Operating Systems

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Inter-process Communication and Synchronization

- Processes/threads may need to exchange information
- Processes/threads should not get in each other's way
- Processes/threads should access resources in the right sequence
- Need to coordinate the activities of multiple threads
- Need to introduce the notion of *synchronization operations*
- These operations allow threads to control the timing of their events relative to events in other threads

Asynchrony and Race Conditions

- Threads need to deal with asynchrony
- Asynchronous events occur arbitrarily during thread execution:
  - An interrupt causes transfer being taken away from the current thread to the interrupt handler
  - A timer interrupt causes one thread to be suspended and another one to be resumed
  - Two threads running on different CPUs read and write the same memory
- Threads must be designed so that they can deal with such asynchrony
- (If not, the code must be protected from asynchrony)

Race Conditions

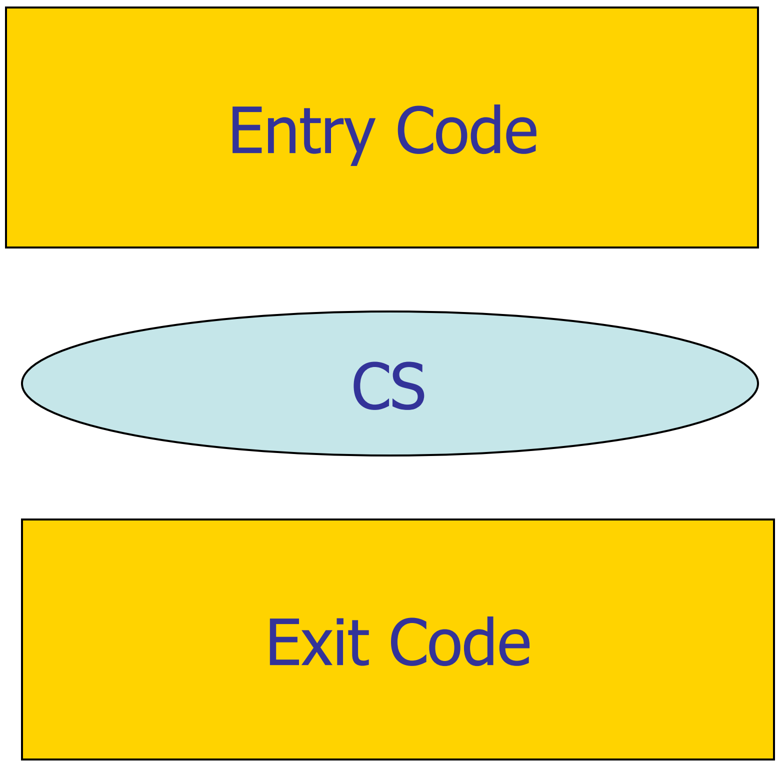
- Two threads, A and B, need to insert objects into a list, so that it can be processed by a third thread, C
- Both A and B
  - Check which is the first available slot in the list
  - Insert the object in the slot
- Everything seems to run fine until...
  - Thread A finds an available slot but gets suspended by the scheduler
  - Thread B finds the same slot and inserts its object
  - Thread B is suspended
  - Thread is resumed and inserts the object in the same slot
- B's object is lost!

Critical Regions and Mutual Exclusion

- The part of the program where shared memory is accessed is called a *critical region* (or *critical section*)
- Critical regions should be accessed in *mutual exclusion*

- Solution: Synchronization
  - No two processes may be simultaneously inside the same critical region
  - No process running outside the critical region should block another process
  - No process should wait forever to enter its critical region
  - No assumptions can be made about speed/number of CPUs

Entering and Exiting Critical Regions



Mutual Exclusion With Busy Waiting

- First solution: Disable interrupts when in critical region
  - What if the process “forgets” to re-enable interrupts?
  - What if there are multiple CPUs?
- Second solution: a lock variable
  - Test if lock is 0
  - If not, loop on check until 0
  - When lock is 0, set it to 1 and start critical region
  - Set it back to 0 when finished
  - ... do you see any problem?
- Third solution: strict alternation

Taking Turns...

turn Initially set to 0

while (turn != 0) { }	while (turn != 1) { }
CS	CS
turn=1;	turn=0;

Taking Turns...

- What if thread 0 is much faster than thread 1?
- Thread 0 may be waiting for its turn even if thread 1 is outside the critical region
- We said:
  - No process running outside the critical region should block another process
- Need for something better: Peterson's algorithm

Peterson's Algorithm

Process 0

```
interested_0 = TRUE;
turn = 0;
while (interested_1 == TRUE
        && turn == 0) { };
```

CS

```
interested_0 = FALSE;
```

Process 1

```
interested_1 = TRUE;
turn = 1;
while (interested_0 == TRUE
        && turn == 1) { };
```

CS

```
interested_1 = FALSE;
```

Test And Set Lock Instruction

- If the hardware (that is, the CPU) provides an atomic way of testing and setting a lock, life is easier
- TSL RX, LOCK
  - Reads contents of address LOCK into RX
  - Stores a nonzero value into location LOCK
- Now back to lock variables

```
enter: TSL RX, LOCK
       CMP RX, #0
       JNE enter
       RET
leave: MOV LOCK, #0
       RET
```

Sleep and Wakeup

- Busy waiting is a waste of CPU
- Need to provide a mechanism so that a thread can suspend when a critical region cannot be entered
  - Sleep() blocks the thread
  - Wakeup() resumes a thread
- Classical problem: Producer and Consumer communicating through a set of buffers
- Number of buffers (N) is limited
  - 0 buffers available ➔ consumer must wait
  - N buffers filled ➔ producer must wait

Producer/Consumer Problem

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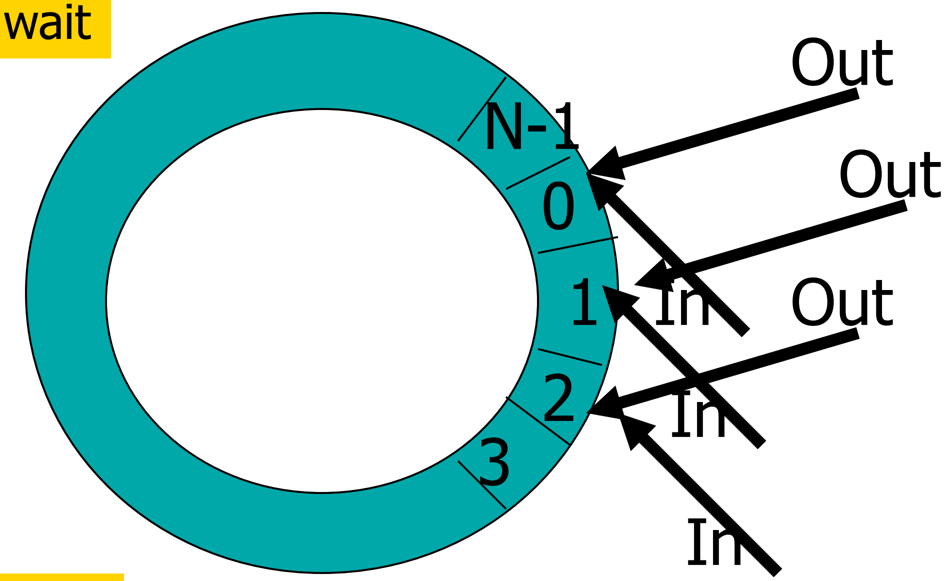
Count=0 ➔ Consumer must wait



Count=N ➔ Producer must wait

Producer/Consumer


```
in = 0;
out = 0;
count = 0;
```

```
Producer:
while (1) {
    item = produce_item();
    if (count == N) sleep();
    buff[in]=item;
    in=(in+1) % N;
    count=count+1;
    if (count == 1)
        wakeup(consumer)
}
```

```
Consumer:
while (1) {
    if (count == 0) sleep();
    item = buff[out];
    out=(out+1) % N;
    count = count-1;
    if (count == N-1)
        wakeup(producer)
    consume_item(item);
}
```

Missing the Wake Up Call

- Buffer is empty
- Consumer reads counter and gets 0
- Before falling asleep, there is a context switch to the Producer thread
- Producer inserts item and, since count==1, sends a wakeup
- Consumer is not sleeping and wakeup signal gets lost
- Control returns to Consumer that falls asleep (the check on count has been done before)
- Producer continues until count reaches N and then falls asleep: Game Over...

Semaphores

- Edward Dijkstra suggested to use an integer variable to count the number of wakeups issued
- New type, the Semaphore
  - Semaphore(count) creates and initializes to count
  - P() or down()
    - If the counter is greater than 0 then decrements the counter and returns
    - If counter = 0 the process suspends. When it wakes up decrements the counter and returns
  - V() or up()
    - Increments the counter
    - If there are any process waiting on the semaphore one is woken up
    - Returns
  - down() and up() are ATOMIC operations

Semaphores and Mutual Exclusion

mutex

Semaphore with count = 1, initial value 1

```
mutex.down();
```

CS

```
mutex.up();
```

```
mutex.down();
```

CS

```
mutex.up();
```

Threads - Revisited


```
 1: int i;
 2: Semaphore sema;
 3:
 4: f()
 5: {
 6:     printf("i is %d\n", i);
 7: }
 8:
 9: int main(int argc, char **argv)
10: {
11:     .. (do stuff here) ..
12:     P(sema);
13:     i = get_input();
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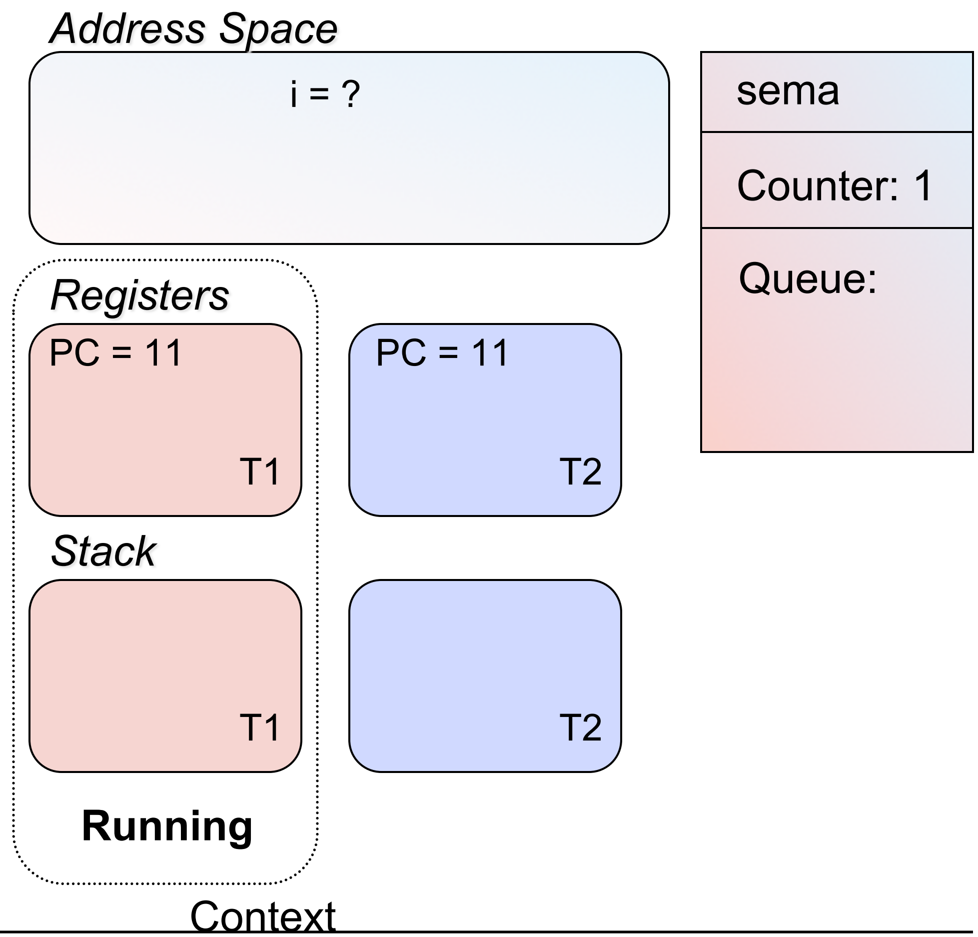
```



Threads - Revisited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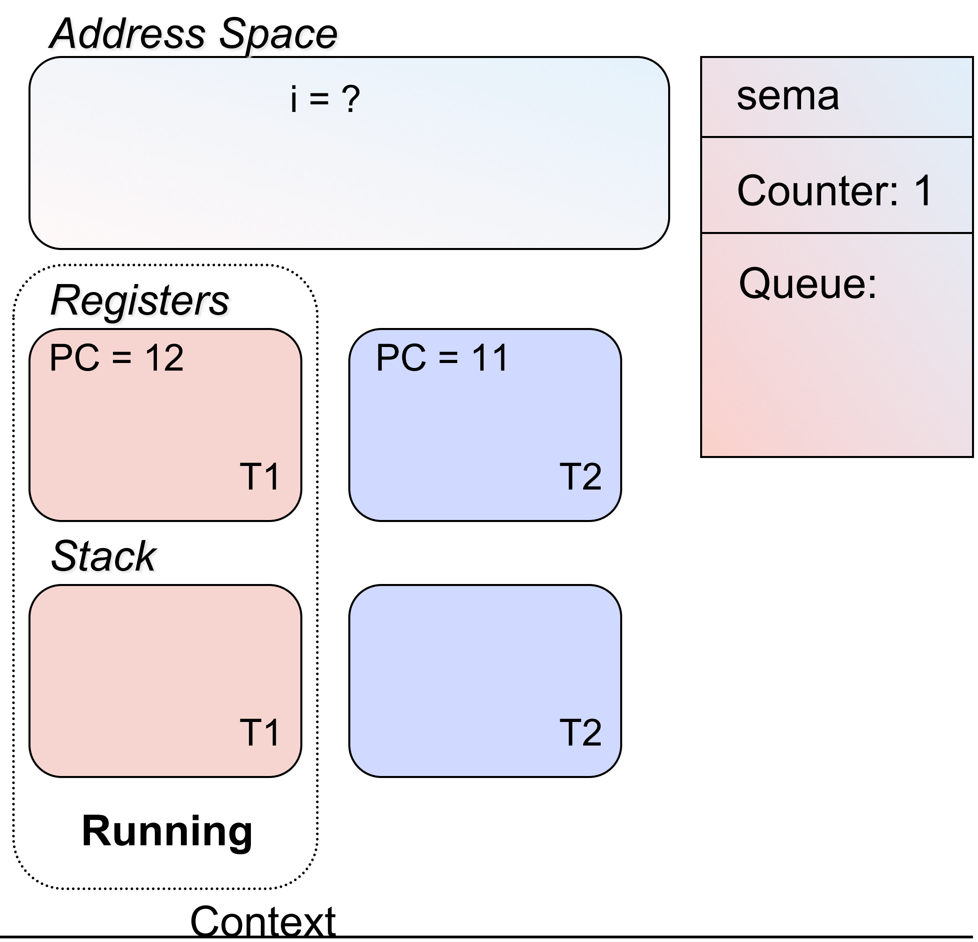

Threads - Revisited


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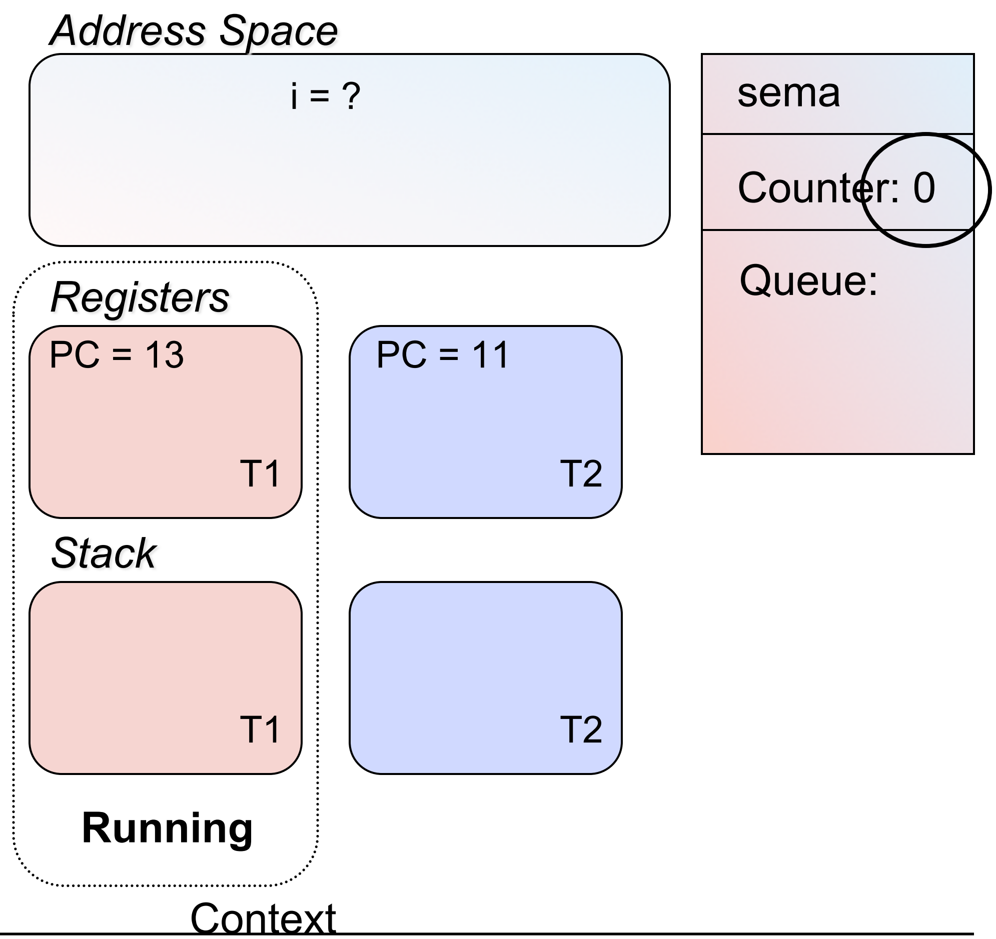

Threads - Revisited


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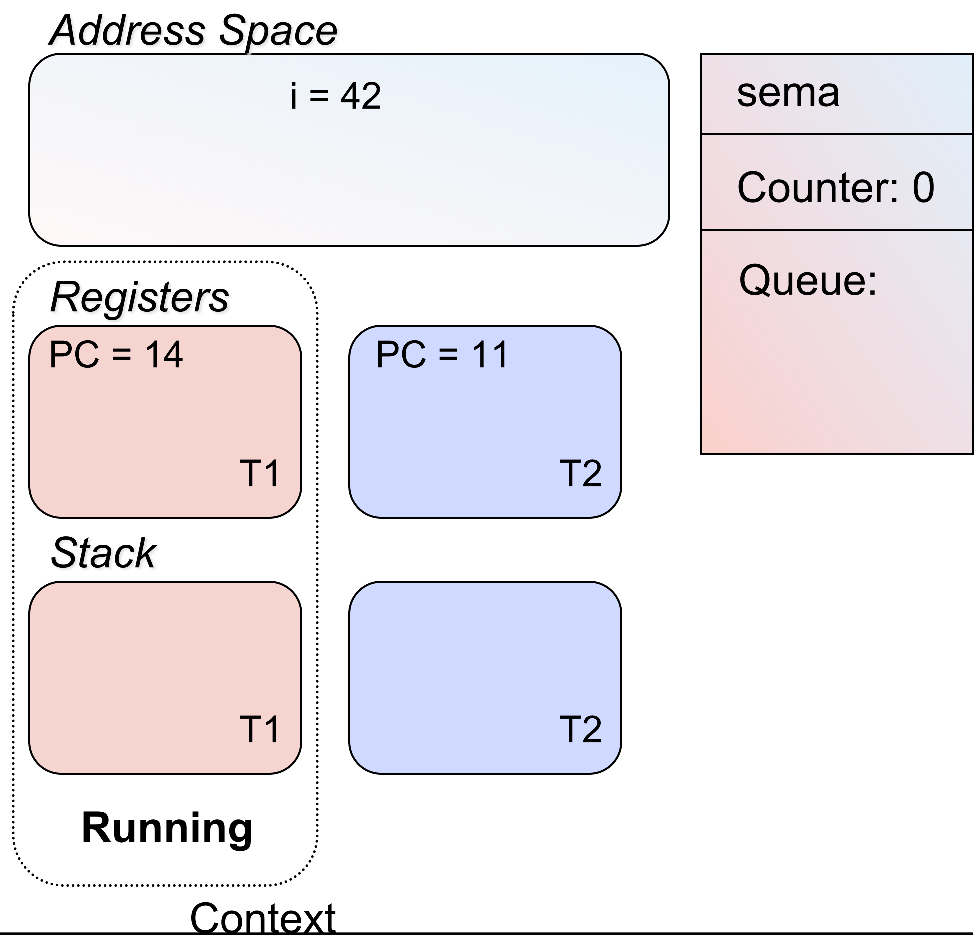
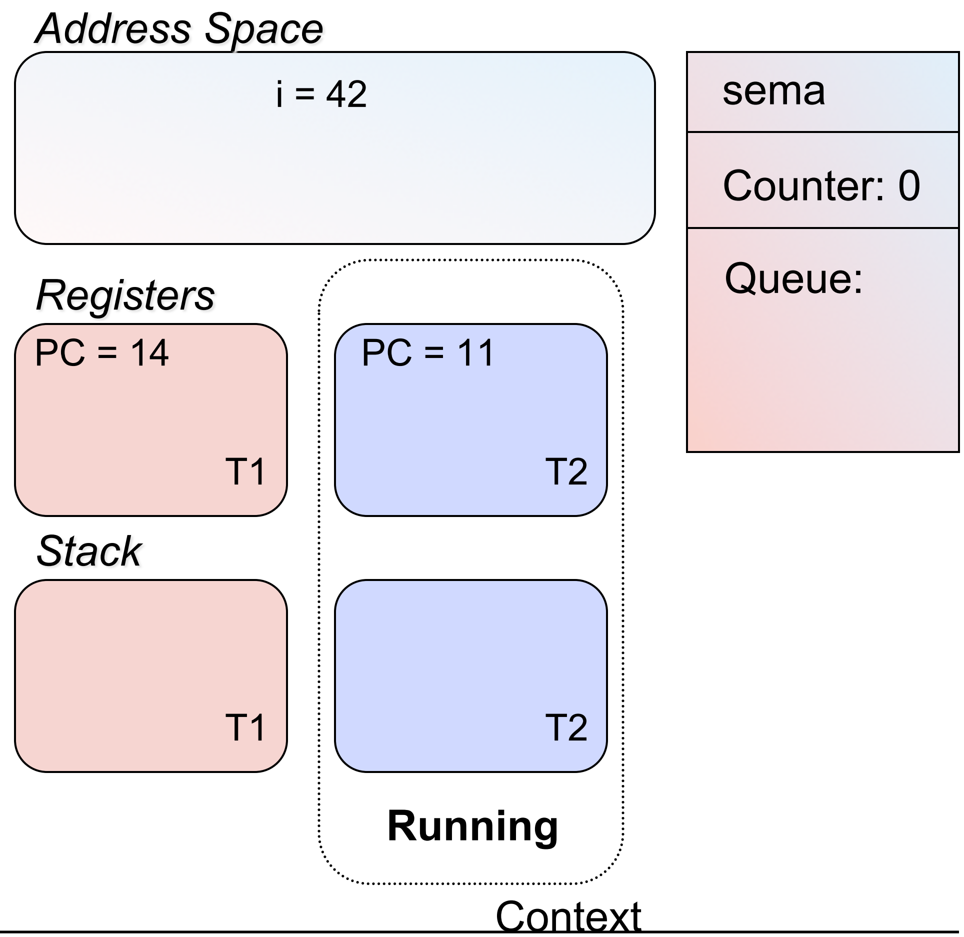


Threads - Revisited


```
int i;
Semaphore sema;

f()
{
    printf(“i is %d\n“, i);
}

int main(int argc, char **argv)
{
    .. (do stuff here) ..
    P(sema);
    i = get_input();
    f();
    V(sema);
    return 0;
}
```



Threads - Revisited

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3:
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5:  {
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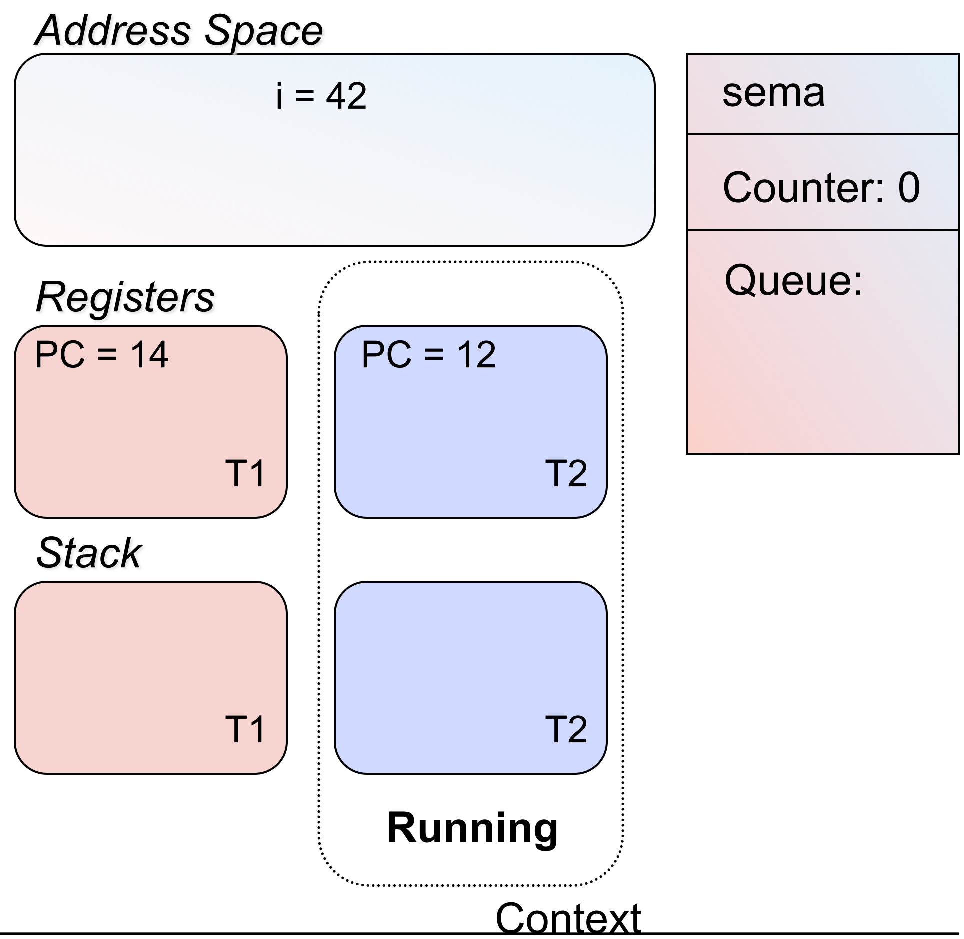
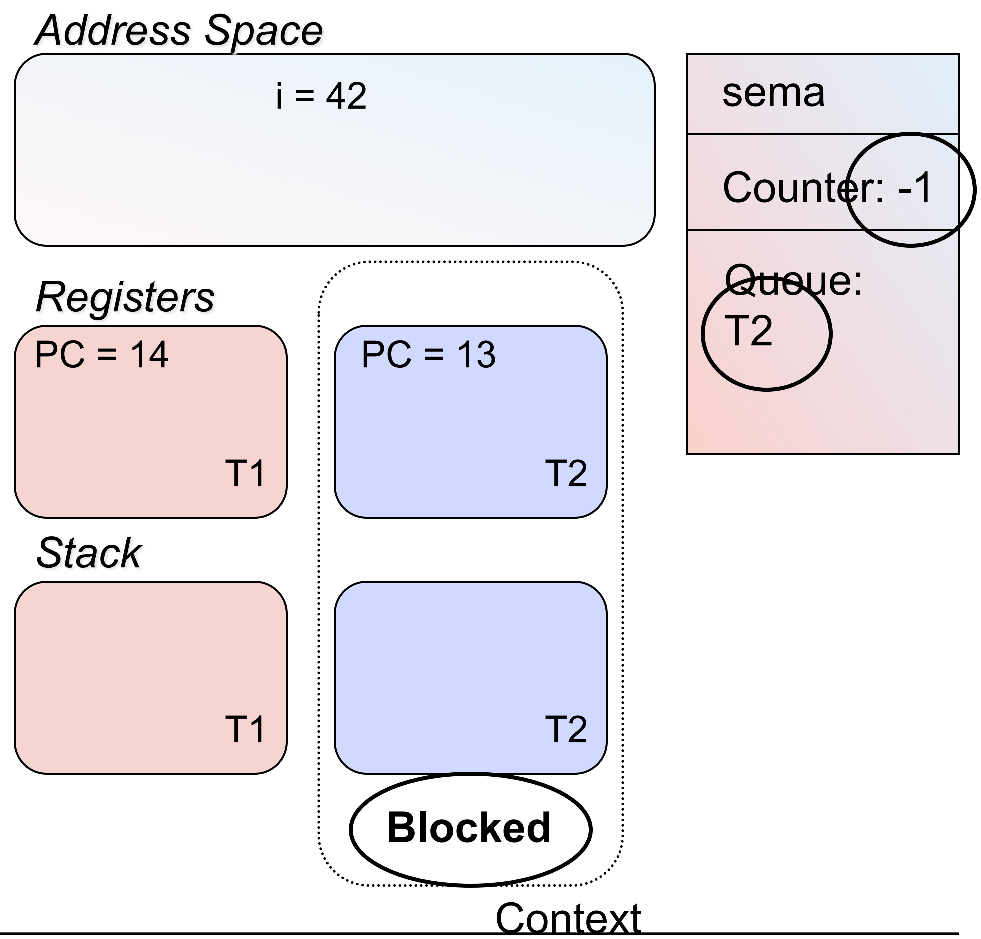


Threads - Revisited


```
int i;
Semaphore sema;

f()
{
   printf("i is %d\n", i);
}

int main(int argc, char **argv)
{
   .. (do stuff here) ..
   P(sema);
   i = get_input();
   f();
   V(sema);
   return 0;
}
```



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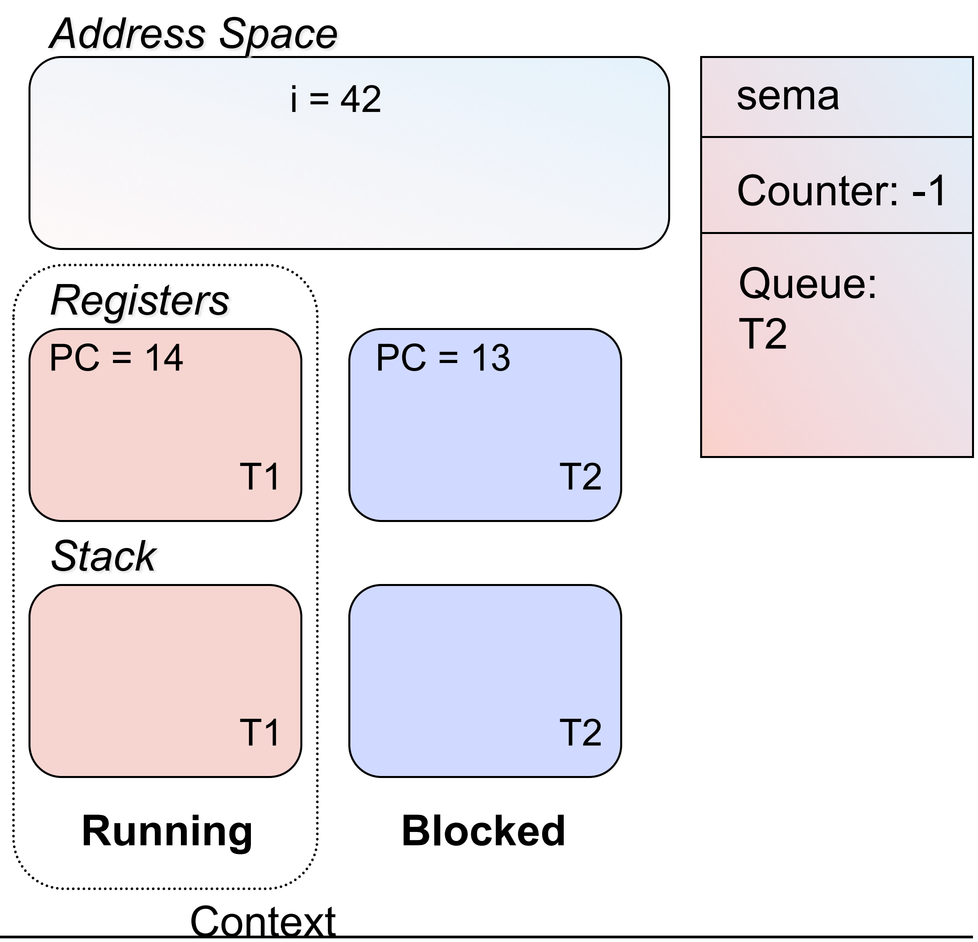

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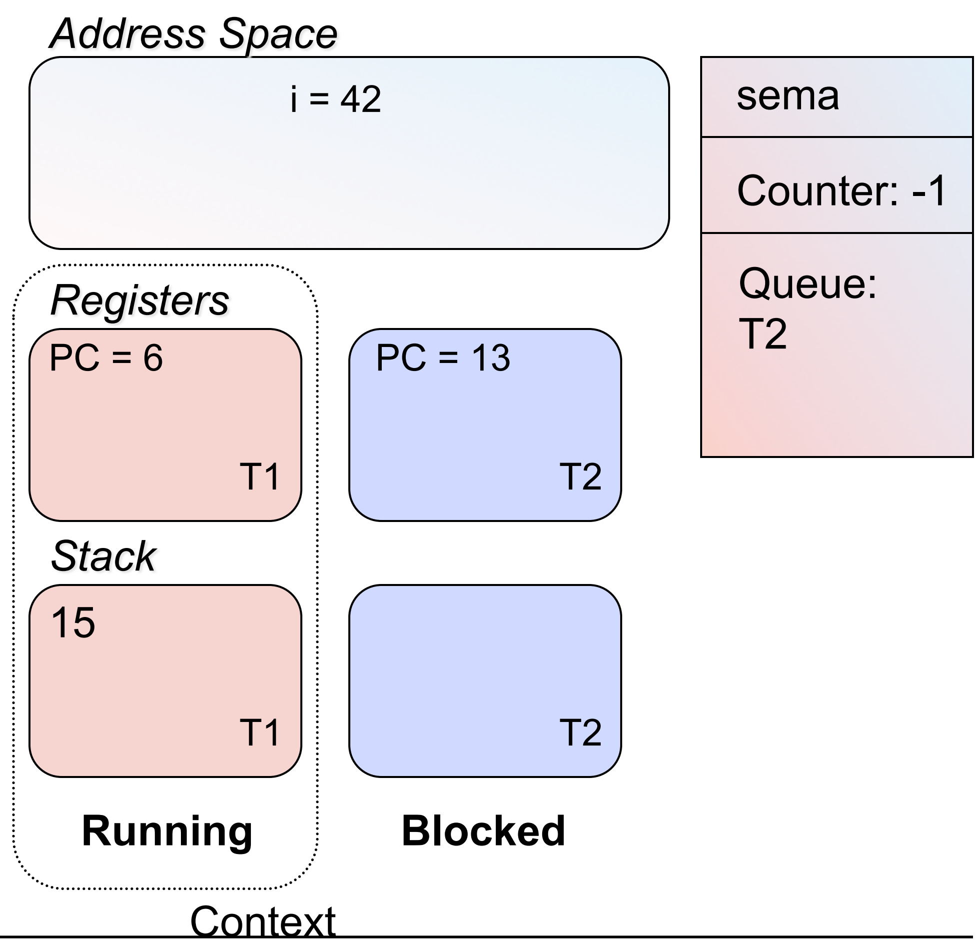

Threads - Revisited

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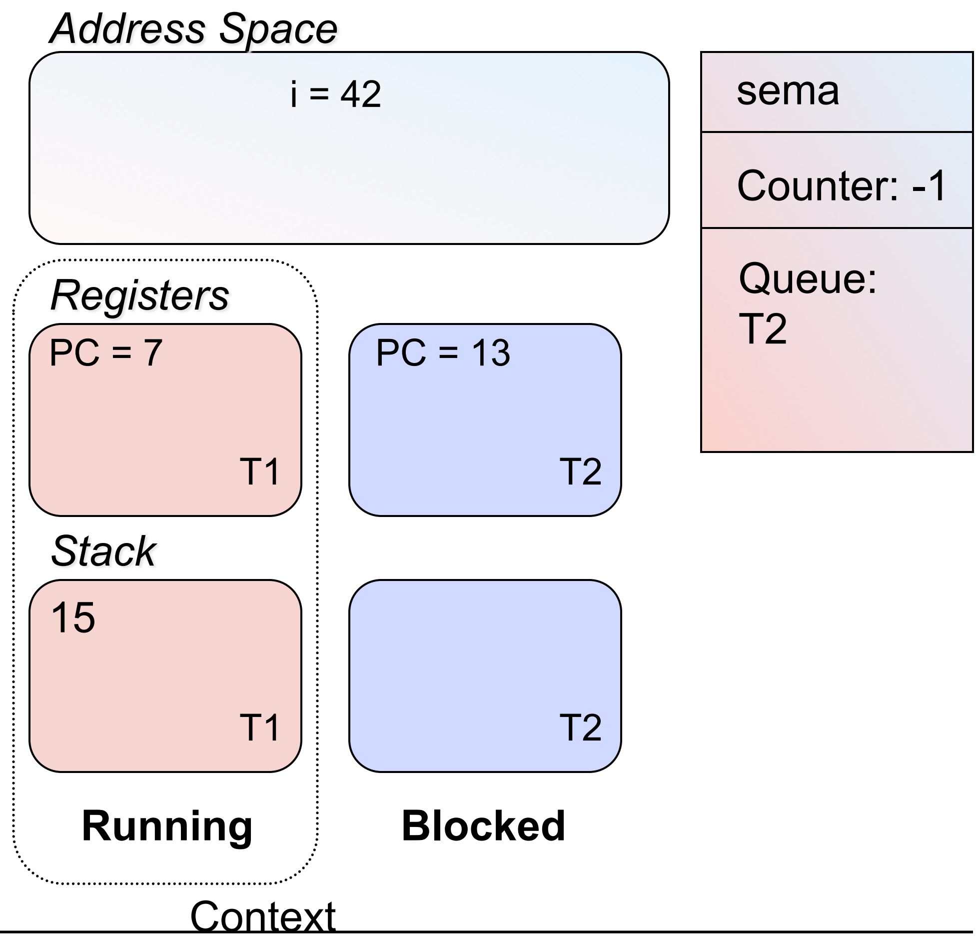
i is 42



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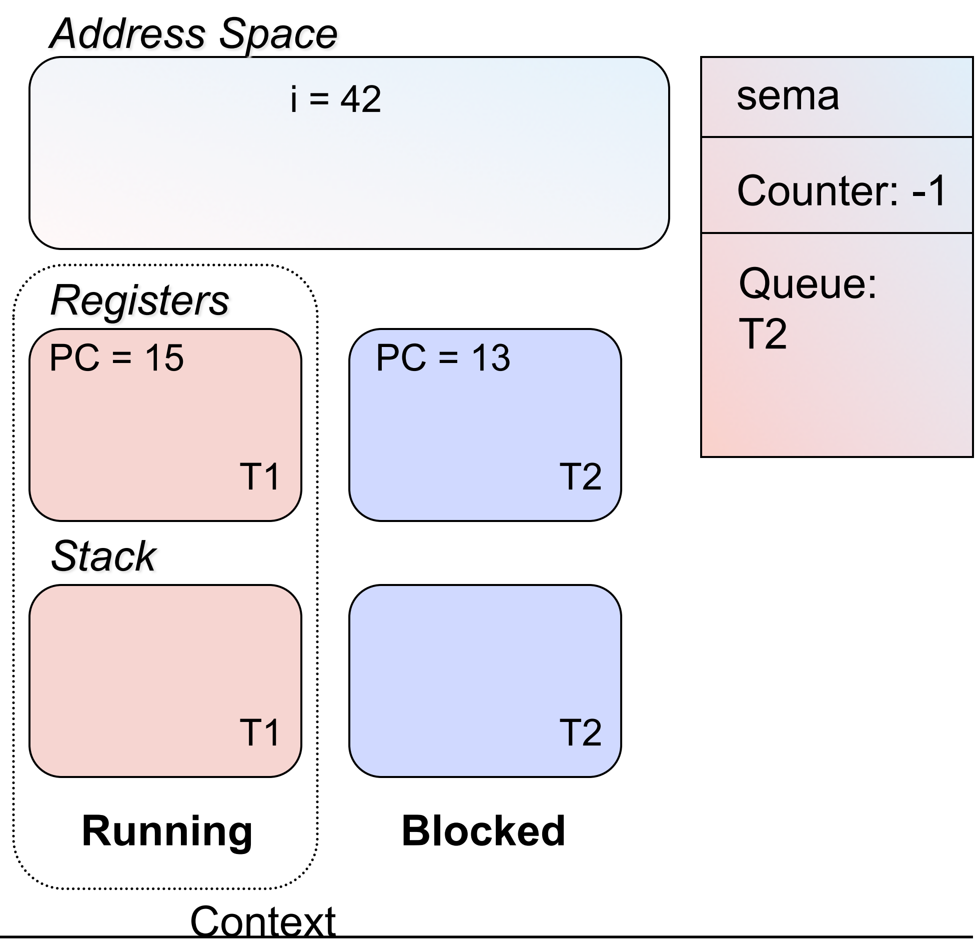

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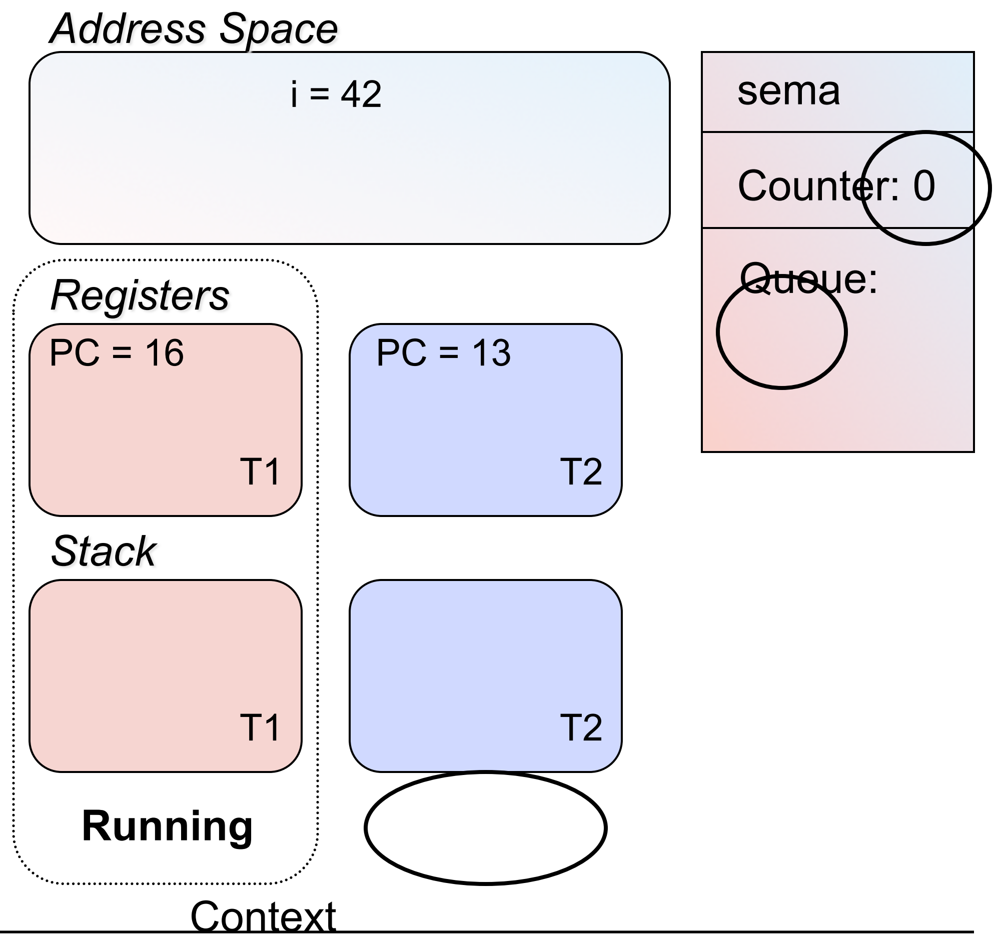

Threads - Revisited


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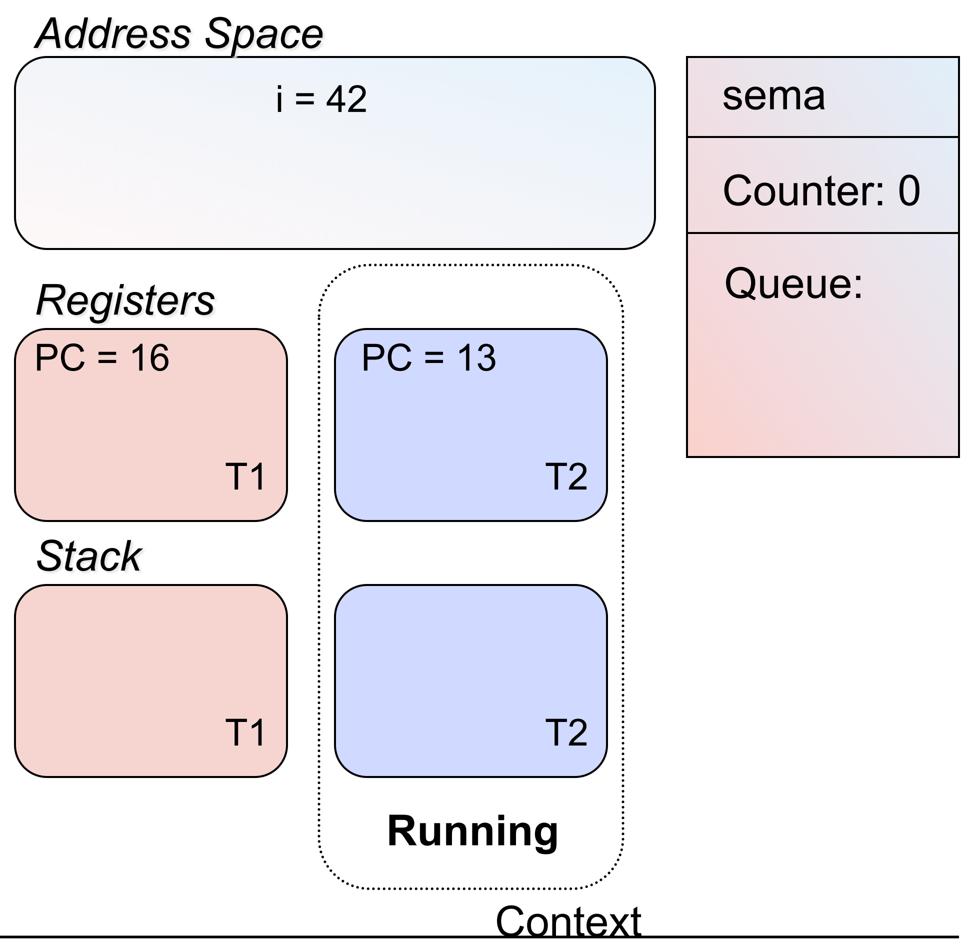

Threads - Revisited

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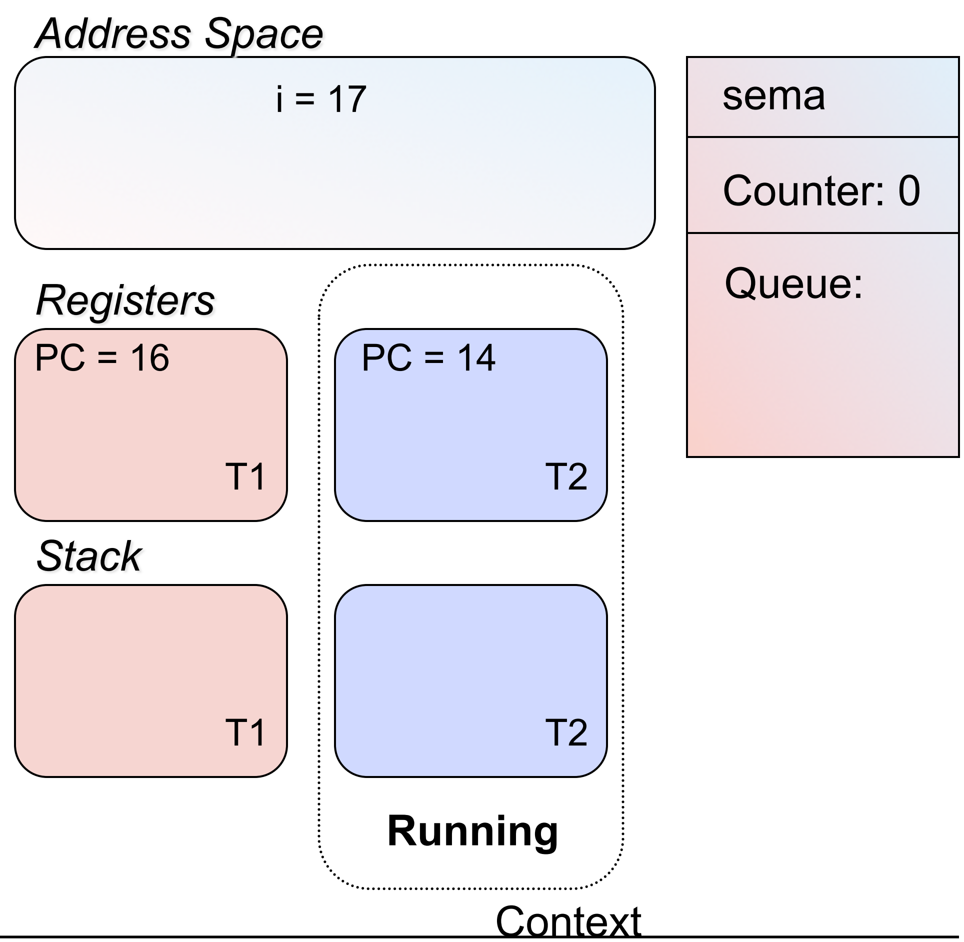

Threads - Revisited

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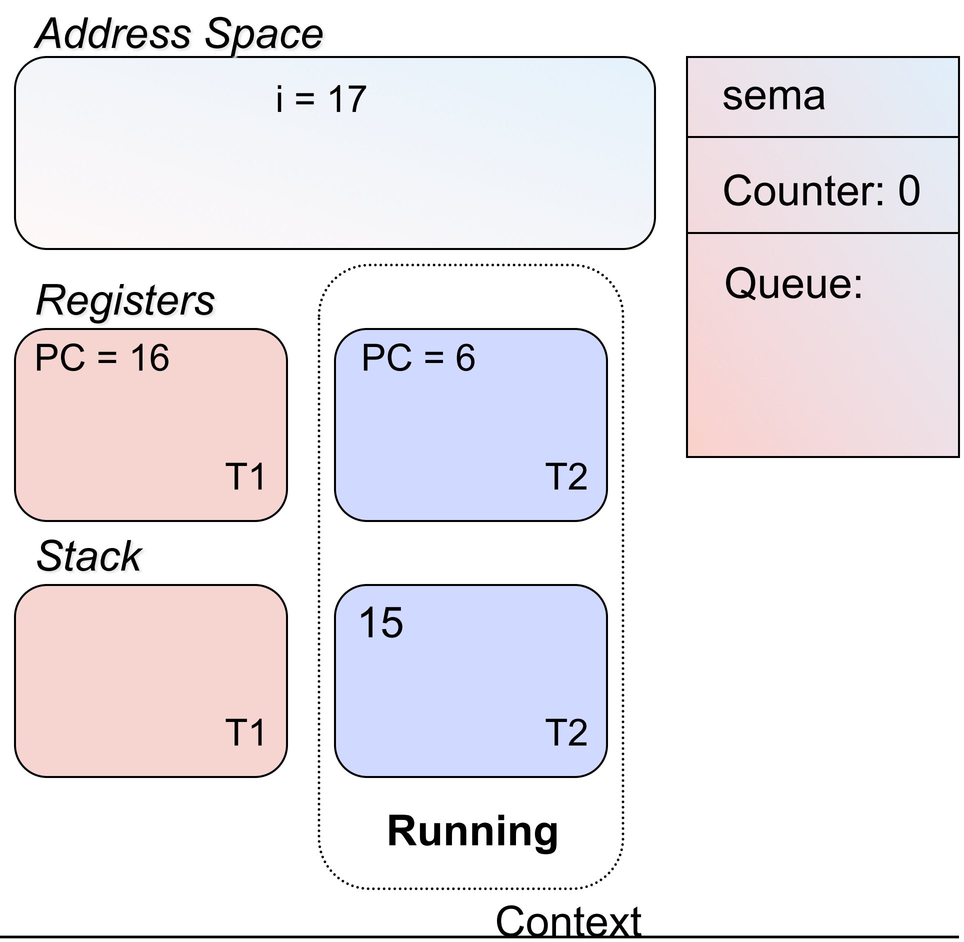

Threads - Revisited


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13:     i = get_input();
14:     f();
15:     V(sema);
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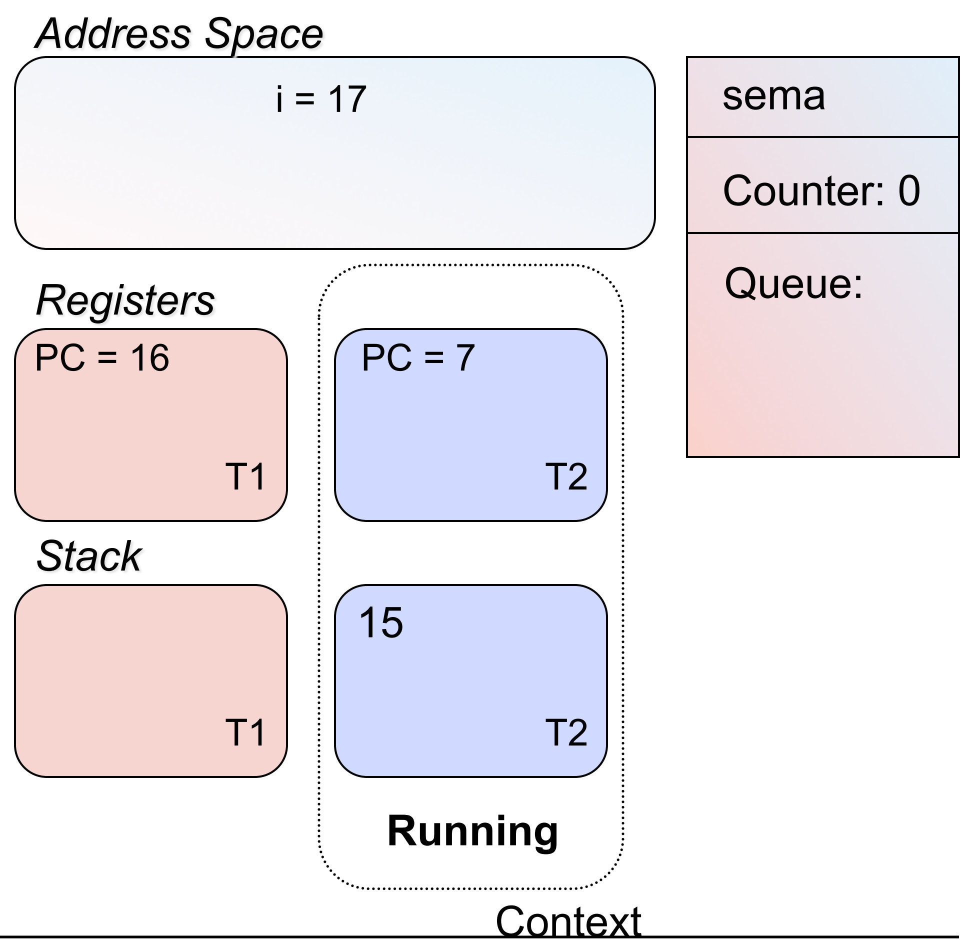
17: }
```

i is 17



Threads - Revisited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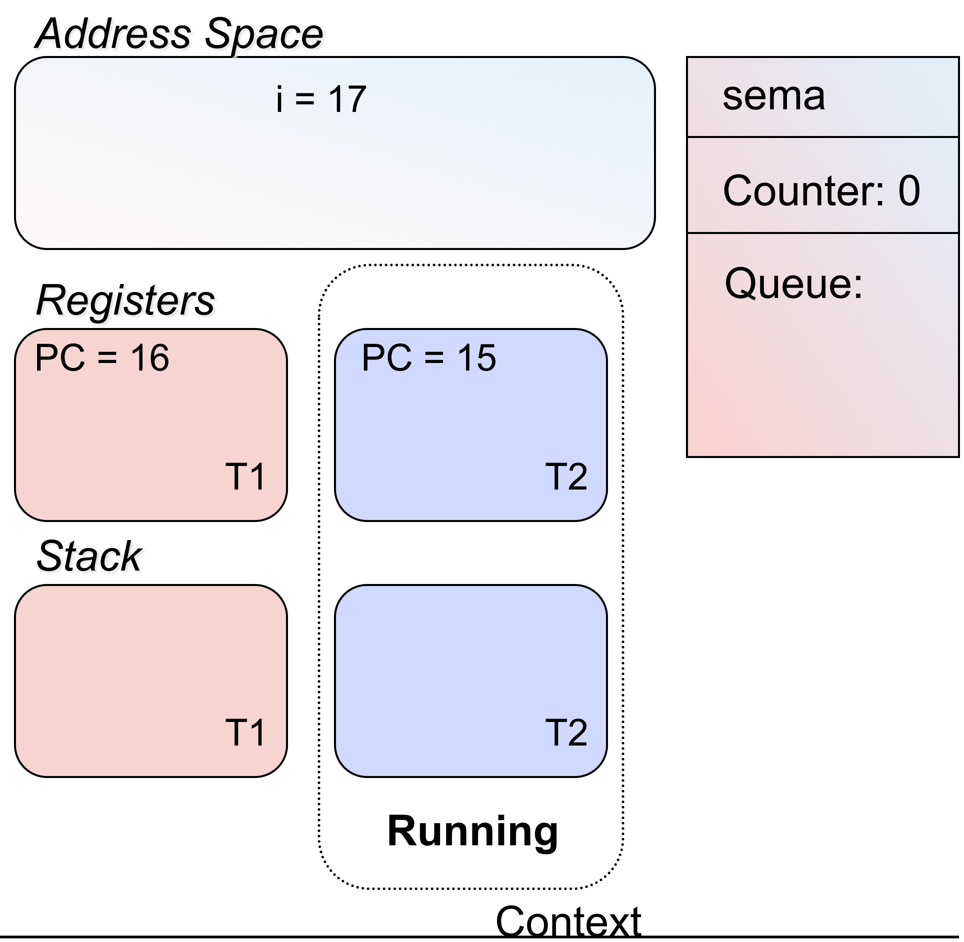
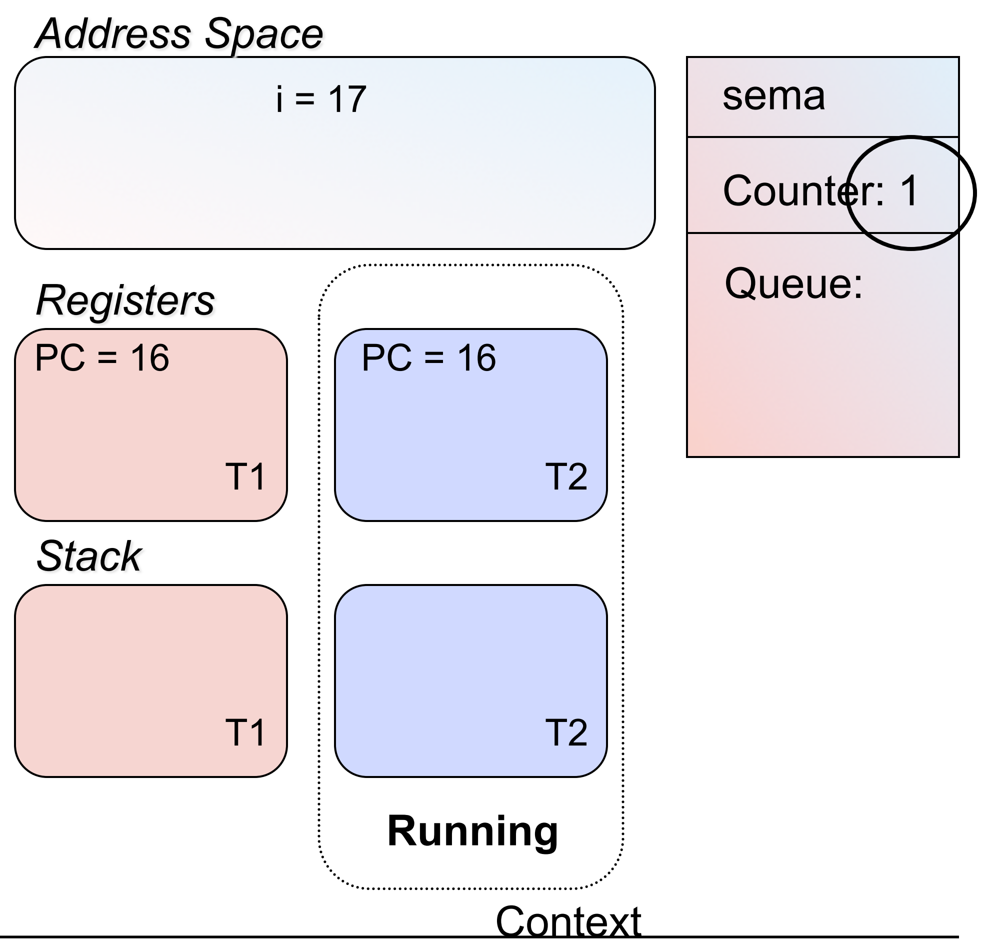


Threads - Revisited


```
int i;
Semaphore sema;

f()
{
    printf("i is %d\n", i);
}

int main(int argc, char **argv)
{
    .. (do stuff here) ..
    P(sema);
    i = get_input();
    f();
    V(sema);
    return 0;
}
```



Producer/Consumer with Semaphores

Three semaphores

1. full: counts the number of slots that are full
2. empty: keeps track of the empty slots
3. mutex: makes sure produce and consumer do not access the buffers at the same time

- Initially:
  - full = 0
  - empty = N
  - mutex = 1

Producer/Consumer with Semaphores


```
item = produce_item();
```

```
empty.down();
mutex.down();
```

```
full.down();
mutex.down();
```

```
insert_item(item)
```

```
item=remove_item()
```

```
mutex.up();
full.up();
```

```
mutex.up();
empty.up();
```

```
consume_item(item);
```

Producer/Consumer with a Mistake...

Producer:

```
item = produce_item();

mutex.down();
empty.down();

insert_item(item)

mutex.up();
full.up();
```

Consumer:

```
full.down();
mutex.down();

item=remove_item()

mutex.up();
empty.up();

consume_item(item);
```

Monitors

- A monitor is collection of procedures, variables, and data structures grouped together in a special module
- Only one thread can be active in a monitor at any instant
- Mutual exclusion is enforced by the compiler and therefore it is less prone to errors
- Monitors introduce the concept of condition variables

```
monitor example
        integer i;
        condition c;

        procedure producer( );
        .
        .
        .
        end;

        procedure consumer( );
        .
        .
        .
        end;
end monitor;
```

Condition Variables

- Condition variables support two operations
  - Wait
  - Signal
- wait(condition): the calling thread blocks and allows another thread to enter the monitor
- signal(condition): the calling thread wakes up a thread blocked on the condition variable
  - If more than one thread is waiting, only one is selected by the scheduler
  - The signal operation must be the last statement executed, so that the caller immediately exits the monitor
- Condition variables do not keep track of signals as semaphores do

Producer/Consumer with Monitors


```
monitor ProducerConsumer
        condition full, empty;
        integer count;
        procedure insert(item: integer);
        begin
                if count = N then wait(full);
                insert_item(item);
                count := count + 1;
                if count = 1 then signal(empty)
        end;
        function remove: integer;
        begin
                if count = 0 then wait(empty);
                remove = remove_item;
                count := count − 1;
                if count = N − 1 then signal(full)
        end;
        count := 0;
end monitor;
```

```
procedure producer;
begin
        while true do
        begin
                item = produce_item;
                ProducerConsumer.insert(item)
        end
end;
procedure consumer;
begin
        while true do
        begin
                item = ProducerConsumer.remove;
                consume_item(item)
        end
end;
```

A Little Problem


```
monitor M
  condition cond1, cond2;
  function sub1();
  begin
    ...
    wait(cond1);
  end;
  function sub2();
  begin
    ...
    signal(cond1);
    ...
    wait(cond2);
  end;
  function sub3();
  begin
    ...
    signal(cond2);
    signal(cond2);
  end;
end;
```

- Process A is waiting on cond1
- Process B is waiting on cond2
- At time t0 process C calls M.sub2()
- At time t1 > t0 process D calls M.sub2()
- At time t2 > t1 process E calls M.sub3()
- Assume that all waiting queues are FIFO
- Assuming that Q has been waiting for condition "x" and P performs "signal(x)", consider two possible policies:
  - P waits until Q either leaves the monitor, or waits for another condition; or
  - Q waits until P either leaves the monitor, or waits for another condition
- Determine the order of execution of the processes

Solution

Policy 1

- C executes signal(cond1) and wakes up A
- C suspends and A starts executing sub1()
- A exits the monitor
- C restarts
- C waits on cond2 (after B)
- D enters the monitor with sub2()
- D executes signal(cond1) and nothing happens
- D waits on cond2 after (B and C)
- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
- E suspends and B starts
- B exits the monitor and E restarts
- E executes the second signal and wakes C
- E suspends and C starts
- C exits the monitor and E restarts
- E exits the monitor

Policy 2

- C executes signal(cond1) and wakes up A
- C continues until it waits on cond2 (after B)
- C suspends and A starts executing sub1()
- A exits the monitor
- D enters the monitor with sub2()
- D executes signal(cond1) and nothing happens
- D waits on cond2 after (B and C)
- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
- E executes the second signal on cond2 and wakes C
- E exits the monitor
- B starts
- B exits the monitor and C starts
- C exits the monitor

The Readers and Writers Problem

- Multiple threads can read from a database at the same time
- If one thread is writing data into the db, no process should be reading or writing at the same time
- First reader gets a hold of a lock on the db
- Subsequent readers just increment the reader counter (critical section with a mutex)
- When they are finished they decrement the counter (critical section with a mutex)
- Last reader does an up() on the database lock letting the writer access the db
- Writer may starve if readers are too "active"

Reader/Writer Solution

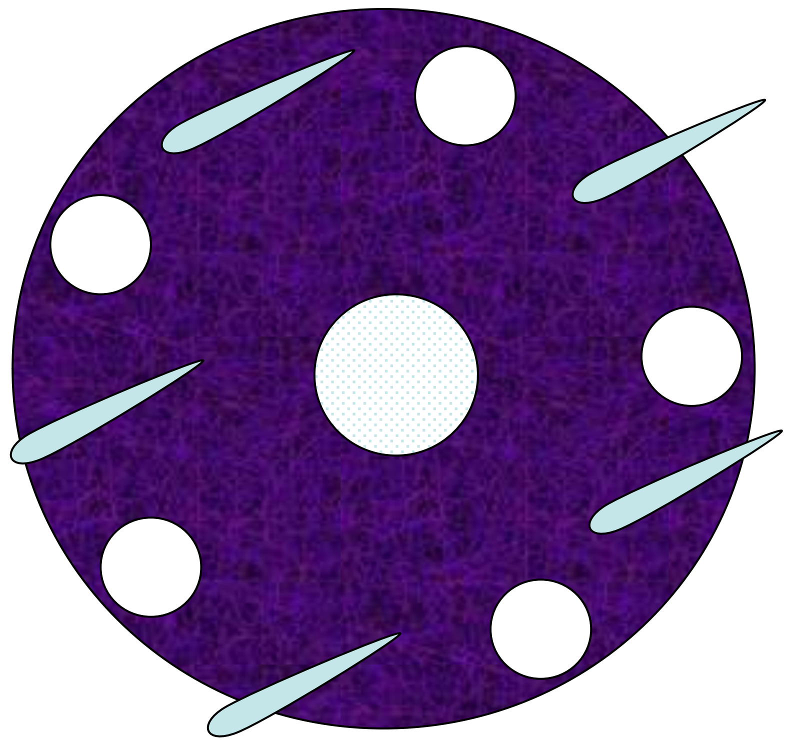

```
reader() {
  mutex.down();
  readerCount++;
  if (readerCount==1) db.down();
  mutex.up();

  read_db();

  mutex.down();
  readerCount--;
  if (readerCount==0) db.up();
  mutex.up();
  use_db_data();
}
```

```
writer() {
  prepare_db_data();
  db.down();
  write_db_data();
  db.up();
}
```

Dining Philosophers Problem



First Solution


```
philosopher(int i) {
 while (1) {
   think();
   take_chopstick(i);
   take_chopstick((i + 1) % N);
   eat();
   put_chopstick(i);
   put_chopstick((i + 1) % N);
  }
}
```

- If all the philosopher take their left chopsticks they get stuck

Second Solution


```
philosopher(int i) {
 while (1) {
   think();
   take_chopstick(i);
   if (!available((i + 1) % N)) {
     put_chopstick(i);
     continue();
     }
   take_chopstick((i + 1) % N);
   eat();
   put_chopstick(i);
   put_chopstick((i + 1) % N);
  }
}
```

- It is possible that all the philosophers put down and pick up their chopsticks at the same time, leading to starvation
- think() should be randomized

Third Solution

- Use one mutex
  - Do a down() when acquiring chopsticks
  - Do an up() when releasing chopsticks

- Problem: only one philosopher can eat at once

Fourth Solution

- Maintain state of philosophers
  - Switch to HUNGRY when ready to eat
  - Sleep if no chopsticks available
  - When finished wake up your neighbors
- Use one semaphore for each philosopher, to be used to suspend in case no chopsticks are available
- Use one mutex for critical regions
- Use take_chopsticks/put_chopsticks to acquire both chopsticks

Fourth Solution


```
philosopher(i) {
  think();
  take_chopsticks(i);
  eat();
  put_chopsticks(i);
}
```

```
take_chopsticks(i) {
  mutex.down();
  state[i] = HUNGRY;
  test(i);
  mutex.up();
  philosopher[i].down();
}
```

```
put_chopsticks(i) {
  mutex.down();
  state[i] = THINKING;
  test((i + 1) % N);
  test((i + N - 1) % N);
  mutex.up();
}
```

```
test(i) {
  if (state[i] == HUNGRY && state[(i + 1) % N] != EATING &&
                                        state[(i + N - 1) % N] != EATING)
{
       state[i] = EATING;
       philosopher[i].up();
  }
}
```

The Sleeping Barber Problem

- Hair Salon with finite capacity (N chairs in the waiting room).
- Barber's life:
  - Get the next customer
  - Give him/her haircut
- Customer's life:
  - Grow hair
  - Enter the Hair Salon if possible (chairs are available)
  - Get haircut
  - Leave the Hair Salon

The Sleeping Barber Problem

- Three semaphores
  - Customers: counts the waiting customers, initially = 0
  - Barber: available barbers (0 or 1), initially = 0
  - Mutex: critical section control, initially = 1

- Variables
  - waiting: keeps track of how many customers, initially = 0
    - Needed because the value of a semaphore cannot be read

The Sleeping Barber Problem


```
barber() {
  while (1) {
    customers.down();
    mutex.down();
    waiting--;
    barber.up();
    mutex.up();
    cut_hair();
  }
}
```

```
customer() {
    mutex.down();
    if (waiting < CHAIRS) {
      waiting++;
      customers.up();
      mutex.up();
      barber.down();
      get_haircut();
    }
    else {
      mutex.up();
    }
}
```