Classic Problems of Synchronization

Classical Problems of Synchronization

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem
- The three problems are important, because they are
  - examples for a large class of concurrency-control problems.
  - used for testing nearly every newly proposed synchronization scheme.
- Semaphores are used for synchronization in our solutions.

Producer-consumer problem with a bounded buffer

- **Problem Definition**
  - Producer puts things into a shared buffer
  - Consumer takes them out
  - Need synchronization to coordinate producer/consumer
- **Put a fixed-size buffer between them**
  - Need to synchronize access to this buffer
  - Producer needs to wait if buffer is full
  - Consumer needs to wait if buffer is empty
- **Example: Coke machine**
  - Producer can put limited number of cokes in machine
  - Consumer can't take cokes out if machine is empty

Bounded-Buffer

- Suppose that we wanted to provide a solution to the consumer-producer problem with a bounded-buffer.
- We can do so by having an integer count that keeps track of the number of products in the buffer.
- Initially, count is set to 0.
  - It is incremented by the producer after it produces a new product.
  - It is decremented by the consumer after it consumes a product.

Bounded-Buffer

- Shared data

```
#define BUFFER_SIZE 10
typedef struct {
. . .
} item;
item buffer[BUFFER_SIZE];
int in = 0;
int out = 0;
int count = 0;
```

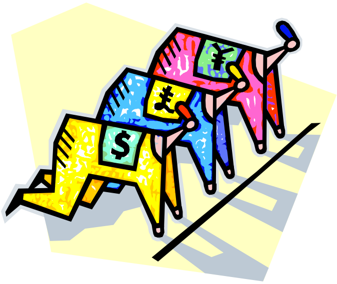
Producer and Consumer

```
while (true) {
    // produce an item and put in nextProduced
    while (count == BUFFER_SIZE)
        ; // do nothing
    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;
}
```

```
while (true)  {
    while (count == 0)
        ; // do nothing
    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;
    //consume the item in nextConsumed
}
```

Producer and Consumer

```
while (true) {
    while (count == BUFFER_SIZE)
      ; // do nothing
    buffer [in] = nextProduced;
    in = (in + 1) % BUFFER_SIZE;
    count++;
}
```

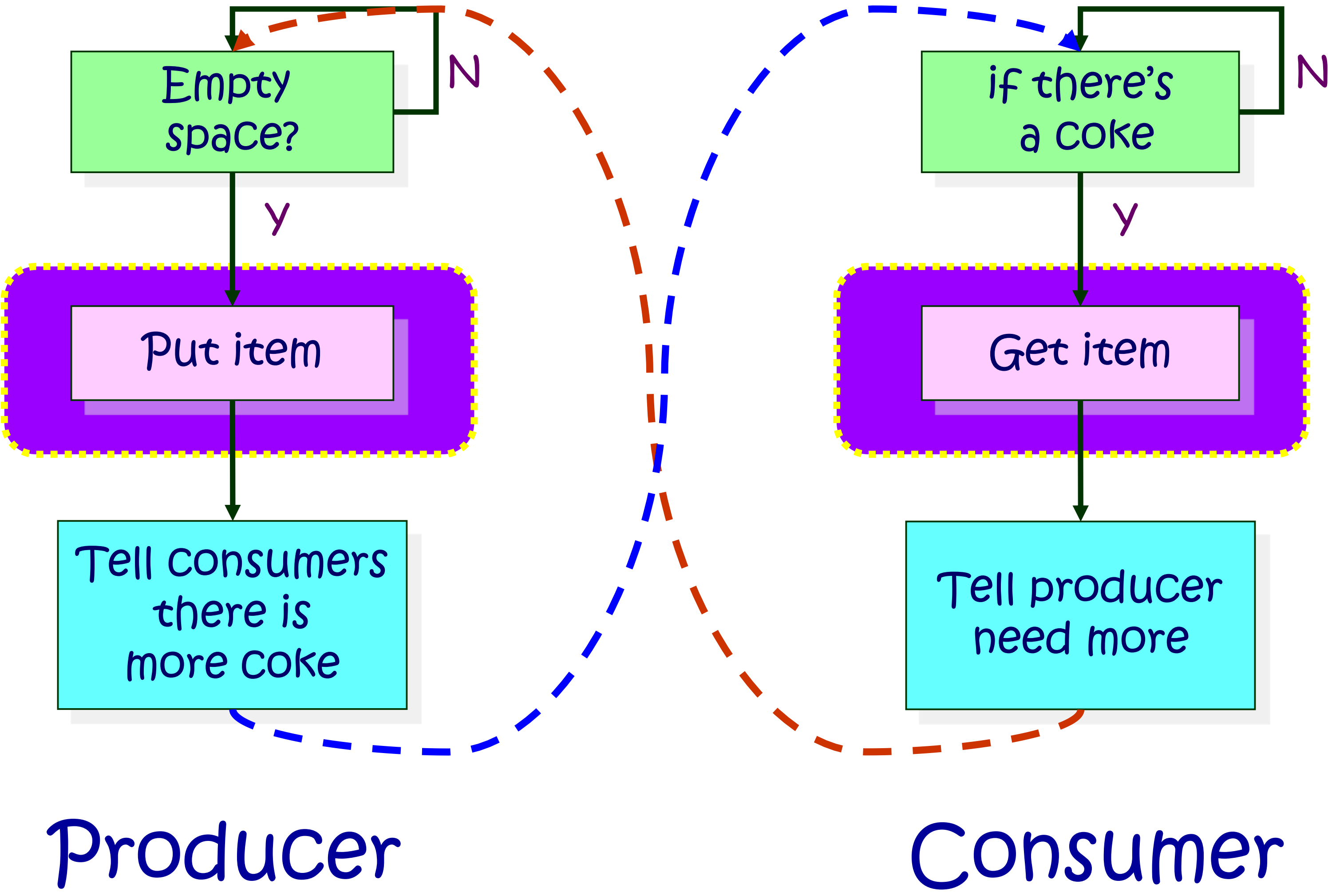


```
while (true)  {
    while (count == 0)
      ; // do nothing
    nextConsumed =  buffer[out];
    out = (out + 1) % BUFFER_SIZE;
    count--;
}
```

Correctness constraints for solution

- **Correctness Constraints:**
  - Consumer must wait for producer to fill the buffer, if no product in the buffer (scheduling constraint)
  - Producer must wait for consumer to empty the buffer, if the buffer is full (scheduling constraint)
  - Only one process can manipulate the buffer at a time (mutual exclusion)

Correctness constraints for solution



Correctness constraints for solution

- General rule of thumb: Use a separate semaphore for each constraint
  - **Semaphore full;**
    // consumer's constraint
    // initialized to the value 0
  - **Semaphore empty;**
    // producer's constraint
    // initialized to the value N.
  - **Semaphore mutex;**
    // mutual exclusion
    // initialized to the value 1

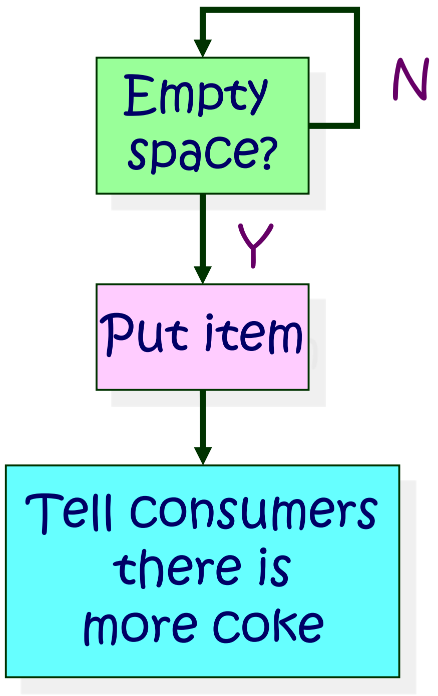
Full Solution

```
Semaphore full = 0;          // Initially, no coke
Semaphore empty = N;         // Initially, num empty slots
Semaphore mutex = 1;         // No one using machine

Producer(item) {
   P(empty);                 // Wait until space
   P(mutex);                 // Wait until machine free
   Enqueue(item);
   V(mutex);
   V(full);                  // Tell consumers there is more coke
}

Consumer() {
   P(full);                  // Check if there's a coke
   P(mutex);                 // Wait until machine free
   item = Dequeue();
   V(mutex);
   V(empty);                 // Tell producer need more
   return item;
}
```

Full Solution

- The structure of the producer process

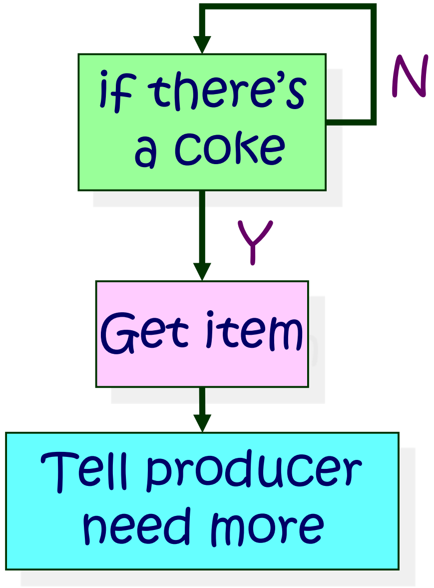
```
while (true) {

    //   produce an item

    wait (empty);
    wait (mutex);

    //  add the item to the buffer

    signal (mutex);
    signal (full);
}
```



Full Solution

- The structure of the consumer process

```
while (true) {

     wait (full);
     wait (mutex);

     //  remove an item from buffer

     signal (mutex);
     signal (empty);

    //  consume the removed item
}
```



Discussion about Solution

- Why asymmetry?
  - Producer does: `P(empty), V(full)`
  - Consumer does: `P(full), V(empty)`
- Is the order of P's important?
- Is the order of V's important?

```
Producer(item) {
   P(empty);
   P(mutex);
   Enqueue(item);
   V(mutex);
   V(full);
}

Consumer() {
   P(full);
   P(mutex);
   item = Dequeue();
   V(mutex);
   V(empty);
   return item;
}
```

Discussion about Solution

Is the order of P's important?

- Yes! Can cause deadlock
- Why?

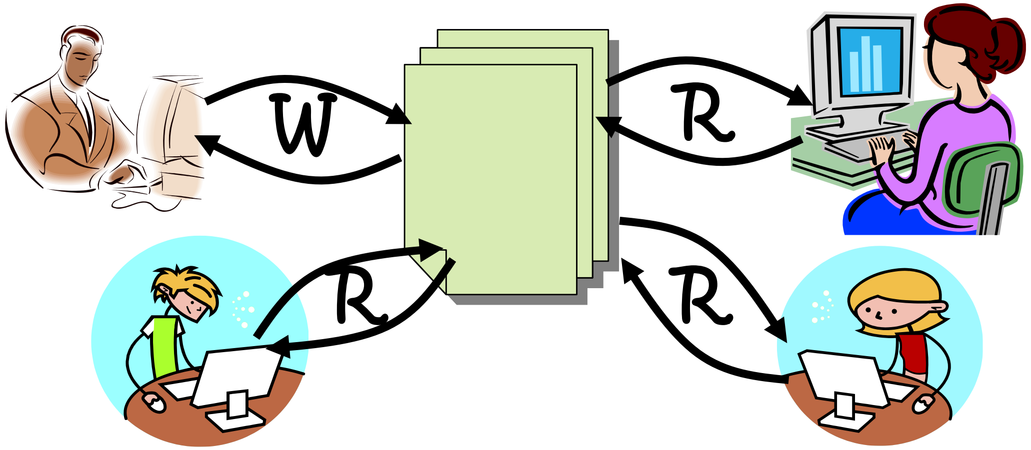
```
Semaphore full = 0;          // Initially, no coke
Semaphore empty = N;         // Initially, num empty slots
Semaphore mutex = 1;         // No one using machine

Producer(item) {
    P(mutex);                // Wait until buffer free
    P(empty);                // Wait until space
    Enqueue(item);
    V(mutex);
    V(full);                 // Tell consumers there is
                             // more coke
}

Consumer() {
    P(full);                 // Check if there's a coke
    P(mutex);                // Wait until machine free
    item = Dequeue();
    V(mutex);
    V(empty);                // tell producer need more
    return item;
}
```

Discussion about Solution

- **Is order of V’s important?**
  - No, except that it might affect scheduling efficiency
- What if we have 2 producers or 2 consumers?
  - Do we need to change anything?

Readers/Writers Problem

- Motivation: Consider a shared database
  - Two classes of users:
    - Readers – only read the data set; they do not perform any updates.
    - Writers – can both read and write.
  - Problem – allow multiple readers to read at the same time. Only one single writer can access the shared data at the same time.

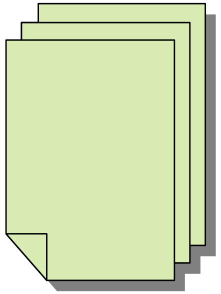


Basic Readers/Writers Solution

- Correctness Constraints:
  - Readers can access database when no writers
  - Writers can access database when no readers or writers
  - Only one process manipulates state variables at a time
- Basic structure of a solution:
  - `Reader()`

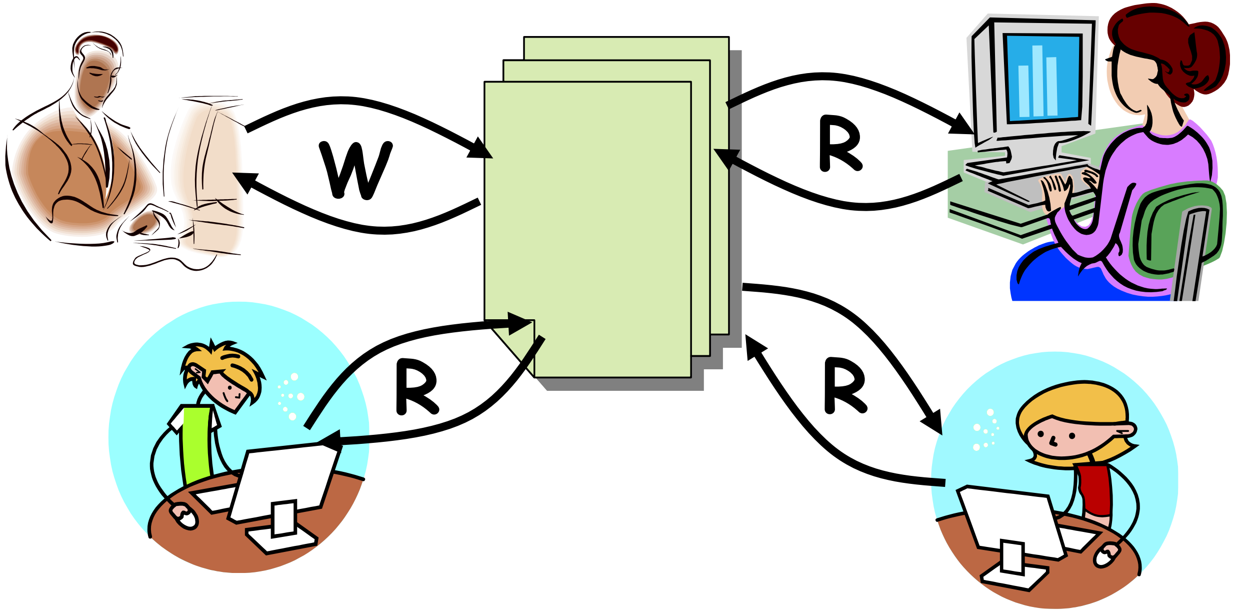
    ```
    Wait until no writers
    Access database
    Check out – wake up a waiting writer
    ```
  - `Writer()`

    ```
    Wait until no active readers or writers
    Access database
    Check out – wake up waiting readers or writers
    ```



Readers/Writers Problem

- Is using a single lock on the whole database sufficient?



The first readers-writers problem

- Suppose we have a shared memory area with the constraints detailed above.
- It is possible to protect the shared data behind a mutex, in which case no process/thread can access the data at the same time.

The first readers-writers problem

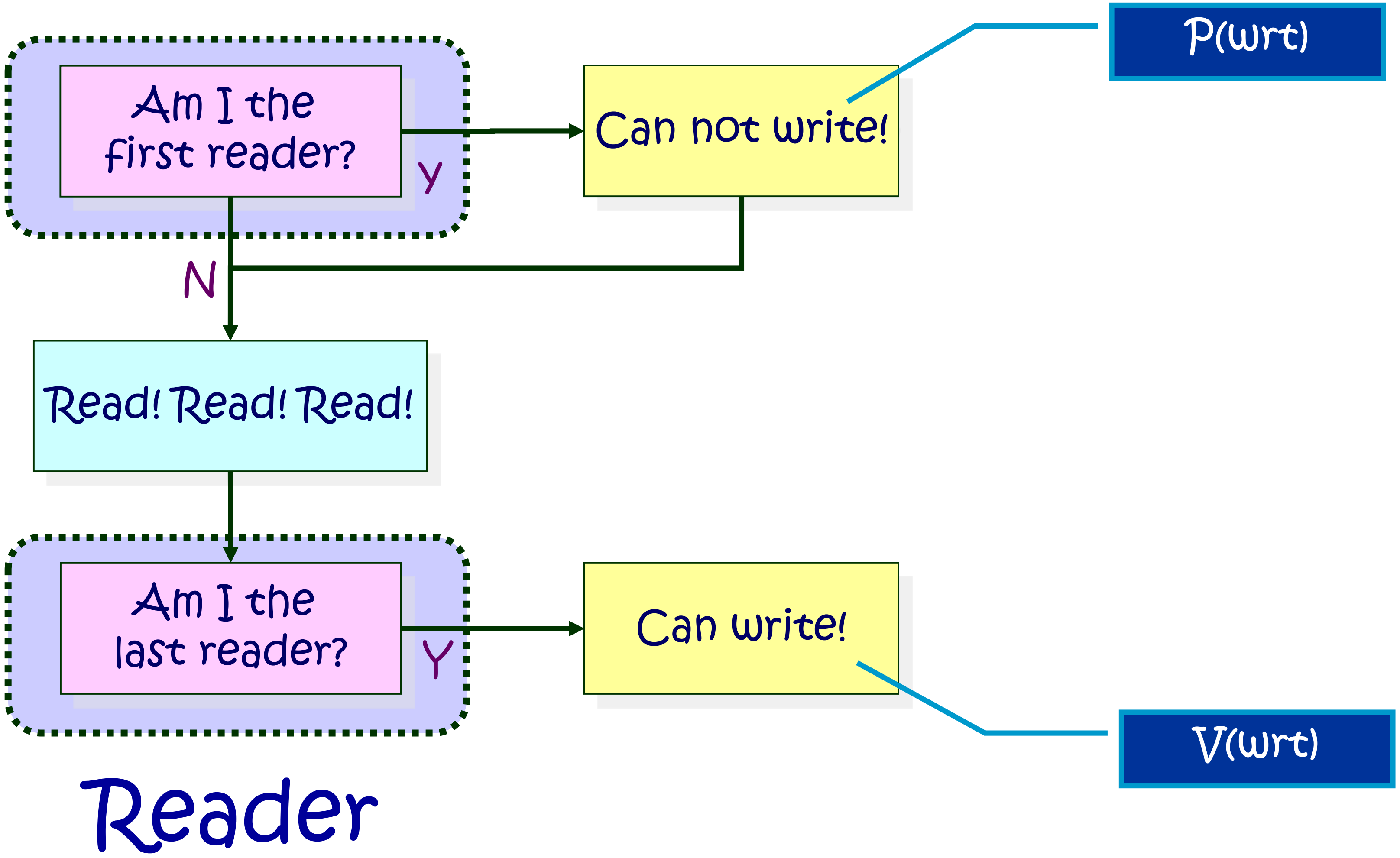
- The solution is sub-optimal.
  - Because it is possible that a reader R1 might have the lock, and then another reader R2 request access.
  - It would be foolish for R2 to wait until R1 was done before starting its own read operation.
  - Instead, R2 should start right away.
- This is the motivation for the first readers-writers problem, in which the constraint is added that no reader shall be kept waiting if the share is currently opened for reading.
- This is also called **readers-preference**.

Readers-Writers Problem: Solution #1

- int readcount = 0;
- semaphore mutex = 1, wrt = 1;
- The structure of a writer process

```
while (true) {
        wait (wrt);
        // writing is performed
        signal (wrt);
}
```

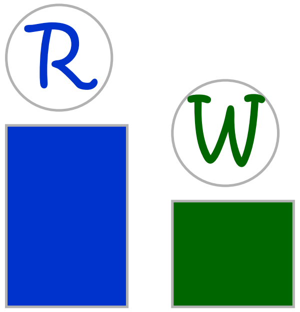
Readers-Writers Problem: Solution #1



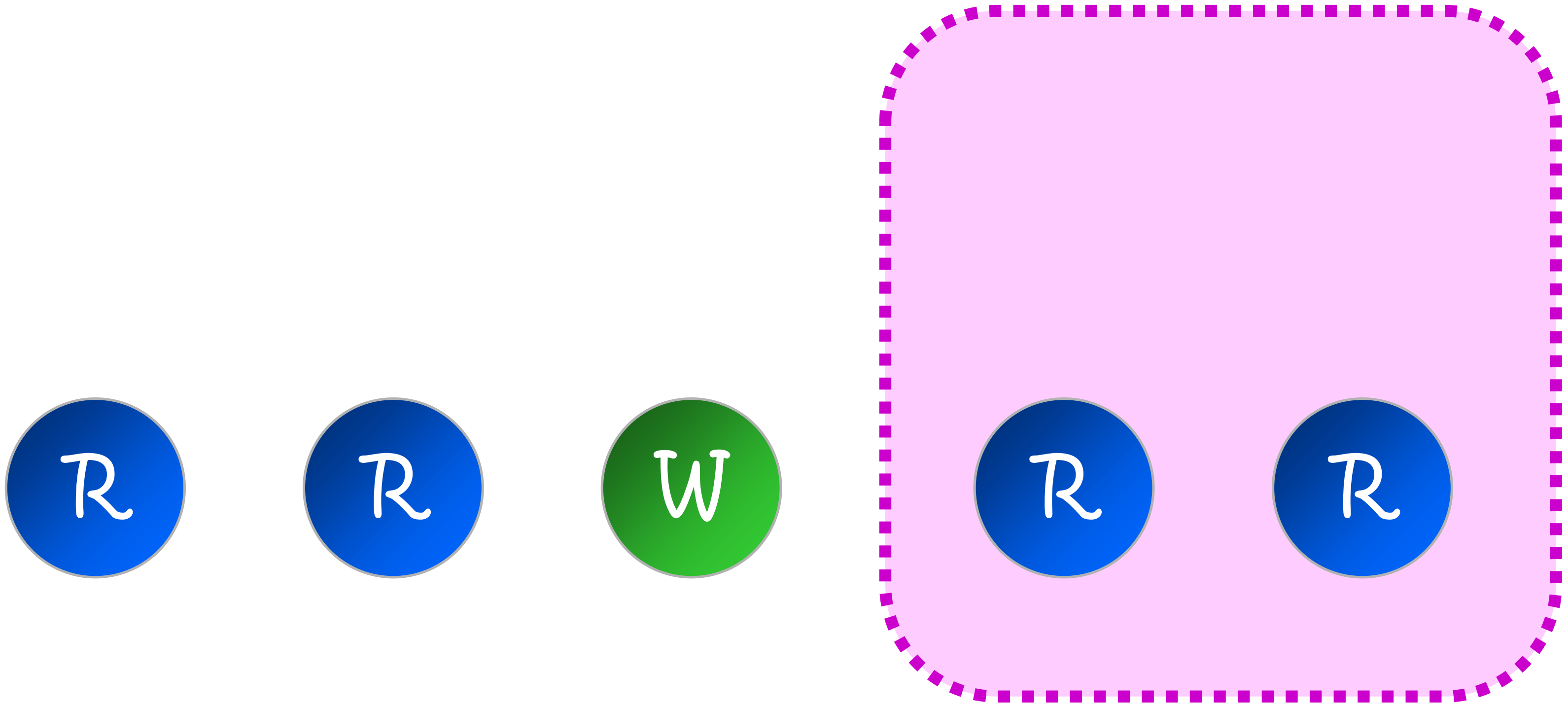
Readers-Writers Problem: Solution #1

- The structure of a reader process

```
while (true) {
      wait(mutex);
         readcount++;
         if (readcount == 1)   wait(wrt);
      signal(mutex);

            // reading is performed

      wait(mutex);
         readcount--;
         if (readcount == 0)   signal(wrt);
      signal(mutex);
}
```



The first readers-writers problem



The second readers-writers problem

- The former solution is sub-optimal.
  - Because it is possible that a reader R1 might have the lock, a writer W be waiting for the lock, and then a reader R2 request access.
  - It would be foolish for R2 to jump in immediately, ahead of W; if that happened often enough, W would **starve**.
  - Instead, W should start as soon as possible.
- This is the motivation for the second readers-writers problem, in which the constraint is added that no writer, once added to the queue, shall be kept waiting longer than absolutely necessary.
- This is also called **writers-preference**.

Readers-Writers Problem: Solution #2

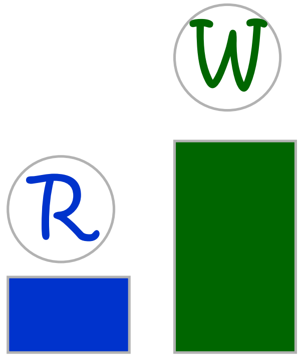
- int readcount = 0, writecount = 0;
- semaphore x = 1, y = 1, wrt = 1, red = 1;
- The structure of a writer process

```
while (true) {
        wait(y);
          writecount++;
          if (writecount == 1)
        wait(red);
        signal(y);
        wait(wrt);
          // writing is performed
        signal(wrt);
        wait(y);
          writecount--;
          if (writecount == 0)
        signal(red);
        signal(y);
    }
```

Readers-Writers Problem: Solution #2

- The structure of a reader process

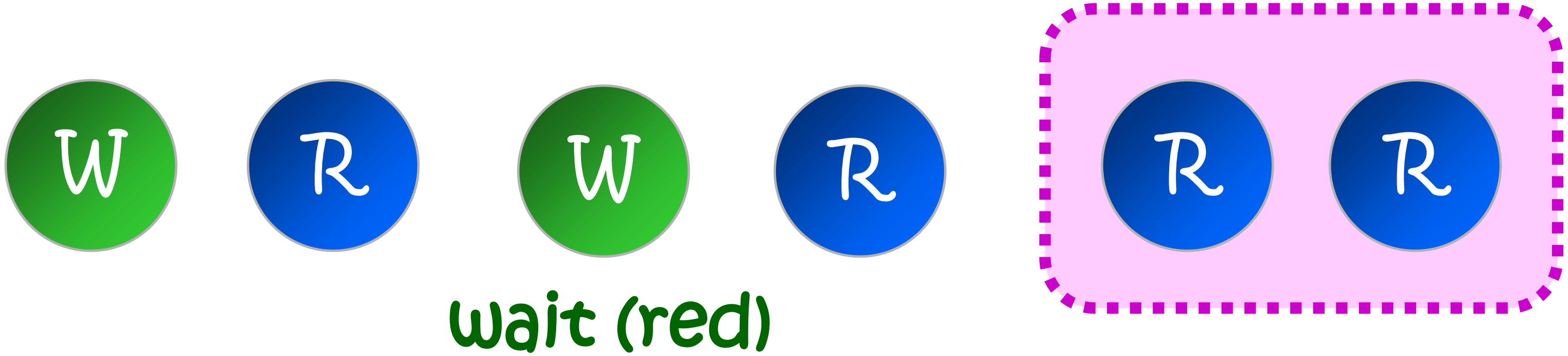
```
while (true) {
    wait(red);
      wait(x);
        readcount++;
        if (readcount == 1)  wait(wrt);
      signal (x);
    signal(red);
      // reading is performed
    wait (x);
      readcount--;
      if (readcount == 0)  signal(wrt);
    signal(x);
}
```



The second readers-writers problem

```
wait (y);
   writecount++;
   if (writecount == 1) wait(red) ;
signal (y);
wait (wrt);
……
```

```
wait (red);
……
```



The third readers-writers problem

- In fact, the solutions implied by both problem statements result in starvation — the first readers-writers problem may starve writers in the queue, and the second readers-writers problem may starve readers.
- Therefore, the third readers-writers problem is sometimes proposed, which adds the constraint that no process/thread shall be allowed to starve; that is, the operation of obtaining a lock on the shared data will always terminate in a bounded amount of time.
- Solutions to the third readers-writers problem will necessarily sometimes require readers to wait even though the share is opened for reading, and sometimes require writers to wait longer than absolutely necessary.

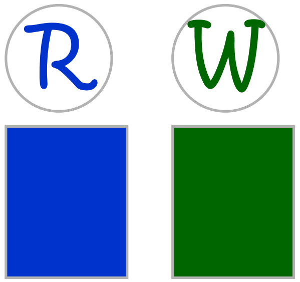
Readers-Writers Problem: Solution #3

- int readcount = 0;
- semaphore mutex = 1, wrt = 1, S=1;
- The structure of a writer process

```
while (true) {
    wait (S);
      wait (wrt);
        // writing is performed
      signal (wrt);
    signal (S);
}
```

Readers-Writers Problem: Solution #3

- The structure of a reader process



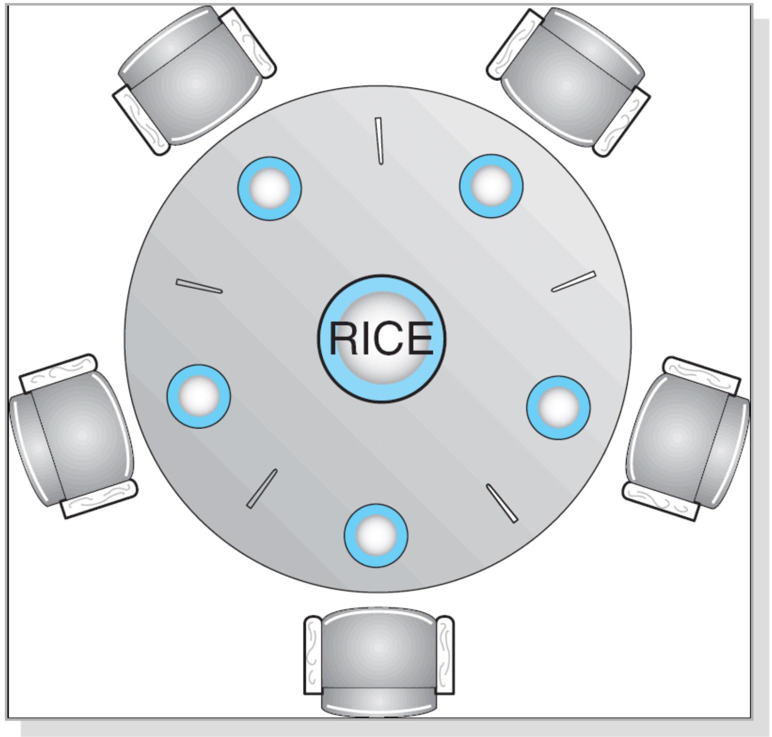

```
while (true) {
    wait (S);
      wait(mutex);
        readcount++;
        if (readcount == 1)  wait(wrt);
      signal(mutex);
    signal (S);

      // reading is performed

    wait(mutex);
      readcount--;
      if (readcount == 0)  signal(wrt);
    signal(mutex);
}
```

```
while (true) {
    wait(mutex);
      readcount++;
      if (readcount == 1)  wait(wrt);
    signal(mutex);

      // reading is performed

    wait(mutex);
      readcount--;
      if (readcount == 0)  signal(wrt);
    signal(mutex);
}
```

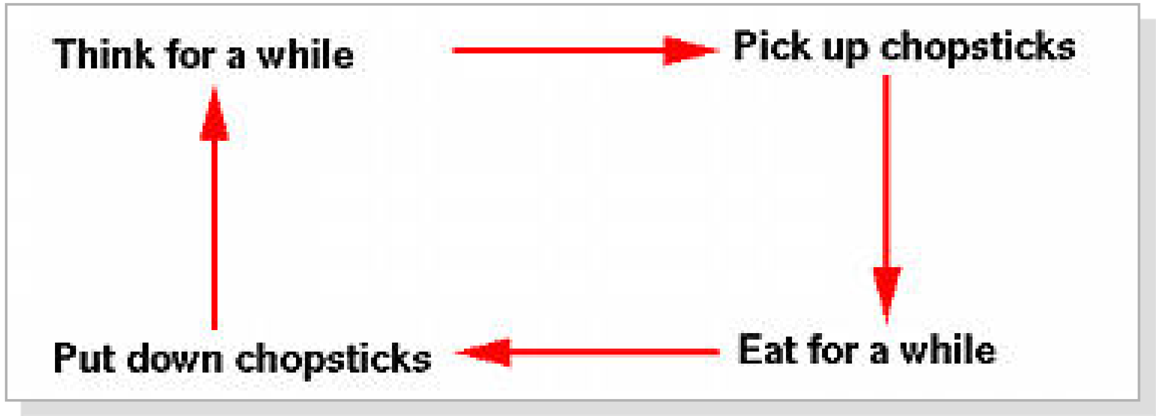
Solution#1

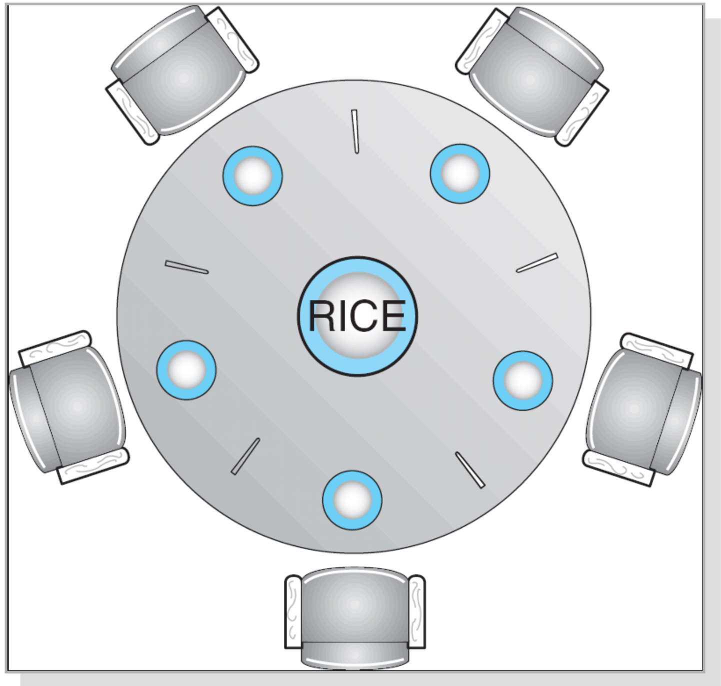
Dining-Philosophers Problem

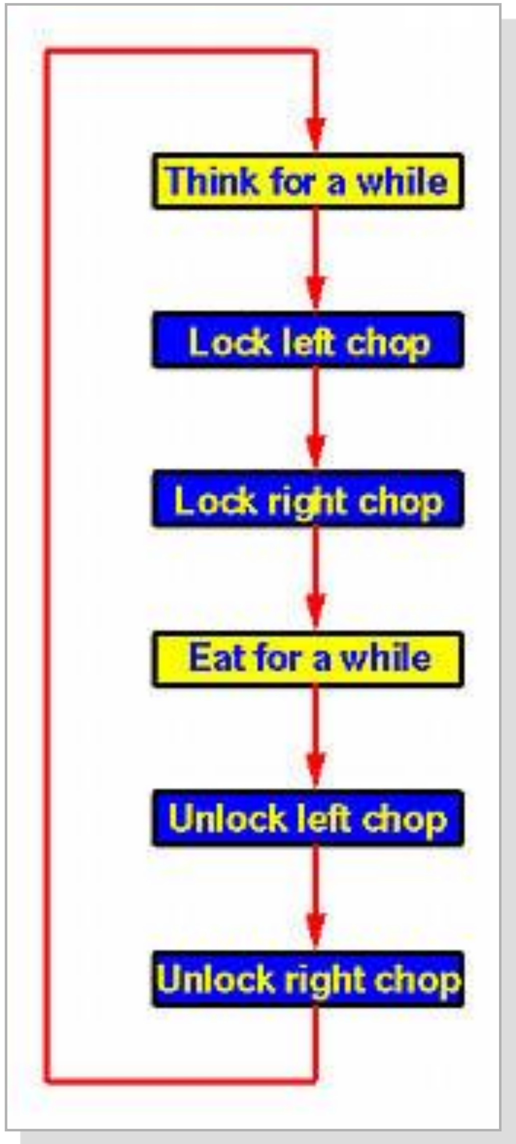
- Five philosophers, either thinking or eating
- To eat, two chopsticks are required
- Taking one chopstick at a time



Dining-Philosophers Problem

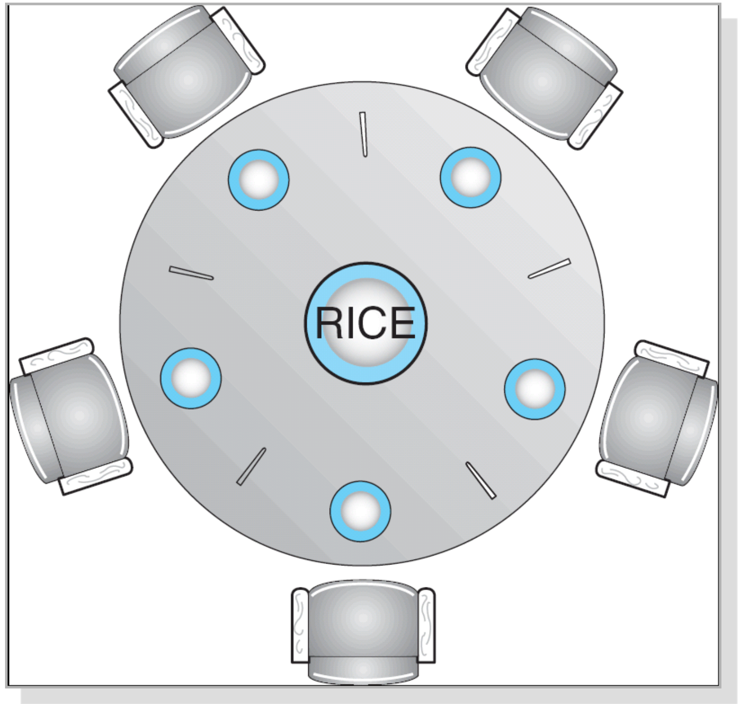






Dining-Philosophers Problem

- Shared data
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1



Dining-Philosophers Problem

- The structure of Philosopher i:

```
While (true)  {
      wait ( chopstick[i] );
      wait ( chopstick[ (i + 1) % 5] );
        //  eat;
      signal ( chopstick[i] );
      signal ( chopstick[ (i + 1) % 5] );
        //  think;
}
```

get chopsticks
left
right

free
chopsticks
left
right

Dining-Philosophers Problem

- Possible solutions to the deadlock problem
  - Allow at most **four** philosophers to be sitting simultaneously at the table.
  - Allow a philosopher to pick up her chopsticks only if **both chopsticks are available** (note that she must pick them up in a critical section).
  - Use an asymmetric solution; that is,
    - odd philosopher: **left first, and then right**
    - even philosopher: **right first, and then left**
- Besides deadlock, any satisfactory solution to the DPP must avoid the problem of **starvation**.

Solution 2 for Dining-Philosophers Problem

- semaphore mutex=1;

```
void philosopher(int i) {
    while(TRUE) {
        think( );
        P(mutex);
        take_chopstick (i);
        take_chopstick ((i + 1) % N);
        eat( );
        put_chopstick (i);
        put_chopstick ((i + 1) % N);
        V(mutex);
    }
}
```

Solution 3 for Dining-Philosophers Problem

- S1 THINKING…
- S2 I am HUNGRY
- S3 If my left neighbor or my right neighbor is EATING then block myself; else goto S4
- S4 Pick up both chopsticks
- S5 EATING …
- S6 Put down the chopsticks and wake up the left neighbor if he can EAT
- S7 Put down the chopsticks and wake up the right neighbor if he can EAT
- S8 Goto S1

Solution 3 for Dining-Philosophers Problem

- Define the data structures:

```
#define  N          5
#define  LEFT       (i+N-1)%N
#define  RIGHT      (i+1)%N
#define  THINKING   0
#define  HUNGRY     1
#define  EATING     2
int   state[N];
semaphore   mutex;    // initial value 1
semaphore   s[N];     // initial value 0
```

Solution 3 for Dining-Philosophers Problem

```
void philosopher(int i)  // i：0~N-1
{
    while(TRUE)
        {
S1 ———— think( );

S2–S4 ———— take_chopsticks(i);

S5 ———— eat( );

S6–S7 ———— put_chopsticks(i);
    }
}
```

Solution 3 for Dining-Philosophers Problem

- // Pick up both chopsticks, or block

```
void take_chopsticks(int i)  // i: 0~N-1
{
    P(mutex);
    state[i] = HUNGRY;
    test(i);
    V(mutex);
    P(s[i]);
}
```

```
void test (int i)
{
    if(state[i] ==  HUNGRY &&
      state[LEFT]  !=  EATING  &&
      state[RIGHT]  !=  EATING )
    {
        state[i] = EATING;
        V(s[i]);
    }
}
```

Solution 3 for Dining-Philosophers Problem

- // put down the two chopsticks and wake up the neighbors if necessary

```
void put_chopsticks(int i)
{
    P(mutex);
    state[i] = THINKING;
    test(LEFT);
    test(RIGHT);
    V(mutex);
}
```

Sleeping Barber Problem

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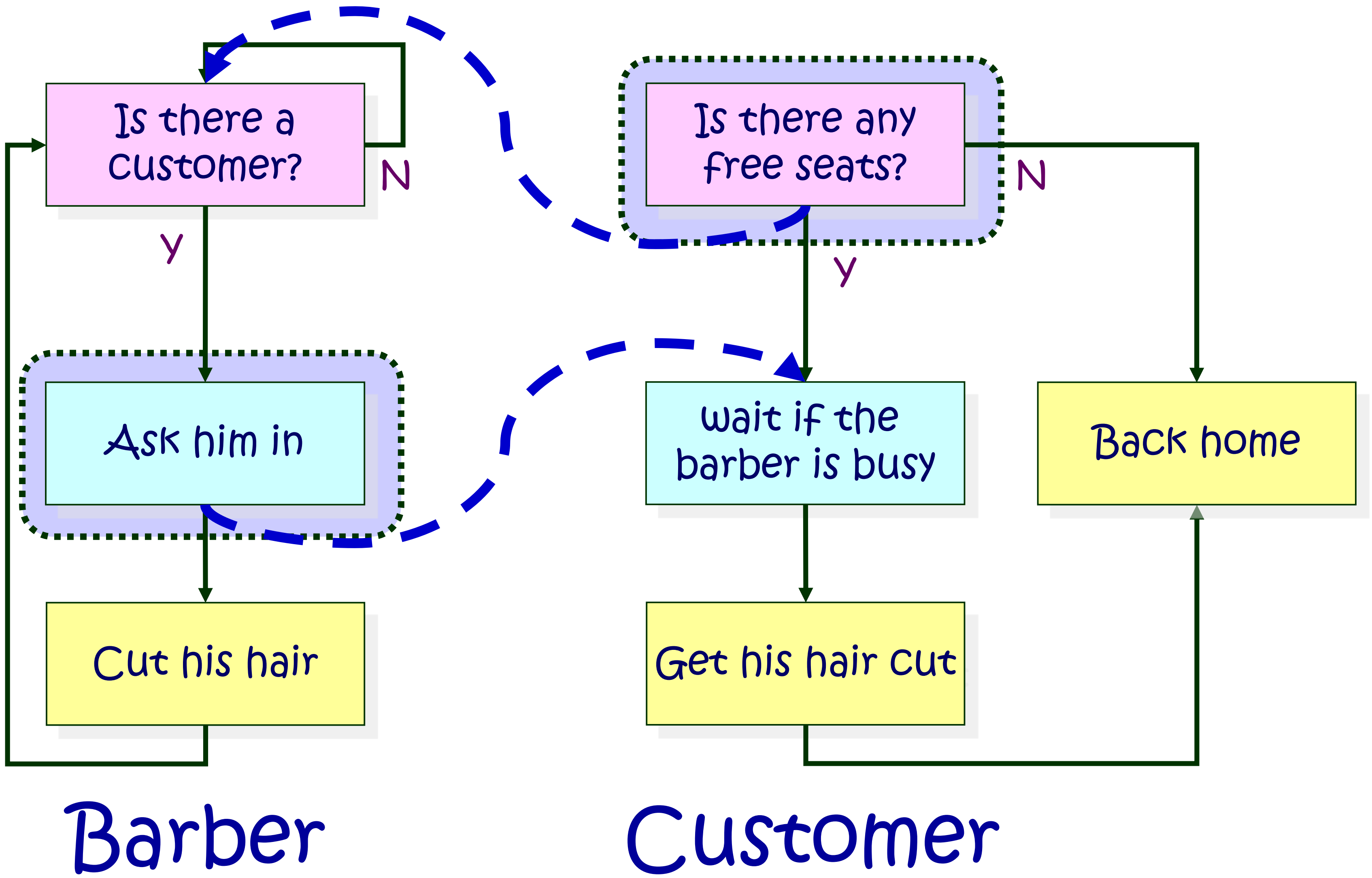
Sleeping Barber Problem

- The sleeping barber problem is a classic inter-process communication and synchronization problem between multiple operating system processes.
- There is a hypothetical barber shop with one barber. The barber has one barber chair and a waiting room with a number of chairs in it.

Sleeping Barber Problem

- When the barber finishes cutting a customer's hair, he dismisses the customer and then goes to the waiting room to see if there are other customers waiting.
  - If yes, he brings one of them back to the chair and cuts his or her hair.
  - If no, he returns to his chair and sleeps in it.
- Each customer, when he arrives, looks to see what the barber is doing.
  - If the barber is sleeping, then he wakes him up and sits in the chair.
  - If the barber is cutting hair, then he goes to the waiting room.
    - If there is a free chair in the waiting room, he sits in it and waits his turn.
    - If there is no free chair, then the customer leaves.

Sleeping Barber Problem



Sleeping Barber Problem

- You need (as mentioned above):

    Semaphore Customers = 0;   //#waiting customers

    Semaphore Barber = 0;

    Semaphore accessSeats (mutex) = 1;

    int NumberOfFreeSeats = N   //total number of seats

$$\text{Customers}\begin{cases} > 0\text{, there are waiting customers} \\ = 0\text{, there are no waiting customers} \\ = -1\text{, the barber is sleeping} \end{cases}$$

$$\text{Barber}\begin{cases} = 1\text{, the barber is not busy} \\ = 0\text{, the barber is busy cutting or sleeping} \\ < 0\text{, there are waiting customers} \end{cases}$$

The Barber Process

```
Void barber(void)
{
     while(true) {                                   // runs in an infinite loop
        P(Customers)                    // tries to acquire a customer
                                        // – if none is available he goes to sleep
        P(accessSeats)          // at this time he has been awakened
                                        //  - want to modify the number of available seats
        NumberOfFreeSeats++  // one chair gets free
        V(Barber)                          // the barber is ready to cut
        V(accessSeats)          // we don't need the lock on the   chairs anymore
        cut_hair();                     //here the barber is cutting hair
      }
}
```

The Customer Process

```
void customer(void)
{
    while(true) {                         // runs in an infinite loop
        P(accessSeats)                            // tries to get access to the chairs
        if ( NumberOfFreeSeats > 0 ) {   // if there are any free seats
            NumberOfFreeSeats--      // sitting down on a chair
            V(Customers)                  // notify the barber, who's waiting that there is a customer
             V(accessSeats)               // don't need to lock the chairs anymore
             P(Barber)                  // now it's this customer's turn, but wait if the barber is busy
             //here the customer is having his hair cut
           } else {                             // there are no free seat, tough luck
               V(accessSeats)                // but don't forget to release the lock on the seats
               //customer leaves without a haircut
          }
      }
}
```