

# The Limitations of Registers

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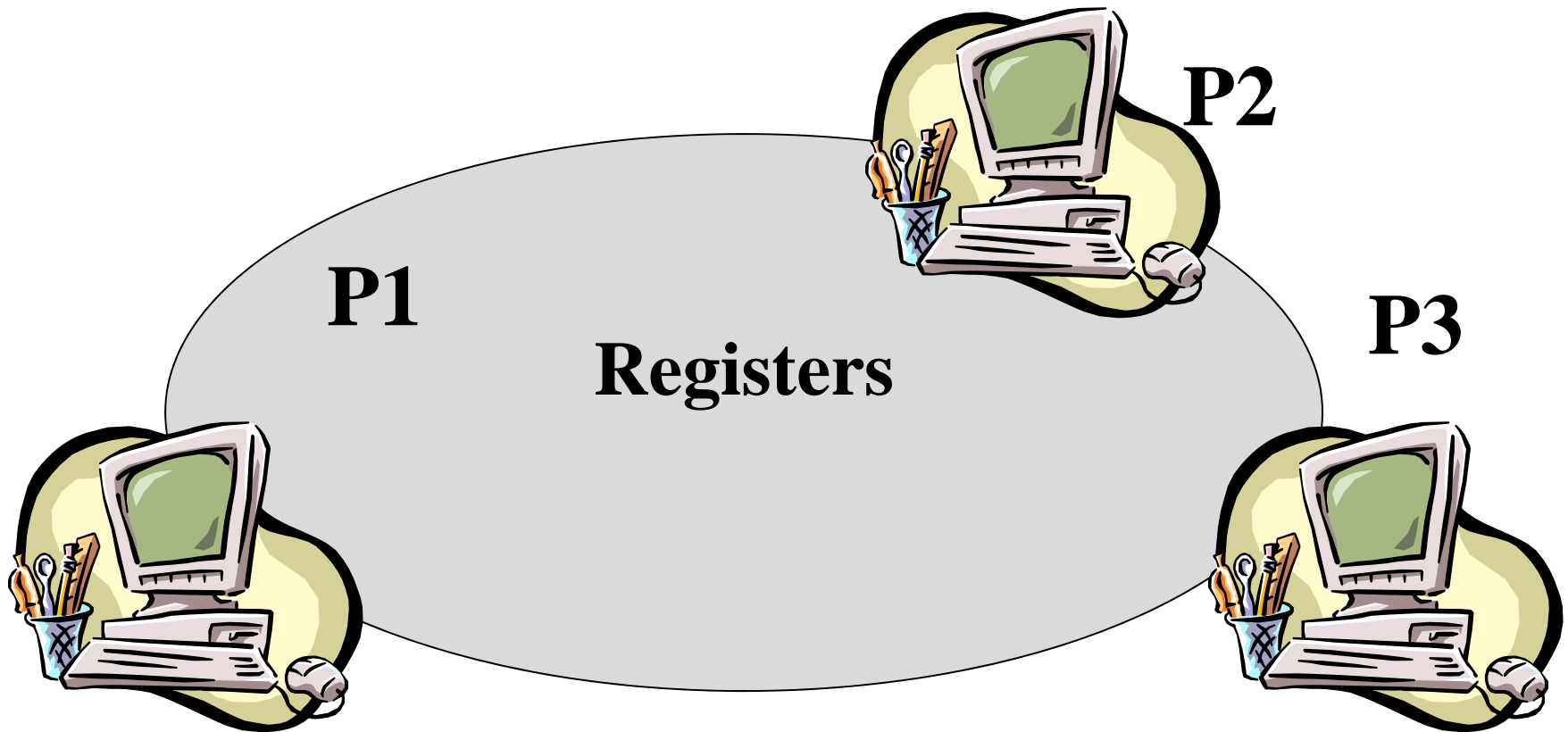
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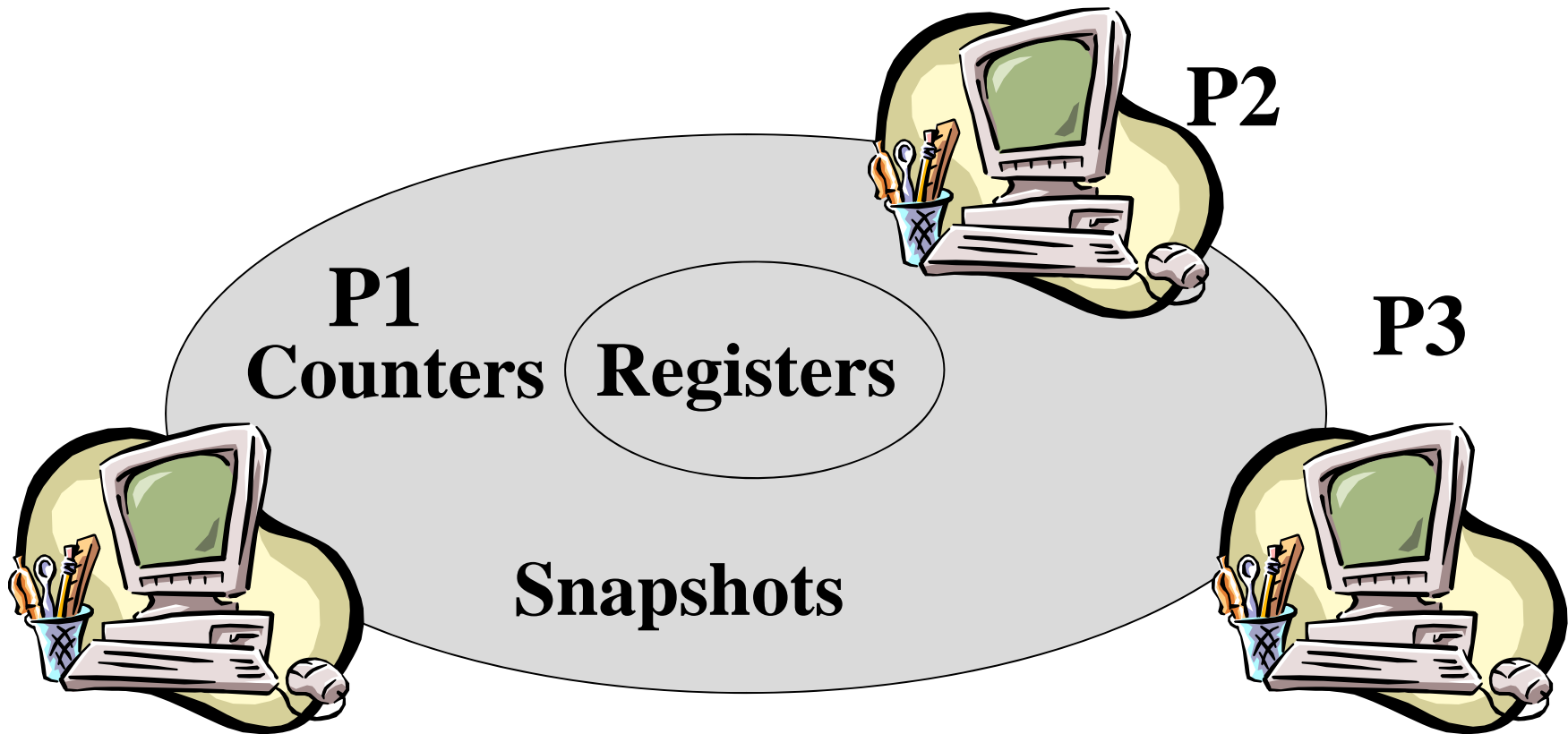
# Registers

- ***Question 1:*** what objects can we implement with registers? ***Counters*** and ***snapshots*** (previous lecture)
- ***Question 2:*** what objects we cannot implement? (this lecture)

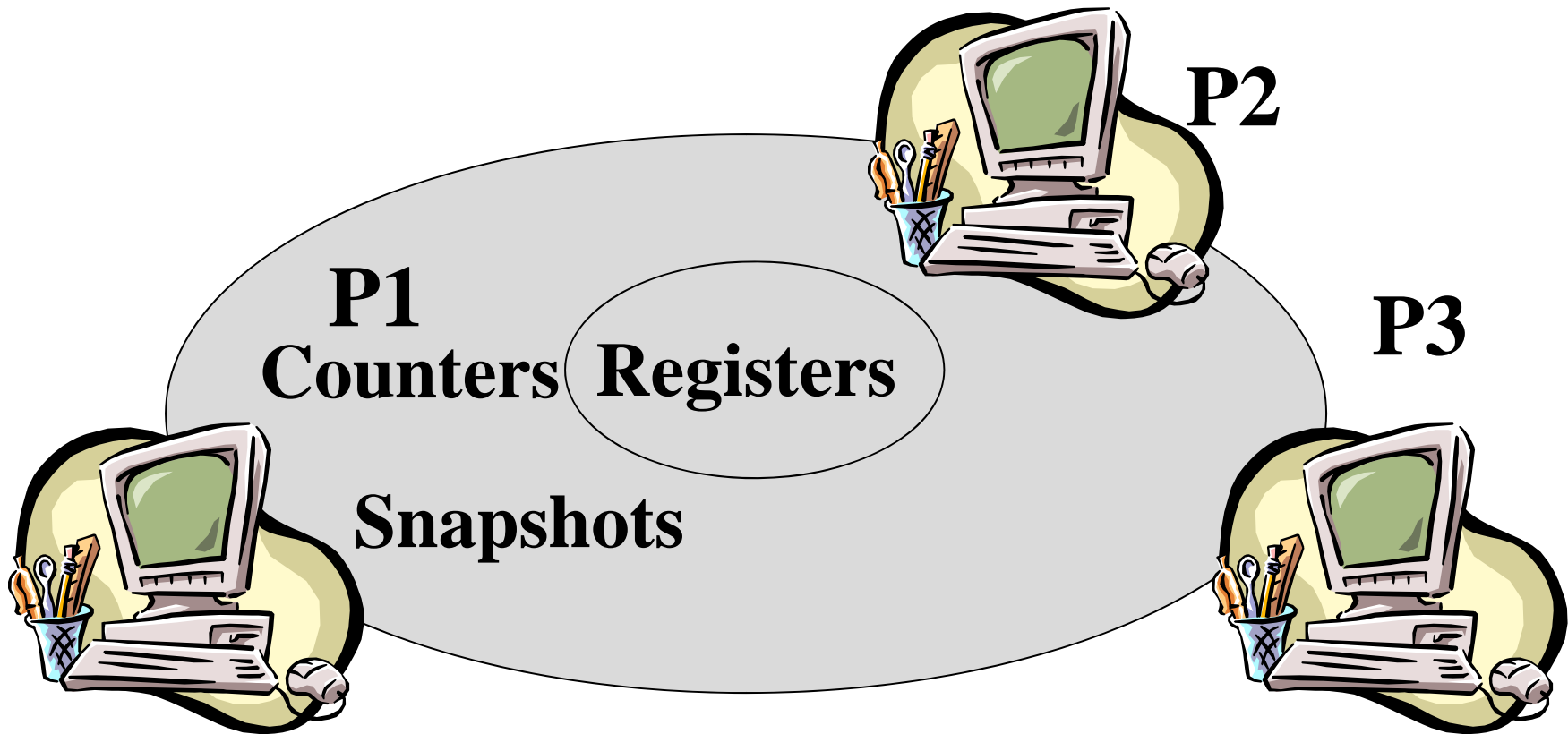
# Shared memory model



# Shared memory model



# Shared memory model



# Queue

- The queue is an object container with two operations: ***enq()*** and ***deq()***
- Can we implement a (atomic wait-free) ***queue***?

# The consensus object

- One operation ***propose()*** which returns a value.  
When a ***propose()*** operation returns, we say that the process *decides*
- No two processes decide differently
- Every decided value is a proposed value

# The consensus object

- **Proposition:**
  - ✓ **Consensus** can be implemented among two processes with **queues** and **registers**
- Proof (algorithm): consider two processes p0 and p1, two **registers** R0 and R1 and a **queue** Q.

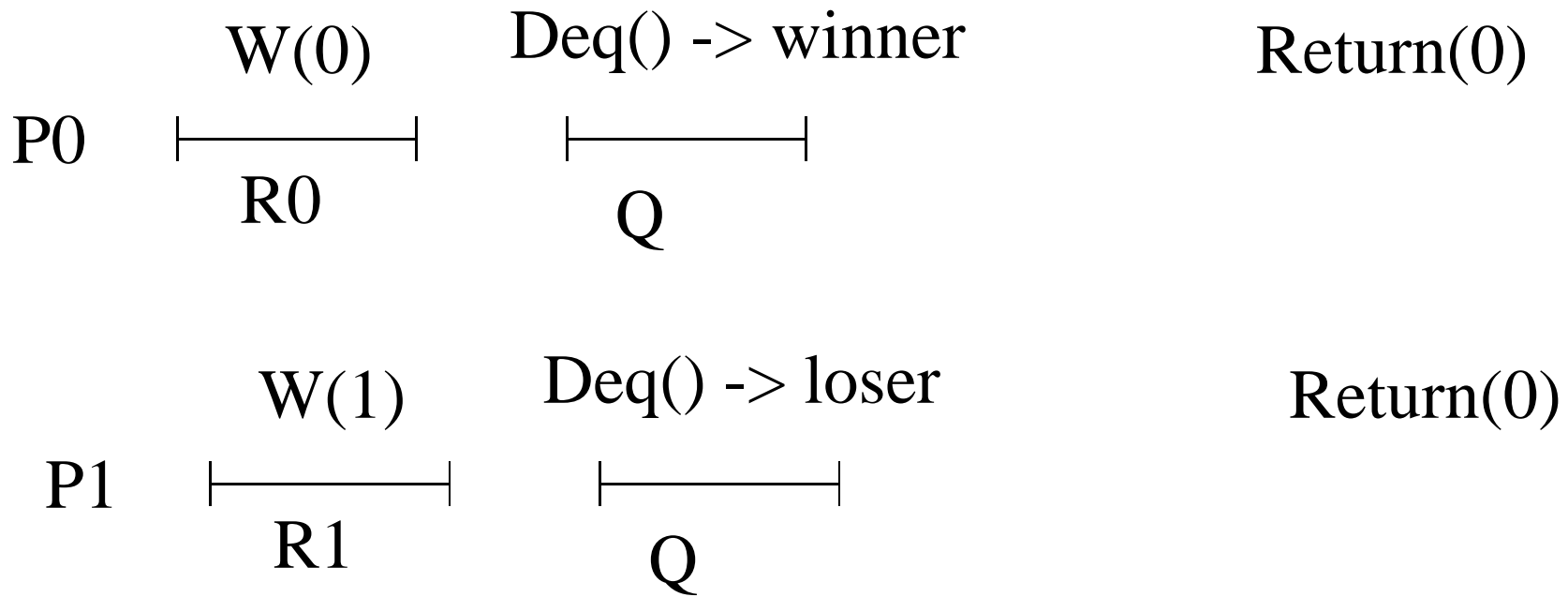


## 2-Consensus with queues

Uses two registers R0 and R1, and a queue Q  
Q is initialized to {winner, loser}

Process p<sub>l</sub>:

```
propose(vl)  
  Rl.write(vl)  
  item := Q.dequeue()  
  if item = winner return(vl)  
  return(R{1-l}.read())
```

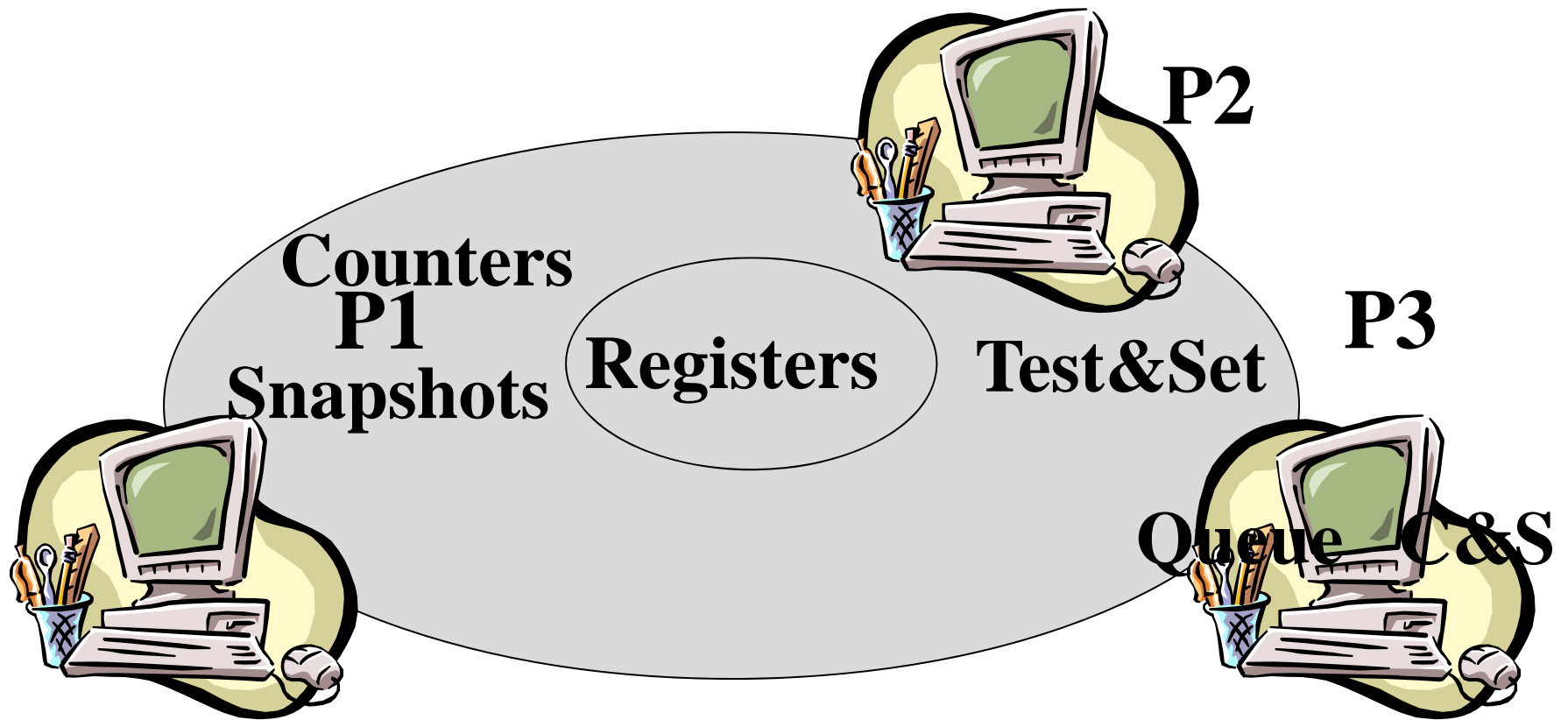


# Correctness

Proof (algorithm):

- (wait-freedom) by the assumption of a wait-free register and a wait-free queue plus the fact that the algorithm does not contain any wait statement
- (validity) If  $p_I$  dequeues winner, it decides on its own proposed value. If  $p_I$  dequeues loser, then the other process  $p_J$  dequeued winner before. By the algorithm,  $p_J$  has previously written its input value in  $R_J$ . Thus,  $p_I$  decides on  $p_J$ 's proposed value;
- (agreement) if the two processes decide, they decide on the value written in the same register.

# Shared memory model



## 2-Consensus with Fetch&Inc

- Uses two registers R0 and R1, and a Fetch&Inc object C (with one `fetch&inc()` operation that returns its value)
- (NB. The value in C is initialized to 0)

- Process  $p_l$ :

- **propose(vl)**
- **Rl.write(vl)**
- **val := C.fetch&inc()**
- **if(val = 1) then**
  - ✓ **return(vl)**
  - **else return(R{1-l}.read())**

# More consensus implementations

- A **Test&Set** object maintains binary values  $x$  and  $y$ , init to 0; it provides one operation: **test&set()**
  - ✓ Sequential spec:
  - ✓ `test&set() {y := x; x := 1; return(y);}`
- A **Compare&Swap** object maintains a value  $x$ , init to  $\perp$ , and provides one operation: **compare&swap(v,w)**:
  - ✓ Sequential spec:
    - `c&s(old,new) {temp = x; if x = old then x := new; return(temp)}`

# 2-Consensus with Test&Set

- Uses two registers R0 and R1, and a Test&Set object T

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- Process  $p_l$ :

- **propose(v<sub>l</sub>)**
- **R<sub>l</sub>.write(v<sub>l</sub>)**
- **val := T.test&set()**
- **if(val = 0) then**
  - ✓ **return(v<sub>l</sub>)**
  - else return(R<sub>{1-l}</sub>.read())**

# N-Consensus with C&S

- Uses a C&S object C

- 

- Process  $p_i$ :

- **propose(v<sub>i</sub>)**
- **val := C.c&s( $\perp$ , v<sub>i</sub>)**
- **if(val =  $\perp$ ) then**
  - ✓ **return(v<sub>i</sub>)**
  - **else return(val)**



# Impossibility [FLP85,LA87]

- **Proposition:** there is no algorithm that implements **consensus** among two processes using only **registers**
- **Corollary:** there is no algorithm that implements a **queue** (**Fetch&Inc**, **Test&Set** or **C&S**) among two processes using only **registers**

# Registers

- ***Question 1:*** what objects can we implement with registers? ***Counters*** and ***snapshots*** (previous lecture)
- ***Question 2:*** what objects we cannot implement? All objects that (together with ***registers***) can implement ***consensus*** (this lecture)

# Impossibility (Proof)

- **Proposition:** there is no algorithm that implements **consensus** among two processes using only **registers**
- Proof (by contradiction): consider two processes  $p_0$  and  $p_1$  and any number of **registers**,  $R_1..R_k..$   
Assume that a consensus algorithm  $A$  for  $p_0$  and  $p_1$  exists.

# Elements of the model

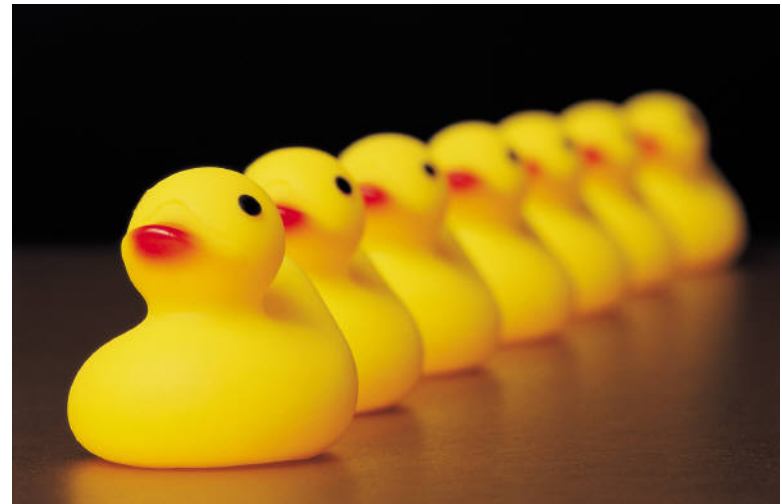
- A **configuration** is a global state of the distributed system
- A new configuration is obtained by executing a **step** on a previous configuration: the step is the unit of execution

# What is distributed computing?

## A game



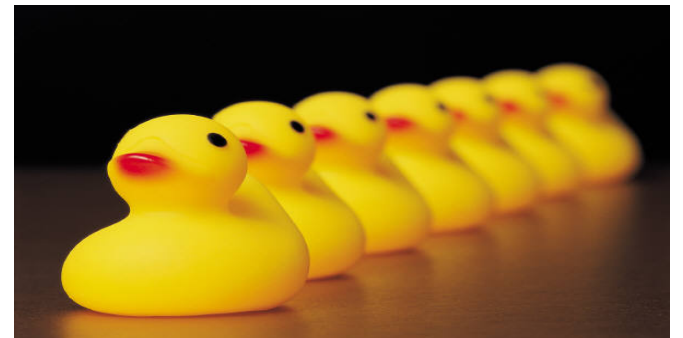
# A game between an adversary and a set of processes



The adversary decides which process goes next



The processes take steps



# Elements of the model

- The adversary decides which process executes the next step and the algorithm deterministically decides the next configuration based on the current one



# Elements of the model

- ***Schedule:*** a sequence of steps represented by process ids
- The schedule is chosen by the system
- An asynchronous system is one with no constraint on the schedules: any sequence of process ids is a schedule

# Consensus

- The algorithm must ensure that *agreement* and *validity* are satisfied in every schedule
- Every process that executes an infinite number of steps eventually decides

# Impossibility (elements)

- (1) a (initial) **configuration**  $C$  is a set of (initial) values of  $p_0$  and  $p_1$  together with the values of the registers:  $R_1..R_k,..$ ;
- (2) a **step** is an elementary action executed by some process  $p_i$ : it consists in reading or writing a value in a register and changing  $p_i$ 's state according to the algorithm  $A$ ;
- (3) a **schedule**  $S$  is a sequence of steps;  $S(C)$  denotes the configuration that results from applying  $S$  to  $C$ .

# Impossibility (elements)

- Consider  $u$  to be 0 or 1; a configuration  $C$  is ***u-valent*** if, starting from  $C$ , no matter how the processes behave, no decision other than  $u$  is possible
- We say that the configuration is ***univalent***. Otherwise, the configuration is called ***bivalent***

P0(0)       $\frac{W(X)}{RI}$        $\frac{R()-> Y}{RJ}$       Return(0)

P1(0)       $\frac{W(Z)}{RK}$        $\frac{W(V)}{RL}$       Return(0)

	$W(X)$	$R() \rightarrow Y$	$\text{Return}(1)$
$P0(1)$	$\frac{\quad}{RI}$	$\frac{\quad}{RJ}$	

	$W(Z)$	$W(V)$	$\text{Return}(1)$
$P1(1)$	$\frac{\quad}{RK}$	$\frac{\quad}{RL}$	

	W(X)	R()-> Y	
P0(1)	-----	-----	Return(1/0)
	RI	RJ	

	W(Z)	W(V)	
P1(0)	-----	-----	Return(1/0)
	RK	RL	

# Impossibility (structure)

- ***Lemma 1:*** there is at least one initial ***bivalent*** configuration
- ***Lemma 2:*** given any bivalent configuration  $C$ , there is an ***arbitrarily long schedule***  $S(C)$  that leads to another bivalent configuration



# The conclusion

- Lemmas 1 and 2 imply that there is a configuration  $C$  and an *infinite* schedule  $S$  such that, for any prefix  $S'$  of  $S$ ,  $S'(C)$  is bivalent.
- In infinite schedule  $S$ , at least one process executes an infinite number of steps and does not decide
- A contradiction with the assumption that  $A$  implements consensus.

# Lemma 1

**The initial configuration  $C(0,1)$  is bivalent**

**Proof: consider  $C(0,0)$  and  $p_1$  not taking any step:  $p_0$  decides 0;  $p_0$  cannot distinguish  $C(0,0)$  from  $C(0,1)$  and can hence decide 0 starting from  $C(0,1)$ ; similarly, if we consider  $C(1,1)$  and  $p_0$  not taking any step,  $p_1$  eventually decides 1;  $p_1$  cannot distinguish  $C(1,1)$  from  $C(0,1)$  and can hence decide 1 starting from  $C(0,1)$ . Hence the bivalency.**

# Lemma 2

**Lemma 2:** Given any bivalent configuration  $C$ , there is an arbitrarily long schedule  $S$  such that  $S(C)$  is bivalent

**Proof** (by contradiction): let  $S$  be the schedule with the maximal length such as  $D = S(C)$  is bivalent;  $p_0(D)$  and  $p_1(D)$  are both univalent: one of them is 0-valent (say  $p_0(D)$ ) and the other is 1-valent (say  $p_1(D)$ )

# Lemma 2

- Proof (cont'd): To go from  $D$  to  $p_0(D)$  (vs  $p_1(D)$ )  $p_0$  (vs  $p_1$ ) accesses a register; the register must be the same in both cases; otherwise  $p_1(p_0(D))$  is the same as  $p_0(p_1(D))$ : in contradiction with the very fact that  $p_0(D)$  is 0-valent whereas  $p_1(D)$  is 1-valent

# Lemma 2

- Proof (cont'd): To go from  $D$  to  $p_0(D)$ ,  $p_0$  cannot read  $R$ ; otherwise  $R$  has the same state in  $D$  and in  $p_0(D)$ ; in this case, the registers and  $p_1$  have the same state in  $p_1(p_0(D))$  and  $p_1(D)$ ; if  $p_1$  is the only one executing steps, then  $p_1$  eventually decides 1 in both cases: a contradiction with the fact that  $p_0(D)$  is 0-valent; the same argument applies to show that  $p_1$  cannot read  $R$  to go from  $D$  to  $p_1(D)$

Thus both  $p_0$  and  $p_1$  write in  $R$  to go from  $D$  to  $p_0(D)$  (resp.,  $p_1(D)$ ). But then  $p_0(p_1(D)) = p_0(D)$  (resp.  $p_1(p_0(D)) = p_1(D)$ ) --- a contradiction.

## The conclusion (bis)

Lemmas 1 and 2 imply that there is a configuration  $C$  and an *infinite* schedule  $S$  such that, for any prefix  $S'$  of  $S$ ,  $S'(C)$  is bivalent.

In infinite schedule  $S$ , at least one process executes an infinite number of steps and does not decide

A contradiction with the assumption that  $A$  implements consensus.