Semaphores

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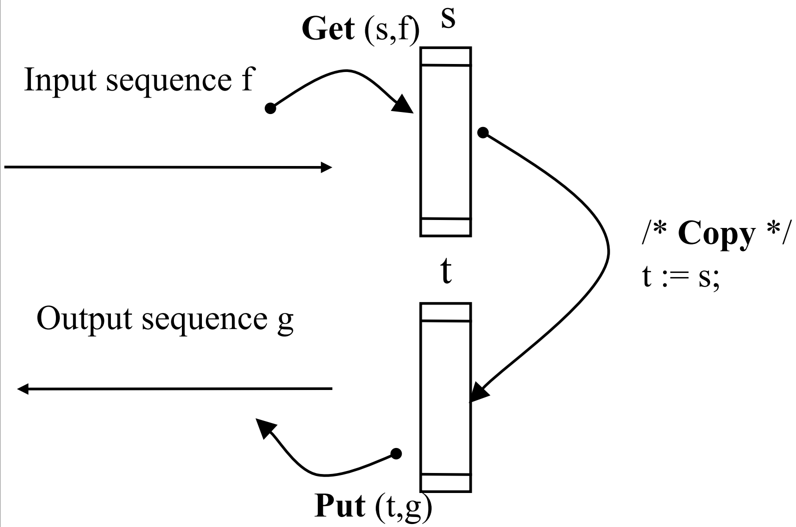
Concurrency: Double buffering

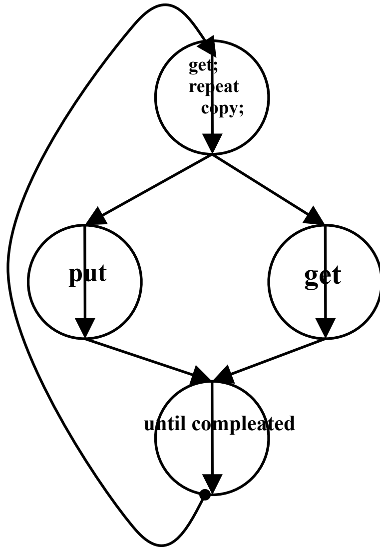
/* **Fill** s and **empty** t ***concurrently*** */



cobegin & *coend* specifies concurrent execution.

```
Get(s,f);
Repeat
    Copy;
    cobegin
        Put(t,g);
        Get(s,f);
    coend;
until completed;
```

(Two threads)
Alternative syntax:
{put() || get()}



- **Put and Get** are disjoint
  - but not with regards to **Copy**
    - The **order** of Copy vs. Put & Get:
      - OK, defined by program

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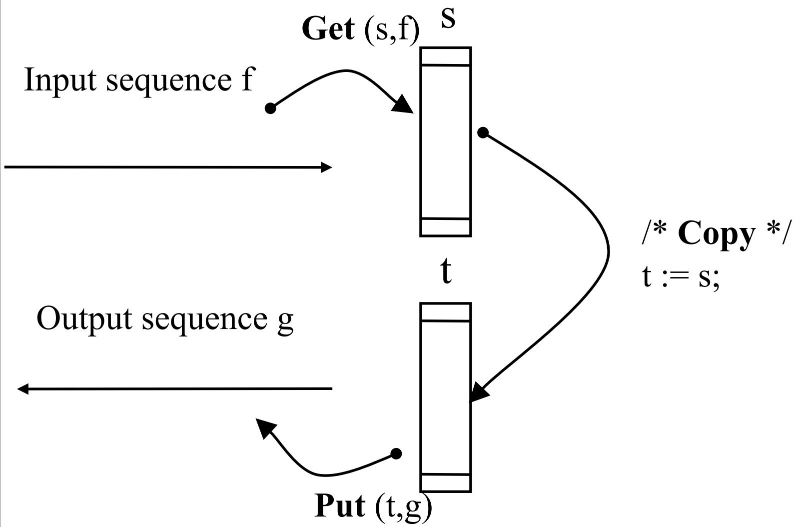

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Repeat

 Copy;

 cobegin

  Put(t,g);

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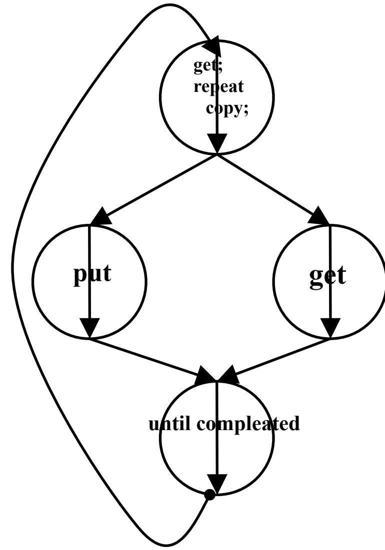

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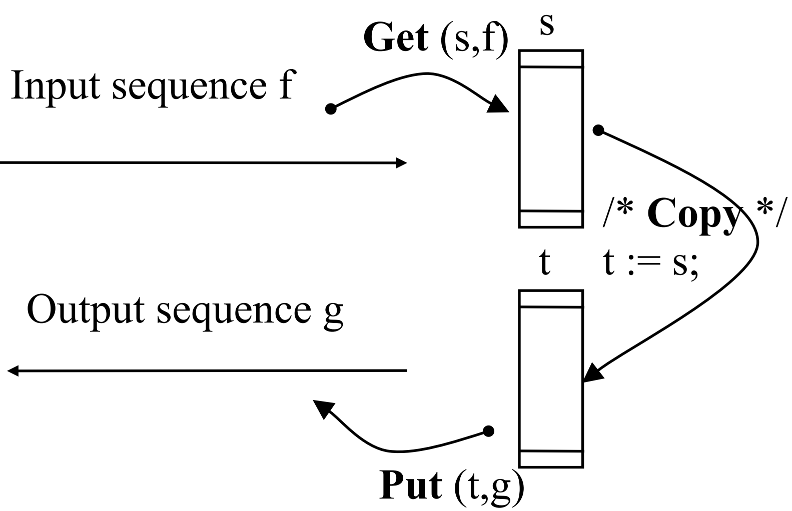
  - but not with regards to **Copy**
    - The **order** of Copy vs. Put & Get:
      - OK, defined by program

Think about non-preemptive vs. preemptive scheduling by OS

Concurrency: Double buffering

/* **Fill** s and **empty** t **concurrently**: OS Kernel will do **preemptive** scheduling of GET, COPY and PUT*/



Three threads executing concurrently:

{put_thread || **get**_thread || **copy**_thread} /*Assume **preemptive** sched. by kernel */

*What is **shared** between the threads?: The buffers **s** and **t**. So what can happen unless we make sure they are used by one and only one thread at a time?: Interference between the threads possible/likely.*

*Need **how** many locks?* **2**, one for each shared resource.

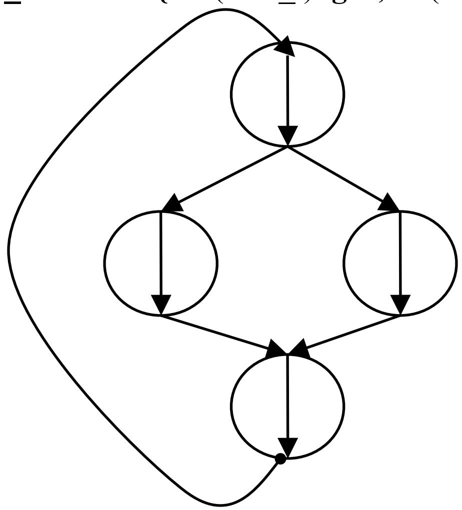
Proposed code (but** not **quite good enough):

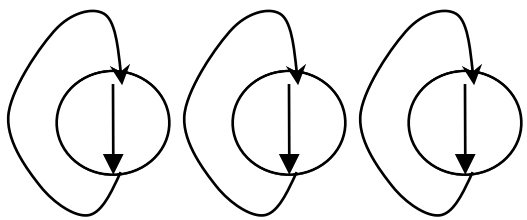
copy_thread:: *{acq(lock_t); acq(lock_s); **t=f;** rel(lock_s); rel(lock_t);}

get_thread:: *{ack(lock_s); **s=f;** rel(lock_s);}

put_thread:: *{ack(lock_t): **g=t;** rel(lock_t);}

- **Not too bad, but NO ORDER**
  - what can happen?
    - same/old **s** values copied again
    - **s** values never copied because Get overwrites
    - same/old **t** values read by Put
    - **t** values lost because Copy overwrites





Threads specifies concurrent execution

Protecting a Shared Variable

- Remember: we need a *shared address space* to share variables (memory)
  - threads inside a process share an address space
  - processes: do not share address space(s) (of course not, that is the point)
    - (but *can* do so by exporting/importing memory regions (buffers) (not in this course))
- Assume we have support in the OS kernel for user and/or kernel level threads: they can be individually scheduled
- ***Acquire(lock_A); count++; Release(lock_A);***
  - **(1) Acquire(lock) system call**
    - User level library
      - **(2) Push parameters (acquire, lock_name) onto stack**
      - **(3) Trap to kernel (*int* instruction)**
    - Kernel level
      - Interrupt handler
        - **(4) Verify valid pointer to *lock_A***
        - Jump to code for Acquire()
          - **(5a) lock closed: block caller: insert(current, lock_A_wait_queue)** (and then do *schedule* and *dispatch* to some other **thread** in same address space or even to another **process**)
          - **(5b) lock open: close lock_A (**and *schedule* and *dispatch* to library routine (or even to another thread or process)
    - User level: **(6) execute count++**
  - **(7) Release(lock) system call**

Lock Performance and Cost Issues

- Implement the lock-mechanism by spinning or blocking?
- Competition for a lock
  - *Un-contended* = rarely in use by someone else
  - *Contended* = often used by someone else
  - *Held* = currently in use by someone
- Think about the implications of these situations
  - *Contended* (**High** contention lock):
    - Spinning: **Worst** (slow in, many cpu cycles wasted)
    - Blocking: **OK** (slow in, but fewer cycles wasted *relative*)
  - *Un-contended* (**Low** contention lock):
    - Spinning: **Best** (fastest in, few cpu cycles wasted)
    - Blocking: **Bad** (fast in, overhead cpu cycles wasted)

Use of locks when implementing

Block/unblock syscalls

(implemented by the OS Kernel)

- **What we want to achieve**

  q_ref *pos* *tcb_ref* *q_ref* *tcb_ref*

  – **Block** thread on a queue called waitq
    - **insert** (waitq, last, **remove** (readyq, current))

  – **Unblock**
    - **insert** (readyq, **scheduler**, **remove** (waitq, first))

- (By the way, useful instruction:)
  – ("test and set" works both at user and kernel level)

Implementation of Block and Unblock **inside** OS Kernel

- Block (lock)
  - Spin until lock is open %*Why*?
    - Save context to the TCB
    - Enqueue the TCB
  - Open lock
  - goto scheduler

- UnBlock (lock)
  - Spin until lock is open
    - -Dequeue first TCB
    - -Put TCB into ready_queue
  - Open lock
  - goto scheduler

Do we really need a lock if this is implemented inside the kernel?

Is spinning such a good idea inside the kernel?

Two Styles of Synchronization

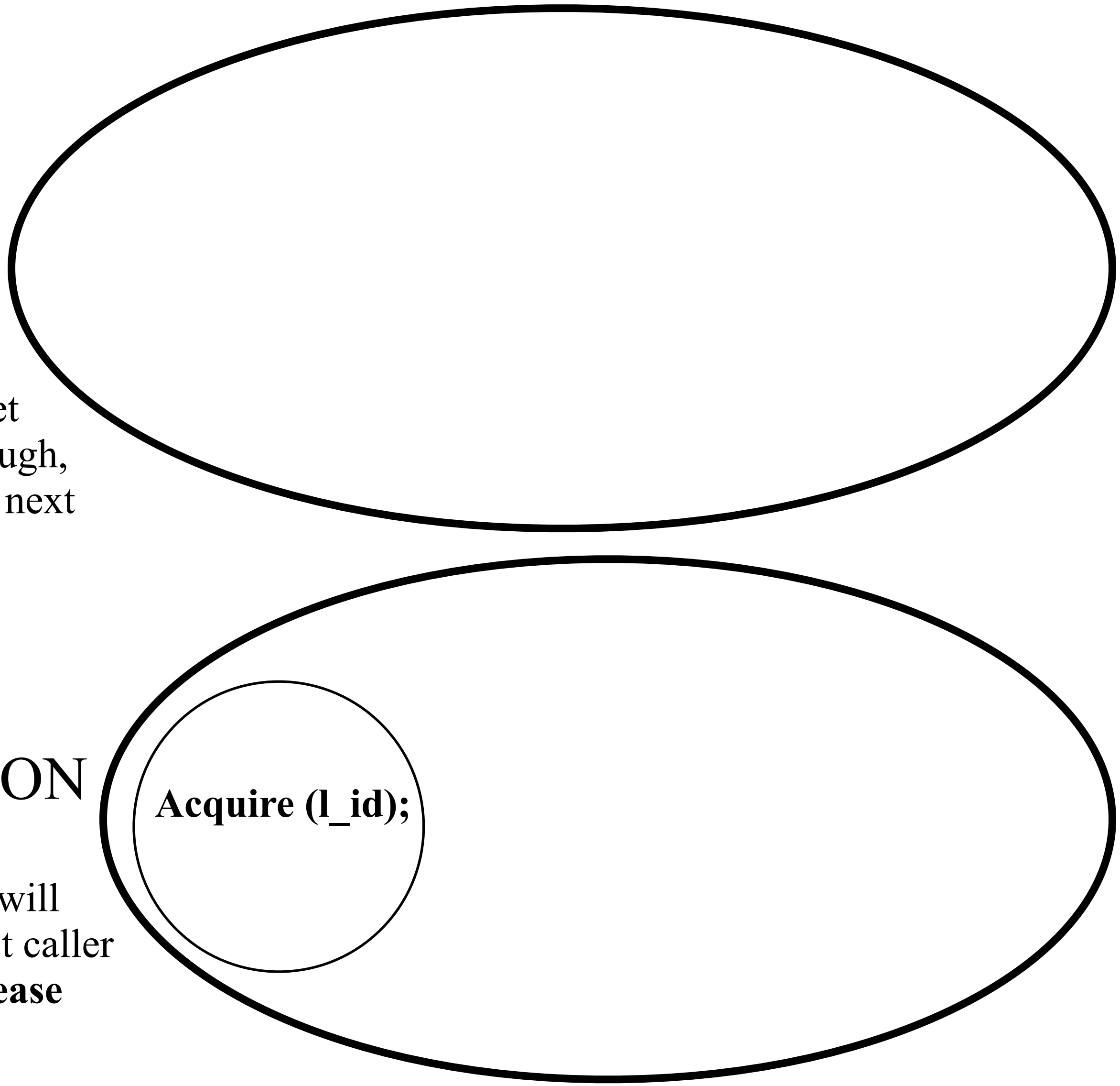
Threads inside one process: Shared address space. They can access the same variables

Process w/two threads

MUTEX

Acquire will let first caller through, and then block next until **Release**

CONDITION SYNCHRONIZATION



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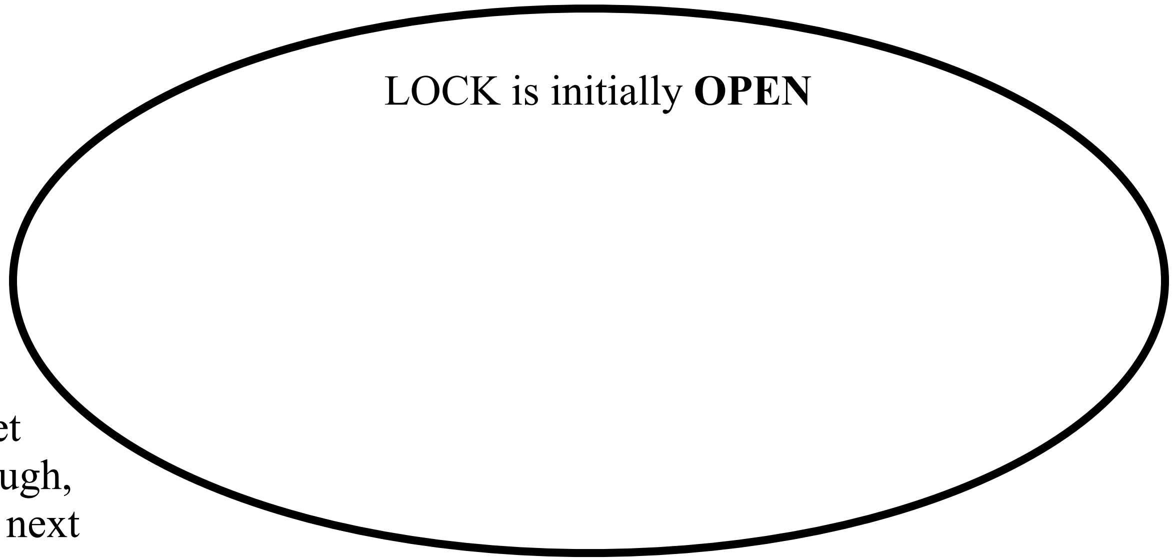

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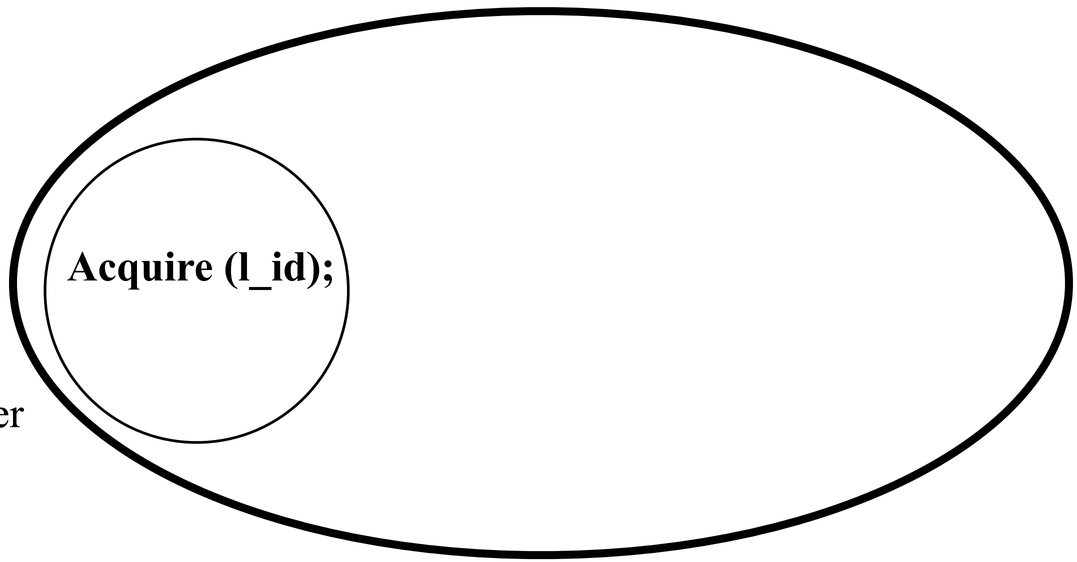

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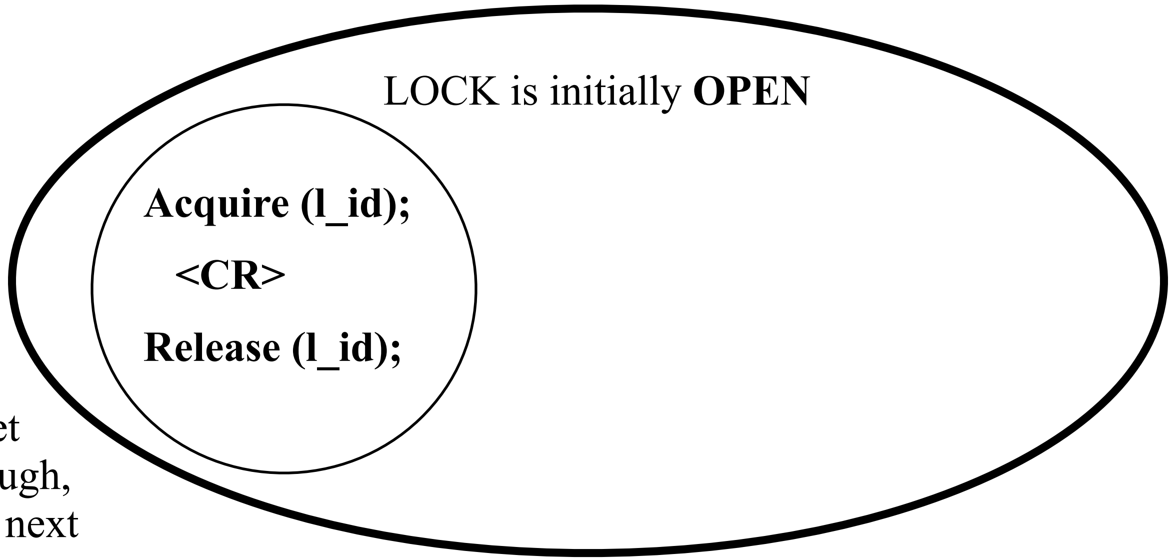

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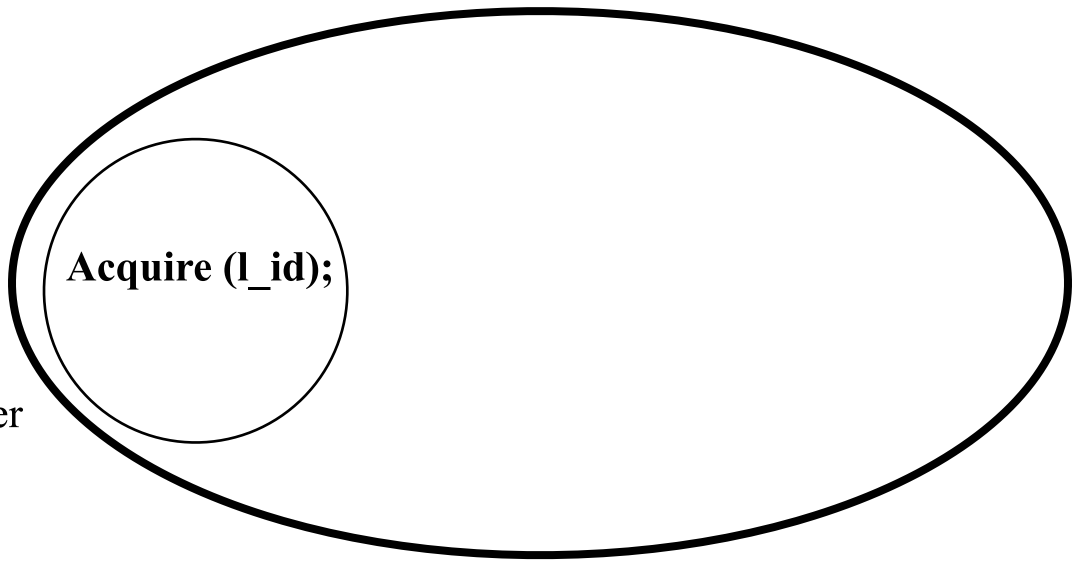

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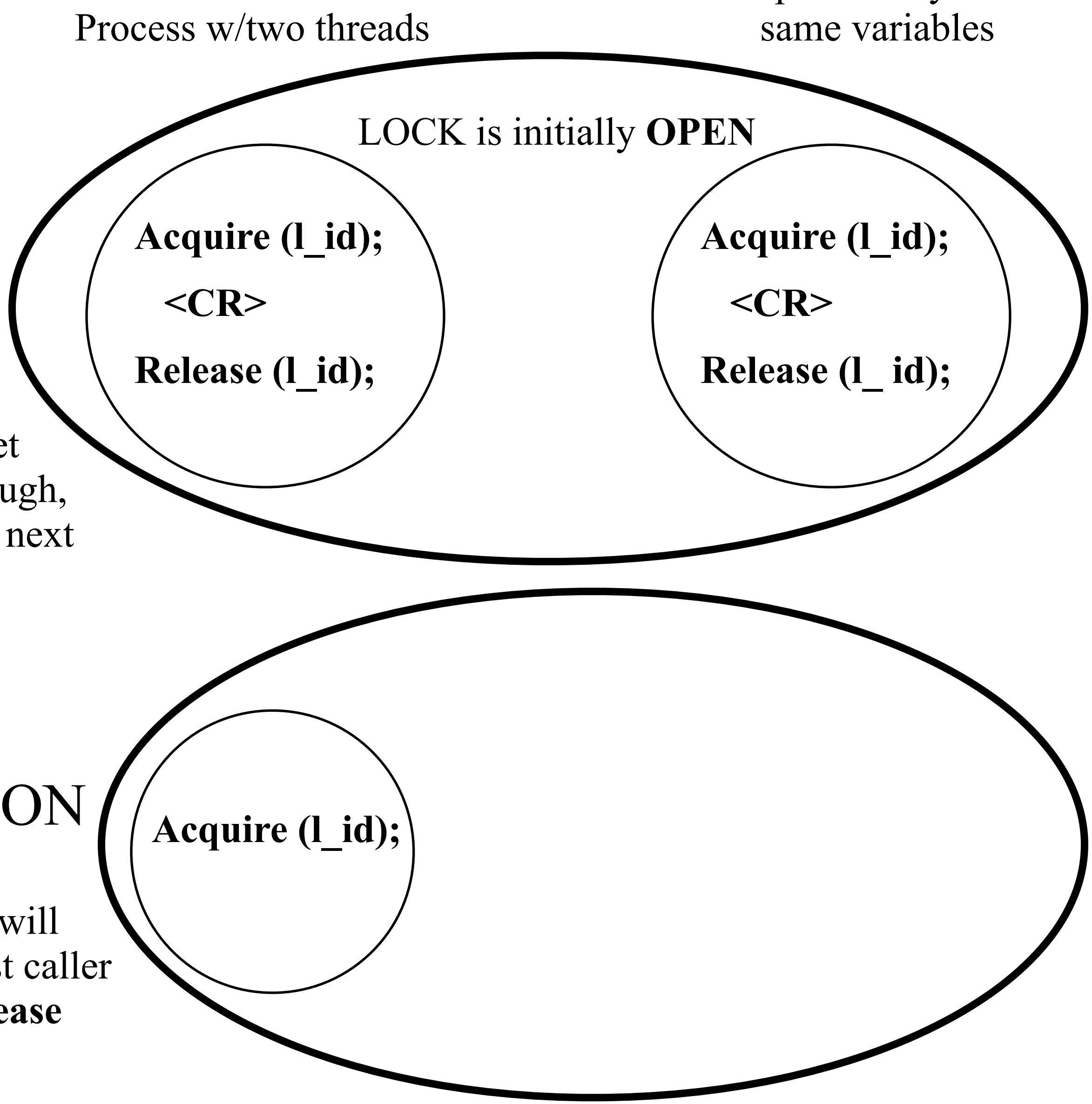

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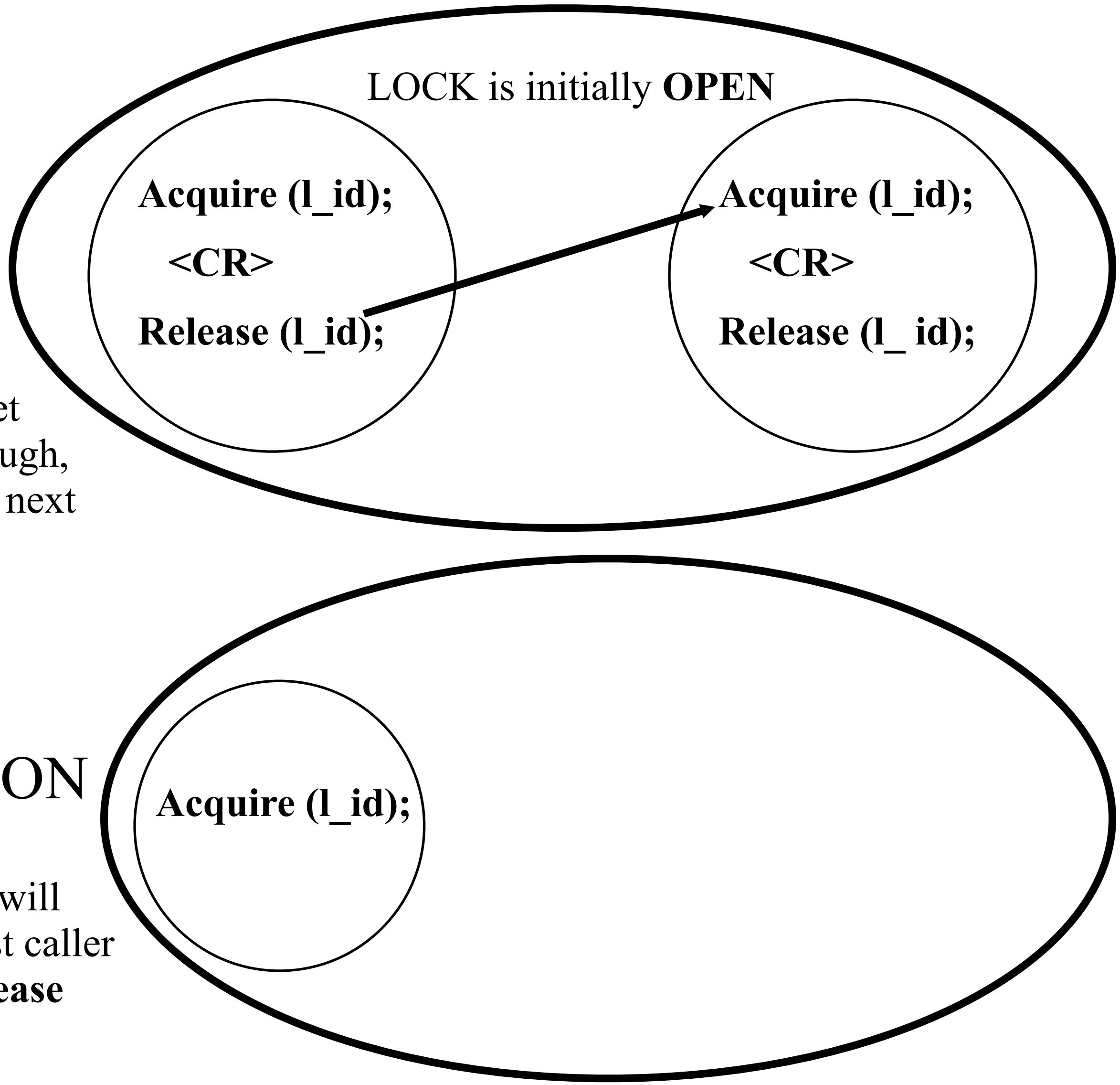

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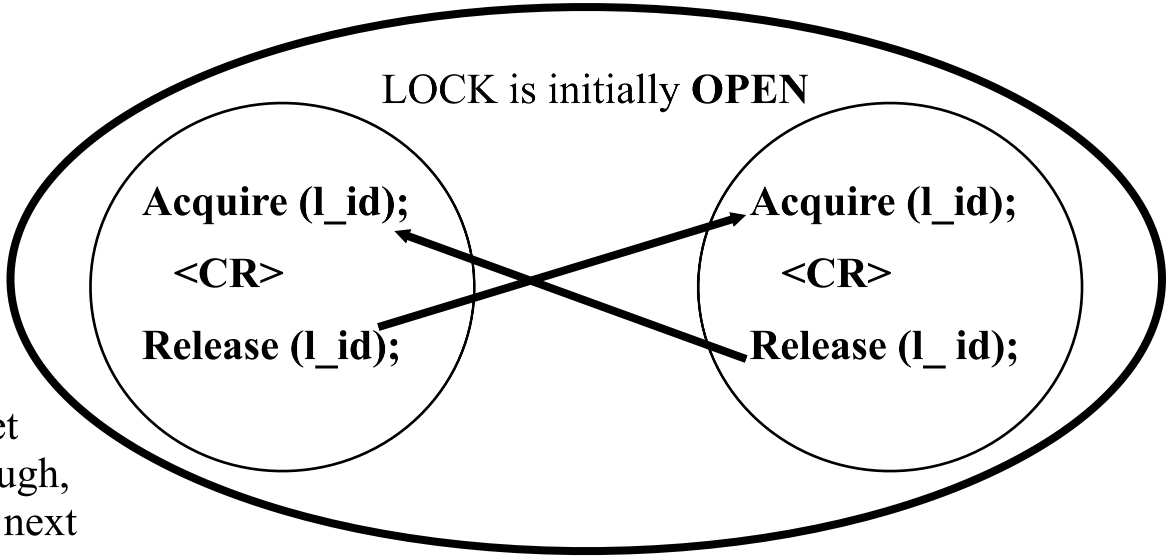

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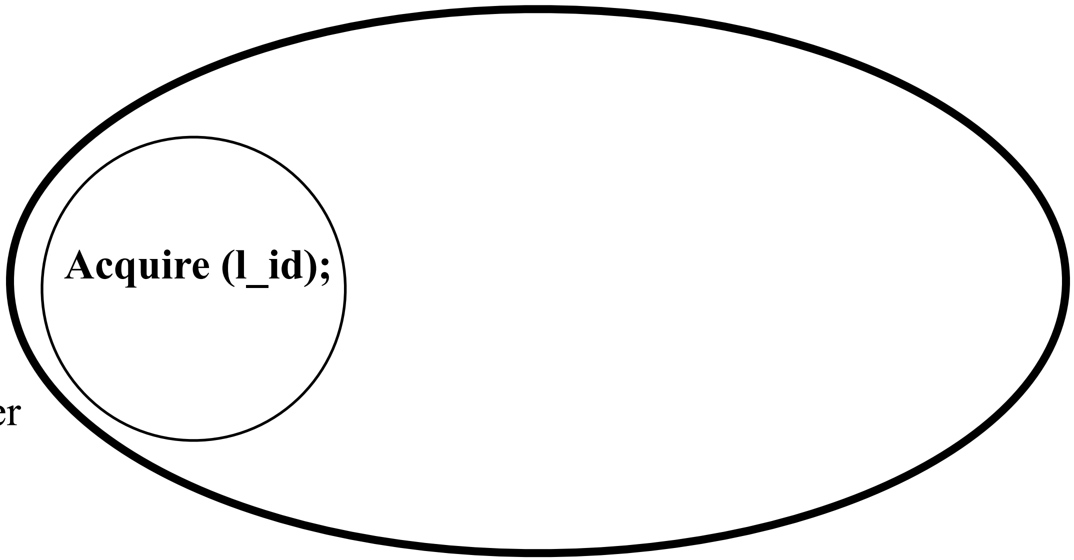

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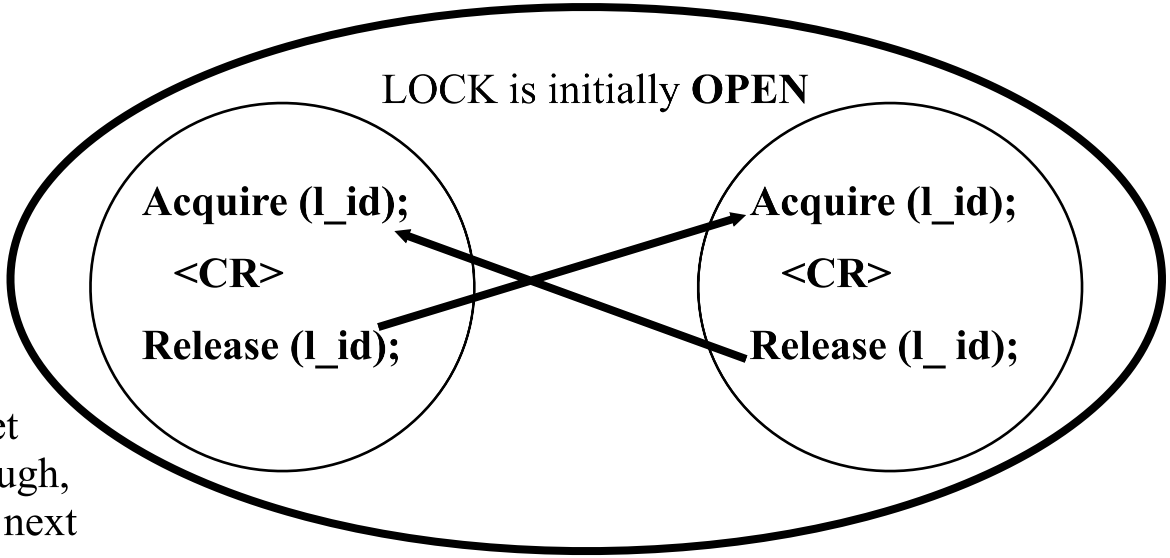

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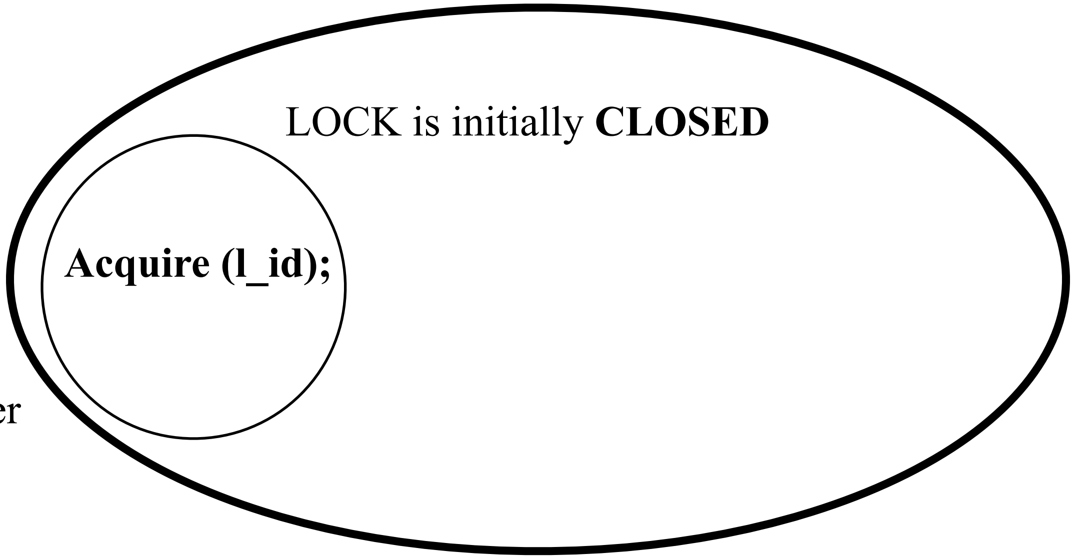

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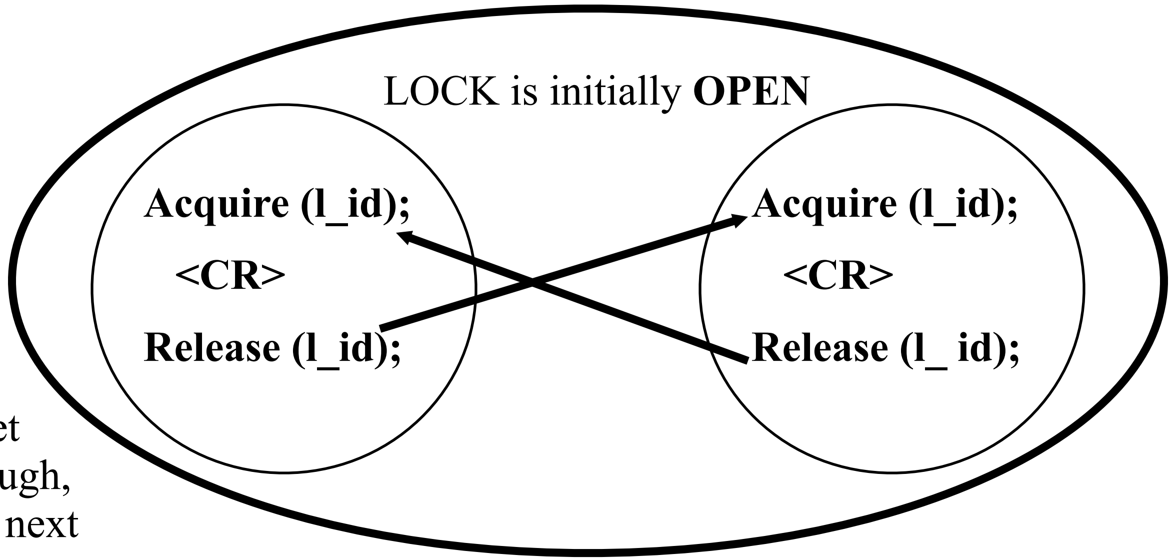

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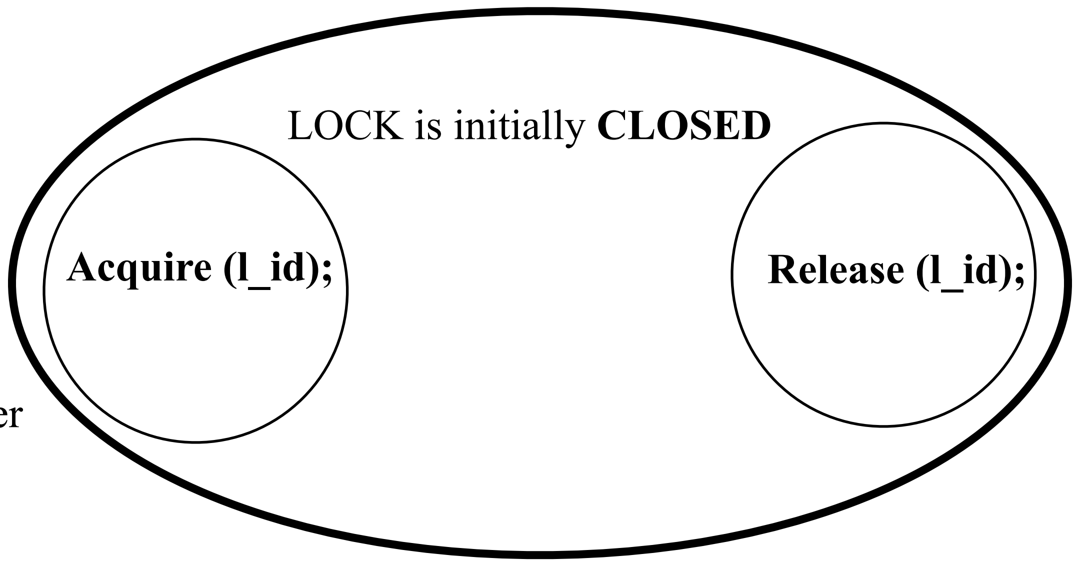

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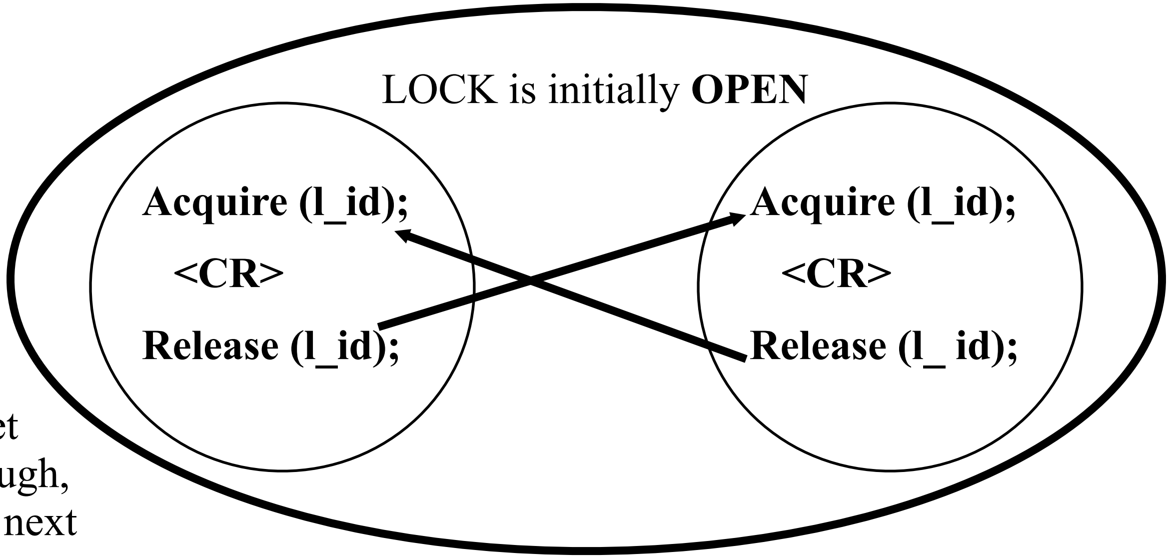

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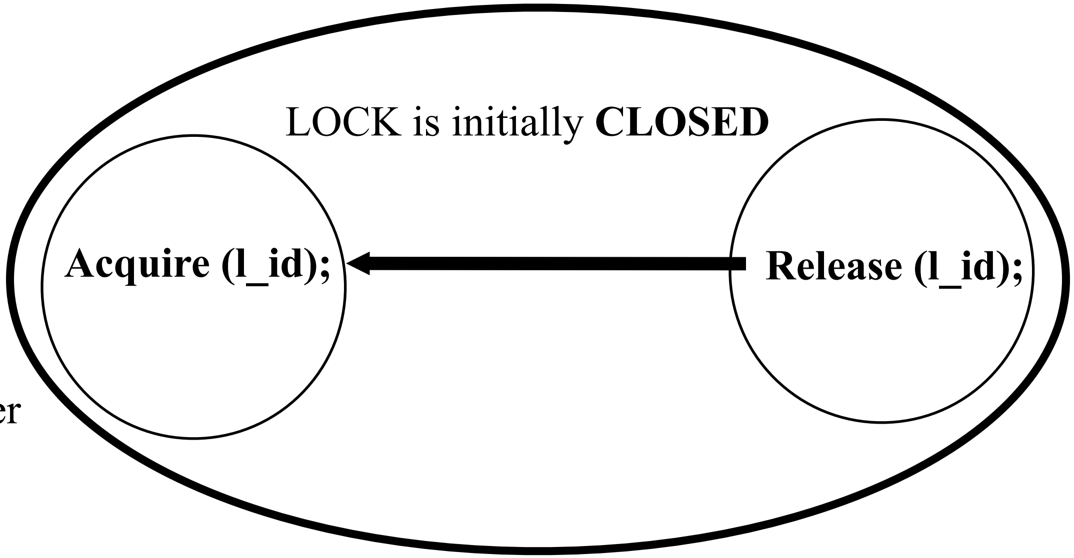

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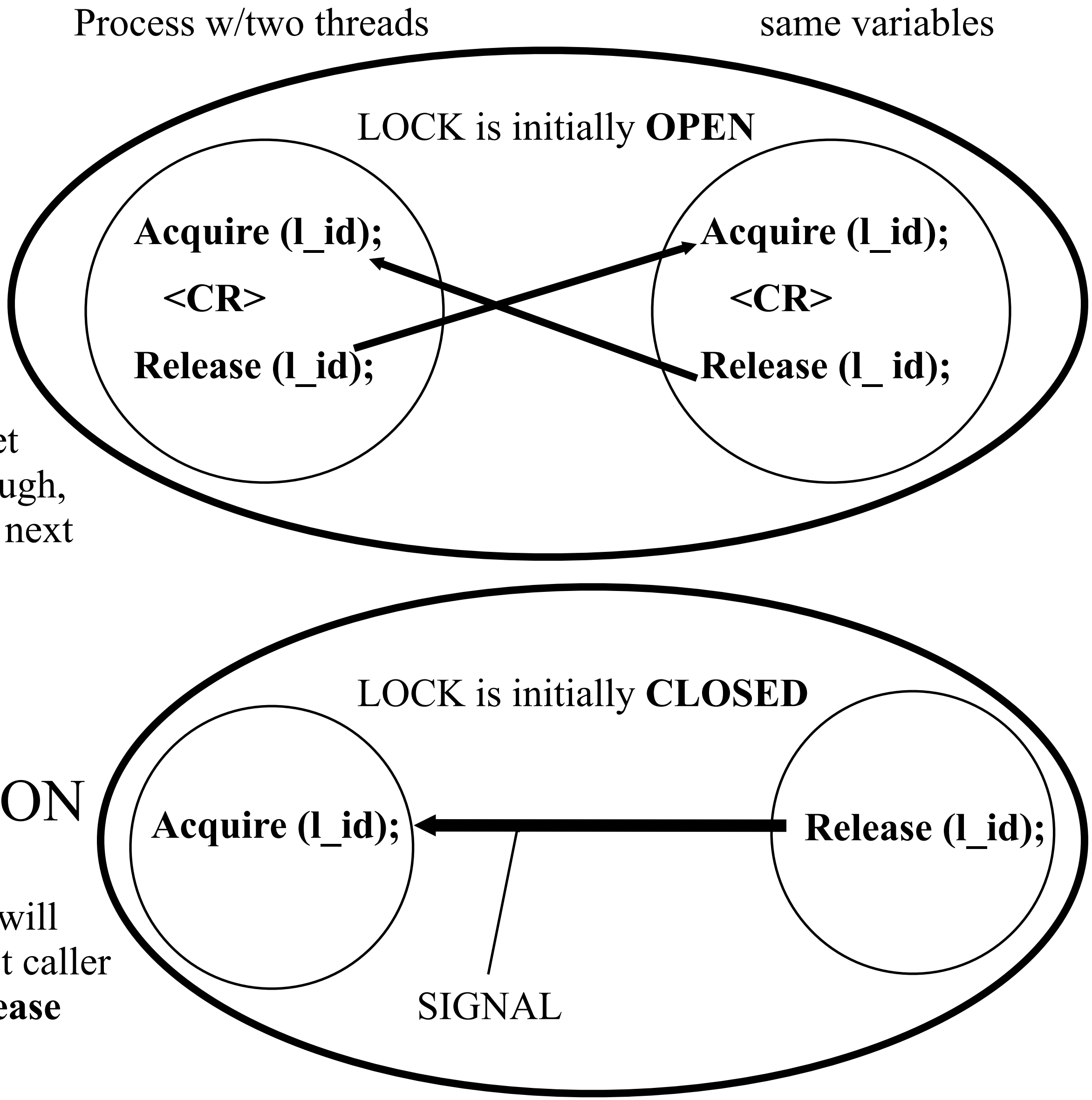

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Acquire will block first caller until **Release**

Think about ...

- Mutual exclusion using Acquire - Release:
  - Easy to forget one of them?
  - Difficult to debug?
    - must check all threads for correct use: “Acquire-CR-Release”
  - No help from the compiler?
    - It does not understand that we mean to say MUTEX
    - But could
      - check to see if we always match them “left-right”
      - associating (by specification/declaration) a variable with a Mutex, and never allow access to the variable outside of CR

Semaphores (Dijkstra, 1965)

Published as an appendix to the paper on the THE operating system

- **Down(s)** a.k.a **Wait(s)** a.k.a **P(s)**
  - itself a critical region: MUTEX
  - DELAY (block, or busy wait) if not positive (s<1)
  - Decrement semaphore value by 1
- **Up(s)** a.k.a **Signal(s)** a.k.a **V(s)**
  - itself a critical region: MUTEX
  - Increment semaphore by 1
  - Wake up the longest waiting thread *if any*

MUTEX

P(s)

```
{
  if (--s < 0)
    Block(s);
}
```

s must NOT be accessible through other means than calling P and V

V(s)

```
{
  if (++s <= 0)
    Unblock(s);
}
```

The semaphore, s, *must* be given an *initial* value

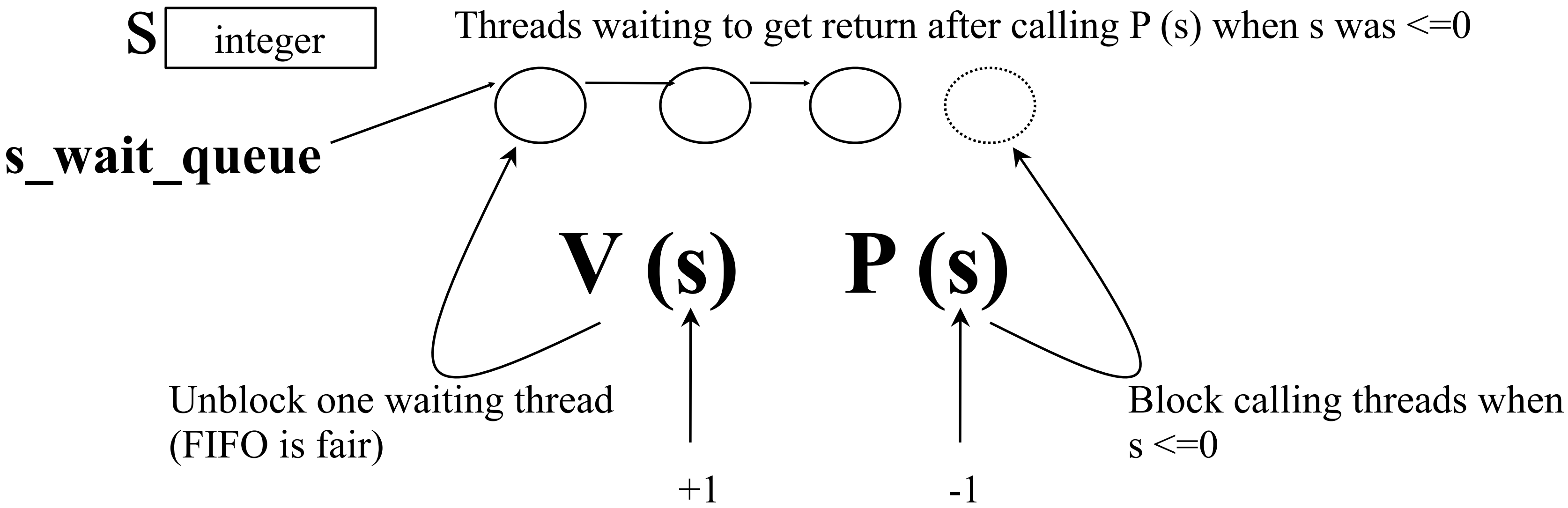
Can get **negative** s: counts number of waiting threads

P: Passieren == to pass
P: Proberen == to test

Dutch words

V: Vrijmagen == to make free
V: Verhogen == to increment

A Blocking Semaphore Implementation



- NB: **s** and **waitq** are *shared resources*

  So what?

- Approaches to achieve atomicity

  Disable interrupts

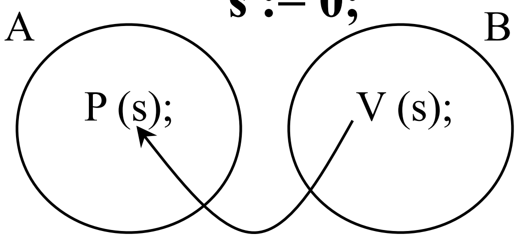
  P() and V() as System calls

  Entry-Exit protocols

Using Semaphores

"The Signal"

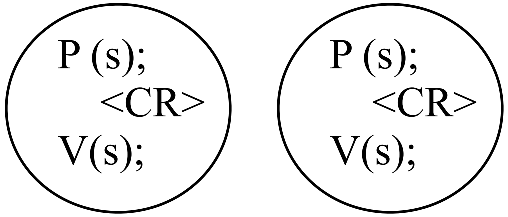
s := 0;



A is delayed until B says V

"The Mutex"

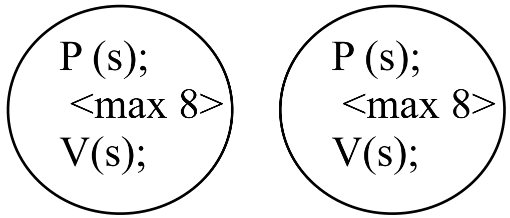
s := 1;



One thread gets in, next is delayed until V is executed

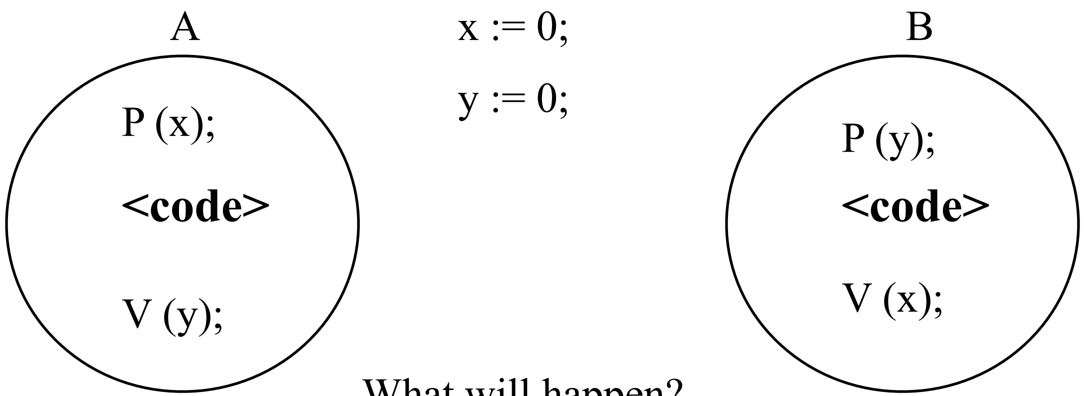
NB: remember to set the initial semaphore value!

s := 8;



Up to 8 threads can pass P, the ninth will block until V is said by one of the eight already in there

Simple to debug?



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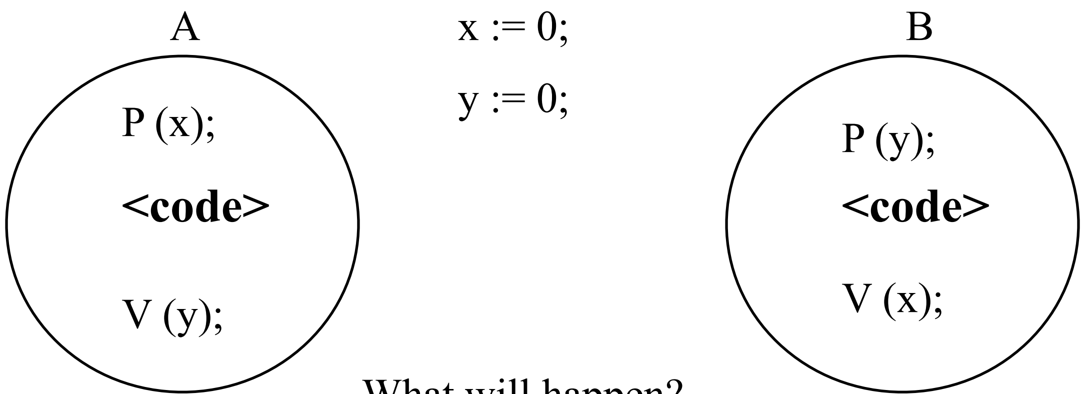

What will happen?

THEY ARE FOREVER WAITING FOR EACH OTHERS SIGNAL

Circular Wait

Classic (but not good) situation resulting in a *Deadlock*

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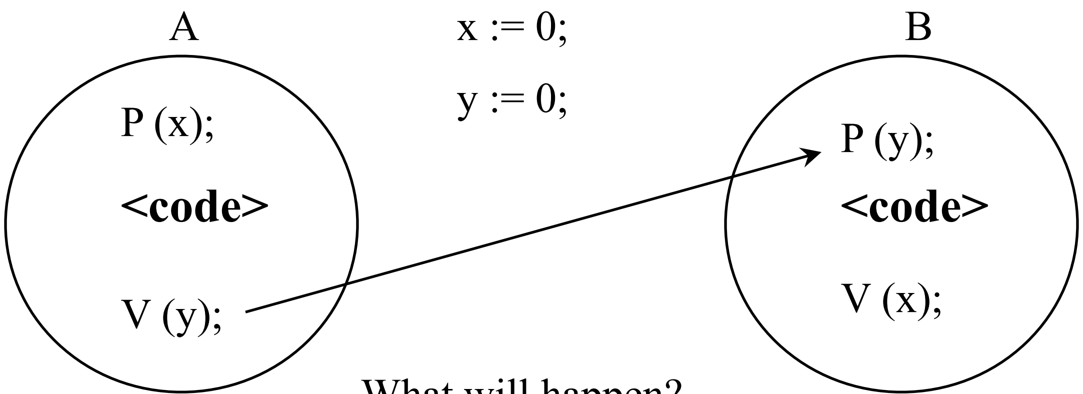

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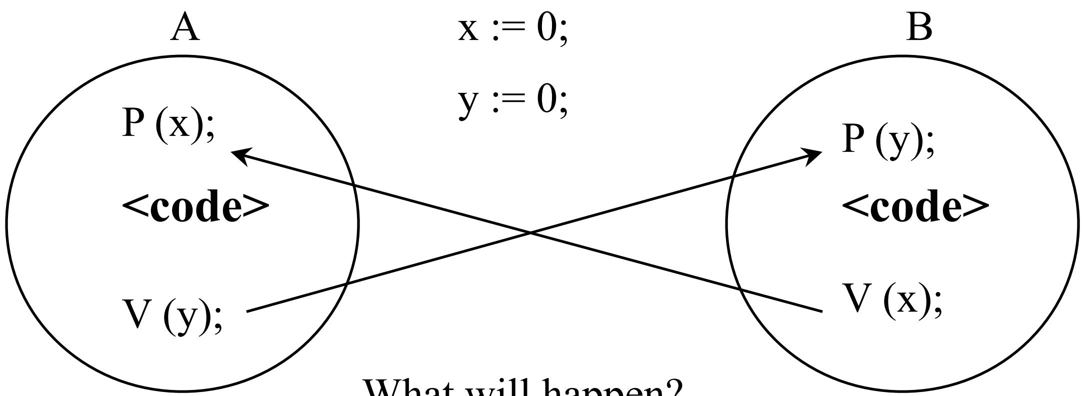

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Circular Wait

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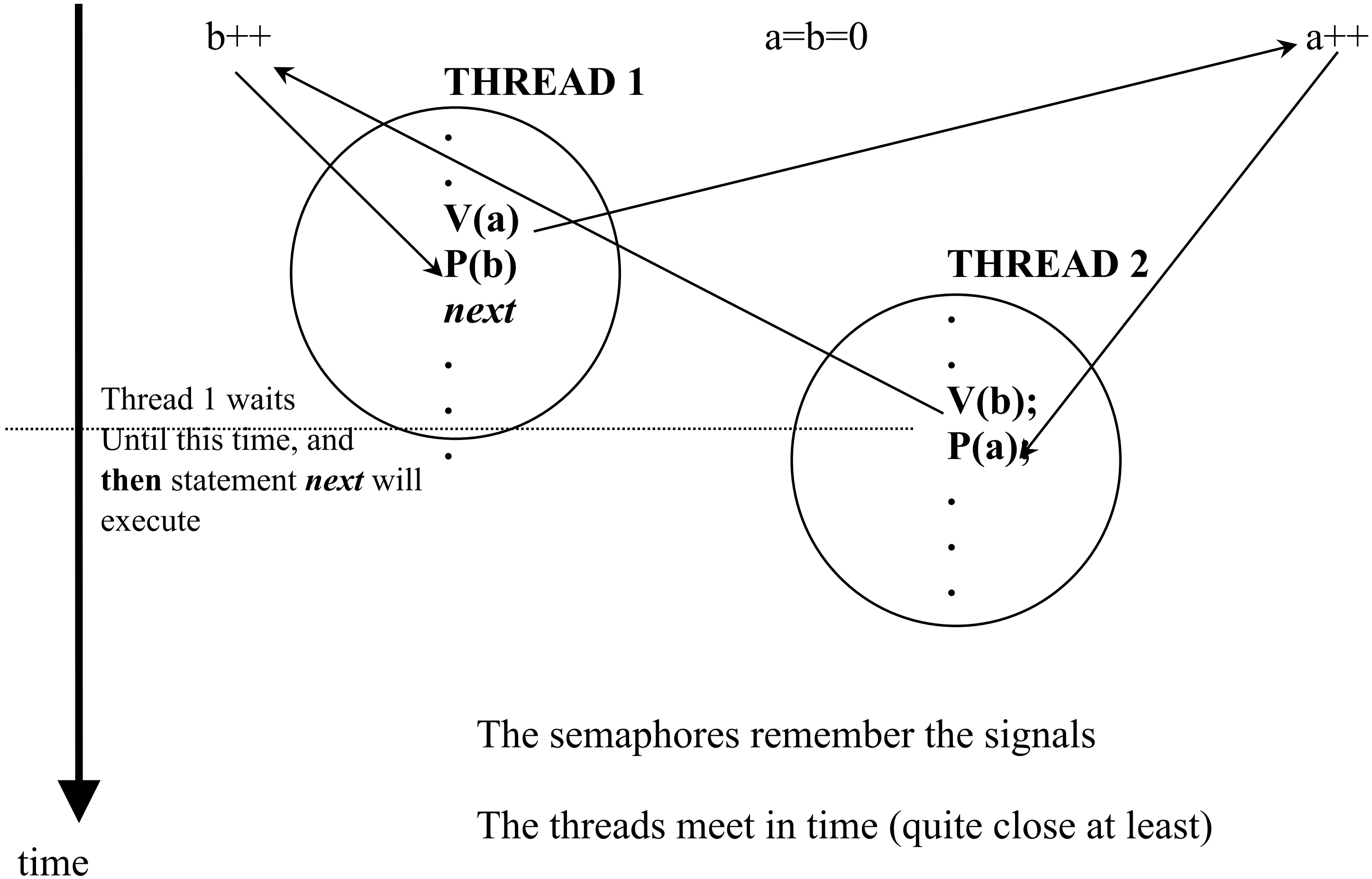
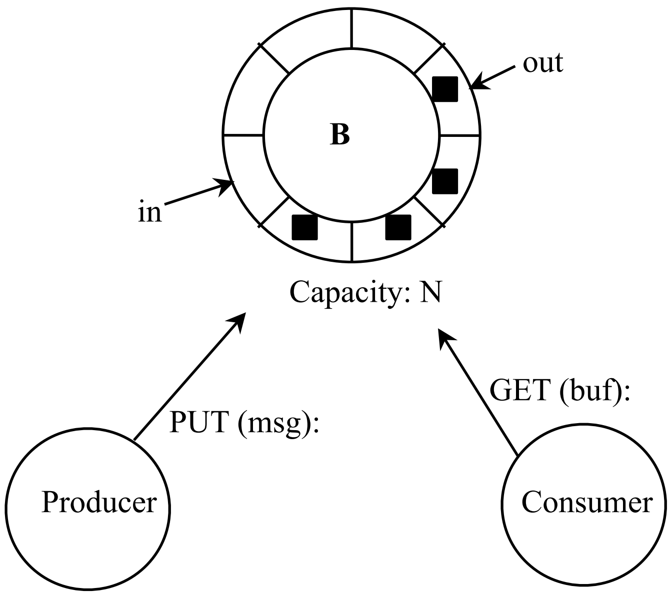
Rendezvous between two threads (or: a *Barrier* for two threads)



The semaphores remember the signals

The threads meet in time (quite close at least)

Bounded Buffer using Semaphores



PUT (msg):
P(nonfull);
P(mutex);
<insert>
V(mutex);
V(nonempty);

GET (buf):
P(nonempty);
P(mutex);
<remove>
V(mutex);
V(nonfull);

Condition synchronization:

•No Get when empty

•No Put when full

Use one semaphore for *each condition* we must wait for to become TRUE:

•B empty: **nonempty**:=**0**

•B full: **nonfull**:=**N**

MUTEX:

•B shared, so must have mutex between Put and Get

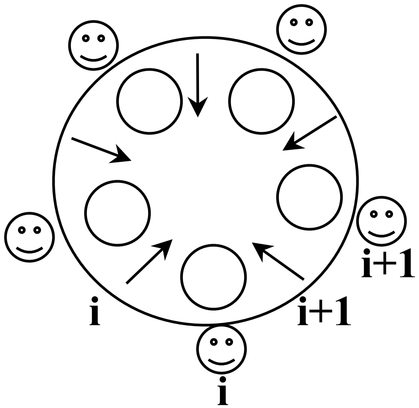
Use one semaphore for *each shared resource* toproytect it from i:

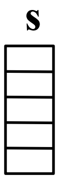
•B mutex: **mutex**:=**1**

•Is Mutex needed when only 1 P and 1 C?

•PUT at one end, GET at other end

“Dining Philosophers”





s(i): One semaphore per fork to be used in **mutex** style P-V

- Each: need 2 forks to eat
- 5 philosophers: 10 forks
- 5 forks: 2 can eat concurrently

Things to observe:

- A fork can only be used by one at a time, please
- No deadlock, please
- No starving, please
- Concurrent eating, please

$\mathbf{T_i}$

$\mathbf{T_i}$

$\mathbf{T_i}$

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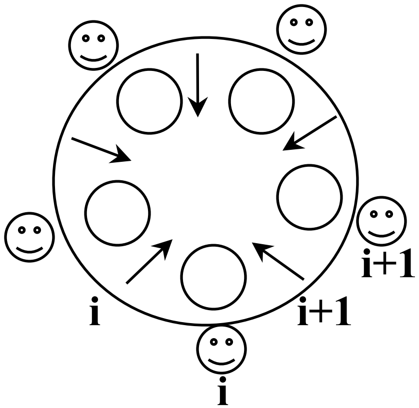

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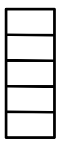

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Mutex on whole table:

•*1 can eat at a time*

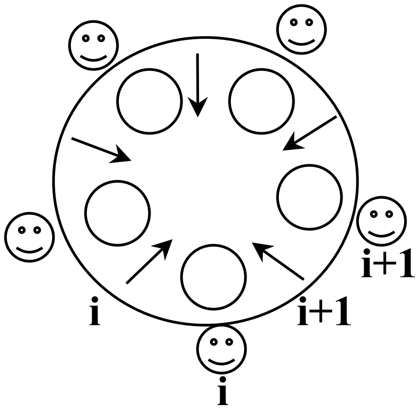
P(mutex);
eat;
V(mutex);

T_i

T_i

T_i

“Dining Philosophers”



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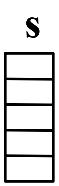

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```
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```

T_i

Get L; Get R;

- *Deadlock possible*

S(i) = 1 initially

```
P(s(i));
  P(s(i+1));
    eat;
  V(s(i+1));
V(s(i));
```

T_i

T_i

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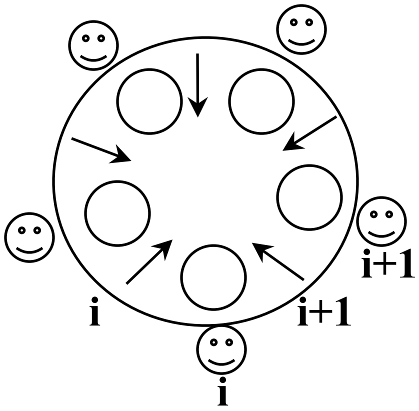

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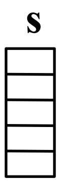
•No starving, please

•Concurrent eating, please



s(i): One semaphore per fork to be used in **mutex** style P-V

Mutex on whole table:

•*1 can eat at a time*

```
P(mutex);
  eat;
V(mutex);
```

T_i

Get L; Get R;

•*Deadlock possible*

S(i) = 1 initially

```
P(s(i));
  P(s(i+1));
    eat;
  V(s(i+1));
V(s(i));
```

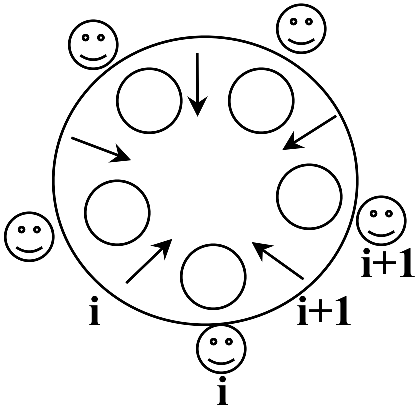
T_i

Get L; Get R if free else Put L;

•*Starvation possible*

T_i

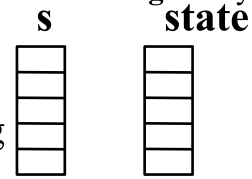
Dining Philosophers



To avoid starvation they could look after each other:

- **Entry**: If L and R is not eating I can
- **Exit**: If L (R) wants to eat and L.L (R.R) is not eating I start him eating

One semaphore per philosopher
Used in **signal** style



- Thinking
- Eating
- Want

S(i) = 0 initially

T_i

```
While (1) {
   <think>
   ENTRY;
      <eat>
   EXIT;
}
```

ENTRY:

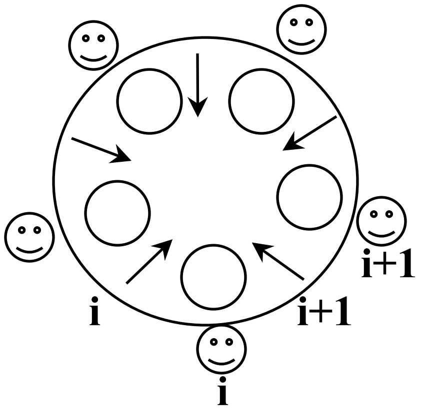
```
P(mutex);
   state(i):=Want;
   if (state(i-1) !=Eating AND state(i+1) != Eating)
   {/*Safe to eat*/
      state(i):=Eating;
      V(s(i));   /*Because  */    }
V(mutex);
P(s(i)); /*Init was 0!! I or right (left) neighbor may have said V(i) to me!*/
```

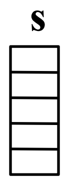
EXIT:

```
P(mutex);
   state(i):=Thinking;
   if (state(i-1)=Want AND state(i-2) !=Eating)
   {
      state(i-1):=Eating;
      V(s(i-1));  /*Start Left neighbor*/
   }
/*Analogue for Right neighbor*/
V(mutex);
```

Trouble: **starvation** pattern possible:
2&4 at table, 1&3 hungry
2 gets up, 1 sits down
4 gets up, 3 sits down
3 gets up, 4 sits down
1 gets up, 2 sits down
Ad infinitum => Phil 0 will starve

Dining Philosophers





S(i) = 1 initially

Can we in a simple way do better than this one?

Get L; Get R;

- Deadlock possible

```
P(s(i));
   P(s(i+1));
      eat;
   V(s(i+1));
V(s(i));
```

- Remove the danger of circular waiting (deadlock)
- T1-T4: Get L; Get R;
- T5: Get R; Get L;

T_1, T_2, T_3, T_4:

```
P(s(i)):
   P(s(i+1));
      <eat>
   V(s(i+1));
V(s(i));
```

T_5

```
P(s(1));
   P(s(5));
      <eat>
   V(s(5));
V(s((1));
```

- **Non-symmetric solution. Still quite elegant**

A Spinning Semaphore Implementation?

MUTEX

P(s):

```
while (s <= 0) {};
s--;
```

V(s):

```
s++;
```

A Spinning Semaphore Implementation?

MUTEX

P(s):

```
while (s <= 0) {};
s--;
```

V(s):

```
s++;
```

“You Got a Problem with This?”

Spinning Semaphore

P(s):

```
while (s <= 0) {};
s--;
```

V(s):

```
s++;
```

Spinning Semaphore

P(s):

```
while (s <= 0) {};
s--;
```

V(s):

```
s++;
```

If P spinning inside mutex then V will not get in

- *Starvation possible (Lady Luck may ignore/favor some threads)*
  - *Of P's*
  - *Of V's*

Must open mutex, say, between every iteration of while() to make it possible for V to get in

- *Costly*
  - *Every 10th iteration?*
    - *Latency*

Implementation of Semaphores

- Implementing the P and V of semaphores
  - If WAIT is done by blocking
    - Expensive
    - Must open mutex
      - But no real problems because we have a waiting queue now and we will not get starvation
  - If done by spinning
    - Must open mutex during spin to let V in
      - Starvation of P's and V's possible
        - May not be a problem in practice
- What can we do to "do better"?

Implementing Semaphores using **Locks**

Using **locks** to implement a **semaphore**

- mutex lock: lock is initially **open**
- “delay me” lock: lock is initially **locked**

- SEMAPHORE value is called “s.value” in the code below: Initially **0**

```
P(s) {
  Acquire(s.mutex);
  if (--s.value < 0) {
    Release(s.mutex);
    Acquire(s.delay);
  } else
    Release(s.mutex);
}
```

```
V(s) {
  Acquire(s.mutex);
  if (++s.value <= 0)
    Release(s.delay);
  Release(s.mutex);
}
```

Trouble

Lost V calls

- Kotulski (1988)
  - Two processes call P(s) (s.value is initialized to 0) and preempted after Release(s.mutex)
  - Two other processes call V(s)

Hemmendinger's solution (1988)

```
P(s) {
  Acquire(s.mutex);
  if (--s.value < 0) {
    Release(s.mutex);
    Acquire(s.delay);
  }
  Release(s.mutex);
}
```

```
V(s) {
  Acquire(s.mutex);
  if (++s.value <= 0)
    Release(s.delay);
  else
    Release(s.mutex);
}
```

- The idea is not to release s.mutex and turn it over individually to the waiting process
- P and V are executing in locksteps

Kearn's Solution (1988)

```
P(s) {
  Acquire(s.mutex);
  if (--s.value < 0) {
    Release(s.mutex);
    Acquire(s.delay);
    Acquire(s.mutex);
    if (--s.wakecount > 0)
      Release(s.delay);
  }
  Release(s.mutex);
}
```

```
V(s) {
  Acquire(s.mutex);
  if (++s.value <= 0) {
    s.wakecount++;
    Release(s.delay);
  }
  Release(s.mutex);
}
```

Two Release(s.delay) calls are also possible

Hemmendinger's Correction (1989)

```
P(s) {
  Acquire(s.mutex);
  if (--s.value < 0) {
    Release(s.mutex);
    Acquire(s.delay);
    Acquire(s.mutex);
    if (--s.wakecount > 0)
      Release(s.delay);
  }
  Release(s.mutex);
}
```

```
V(s) {
  Acquire(s.mutex);
  if (++s.value <= 0) {
    s.wakecount++;
    if (s.wakecount == 1)
      Release(s.delay);
  }
  Release(s.mutex);
}
```

Correct but a complex solution

Hsieh's Solution (1989)

```
P(s) {
  Acquire(s.delay);
  Acquire(s.mutex);
  if (--s.value > 0)
    Release(s.delay);
  Release(s.mutex);
}
```

```
V(s) {
  Acquire(s.mutex);
  if (++s.value == 1)
      Release(s.delay);
  Release(s.mutex);
}
```

- Use Acquire(s.delay) to block processes
- Correct but still a constrained implementation

Example: Condition Synchronization between Interrupt Handler and Device Driver

- A device thread and the interrupt handler
  - need to handle shared data between them

semaphore s; s=0;