Concepts of Concurrent Computation
Spring 2015
Lecture 4: Semaphores

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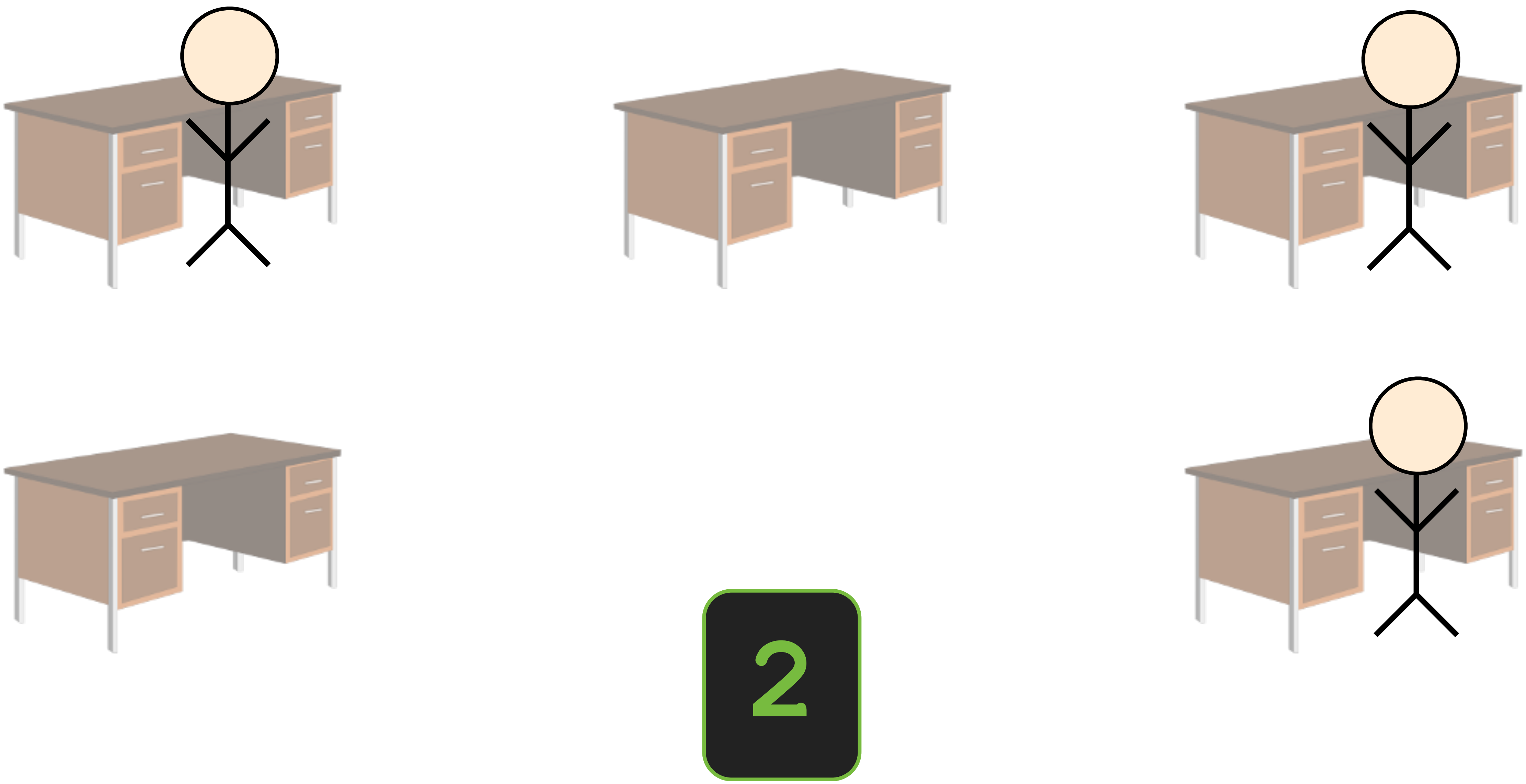
Last week: synchronisation, but lacking the simplicity

- we looked at various solutions to the mutual exclusion problem

- algorithms were limited to the simplest tools - atomic read and write to shared memory

  => *difficult to implement; complex*
  => *reliance on busy waiting*
  => *no encapsulation of synchronisation variables*

Short diversion: hot desks



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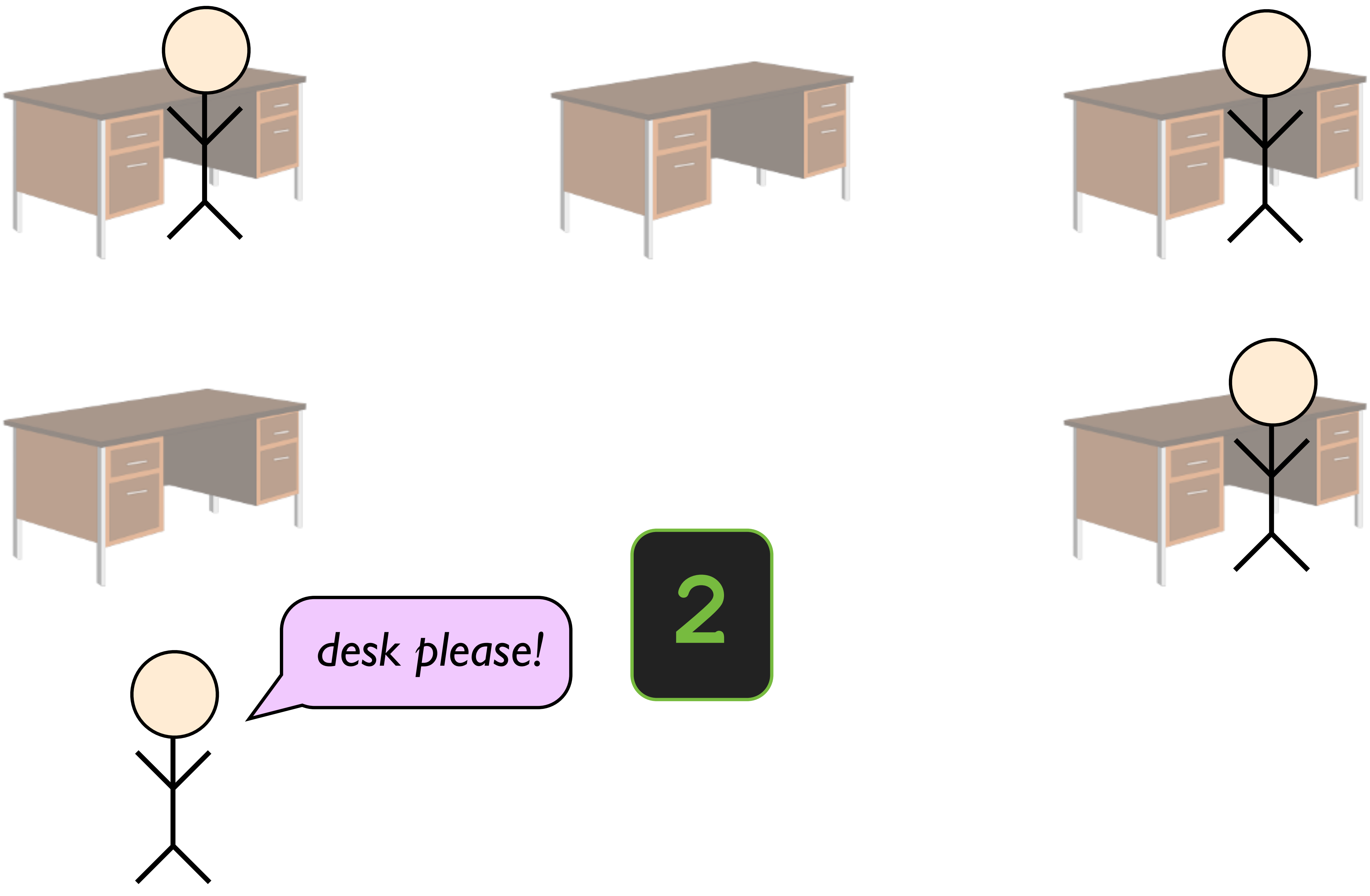

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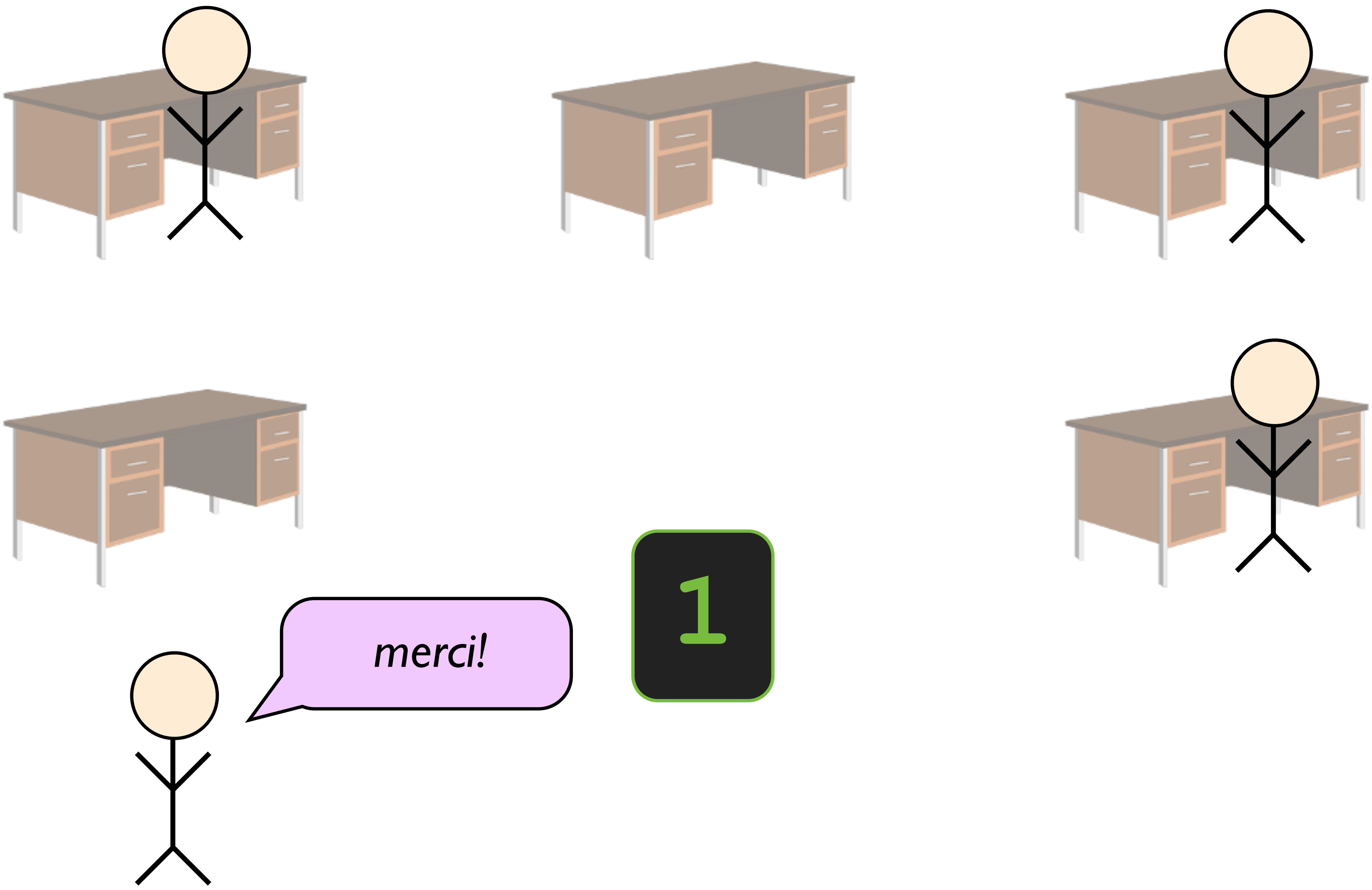

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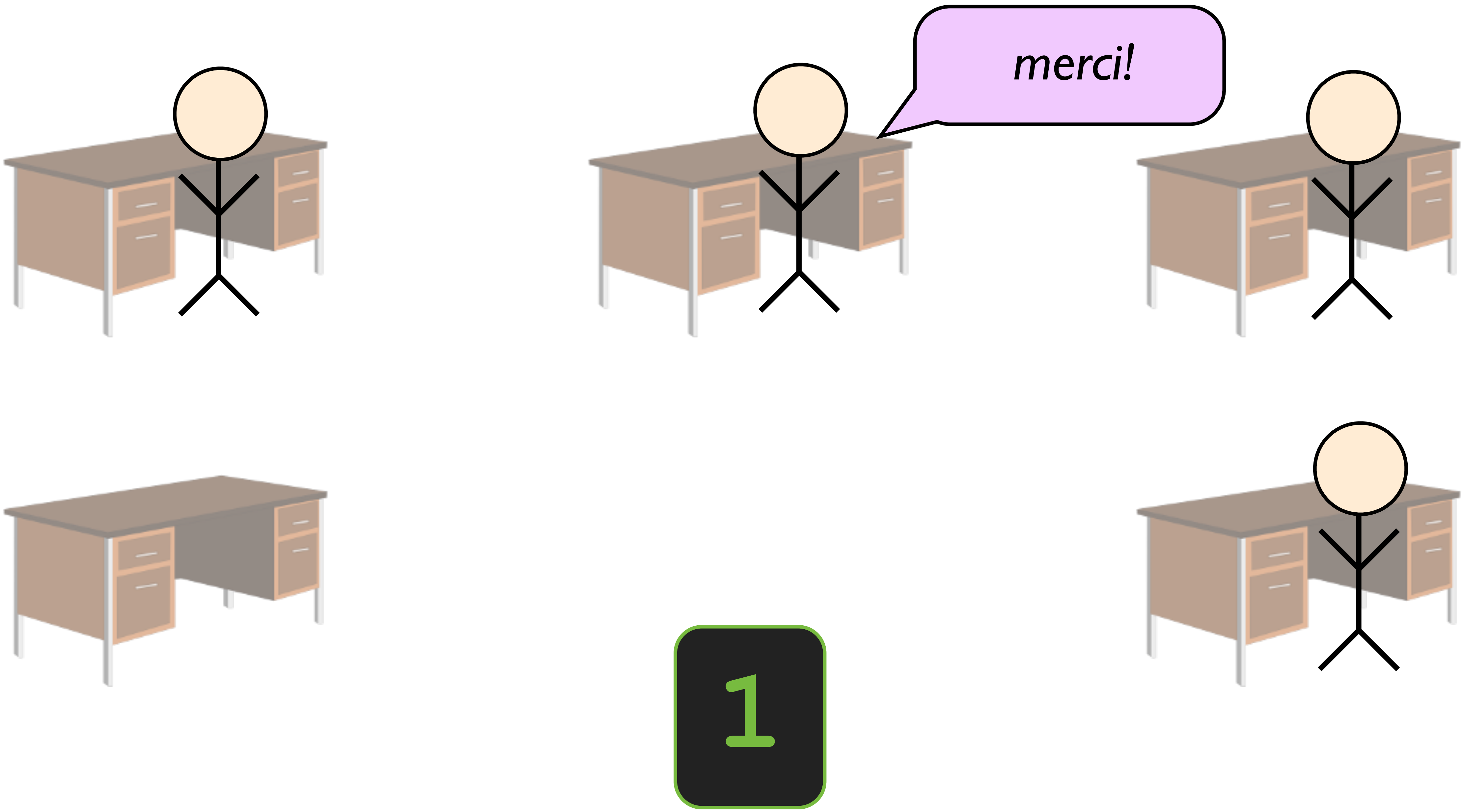

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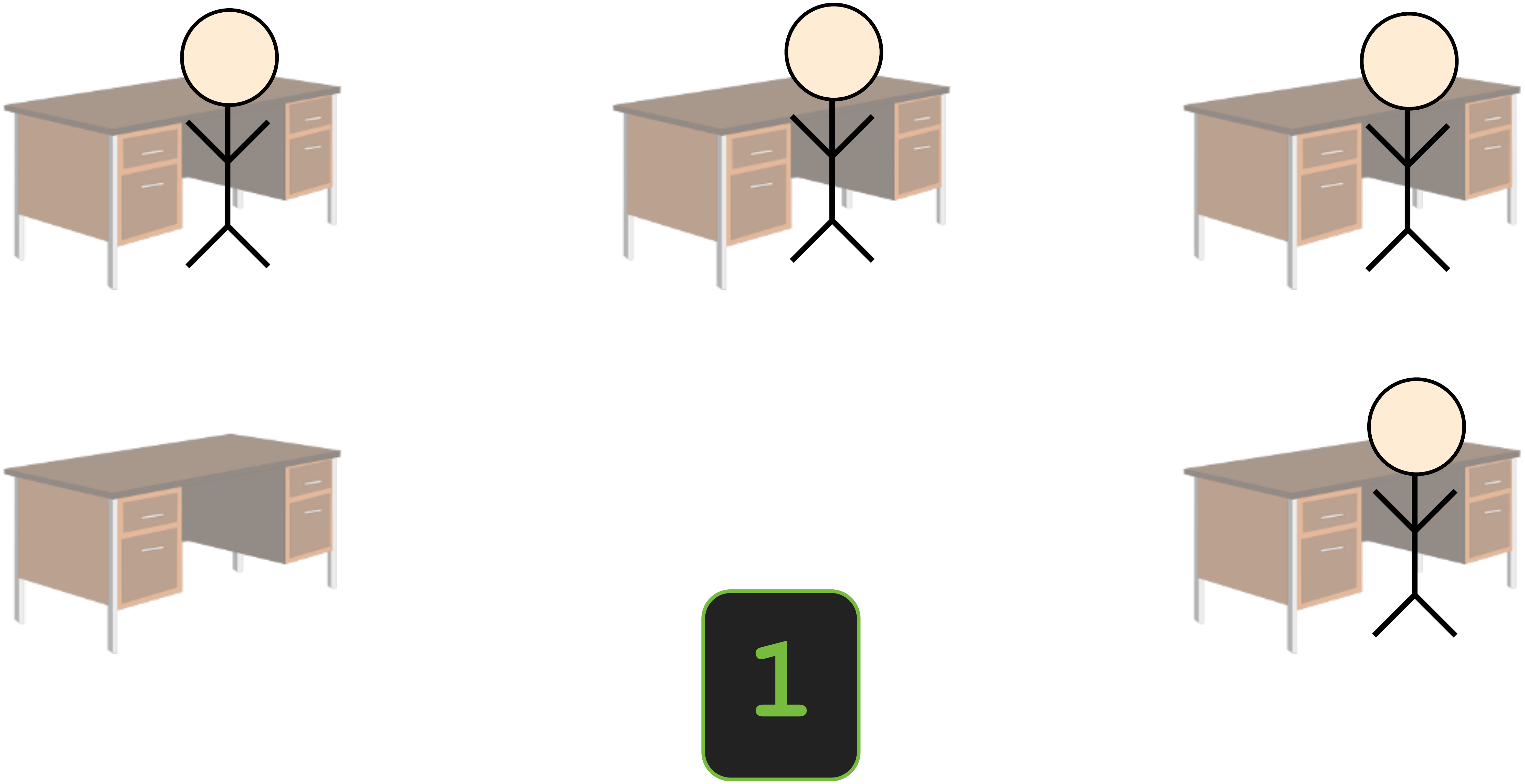

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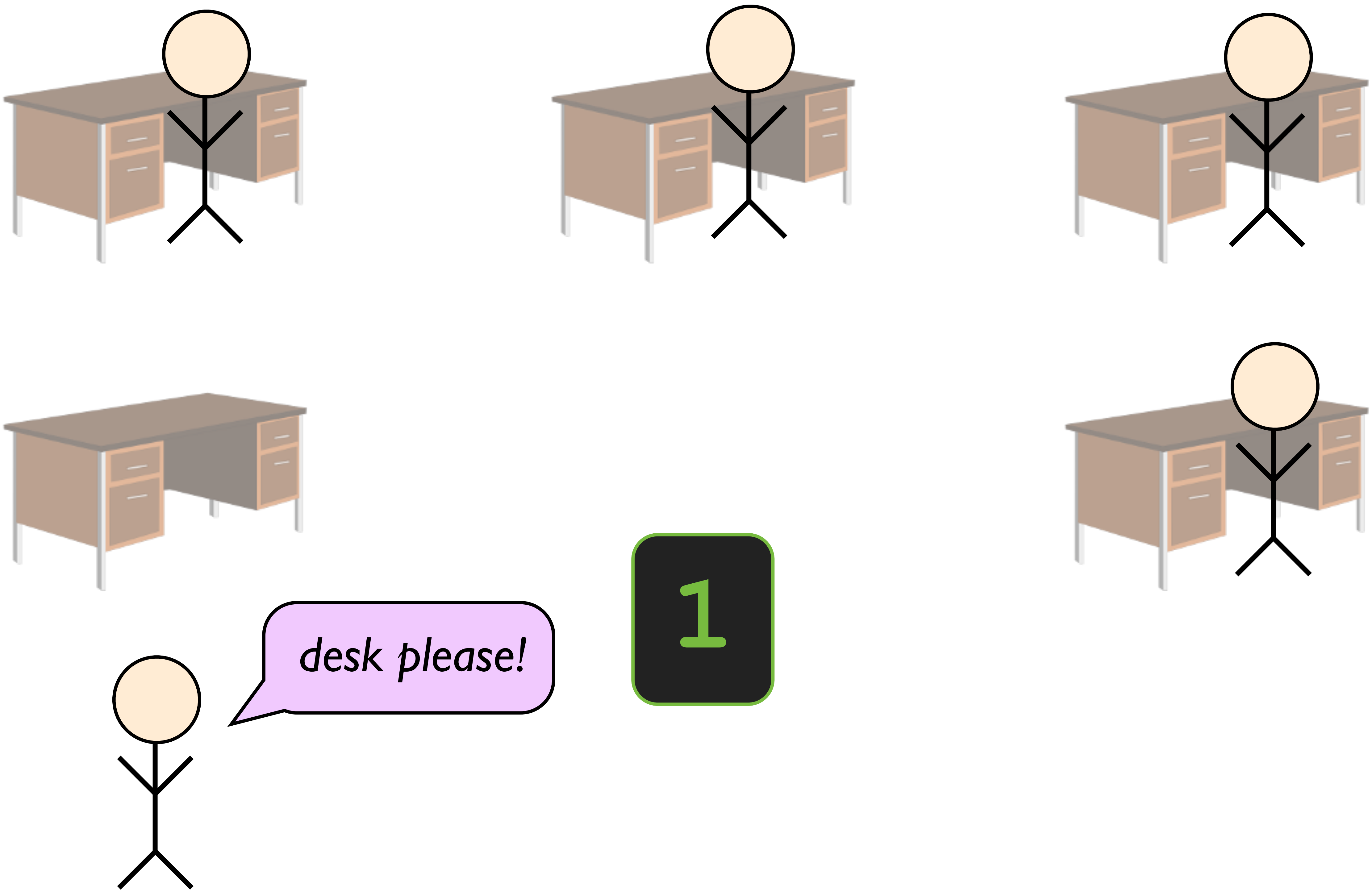

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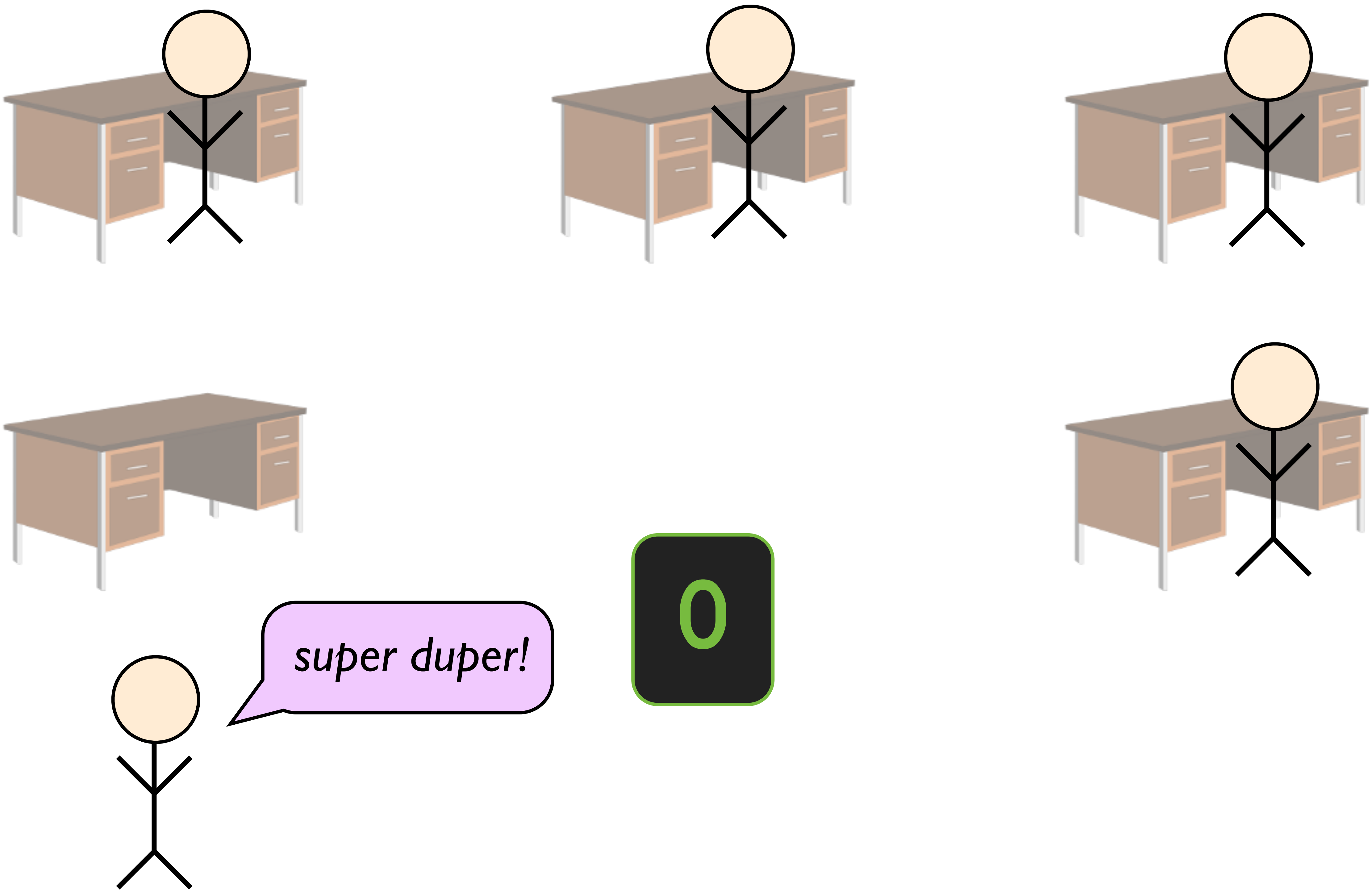

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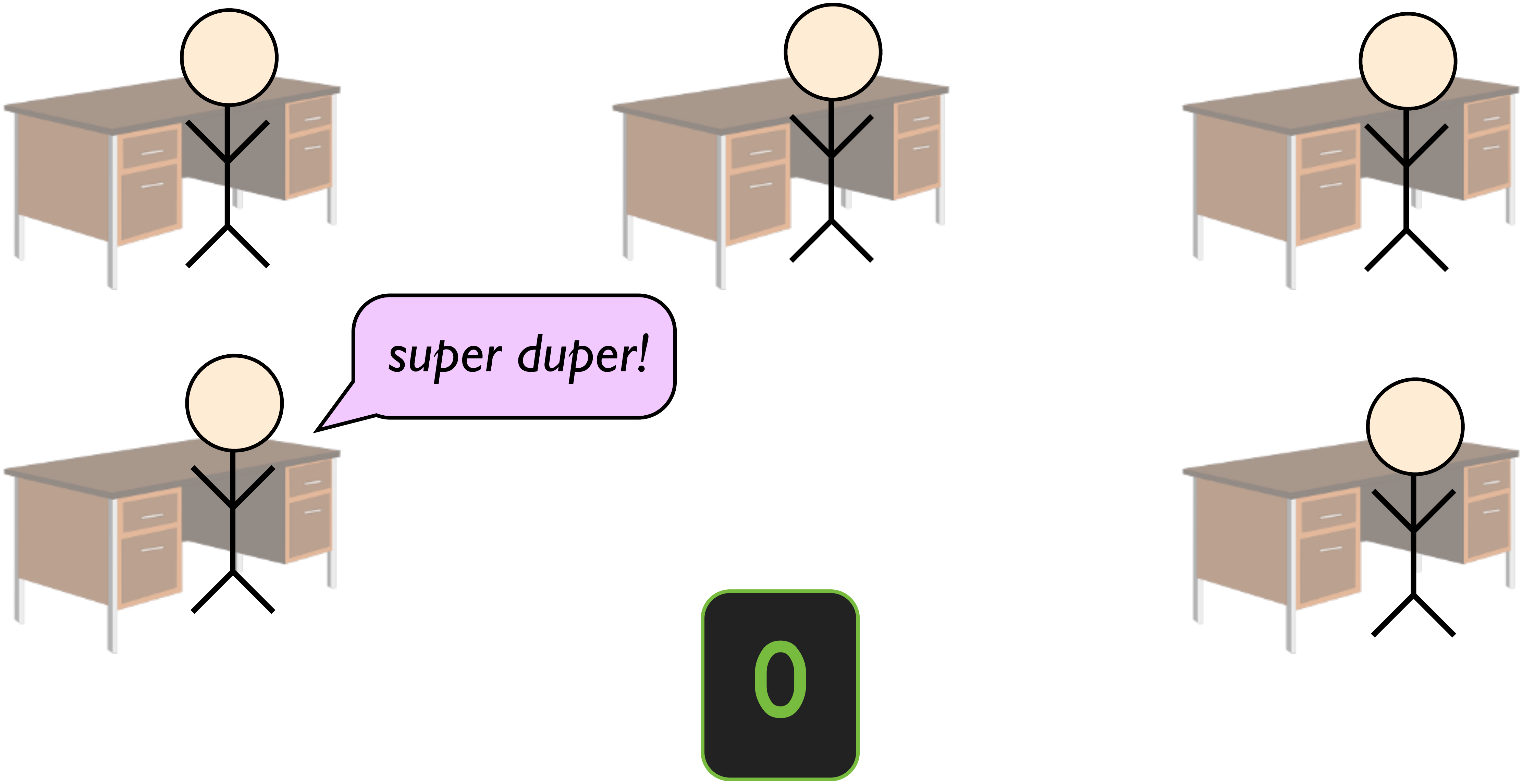

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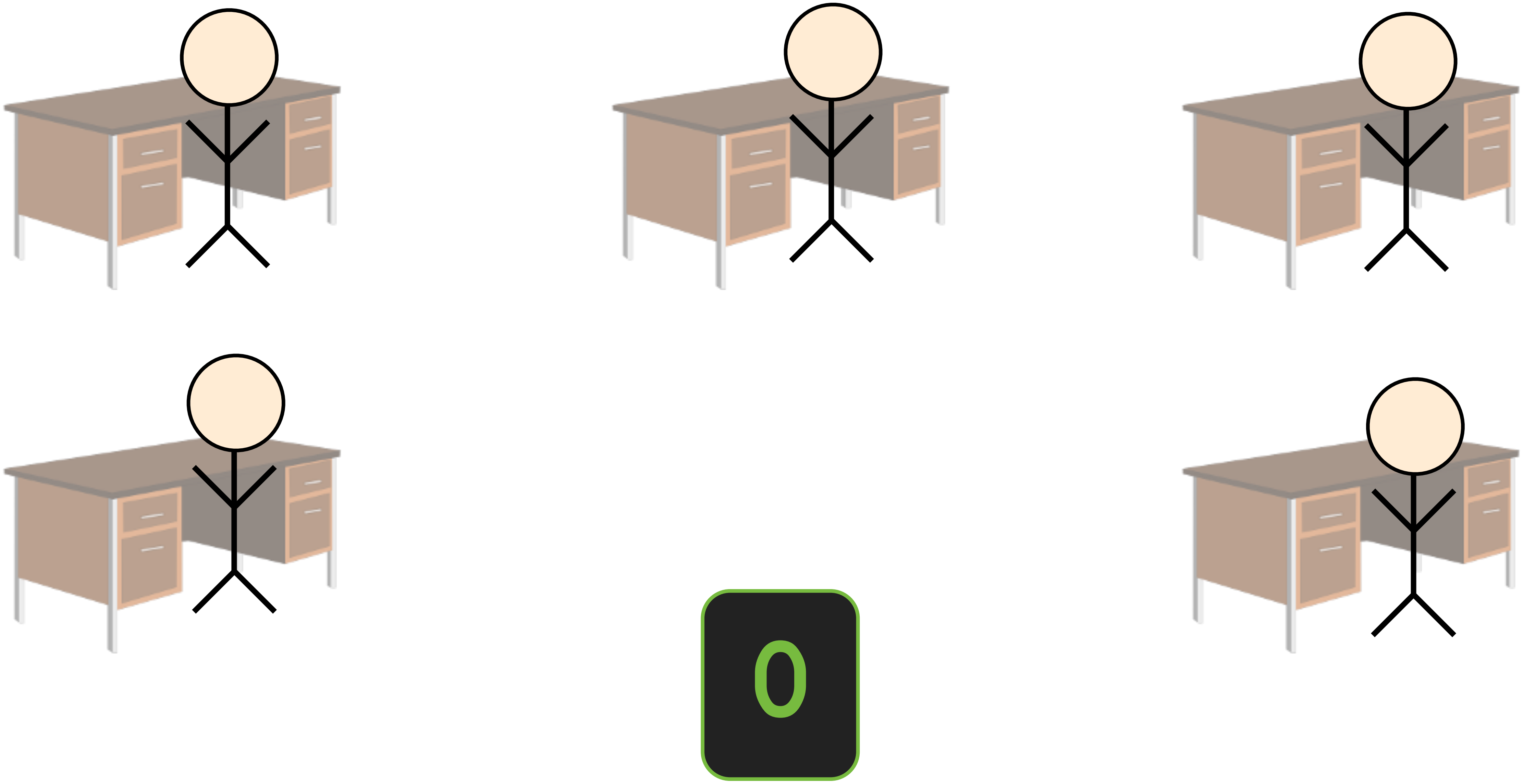

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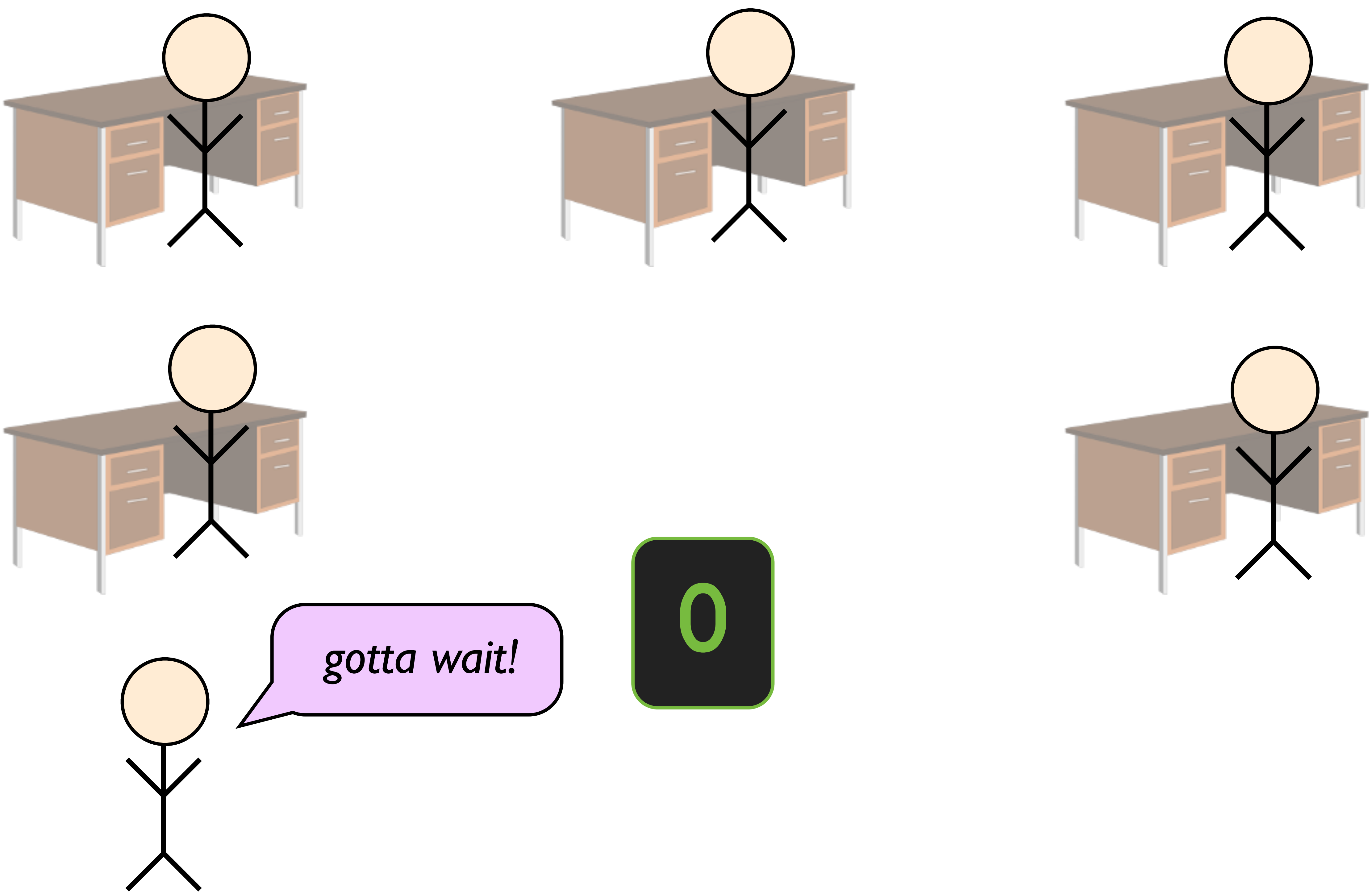

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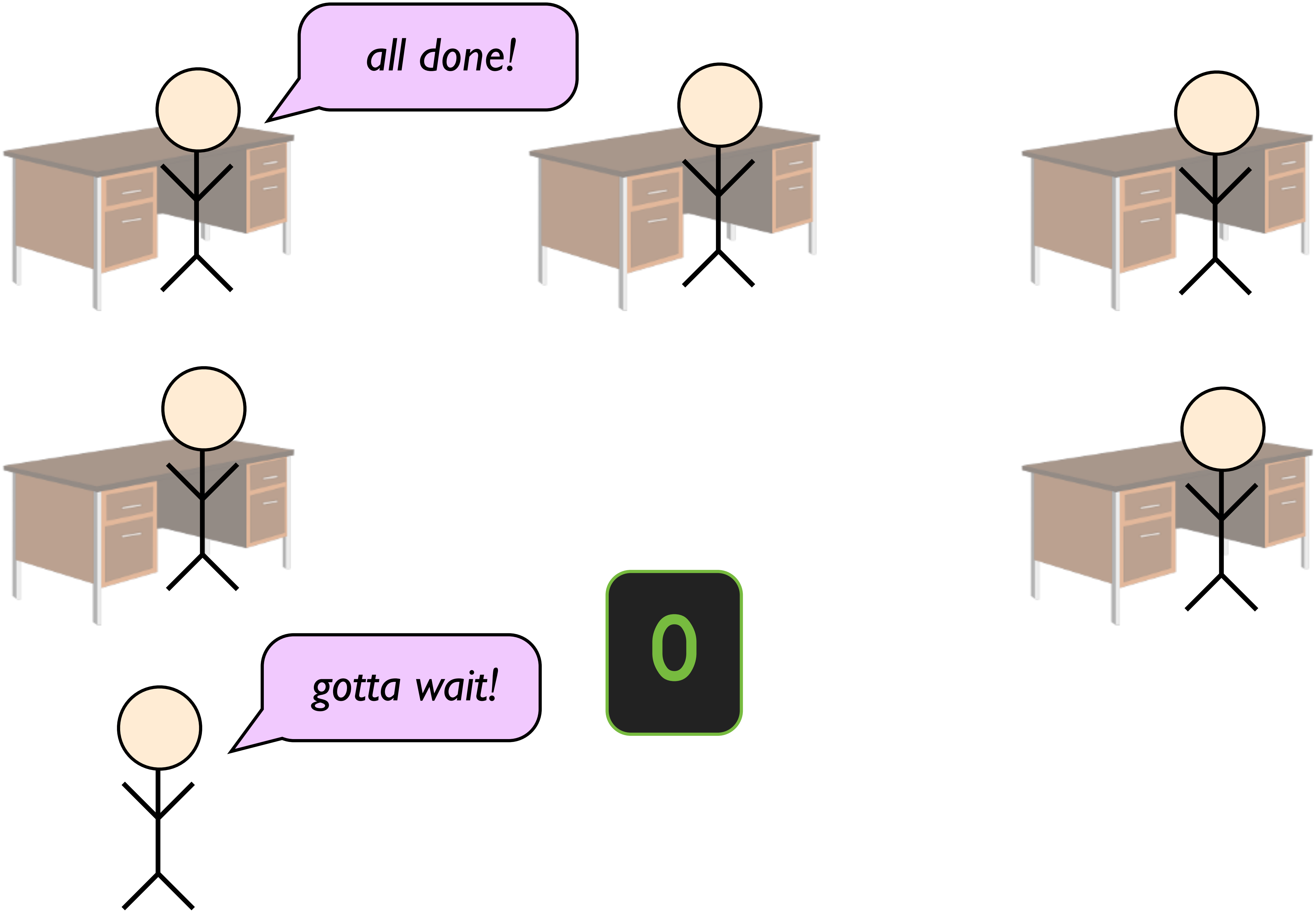

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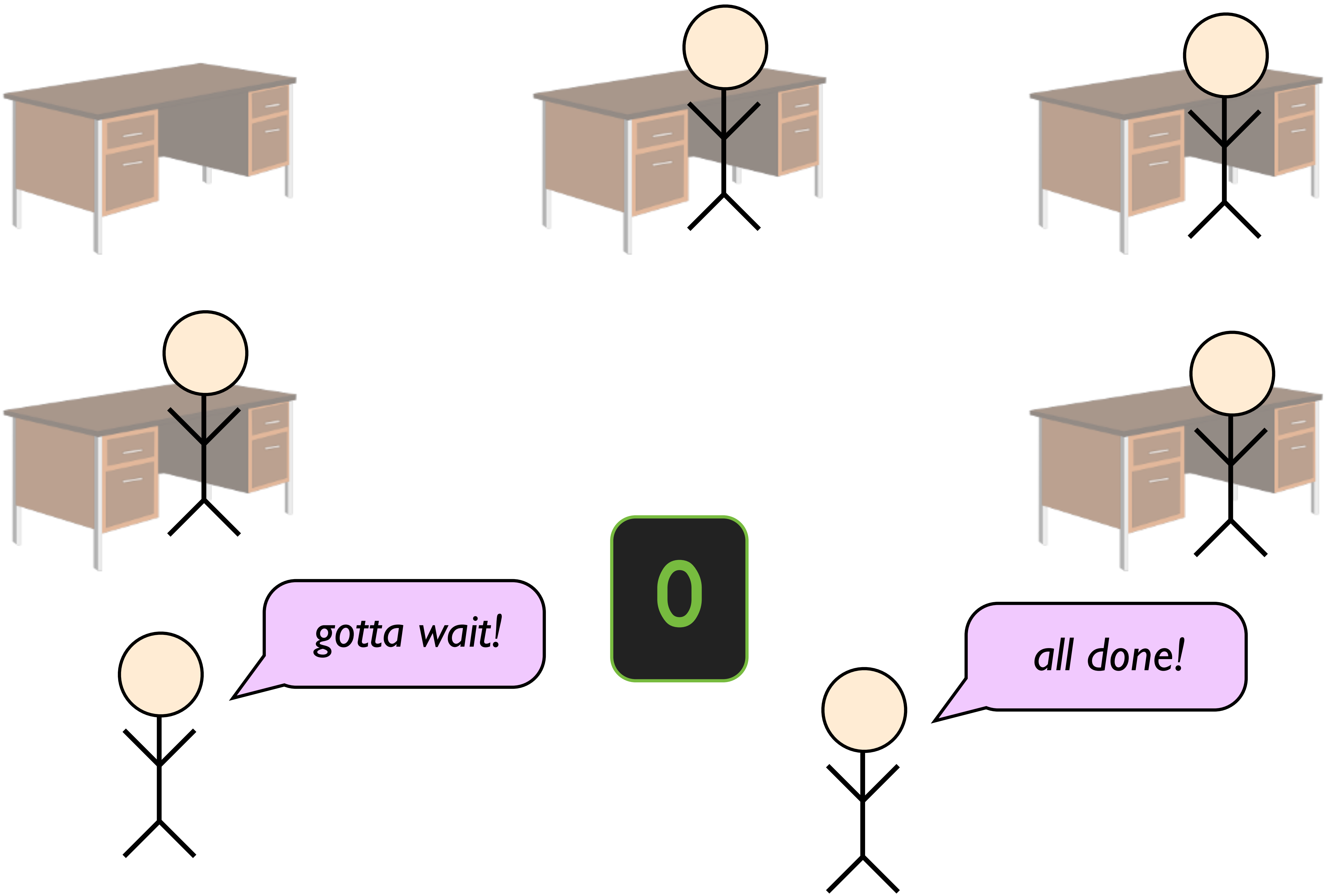

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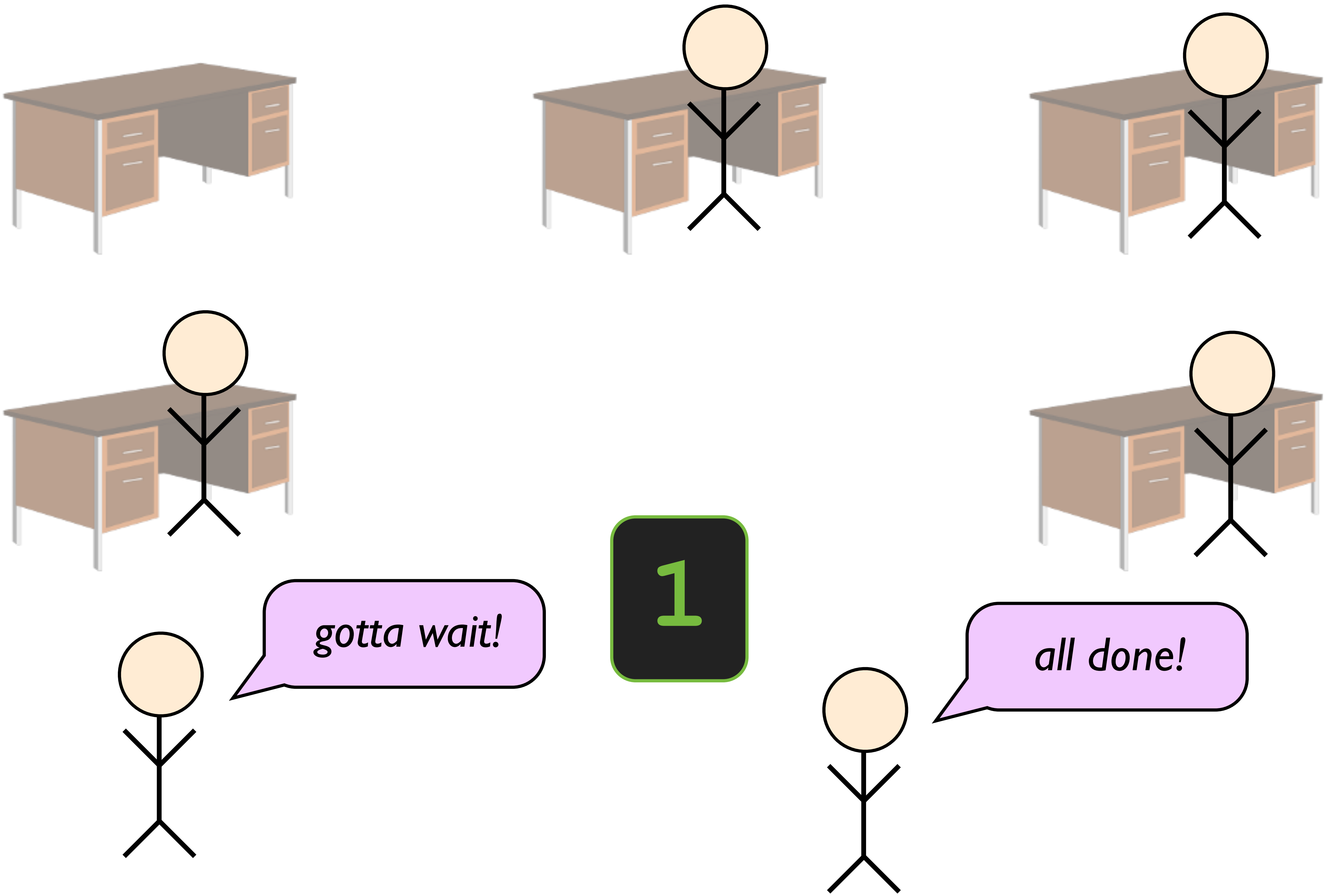

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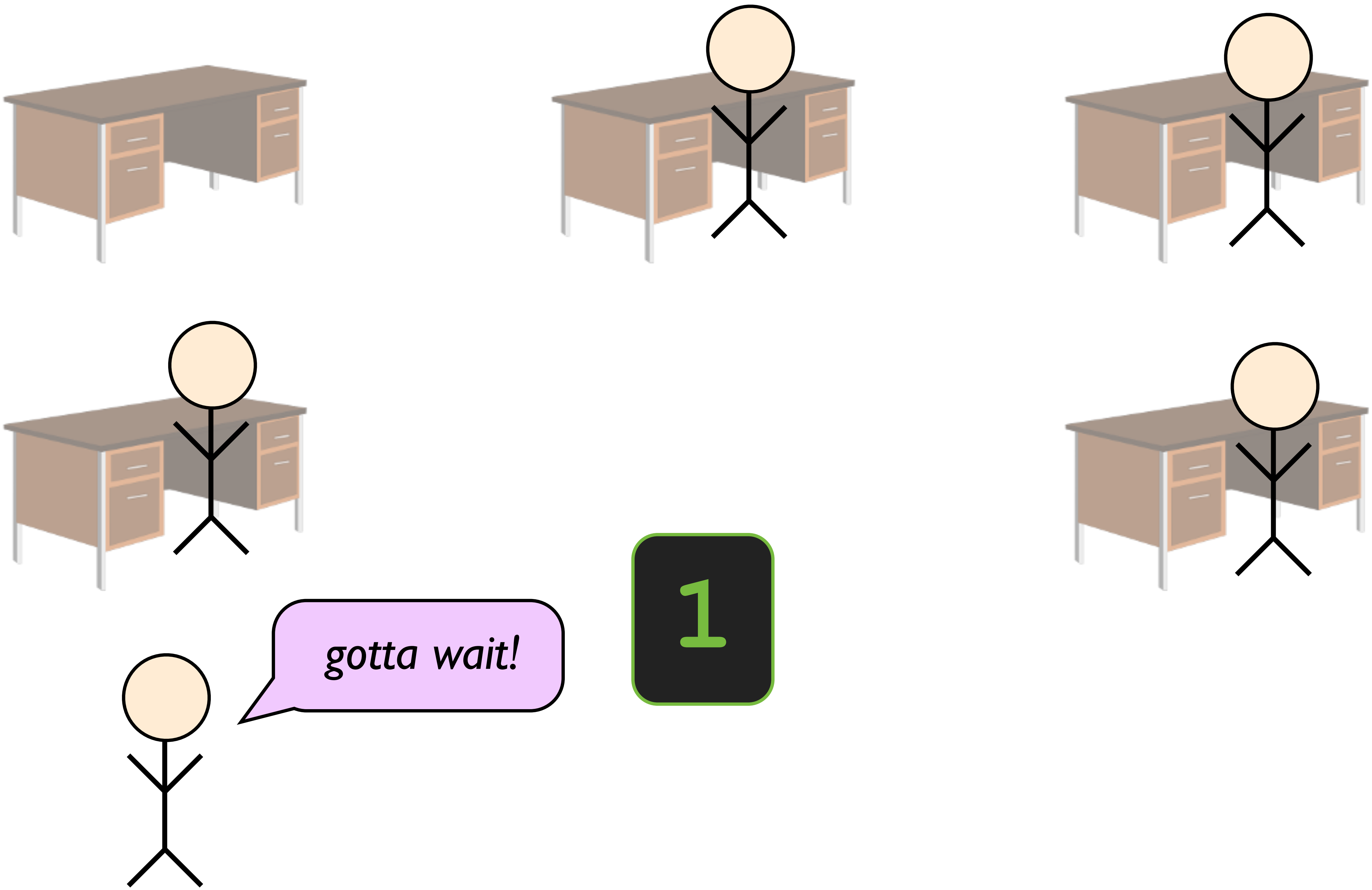

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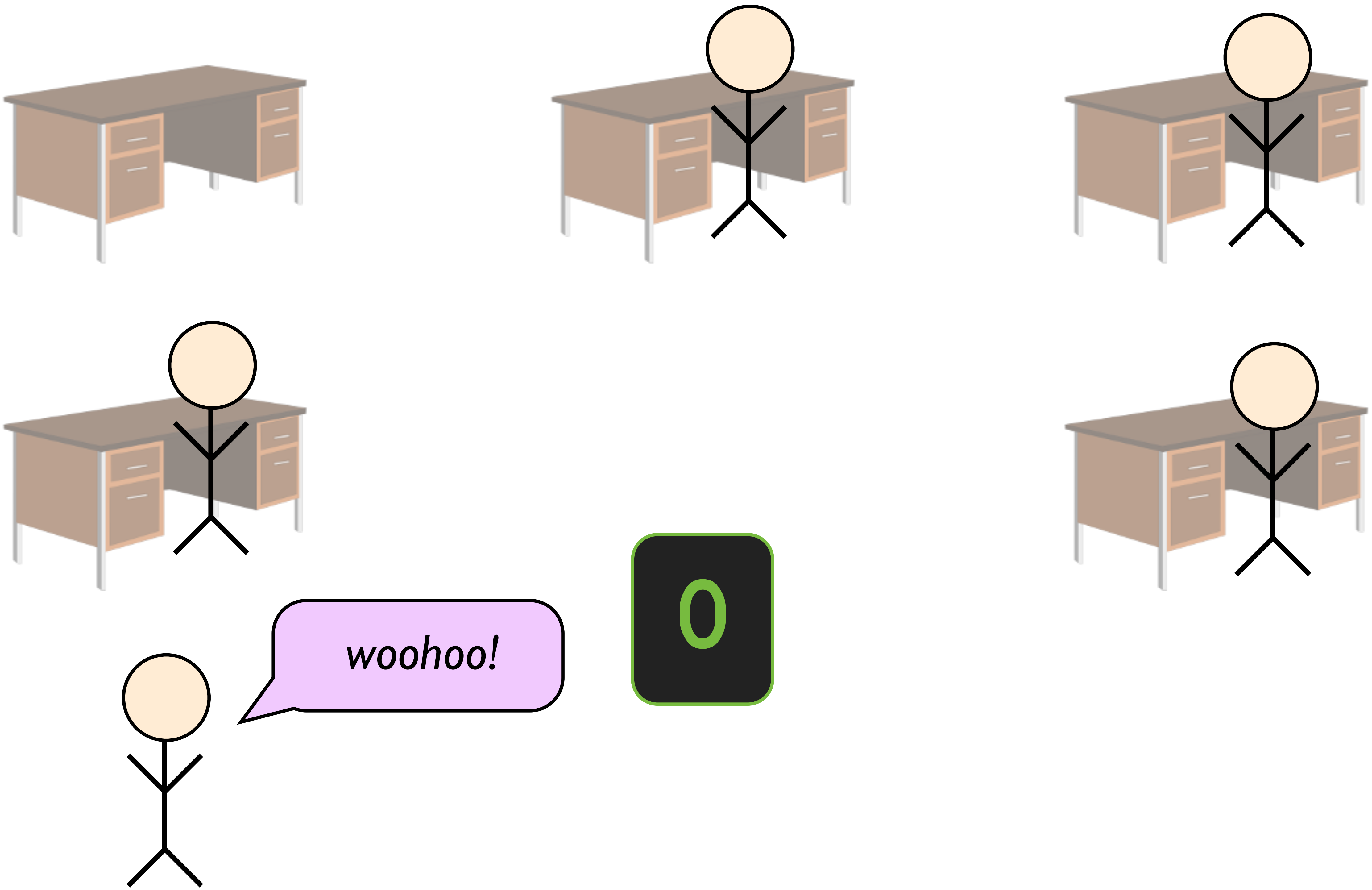

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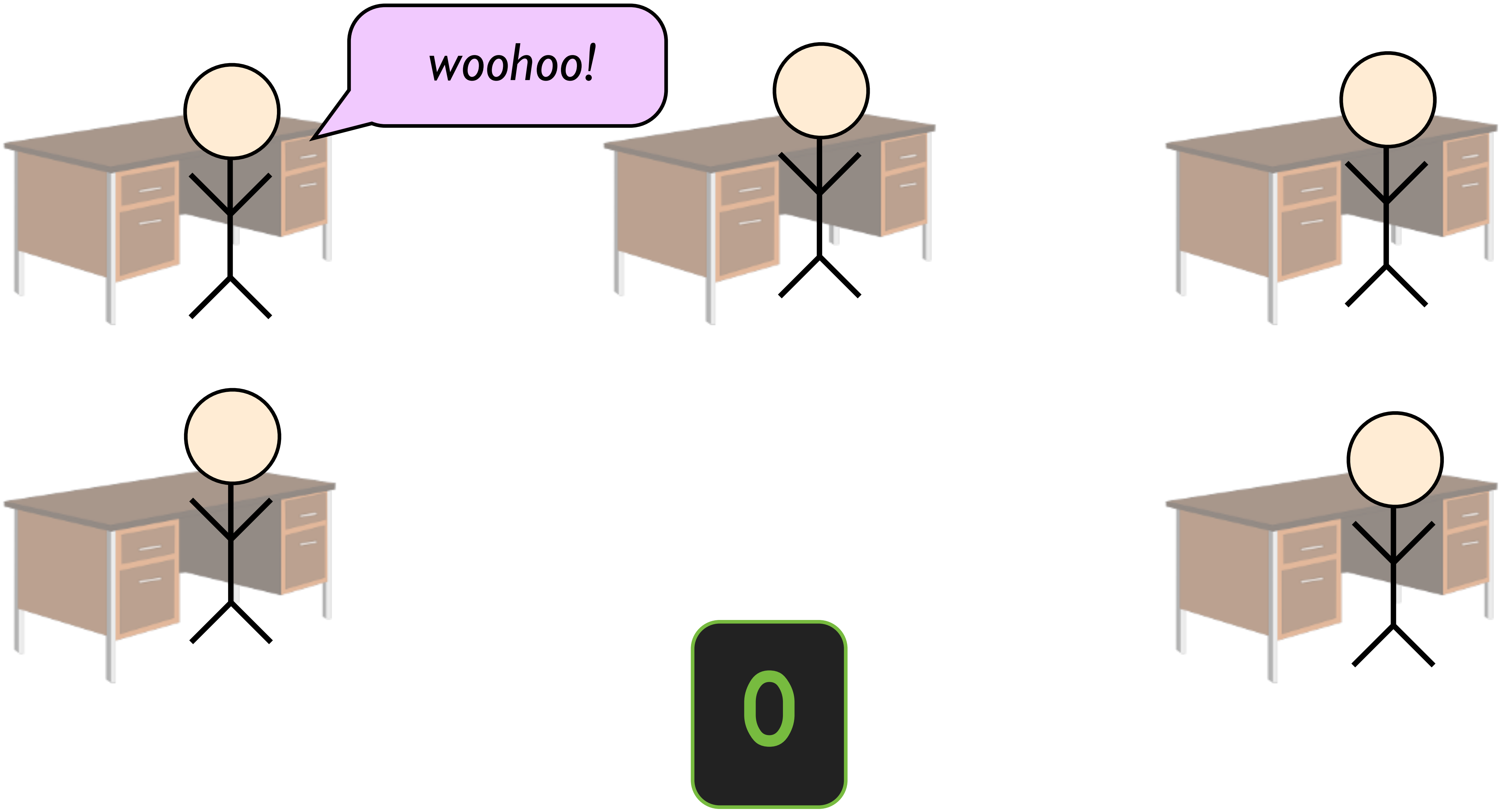

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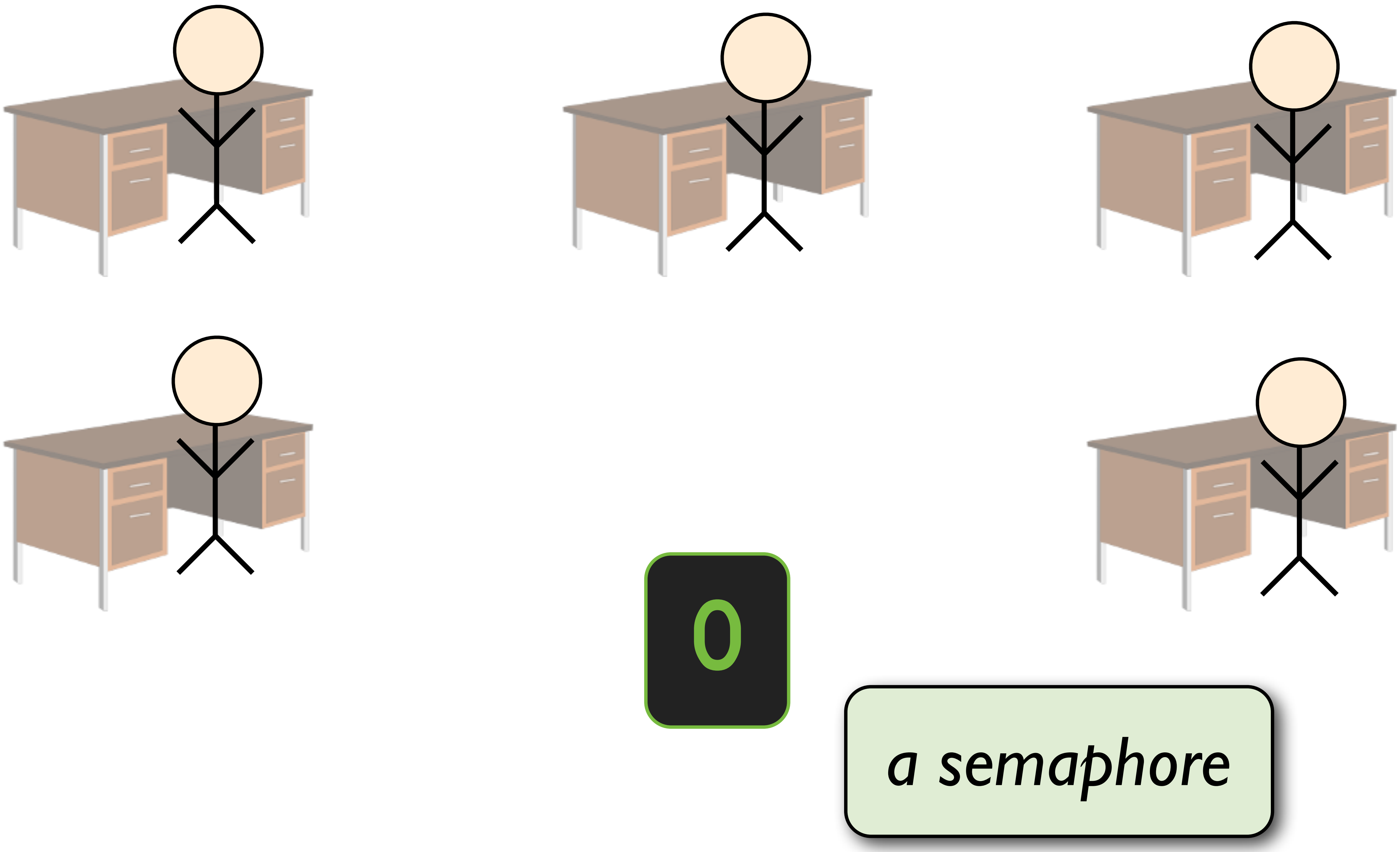

Today's lecture: semaphores

- we will discuss semaphores, an important synchronisation primitive
- conceptually simple, although their implementations require stronger atomic operations
- widespread use in operating systems
- invented by Dijkstra in 1965

Next on the agenda

1. general and binary semaphores
2. implementing semaphores
3. beyond the mutual exclusion problem
4. simulating general semaphores

General semaphores

(aka "counting semaphores")

- a general semaphore is an object consisting of:

  (1) an integer variable *count* such that *count* ≥ *0*

  (2) two atomic operations: *down* and *up*

if a process calls *down* when *count* > *0*, then *count* is decremented by 1 (otherwise it first waits)

if a process calls *up*, then *count* is incremented by 1

General semaphores
(in Eiffel-like pseudocode)

```
class SEMAPHORE
feature
   count : INTEGER

   down
     do-atomic
        await count > 0
        count := count - 1
     end

   up
     do-atomic
        count := count + 1
     end
end
```

General semaphores
(in Eiffel-like pseudocode)

```
class SEMAPHORE
feature
   count : INTEGER

   down
     do-atomic
        await count > 0
        count := count - 1
     end

   up
     do-atomic
        count := count + 1
     end
end
```

will discuss how to implement atomicity of "test and decrement", and how to avoid busy wait later!

Mutual exclusion for two processes

- create a semaphore *s* and initialise *s.count* to 1; then:

s.down
critical section
s.up

Mutual exclusion for <u>two</u> processes

- create a semaphore *s* and initialise *s.count* to 1; then:

s.down
critical section
s.up

one process at a time;
or one hot desk!

Mutual exclusion for <u>two</u> processes

- or in the style of last week's mutual exclusion problems:

count := 1			
P1		P2	
	while true loop		**while true loop**
1	**await** count > 0	1	**await** count > 0
	count := count - 1		count := count - 1
2	critical section	2	critical section
3	count := count + 1	3	count := count + 1
4	non-critical section	4	non-critical section
	end		**end**

Mutual exclusion for two processes

- mutual exclusion and deadlock freedom can be proven

  => *remember the atomicity of down and up!*

- solution does not satisfy starvation freedom

  => *a different implementation later will fix this*

The general semaphore invariant

- general semaphores are characterised by the following invariant -- important for proofs!

- given some semaphore, let:

  => *k denote its <u>initial</u> value with* $k \geq 0$
  => *count denote its <u>current</u> value*
  => *#down denote the number of completed down operations*
  => *#up denote the number of completed up operations*

- then the following equations are invariant:

(1) $count \geq 0$
(2) $count = k + \#up - \#down$

Binary semaphores

- in the previous example, *s.count* is always either 0 or 1
- such a semaphore is called a binary semaphore and can be implemented using a Boolean variable

```
b : BOOLEAN

down
  do-atomic
     await b
     b := false
  end

up
  do-atomic
     b := true
  end
```

Binary semaphores

- in the previous example, *s.count* is always either 0 or 1

- such a semaphore is called a binary semaphore and can be implemented using a Boolean variable

```
b : BOOLEAN

down
  do-atomic
    await b
    b := false
  end

up
  do-atomic
    b := true
  end
```

> *This is deceptively similar to the previous week's early, and wrong attempts at providing mutual exclusion. What's different?*

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Avoiding busy waiting

- busy-wait semaphores are not ideal

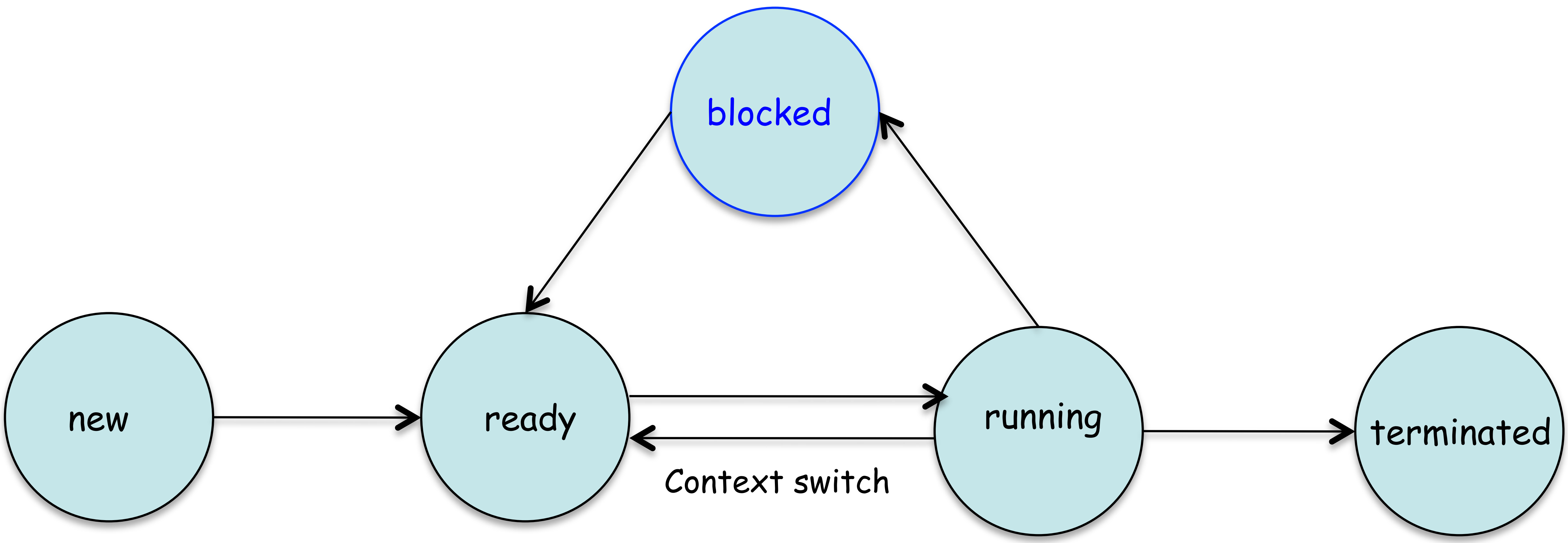
  => *they are not starvation free*
  => *inefficient in the context of multitasking*

- more preferable would be for processes to block themselves when having to wait

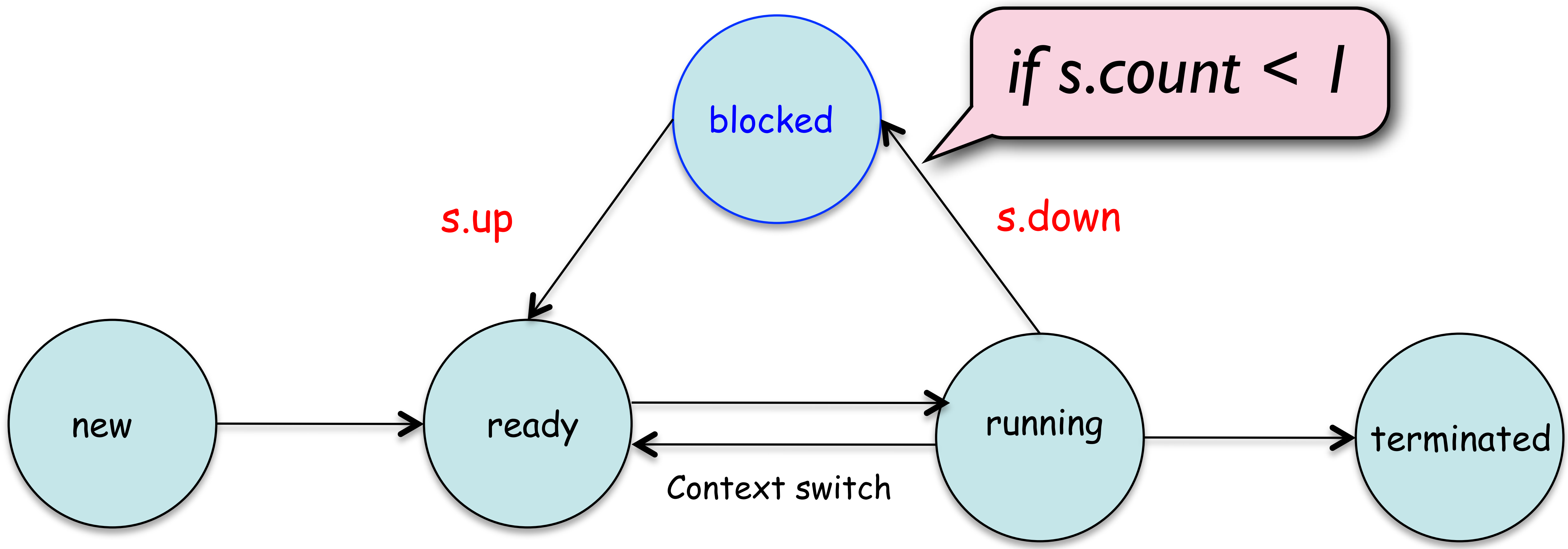
  => *thus freeing processing resources as early as possible*

- idea: keep track of blocked processes, "waking them" upon *up* calls on the semaphore

Avoiding busy waiting



Avoiding busy waiting



Implementing the scheme

- to avoid starvation, we will track blocked processes in a collection *blocked*

- we equip *blocked* with the following operations, which will be integrated into *down* and *up*

  => *add(P)* -- *insert process P into collection*
  => *remove* -- *select, remove, and return an item from the collection*
  => *is_empty* -- true *if collection empty;* false *otherwise*

- if *blocked* is implemented as a set, we call the semaphore weak; if as a FIFO queue, then strong

Weak semaphore

- a weak semaphore is a blocking semaphore in which the collection *blocked* is implemented as a set

  => blocked.remove *will pick and remove a random process from* blocked

down

```
do-atomic
    if count > 0 then
        count := count - 1
    else
        blocked.add(P)
        P.state := blocked
    end
end
```

up

```
do-atomic
    if blocked.is_empty then
        count := count + 1
    else
        Q := blocked.remove
        Q.state := ready
    end
end
```

Weak semaphore

- a weak semaphore is a blocking semaphore in which the collection *blocked* is implemented as a set

  => blocked.remove *will pick and remove a random process from* blocked

```
down
  do-atomic
    if count > 0 then
      count := count - 1
    else
      blocked.add(P)
      P.state := blocked
    end
  end
```

-- *add current process P to blocked*
-- *block P (instead of busy wait)*

```
up
  do-atomic
    if blocked.is_empty then
      count := count + 1
    else
      .remove
      ady
    end
  end
```

Weak semaphore

- a weak semaphore is a blocking semaphore in which the collection *blocked* is implemented as a set

=> blocked.remove *will pick and remove a random process from* blocked

```
down
  do-atomic
    if count > 0 then
      count := count - 1
    else
  end
```

```
up
  do-atomic
    if blocked.is_empty then
      count := count + 1
    else
      Q := blocked.remove
      Q.state := ready
    end
  end
```

-- select and remove some process Q from blocked
-- unblock Q so that it can access the resource
(Question: why is count left unchanged?)

Mutual exclusion for two processes

- weak semaphores provide starvation-freedom in the two process scenario

  => *why?*

- what about mutual exclusion for *n* processes?

Mutual exclusion for $\underline{n}$ processes

- create a semaphore *s* and initialise *s.count* to 1; then:

s.down
critical section
s.up

for each process

- starvation is possible for $n > 2$ with weak semaphores because we select a process from *blocked* at random

- solution is to use a strong semaphore, in which *blocked* is implemented as a FIFO queue

Strong semaphores provide a solution to the mutual exclusion problem with *n* processes

(how to prove)

- mutual exclusion -- prove that the following is <u>invariant</u>:

  $$\#cs + count = 1$$

  where #cs is the number of processes in critical sections

- starvation freedom -- apply *proof by contradiction*

  => *begin by assuming that a process in* blocked *is starved*

- see Theorem 4.6 in the course notes

A note on implementing atomicity

- you will typically never have to implement the atomic *down* and *up* operations of a semaphore yourself

  => *provided, e.g. in Java*

- *down* and *up* can be built in software from lower-level primitives, using e.g. synchronisation algorithms

- alternatively:

  => *using "test-and-set" instructions*
  (atomic read and write -- see later lecture)
  => *disabling interrupts (only realistic on a single processing unit)*

A note on semaphores in Java

- java.util.concurrent.Semaphore

  http://docs.oracle.com/javase/8/docs/api/java/util/concurrent/Semaphore.html

- constructors

  => Semaphore(int k) -- *a weak semaphore*
  => Semaphore(int k, boolean b) -- *a strong semaphore if b true*

- operations

  => acquire() -- *corresponds to down*
  => release() -- *corresponds to up*

Next on the agenda

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The *k*-exclusion problem

- in the *k*-exclusion problem, we allow up to *k* processes to simultaneously be in their critical sections

  => *mutual exclusion is the k = 1 instance*

- use a general semaphore corresponding to the number of processes allowed to be in their critical sections

```
s.count := k

P_i

while true loop
    s.down
    critical section
    s.up
    non-critical section
end
```

The *k*-exclusion problem

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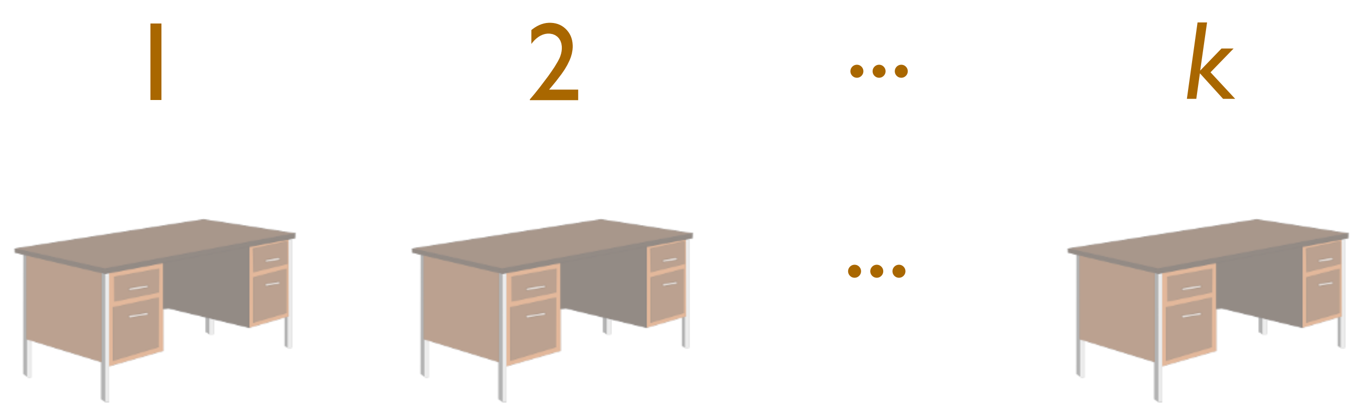


Barriers

- semaphores can be used to control the ordering of events in a system

- a barrier is a form of synchronisation that determines a point in a program's execution that all processes in a group have to reach before any of them may move on

  => *important for concurrent iterative algorithms*

Barriers

- semaphores can be used to control the ordering of events in a system

- a barrier is a form of synchronisation that determines a point in a program's execution that all processes in a group have to reach before any of them may move on

  => *important for concurrent iterative algorithms*

```
s1.count := 0
s2.count := 0
```

P1	P2
code before the barrier	code before the barrier
s1.up	s2.up
s2.down	s1.down
code after the barrier	code after the barrier

Barriers

- semaphores can be used to control the ordering of events in a system

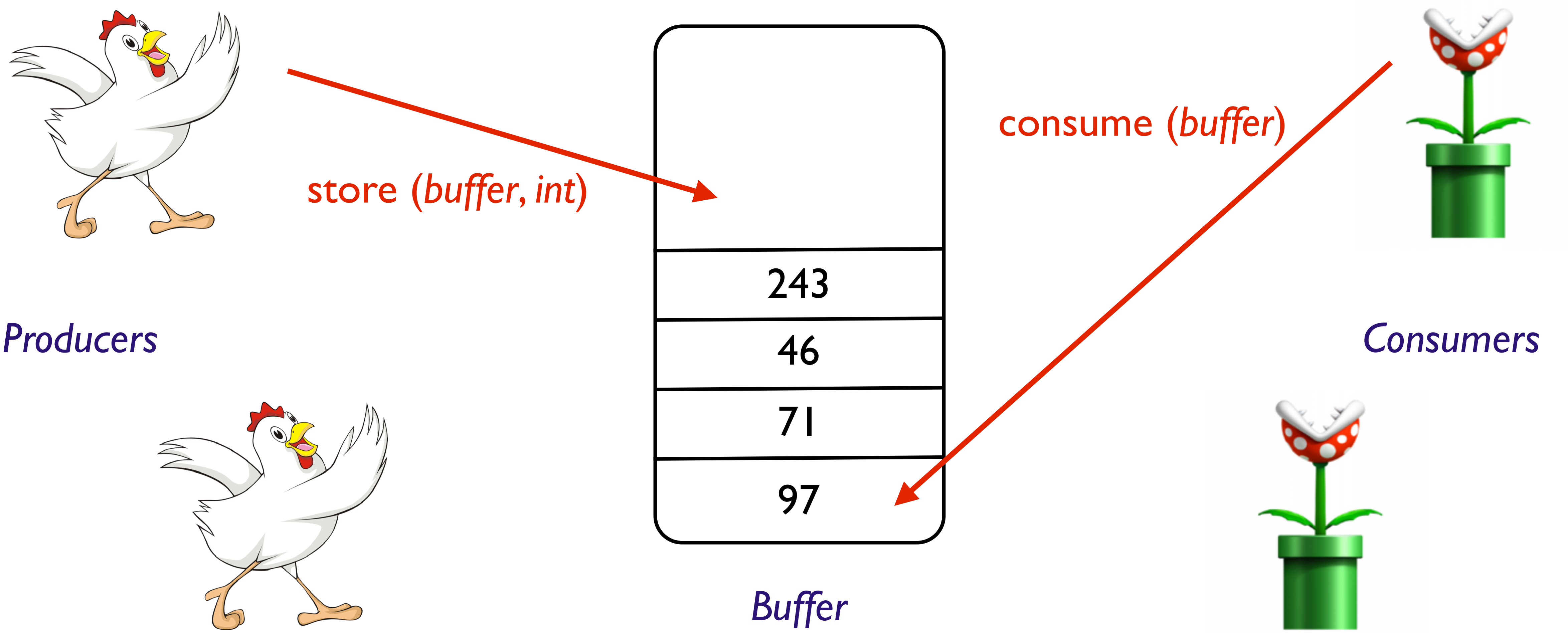
- a barrier is a form of synchronisation that determines a point in a program's execution that all processes in a group have to reach before any of them may move on

=> *important for concurrent iterative algorithms*

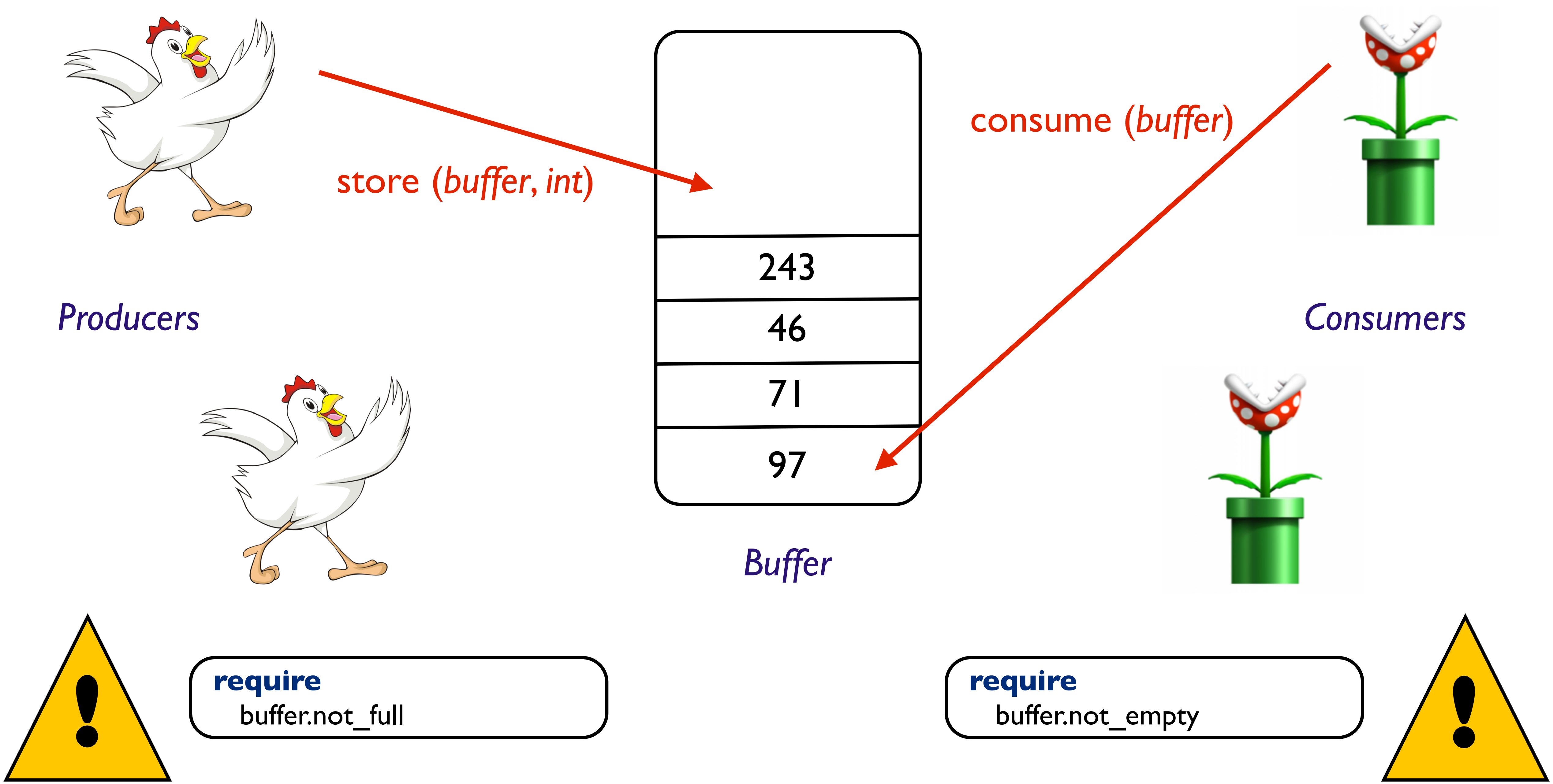
s1 is the barrier for P2; s2 is the barrier for P1 -- why are they initialised to 0?

s1.count := 0 s2.count := 0			
P1		P2	
1	code before the barrier	1	code before the barrier
2	s1.up	2	s2.up
3	s2.down	3	s1.down
4	code after the barrier	4	code after the barrier

The producer-consumer problem



The producer-consumer problem



The producer-consumer problem

- a good solution would:

  => *ensure that every data item produced is eventually consumed*
  => *be deadlock-free*
  => *be starvation-free*

- need a semaphore for mutual exclusion (the buffer)

- but additional semaphore(s) for condition synchronisation

  => *e.g. consumer should block until the buffer is non-empty*

Solution for an unbounded buffer

```
mutex.count := 1
not_empty.count := 0
```

Producer$_i$	Consumer$_i$

while true loop
    d := produce
    mutex.down
    b.append(d)
    mutex.up
    not_empty.up
end
	while true loop
	    not_empty.down
	    mutex.down
	    d := b.remove
	    mutex.up
	    consume(d)
	end

Solution for an unbounded buffer

observe that not_empty.count = #items_in_buffer

```
mutex.count := 1
not_empty.count := 0
```

Producer$_i$	Consumer$_i$

`while true loop`
`    d := produce`
`    mutex.down`
`    b.append(d)`
`    mutex.up`
`    not_empty.up`
`end`
	`while true loop`
	`    not_empty.down`
	`    mutex.down`
	`    d := b.remove`
	`    mutex.up`
	`    consume(d)`
	`end`

Solution for an unbounded buffer

observe that not_empty.count = #items_in_buffer

mutex.count := 1 not_empty.count := 0	
Producer$_i$	Consumer$_i$

while true loop
    d := produce
 	
    mutex.up
    not_empty.up
end
	while true loop
	    not_empty.down
	    mutex.down
	    d := b.remove
	    mutex.up
	    consume(d)
	end

blocks until not_empty.count > 0

Solution for a bounded buffer

```
mutex.count := 1
not_empty.count := 0
not_full.count := k
```

Producer$_i$		Consumer$_i$	
	while true loop		**while true loop**
1	d := produce	1	not_empty.down
2	not_full.down	2	mutex.down
3	mutex.down	3	d := b.remove
4	b.append(d)	4	mutex.up
5	mutex.up	5	not_full.up
	not_empty.up		consume(d)
	end		**end**

Solution for a bounded buffer

where k is the size of the buffer

```
mutex.count := 1
not_empty.count := 0
not_full.count := k
```

$Producer_i$

```
while true loop
    d := produce
    not_full.down
    mutex.down
    b.append(d)
    mutex.up
    not_empty.up
end
```

$Consumer_i$

```
while true loop
    not_empty.down
    mutex.down
    d := b.remove
    mutex.up
    not_full.up
    consume(d)
end
```

Dining philosophers problem

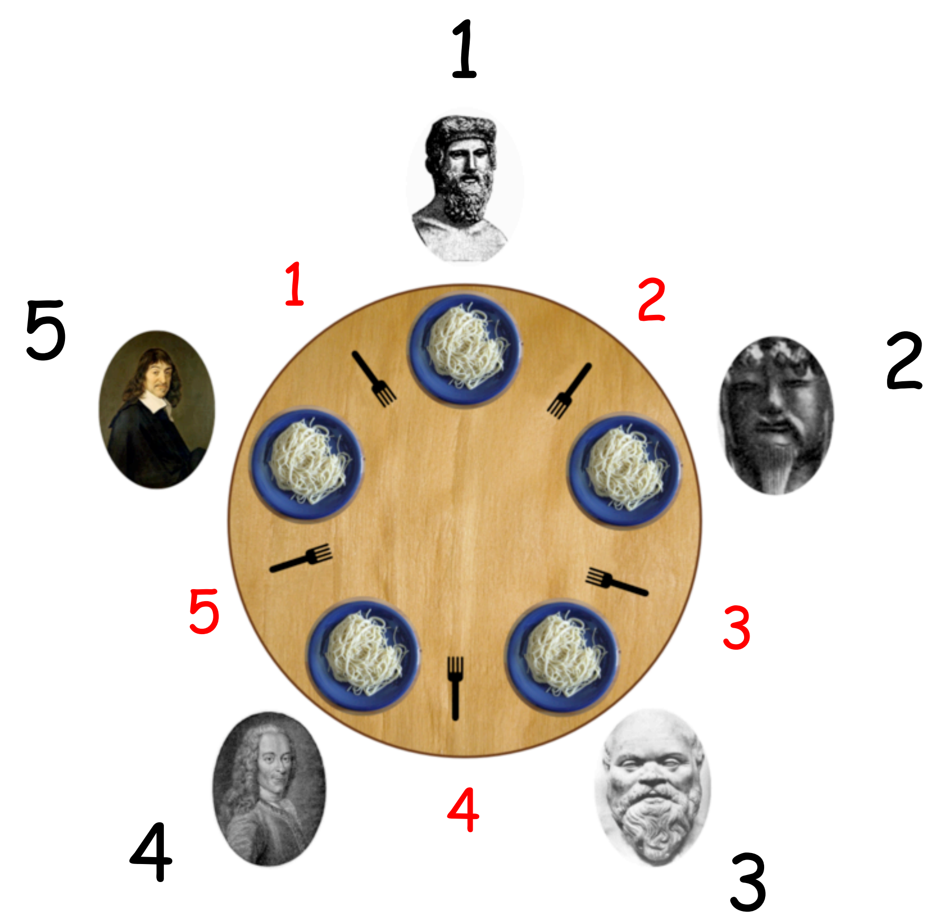
(a solution that can deadlock)

- multiple semaphores must be used with care -- they are prone to deadlock!

```
s[1].count := 1, ..., s[n].count := 1
```

Philosopher$_i$

```
while true loop
    think
    s[i].down
    s[(i mod n) + 1].down
    eat
    s[(i mod n) + 1].up
    s[i].up
end
```



Dining philosophers problem

(a solution that can deadlock)

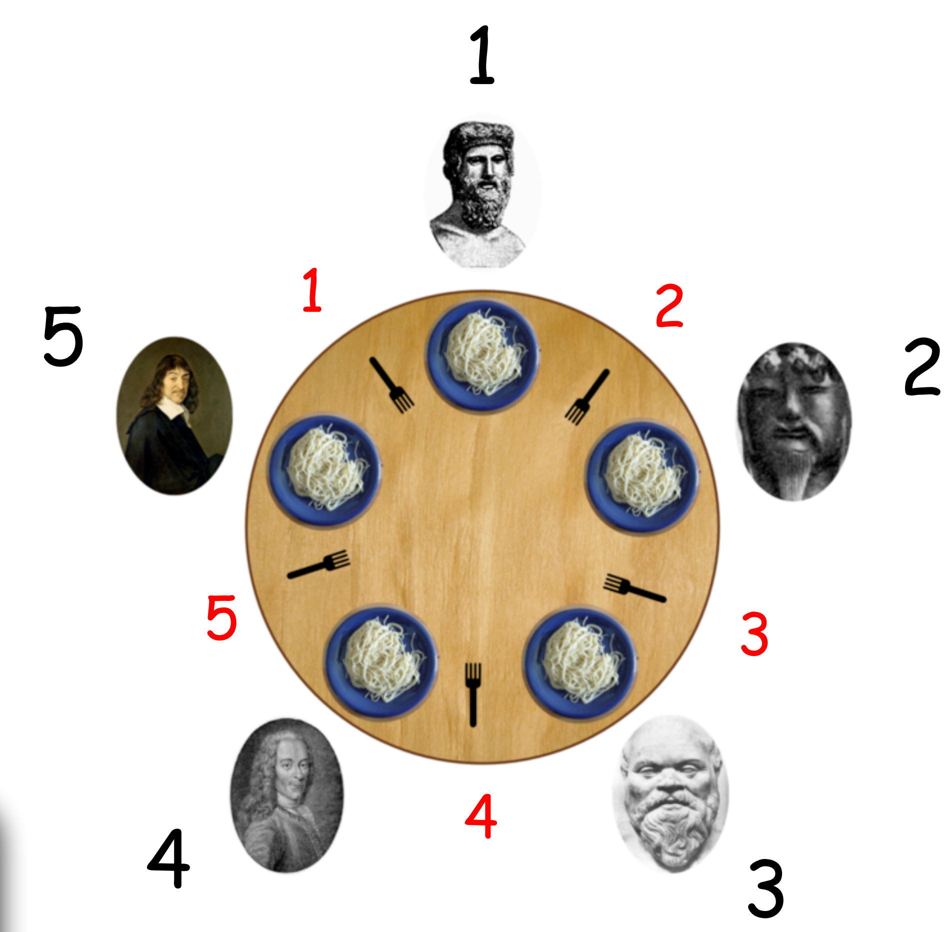
- multiple semaphores must be used with care -- they are prone to deadlock!

```
s[1].count := 1, ..., s[n].count := 1

Philosopher_i

while true loop
    think
    s[i].down
    s[(i mod n) + 1].down
    eat
    s[(i mod n) + 1].up
    s[i].up
end
```

circular waiting!



Dining philosophers problem

(an asymmetric fix!)

- assume that philosopher *n* picks up the left fork before the right fork

- this breaks the circle of resource requests; there will always be one philosopher who can acquire both forks and release them again

Philosopher$_n$

```
while true loop
    think
    s[1].down
    s[n].down
    eat
    s[n].up
    s[1].up
end
```

Next on the agenda

1. general and binary semaphores ✓
2. implementing semaphores ✓
3. beyond the mutual exclusion problem ✓
4. simulating general semaphores

General semaphores are superfluous

- while conceptually useful, general semaphores (theoretically) are not necessary -- they can be implemented through binary semaphores alone

General semaphores are superfluous

```
mutex.count := 1  -- binary semaphore
delay.count := 1    -- binary semaphore
count := k

general_down
   do
      delay.down
      mutex.down
      count := count - 1
      if count > 0 then
         delay.up
      end
      mutex.up
   end

general_up
   do
      mutex.down
      count := count + 1
      if count = 1 then
         delay.up
      end
      mutex.up
   end
```

General semaphores are superfluous

```
mutex.count := 1  -- binary semaphore
delay.count := 1    -- binary semaphore
count := k
```

value of the general semaphore

protects count

```
general_down
    do
        delay.down
        mutex.down
        count := count - 1
        if count > 0 then
            delay.up
        end
        mutex.up
    end
```

not called when count = 0

```
general_up
    do
        mutex.down
        count := count + 1
        if count = 1 then
            delay.up
        end
        mutex.up
    end
```

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Summary

- semaphores are conceptually simple but powerful tools for solving synchronisation problems

- choice of implementation can affect starvation-freedom

- applications beyond mutual exclusion: *k*-exclusion, barriers, condition synchronisation

but: correct usage is still far from trivial

- essential reading: Chapter 4 of the CCC textbook