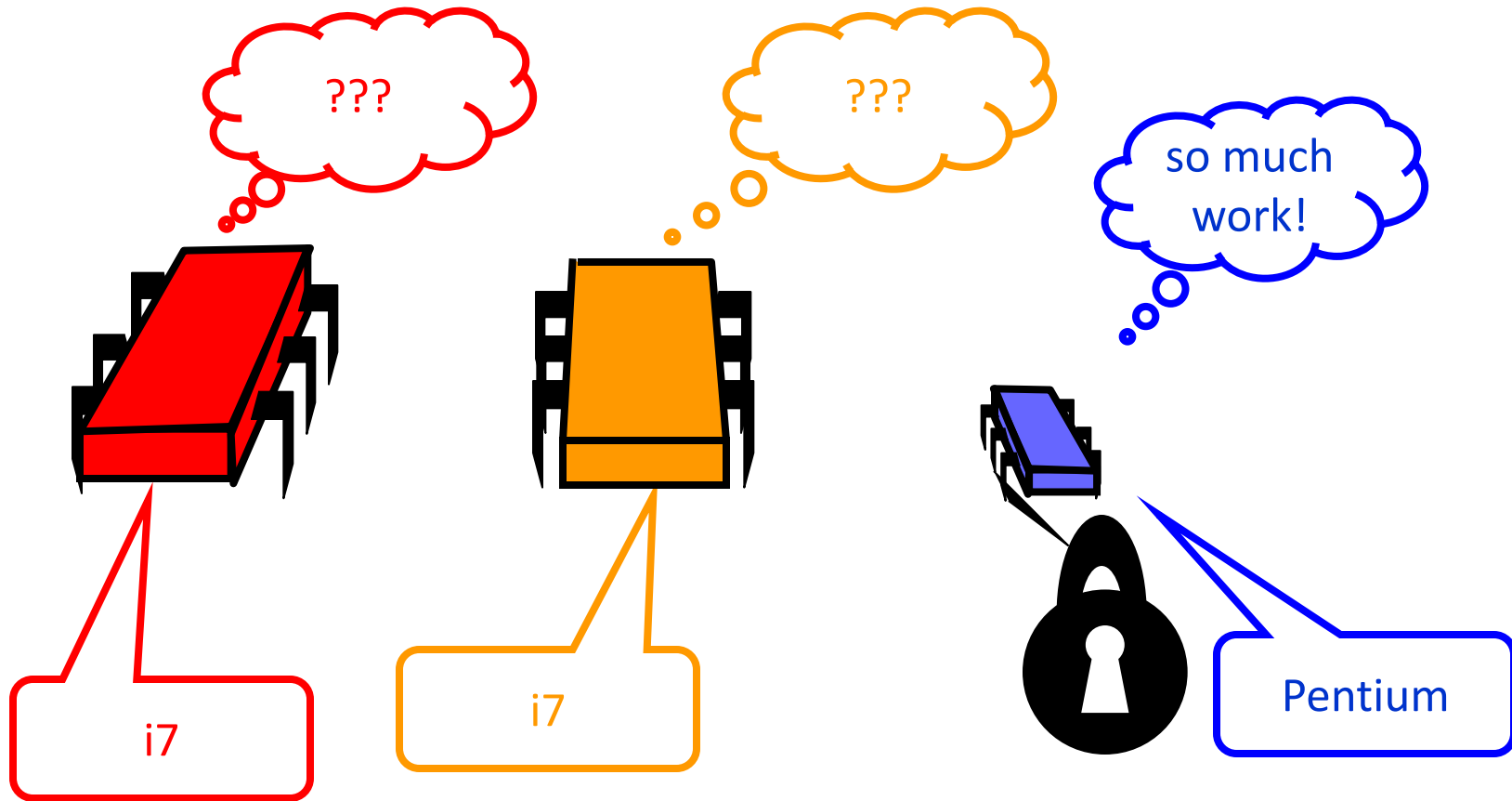
## Protocol:

- There is a designated memory cell  $c$ .
  - Initially  $c$  is in a special state “?”
  - Processor 1 writes its value  $v_1$  into  $c$ , then decides on  $v_1$ .
  - A processor  $j \neq 1$  reads  $c$  until  $j$  reads something else than “?”, and then decides on that.
- 
- Problems with this approach?

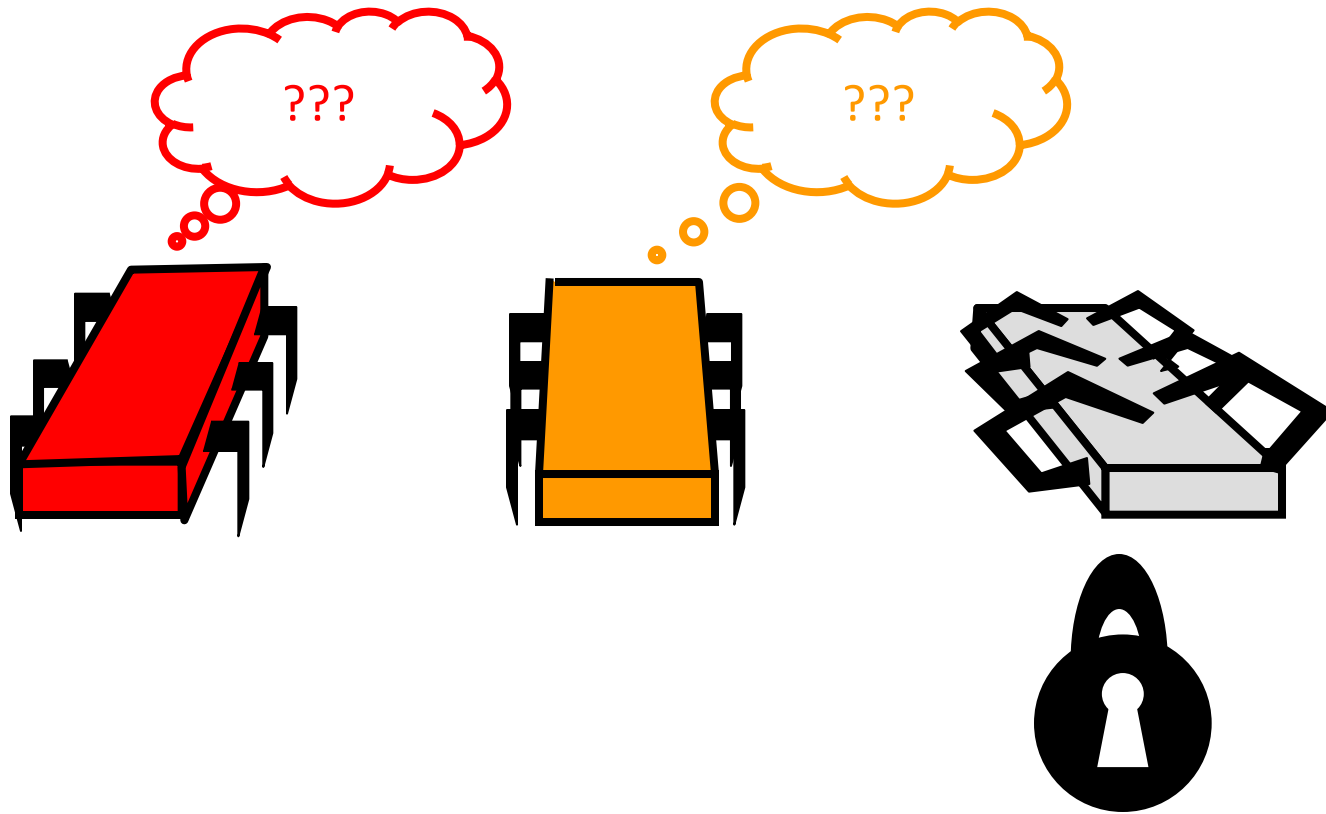
# Unexpected Delay



# Heterogeneous Architectures



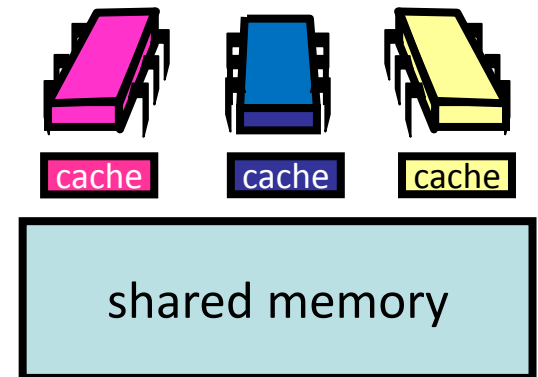
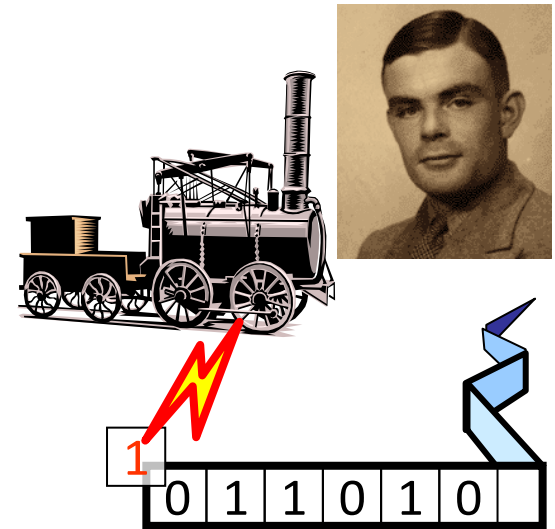
# Fault-Tolerance





# Computability

- Definition of computability
  - Computable usually means Turing-computable, i.e., the given problem can be solved using a Turing machine
  - Strong mathematical model!
  
- Shared-memory computability
  - Model of asynchronous concurrent computation
  - Computable means it is wait-free computable on a multiprocessor
  - Wait-free...?



## Consensus #2: Wait-free Shared Memory

- $n > 1$  processors
- Processors can atomically *read* or *write* (not both) a shared memory cell
- Processors might crash (stop... or become very slow...)

### **Wait-free implementation:**

- Every process (method call) completes in a finite number of steps
- Implies that locks cannot be used → The thread holding the lock may crash and no other thread can make progress
- We assume that we have wait-free atomic registers (that is, reads and writes to same register do not overlap)

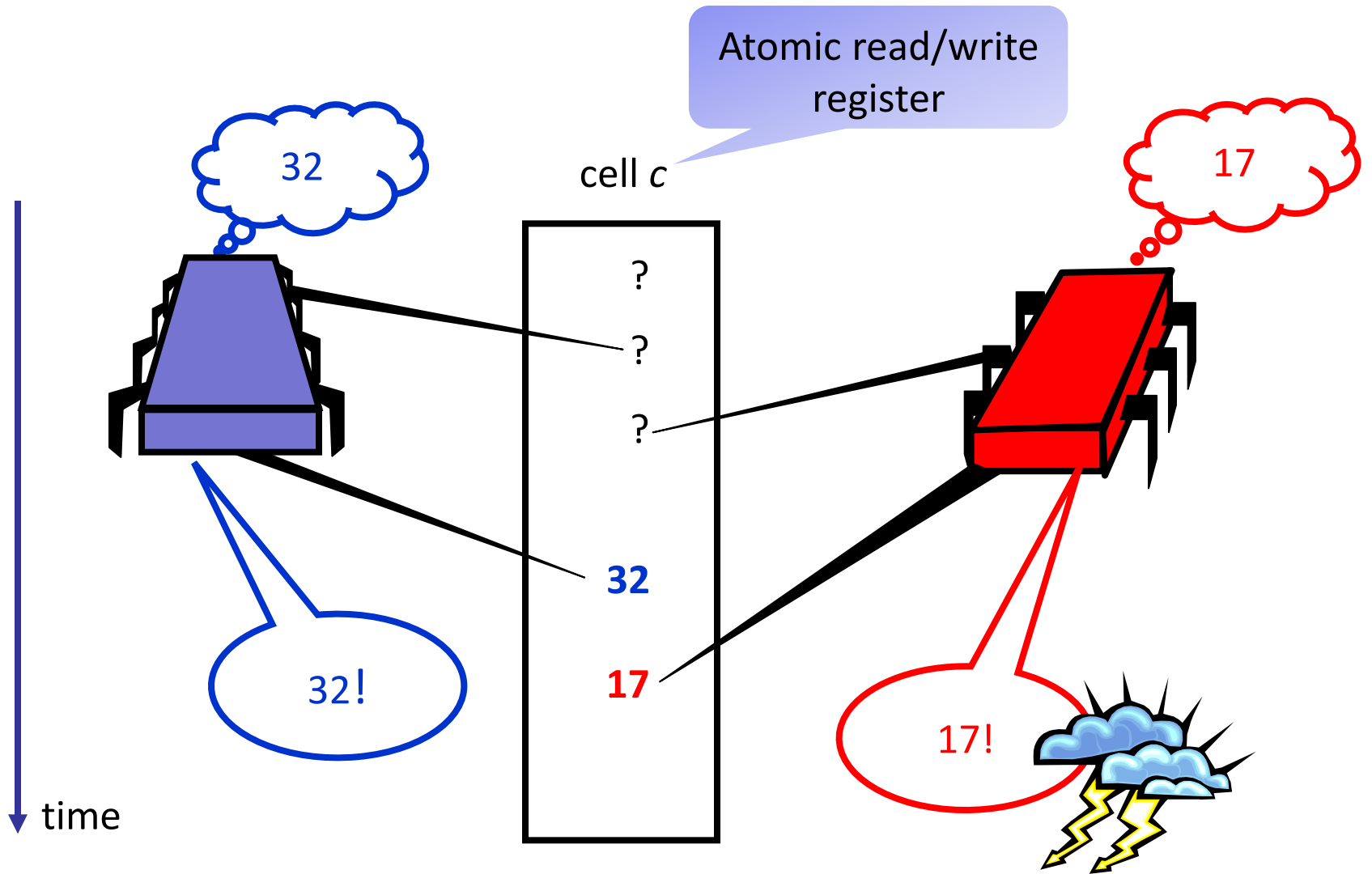
# A Wait-free Algorithm

- There is a cell  $c$ , initially  $c = "?"$
- Every processor  $i$  does the following:

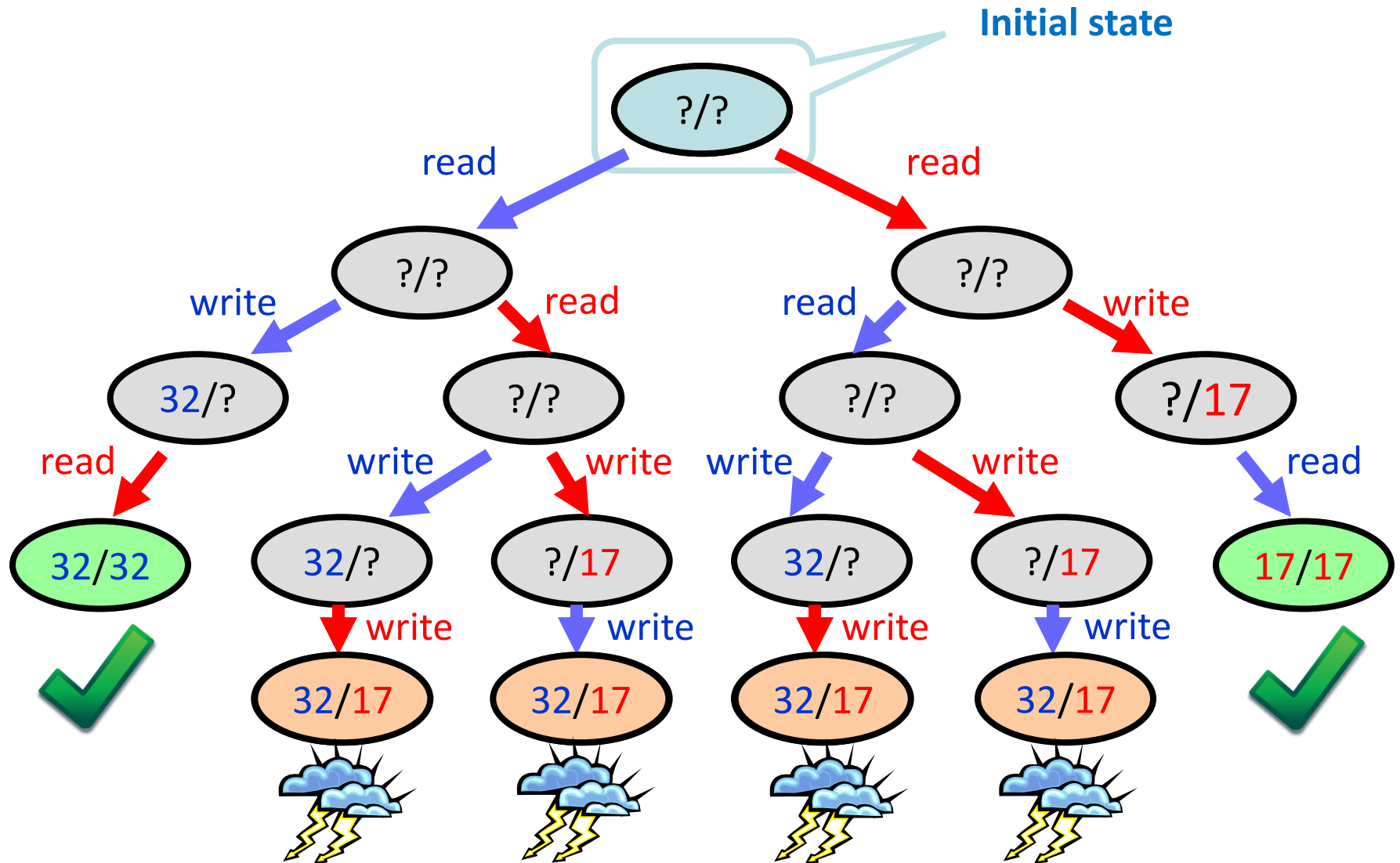
```
r = Read(c);  
if (r == "?") then  
    write(c, vi); decide vi;  
else  
    decide r;
```

- Is this algorithm correct...?

# An Execution



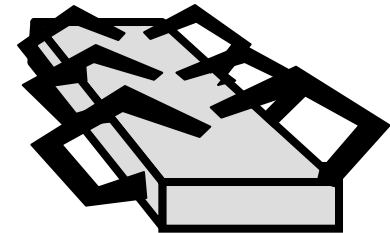
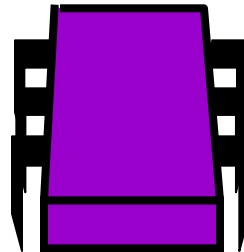
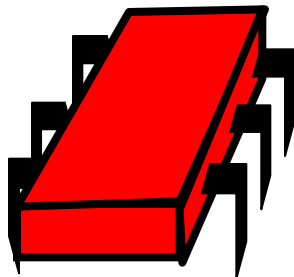
# Execution Tree



# Theorem

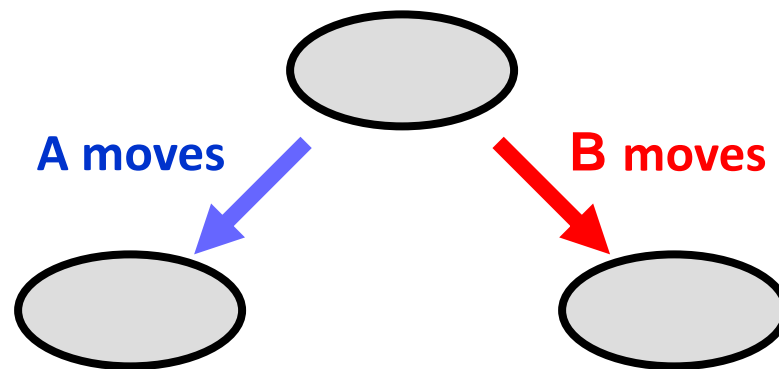
Theorem

There is no wait-free consensus algorithm using read/write atomic registers



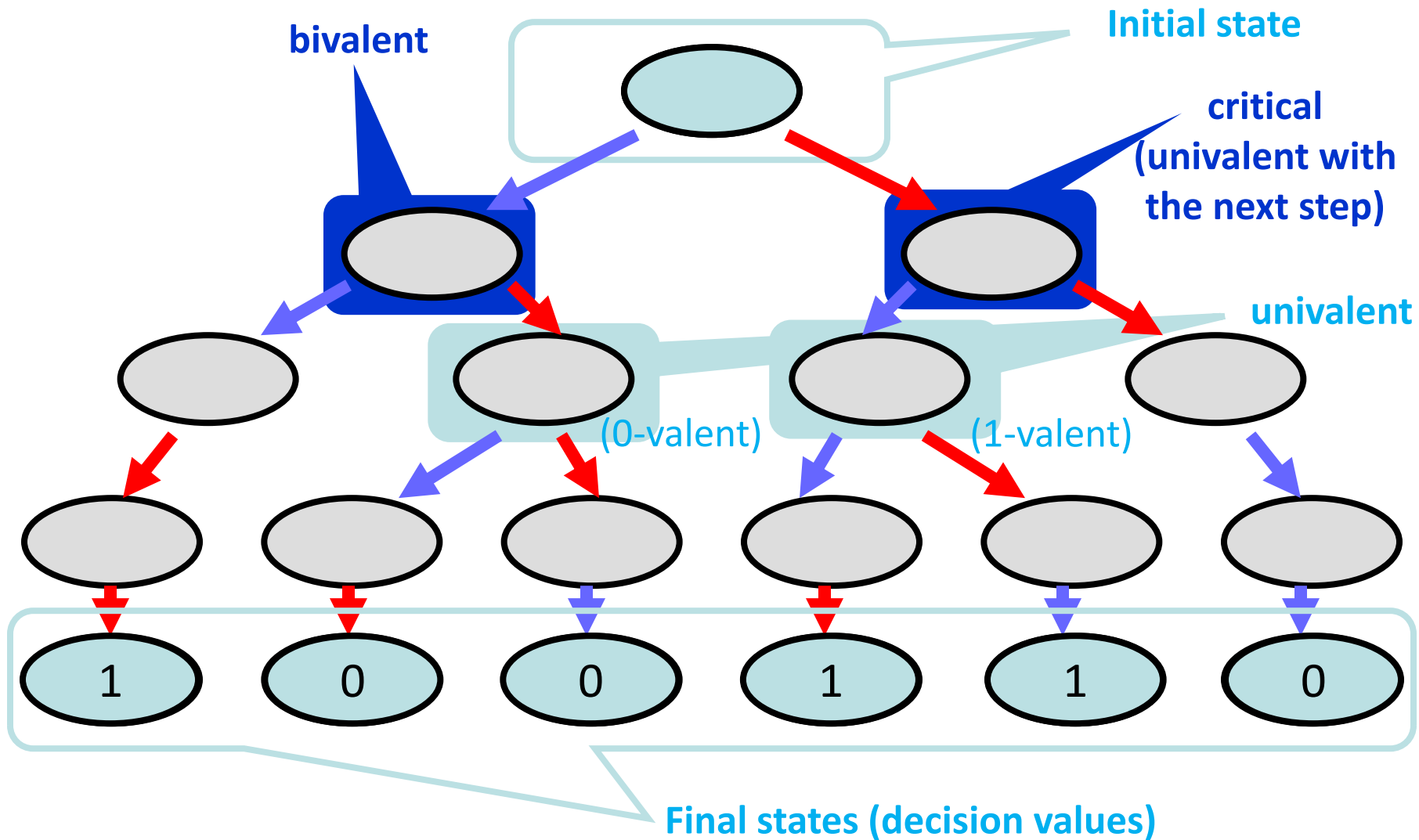
# Proof

- Make it simple
  - There are only two threads **A** and **B** and the input is binary
- Assume that there is a protocol
- In this protocol, either **A** or **B** “moves” in each step
- Moving means
  - Register read
  - Register write





# Execution Tree (of abstract but “correct” algorithm)

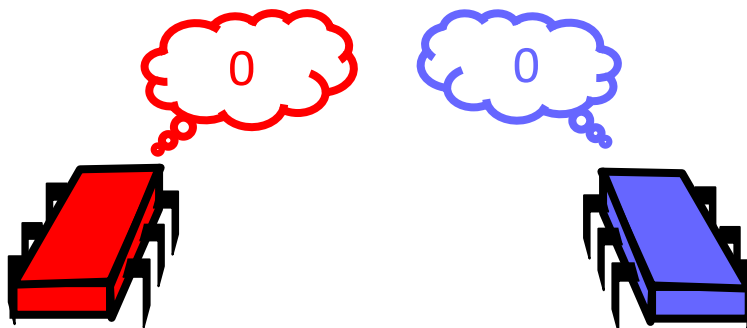


# Bivalent vs. Univalent

- Wait-free computation is a tree
- Bivalent system states
  - Outcome is not fixed
- Univalent states
  - Outcome is fixed
  - Maybe not “known” yet
  - 1-valent and 0-valent states
  
- Claim
  - Some initial system state is bivalent
  - This means that the outcome is not always fixed from the start

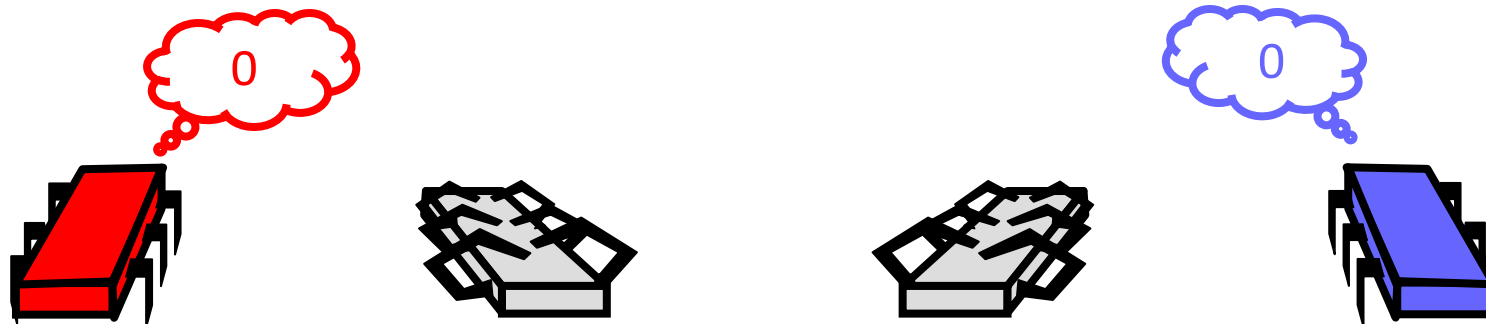
# Proof of Claim: A 0-Valent Initial State

- All executions lead to the decision 0



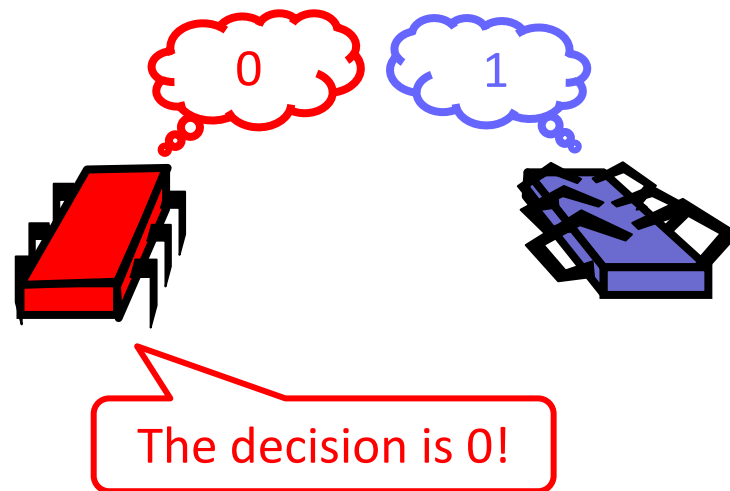
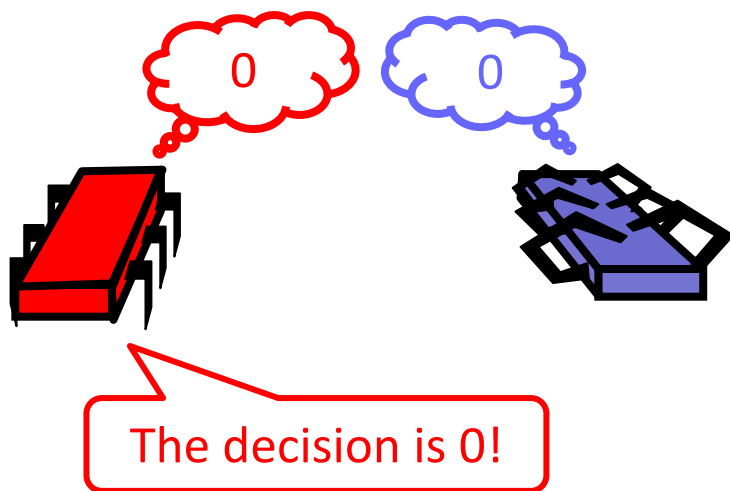
Similarly, the decision is always 1 if both threads start with 1!

- Solo executions also lead to the decision 0



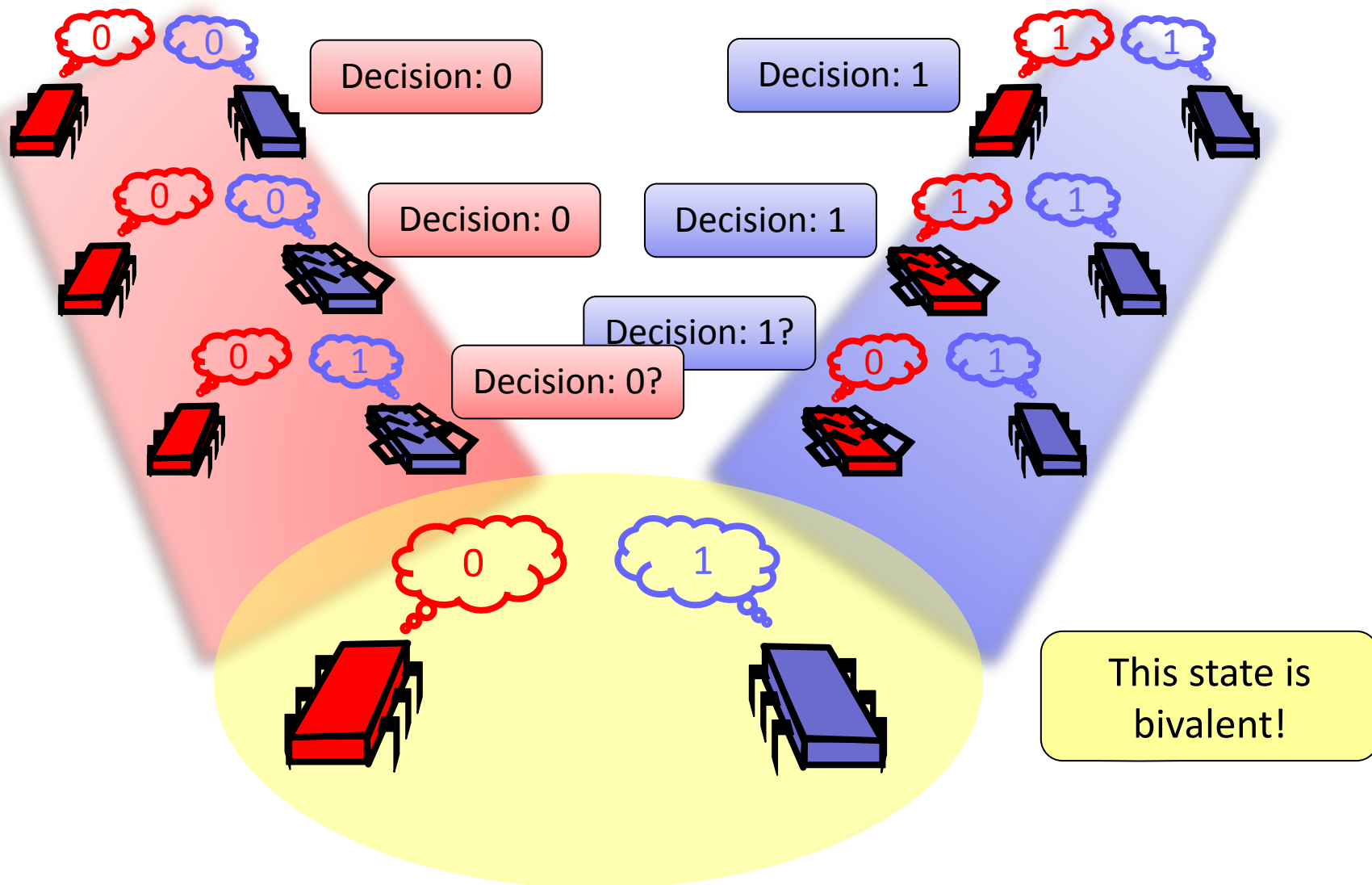
# Proof of Claim: Indistinguishable Situations

- These two situations are indistinguishable → The outcome must be the same



Similarly, the decision is 1 if the red thread crashed!

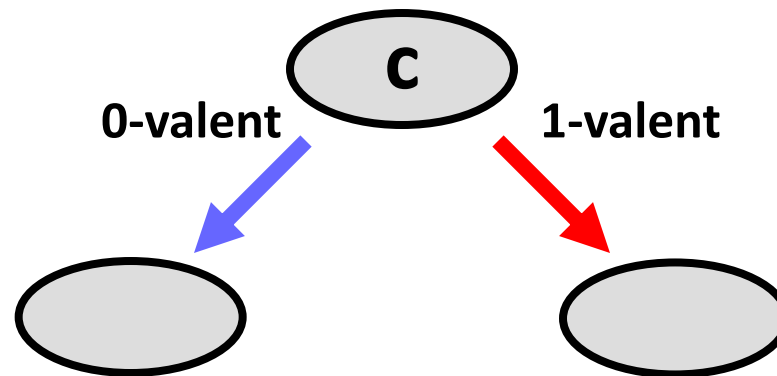
# Proof of Claim: A Bivalent Initial State



# Critical States

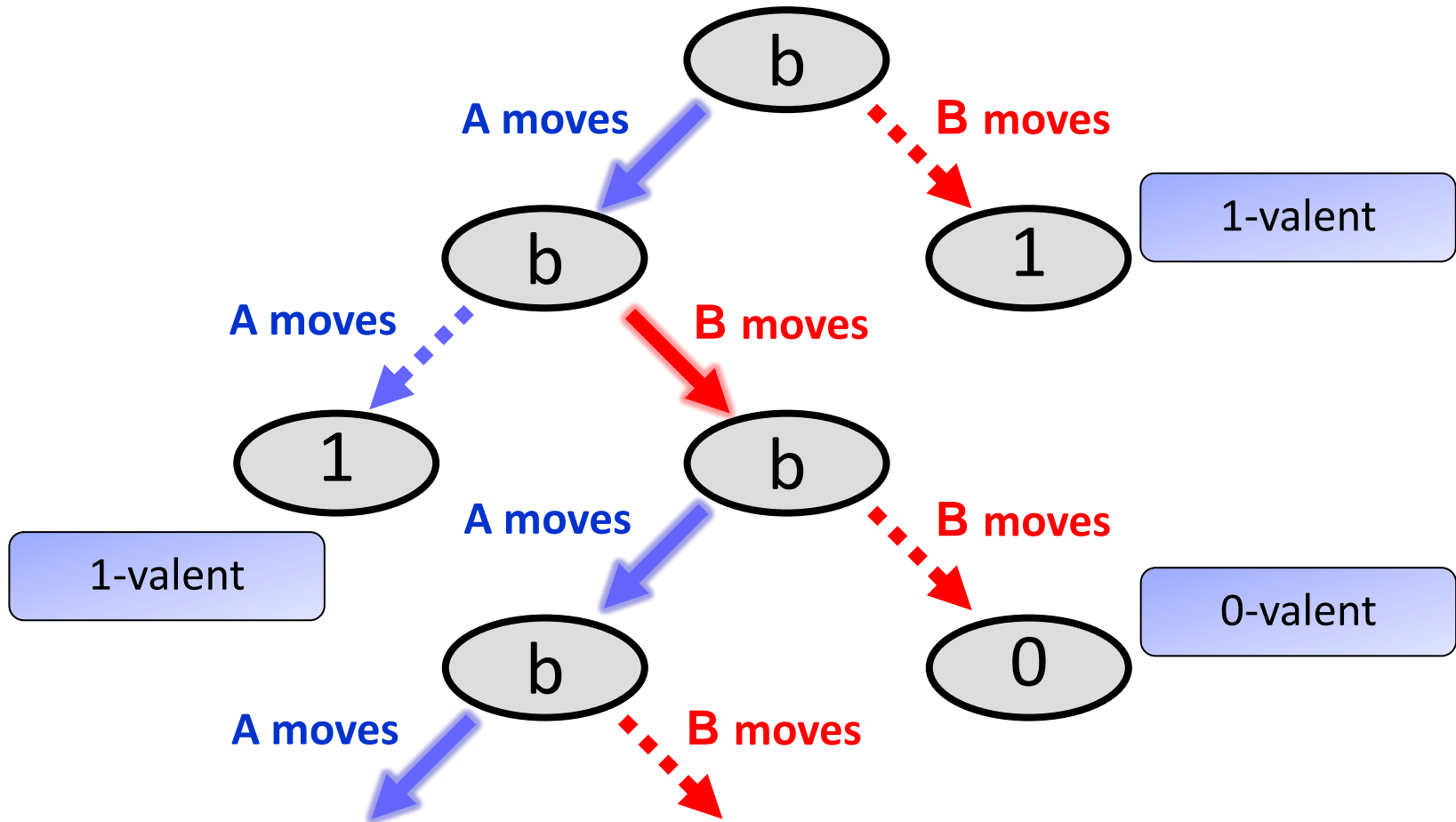
- Starting from a bivalent initial state
- The protocol must reach a **critical state**
  - Otherwise we could stay bivalent forever
  - And the protocol is not wait-free
- The goal is now to show that the system can always remain bivalent

A state is critical if the next state is univalent



# Reaching a Critical State

- The system can remain bivalent forever if there is always an action that prevents the system from reaching a critical state:



# Model Dependency

- So far, everything was memory-independent!
- True for
  - Registers
  - Message-passing
  - Carrier pigeons
  - Any kind of asynchronous computation
- Threads
  - Perform reads and/or writes
  - To the same or different registers
  - Possible interactions?



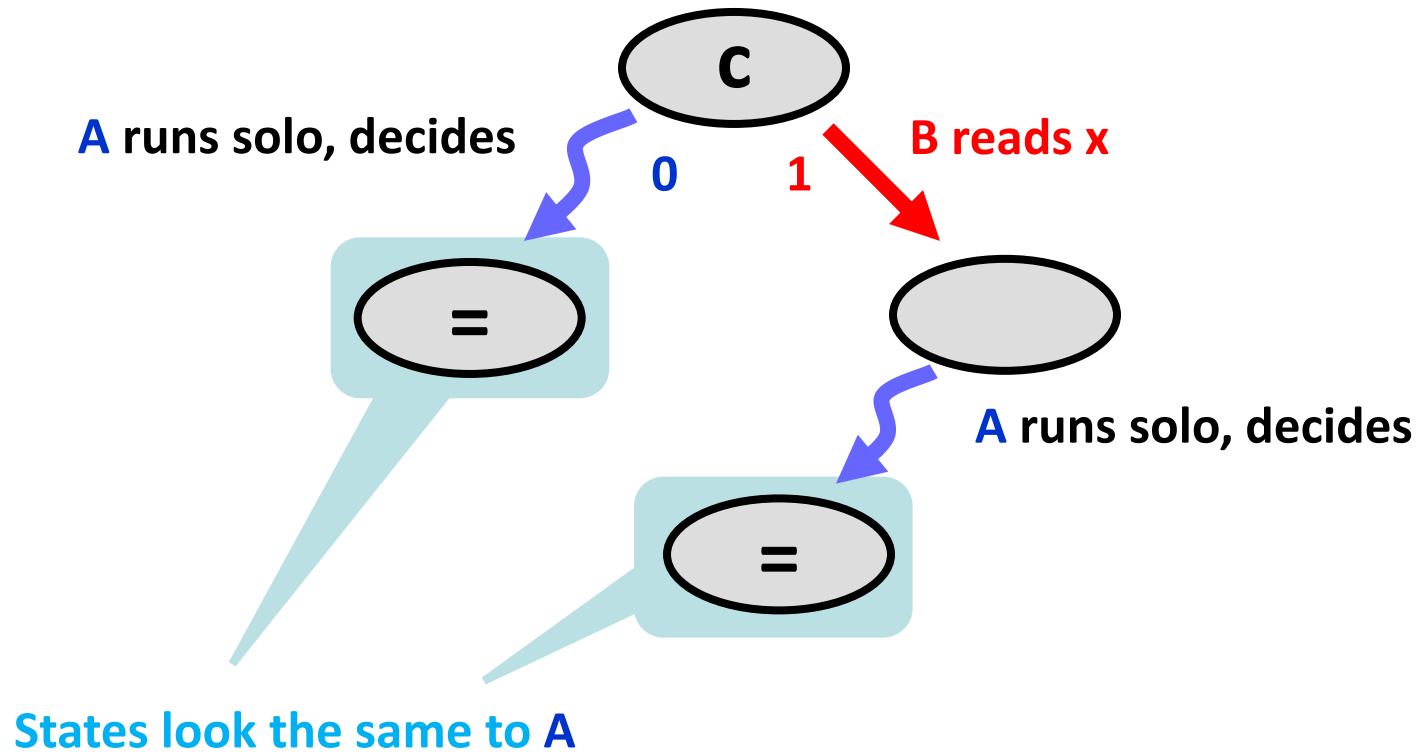
# Possible Interactions

	<code>x.read()</code>	<code>y.read()</code>	<code>x.write()</code>	<code>y.write()</code>
<code>x.read()</code>	?	?	?	?
<code>y.read()</code>	?	?	?	?
<code>x.write()</code>	?	?	?	?
<code>y.write()</code>	?	?	?	?

A reads x

B writes y

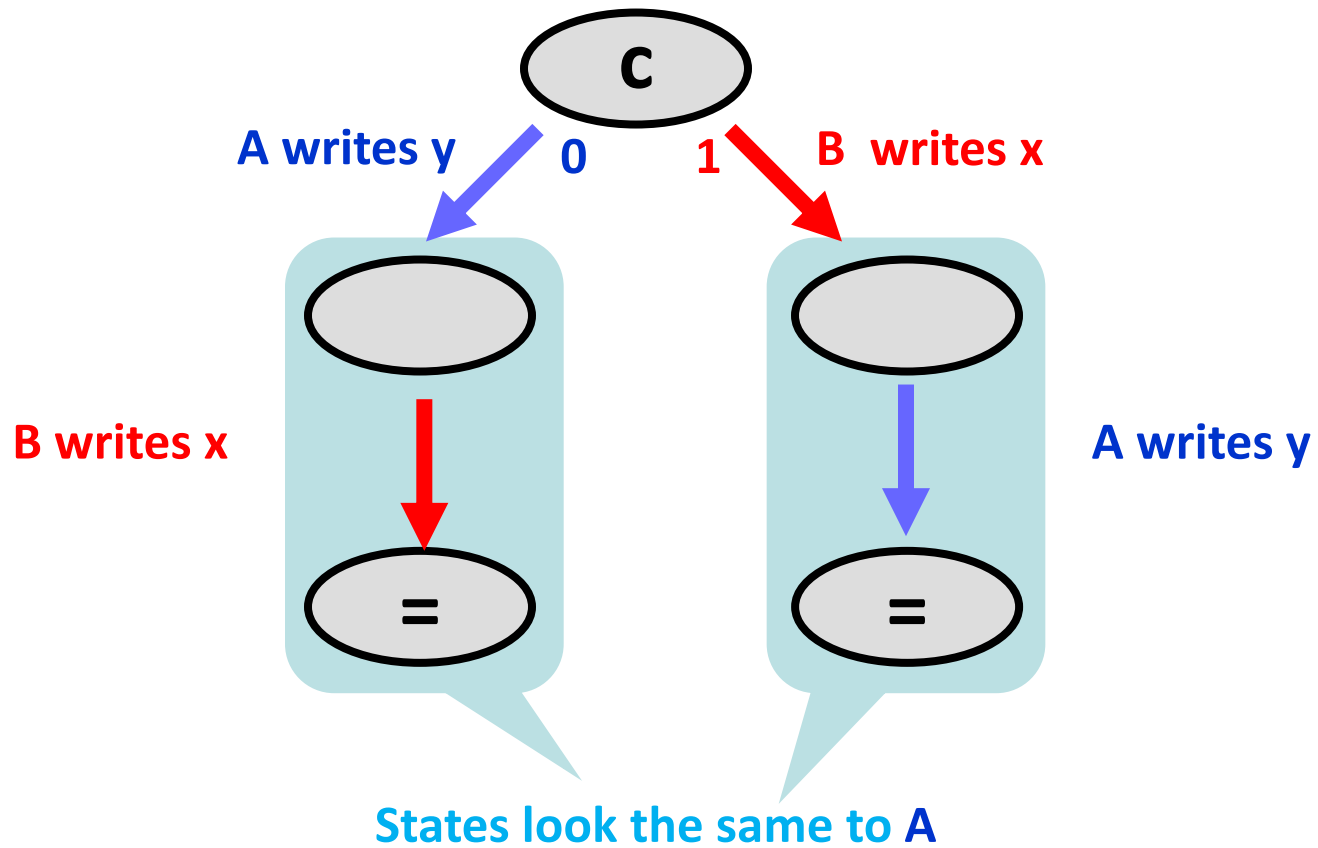
# Reading Registers



# Possible Interactions

	x.read()	y.read()	x.write()	y.write()
x.read()	no	no	no	no
y.read()	no	no	no	no
x.write()	no	no	?	?
y.write()	no	no	?	?

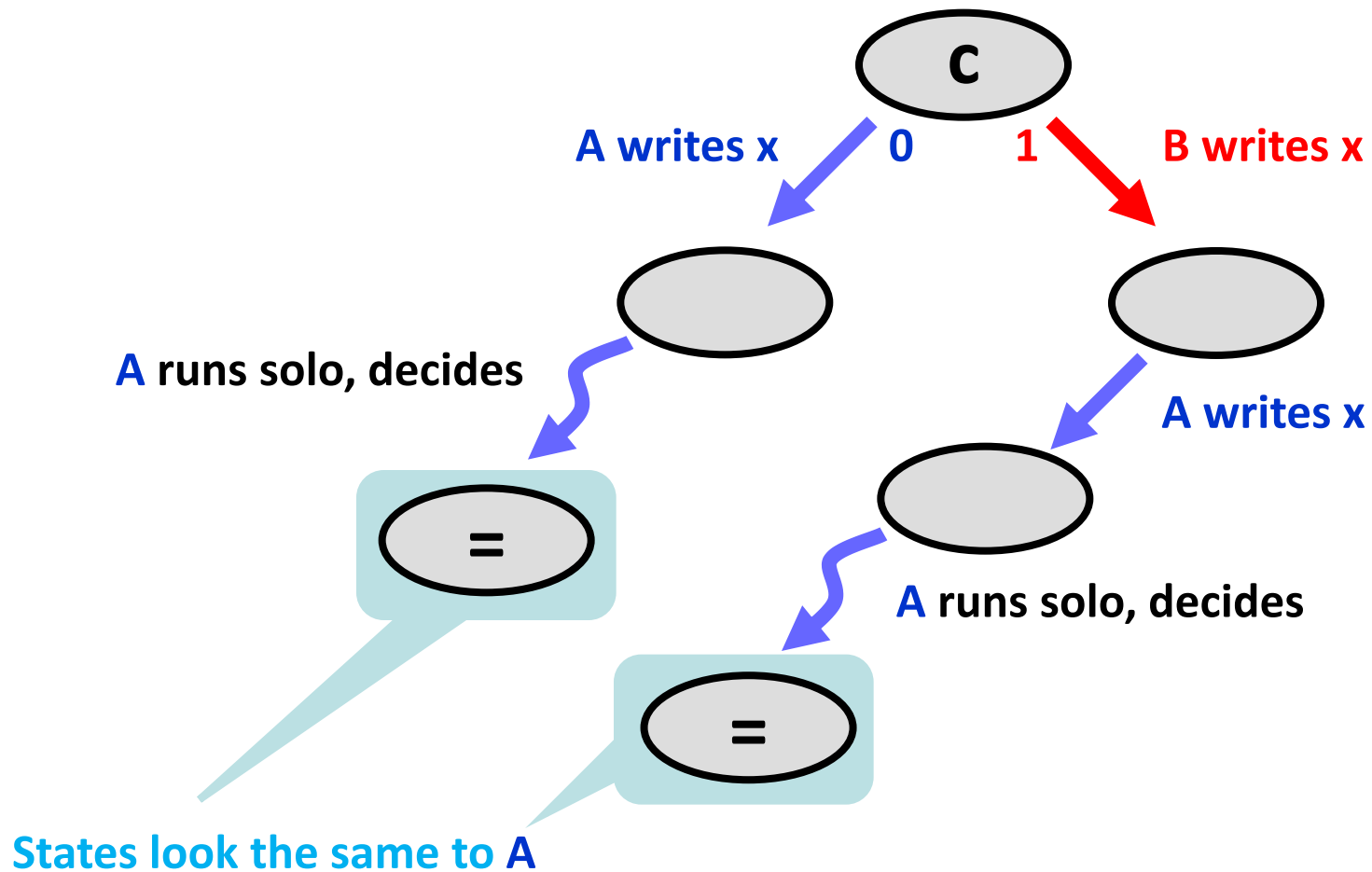
# Writing Distinct Registers



# Possible Interactions

	x.read()	y.read()	x.write()	y.write()
x.read()	no	no	no	no
y.read()	no	no	no	no
x.write()	no	no	?	no
y.write()	no	no	no	?

# Writing Same Registers

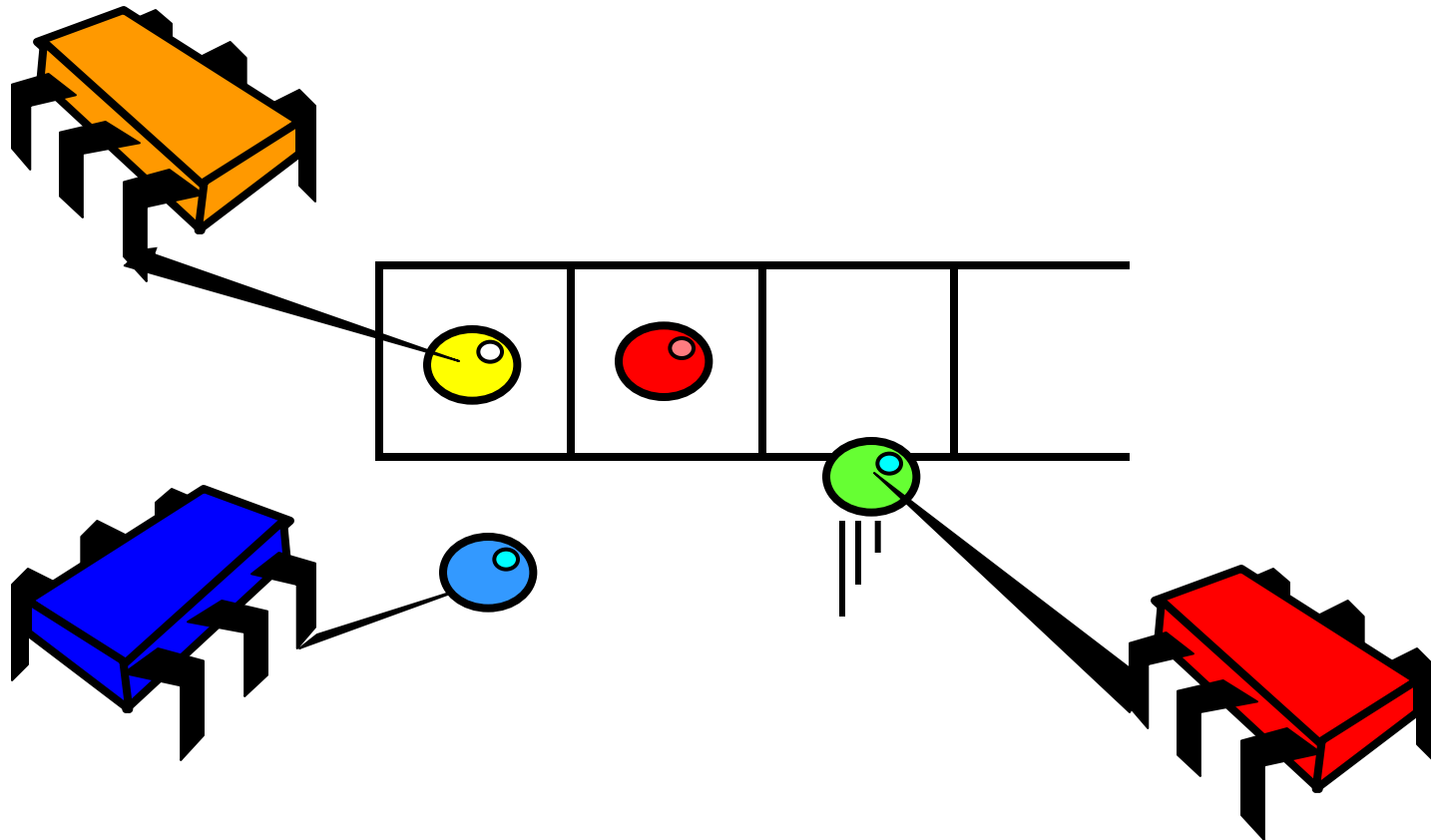


# That's All, Folks!

	x.read()	y.read()	x.write()	y.write()
x.read()	no	no	no	no
y.read()	no	no	no	no
x.write()	no	no	no	no
y.write()	no	no	no	no

# What Does Consensus Have to Do With Distributed Systems?

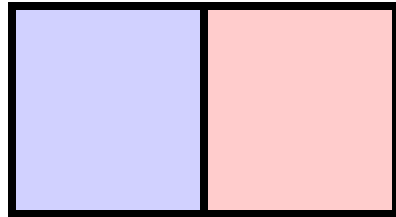
- We want to build a concurrent FIFO Queue with multiple dequeuers



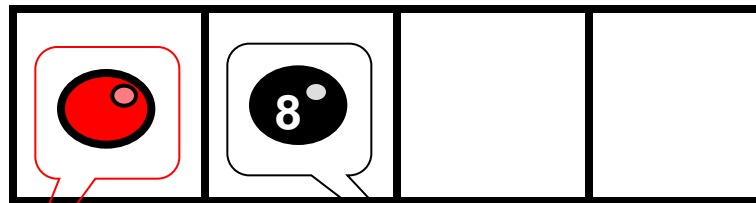


# A Consensus Protocol

- Assume we have such a FIFO queue and a 2-element array



**2-element array**



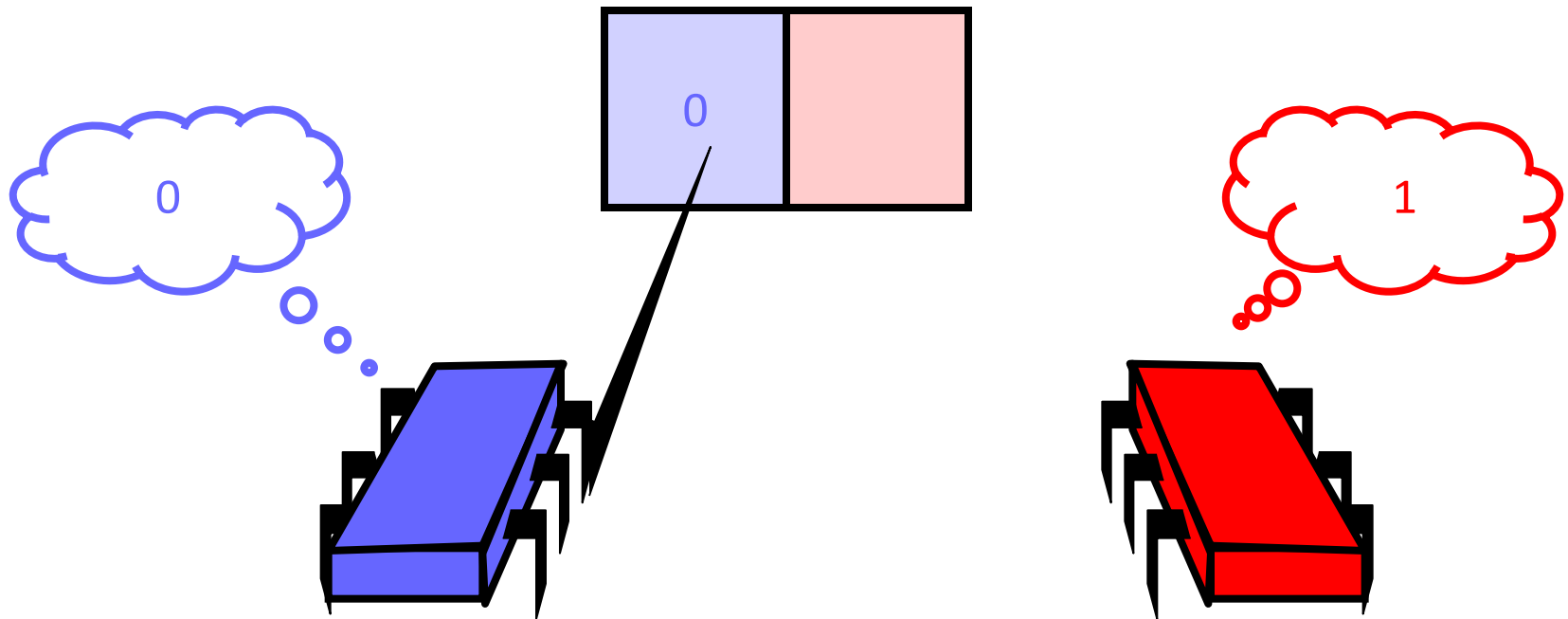
**Coveted red ball**

**Dreaded black ball**

**FIFO Queue with red and black balls**

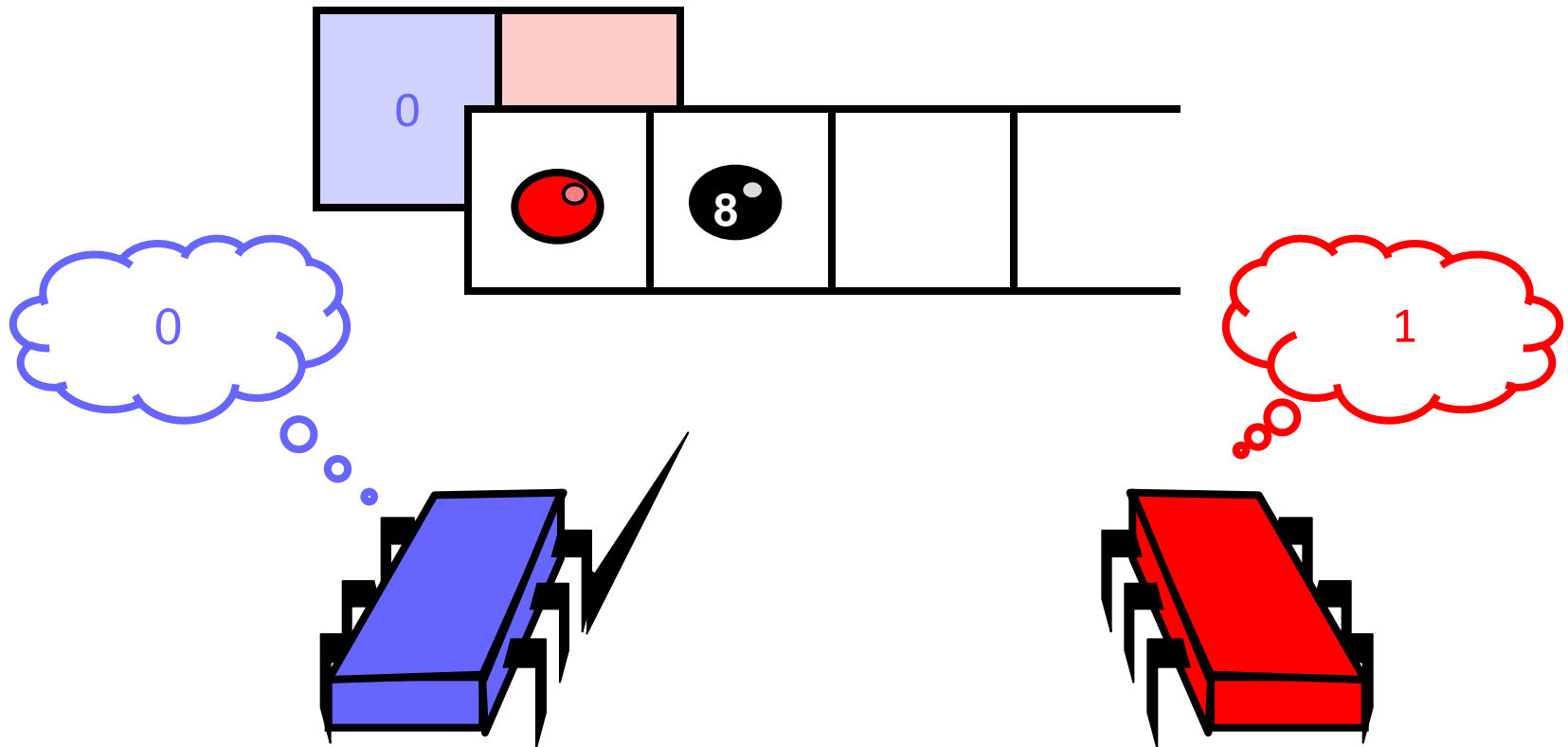
# A Consensus Protocol

- Thread  $i$  writes its value into the array at position  $i$

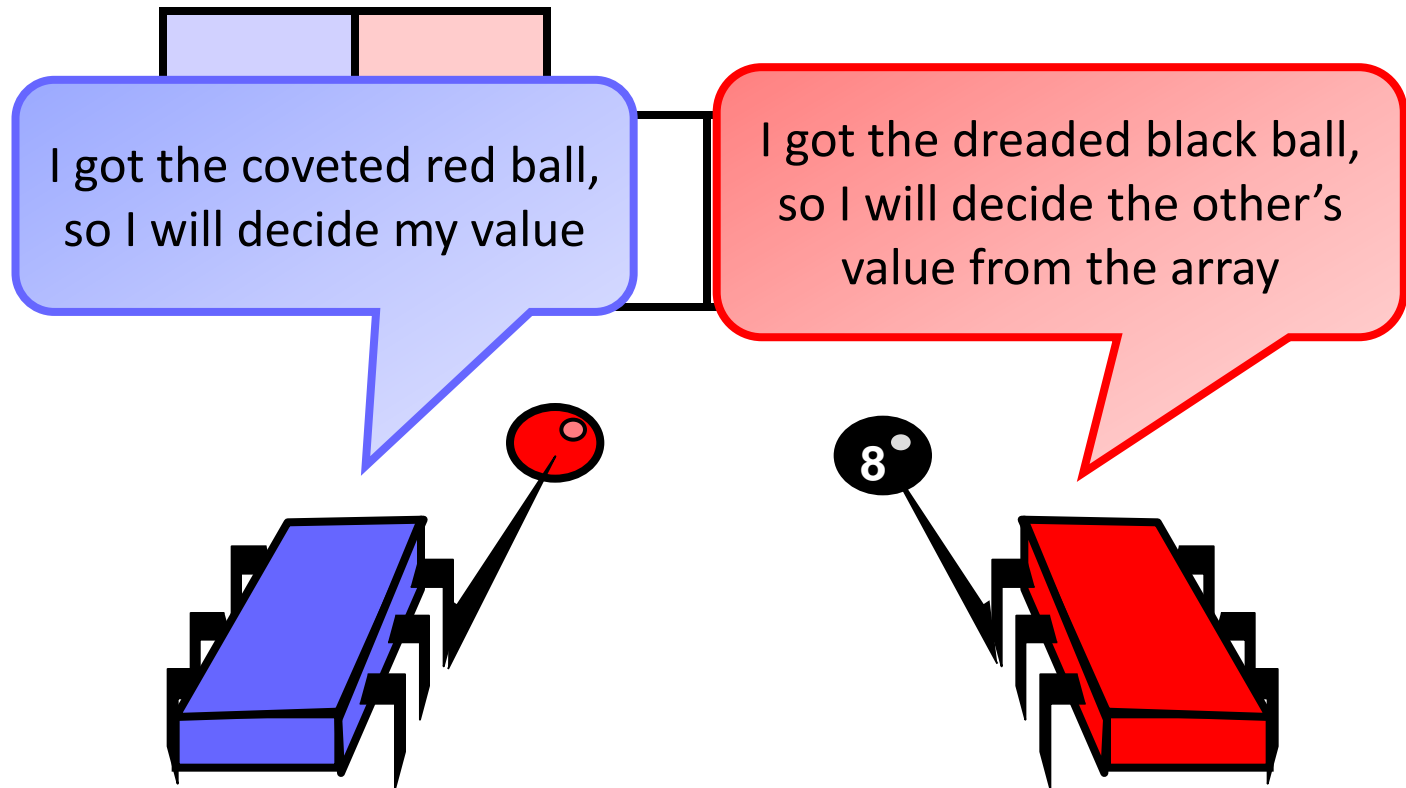


# A Consensus Protocol

- Then, the thread takes the next element from the queue



# A Consensus Protocol



# A Consensus Protocol

## Why does this work?

- If one thread gets the red ball, then the other gets the black ball
- Winner can take its own value
- Loser can find winner's value in array
  - Because threads write array before dequeuing from queue

## Implication

- We can solve 2-thread consensus using only
  - A two-dequeuer queue
  - Atomic registers

# Implications

- Assume there exists
  - A queue implementation from atomic registers
- Given
  - A consensus protocol from queue and registers
- Substitution yields
  - A wait-free consensus protocol from atomic registers

**contradiction**

## Corollary

- It is **impossible** to implement a two-dequeuer wait-free FIFO queue with read/write shared memory.
- This was a proof by reduction; important beyond NP-completeness...

## Consensus #3: Read-Modify-Write Shared Memory

- $n > 1$  processors
- Wait-free implementation
- Processors can **read and write** a shared memory cell **in one atomic step**: the value written can depend on the value read
- We call this a read-modify-write (RMW) register
- Can we solve consensus using a RMW register...?

# Consensus Protocol Using a RMW Register

- There is a cell  $c$ , initially  $c="?"$
- Every processor  $i$  does the following

RMW( $c$ )

```
if (c == "?") then  
  write(c, vi); decide vi  
else  
  decide c;
```

atomic step



# Discussion

- Protocol works correctly
  - One processor accesses  $c$  first; this processor will determine decision
- Protocol is wait-free
- RMW is quite a strong primitive
  - Can we achieve the same with a weaker primitive?

# Read-Modify-Write More Formally

- Method takes 2 arguments:
  - Cell  $\mathbf{c}$
  - Function  $\mathbf{f}$
- Method call:
  - Replaces value  $\mathbf{x}$  of cell  $\mathbf{c}$  with  $\mathbf{f(x)}$
  - Returns value  $\mathbf{x}$  of cell  $\mathbf{c}$

# Read-Modify-Write

```
public class RMW {  
    private int value;  
  
    public synchronized int rmw(function f) {  
        int prior = this.value;  
        this.value = f(this.value);  
        return prior;  
    }  
}
```

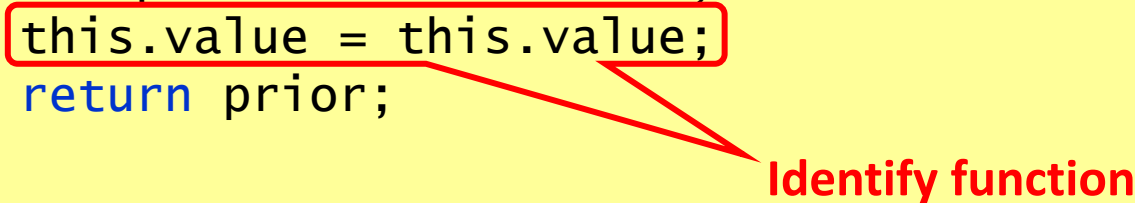
**Return prior value**

**Apply function**

## Read-Modify-Write: Read

```
public class RMW {  
    private int value;  
  
    public synchronized int read() {  
        int prior = this.value;  
        this.value = this.value;  
        return prior;  
    }  
}
```

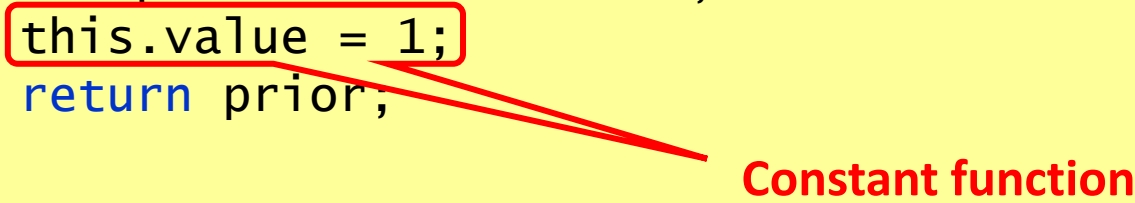
**Identify function**



## Read-Modify-Write: Test&Set

```
public class RMW {  
    private int value;  
  
    public synchronized int TAS() {  
        int prior = this.value;  
        this.value = 1;  
        return prior;  
    }  
}
```

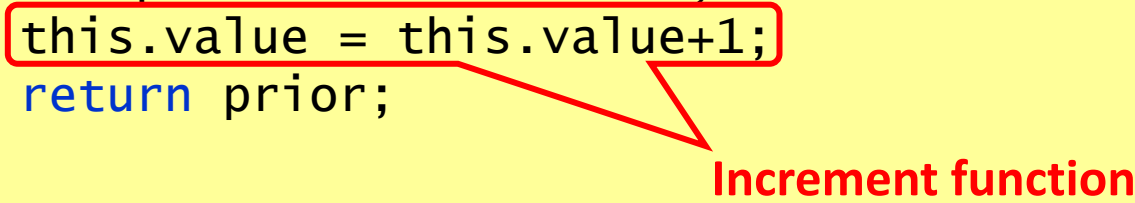
**Constant function**



## Read-Modify-Write: Fetch&Inc

```
public class RMW {  
    private int value;  
  
    public synchronized int FAI() {  
        int prior = this.value;  
        this.value = this.value+1;  
        return prior;  
    }  
}
```

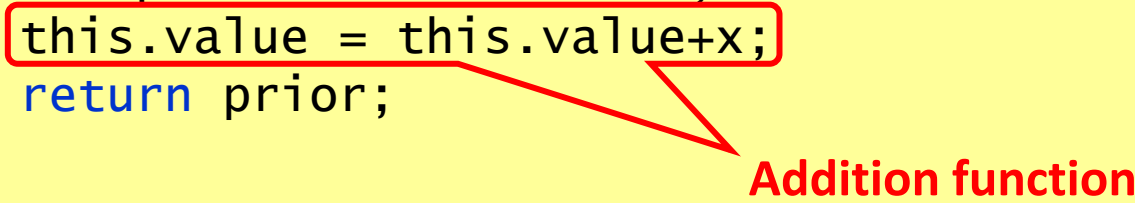
**Increment function**



## Read-Modify-Write: Fetch&Add

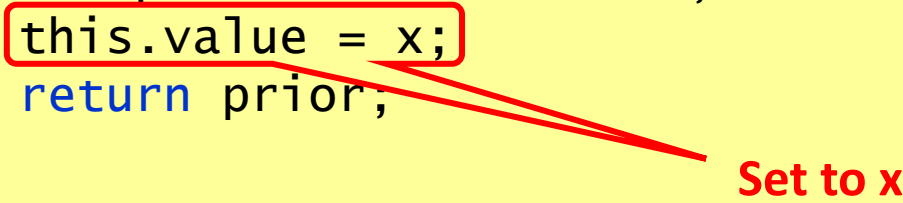
```
public class RMW {  
    private int value;  
  
    public synchronized int FAA(int x) {  
        int prior = this.value;  
        this.value = this.value+x;  
        return prior;  
    }  
}
```

**Addition function**



# Read-Modify-Write: Swap

```
public class RMW {  
    private int value;  
  
    public synchronized int swap(int x) {  
        int prior = this.value;  
        this.value = x;  
        return prior;  
    }  
}
```



**Set to x**



## Read-Modify-Write: Compare&Swap

```
public class RMW {  
    private int value;  
  
    public synchronized int CAS(int old, int new) {  
        int prior = this.value;  
        if(this.value == old)  
            this.value = new;  
        return prior;  
    }  
}
```

**“Complex” function**

# Definition of Consensus Number

- An object has **consensus number  $n$** 
  - If it can be used
    - Together with atomic read/write registers
  - To implement  $n$ -thread consensus, but not  $(n+1)$ -thread consensus
- Example: Atomic read/write registers have consensus number 1
  - Works with 1 process
  - We have shown impossibility with 2

# Consensus Number Theorem

Theorem

If you can implement  $X$  from  $Y$   
and  $X$  has consensus number  $c$ ,  
then  $Y$  has consensus number at least  $c$

- Consensus numbers are a useful way of measuring synchronization power
- An alternative formulation:
  - If  $X$  has consensus number  $c$
  - And  $Y$  has consensus number  $d < c$
  - Then there is no way to construct a wait-free implementation of  $X$  by  $Y$
- This theorem will be very useful
  - Unforeseen practical implications!

# Theorem

- A RMW is *non-trivial* if there exists a value  $v$  such that  $v \neq f(v)$ 
  - Test&Set, Fetch&Inc, Fetch&Add, Swap, Compare&Swap, general RMW...
  - But not read



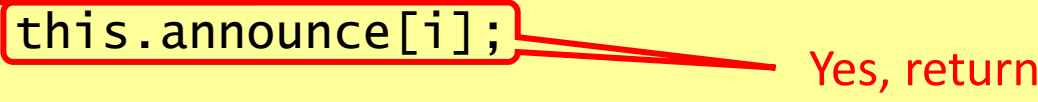
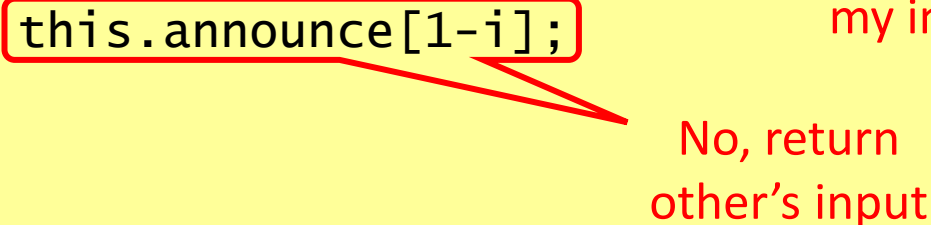
Theorem

Any non-trivial RMW object has  
consensus number at least 2

- Implies no wait-free implementation of RMW registers from read/write registers
- Hardware RMW instructions not just a convenience

# Proof

- A two-thread consensus protocol using any non-trivial RMW object:

```
public class RMWConsensusFor2 implements Consensus{  
    private RMW r;  Initialized to v  
  
    public Object decide() {  
        int i = Thread.myIndex();  
        if(r.rmw(f) == v)  Am I first?  
            return this.announce[i];  Yes, return  
            my input  
        else  
            return this.announce[1-i];  No, return  
            other's input  
    }  
}
```

# Interfering RMW

- Let  $F$  be a set of functions such that for all  $f_i$  and  $f_j$ , either
  - They commute:  $f_i(f_j(x))=f_j(f_i(x))$
  - They overwrite:  $f_i(f_j(x))=f_i(x)$
- Claim: Any such set of RMW objects has consensus number **exactly 2**

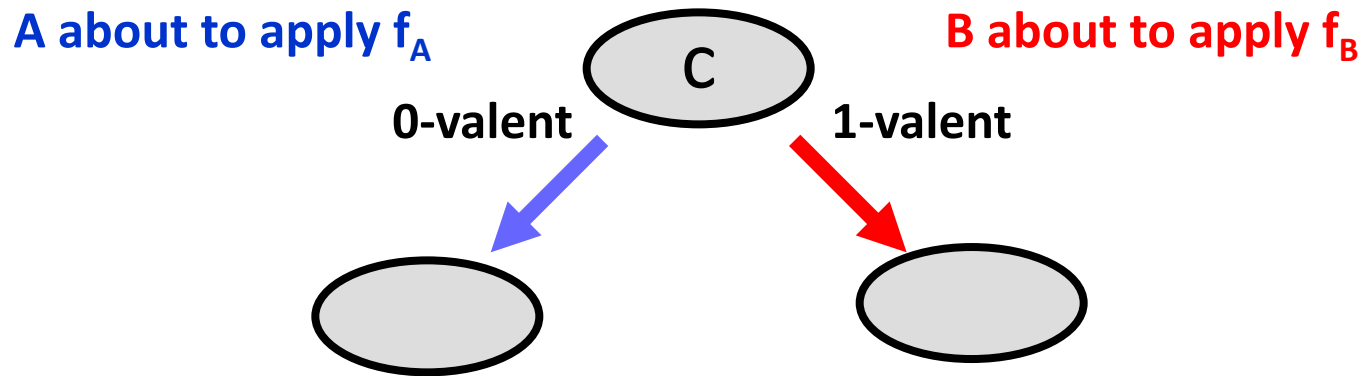
$f_i(x)$  = new value of cell  
(not return value of  $f_i$ )

## Examples:

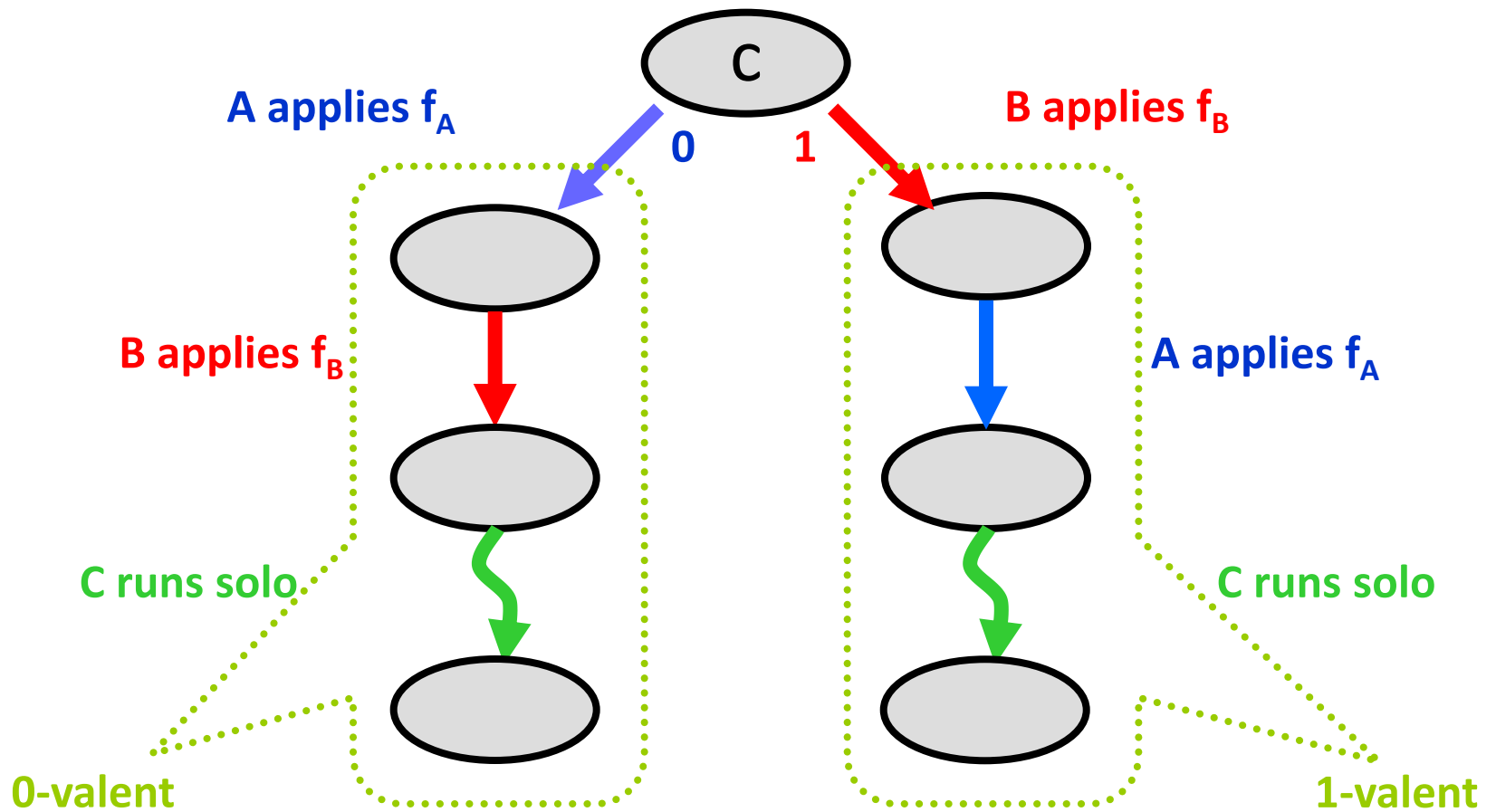
- Overwrite
  - Test&Set , Swap
- Commute
  - Fetch&Inc, Fetch&Add

# Proof

- There are three threads, **A**, **B**, and **C**
- Consider a critical state  $c$ :

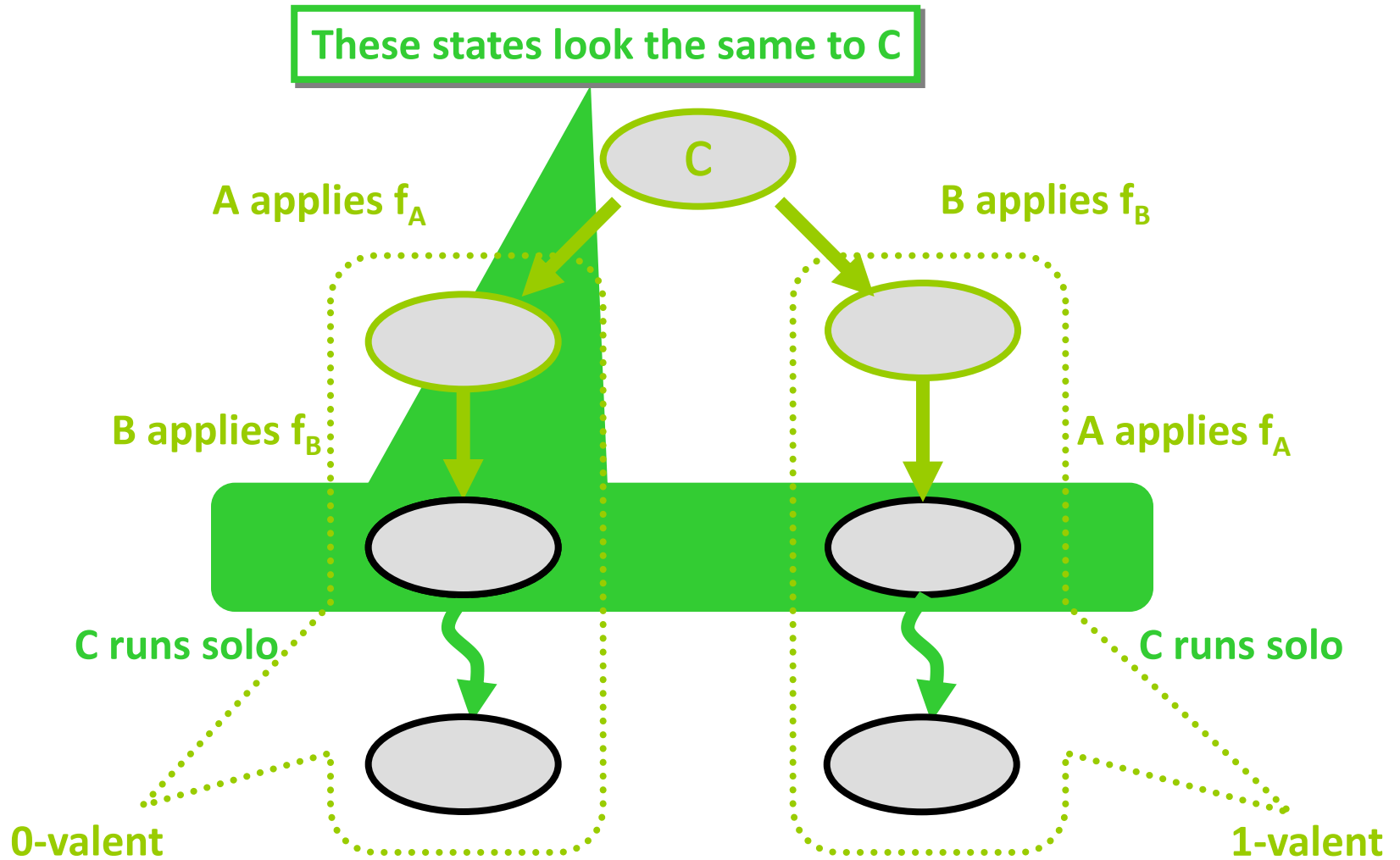


# Proof: Maybe the Functions Commute

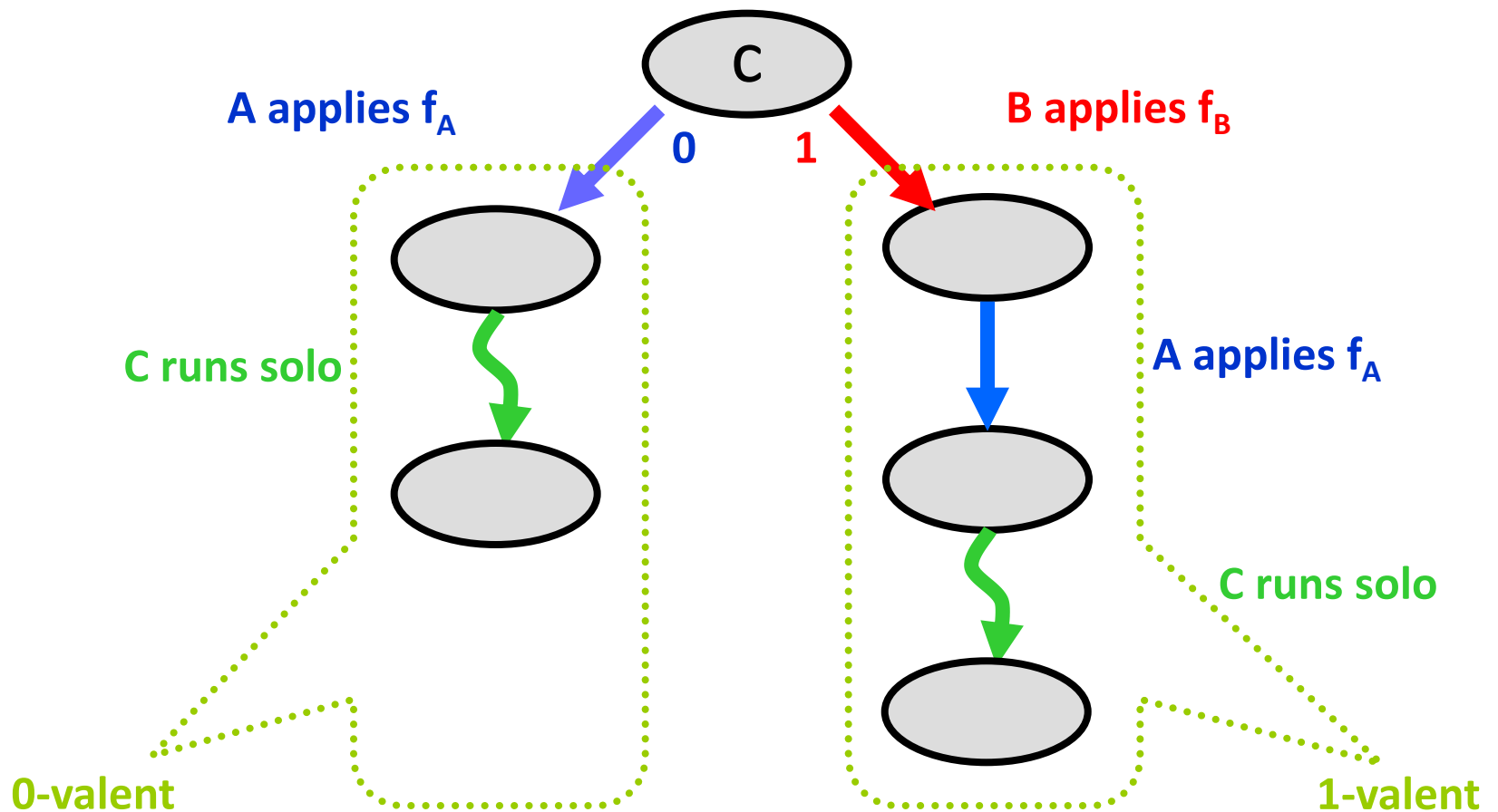




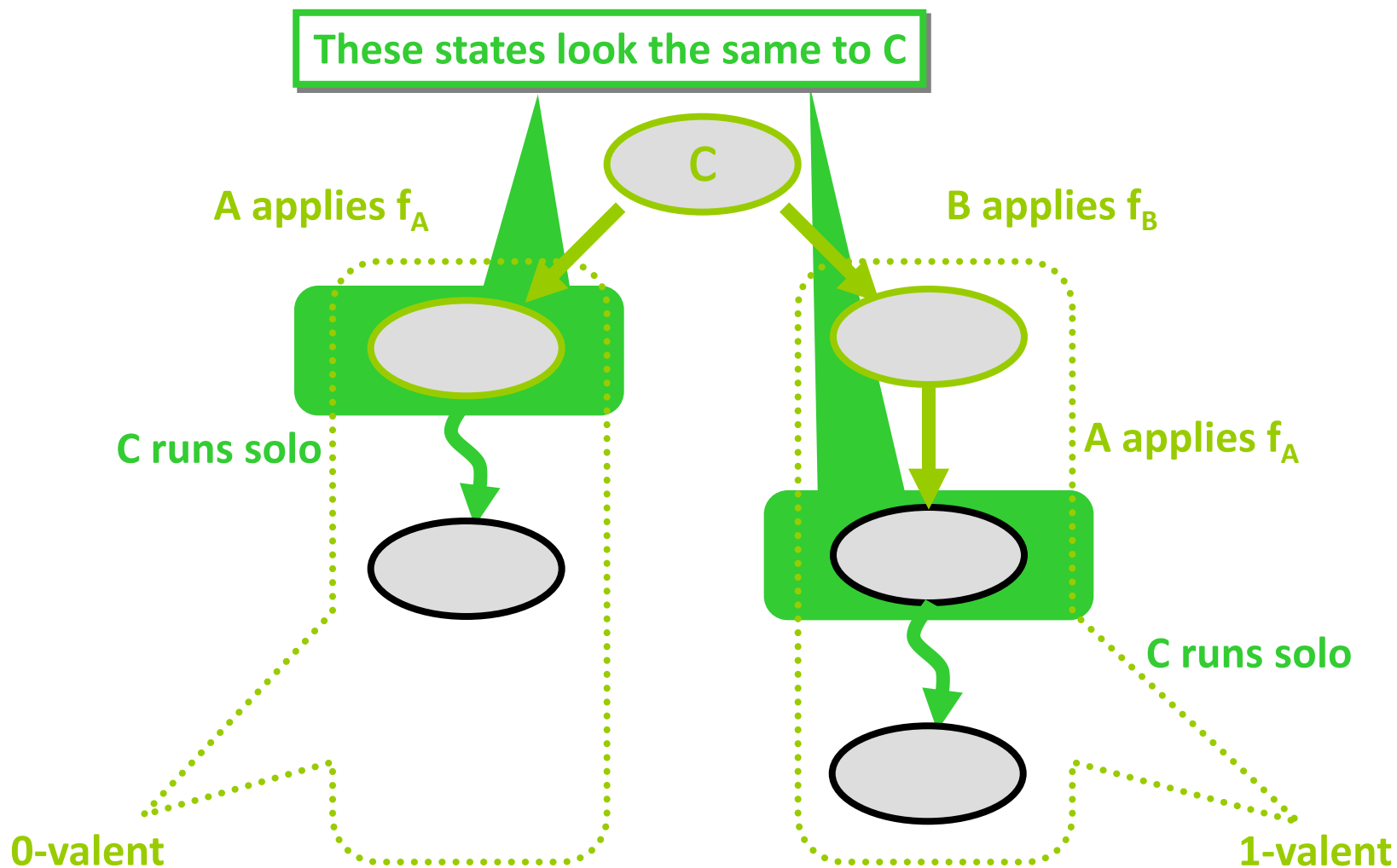
# Proof: Maybe the Functions Commute



# Proof: Maybe the Functions Overwrite



# Proof: Maybe the Functions Overwrite



# Impact

- Many early machines used these “weak” RMW instructions
  - Test&Set (IBM 360)
  - Fetch&Add (NYU Ultracomputer)
  - Swap
- We now understand their limitations

# Consensus with Compare & Swap

```
public class RMWConsensus implements Consensus {  
    private RMW r;  
  
    public Object decide() {  
        int i = Thread.myIndex();  
        int j = r.CAS(-1, i);  
        if(j == -1)  
            return this.announce[i];  
        else  
            return this.announce[j];  
    }  
}
```

Initialized to -1

Am I first?

Yes, return my input

No, return other's input

# The Consensus Hierarchy

1

- Read/Write Registers

2

- Test&Set
- Fetch&Inc
- Fetch&Add
- Swap

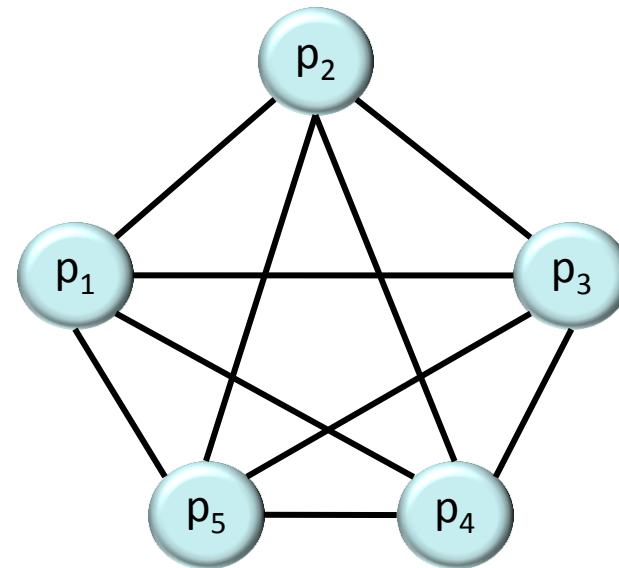
...

$\infty$

- CAS
- LL/SC

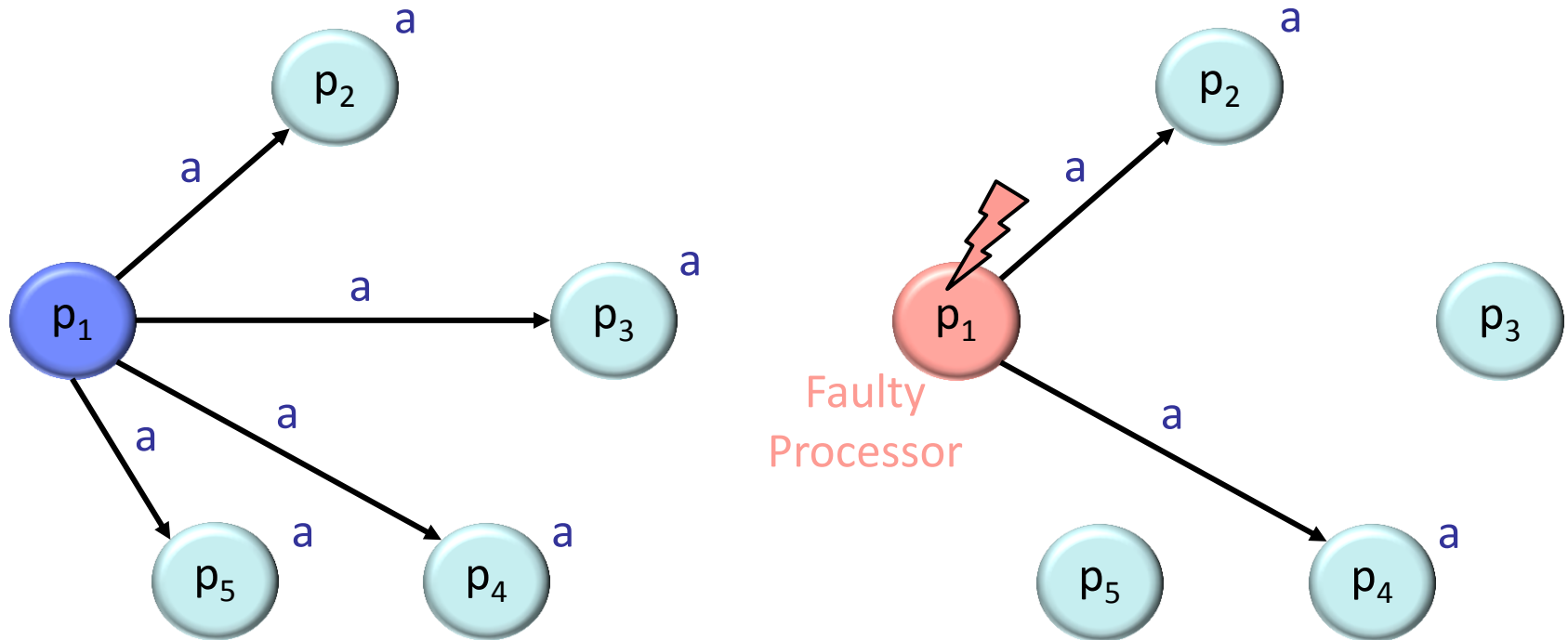
# Consensus #4: Synchronous Systems

- One can sometimes tell if a processor had crashed
  - Timeouts
  - Broken TCP connections
- Can one solve consensus at least in synchronous systems?
- Model
  - All communication occurs in synchronous rounds
  - Complete communication graph



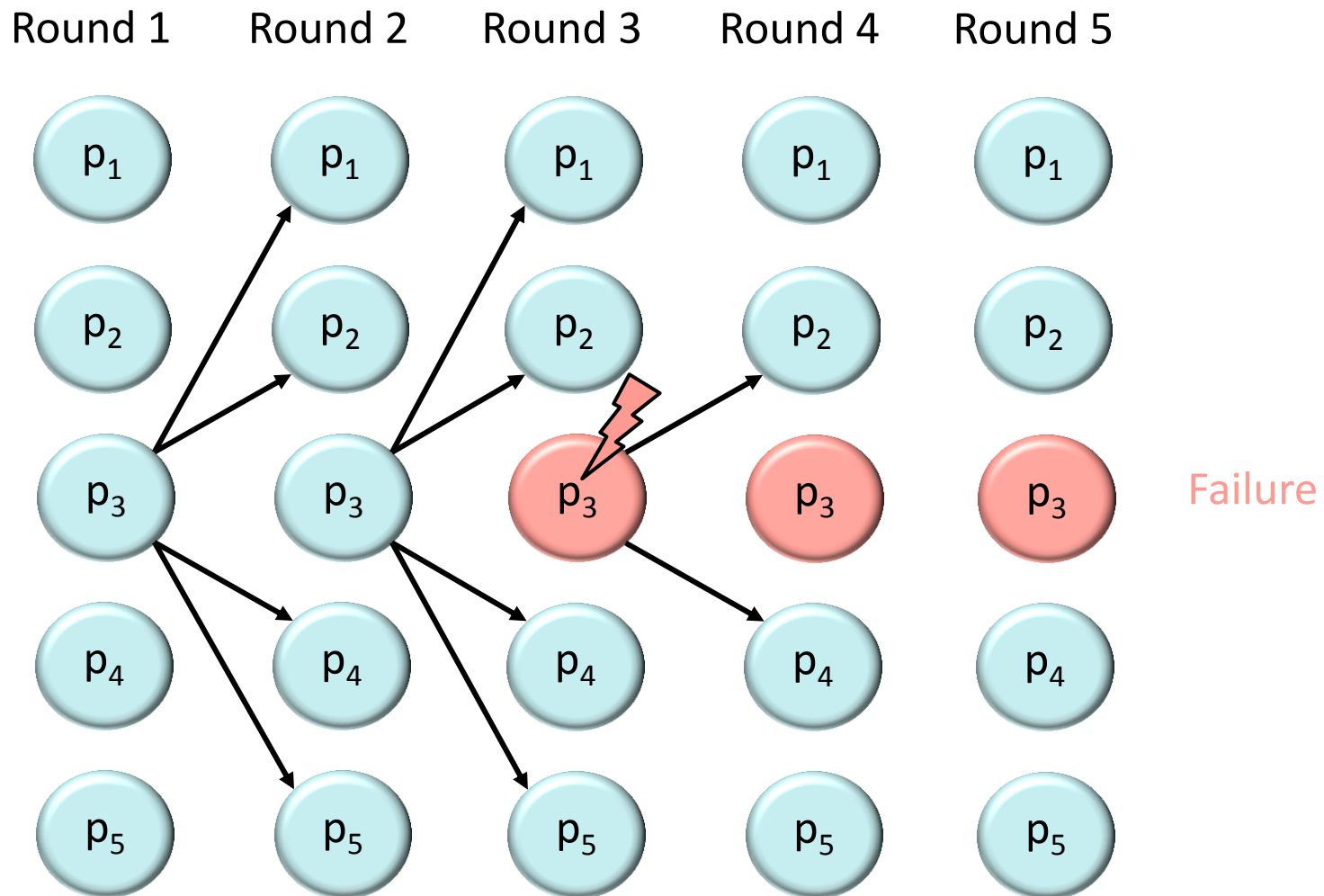
# Crash Failures

- Broadcast: Send a Message to All Processes in One Round
  - At the end of the round everybody receives the message  $a$
  - Every process can broadcast a value in each round
- Crash Failures: A broadcast can fail if a process crashes
  - Some of the messages may be lost, i.e., they are never received





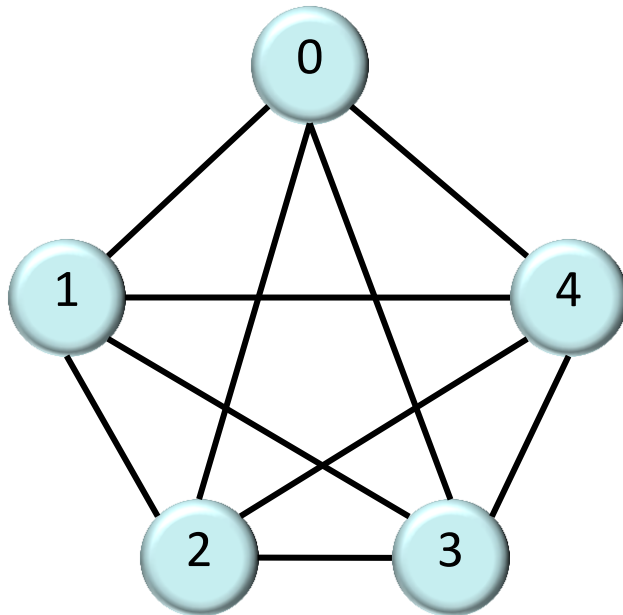
# After a Failure, the Process Disappears from the Network



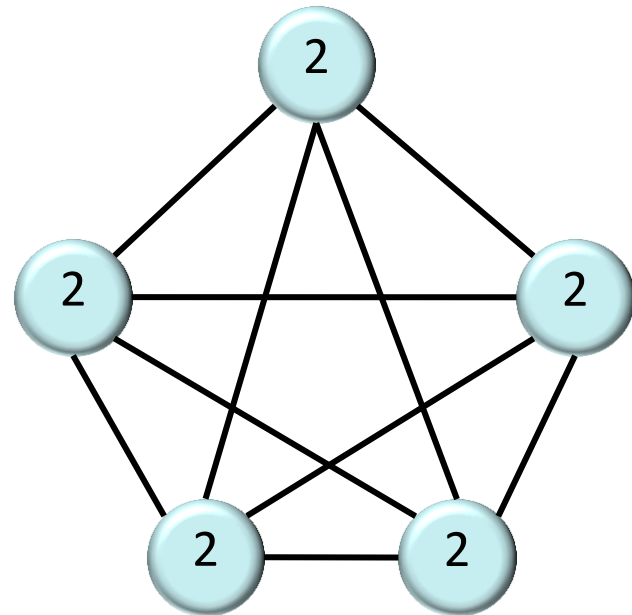
# Consensus Repetition

- Everybody has an initial value
- Everybody must decide on the same value

Start



Finish

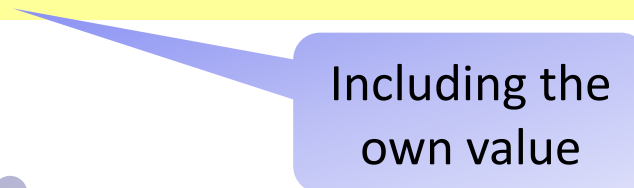


- **Validity condition:**  
If everybody starts with the same value, they must decide on that value

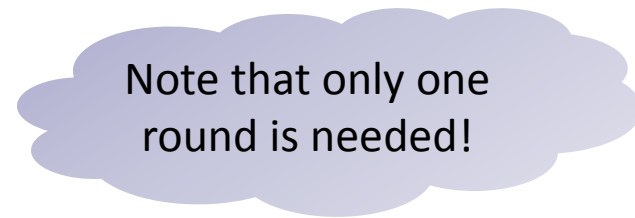
# A Simple Consensus Algorithm

Each process:

1. Broadcast own value
2. Decide on the minimum of all received values



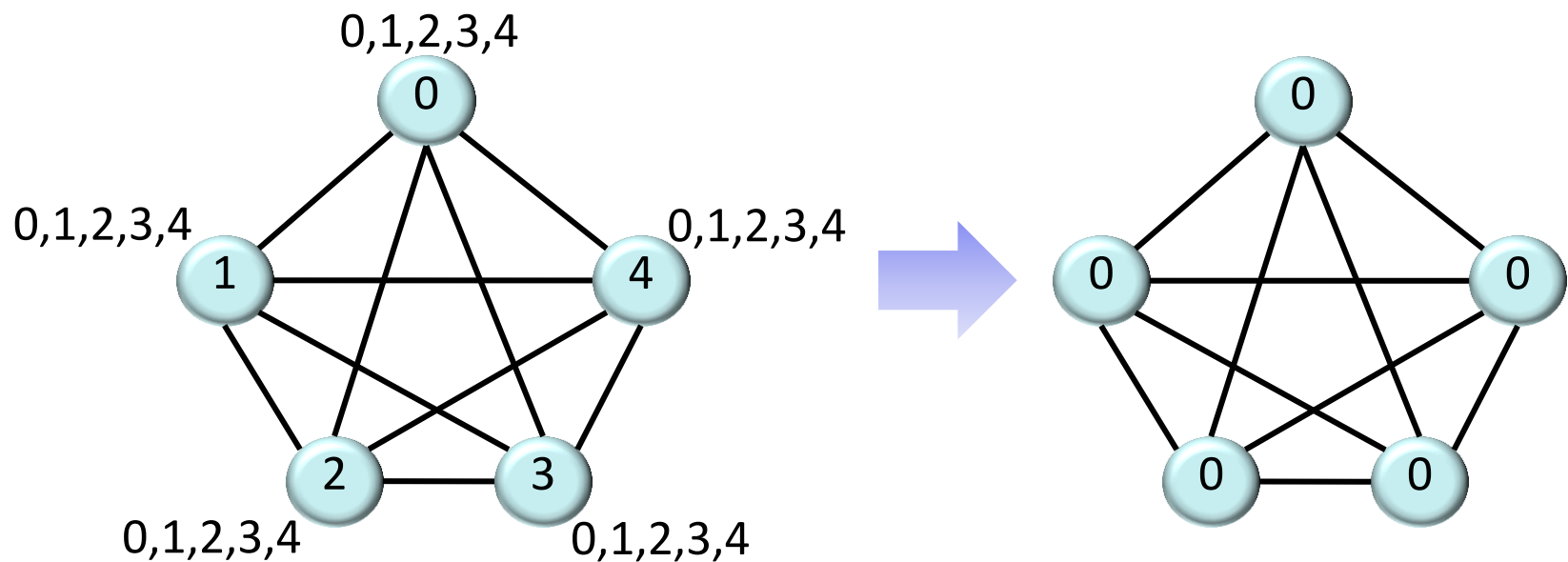
Including the  
own value



Note that only one  
round is needed!

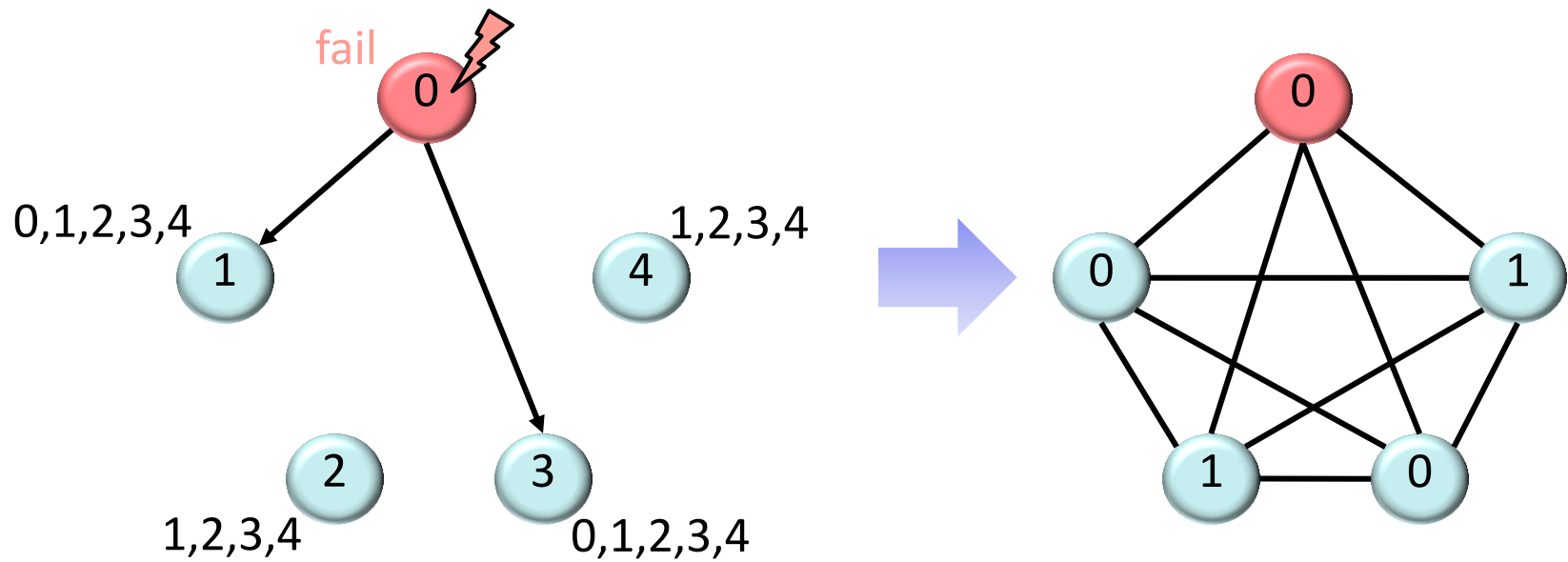
# Execution Without Failures

- Broadcast values and decide on minimum → Consensus!
- Validity condition is satisfied: If everybody starts with the same initial value, everybody sticks to that value (minimum)



# Execution With Failures

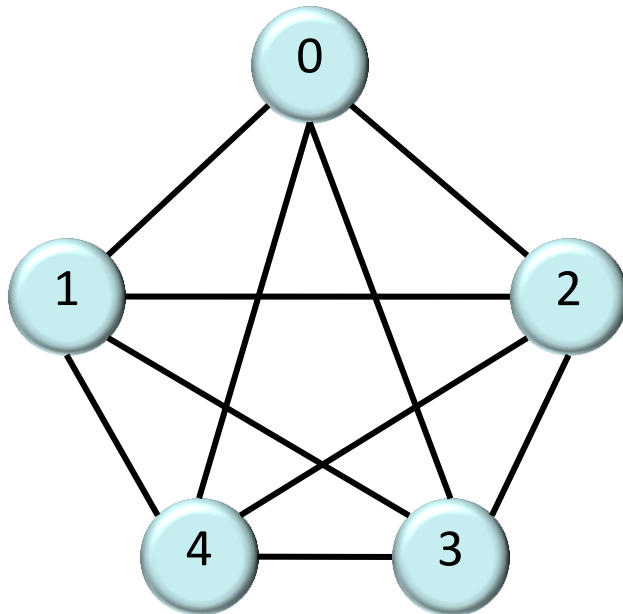
- The failed processor doesn't broadcast its value to all processors
- Decide on minimum  $\rightarrow$  No consensus!



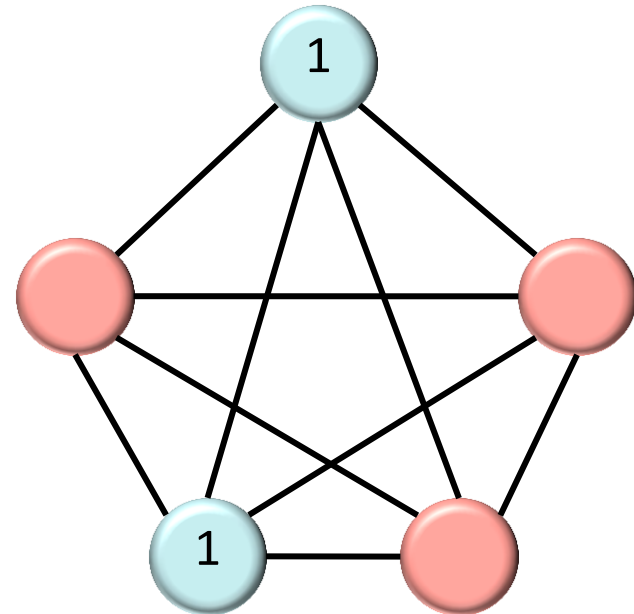
# $f$ -resilient Consensus Algorithm

- If an algorithm solves consensus for  $f$  failed processes, we say it is an  $f$ -resilient consensus algorithm
- Example: The input and output of a 3-resilient consensus algorithm:

Start



Finish



- **Refined validity condition:**  
All processes decide on a value that is available initially

# An $f$ -resilient Consensus Algorithm

Each process:

Round 1:

Broadcast own value

Round 2 to round  $f+1$ :

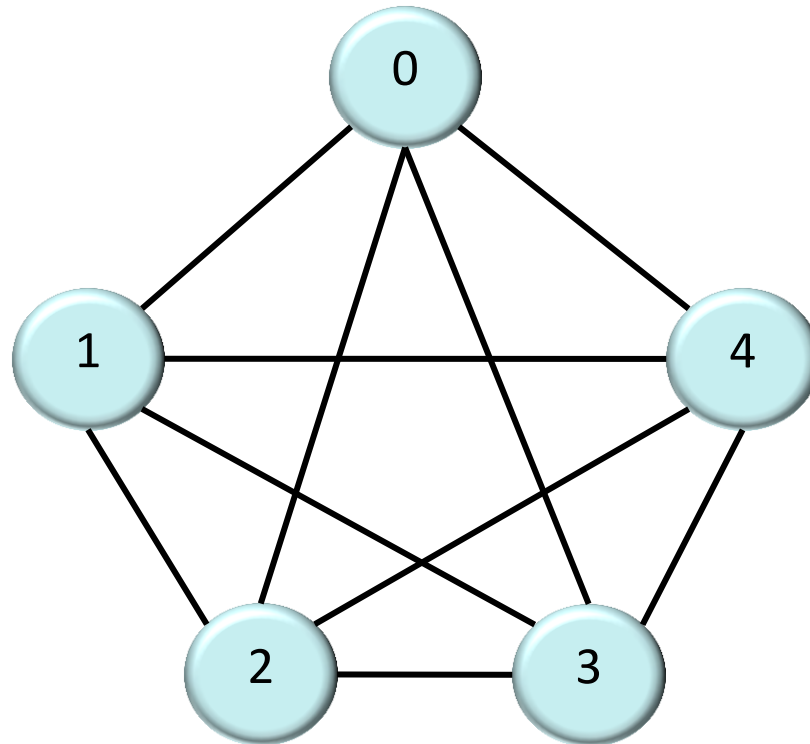
Broadcast the minimum of received values unless it has been sent before

End of round  $f+1$ :

Decide on the minimum value received

# An $f$ -resilient Consensus Algorithm

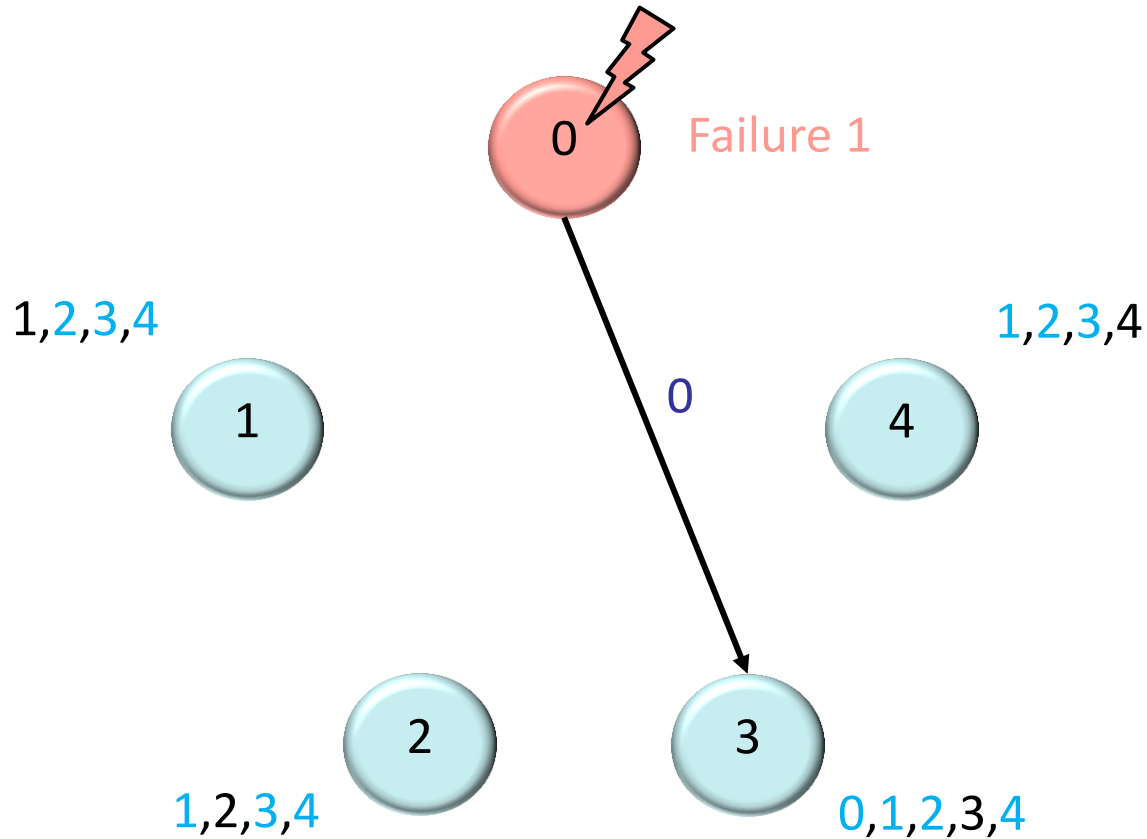
- Example:  $f=2$  failures,  $f+1 = 3$  rounds needed





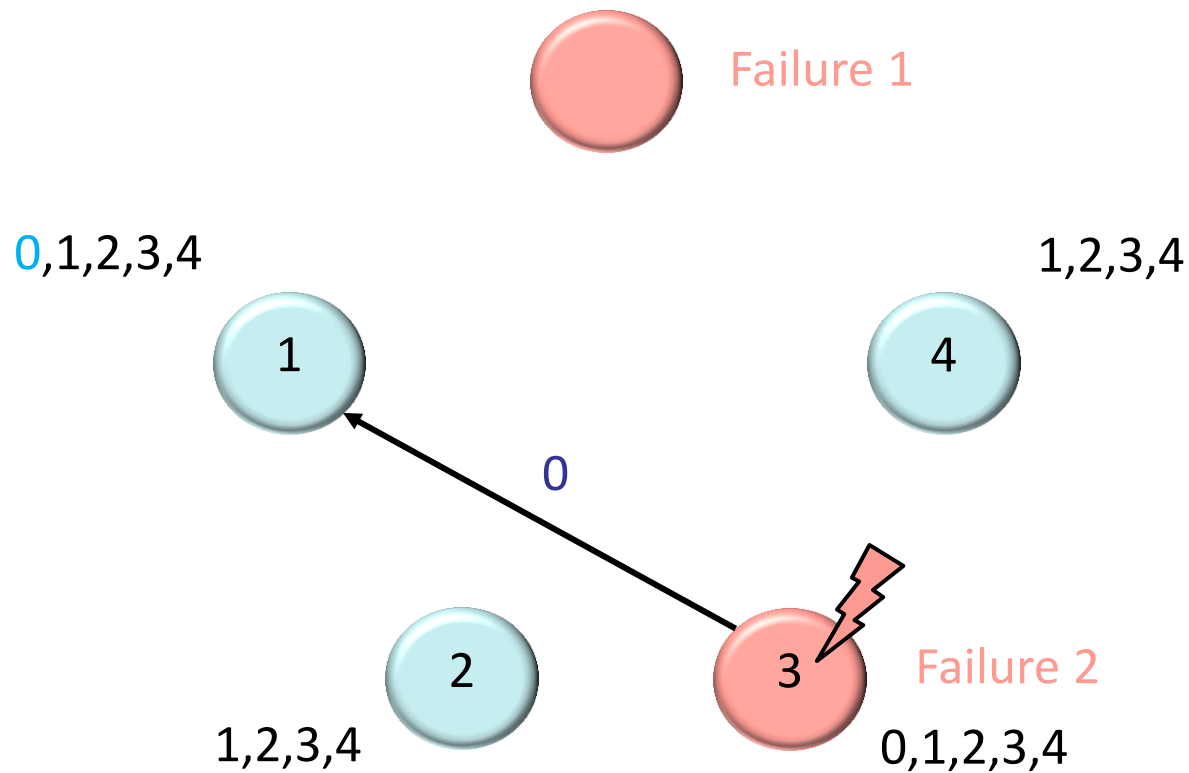
# An $f$ -resilient Consensus Algorithm

- Round 1: Broadcast all values to everybody



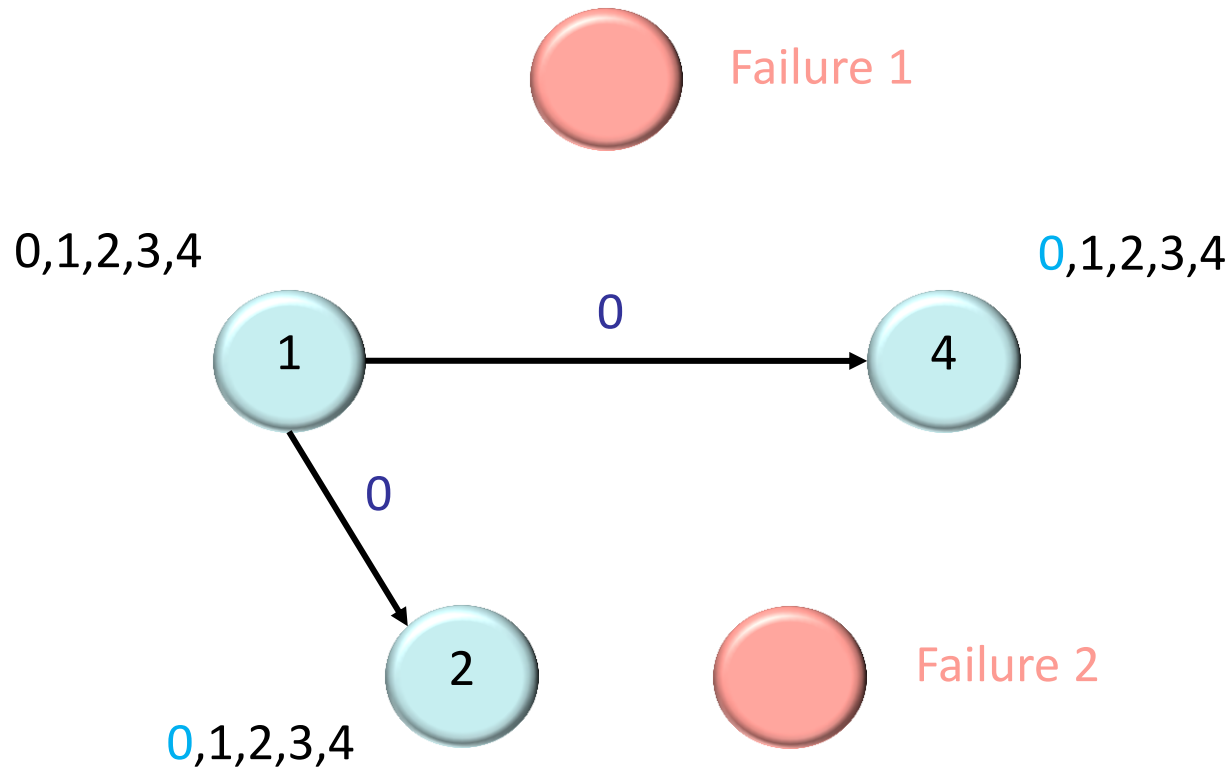
# An $f$ -resilient Consensus Algorithm

- Round 2: Broadcast all new values to everybody



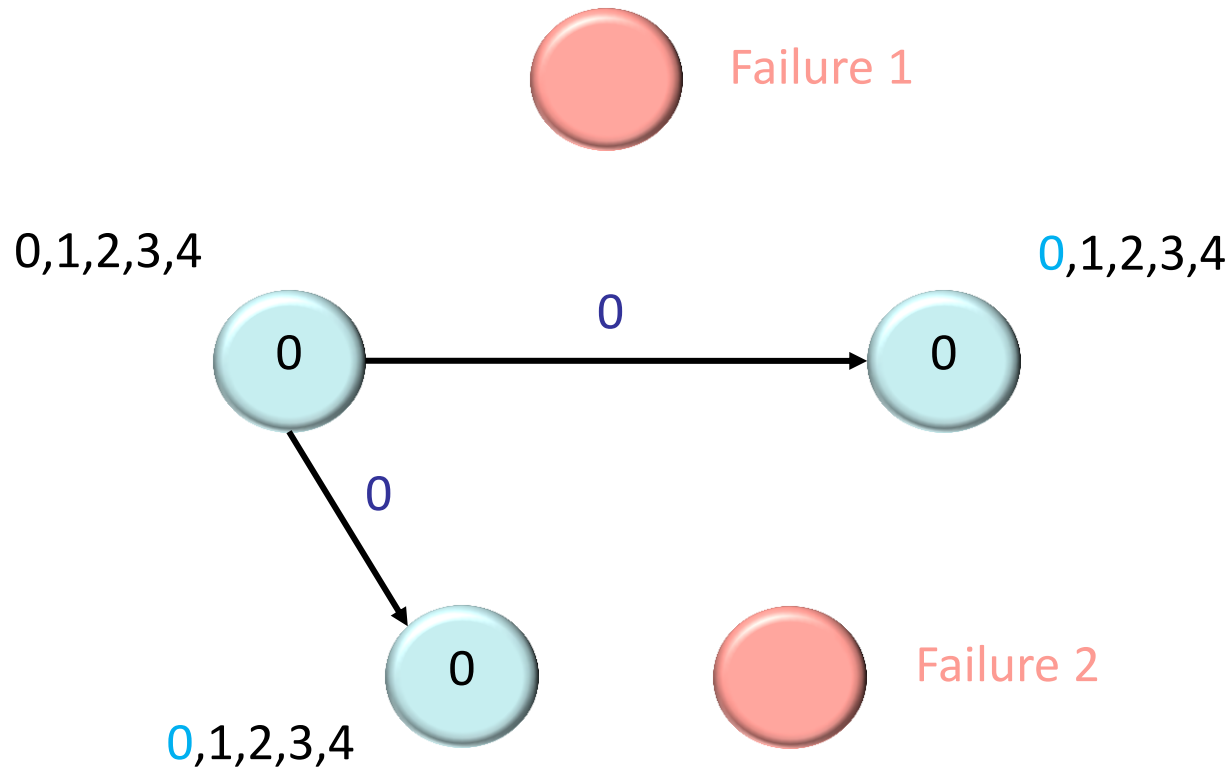
# An $f$ -resilient Consensus Algorithm

- Round 3: Broadcast all new values to everybody



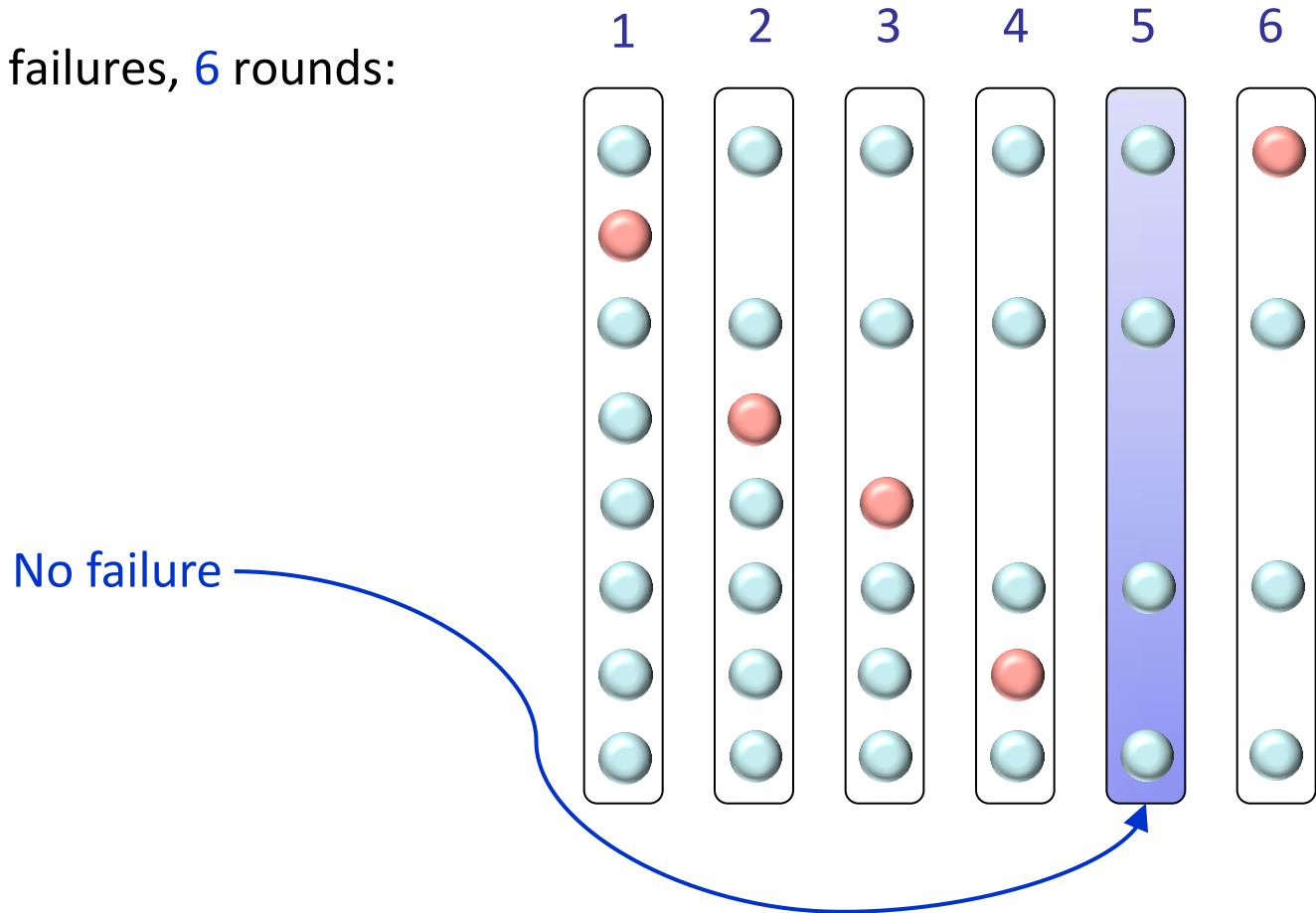
# An $f$ -resilient Consensus Algorithm

- Decide on minimum  $\rightarrow$  Consensus!



# Analysis

- If there are  $f$  failures and  $f+1$  rounds, then there is a round with no failed process
- Example: 5 failures, 6 rounds:



# Analysis

- At the end of the round with no failure
  - Every (non faulty) process knows about all the values of all the other participating processes
  - This knowledge doesn't change until the end of the algorithm
- Therefore, everybody will decide on the same value
- However, as we don't know the exact position of this round, we have to let the algorithm execute for  $f+1$  rounds
- Validity: When all processes start with the same input value, then consensus is that value

# Theorem

Theorem

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

Note that this is  
not a formal proof!

## Proof sketch:

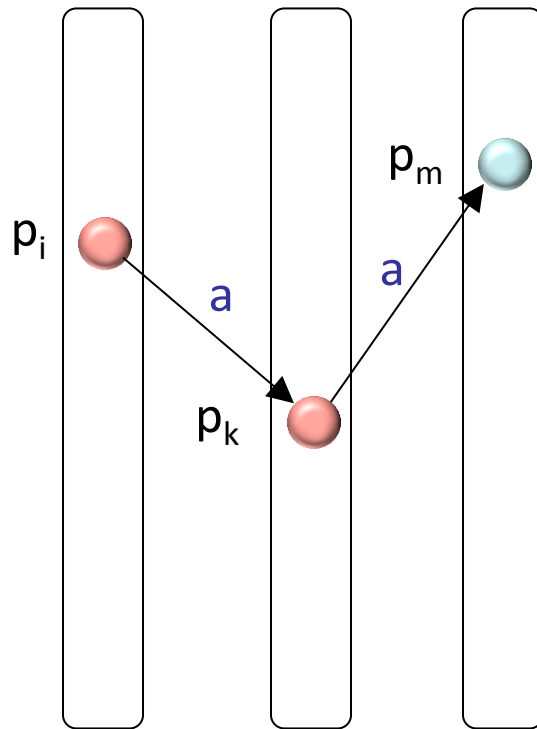
- Assume for contradiction that  $f$  or less rounds are enough
- Worst-case scenario: There is a process that fails in each round

# Worst-case Scenario

Round

1

2



- Before process  $p_i$  fails, it sends its value  $a$  only to one process  $p_k$
- Before process  $p_k$  fails, it sends its value  $a$  to only one process  $p_m$



# Worst-case Scenario

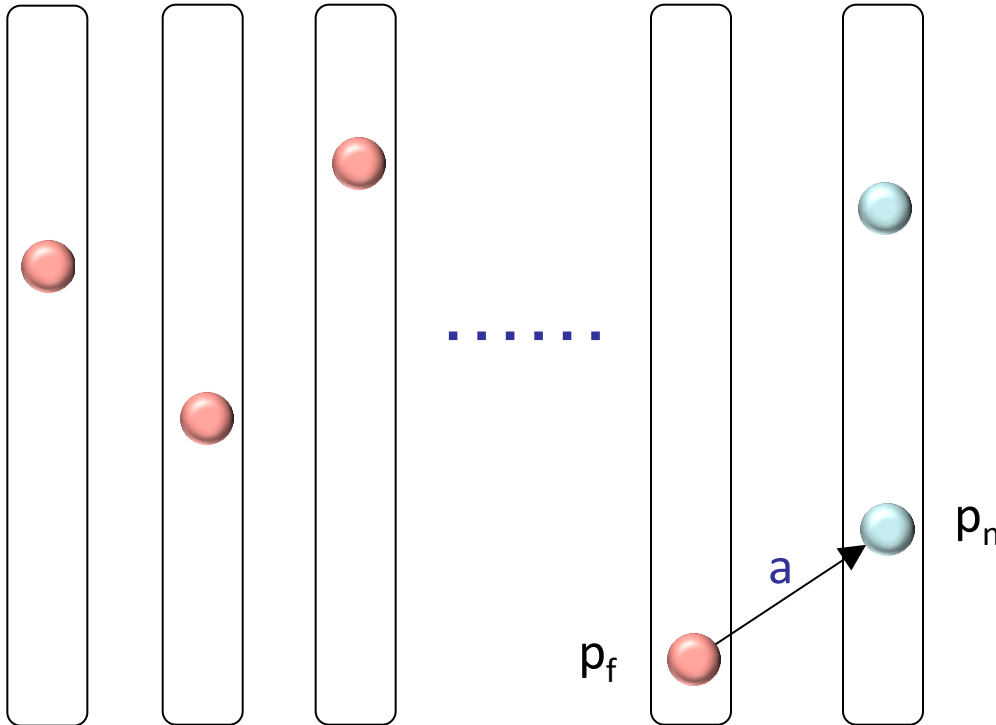
Round

1

2

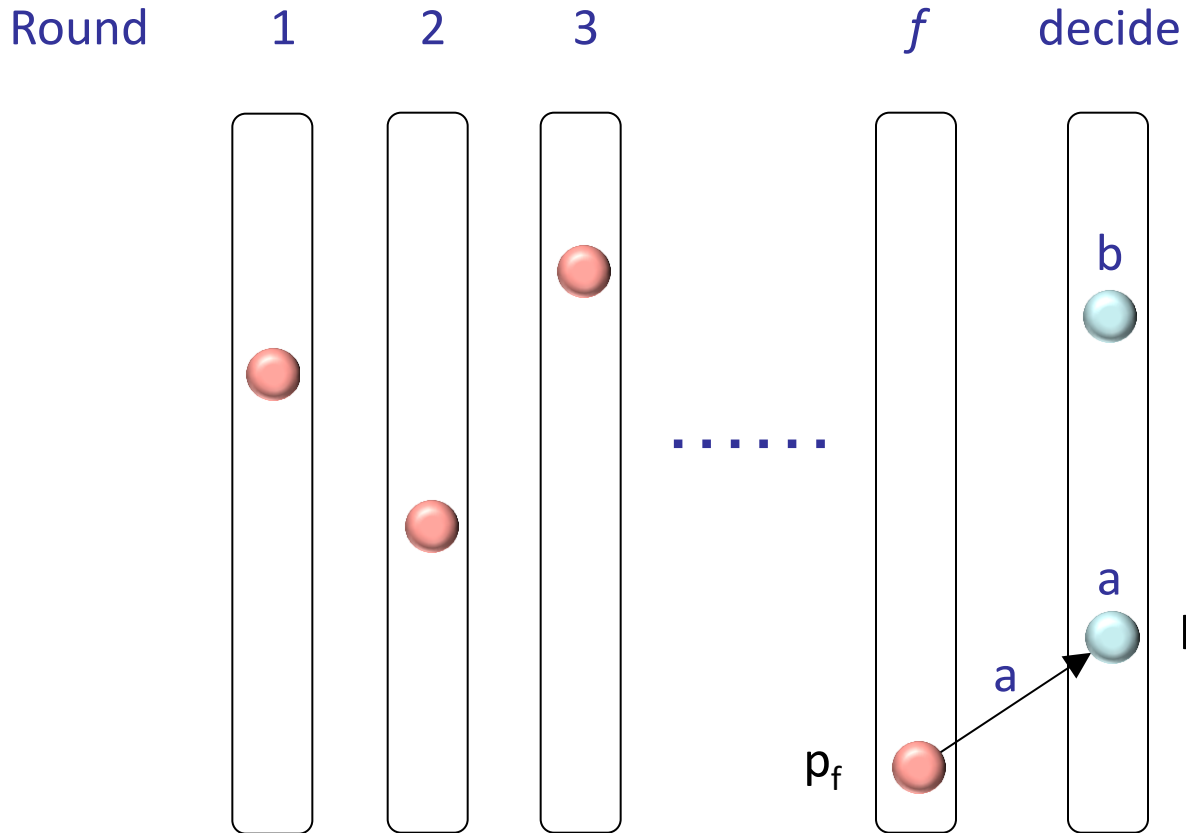
3

$f$



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

# Worst-case Scenario

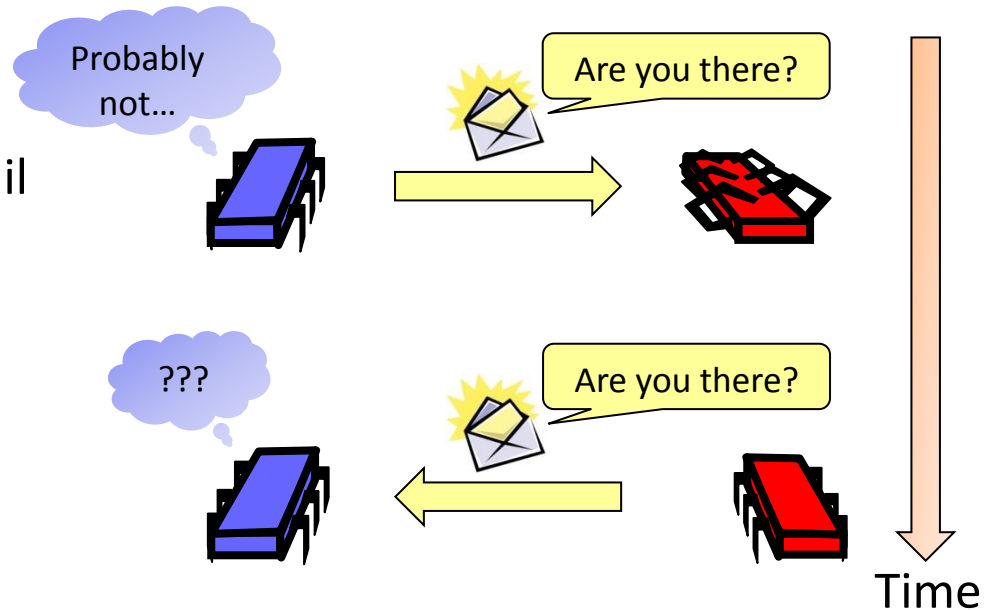


- Process  $p_n$  may decide on  $a$  and all other processes may decide on another value  $b$
- Therefore  $f$  rounds are not enough  $\rightarrow$  At least  $f+1$  rounds are needed

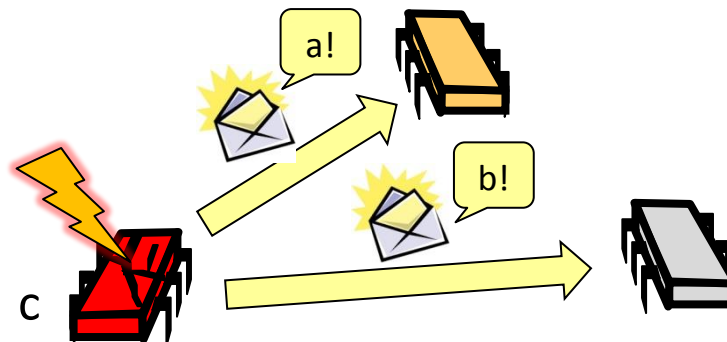
# Arbitrary Behavior

- The assumption that processes crash and stop forever is sometimes too optimistic

- Maybe the processes fail and recover:

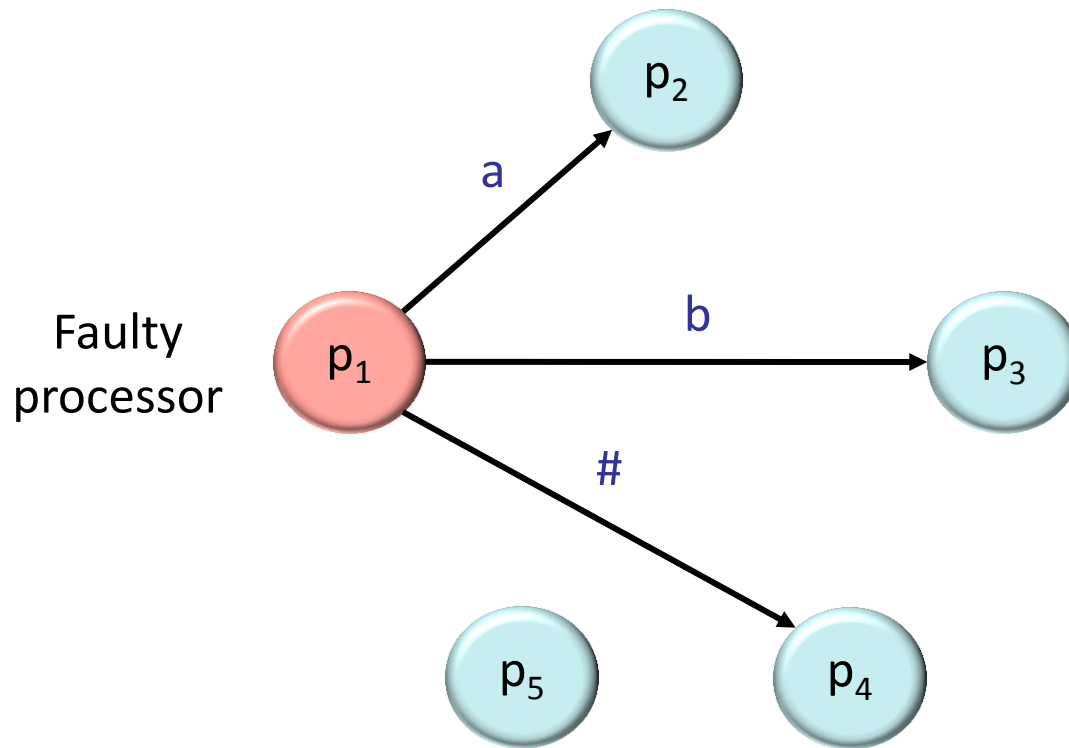


- Maybe the processes are damaged:

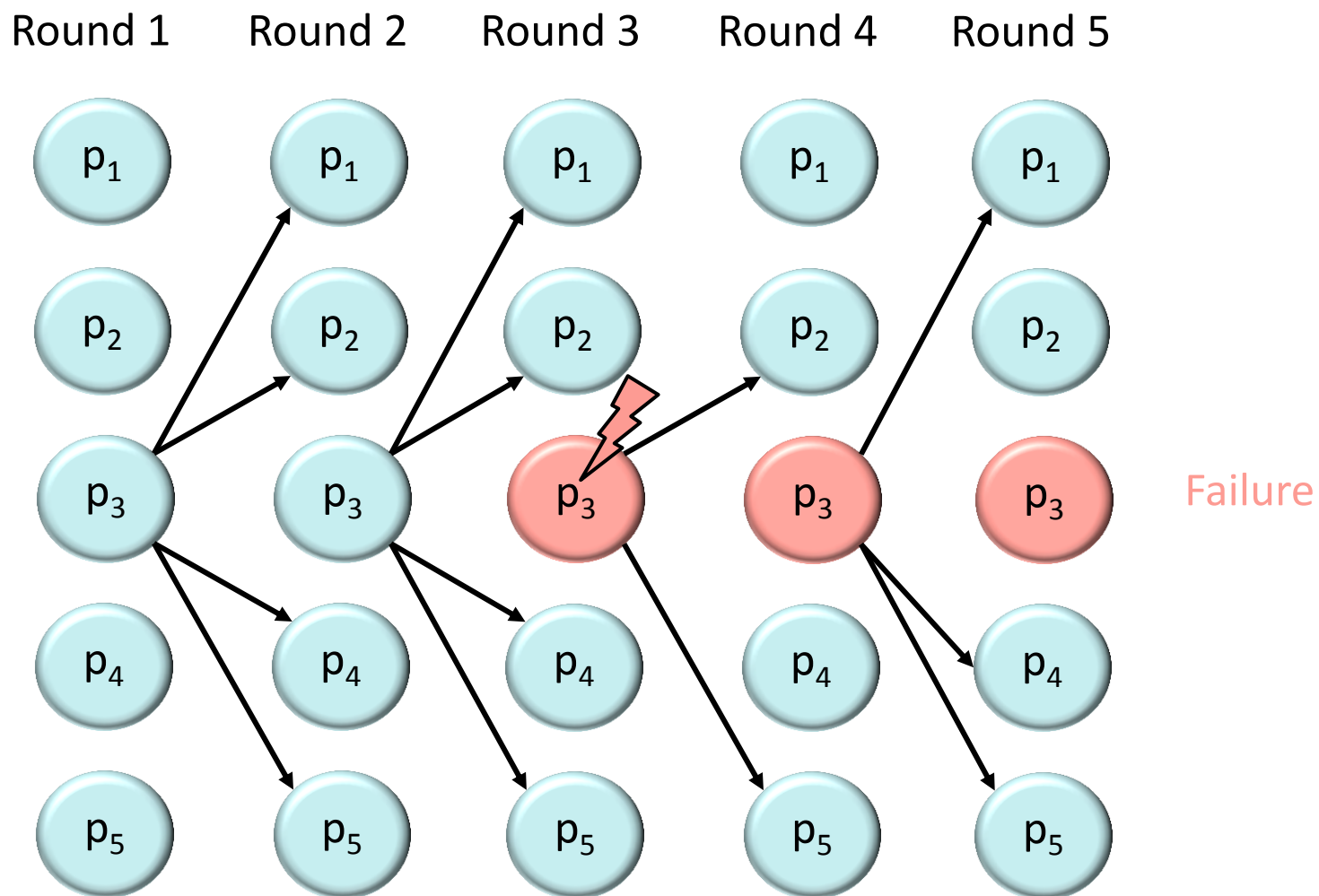


## Consensus #5: Byzantine Failures

- Different processes may receive different values
- A Byzantine process can behave like a crash-failed process



# After a Failure, the Process Remains in the Network



# Consensus with Byzantine Failures

- Again: If an algorithm solves consensus for  $f$  failed processes, we say it is an  $f$ -resilient consensus algorithm
- Validity condition: If all non-faulty processes start with the same value, then all non-faulty processes decide on that value
  - Note that in general this validity condition does not guarantee that the final value is an input value of a non-Byzantine process
  - However, if the input is binary, then the validity condition ensures that processes decide on a value that at least one non-Byzantine process had initially
- Obviously, any  $f$ -resilient consensus algorithm requires at least  $f+1$  rounds (follows from the crash failure lower bound)
- How large can  $f$  be...? Can we reach consensus as long as the majority of processes is correct (non-Byzantine)?

# Theorem

Theorem

There is no  $f$ -resilient algorithm for  $n$  processes,  
where  $f \geq n/3$

## Proof outline:

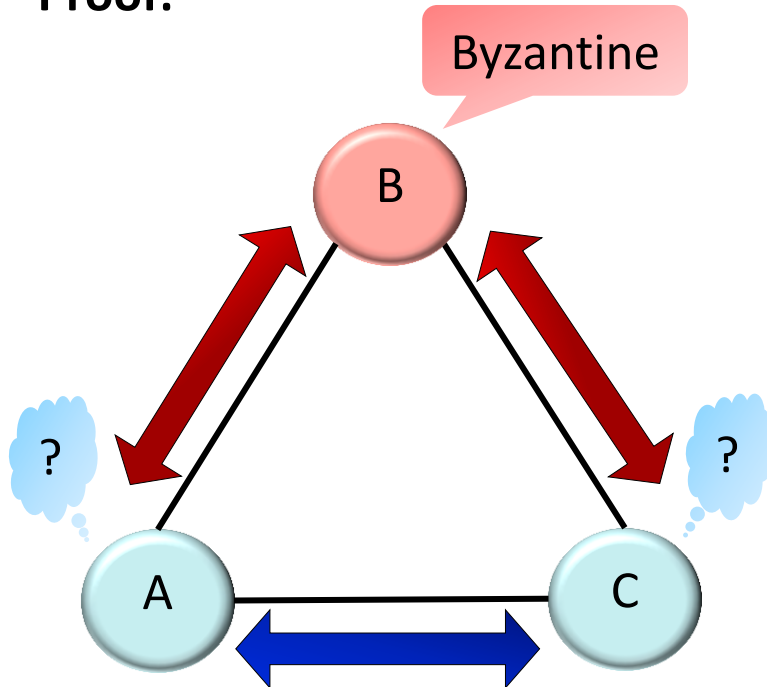
- First, we prove the 3 processes case
- The general case can be proved by reducing it to the 3 processes case

# The 3 Processes Case

Lemma

There is no 1-resilient algorithm for 3 processes

**Proof:**

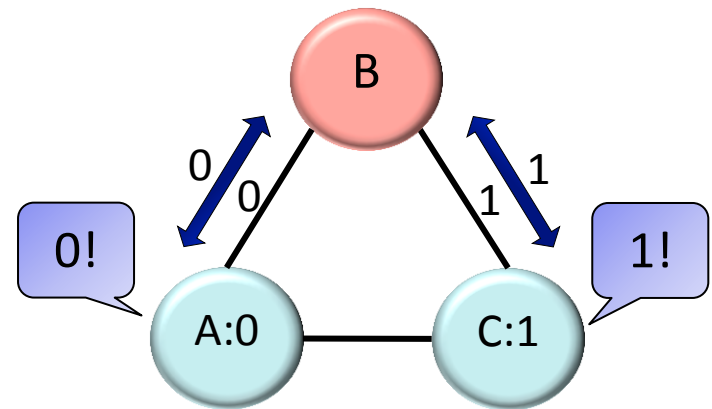
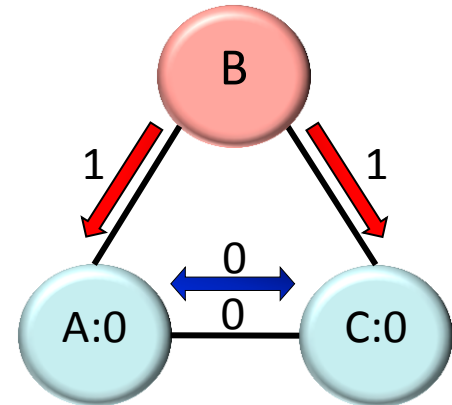
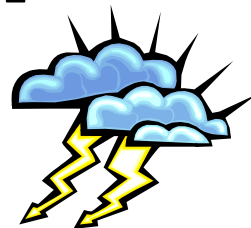


- Intuition:
- Process **A** may also receive information from **C** about **B**'s messages to **C**
- Process **A** may receive conflicting information about **B** from **C** and about **C** from **B** (the same for **C**!)
- It is impossible for **A** and **C** to decide which information to base their decision on!



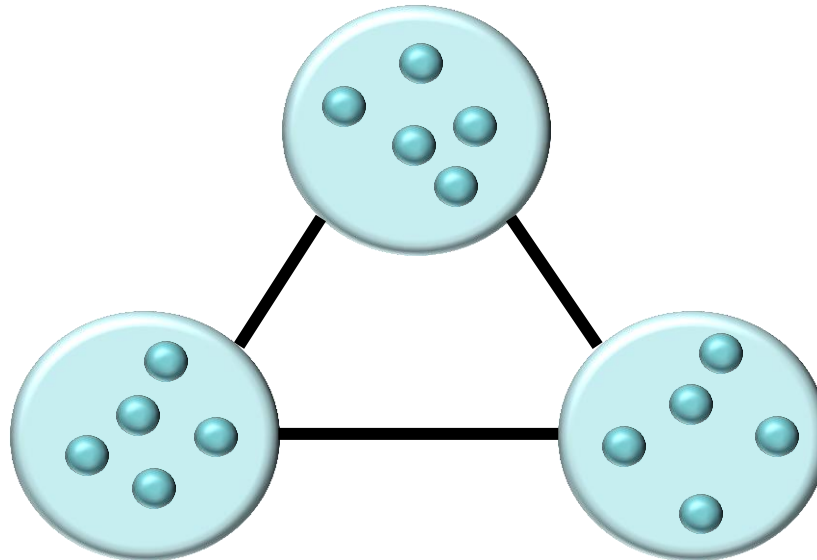
# Proof

- Assume that both **A** and **C** have input 0. If they decided 1, they could violate the validity condition  $\rightarrow$  **A** and **C** must decide 0 independent of what **B** says
- Similarly, **A** and **C** must decide 1 if their inputs are 1
- We see that the processes must base their decision on the majority vote
- If **A**'s input is 0 and **B** tells **A** that its input is 0  $\rightarrow$  **A** decides 0
- If **C**'s input is 1 and **B** tells **C** that its input is 1  $\rightarrow$  **C** decides 1



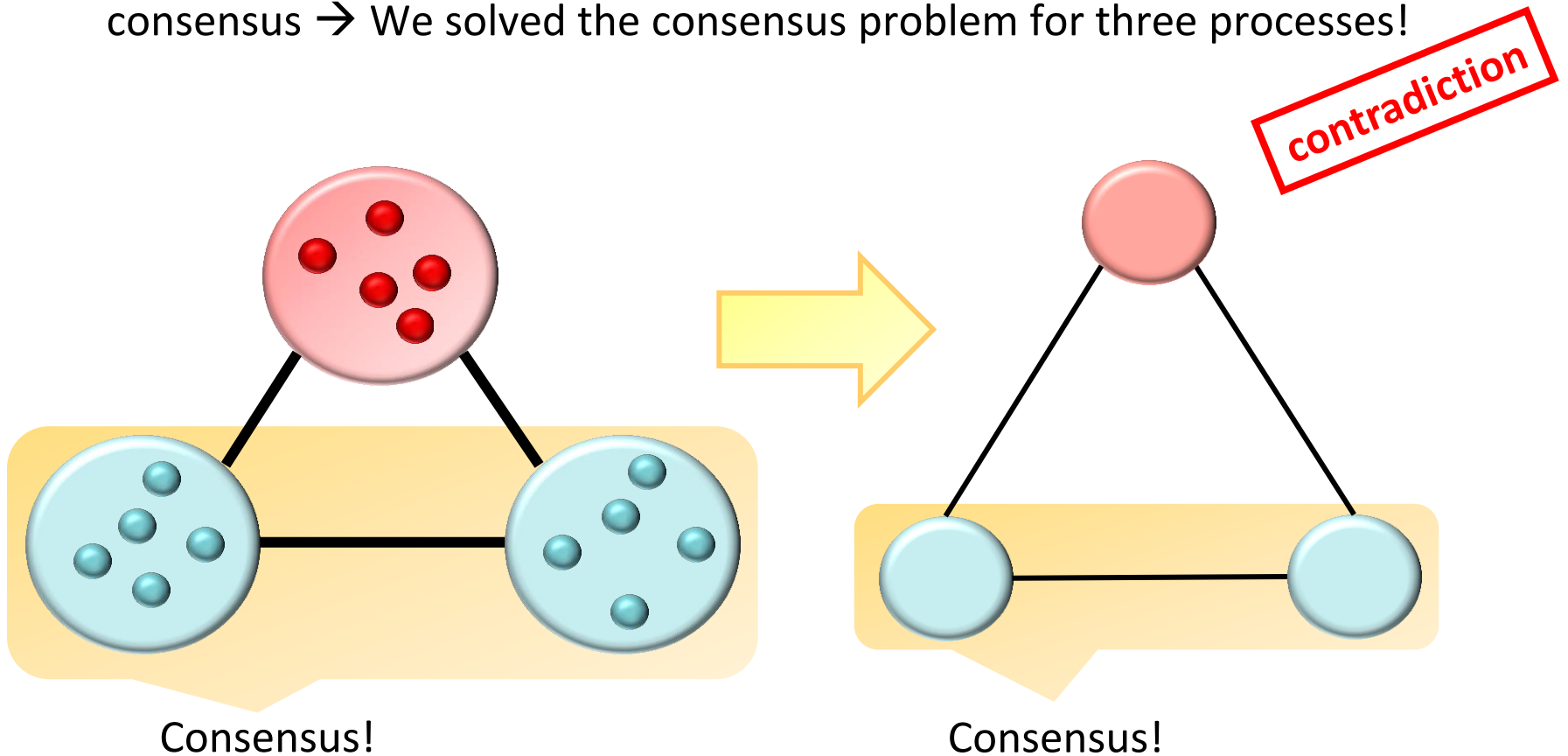
# The General Case

- Assume for contradiction that there is an  $f$ -resilient algorithm  $A$  for  $n$  processes, where  $f \geq n/3$
- We use this algorithm to solve the consensus algorithm for 3 processes where one process is Byzantine!
- If  $n$  is not evenly divisible by 3, we increase it by 1 or 2 to ensure that  $n$  is a multiple of 3
- We let each of the three processes simulate  $n/3$  processes



# The General Case

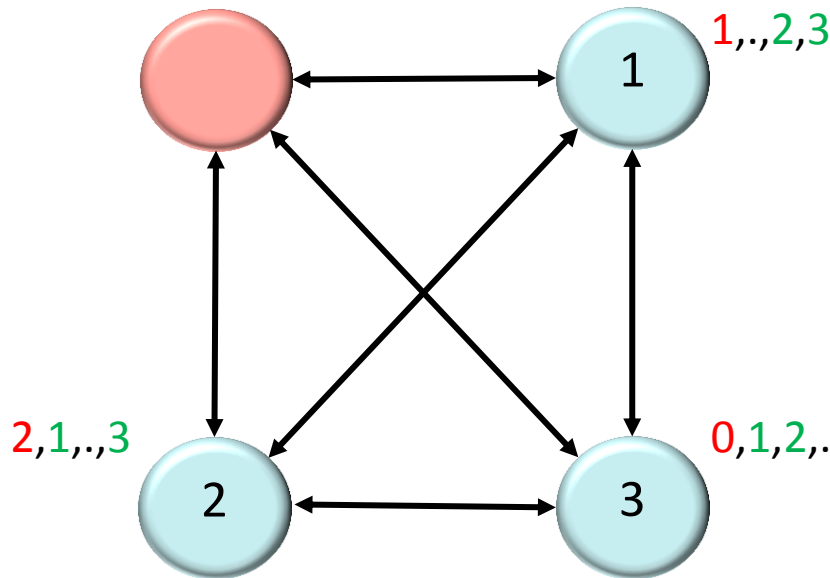
- One of the 3 processes is Byzantine  $\rightarrow$  Its  $n/3$  simulated processes may all behave like Byzantine processes
- Since algorithm A tolerates  $n/3$  Byzantine failures, it can still reach consensus  $\rightarrow$  We solved the consensus problem for three processes!



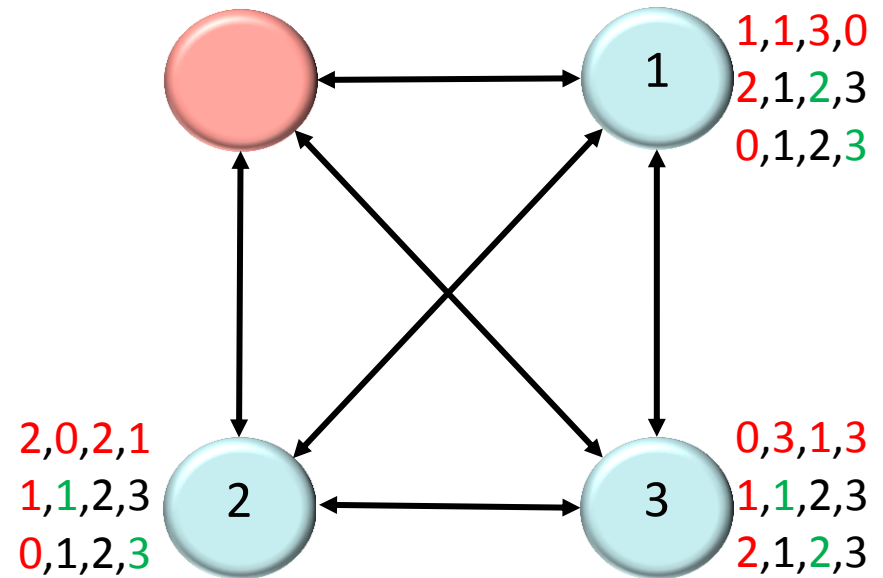
# Consensus #6: A Simple Algorithm for Byzantine Agreement

- Can the processes reach consensus if  $n > 3f$ ?
- A simpler question: Can the processes reach consensus if  $n=4$  and  $f=1$ ?
- The answer is yes. It takes two rounds:

Round 1: Exchange all values



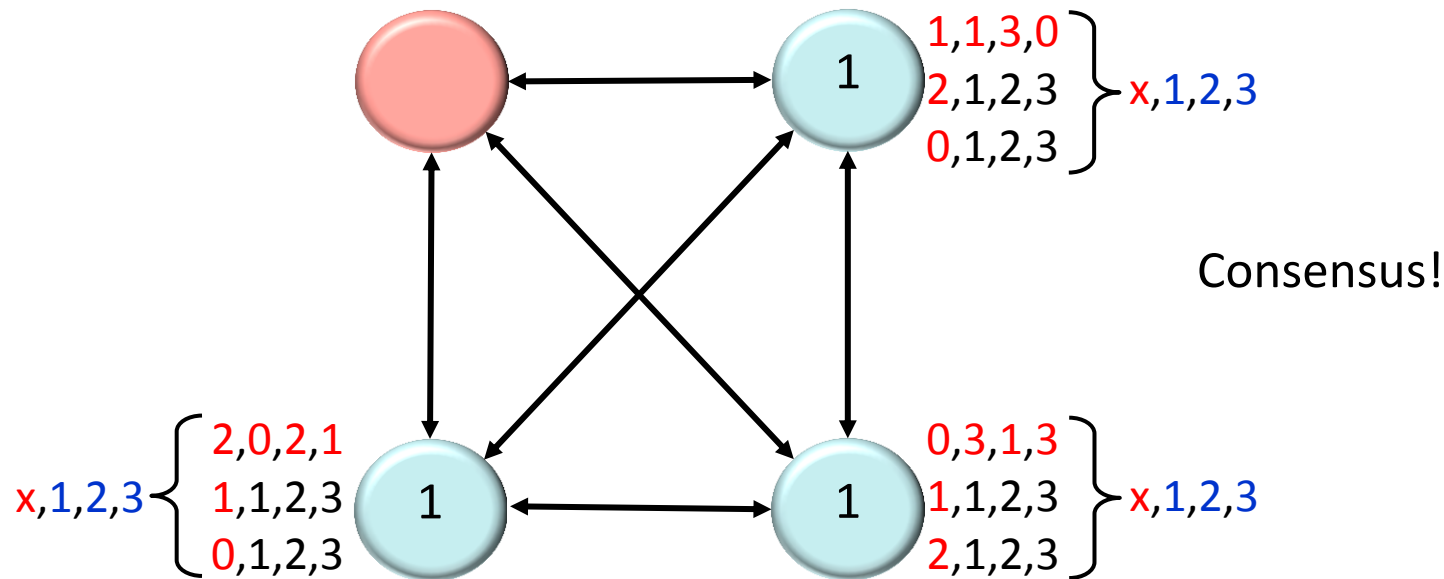
Round 2: Exchange the received info



[matrix: one column for each original value, one row for each neighbor]

# A Simple Algorithm for Byzantine Agreement

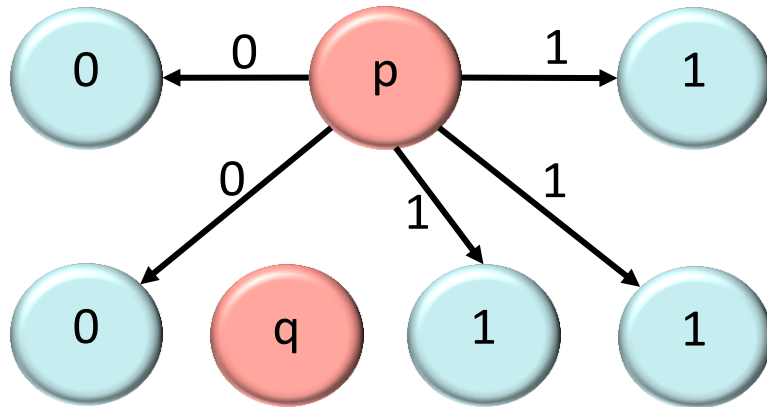
- After the second round each node has received 12 values, 3 for each of the 4 input values (columns). If at least 2 of 3 values of a column are equal, this value is accepted. If all 3 values are different, the value is discarded
- The node then decides on the minimum accepted value



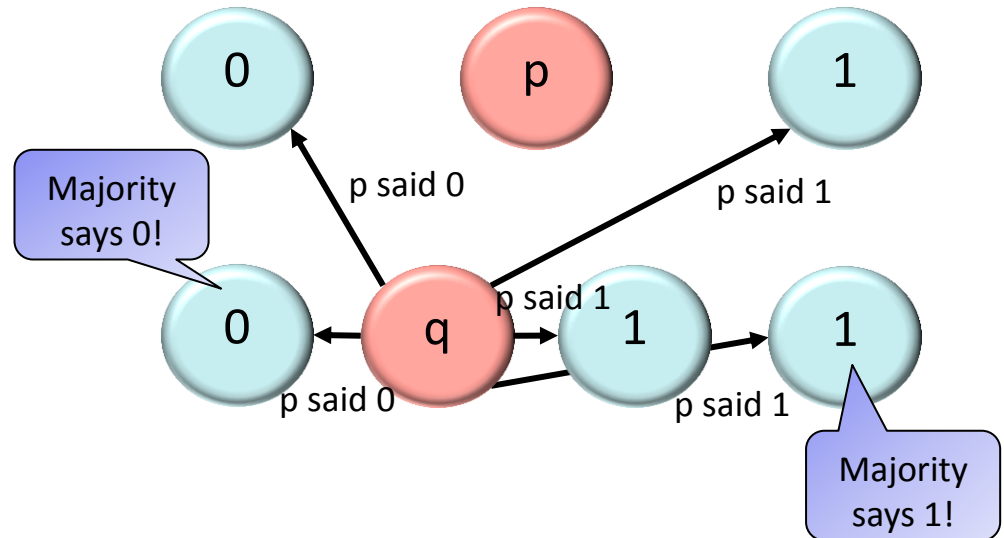
# A Simple Algorithm for Byzantine Agreement

- Does this algorithm still work in general for any  $f$  and  $n > 3f$ ?
- The answer is no. Try  $f=2$  and  $n=7$ :

Round 1: Exchange all values



Round 2: Exchange the received info



- The problem is that q can say different things about what p sent to q!
- What is the solution to this problem?

# A Simple Algorithm for Byzantine Agreement

- The solution is simple: Again exchange all information!
- This way, the processes can learn that  $q$  gave inconsistent information about  $p \rightarrow q$  can be excluded, and also  $p$  if it also gave inconsistent information (about  $q$ ).
- If  $f=2$  and  $n > 6$ , consensus can be reached in 3 rounds!
- In fact, the algorithm

Exchange all information for  $f+1$  rounds

Ignore all processes that provided inconsistent information

Let all processes decide based on the same input

solves the problem for any  $f$  and any  $n > 3f$

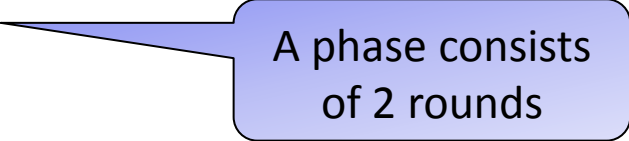
# A Simple Algorithm for Byzantine Agreement: Summary

- The proposed algorithm has several advantages:
  - + It works for any  $f$  and  $n > 3f$ , which is optimal
  - + It only takes  $f+1$  rounds. This is even optimal for crash failures!
  - + It works for any input and not just binary input
- However, it has some considerable disadvantages:
  - “Ignoring all processes that provided inconsistent information” is not easy to formalize
  - The size of the messages increases exponentially! This is a severe problem  
It is worth studying whether it is possible to solve the problem with small(er) messages



## Consensus #7: The Queen Algorithm

- The Queen algorithm is a simple Byzantine agreement algorithm that uses small messages
- The Queen algorithm solves consensus with  $n$  processes and  $f$  failures where  $f < n/4$  in  $f+1$  phases



A phase consists of 2 rounds

### Idea:

- There is a different (a priori known) queen in each phase
- Since there are  $f+1$  phases, in one phase the queen is not Byzantine
- Make sure that in this round all processes choose the same value and that in future rounds the processes do not change their values anymore

# The Queen Algorithm

In each phase  $i \in 1 \dots f+1$ :

At the end of phase  $f+1$ ,  
decide on own value

## Round 1:

Broadcast own value

Also send own  
value to oneself

Set own value to the value that was received most often

If own value appears  $> n/2+f$  times

support this value

else

do not support any value

If several values have  
the same (highest)  
frequency, choose any  
value, e.g., the smallest

## Round 2:

The queen broadcasts its value

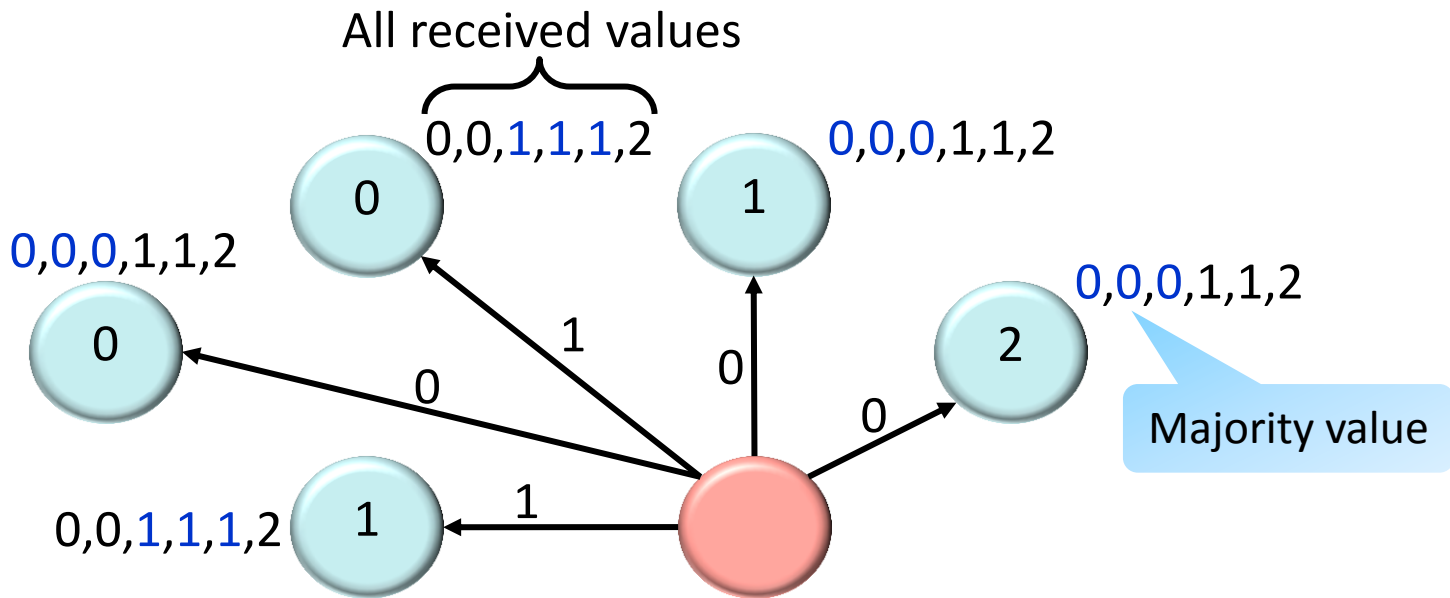
If not supporting any value

set own value to the queen's value

# The Queen Algorithm: Example

- Example:  $n = 6, f = 1$
- Phase 1, round 1 (All broadcast):

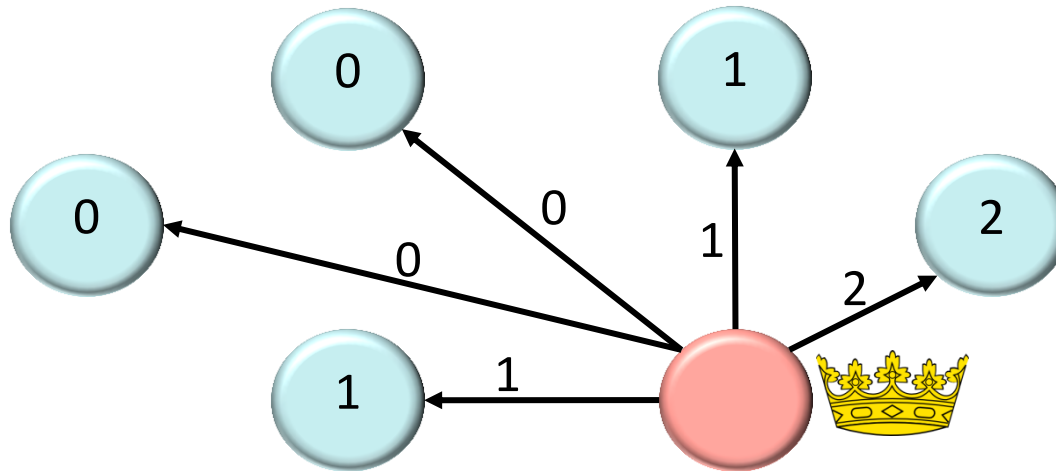
No process supports a value



# The Queen Algorithm: Example

- Phase 1, round 2 (Queen broadcasts):

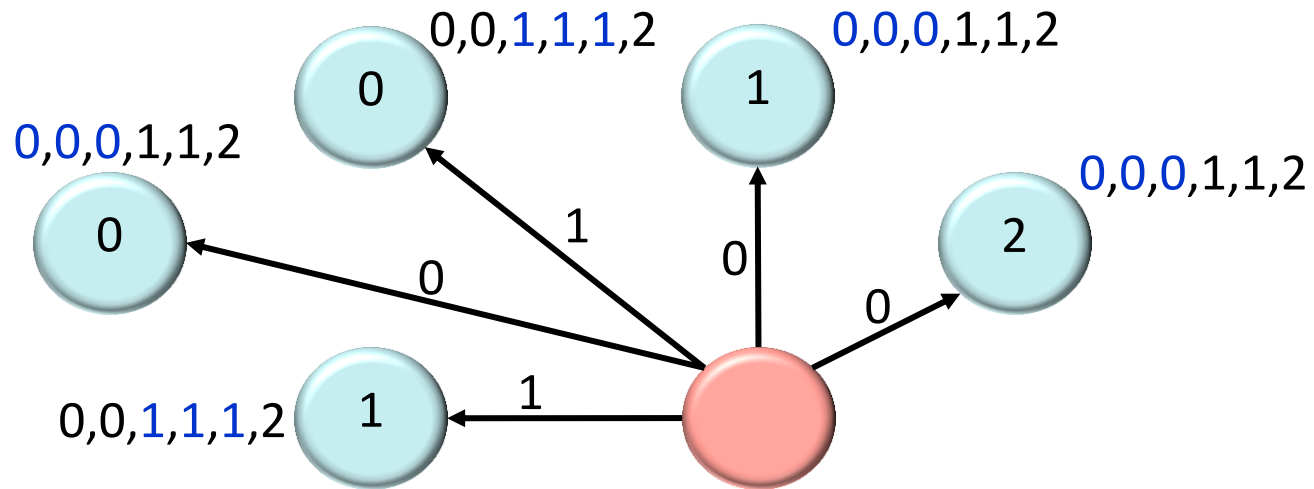
All processes choose the queen's value



# The Queen Algorithm: Example

- Phase 2, round 1 (All broadcast)

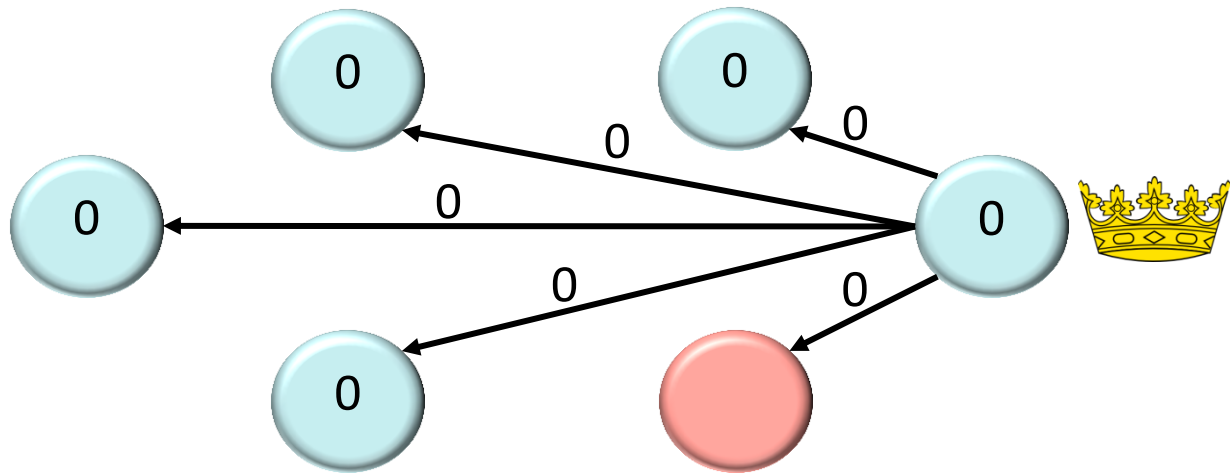
No process supports a value



# The Queen Algorithm: Example

- Phase 2, round 2 (Queen broadcasts):

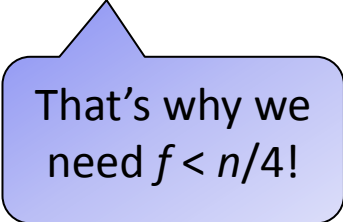
All processes choose the queen's value



Consensus!

# The Queen Algorithm: Analysis

- After the phase where the queen is correct, all correct processes have the same value
  - If all processes change their values to the queen's value, obviously all values are the same
  - If some process does not change its value to the queen's value, it received a value  $> n/2+f$  times  $\rightarrow$  All other correct processes (including the queen) received this value  $> n/2$  times and thus all correct processes share this value
- In all future phases, no process changes its value
  - In the first round of such a phase, processes receive their own value from at least  $n-f > n/2$  processes and thus do not change it
  - The processes do not accept the queen's proposal if it differs from their own value in the second round because the processes received their own value at least  $n-f > n/2+f$  times. Thus, all correct processes support the same value



That's why we need  $f < n/4$ !


# The Queen Algorithm: Summary

- The Queen algorithm has several advantages:
  - + The messages are small: processes only exchange their current values
  - + It works for any input and not just binary input
- However, it also has some disadvantages:
  - The algorithm requires  $f+1$  phases consisting of 2 rounds each  
This is twice as much as an optimal algorithm
  - It only works with  $f < n/4$  Byzantine processes!
- Is it possible to get an algorithm that works with  $f < n/3$  Byzantine processes and uses small messages?



## Consensus #8: The King Algorithm

- The King algorithm is an algorithm that tolerates  $f < n/3$  Byzantine failures and uses small messages
- The King algorithm also takes  $f+1$  phases



A phase now consists of 3 rounds

### Idea:

- The basic idea is the same as in the Queen algorithm
- There is a different (a priori known) king in each phase
- Since there are  $f+1$  phases, in one phase the king is not Byzantine
- The difference to the Queen algorithm is that the correct processes only propose a value if many processes have this value, and a value is only accepted if many processes propose this value

# The King Algorithm

In each phase  $i \in 1 \dots f+1$ :

At the end of phase  $f+1$ ,  
decide on own value

Round 1:

Broadcast own value

Also send own  
value to oneself

Round 2:

If some value  $x$  appears  $\geq n-f$  times

Broadcast "Propose  $x$ "

If some proposal received  $> f$  times

Set own value to this proposal

Round 3:

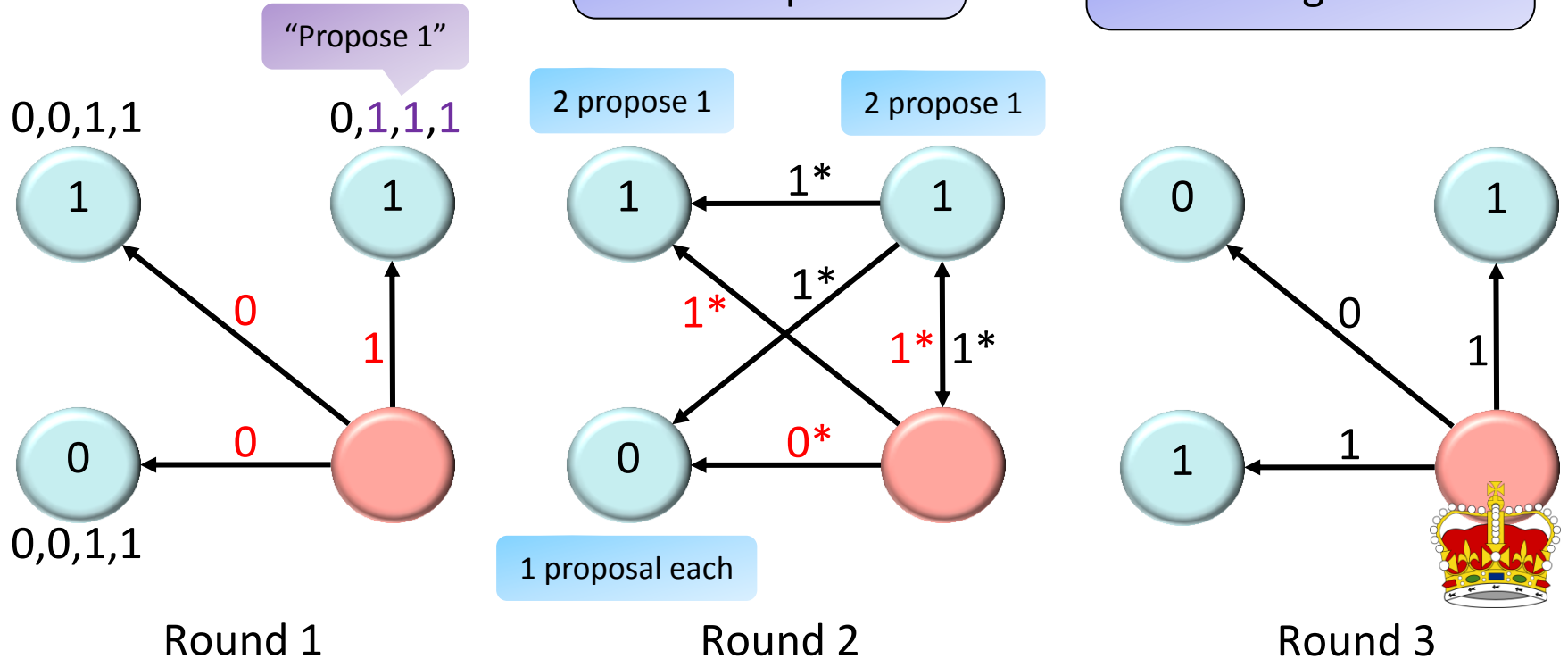
The king broadcasts its value

If own value received  $< n-f$  proposals

Set own value to the king's value

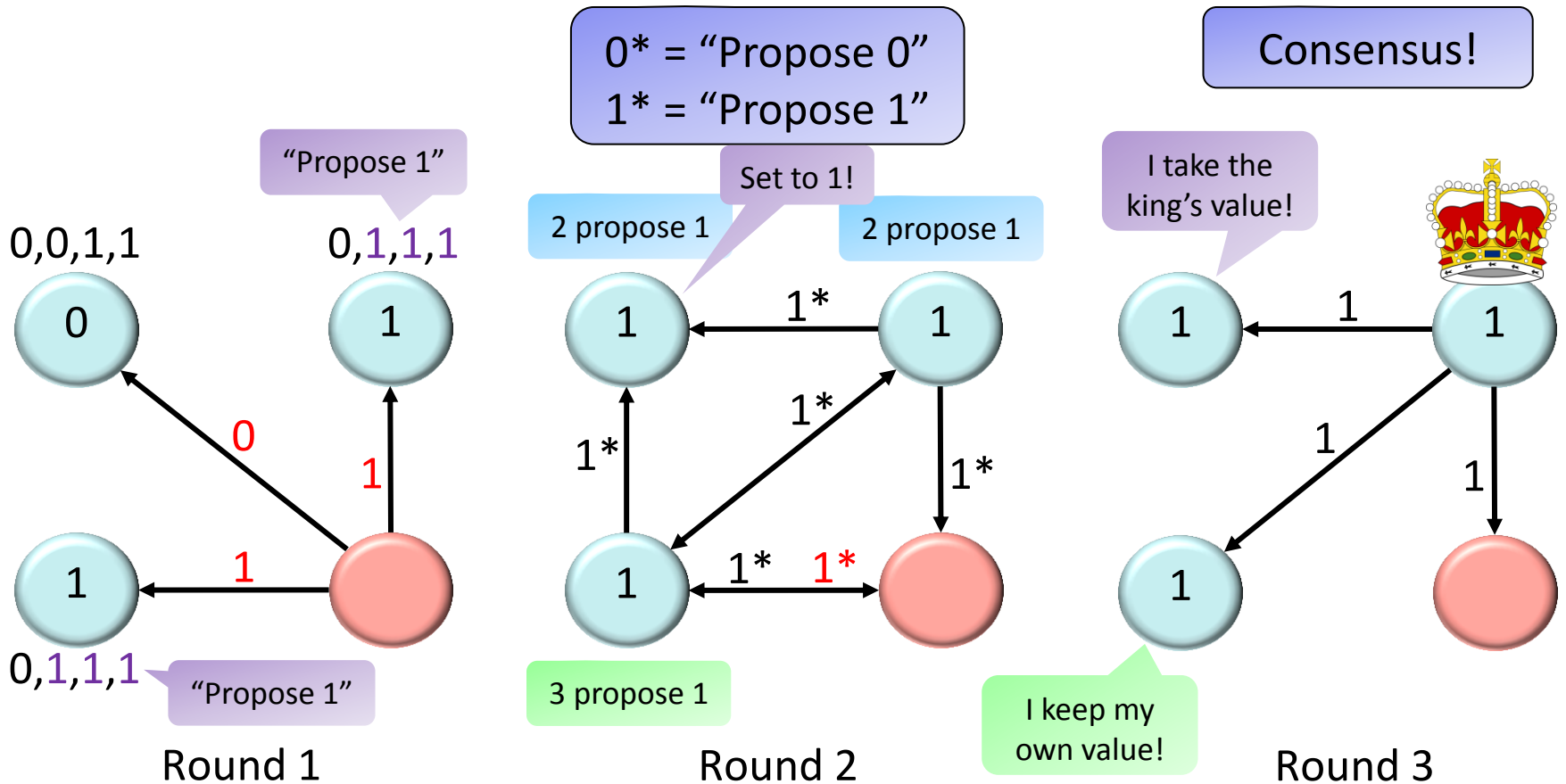
# The King Algorithm: Example

- Example:  $n = 4, f=1$
- Phase 1:




# The King Algorithm: Example

- Example:  $n = 4, f = 1$
- Phase 2:



# The King Algorithm: Analysis

- Observation: If some correct process proposes  $x$ , then no other correct process proposes  $y \neq x$ 
  - Both processes would have to receive  $\geq n-f$  times the same value, i.e., both processes received their value from  $\geq n-2f$  distinct correct processes
  - In total, there must be  $\geq 2(n-2f) + f > n$  processes, a contradiction!
- The validity condition is satisfied
  - If all correct processes start with the same value, all correct processes receive this value  $\geq n-f$  times and propose it
  - All correct processes receive  $\geq n-f$  times proposals, i.e., no correct process will ever change its value to the king's value



We used  
that  $f < n/3$ !

# The King Algorithm: Analysis

- After the phase where the king is correct, all correct processes have the same value
  - If all processes change their values to the king's value, obviously all values are the same
  - If some process does not change its value to the king's value, it received a proposal  $\geq n-f$  times  $\rightarrow \geq n-2f$  correct processes broadcast this proposal and all correct processes receive it  $\geq n-2f > f$  times  $\rightarrow$  All correct processes set their value to the proposed value. Note that only one value can be proposed  $> f$  times, which follows from the observation on the previous slide
- In all future phases, no process changes its value
  - This follows immediately from the fact that all correct processes have the same value after the phase where the king is correct and the validity condition

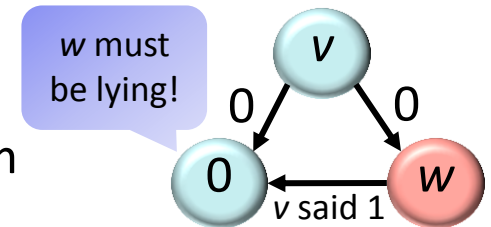
# The King Algorithm: Summary

- The King algorithm has several advantages:
  - + It works for any  $f$  and  $n > 3f$ , which is optimal
  - + The messages are small: processes only exchange their current values
  - + It works for any input and not just binary input
- However, it also has a disadvantage:
  - The algorithm requires  $f+1$  phases consisting of 3 rounds each  
This is three times as much as an optimal algorithm
- Is it possible to get an algorithm that uses small messages and requires fewer rounds of communication?

# Consensus #9: Byzantine Agreement Using Authentication

- A simple way to reach consensus is to use authenticated messages

- Unforgeability condition: If a process never sends a message  $m$ , then no correct process ever accepts  $m$



- Why is this condition helpful?
  - A Byzantine process cannot convince a correct process that some other correct processes voted for a certain value if they did not!
- **Idea:**
  - There is a designated process  $P$ . The goal is to decide on  $P$ 's value
  - For the sake of simplicity, we assume a binary input. The default value is 0, i.e., if  $P$  cannot convince the processes that  $P$ 's input is 1, everybody chooses 0



# Byzantine Agreement Using Authentication

If I am P and own input is 1

value := 1

broadcast "P has 1"

else

value := 0

In each round  $r \in 1 \dots f+1$ :

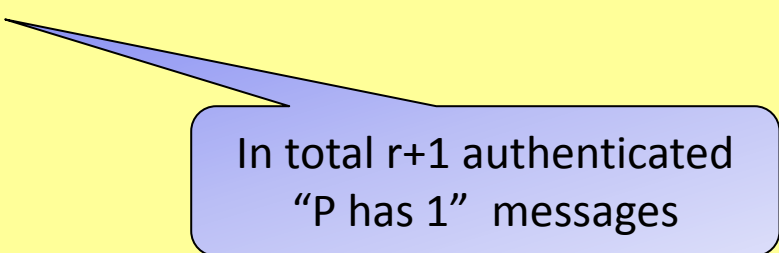
If value = 0 and accepted  $r$  messages "P has 1" in total including a message from P itself

value := 1

broadcast "P has 1" plus the  $r$  accepted messages that caused the local value to be set to 1

After  $f+1$  rounds:

Decide value



In total  $r+1$  authenticated  
"P has 1" messages

# Byzantine Agreement Using Authentication: Analysis

- Assume that P is correct
  - P's input is 1: All correct processes accept P's message in round 1 and set value to 1. No process ever changes its value back to 0
  - P's input is 0: P never sends a message "P has 1", thus no correct process ever sets its value to 1
- Assume that P is Byzantine
  - P tries to convince some correct processes that its input is 1
  - Assume that a correct process p sets its value to 1 in a round  $r < f+1$ :  
Process p has accepted  $r$  messages including the message from P. Therefore, all other correct processes accept the same  $r$  messages plus p's message and set their values to 1 as well in round  $r+1$
  - Assume that a correct process p sets its value to 1 in round  $f+1$ :  
In this case, p accepted  $f+1$  messages. At least one of those is sent by a correct process, which must have set its value to 1 in an earlier round. We are again in the previous case, i.e., all correct processes decide 1!

# Byzantine Agreement Using Authentication: Summary

- Using authenticated messages has several advantages:
  - + It works for any number of Byzantine processes!
  - + It only takes  $f+1$  rounds, which is optimal
  - + Small messages: processes send at most  $f+1$  “short” messages to all other processes in a single round
- However, it also has some disadvantages:
  - If  $P$  is Byzantine, the processes may agree on a value that is not in the original input
  - It only works for binary input
  - The algorithm requires authenticated messages...

sub-exponential length

# Byzantine Agreement Using Authentication: Improvements

- Can we modify the algorithm so that it satisfies the validity condition?
  - Yes! Run the algorithm in parallel for  $2f+1$  “masters”  $P$ . Either 0 or 1 occurs at least  $f+1$  times, i.e., at least one correct process had this value. Decide on this value!
  - Alas, this modified protocol only works if  $f < n/2$
- Can we modify the algorithm so that it also works with an arbitrary input?
  - Yes! In fact, the algorithm does not have to be changed much
  - We won’t discuss this modification in class
- Can we get rid of the authentication?
  - Yes! Use *consistent-broadcast*. This technique is not discussed either
  - This modified protocol works if  $f < n/3$ , which is optimal
  - However, each round is split into two
    - The total number of rounds is  $2f+2$

# Consensus #10: A Randomized Algorithm

- So far we mainly tried to reach consensus in *synchronous* systems. The reason is that no deterministic algorithm can guarantee consensus in asynchronous systems even if only one process may crash

Synchronous system:  
Communication proceeds  
in synchronous rounds

- Can one solve consensus in *asynchronous* systems if we allow our algorithms to use randomization?

Asynchronous system:  
Messages are delayed  
indefinitely

- The answer is yes!
- The basic idea of the algorithm is to push the initial value. If other processes do not follow, try to push one of the suggested values randomly
- For the sake of simplicity, we assume that the input is binary and at most  $f < n/9$  processes are Byzantine

# Randomized Algorithm

$x :=$  own input;  $r := 0$   
Broadcast proposal( $x, r$ )

In each round  $r = 1, 2, \dots$ :

Wait for  $n-f$  proposals

If at least  $n-2f$  proposals have some value  $y$

$x := y$ ; decide on  $y$

else if at least  $n-4f$  proposals have some value  $y$

$x := y$ ;

else

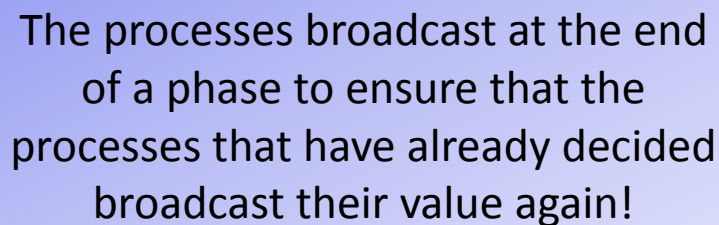
choose  $x$  randomly with  $P[x=0] = P[x=1] = \frac{1}{2}$

Broadcast proposal( $x, r$ )

If decided on a value  $\rightarrow$  stop

# Randomized Algorithm: Analysis

- Validity condition (If all have the same input, all choose this value)
  - If all correct processes have the same initial value  $x$ , they will receive  $n-2f$  proposals containing  $x$  in the first round and they will decide on  $x$
- Agreement (if the processes decide, they agree on the same value)
  - Assume that some correct process decides on  $x$ . This process must have received  $x$  from  $n-3f$  correct processes. Every other correct process must have received  $x$  at least  $n-4f$  times, i.e., all correct processes set their local value to  $x$ , and propose and decide on  $x$  in the next round



The processes broadcast at the end of a phase to ensure that the processes that have already decided broadcast their value again!

# Randomized Algorithm: Analysis

- Termination (all correct processes eventually decide)
  - If some processes do not set their local value randomly, they set their local value to the same value. Proof: Assume that some processes set their value to 0 and some others to 1, i.e., there are  $\geq n-5f$  correct processes proposing 0 and  $\geq n-5f$  correct processes proposing 1.  
In total there are  $\geq 2(n-5f) + f > n$  processes. Contradiction!

That's why we need  $f < n/9$ !

- Thus, in the worst case all  $n-f$  correct processes need to choose the same bit randomly, which happens with probability  $(\frac{1}{2})^{(n-f)}$
  - Hence, all correct processes eventually decide. The expected running time is smaller than  $2^n$
- The running time is awfully slow. Is there a clever way to speed up the algorithm?
- What about simply setting  $x:=1$ ?! (Why doesn't it work?)



# Can we do this faster?! Yes, with a Shared Coin

- A better idea is to replace

choose  $x$  randomly with  $P[x=0] = P[x=1] = \frac{1}{2}$

with a subroutine in which all the processes compute a so-called shared (a.k.a. common, “global”) coin

- A shared coin is a random binary variable that is 0 with constant probability, and 1 with constant probability
- For the sake of simplicity, we assume that there are at most  $f < n/3$  crash failures (no Byzantine failures!!!)



All correct processes know the outcome of the shared coin toss after each execution of the subroutine

# Shared Coin Algorithm

Code for process  $i$ :

Set local coin  $c_i := 0$  with probability  $1/n$ , else  $c_i := 1$

Broadcast  $c_i$

Wait for exactly  $n-f$  coins and collect all coins in the local coin set  $s_i$

Broadcast  $s_i$

Wait for exactly  $n-f$  coin sets

If at least one coin is 0 among all coins in the coin sets

    return 0

else

    return 1

Assume the worst case:  
Choose  $f$  so that  $3f+1 = n$ !

# Shared Coin: Analysis

- Termination (of the subroutine)
  - All correct processes broadcast their coins. It follows that all correct processes receive at least  $n-f$  coins
  - All correct processes broadcast their coin sets. It follows that all correct processes receive at least  $n-f$  coin sets and the subroutine terminates
- We will now show that at least  $1/3$  of all coins are **seen** by everybody

A coin is *seen* if it is in at least one received coin set

- More precisely: We will show that at least  $f+1$  coins are in at least  $f+1$  coin sets
  - Recall that  $3f+1 = n$ , therefore  $f+1 > n/3$
  - Since these coins are in at least  $f+1$  coin sets and all processes receive  $n-f$  coin sets, all correct processes see these coins!




# Shared Coin: Analysis

- Proof that at least  $f+1$  coins are in at least  $f+1$  coin sets
  - Draw the coin sets and the contained coins as a matrix
  - Example:  $n=7$ ,  $f=2$

x means coin  $c_i$  is in set  $s_j$

	$s_1$	$s_3$	$s_5$	$s_6$	$s_7$
$c_1$	x	x	x	x	x
$c_2$		x	x		
$c_3$	x	x	x	x	x
$c_4$		x	x		x
$c_5$	x			x	
$c_6$	x		x	x	x
$c_7$	x	x		x	x

# Shared Coin: Analysis

- At least  $f+1$  rows (coins) have at least  $f+1$  x's (are in at least  $f+1$  coin sets)
  - First, there are exactly  $(n-f)^2$  x's in this matrix
  - Assume that the statement is wrong: Then at most  $f$  rows may be full and contain  $n-f$  x's. And all other rows (at most  $n-f$ ) have at most  $f$  x's
  - Thus, in total we have at most  $f(n-f) + (n-f)f = 2f(n-f)$  x's
  - But  $2f(n-f) < (n-f)^2$  because  $2f < n-f$  

Here we use  $3f < n$

	$S_1$	$S_3$	$S_5$	$S_6$	$S_7$
$C_1$	X	X	X	X	X
$C_2$		X	X		
$C_3$	X	X	X	X	X
$C_4$		X	X		X
$C_5$	X			X	
$C_6$	X		X	X	X
$C_7$	X	X		X	X

# Shared Coin: Theorem

## Theorem

All processes decide 0 with constant probability, and all processes decide 1 with constant probability

## Proof:

- With probability  $(1-1/n)^n \approx 1/e \approx 0.37$  all processes choose 1. Thus, all correct processes return 1
- There are at least  $f+1 \approx n/3$  coins seen by all correct processes. The probability that at least one of these coins is set to 0 is at least  $1-(1-1/n)^{n/3} \approx 1-(1/e)^{1/3} \approx 0.28$

## Back to Randomized Consensus

- If this shared coin subroutine is used, there is a constant probability that the processes agree on a value
- Some nodes may not want to perform the subroutine because they received the same value  $x$  at least  $n-4f$  times. However, there is also a constant probability that the result of the shared coin toss is  $x$ !
- Of course, all nodes must take part in the execution of the subroutine
- This randomized algorithm terminates in a constant number of rounds (in expectation)!

# Randomized Algorithm: Summary

- The randomized algorithm has several advantages:
  - + It only takes a constant number of rounds in expectation
  - + It can handle crash failures even if communication is asynchronous
- However, it also has some disadvantages:
  - It works only if there are  $f < n/9$  crash failures. It doesn't work if there are Byzantine processes
  - It only works for binary input
- Can it be improved?
  - There is a constant expected time algorithm that tolerates  $f < n/2$  crash failures
  - There is a constant expected time algorithm that tolerates  $f < n/3$  Byzantine failures

There are similar algorithms for the shared memory model



# Message Complexity

- In all of the previously discussed message passing algorithms, each (good) node broadcasts. Message complexity is  $\Omega(n^2)$ .
- “The communication overhead of Byzantine Agreement is inherently large” (Cheng et al. 2009)
- Can the message complexity be improved?
  - + Yes!
  - + Byzantine Agreement can be solved in a synchronous environment with  $\tilde{O}(n\sqrt{n})$  messages.
  - Requires polylogarithmic time.

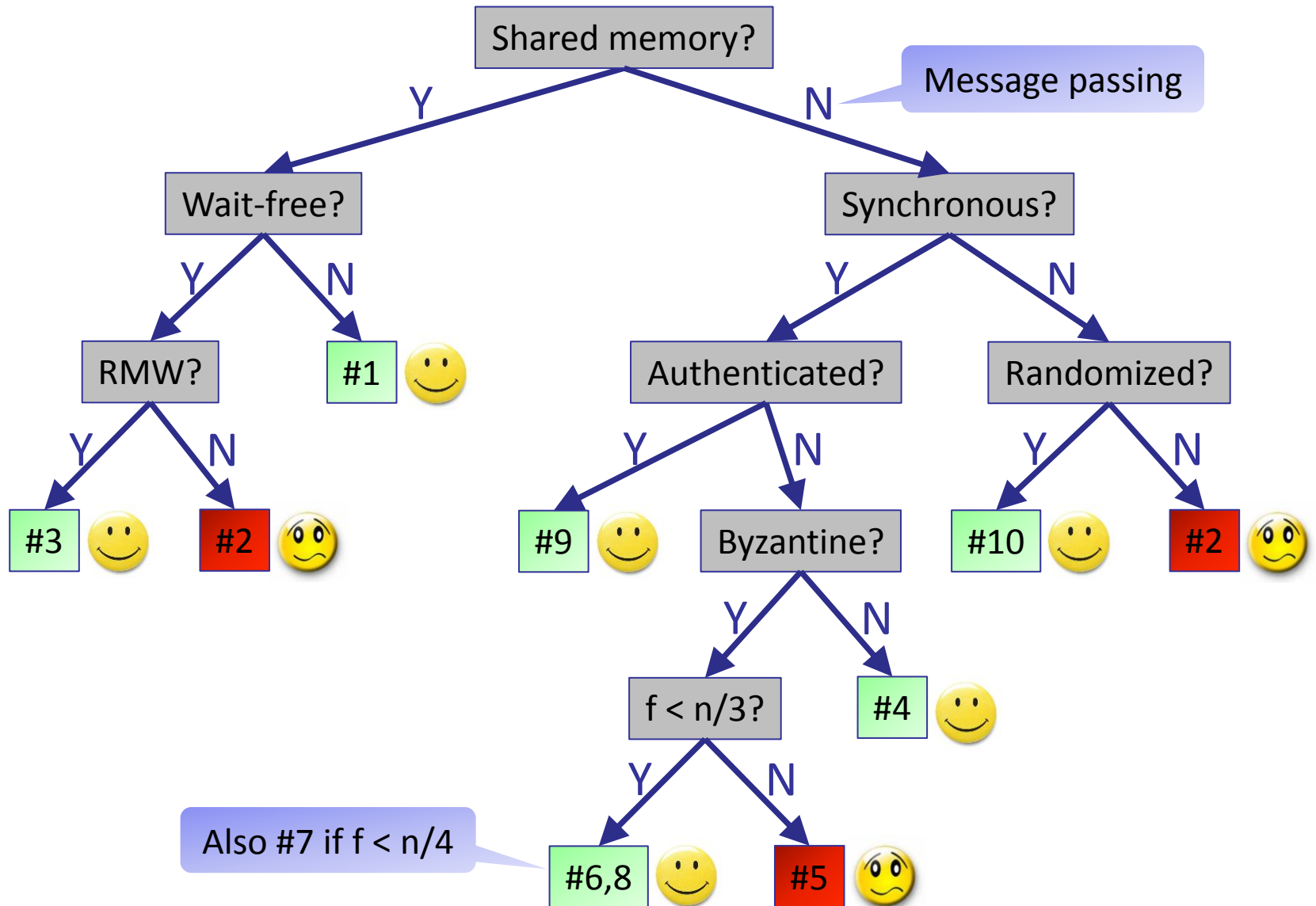
# Byzantine AND Asynchronous?

- Are there algorithms that can solve Byzantine agreement in an asynchronous environment?
- + Yes, there are.
- However, the solution comes with a cost. The fraction of nodes that can be Byzantine decreases to  $1/35715$ . Also, the expected message complexity of the state of the art algorithm is  $O(n^3)$ .
- + Message sizes remain polynomial.
- + The algorithm does not use a global coin, but tries to detect (biased) local coinflips from Byzantine processes.

# Summary

- We have solved consensus in a variety of models
- In particular we have seen
  - algorithms
  - wrong algorithms
  - lower bounds
  - impossibility results
  - reductions
  - etc.
- In the next part, we will discuss fault-tolerance in practice

# Consensus: Decision Tree



# Credits

- The impossibility result (#2) is from Fischer, Lynch, Patterson, 1985
- The hierarchy (#3) is from Herlihy, 1991.
- The synchronous studies (#4) are from Dolev and Strong, 1983, and others.
- The Byzantine agreement problem (#5) and the simple algorithm (#6) are from Lamport, Shostak, Pease, 1980ff., and others
- The Queen algorithm (#7) and the King algorithm (#8) are from Berman, Garay, and Perry, 1989.
- The algorithm using authentication (#9) is due to Dolev and Strong, 1982.
- The first randomized algorithm (#10) is from Ben-Or, 1983.
- The concept of a shared coin was introduced by Bracha, 1984.
- Byzantine Agreement with less than  $n^2$  messages is from King and Saia 2011.
- Byzantine Agreement in an asynchronous setting is from King and Saia 2013.

# *That's all, folks!*

*Questions & Comments?*



*Roger Wattenhofer*