Chapter V
INTER-PROCESS SYNCHRONIZATION

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Chapter overview

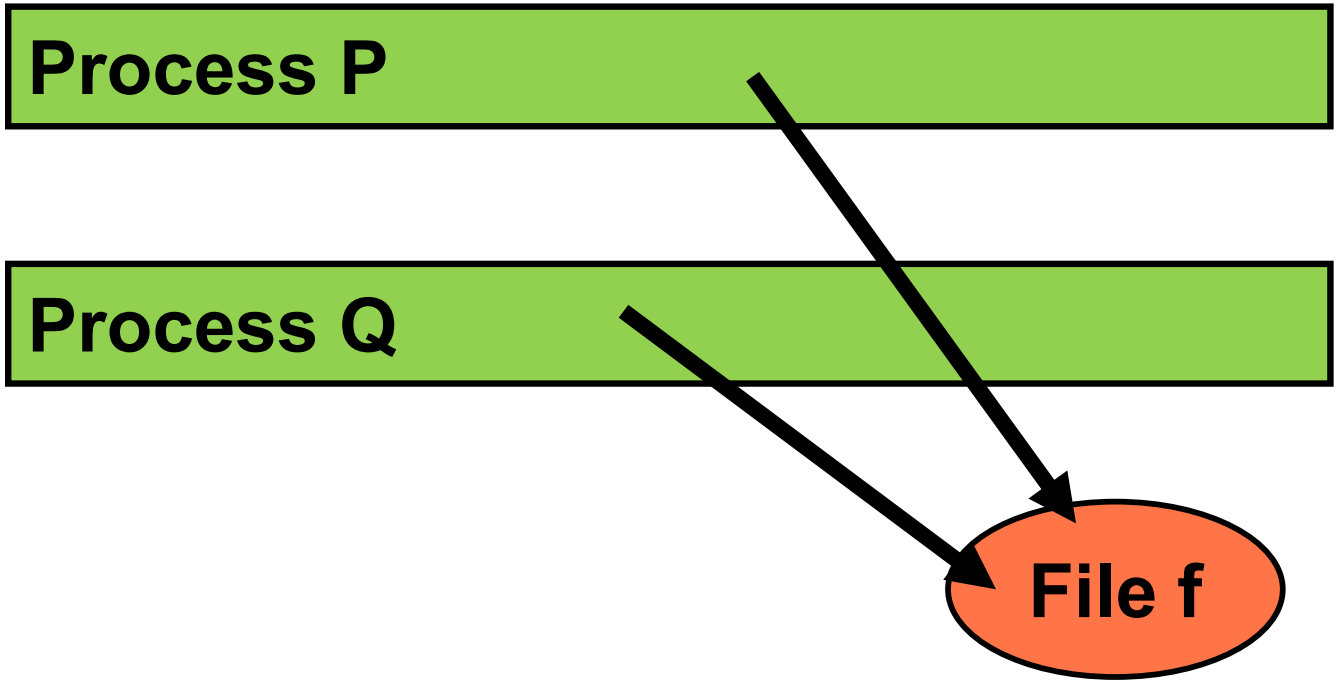
- ***The critical section problem***
- ***Purely software solutions***
- ***Spin locks***
  - Intel realization
- ***Semaphores***
- ***Classical synchronization problems***
- ***Monitors***
- ***Advanced pthread synchronization***

Shared Memory

- Name says it
  - Two or more processes share a part of their address space

Shared files

- Two processes access the same file at the same time



The outcome

- We can expect incorrect results whenever two processes (or two threads of a process) modify the same data at the same time

First example (I)

- **Bank Account Management**
  - Each account has a balance
  - One process tries to ***credit*** an account
  - Another process tries to ***debit*** the same account

The credit function

```
do_credit(int account, float amount) {
    float balance;
    fp = fopen(...); // open file
    fseek(fp, ...); // locate account
A   fscanf(fp,"%f", &balance); // read balance
    balance += amount; // update balance
    fseek(fp, ...); // go back to account
B   fprintf(fp,"%f", balance); //  save result
} // do_credit
```

The debit function

```
do_debit(int account, float amount) {
      float balance;
      fp = fopen(...);// open file
      fseek(fp, ...); // locate account
   C  fscanf(fp,"%f", &balance); // read balance
      balance -= amount; // update balance
      fseek(fp, ...); // go back to account
   D  fprintf(fp,"%f", balance);  // save result
  } // do_debit
```

First example (II)

- Assuming
  - Balance is $500
  - Amount to be credited is $3000
  - Amount to be debited is $100
- Sole correct value for final balance is $3400
- We can also get **$3500** and **$400**!
  - ***Everything depends on ordering of reads and writes***

Explanation (I)

- Correct result is guaranteed if the two processes access the data one after the other
  - I/Os are done in the order
    - A, B then C, D
    - C, D then A, B
  - ***Final balance will be* $3400**

Explanation (II)

- Account will not be credited if both functions read the old value of the balance and the ***debit*** function updates the file last
  - Disk accesses are done in the order
    - A, C then B, D
    - C, A then B, D
  - ***Final balance will be* $400**

Explanation (III)

- Account will not be debited if both functions read the old value of the balance and the ***credit*** function updates the file ***last***
  - Disk accesses are done in the order
    - A, C then D, B
    - C, A then D, B
  - ***Final balance will be*** **$3500**

The problem

- We have a ***race condition***
  - Outcome of concurrent execution of the processes will depend on process speeds
- We will observe ***irreproducible errors***
  - ***Hard to detect and debug***

The solution

- Define ***critical sections*** in the two functions

- Control access to critical sections

The credit function

```
do_credit(int account, float amount) {
    float balance;
    fp = fopen(...); // open file
    fseek(fp,...); // locate account
    fscanf(fp,"%f", &balance); // read balance
    balance += amount; // update balance
    fseek(fp,...); // go back to account
    fprintf(fp,"%f", balance); //  save result
} // do_credit
```

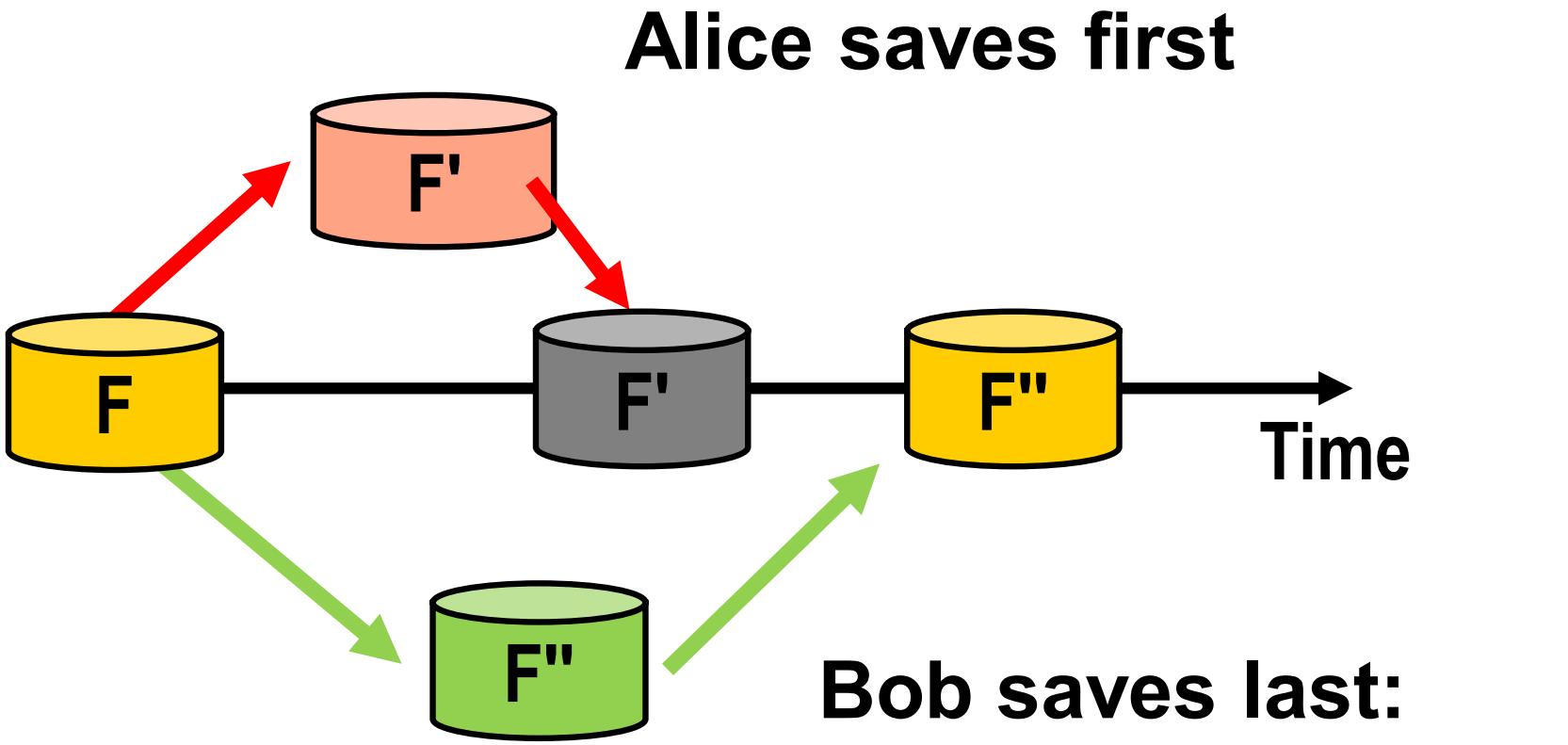
The debit function

```
do_debit(int account, float amount) {
    float balance;
    fp = fopen(...);// open file
    fseek(fp,...); // locate account
    fscanf(fp, %f", &balance); // read balance
    balance -= amount; // update balance
    fseek(fp,...); // go back to account
    fprintf(fp,"%f", balance);  // save result
} // do_debit
```

Second example (I)

- Most text editors and word processors do not update directly the files on which they operate
  - Create a temporary *tempFile*
  - Modify the original file when the user issues a ***save*** command
- ***What will happen if two users edit the same file at the same time?***

Second example (II)



The problem

- Another ***race condition***
  - Should never have two users/processes updating the same file at the same time

- *Don't let other people edit our files*
  - *Send them a copy!*

A real race condition

- Pthread program creating a child thread
- Set a global counter to 0
- Both parent and child add one to counter 100,000 times
- When both are done, final counter value is 200,000
  - Right?

Realrace.cpp (I)

```
#include <iostream>
#include <pthread.h>
using namespace std;
```

```
//Shared counter
static int counter = 0;
```

Realrace.cpp (II)

```
// The thread function
void *child_fn(void *arg) {
     int i,  ntimes;
     ntimes = (int) arg;
     for (i = 0; i < ntimes ; i++) {
          counter++;
     } // for
} // child_thread
```

Realrace.cpp (III)

```
void main() {
        pthread_t tid;
        int ntimes =100000;
        int i = 0;

        pthread_create(&tid, NULL, child_fn,
                              (void *) ntimes);
```

Realrace.cpp (IV)

```
    for (i = 0; i < ntimes ; i++) {
        counter++;
    } // for
    pthread_join(tid, NULL);
    cout << "Final value of counter: " << counter
         << endl ;
} // main
```

The outcome

- Final value of counter is ***smaller*** than 200,000

- Frequent ***race conditions*** result in conflicting increments
  - Both parent and child access the same counter
  - Increment it ***twice***

Searching for a solution

- Three approaches
  - Disabling interrupts
  - Enforcing mutual exclusion 
  - Using an atomic transaction mechanism

Disabling interrupts

- ***Very dangerous*** solution for user programs
- Was sometimes used for ***very short*** critical sections in the kernel
- Does not work for multithreaded kernels running on multiprocessor architectures.

Enforcing mutual exclusion

- Portions of code where the shared data are read and modified are defined as **critical sections**
- **Must guarantee** that we will never have more than only one process in a critical section for the same shared data
- Works best with ***short critical regions***
- ***Preferred solution***

Norace.cpp (I)

```
#include <iostream>
#include <pthread.h>
using namespace std;
```

```
//Shared counter and shared lock
static int counter = 0;
static pthread_mutex_t lock;
```

Norace.cpp (II)

```
// The thread function
void *child_fn(void *arg) {
     int i, ntimes;
     ntimes = (int) arg;
     for ( i = 0; i < ntimes ; i++) {
          pthread_mutex_lock(&lock);
               counter++;
          pthread_mutex_unlock(&lock);
     } // for
} // child_thread
```

Norace.cpp (III)

```
void main() {
        pthread_t tid;
        int ntimes =100000;
        int i = 0;
        // Create the lock
        pthread_mutex_init(&lock, NULL);
        // Create the thread
        pthread_create(&tid, NULL, child_fn,
                                (void *) ntimes);
```

Norace.cpp (IV)

```
    for (i = 0; i < ntimes ; i++) {
        pthread_mutex_lock(&lock);
            counter++;
        pthread_mutex_unlock(&lock);
    } // for

    pthread_join(tid, NULL);
    cout << "Final value of counter: " << counter
         << endl;
} // main
```

The outcome

- Program is much slower
- Gets the expected result

Using atomic transactions

- Will allow several processes to access the same shared data without interfering with each other

- Preferred solution for database access since
  - Most databases are shared
  - Their critical sections can be very long as they often involve a large number of disk accesses

Criteria to satisfy (I)

- Any solution to the critical section problem should satisfy the ***four following criteria***

1. No two processes may be simultaneously into their critical sections for the same shared data

   We want to enforce mutual exclusion

Criteria to satisfy (II)

2. No assumptions should be made about the speeds at which the processes will execute.

   The solution should be general:
   the actual speeds at which processes complete are often impossible to predict because running processes can be interrupted at any time!

Criteria to satisfy (III)

3. No process should be prevented to enter its critical section when no other process is inside its own critical section for the same shared data

   Should not prevent access to the shared data when it is not necessary.

Criteria to satisfy (IV)

4. No process should have to wait forever to enter a critical section

   Solution should not cause starvation

My mnemonics

- Solution should provide
  1. Mutual exclusion
  2. All the mutual exclusion
  3. Nothing but mutual exclusion
  4. No starvation

Solutions

- Five approaches
  - ***Pure software***
    - *Peterson's Algorithm*
  - ***Spin locks***
    - Use **xchg** instruction
  - ***Semaphores***
  - ***Monitors***
  - ***Locks and condition variables***

Pure software solutions

Pure Software Solutions

- Make no assumption about the hardware
  - *Peterson's Algorithm*
  - Easier to understand than *Dekker's algorithm*
    - Original solution

A bad solution (I)

```
#define LOCKED 1
#define UNLOCKED 0
int lock = UNLOCKED; // shared
// Start busy wait
while (lock == LOCKED);
lock = LOCKED;
    Critical_Section(…);
// Leave critical section
lock = UNLOCKED;
```

A bad solution (II)

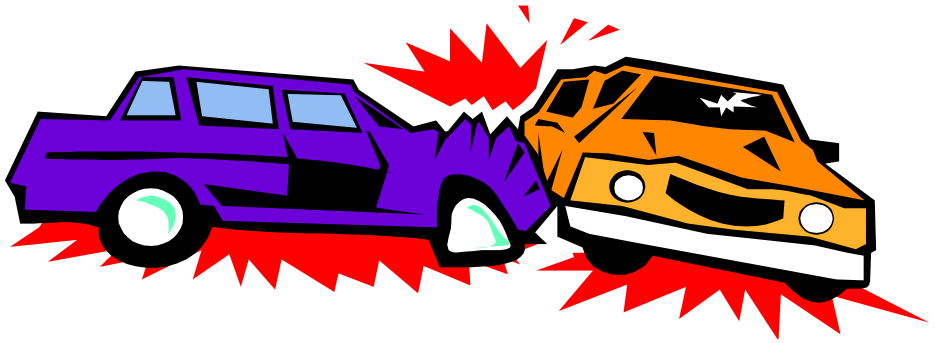
- Solution fails if two or more processes reach the critical section ***in lockstep*** when the critical section is UNLOCKED
  - Will both exit the busy wait
  - Will both set Lock variable to LOCKED
  - Will both enter the critical section at the same time
- ***Which condition does this solution violate?***

Examples (I)

- You live in a dorm
  - Go to the showers
  - Find a free stall
  - Return to your room to bring your shampoo
  - Get into the free stall and find it occupied!

Examples (II)

- You see a free parking spot
- Move towards it
- Do not see another car whose driver did not see you



A bad solution (III)

- ***Solution violates second condition***
  - Does not ***always*** guarantee mutual exclusion

Other bad solutions

- People have tried plenty of bad solutions

Peterson Algorithm (I)

- Simplest case
  - Two processes
  - Process IDs are **`0`** and **`1`**
- Philosophy is
  - Grab a lock for CS ***before*** checking that CS is free
  - Use a tie-breaker to handle conflicts

Peterson Algorithm (II)


```
#define F 0
#define T 1
// shared variables
int reserved[2] = {F, F};
int mustWait; // tiebreaker
```

Peterson Algorithm (III)


```
void enter_region(int pid) {
    int other; //other process
    other = 1 - pid;
    reserved[pid] = T;
    // set tiebraker
    mustWait = pid;
    while (reserved[other]&&
    mustWait==pid);
} // enter_region
```

Peterson Algorithm (IV)


```
void leave_region(int pid) {
    reserved[pid] = F;
} // leave_region
```

Peterson Algorithm (V)

- Essential part of algorithm is

```
reserved[pid] = T;
mustWait = pid;
while reserved[other]&&
mustWait==pid);
```

- When two processes arrive ***in lockstep, last one will wait***

Spin locks

Spin locks

- These solutions use special instructions to achieve an ***atomic test and set***:
  - Putting the lock testing and the lock setting functions into a single instruction makes the two steps ***atomic***
    - ***Cannot be separated by an interrupt***

The exchange instruction (I)

- We assume the existence of a shared lock variable

```
int lockvar = 0; // shared
```

- Will only have two possible values
  - 0 meaning nobody is inside the critical section
  - 1 meaning somebody has entered the critical section

The exchange instruction (II)

- We introduce an ***atomic*** instruction

  `exch register, lockvar`

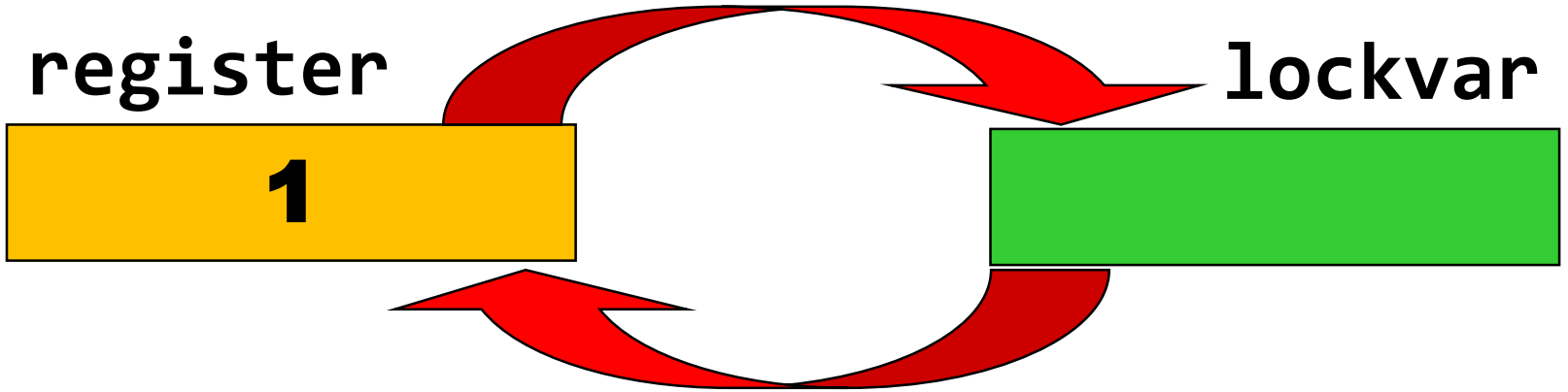
  - swaps contents of **`register`** and **`lockvar`**

How we use it

- We set **`register`** to ***one*** before doing

`exch register, lockvar`

- What will be the outcome?



The two possible outcomes (I)

- If `register == 1`
  - `lockvar` was already set to 1
  - We ***cannot enter*** the critical section
  - We must ***retry***
- If `register == 0`
  - `lockvar` was equal to 0
  - We have successfully set it to 1
  - We ***have entered*** the critical section

Before the exchange

- We do not know the state of lockvar
- Could be
  - Unlocked and free to grab?
  - Locked and in use by another process?

After the exchange (I)

Register

Lockvar

- The lock was already locked
- Attempt failed
- Must retry

After the exchange (II)

- Lockvar was unlocked
- It is now locked
  - We succeeded!
- Can enter the critical region

Entering a critical region

- To enter a critical region, repeat **`exchange`** until it succeeds

```
do {
  exchange(int *pregister,int &plockvar)
  // pregister points to register
  // plockvar points to lock var
} while (*pregister == 1);
```

Leaving a critical section

- To leave a critical region, do

```
*plockvar = 0;
```

The x86 xchg instruction

- **`xchg op1, op2`**
  - Exchanges values of two operands
  - Always atomic (implicit **`lock`** prefix) if one of the operands is a memory address
    - **`xchg %eax, lockvar`**

How to use it

- ```
  enter_region:
      movl 1, %eax # set to one
      xchg %eax, lockvar
      test %eax, %eax
      jnz enter_region # try again
  ```

- ```
  leave_region:
      movl 0, %eax # reset to zero
      xchg %eax, lockvar
  ```

Same code in MASM

- ```
  enter_region:
      movl eax, 1 ; set to one
      xchg eax, [lockvar]
      test eax, eax
      jnz enter_region ; try again
  ```

- ```
  leave_region:
      movl eax, 0 ; reset to zero
      xchg eax, [lockvar]
  ```

Underlying assumptions

- Peterson's algorithm and spinlocks assume that
  - Instructions execute in sequence
  - Instructions execute in an atomic fashion
- Less and less true in modern CPU architectures
  - Intel x86 architecture has an instruction prefix **`lock`** making any instruction writing into memory atomic
    - **`lock  movl 1, lockvar`**

The bad news

- Peterson's algorithm and spinlocks rely on ***busy waits*.**
- Busy waits ***waste CPU cycles*:**
  - Generate ***unnecessary context switches*** on single processor architectures
  - Slow down the progress of other processes

Priority inversion

- A ***high priority process*** doing a busy wait may prevent a lower priority process to do its work and leave its critical region.
  - *Think about a difficult boss calling you every two or three minutes to ask you about the status of the report you are working on*

In conclusion (I)

- **We *had to avoid* busy waits on single-core architectures**
- **We can use them only for *short waits* on *multicore architectures***

In conclusion (II)

- Several operating systems for multiprocessor architectures offer two different mutual exclusion mechanisms:
  - ***Busy waits*** for very ***short waits***
    - ***Spinlocks***
  - Putting the waiting process in the ***blocked state*** until the resource becomes free for longer waits

In conclusion (III)

- *Like waiting for a table in a restaurant:*
  - *If we are promised a very short wait, we will wait there*
  - *Otherwise, we might prefer to go for a walk (especially if it is a beach restaurant) or have a drink at the bar*

Semaphores

Semaphores

- Introduced in 1965 by E. Dijkstra
- Semaphores are special integer variables that can be initialized to any value ≥ 0 and can only be manipulated through two ***atomic operations***: **P( )** and **V( )**
- Also called **wait()** and **signal()**
  - Best to reserve these two names for operations on ***conditions*** in ***monitors*.**

The P( ) operation

- If semaphore value is zero,
  - Wait until value become positive
- Once value of semaphore is greater than zero,
  - Decrement it

The V( ) operation

- Increment the value of the semaphore

How they work

- The normal implementation of semaphores is through *system calls*:
  - ***Busy waits*** are ***eliminated***
  - Processes waiting for a semaphore whose value is zero are put in the ***blocked state***

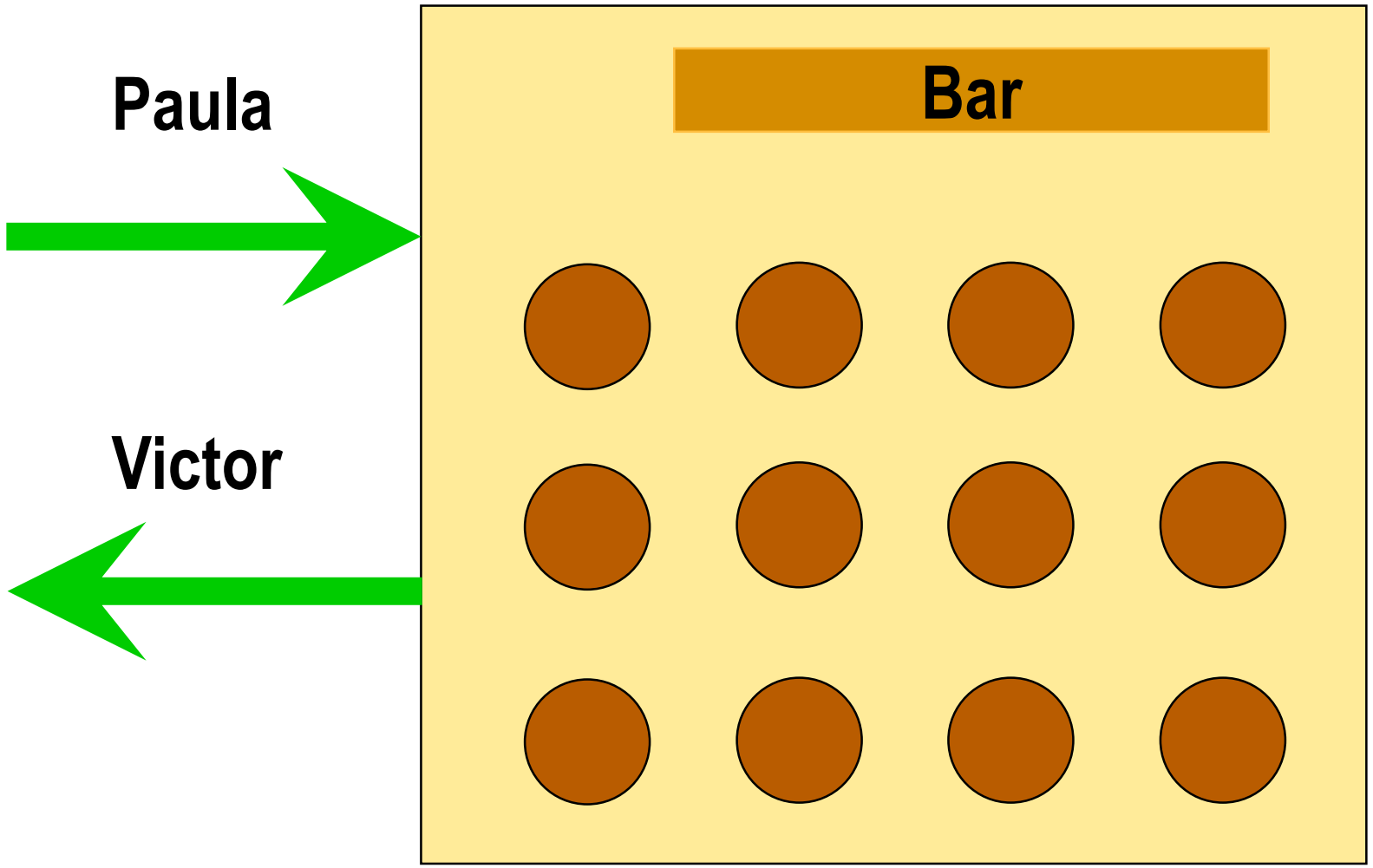
An analogy

- Paula and Victor work in a restaurant:
- Paula handles customer arrivals:
  - Prevents people from entering the restaurant when all tables are busy.
- Victor handles departures
  - Notifies people waiting for a table when one becomes available

An analogy (II)

- The semaphore represents the number of available tables
  - Initialized with the ***total number of tables*** in restaurant

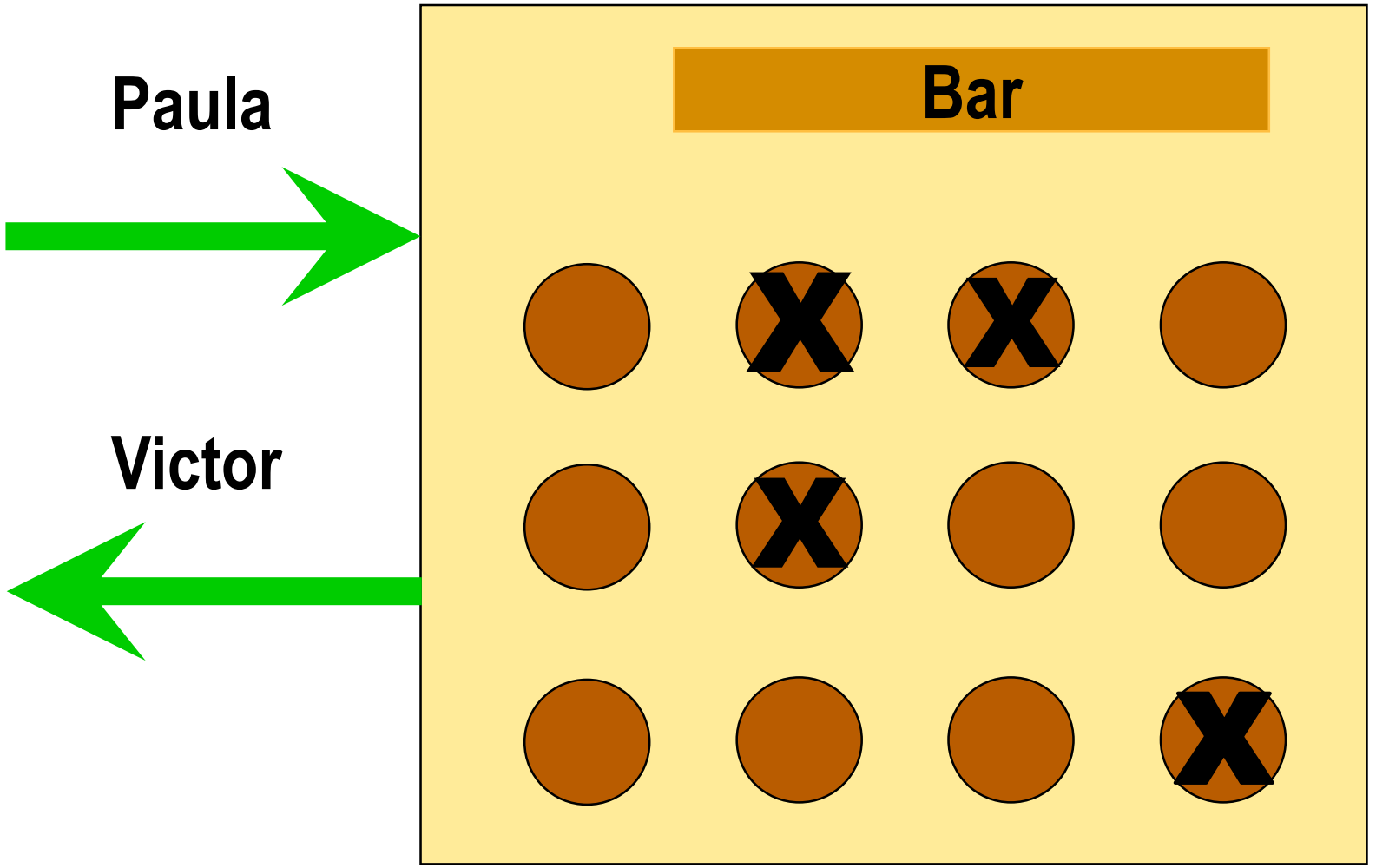
An analogy (III)



An analogy (IV)

- When people come to the restaurant, they wait for Paula to direct them:
  - If a table is available, she let them in and decrements the table count
  - Otherwise, she directs them to the bar

An analogy (V)



An analogy (VI)

- When people leave, they tell Victor:
  - Victor increments the semaphore and checks the waiting area:
  - If there is anyone in there, he lets one group in and decrements the semaphore
- *Paula and Victor have worked long enough together and don't interfere with each other*

Two problems

- What if somebody sneaks in the restaurant and bypasses Paula?
  - *Paula will let a group of people in when all tables are busy.*
- What if people forget to tell Victor they are leaving?
  - *Their table will never be reassigned.*

Implementation (I)

- To avoid busy waits, we will implement semaphores as ***kernel objects***
- Each semaphore will have a ***value*** and an ***associated queue***.
- New system calls:
  - `sem_create( )`
  - `sem_P( ):`
  - `sem_V( )`
  - `sem_destroy( )`

Implementation (II)

- **`sem_create( ):`**
  - Creates a semaphore and initializes it
- **`sem_destroy( ):`**
  - Destroys a semaphore

Implementation (III)

- **`sem_P( ):`**
  - If the semaphore value is greater than zero, the kernel decrements it by one and lets the calling process continue.
  - Otherwise the kernel puts the calling process in the waiting state and stores its process-id in the semaphore queue.

Implementation (IV)

- **`sem_V( ):`**
  - If the semaphore queue is not empty, the kernel selects one process from the queue and puts it in the ready queue
  - Otherwise, the kernel increments by one the semaphore value

Binary semaphores

- Their value can only be ***zero*** or ***one***
- Mostly used to provide ***mutual exclusion***
- Semantics of P( ) operations not affected
- V( ) now sets semaphore value to one

Mutual Exclusion (I)

- Assign one semaphore to each group of data that constitutes a critical section
- ***Initial value*** of semaphore must be ***one***:

```
semaphore mutex = 1;
```

Mutual exclusion (II)

- Before entering a critical region, processes must do:
  - **`P(&mutex);`**
  - ***Wait*** *until critical region becomes free*
- Processes leaving a critical region must do
  - **`V(&mutex);`**
  - ***Signal*** *the process is leaving the critical section*

Making a process wait

- The ***initial value*** of semaphore must be ***zero***.

```
semaphore waitforme = 0;
```

- Process that needs to wait for another process does:

```
sem_P(&waitforme);
```

- When the other process is ready, it will do:

```
sem_V(&waitforme);
```

Example (I)

- Alice has promised to take her friends to the beach in her new car
- Everybody will meet on campus in front of the University Center
- Her three friends are Beth, Carol and Donna

Example (II)

- We will have three semaphores

```
semaphore beth_is_there = 0;
semaphore carol_is_there = 0;
semaphore donna_is_there = 0;
```

- There are all initialized to ***zero***

Example (III)

- Alice will do

```
sem_P(&Beth_is_there);
sem_P(&Carol_is_there);
sem_P(&Donna_is_there);
```

Example (IV)

- When her friends arrive, they will do

```
sem_V(&Beth_is_there);
sem_V(&Carol_is_there);
sem_V(&Donna_is_there);
```

Example (V)

- Our solution assumes that Alice will definitively be the first to arrive
  - *Her friends will never have to wait for her*
- If this is not the case, we need to force everyone to wait for everyone

Setting up a rendezvous (I)

- To force two processes to wait for each other, we need **two** semaphores both initialized at **zero**

```
semaphore waitforfirst = 0;
semaphore waitforsecond = 0;
```

Setting up a rendezvous (II)

- When the first process is ready, it will do

```
sem_V(&waitforfirst);
sem_P(&waitforsecond);
```

- When the second process is ready, it will do

```
sem_V(&waitforsecond);
sem_P(&waitforfirst);
```

Setting up a rendezvous (III)

- What will happen if the first process does

```
sem_P(&waitforsecond);
sem_V(&waitforfirst);
```

  and the second process does

```
sem_P(&waitforfirst);
sem_V(&waitforsecond);
```

Setting up a rendezvous (IV)

- We will have a ***deadlock***

Advantages of semaphores (I)

- Semaphores are machine-independent
- They are simple but very general
- They work with any number of processes
- We can have as many critical regions as we want by assigning a different semaphore to each critical region

Advantages of semaphores (II)

- We can use semaphores for synchronizing processes in an arbitrary fashion
- The key idea is ***layering***:
  - Pick a powerful and flexible mechanism that apply to many problems
  - Build later better user interfaces

Implementations

Implementations

- UNIX has three noteworthy implementations of semaphores:
  - The old System V semaphores
    - Now obsolete
  - The newer POSIX semaphores
    - ***For reference only***
  - The Pthread semaphores
    - ***For reference only***

Overview

- Six operations:
  - `sem_open()`
  - `sem_wait()`
  - `sem_post()`
  - `sem_getvalue()`
  - `sem_close()`
  - `sem_unlink()`

Will focus on *named* POSIX semaphores

“named” means here having a global system-wide name

Sem_open()

- Sole non-trivial call
  - Works like **`open()`** with **`O_CREAT`** option
    - Accesses the named semaphore
    - Creates it ***if and only if*** it did not already exist

WARNING:
If you are debugging a program that has crashed, `sem_open` will not reinitialize any semaphore that has survived the crash

Sem_open syntax

```
sem_t *mysem;
char name[] = "Sem Name";
unsigned int initial_value;
mysem = sem_open(name,
         O_CREAT, 0600,
         initial_value);
```

0600 prevents other users from accessing the new semaphore

Semaphore names

- Semaphores appear in the file system in subdirectory of **`/dev/shm`**
  - Names prefixed with "**`sem.`**"
- Can be removed just like regular files using "**`rm`**"
- The names of the semaphores you are using must be ***unique***
  - All stored in a system wide directory

A source of troubles

- **`sem_open(…)`** does ***not change*** the value of an existing semaphore
  - **`initial_value`** is only used if the semaphore did not already exist
- Must be sure that all your semaphores have been deleted before restarting your program
  - **`ls /dev/shm/sem.*`**

Sem_wait() and sem_post()

- `sem_t *mysem;`
  `sem_wait(mysem);`
  - Implements the sem_P() operation
- `sem_t *mysem;`
  `sem_post(mysem);`
  - Implements the sem_V() operation

Sem_getvalue()

- Can test at any time the value of any opened semaphore:

```
sem_t *mysem;
int value;
sem_getvalue(mysem,&value);
```

- Non-standard feature of POSIX semaphores

Sem_close()

- `sem_t *mysem;`
  `sem_close(mysem);`
  - Closes the semaphore (without changing its value)

Sem_unlink()

- **`char name[];`**
  `sem_unlink(name);`
  - Removes the semaphore unless it is accessed by another process
    - That process will still be able to access the semaphore until it closes it

Pthread synchronization

- Pthreads offer three synchronization primitives
  - ***POSIX semaphores***
    - Can use private semaphores
      - Unnamed
  - ***Mutexes***
  - ***Condition variables***

For reference only

Unnamed semaphores (I)

- Have no system-wide name in **`/dev/shm`**
- Work like regular POSIX semaphores but for creation and deletion
  - **`sem_init()`** and **`sem_destroy()`**
- Given a regular variable name
- To remain visible to all users, variable must be declared
  - Static if only shared by pthreads
  - In a shared memory segment if shared by processes

Unnamed semaphores (II)

- Creating a semaphore
  - ```
    static sem_t sem;
    int sem_init(sem_t *sem, int pshared,
                 unsigned initial_value);
    ```
  - If **`pshared`** is 0
    - Semaphore is only shared by the threads ***within*** the process
    - Otherwise it can be shared with *other* processes
    ```

Mutexes

- Built-in mutexes
  - `static pthread_mutex_t name;`
  - `pthread_mutex_init(&name, NULL);`
  - `pthread_mutex_lock(&name);`
  - `pthread_mutex_unlock(&name);`
- Mutexes are always initialized to ***one***
  - As they should

Mutexes and binary semaphores

Binary semaphores

- Can only have two values
- Any process can lock or unlock a binary semaphore
  - Great for rendez-vous

Mutexes

- Can only have two values
- ***A mutex can only be unlocked by the thread that locked it***
  - Less general

Classical synchronization problems

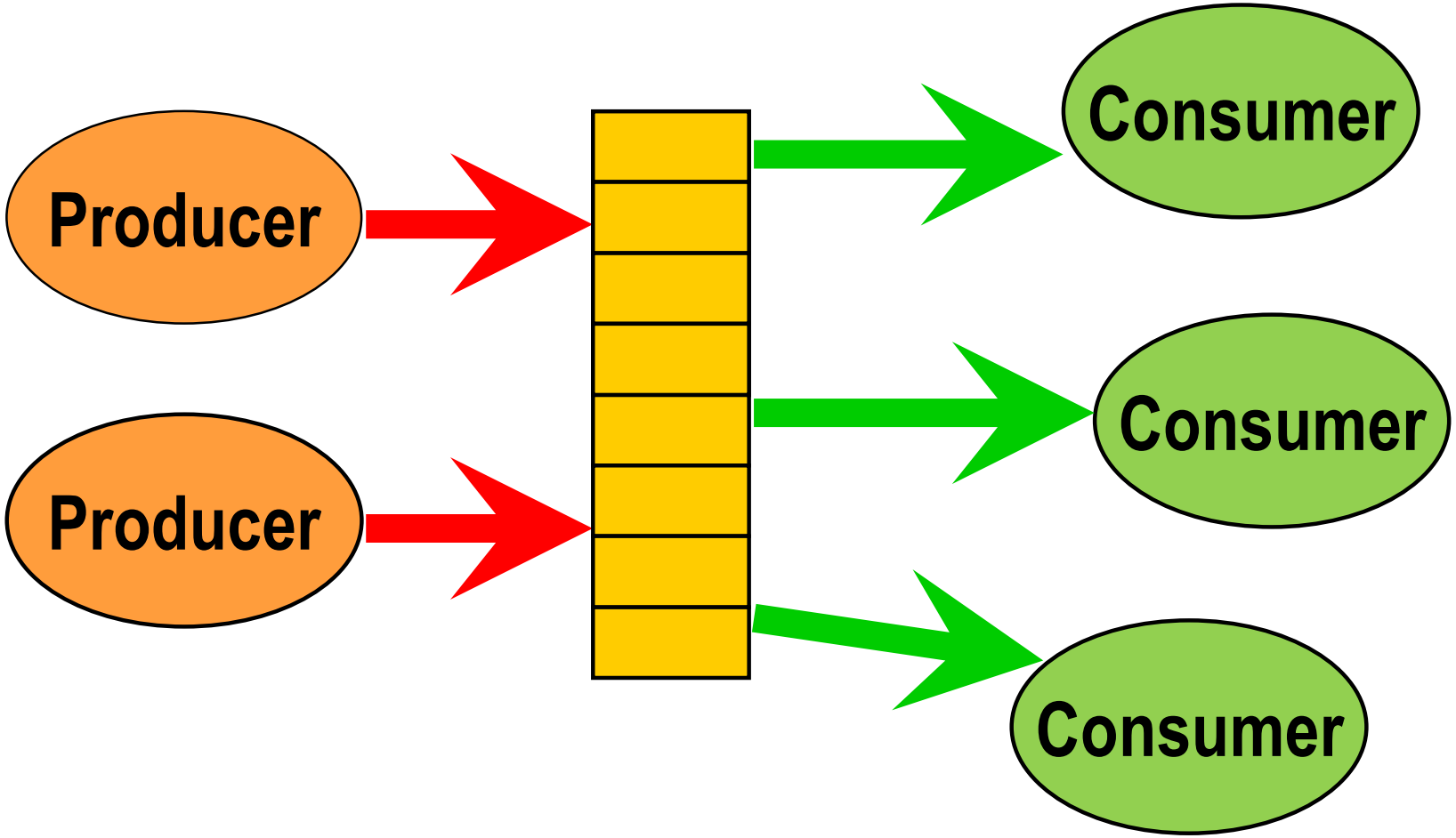
What are they?

- Will cover three problems
  - Bounded buffer
  - Readers and writers
  - Dining philosophers
- Will mention but not cover
  - Sleeping barber

Bounded buffer (I)

- One or more producer processes put their output in a bounded buffer
  - Must wait when buffer is full
- One or more consumer processes take items from the buffer
  - Must wait when buffer is empty

Bounded buffer (II)



The three rules

- Producers cannot put items in the buffer when it is full
- Consumers cannot take items from the buffer when it is empty
- Producers and consumers must access the buffer one at a time

Two analogies

- ***The supermarket***
  - Supermarket is the buffer
  - We are the consumers
  - Suppliers are the producers

- ***Our garbage***
  - Our garbage can is the buffer
  - We are the producers
  - Garbage truck is the consumer

The solution

- Declarations

```
#define NSLOTS ... // size
semaphore mutex = 1;
semaphore notFull = NSLOTS;
semaphore notEmpty = 0;
```

The functions

```
producer() {
    struct x item;
    for (;;) {
        produce(&item);
        sem_P(&notFull);
        sem_P(&mutex);
        put(item);
        sem_V(&mutex);
        sem_V(&notEmpty);
    } // for
} // producer
```

```
consumer() {
    struct x item;
        for (;;) {
            sem_P(&notEmpty);
            sem_P(&mutex);
            take(item);
            sem_V(&mutex);
            sem_V(&notFull);
            consume(item);
        } // for
} // consumer
```

A bad solution

```
producer() {
    struct x item;
    for (;;) {
        produce(&item);
        sem_P(&notFull);
        sem_P(&mutex);
        put(item);
        sem_V(&mutex);
        sem_V(&notEmpty);
    } // for
} // producer
```

```
consumer() {
    struct x item;
    for (;;) {
        sem_P(&mutex);
        sem_P(&notEmpty);
        take(item);
        sem_V(&mutex);
        sem_V(&notFull);
        consume(item);
    } // for
} // consumer
```

Order matters

- The order of the two **P( )** operations is ***very important***
  - Neither the producer or the consumer should request exclusive access to the buffer before being sure they can perform the operation they have to perform
- The order of the two V( ) operations does not matter

The readers-writers problem (I)

- We have a file (or a database) and two types of processes:
  - **Readers** that need to access the file
  - **Writers** that need to update it.
- A ***real problem***

The readers-writers problem (II)

- Readers must be prevented from accessing the file while a writer updates it.
- Writers must be prevented from accessing the file while any other process accesses it
  - They require ***mutual exclusion***

An analogy

- Sharing a classroom between teachers and students
  - Teachers use it to lecture
    - *They cannot share the room*
  - Students use it for quiet study
    - *They can share the room with other students*
- Classroom is assumed to be in use if the light is turned on

Rules for teachers

- Do not enter a classroom if its light is turned on
- Otherwise
  - Turn the light on when you come in
  - Turn the light off when you leave

Rules for students

- If the light is on and you see students but no teacher
  - Enter the room
- If the light is off, you are the ***first student*** to enter the room
  - Turn the light on and enter the room
- If you are the ***last student*** to leave the room
  - Turn the light off after leaving

The readers-writers problem (III)

- Shared variables and semaphores

```
int readersCount = 0;
semaphore mutex = 1;
semaphore access = 1;
```

The readers-writers problem (IV)

```
write_to_file() {
    P(&access);
          . . .
    V(&access);
} // write_to_file
```

The readers-writers problem (V)

```
read_the_file(){
    readersCount++;
    if(readersCount == 1)
        sem_P(&access);
            . . .
    readersCount--;
     if(readersCount == 0)
         sem_V(&access);
} // read_the_file
```

TENTATIVE SOLUTION

Classrooms with two doors

- What if ***two students enter in lockstep*** using different doors?
  - Second will think he is the first to enter the room
  - Will see the light on and not enter
- What if ***two students leave in lockstep*** using different doors?
  - Neither of them will notice they are the last ones to leave
  - Neither will turn the light off

The readers-writers problem (VI)

```
read_the_file(){
    sem_P(&mutex);
    readersCount++;
    if(readersCount == 1)
        sem_P(&access);
    sem_V(&mutex);
     . . .
```

The readers-writers problem (VII)

```
    sem_P(&mutex);
    readersCount--;
    if(readersCount == 0)
        sem_V(&access);
    sem_V(&mutex);
} // read_the_file
```

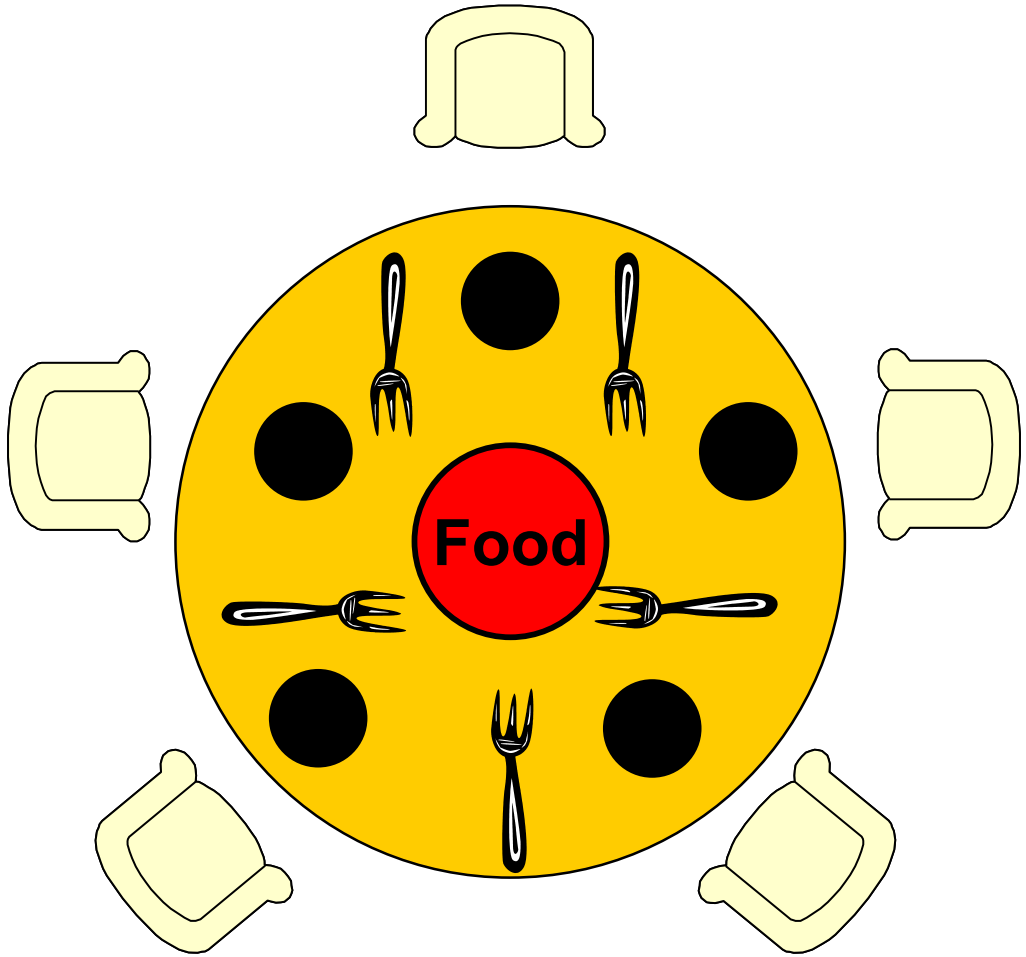
Starvation

- Solution favors the readers over the writers
  - A continuous stream of incoming readers could block writers forever
    - ***Result would be writers' starvation***.

The dining philosophers (I)

- Five philosophers sit at a table. They spend their time thinking about the world and eating spaghetti
  - The problem is that there are only five forks.
  - If all five philosophers pick their left forks at the same time, a ***deadloc***k will occur

The table layout



The dining philosophers (II)

```
#define N 5
semaphore mutex = 1;
```

The dining philosophers (III)

```
philosopher(int i) {
    for (;;) {
        think();
        take_fork(i); // left before
        take_fork((i+1)%N); // right
        eat();
        put_fork(i);
        put_fork((i+1)%N);
    } // for loop
} // philosopher
```

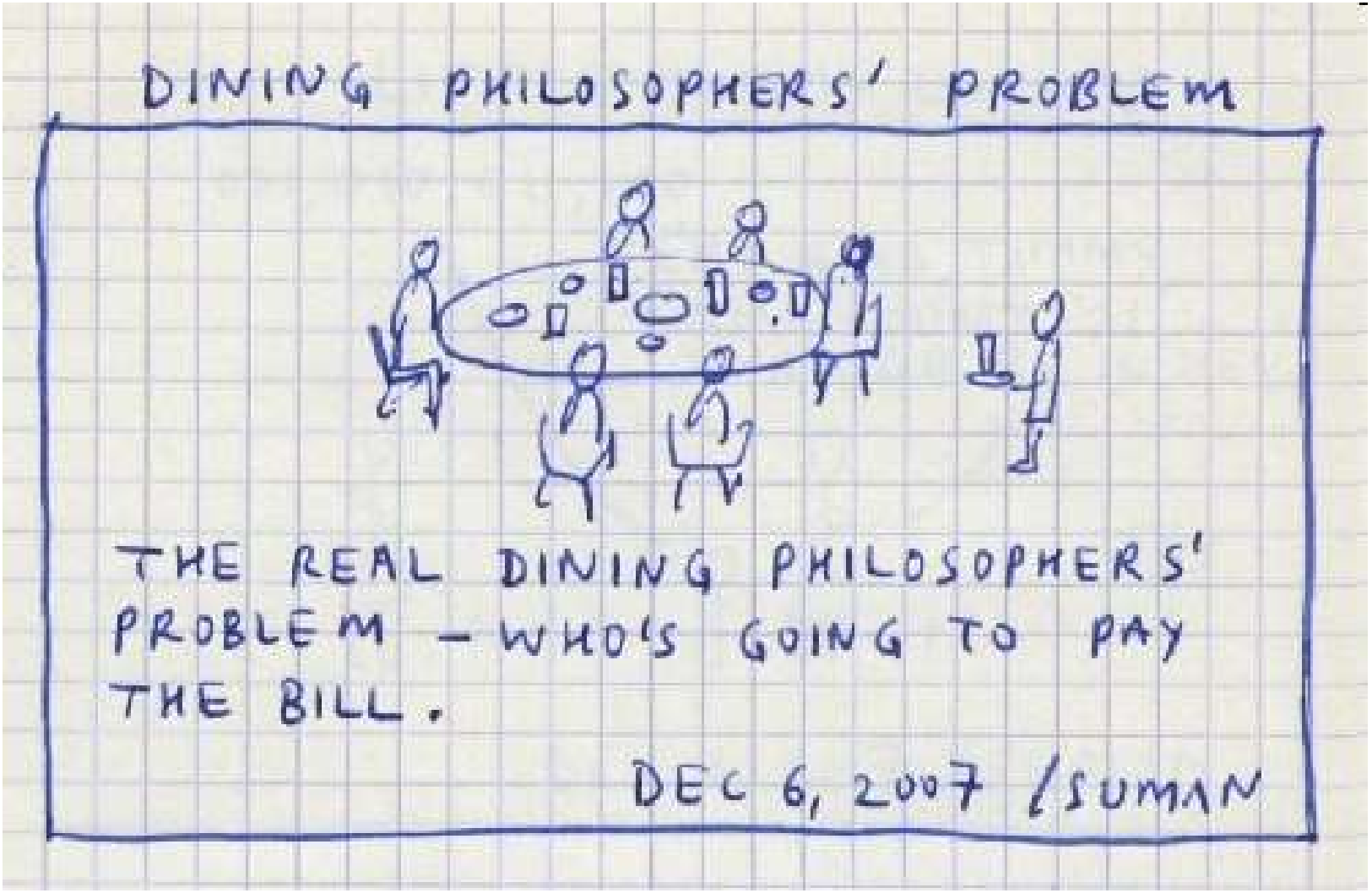
Avoiding the deadlock

```
philosopher(int i) {
   for (;;) {
      think();
      if (i == 0) {
         take_fork((i+1)%N); // right
         take_fork(i); // before left
       } else {
          take_fork(i); // left before
          take_fork((i+1)%N); // right
       } // if-else
       …
   } // for loop
} // philosopher
```

The dining philosophers (IV)

- To break the deadlock, we force one of the philosophers to grab their ***right fork before*** their ***left fork***
- ***The main interest of this problem is that it belongs to the operating system folklore***

The dining philosophers (V)



The sleeping barber (I)

- Proposed by Andrew Tanenbaum in his textbook *Modern Operating Systems*.
  - ***Not covered it in class.***
  - Shows how to track the value of a semaphore using a global variable.

The sleeping barber (II)

- A barber shop has several chairs for waiting customers and one barber who sleeps when there are no customers.
- Customers don't wait if the shop is full and there are no free chairs to sit upon.
  - Must keep track of the number of customers in the shop

Global declarations

```
#define NCHAIRS  4
// number of chairs
semaphore mutex = 1; semaphore ready_barber = 0;
semaphore waiting_customers = 0;
int nwaiting = 0;
// tracks value of waiting_customers
```

The barber function

```
barber() {
    for(;;) {
        sem_P(&waiting_customers);
        sem_P(&mutex);
        nwaiting--;
        sem_V(&ready_barber);
        sem_V(&mutex);
        cut_hair();
    } // for
} // barber
```

The customer function

```
customer() {
    P(&mutex);
    if (nwaiting < NCHAIRS) {
        nwaiting++;
        sem_V(&waiting_customers);
        V(&mutex);
        sem_P(&ready_barber);
        get_haircut();
    } // if
    sem_V(&mutex);
} // customer
```

Limitation of semaphores

- Semaphore are a **low level** construct:
  - Deadlocks will occur if **V()** calls are forgotten
  - Mutual exclusion is not guaranteed if **P()** calls are forgotten
- *Same situation as FORTRAN **if** and **goto** compared to more structured constructs*

A better solution

- We need a ***programming language construct*** that guarantees mutual exclusion
  - Will ***not trust processes*** accessing the critical region
- We can build it on the top of semaphores

Monitors

Monitors

- A ***programming language construct*** introduced by Hoare (1974) & Brinch-Hansen (1975)
- Finally implemented in Java
  - without *named conditions*
- A ***monitor*** is a package encapsulating procedures, variables and data structures.

Monitors

- To access the monitor variables, processes ***must*** go through one of the ***monitor procedures***.
- Monitor procedures are always executed ***one at a time***
  - Mutual exclusion is ***always guaranteed***.

User view


Monitor procedures (always executed one by one)
Shared data themselves

Monitors

- Monitor procedures can
  - ***wait*** on a ***condition*** (`cond.wait`)
  - until they get a ***signal*** (`cond.signal`) from another monitor procedure.
- Although conditions look like normal variables, they have ***no value***

Monitors

- *If a monitor procedure signals a condition and no other procedure is waiting for it, the signal will be lost:*
- ***It does not help to scream when nobody is listening!***

Monitors

- *If a monitor procedure waits for a condition that has already been signaled, it will remain blocked until the condition is signaled again*

- ***It does not help either to wait for something that has already happened!***

Not the same as semaphores

- If a process does a V( ) operation on a semaphore and no other process is doing a P( ) operation on the semaphore, the value of the semaphore will be changed
- This is ***not true*** for condition variables

The monitor body

- The monitor **body** is executed when monitor is started
  - Its major purpose is to *initialize* the monitor variables and data structures.

First example (I)

- Implementing semaphores on top of monitors
  - Class semaphore with methods P( ) and V( )
- No practical application
  - *Monitors are implemented on top of semaphores and not the other way around!*
- Shows that monitors are
  as powerful as semaphores

First example (II)

```
Class semaphore {
 //  private declarations
     private condition notZero;
     private int value; // semaphore's value
```

First example (III)

```
// must be public and syn'd
    public void synchronized sem_P(){
        // check  before waiting
        if (value == 0)
            notZero.wait();
        value--; // decrement
     } // P
```

First example (IV)

```
// must be public and syn'd
    public void synchronized sem_V(){
        value++;
        notZero.signal();
    } // V
```

Note that the V() method always signals the notZero condition even when it was already true

First example (V)

```
    // constructor
    semaphore(int initial_val){
        value = initial_val;
    } //constructor
}// Class semaphore
```

Second example (I)

- The bounded buffer
  - Class **Bounded_Buffer** with methods **put( )** and **get( )**

Second example (II)

```
Class Bounder_Buffer {

// private declarations
   private condition notFull;
   private condition notEmpty;
   private int bufferSize;
   private int nFullSlots;
```

Second example (III)

```
// monitor procedures
   // must be public and sync'd
   public void synchronized put(){
      // MUST CHECK FIRST
      if (nFullSlots == bufferSize)
          notFull.wait();
      . . .
      nFullSlots++;
      notEmpty.signal();
   } // put
```

Second example (III)

```
// monitor procedures (cont'd)
   // must be public and sync'd
    public void synchronized get(){
       //  MUST CHECK FIRST
       if (nFullslots == 0)
           notEmpty.wait();
       . . .
       nFullSlots--;
       notFull.signal;
    } // get
```

Second example (IV)

```
// monitor procedures (cont'd)
   // must be public and sync'd
    public void synchronized get(){
       //  MUST CHECK FIRST
       if (nFullslots == 0)
           notEmpty.wait();
       . . .
       nFullslots--;
       notFull.signal;
    } // get
```

Second example (V)

```
// constructor is monitor body
   Bounded_Buffer(int size) {
        nFullSlots = 0;
        bufferSize= size;
   } //constructor
```

Semantics of signal (I)

- Gives ***immediate control*** of the monitor to the procedure that was waiting for the signal
  - The procedure that issued the signal is then put ***temporarily on hold***
- Has ***no effect*** if there is no procedure waiting for the signal

Semantics of signal (II)

- Causes two types of problems
  - Too many context switches
  - Prevents programmers from putting signal calls inside their critical sections
    - Sole truly safe place to put them is at the ***end of procedure***
    - *Not an ideal solution as the programmer can forget to put them there*

The notify primitive (I)

- Introduced by Lampson and Redell in Mesa
  - Adopted by Gosling for Java
- When a monitor procedure issues a **`condition.notify( )`**, the procedure that was waiting for the notify does not regain control of the monitor until the procedure that issued the signal
  - Terminates
  - Waits on a condition

The notify primitive (II)

- ***Advantages:***
  - Fewer context switches
  - Programmers can put **`notify()`** calls anywhere

The notify primitive (III)

- ***Very minor disadvantage:***
  - Condition might not be true anymore
  - Should replace ***if*** in

```
if(condition_is_false)
    condition.wait()
```

  - By a ***while***

```
while(condition_is_false)
    condition.wait()
```

Java implementation

- The Java equivalent of a monitor is a Java class whose access methods have been declared ***synchronized***
  - Java does not support ***named conditions***:
    - When a synchronized method does a **wait()**, it cannot specify the condition it wants to wait on
  - Java has ***notify( )*** and ***notifyAll( )***

Advanced pthread synchronization

The big idea

- Monitors are safer and easier to use than semaphores
  - But they are a language-based construct
- Want to provide the same ease of use through pthread functions
- Introduce condition variables

Back to the bounded buffer problem

```
producer() {
    struct x item;
    for (;;) {
        produce(&item);
        sem_P(&notFull);
        sem_P(&mutex);
        put(item);
        sem_V(&mutex);
        sem_V(&notEmpty);
    } // for
} // producer
```

```
consumer() {
    struct x item;
        for (;;) {
            sem_P(&notEmpty);
            sem_P(&mutex);
            take(item);
            sem_V(&mutex);
            sem_V(&notFull);
            consume(item);
        } // for
} // consumer
```

Condition variables

- Pthread feature
- Always used in conjunction with pthread mutexes
- Let threads to synchronize based upon the actual values of data
  - Buffer full/not full

The new approach

```
producer() {
  struct x item;
  for(;;) {
    produce(&item)
    mutex_lock(&bLock); NEW
    while (nFull == bsize)
       wait(&notFul, &bLock);
    put(item);
    nFull++;
    pthread_cond_signal(&notEmpty);
    mutex_unlock(&bLock); NEW
  } // for
} // producer
```

```
consumer() {
  struct x item;
  for(;;) {
    mutex_lock(&bLock); NEW
    while (nFull == 0)
      wait(&notEmpty, &bLock);
    take(item);
    nFull--;
    pthread_cond_signal(&notFull);
    mutex_unlock(&bLock);  NEW
   consume(&item);
  } // for
} // consumer
```

Creating conditional variables

- Must be declared **`pthread_cond_t`**
- ***Static method:***

```
pthread_cond_t mycv = PTHREAD_COND_INITIALIZER;
```

- ***Dynamic method:***

```
pthread_cond_t mycv;
…
int pthread_cond_init(&mycv, NULL);
```

Comments

- Using **`pthread_cond_init( )`** lets the programmer set the optional **`process-shared`** attribute:
  - Allows the condition variable to be seen by threads in other processes.
  - Use NULL to specify the default
- We will not discuss
  - **`pthread_condattr_init (attr)`**
  - **`pthread_condattr_destroy (attr)`**

Deleting condition variables

- **`int pthread_cond_destroy(&cv);`**
  - As with **`pthread_cond_init()`**, **`pthread_cond_destroy()`** will return zero if successful and an error code otherwise.

Operations on condition variables

- Three operations:
  - `pthread_cond_wait(&cv, &amutex)`
  - `pthread_cond_signal(&cv)`
  - `pthread_cond_broadcast(&cv)`

pthread_cond_wait ( )

- **`pthread_cond_wait(&cv, &aMutex)`**
  - Waits until condition variable **`cv`** is signaled
  - Mutex **`aMutex`** **must** by ***locked*** and ***owned*** by calling thread
  - While waiting for the signal, calling thread releases **`aMutex`**
  - Upon successful return, **`aMutex`** will be ***locked*** and ***owned*** by the calling thread

Usage

```
pthread_mutex_lock(&bLock);
while (nFull == 0)
     pthread_cond_wait(&notEmpty, &bLock);
. . .
pthread_mutex_unlock(&bLock);
```

Could use an **`if`** but using a **while** is ***safer***

Signaling a condition

- **`pthread_cond_signal(&cv)`**
  - Unblocks at least one thread currently blocked on the condition variable **`cv`**
- **`pthread_cond_broadcast(&cv)`**
  - Unblocks all threads currently blocked on the condition variable **`cv`**

Warning

- The thread calling **`pthread_cond_broadcast()`** or **`pthread_cond_signal()`** must ***own*** the mutex that the threads calling **`pthread_cond_wait()`** have associated with the condition variable during their waits
- Otherwise expect unpredictable behavior

Usage

```
pthread_mutex_lock(&bLock);
while (nFull == 0)
      pthread_cond_wait(&notEmpty, &bLock);
        …
pthread_cond_signal(&notFull);
pthread_mutex_unlock(&bLock);
```

What it means

```
pthread_mutex_lock(&bLock);
    …
while (nFull == 0)
    pthread_cond_wait(&notEmpty, &bLock);
     …
pthread_mutex_unlock(&bLock);
```

```
pthread_mutex_lock(&bLock);
     …
pthread_cond_signal(&notEmpty);
pthread_mutex_unlock(&bLock);
```

The signal waking up a waiting thread must ***own*** the lock that the signal had released (and will regain)

Notes

- There is also a **`pthread_cond_timedwait(…)`**
  - Not covered
- For more details on pthreads, refer to the LLNL tutorial:
  - **POSIX Threads Programming**

https://computing.llnl.gov/tutorials/pthreads/