Synchronizing with semaphores: classic problems

- Producer/consumer
- Dining philosophers
- Cigarette smokers
- Synchronization barrier
- Readers/writers
- Sleeping barber

A.B.Downey, “The Little Book of Semaphores”, 2016

Synchronization

Example: a stack consisting of a shared array T and an index S

```
push(v)          v ← pop
++S              v=T[S]
T[S]=v           --S
                 return v
```

```
T = {1,2,3,4,5}
S = 4

T = {1,2,3,4,6}
S = 4
```

Process 1 pushes 6

Process 2 pops #!_?

```
++S
```

context switch

```
                 v=T[S]          // wrong
                 --S
                 return v
```

context switch

```
T[S]=v           // wrong
```

Synchronization

There is **no way** of stopping process scheduling or predicting it reliably.

A **critical section** is a block of code using a shared resource, such as the stack in our example.

The golden rule is that at any given moment, there must be at most one process (or thread) inside a critical section.

This way even if the kernel schemes against us, no harm can come to our resources.

Synchronization

Assuming that m is a semaphore initialized to 1.

```
Process p1          Process p2
wait(m)             wait(m)
push(v)             v = pop()       // critical section
post(m)             post(m)
```

A semaphore acquiring only the values 0 and 1 is called a binary semaphore (don't confuse it with a mutex!).

Generally semaphores are used to model "a number of available resources" (that's why they are called **counting semaphores**).

Synchronization

The **producer-consumer** model is by far the most widely encountered synchronization model. A producer process produces data, and a consumer process consumes the said data.

1) Unbounded buffer case: the consumer process must execute only if there is something to consume in the buffer; otherwise it must wait.

The `full=0` semaphore represents the number of products in the buffer

```
Producer                    Consumer
while(true)                 while(true)
    add(buffer, data)           wait(full)
    post(full)                  take(buffer)
```

This should work...right?

Synchronization

What happens if both processes enter the buffer at the same time?

Then the buffer becomes corrupted like our stack! We need to protect the access to the critical section through a binary semaphore m = 1!

```
Producer                    Consumer
while(true)                 while(true)
    wait(m)                     wait(full)
    add(buffer, data)           wait(m)
    post(m)                     take(buffer)
    post(full)                  post(m)
```

We solved the underflow problem, but what about the overflow problem?

Synchronization

2) Bounded buffer case

Now we also have an upper limit to our buffer. The producer must not produce if the buffer is full! Empty spaces are now a resource too!

Semaphore `full`: number of products in the buffer

Semaphore `empty`: number of empty spaces in the buffer

Semaphore `m`: concurrent access lock

Initially

```
full=0      // no products
empty=N     // size of the buffer
m=1         // unlocked
```

Synchronization

Producer

```
while(true)
    wait(empty)
    wait(m)
    add(buffer, data)
    post(m)
    post(full)
```

Consumer

```
while(true)
    wait(full)
    wait(m)
    take(buffer)
    post(m)
    post(empty)
```

At any given moment `empty+full <= N`

Synchronization

The order of waits is crucial! Let's see what happens if we exchange them.

```
Producer                        Consumer
while(true)                     while(true)
    wait(m)                         wait(full)
    wait(empty)                     wait(m)
    add(buffer, data)               take(buffer)
    post(m)                         post(m)
    post(full)                      post(empty)
```

Imagine the producer getting the lock and then encountering a full buffer..the system will be blocked indefinitely!

Synchronization

What happens when the consumer needs more than 1 resource?

Process P1 needs 3 resources and process P2 needs 2 resources.

Initially we have s=2 resources.

	P1	P2
	`wait(s) // s=1`	
context switch		
		`wait(s) // s=0`
		`wait(s) // blocked`
context switch		
	`wait(s) //blocked`	
	`wait(s)`	

It's a pity, process 2 could have been served with 2 resources; now they'll have to wait until some other process calls `post`.

Synchronization

Calling wait k times is not the same as an atomic wait decreasing the semaphore by k.

This functionality is provided readily by System V semaphores; (POSIX semaphores can do it too, albeit indirectly)

```
P1                  P2
wait(s,3)           wait(s,2)
// work             // work
post(s,3)           post(s,2)
```

System V IPC

Unix System V (System 5, SysV) is one of the first commercial versions of Unix (AT&T, 1983). As of 2020 there are 3 variants based on it: IBM AIX, HP-UX and Oracle's Solaris

System V IPC is widely supported by *x flavors, and is older than POSIX (IEEE-1988-2017); is nowadays present in POSIX-XSI

Linux has supported System V IPC since before, while full POSIX IPC has been available since kernel > 2.6

System V IPC has the same tools as POSIX IPC, with varying degrees of differences

Some info on standards

- POSIX (Portable Operating System Interface) IEEE (1988-)
- SUS (Single Unix Specification) IEEE and The Open Group (industry) (mid 1990s) a.k.a. POSIX XSI ("extended posix")

- POSIX is a subset of SUS

- Certified SUS systems: AIX, HP-UX, macOS, Solaris,etc
- Mostly POSIX/SUS compliant: Android NDK, FreeBSD, Linux, OpenBSD, etc

- Certification is expensive.

System V semaphores

System V semaphores are more powerful than POSIX semaphores, but are heavy-weight; main difference: this is a set of semaphores

General steps:

- Create or open a semaphore set using `semget()`
- Initialize the semaphores in the set using `semctl()` `SETALL` or `SETVAL` operation
- Perform operations on semaphore values using `semop()`
- When all processes have finished using the semaphore set, remove the set using the `semctl()` `IPC_RMID` operation

System V semaphores

```
#include <sys/types.h>
#include <sys/sem.h>
int semget(key_t key, int nsems, int semflg);
 Returns the semaphore set identifier on success, or -1 on error
```

The semget() system call creates a new semaphore set or obtains the identifier of an existing set (uninitialized values)

`key`: unique integer identifier of the IPC object; usually set to IPC_PRIVATE or generated through `ftok()`

`nsems`: number of semaphores in the set

`semflg`: bit mask of permissions

System V semaphores

```
#include <sys/types.h>
#include <sys/sem.h>
int semctl(int semid, int semnum, int cmd /*, union semun */);
        Returns a nonnegative integer on success and -1 on error
```

The `semctl()` system call performs a variety of control operations on a semaphore set or on an individual semaphore within a set

`semid`: identifier of the semaphore set

`semnun`: number of semaphore in the set (starts from 0, ignored for *ALL cmds)

`cmd`: operation to be performed (GET/SETVAL, GET/SETALL, IPC_STAT, etc)

Depending on `cmd`'s value a fourth argument is supplied

System V semaphores

Arguments and return values for all semctl commands are conveyed by semun, that must be **defined by your programs** as follows:

```
union semun  {
    int val;                    /*individual  semaphore  value*/
    struct semid_ds * buf ;     /*semaphore  data  structure*/
    unsigned  short* array;     /*multiple  semaphore  values*/
    struct seminfo* __buf;      /* linux specific */
};
```

`semctl` allows access to a wealth of information: PID of process that last modified a semaphore, number of processes currently waiting for a semaphore, time of last change, etc

System V semaphores

```
/* Initialize a binary semaphore with a value of 1. */
int binary_semaphore_initialize (int semid)
{
    union semun argument;
    unsigned short values[1];
    values[0] = 1;
    argument.array = values;
    return semctl (semid, 0, SETALL, argument);
}
```

System V semaphores

```
#include <sys/types.h>
#include <sys/sem.h>
int semop(int semid, struct sembuf *sops, unsigned int nsops);
                                    Returns 0 on success, or -1 on error
```

The `semop()` system call performs one or more operations on the semaphores

`semid`: identifier of the semaphore set

`sops`: array that contains the operations to be performed

`nsops`: size of `sops`

```
struct sembuf {
    unsigned short sem_num; /* Semaphore number (starts from 0) */
    short sem_op;           /* Operation to be performed */
    short sem_flg; /* Operation flags (IPC_NOWAIT and SEM_UNDO) */
};
```

System V semaphores

```
struct sembuf {
    unsigned short sem_num; /* Semaphore number */
    short sem_op;           /* Operation to be performed */
    short sem_flg;      /* Operation flags (IPC_NOWAIT and SEM_UNDO) */
};
```

`sem_op > 0`: added to the semaphore; **post**

`sem_op == 0`: block until the semaphore is zero; **zero**

`sem_op < 0`: subtracted from the semaphore; **wait**

In case of a signal, semop is interrupted and errno is set to EINTR. It is not automatically restarted.

`IPC_NOWAIT`: unblocking operation, errno is set to EAGAIN instead

`SEM_UNDO`: the operation will be automatically undone when the process terminates

System V semaphores

The fact that semaphore creation and initialization must be performed by separate system calls, instead of in a single atomic step, leads to possible race conditions when initializing a semaphore (another process might attempt to use before it's initialized).

Solutions:

1) **avoidance**: ensure that a single process is in charge of creating & initializing the semaphore

2) A trick with the **sem_otime** field in the semid_ds data structure based on the historical (and now standard) fact that the field is set to 0 upon creation and only changes with a semop. The process that does not create the semaphore can wait until the first process has both initialized the semaphore and executed a no-op semop() call that updates the sem_otime field, but does not modify the semaphore's value

Your textbook has a full example

System V semaphores

Limits (customizable)

```
$ipcs -l      // on my machine
------ Semaphore Limits --------
max number of arrays = 32000
max semaphores per array = 32000
max semaphores system wide = 1024000000
max ops per semop call = 500
semaphore max value = 32767
```

Overall

- Complex API, initialization race condition, keys

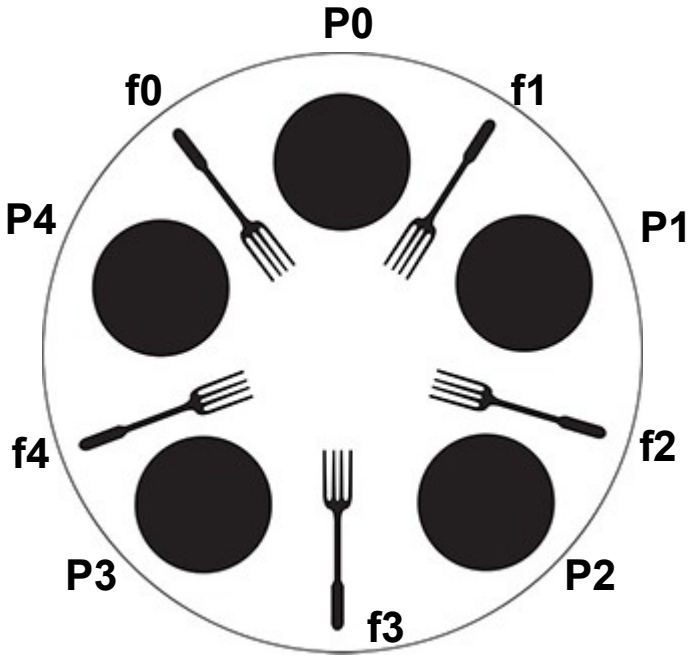
+ set granularity

Synchronization

The **dining philosophers** is a classic synchronization problem introduced by Dijkstra.

Five philosophers are sitting around a dinner table, with a fork in between each pair of adjacent philosophers.

In order to eat, a philosopher needs to pick up the two forks that lie at the philosopher's left and right sides

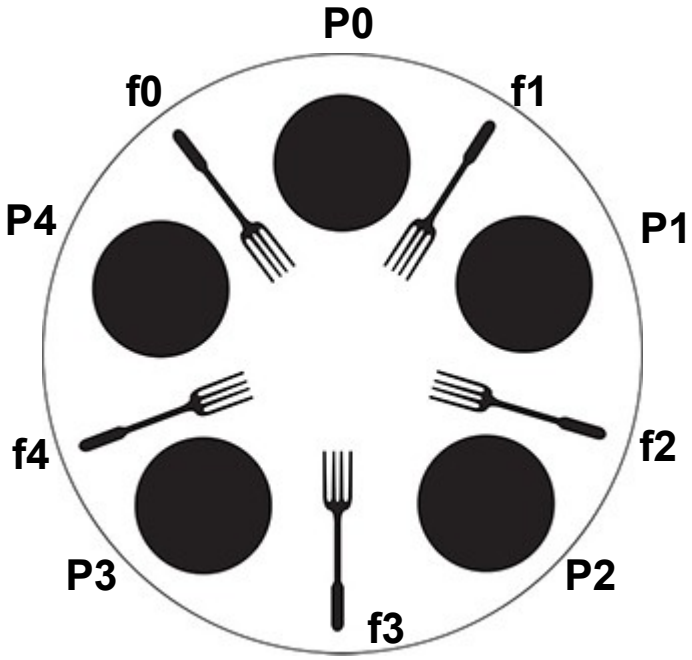


Synchronization

Each philosopher alternates between thinking (non-critical section) and eating (critical section).

Since the forks are shared, there is a synchronization problem between philosophers (processes or threads).

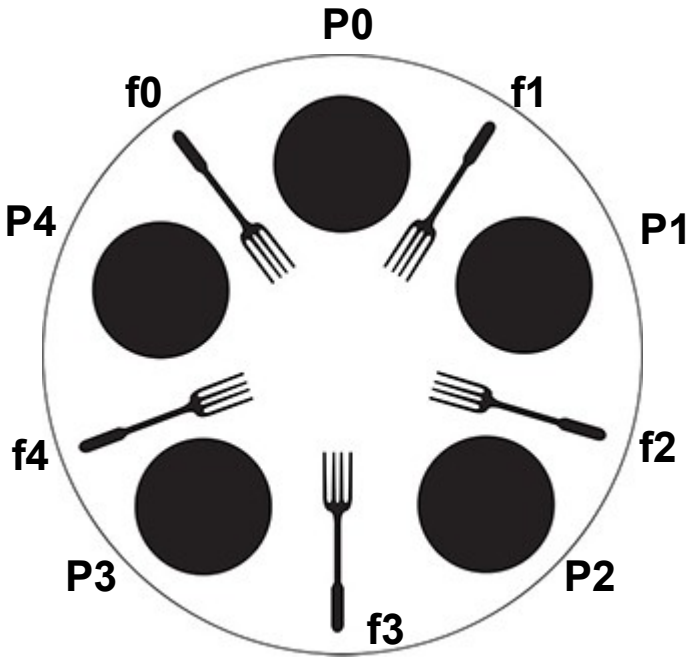
The forks are our shared resources, so we'll have a semaphore representing each of them.



Synchronization

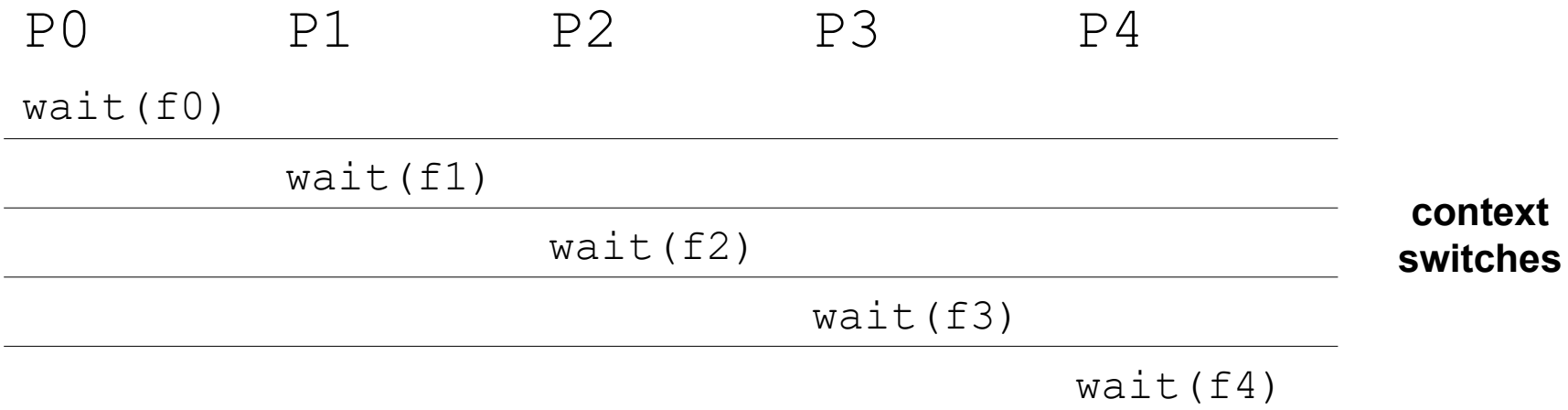
A first attempt at solving the problem:

```
P2
think()     // non critical section
wait(f2)    // get fork
wait(f3)    // get fork
eat()       // crit. section
post(f2)    // put down fork
post(f3)    // put down fork
```



Synchronization

This scheduling can happen if the kernel dislikes you:



All philosophers end up starving even though 2 of them could have been served.

Main challenge: a philosopher must either get both forks, if available, or otherwise none!

Synchronization-SysV

Easy to solve with IPC/System V semaphores

```
int forks = semget(IPC_PRIVATE, 5, IPC_CREAT|ICP_EXCL|
0600);
...
int getFork(int i){
   // for the i-th philosopher
   struct sembuf ops[2];
   ops[0].sem_num = i;          // semaphore to process
   ops[1].sem_num = (i+1) % 5;// semaphore to process
   ops[0].sem_op = ops[1].sem_op = -1;
   ops[0].sem_flg = ops[1].sem_flg = 0;
   return semop(forks, ops, 2);
}
```

Synchronization-POSIX

More complicated with POSIX semaphores: if only four philosophers are allowed at the table at a time, deadlock is impossible!

If there are only four philosophers at the table, then in the worst case each one picks up a fork. Even then, there is a fork left on the table, and that fork has two neighbors, each of which is holding another fork. Therefore, either of these neighbors can pick up the remaining fork and eat.

We can control the number of philosophers at the table with a semaphore named **footman that is initialized to 4** (multiplex pattern: enforces an upper limit on the number of concurrent threads/processes)

Synchronization-POSIX

```
get_forks(i)
   wait(footman)
   wait(left_fork(i))
   wait(right_fork(i))

put_forks_down(i)
   post(left_fork(i))
   post(right_fork(i))
   post(footman)
```

Synchronization-POSIX

This solution also guarantees that no philosopher starves. Imagine that you are sitting at the table and both of your neighbors are eating. You are blocked waiting for your right fork.

Eventually your right neighbor will put it down, because eat can’t run forever. Since you are the only thread/process waiting for that fork, you will necessarily get it next.

By a similar argument, you cannot starve waiting for your left fork.

Synchronization

Another classic problem are the **cigarette smokers** (1971).

Assume a cigarette requires three ingredients to make and smoke: tobacco, paper, and matches.

There are three smokers around a table, each of whom has an infinite supply of one of the three ingredients — one smoker has an infinite supply of tobacco, another has paper, and the third has matches.

Synchronization

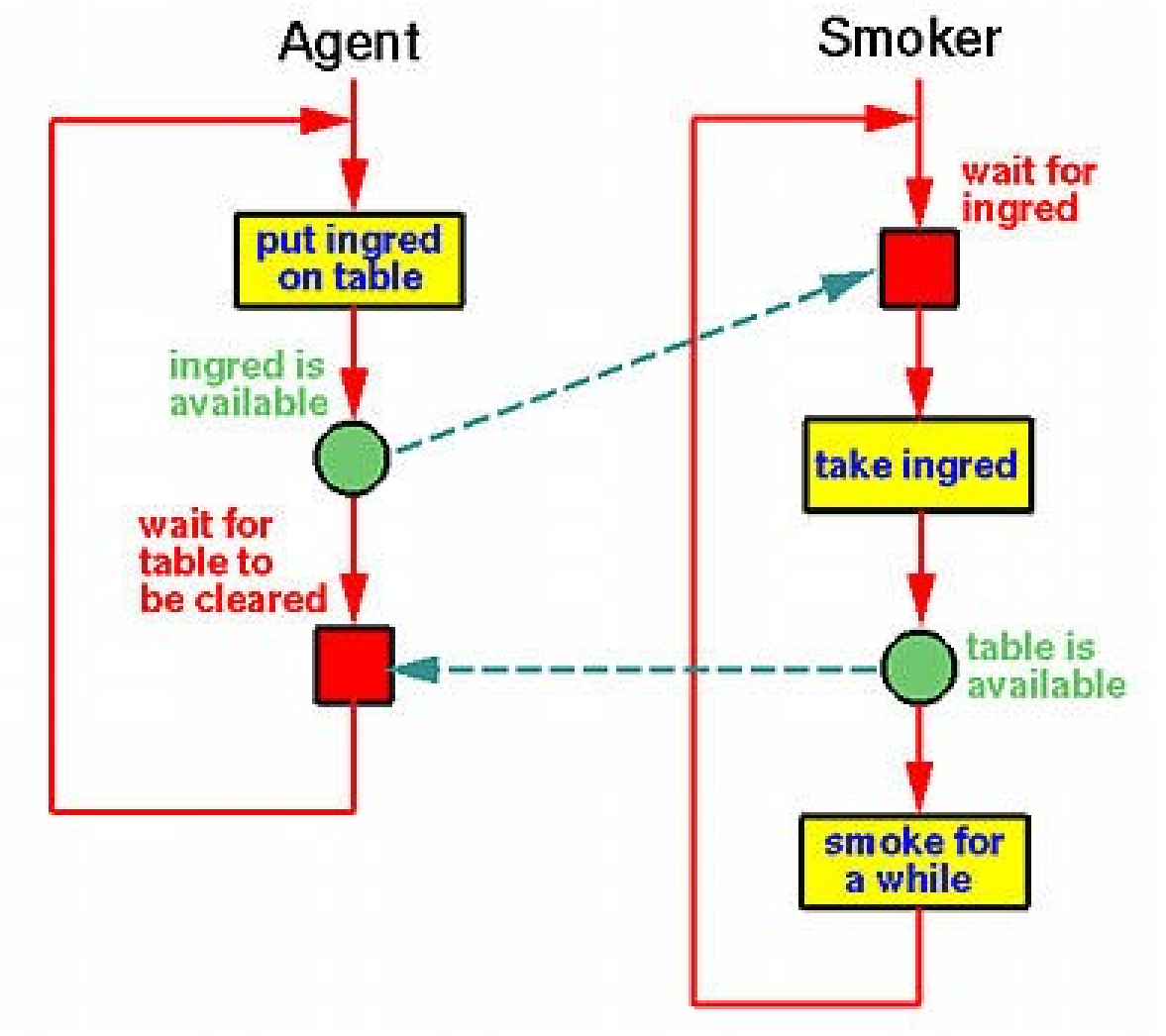
There is also a non-smoking agent who enables the smokers to make their cigarettes by arbitrarily (non-deterministically) selecting two of the supplies to place on the table.

The smoker who has the third supply should remove the two items from the table, using them (along with their own supply) to make a cigarette, which they smoke for a while.

Once the smoker has finished his cigarette, the agent places two new random items on the table. This process continues forever.

The ingredients are resources so we'll have one semaphore for each.

Synchronization



Synchronization

A first attempt (`agentSem=1, tobacco=paper=matches=0`)

```
[smoker-has matches]
while(true)
    wait(tobacco)
    wait(paper)
    get_ingred.()   // crit. sect.
    smoke()
    post(agentSem)
```

```
[agent]
while(true)
    wait(agentSem)
    post(paper)
    post(tobacco)
```

Does it look good…?

Synchronization

Looks good? No..

```
[has matches]
wait(tobacco)
wait(paper)
get_ingred.()
smoke()
post(agentSem)
```

```
[has tobacco]
wait(paper)
wait(matches)
get_ingred.()
smoke()
post(agentSem)
```

What if the agent brings **tobacco and paper**, but one smoker gets the tobacco and the other the paper? None will be able to smoke, the system will be deadlocked (good for the smokers, bad for the system)!

Synchronization-SysV

Similarly to the dining philosophers, each smoker must either get both ingredients, if available, or otherwise none; in order to avoid effectively the deadlocks. e.g.:

```
[has matches]
while(true){
    wait(tobacco, paper)
    get_ingred.()
    smoke()
    post(agentSem)
}
```

Synchronization-POSIX

A bit messy with POSIX semaphores. We have **three** helper processes called “pushers” that respond to the signals from the agent, keep track of the available ingredients, and signal the appropriate smoker

Flags

```
isMatch=isTobacco=isPaper=0
```

Semaphores (3 for pushers, 3 for smokers)

```
agentSem=1, tobacco=paper=matches=0 and a mutex m
tobacco2=paper2=matches2=0 // for the smokers
```

The boolean variables indicate whether or not an ingredient is on the table. The pushers use `tobacco2` to signal the smoker with tobacco, and the other semaphores likewise

Synchronization

Pusher A

```
wait (tobacco)
wait(m)
if isPaper:
    isPaper=False
    post(matches2)
elif isMatch :
    isMatch=False
    post(paper2)
else :
    isTobacco=True
post(m)
```

This pusher wakes up any time there is tobacco on the table.

If it finds `isPaper` true, it knows that Pusher B has already run, so it can signal the smoker with matches.

Similarly, if it finds a match on the table, it can signal the smoker with paper.

Synchronization

Pusher A

```
wait (tobacco)
wait(m)
if isPaper:
    isPaper=False
    post(matches2)
elif isMatch :
    isMatch=False
    post(paper2)
else :
    isTobacco=True
post(m)
```

Pusher B

```
wait (paper)
wait(m)
if isTobacco:
    isTobacco=False
    post(matches2)
elif isMatch :
    isMatch=False
    post(tobacco2)
else :
    isPaper=True
post(m)
```

Pusher C

```
wait (matches)
wait(m)
if isTobacco:
    isTobacco=False
    post(paper2)
elif isPaper :
    isPaper=False
    post(tobacco2)
else :
    isMatch=True
post(m)
```

Synchronization

Smoker A

```
wait(tobacco2)
get_ingredients()
smoke()
post(agentSem)
```

Smoker B

```
wait(paper2)
get_ingredients()
smoke()
post(agentSem)
```

Smoker C

```
wait(matches2)
get_ingredients()
smoke()
post(agentSem)
```

Agent

```
wait(agentSem)
post(paper)
post(matches)
```

Synchronization

The **synchronization barrier** is another often encountered problem. We have N processes (or threads), and any of them reaching this point must stop and cannot proceed unless all other threads/processes have reached this barrier.

e.g. worker processes and a boss process: the boss process does not pay their salary, unless all workers have completed a required task.

boss	**worker x N**	
`prepare()`		
	`work()`	**Synchronization barrier**
	`work2()`	
`pay_salaries()`		

Synchronization-SysV

We have a single semaphore T initialized at N.

Every process/thread reaching the rendez-vous point will call `wait` on it, and then wait for it to become zero. If T becomes zero, that means everyone has reached the barrier.

```
// worker
wait(T)
zero(T) // wait for T to become zero
```

`zero` is a call specific to System V/IPC semaphores.

Synchronization-SysV

```
int barr_init(int semid, int num, int N)
{return semctl(semid, SETVAL, N);}  // initialization

int barr_wait(int semid, int num){
   struct sembuf w,z;           // two distinct operations
   w.sem_num = z.sem_num = num;
   w.sem_flg = z.sem_flg = 0;
   w.sem_op = -1;                    // wait
   z.sem_op = 0;                     // zero
   return sem_op(semid,&w,1) !=-1 &&              // WAIT
               sem_op(semid,&z,1) !=-1? 0: -1;   // ZERO
}
```

Synchronization-POSIX

And with POSIX semaphores..

variable `count=0`

semaphores `lock=1, barrier=0`

`count` keeps track of how many processes have arrived.

`lock` provides exclusive access to `count` so that processes can increment it safely

`barrier` is locked (zero or negative) until all processes arrive; then it should be unlocked (1 or more)

Synchronization-POSIX

And with POSIX semaphores..

```
wait (lock)
    count = count + 1
post(lock)

if count == n:
    post(barrier)

wait (barrier)
post(barrier)
```

Synchronization-POSIX

The **readers-writers** is another classic synchronization problem (1971).

We have a shared resource that two types of processes (or threads) access:

- The readers: that do not modify the resource
- The writers: that modify the resource

Readers can access the data in any order and number they like. However at most one writer is allowed to write at any given moment. And of course no reader should be reading while a writer is writing.

Synchronization-POSIX

```
READER                                          WRITER
wait(lock)              // avoid race           wait(rsc)
++readers                                       write()
if(readers == 1)        // 1st reader           post(rsc)
    wait(rsc)           // no writers allowed
post(lock)
read() // read the data
wait(lock)
--readers
if(readers == 0)        // last reader
    post(rsc)               // let the writer enter
post(lock)
```

Initially: lock=1, rsc=1

Synchronization-POSIX

`readers`: the number of active readers

`rsc`: makes sure we have only one writer

`lock`: makes sure the shared variable readers is modified safely

While a writer is writing, the first reader will be blocked at `wait(rsc)` and the subsequent ones at `wait(lock)`

In the database world this is known as a "lock".

Readers ask the Database Managament System (DBMS) for a "**shared lock**" and writers ask for a "**exclusive lock**".

Synchronization-POSIX

However, imagine the following scenario:

```
Reader1 is reading
Writer1 is blocked at wait(rsc)
Reader2 is reading
Reader1 exits (Writer1 is still blocked)
Reader3 and Reader4 are reading
Reader2 exits (Writer1 is still blocked)
Reader4 exits (Writer1 is still blocked)
Reader5 is reading…
```

i.e. if the readers are too many, a writer might have to wait indefinitely.

Synchronization-POSIX

Solution: prioritize writers!

i.e. no writer, once added to the queue, shall be kept waiting longer than absolutely necessary. This is also called **writers-preference**.

This is accomplished by forcing every reader to lock and release a “readtry” semaphore individually. The writers on the other hand don't need to lock it individually.

Only the first writer will lock the “readtry” and then all subsequent writers can simply use the resource as it gets freed by the previous writer. The very last writer must release the “readtry” semaphore, thus opening the gate for readers to try reading.

Synchronization-POSIX

READER

```
  wait(readTry)     // a reader is trying to enter
  wait(rlock)       // avoid race condition with other readers
  readcount++;      // report yourself as a reader
  if (readcount == 1)     // if you are the first reader
    wait(rsc)             // lock  the resource and prevent writers
  post(rlock);            // allow other readers
  post(readTry)           // you are done trying to access the resource
  read()
  wait(rlock)             // avoids race condition with readers
  readcount--;            //indicate you're leaving
  if (readcount == 0)     // if you are last reader leaving
    post(rsc)             // you must release the locked resource
  post(rlock)             //release exit section for other readers
```

readTry=1, rlock=1, rsc=1 - readcount=0

Synchronization-POSIX

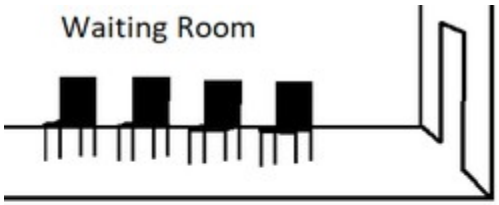
```
WRITER
  wait(wlock)                 // avoids race conditions
  writecount++;               // report yourself as a writer entering
  if (writecount == 1)        // if you're the first writer
    wait(readTry)             // no new readers!
  post(wlock)                 // release entry section
  wait(rsc)                   // prevents other writers
  write()                     // only 1 writer allowed here
  post(rsc)                   // release resource
  wait(wlock)                 // reserve exit section
  writecount--;               // indicate you're leaving
  if (writecount == 0)        // checks if you're the last writer
    post(readTry)       // if you're the last writer, unlock the readers
  post(wlock)


wlock=1
```

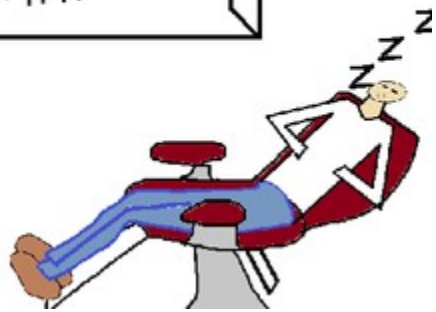
Synchronization-POSIX

Another famous problem is the **sleeping barber**; also attributed to Dijkstra (1965).

The barber shop has one barber and two rooms. The waiting room with N chairs, and the cutting room with a single chair.

Barber: When he finishes cutting a customer's hair, he dismisses the customer and goes to the waiting room to see if there are others waiting. If there are, he brings one of them back to the chair and cuts his hair. If there are none, he returns to the chair and sleeps in it





Synchronization-POSIX

Customer: each customer, when he arrives, looks to see what the barber is doing. If the barber is sleeping, the customer wakes him up and sits in the cutting room chair. If the barber is cutting hair, the customer stays in the waiting room. If there is a free chair in the waiting room, the customer sits in it and waits his turn. If there is no free chair, the customer leaves.

All actions (cutting hair, etc) can take an unknown amount of time. This can cause a lot of issues.

Synchronization-POSIX

Issues: for instance a customer may arrive and observe that the barber is cutting hair, so he goes to the waiting room. While they're on their way, the barber finishes their current haircut and goes to check the waiting room. Since there is no one there (the customer not having arrived yet), he goes back to their chair and sleeps. The barber is now waiting for a customer, but the customer is waiting for the barber.

Or, two customers may arrive at the same time when there happens to be a single seat in the waiting room. They observe that the barber is cutting hair, go to the waiting room, and both attempt to occupy the single chair.

Synchronization-POSIX

// mutex; whether the barber is ready to cut or not

```
Semaphore barberReady = 0
```

// mutex to control access to the number of waiting room seats

```
Semaphore accessWRSeats = 1
```

// the number of customers currently waiting at the waiting room

```
Semaphore custReady = 0
```

// total number of free seats in the waiting room

```
int numberOfFreeWRSeats = N
```

Synchronization-POSIX

Barber

```
while(true)
    wait(custReady)  // acquire a customer – if none, sleep
    wait(accessWRSeats)          // there is a customer
    numberOfFreeWRSeats += 1  // increase # of free seats
    post(barberReady)            // ready to cut.
    post(accessWRSeats)     // no need for chair lock any more
    cutting_hair()
```

Synchronization-POSIX

Customer

```
wait(accessWRSeats)              // access waiting room chairs
if(numberOfFreeWRSeats > 0)      // If there are any free seats:
   numberOfFreeWRSeats -= 1      // sit down in a chair
   post(custReady)               // notify the barber that there is a customer
   post(accessWRSeats)           // release the chairs' lock
   wait(barberReady)             // wait until the barber is ready
   have_haircut()
else                             // there are no free seats
   post(accessWRSeats)           // release the lock
   leave_without_a_haircut()
```