Synchronization

Semaphores

Stefano Quer, Pietro Laface, and Stefano Scanzio

Dipartimento di Automatica e Informatica

Politecnico di Torino

skenz.it/os stefano.scanzio@polito.it

Introduction

- The previous solutions are not satisfactory, because
  - software solutions are complex to use from the point of view of the programmer
  - hardware solutions are difficult to implement from the point of view of the hardware designer
- OSs provide more appropriate primitives called **semaphores**
  - Introduced by Dijkstra in 1965
  - They are not based on busy waiting implementation, and therefore they do not waste resources

Definition

- A semaphore **S** is a shared structure including
  - A counter
  - A waiting queue, managed by the kernel
  - Both protected by a lock

```
typedef struct semaphore_tag  {
  char lock;                // Lock variable protects count
                            // and queue management
  int cnt;                  // Counter
  process_t *head;          // Thread list
} semaphore_t;
```

- Operations on **S** are **atomic**
  - Atomicity is managed by the OS
  - It is impossible for two threads to perform simultaneous operations on the same semaphore

Manipulation functions

- Typical operations on a semaphore S
  - init (S, k)
    - Defines and initializes the semaphore S to the value k
  - wait (S)
    - Allows (in the reservation code) to obtain the access of the CS protected by the semaphore S
  - signal (S)
    - Allows (in the release code) to release the CS protected by the semaphore S
  - destroy (S)
    - Frees the semaphore S

sleep, down, P

wakeup, up, V

They are not the "wait" and "signal" seen in the past

Semaphore primitives

- **`init(S, k)`**
  - Defines and initializes semaphore S to value k
  - Two types of semaphores
    - Binary semaphores
      - The value of **`k`** is only **0** or **1**
    - Counting semaphores
      - The value of **`k`** is **non negative**

`k` is a counter

known as "mutex lock" (mutex ≡ MUTual EXclusion)

```
init (S, k) {
  alloc (S);
  S=k;
}
```

Logical implementation

Atomic operation

Semaphore primitives

- `wait(S)`
  - If the counter value of **S** is negative or zero blocks the calling T/P
    - If S is negative, its absolute value S indicates the number of waiting threads
  - The counter is decremented at each call

Logical implementation

```
wait (S) {
  while (S<=0);
  S--;
}
```

In the logical versions S is always positive

Real implementations do **not** use busy waiting

Atomic operation

Other possible (and equivalent) logical implementation

```
wait (S) {
  if (S==0) block();
  else S--;
}
```

Semaphore primitives

- `wait(S)`
  - Originally called `P()` from the Dutch language "probeer te verlagen", i.e., "try to decrease"
  - **Not** to be confused with the **wait** system call used to wait for a child process

Logical implementation

```
wait (S) {
  while (S<=0);
  S--;
}
```

In the logical versions S is always positive

Real implementations do **not** use busy waiting

Atomic operation

Other possible (and equivalent) logical implementation

```
wait (S) {
  if (S==0) block();
  else S--;
}
```

Semaphore primitives

- `signal(S)`
  - Increases the semaphore `S`
    - If `S` counter is negative or zero some T/P was blocked on the semaphore queue, and it can be wakeup
  - Originally called `V()`, from the Dutch language "verhogen", i.e., "to increment"
  - **Not to be confused** with system call **signal** that is used to declare a signal handler

Logical implementation

```
signal (S) {
  S++;
}
```

Atomic operation (register=s;register++;s=register;)

Other possible (and equivalent) logical implementation

```
signal (S) {
  if (blocked())
    wakeup();
  else S++;
}
```

Semaphore primitives

- **`destroy(S)`**
  - Release semaphore `S` memory
    - Actual implementations of a semaphore require much more of a simple global variable to define a semaphore
  - This function is often not used in the examples

```
destroy (S) {
  free (S);
}
```

Logical implementation

Semaphore primitives

- The semaphore queue
  - Is implemented in kernel space by means of a queue of Thread Control Blocks
  - The kernel scheduler decides the queue management strategy (not necessarily FIFO)

Mutual exclusion with semaphore

```
init (S, 1);
```

P_i / T_i

```
while (TRUE) {
   wait (S);
   CS
   signal (S);
   non critical section
}
```

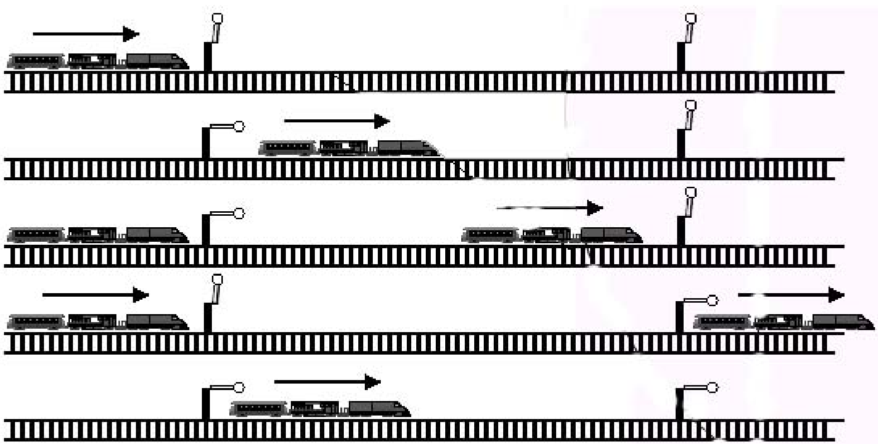
P_j / T_j

```
while (TRUE) {
   wait (S);
   CS
   signal (S);
   non critical section
}
```

Remember:

```
wait (S) {
  while (S<=0);
  S--;
}

signal (S) {
  S++;
}
```



Critical sections of N threads

```
init (S, 1);
...
wait (S);
CS
signal (S);
```

T_1	T_2	T_3	S	queue
			1	
wait			0	
CS_1	wait		-1	T_2
	blocked	wait	-2	T_2, T_3
	blocked	blocked	-2	T_2, T_3
signal	blocked	blocked	-2	T_2, T_3
	CS_2	blocked	-1	T_3
	signal	blocked	0	
		CS_3	0	
		signal	1	

At most **one** T/P at a time in the critical section

Critical sections of N threads

```
init (S, 2);
...
wait (S);
CS
signal (S);
```

T_1	T_2	T_3	S	queue
			2	
wait			1	
CS_1	wait		0	
	CS_2	wait	-1	T_3
		blocked	-1	T_3
signal		blocked	0	
		CS_3	0	
	signal		1	
		signal	2	

Threads 1 and 2 in their CSs

Threads 2 and 3 in their CSs

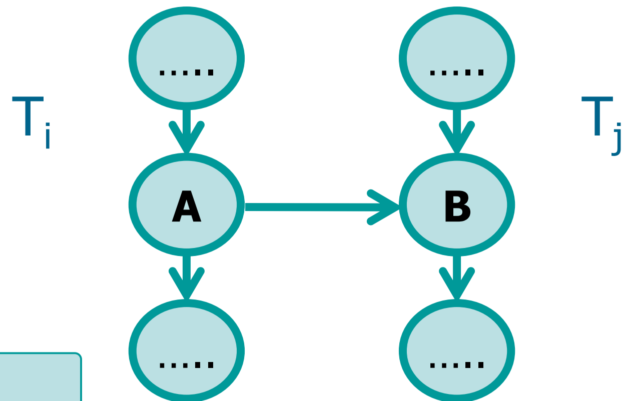
At most **two** T/P at a time in the critical section

Synchronization with semaphores

- The use of semaphores is not limited to the Critical Section access protocol
- Semaphores can be used to solve **any synchronization problem** using
  - An appropriate positioning of semaphores in the code
  - Possibly, more than one semaphore
  - Possibly, additional shared variables

Pure synchronization: Example 1

- Obtain a specific order of execution
  - T_i executes code A before T_j executes code B




```
init (S, 0);
```

T_i

```
......
A;
signal (S);
......
```

T_j

```
......
wait (S);
B;
......
```

Pure synchronization: Example 2

- Synchronize two T/P so that
  - T_j waits T_i
  - then, T_i waits T_j
  - It is a client-server schema

```
init (S1, 0);
init (S2, 0);
```

T_i / P_i

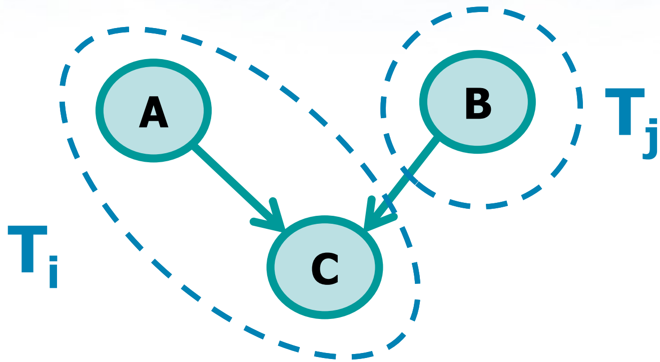
```
while (TRUE) {
  prepare data
  signal (S1);
  wait (S2);
  get processed data
}
```

T_j / P_j

```
while (TRUE) {
  wait (S1);
  process data
  signal (S2);
  ...
}
```

Pure synchronization : Example 3

- Implement this precedence graph




```
init (S, 0);
```

T_i

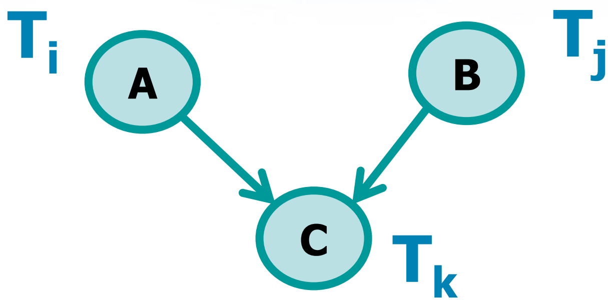
```
A;
wait (S);
C;
```

T_j

```
B;
signal (S);
```

Pure synchronization : Example 3

- Other possible solution involving 3 P/T




```
init (S, 0);
```

T_i

```
A;
signal (S);
```

T_k

```
wait (S);
wait (S);
C;
```

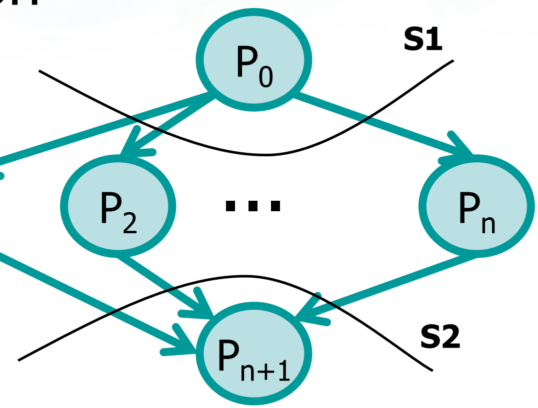
T_j

```
B;
signal (S);
```

Pure synchronization : Example 4

- Implement this precedence graph

cobegin-coend
(concurrent begin-end)




```
init (S1, 0);
init (S2, 0);
```

Note: These threads are not cyclic

P_0/T_0

```
P0
for(i=1;i<=n;i++)
   signal (S1);
...
```

P_i/T_i

```
wait (S1);
Pi
signal (S2);
...
```

P_{n+1}/T_{n+1}

```
...
for(i=1;i<=n;i++)
   wait (S2);
Pn+1
```

Errors using semaphores: Example 1

- Just **a single** thread is **incorrect**

```
init (S, 1);
```

T_1

```
while (TRUE) {
  ...
  signal (S); !!
  CS1
  wait (S);   !!
  ...
}
```

T_2

```
while (TRUE) {
  ...
  wait (S);
  CS2
  signal (S);
  ...
}
```

T_3

```
while (TRUE) {
  ...
  wait (S);
  CS3
  signal (S);
  ...
}
```

Enters its CS and makes possible that the two other threads enter their CSs

Errors using semaphores: Example 2

- Just **a single** thread is **incorrect**

```
init (S, 1);
```

T_1

```
while (TRUE) {
   ...
   wait (S);
   CS1
   wait (S);   !!
   ...
}
```

T_2

```
while (TRUE) {
   ...
   wait (S);
   CS2
   signal (S);
   ...
}
```

T_3

```
while (TRUE) {
   ...
   wait (S);
   CS3
   signal (S);
   ...
}
```

When the second wait is executed all thread are in deadlock

Errors using semaphores: Example 3

- Just **a single** thread is **incorrect**

```
init (S, 1);
```

T_1

```
while (TRUE) {
   ...
   signal(S); !!
   CS1
   signal(S);
   ...
}
```

T_2

```
while (TRUE) {
   ...
   wait (S);
   CS2
   signal (S);
   ...
}
```

T_3

```
while (TRUE) {
   ...
   wait (S);
   CS3
   signal (S);
   ...
}
```

When the first signal is executed, two threads can enter their CSs.
When the second signal is executed, all threads can enter their CSs.

Errors using semaphores: Example 4

- Just **a single** thread is **incorrect**

```
init (S, 1);
```

T_1

```
while (TRUE) {
  ...
  wait(S);
  CS1
  !! no signal(S)
  ...
}
```

T_2

```
while (TRUE) {
  ...
  wait (S);
  CS2
  signal (S);
  ...
}
```

T_3

```
while (TRUE) {
  ...
  wait (S);
  CS3
  signal (S);
  ...
}
```

After T_1 exit its CS, all threads will be in deadlock

If T_3 is fast, all threads can enter their CSs

Errors using semaphores: Example 5

- Just **a single** thread is **incorrect**

```
init (S, 1);
```

T_1

```
while (TRUE) {
   ...
   !! no wait(S);
   CS1
   signal (S);
   ...
}
```

T_2

```
while (TRUE) {
   ...
   wait (S);
   CS2
   signal (S);
   ...
}
```

T_3

```
while (TRUE) {
   ...
   wait (S);
   CS3
   signal (S);
   ...
}
```

If T_3 is fast (i.e., it does two loops in the while cycle), all threads can enter their CSs

Errors using semaphores: Example 6

Acquiring two resources

```
init (S, 1);
init (Q, 1);
```

T_1

```
while (TRUE) {
  ...
  wait (S);
  ... Use S
  wait (Q);
  ... Use S and Q
  signal (Q);
  signal (S);
  ...
}
```

Access to pen-drive, then to HD

T_2

```
while (TRUE) {
  ...
  wait (Q);
  ... Use Q
  wait (S);
  ... Use Q and S
  signal (S);
  signal (Q);
  ...
}
```

Access to HD, then to pen-drive

Exercise

- Given the code of these three threads
  - Which is the possible execution order?

```
init (S1, 1);
init (S2, 0);
```

T_1

```
...
while (1) {
  wait (S1);
  T1 code
  signal (S2);
}
...
```

T_2

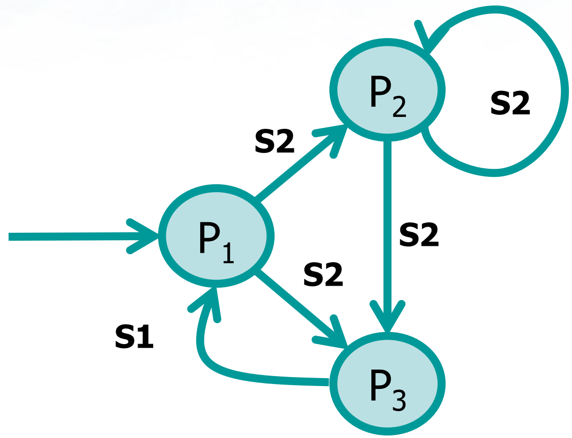
```
...
while (1) {
  wait (S2);
  T2 code
  signal (S2);
}
...
```

T_3

```
...
while (1) {
  wait (S2);
  T3 code
  signal (S1);
}
...
```

Solution

- It is a peculiar synchronization example !!




```
init (S1, 1);
init (S2, 0);
```

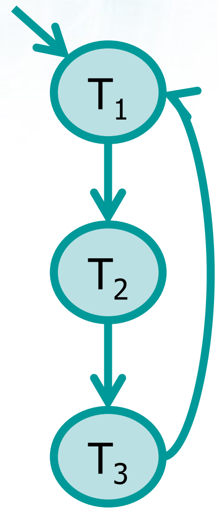
T1
```
...
while (1) {
  wait (S1);
  T1 code
  signal (S2);
}
...
```

T2
```
...
while (1) {
  wait (S2);
  T2 code
  signal (S2);
}
...
```

T3
```
...
while (1) {
  wait (S2);
  T3 code
  signal (S1);
}
...
```

Exercise

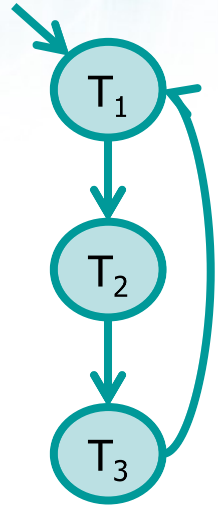
- Implement this precedence graph using semaphores
  - **All** T/P must be **cyclic**



This way they don't have to be instantiated several times

Solution

- Implement this precedence graph using semaphores
  - **All** T/P must be **cyclic**




```
init (S1, 1);
init (S2, 0);
init (S3, 0);
```

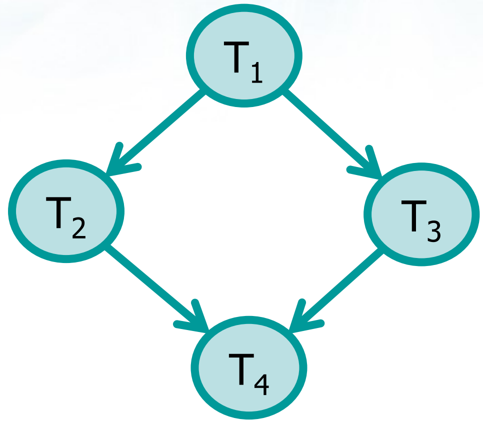
T_1
```
...
while (1) {
  wait (S1);
  T1 code
  signal (S2);
}
...
```

T_2
```
...
while (1) {
  wait (S2);
  T2 code
  signal (S3);
}
...
```

T_3
```
...
while (1) {
  wait (S3);
  T3 code
  signal (S1);
}
...
```

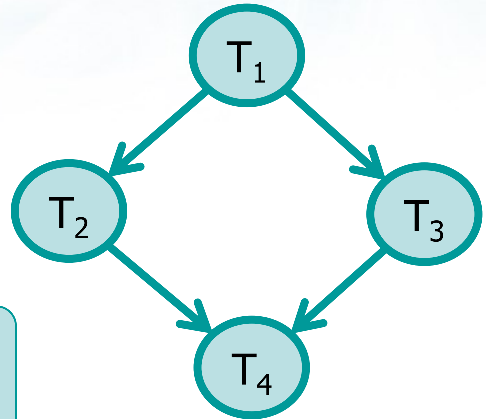
Exercise

- Implement this precedence graph using semaphores
  - T/P are not **cyclic**



Solution

- Implement this precedence graph using semaphores
  - T/P are not **cyclic**




```
init (S1, 0);
init (S2, 0);
```

T2
```
...
wait (S1);
T2 code
signal (S2);
...
```

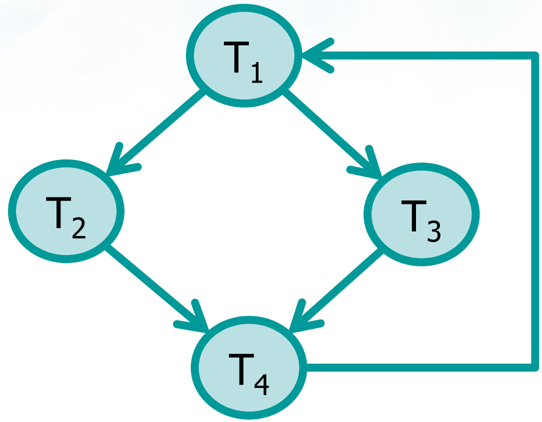
T1
```
T1 code
signal (S1);
signal (S1);
...
```

T3
```
...
wait (S1);
T3 code
signal (S2);
...
```

T4
```
...
wait (S2);
wait (S2);
T4 code
```

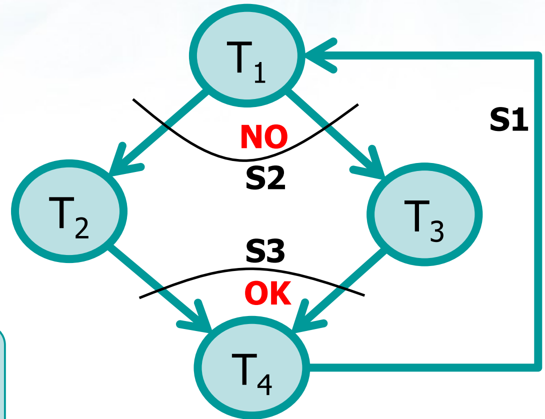
Exercise

- Implement this precedence graph using semaphores
  - **All** T/P must be **cyclic**



Erroneous solution

- Implement this precedence graph using semaphores
  - **All** T/P must be **cyclic**




```
init (S1, 1);
init (S2, 0);
init (S3, 0);
```

T1
```
while (1) {
  wait (S1);
  T1 code
  signal (S2);
  signal (S2);
}
```

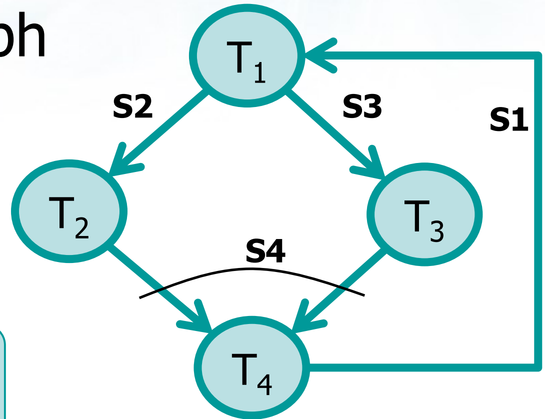
T2
```
while (1) {
  wait (S2);
  T2 code
  signal (S3);
}
```

T3
```
while (1) {
  wait (S2);
  T3 code
  signal (S3);
}
```

T4
```
while (1) {
  wait (S3);
  wait (S3);
  T4 code
  signal (S1);
}
```

Solution

- Implement this precedence graph using semaphores
  - **All** T/P must be **cyclic**




```
init (S1, 1);
init (S2, 0);
init (S3, 0);
init (S4, 0);
```

T2
```
while (1) {
  wait (S2);
  T2 code
  signal (S4);
}
```

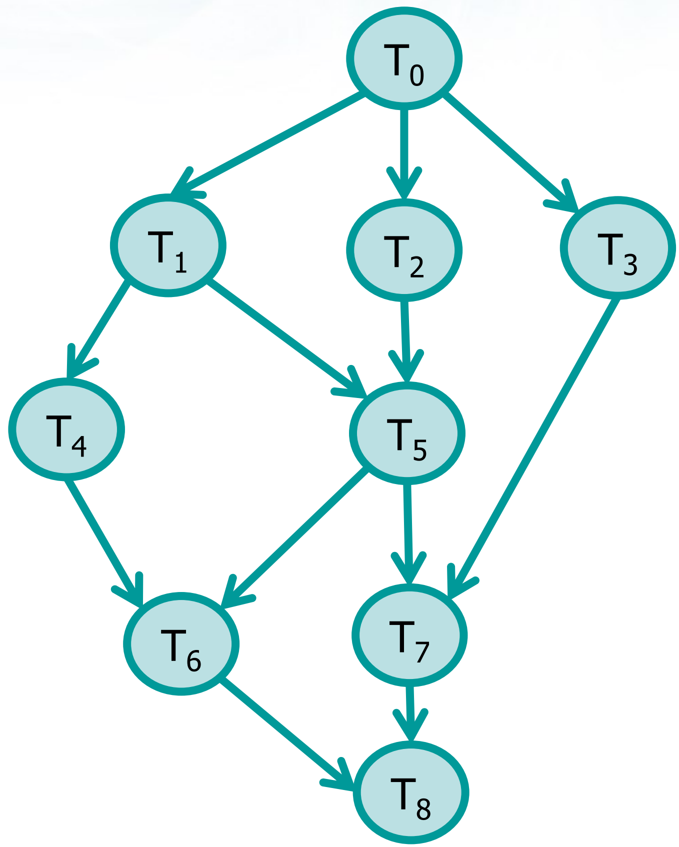
T1
```
while (1) {
  wait (S1);
  T1 code
  signal (S2);
  signal (S3);
}
```

T3
```
while (1) {
  wait (S3);
  T3 code
  signal (S4);
}
```

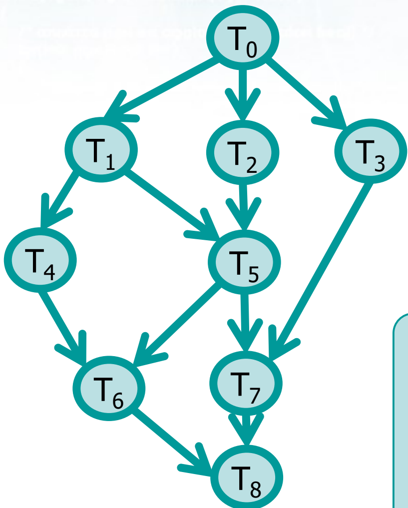
T4
```
while (1) {
  wait (S4);
  wait (S4);
  T4 code
  signal (S1);
}
```

Exercise

- Implement this precedence graph using semaphores
  - T/P are **not cyclic**



Erroneous solution




```
T0
T0 code
signal(S1);
signal(S1);
signal(S1);
```

```
T1
wait(S1);
T1 code
signal(S2);
signal(S2);
```

```
T2
wait(S1);
T2 code
signal(S2);
```

```
T3
wait(S1);
T3 code
...
```

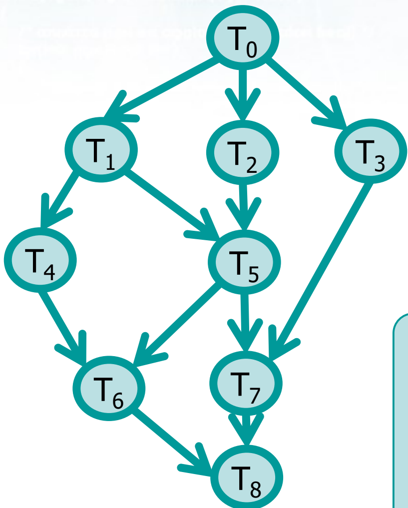
```
init (S1, 0);
init (S2, 0);
init (S3, 0);
...
```

```
T4
wait(S2);
T4 code
...
```

```
T5
wait(S2);
wait(S2);
T5 code
...
```

...

Solution




```
T0
T0 code
signal(S1);
signal(S2);
signal(S3);
```

```
T1
wait(S1);
T1 code
signal(S4);
signal(S5);
```

```
T2
wait(S2);
T2 code
signal(S5);
```

```
T3
wait(S3);
T3 code
signal(S7);
```

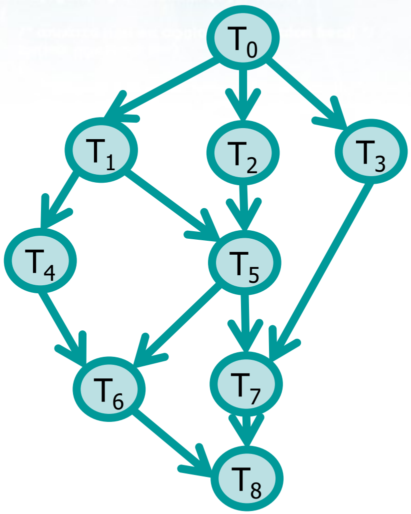
```
init (S1, 0);
init (S2, 0);
init (S3, 0);
...
```

```
T4
wait(S4);
T4 code
signal(S6);
```

```
T5
wait(S5);
wait(S5);
T5 code
signal(S6);
signal(S7);
```

...

Solution




```
T6
wait(S6);
wait(S6);
T6 code
signal(S8);
```

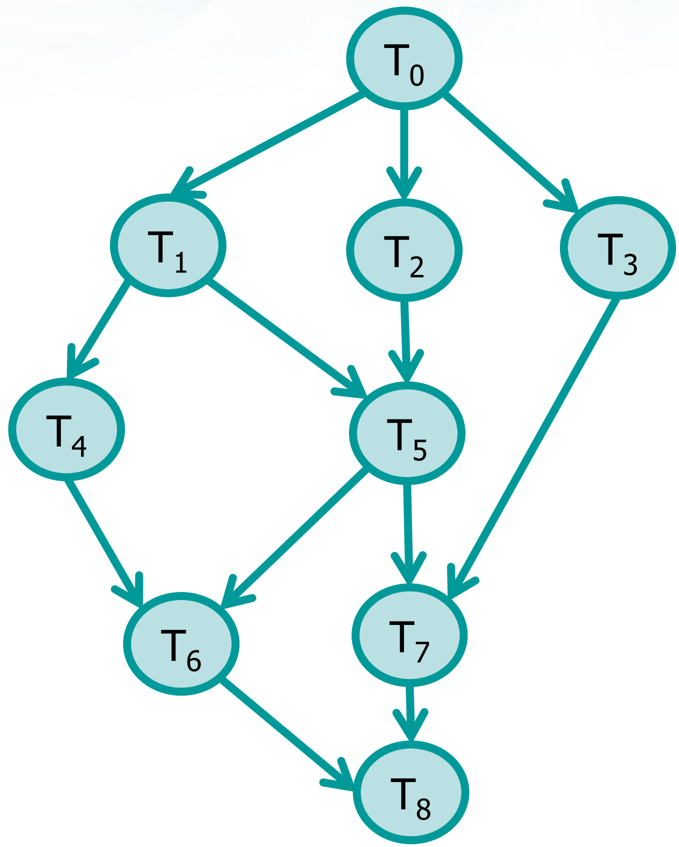
```
T7
wait(S7);
wait(S7);
T7 code
signal(S8);
```

```
T8
wait(S8);
wait(S8);
T8 code
```

This solution is correct, but the number of semaphores is **not minimal**.

Exercise

- Implement this precedence graph using semaphores
  - Version A: T/P are **not cyclic, but** use the **minimum number of semaphores**
  - Version B: T/P are **cyclic**



Real implementations

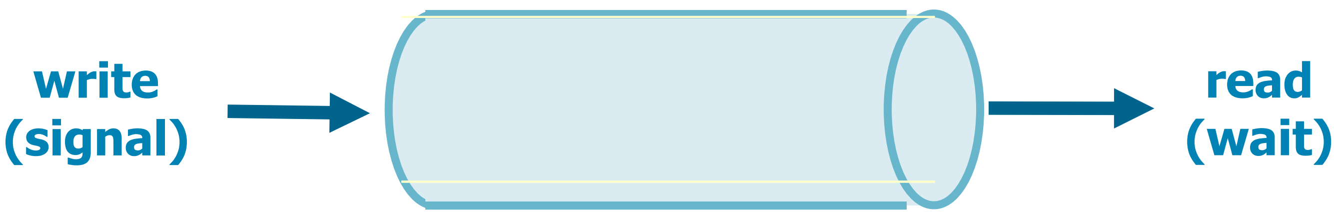
- There are several semaphores implementations
  - **Semaphores by means of a pipe**
  - **POSIX Pthread**
    - Condition variables
    - **Semaphores**
      - The most important
    - **Mutex** (for mutual exclusion)
  - Linux semaphores
- Notice that semaphores are
  - Global share objects (see **sem_init**)
  - They are allocated by a thread, but they are kernel objects

System call:
pthread_cond_init
pthread_cond_wait
pthread_cond_signal
pthread_cond_broadcast
pthread_cond_destroy

System call:
semget, semop, semctl (in **sys/sem.h**) they are complex to use

Semaphore by means of a pipe

- Given a pipe
  - The counter of a semaphore is achieved by means of **tokens**
  - **Signal** implemented using the **write** system call to write a token on the pipe (non-blocking)
  - **Wait** implemented using the **read** system call to read a token from the pipe (blocking)



semaphoreInit (s)

```
#include <unistd.h>

void semaphoreInit (int *S, int k) {
  char ctr = 'X';
  int i;
  if (pipe (S) == -1) {
    printf ("Error"); exit (-1);
  }
  for(i=0; i<k; i++)
    if (write(S[1], &ctr, sizeof(char)) != 1) {
      printf ("Error"); exit (-1);
    }
  return;
}
```

Writes k characters, i.e., initializes the semaphore counter to k

- Semaphore initialization
  - The variable S must be defined as a global variable
    - int S[2];
    - int *S = malloc (2 * sizeof (char));

semaphoreSignal (s)

```
#include <unistd.h>

void semaphoreSignal (int *S) {
  char ctr = 'X';
  if (write(S[1], &ctr, sizeof(char)) != 1) {
    printf ("Error");
    exit (-1);
  }
  return;
}
```

Writes a single character, i.e., increments the semaphore counter k

- Writes a character (any) on a pipe
  - Suppose the number of writes (signals) before a read (wait) not exceed the dimension of the pipe

semaphoreWait (s)

```
#include <unistd.h>

void semaphoreWait (int *S) {
  char ctr;
  if (read (S[0], &ctr, sizeof(char)) != 1) {
    printf ("Error");
    exit (-1);
  }
  return;
}
```

If the pipe is empty, read() waits

- Reads a character from a pipe (read is blocking)

Example

Use of a pipe as a synchronization semaphore between P parent and P child

```
int main() {
  int S[2];
  pid_t pid;
  semaphoreInit (S, 0);
  pid = fork();
  // Check for correctness
  if (pid == 0) {                    // child
    semaphoreWait (S);
    printf("Wait done.\n");
  } else {                           // parent
    printf("Sleep 3s.\n");
    sleep (3);
    semaphoreSignal (S);
    printf("Signal done.\n");
   }
   return 0;
}
```

POSIX semaphores

- Kernel and OS independent system calls (POSIX)
- Header file
  - `#include <semaphore.h>`
- A semaphore is a type **`sem_t`** variable
- **`sem_t *sem1, *sem2, ...;`**
- All semaphore system calls
  - Have name **sem_xxxx**
  - On error returns -1

System calls:
`sem_init`
`sem_wait`
`sem_trywait`
`sem_post`
`sem_getvalue`
`sem_destroy`

sem_init ()

```
int sem_init (
  sem_t *sem,
  int pshared,
  unsigned int value
);
```

- Initializes the semaphore counter at value **`value`**
- The **`pshared`** value identifies the type of semaphore
  - If equal to `0`, the semaphore is local to the **threads of current process**
  - Otherwise, the semaphore can be **shared between different processes** (parent that initializes the semaphore and its children)

Linux does not currently support shared semaphores

sem_wait ()

```
int sem_wait (
   sem_t *sem
);
```

- Standard wait
  - If the semaphore is equal to 0, it blocks the caller until it can decrease the value of the semaphore

sem_trywait ()

```
int sem_trywait (
  sem_t *sem
);
```

- Non-blocking wait
  - If the semaphore counter has a value greater than 0, perform the decrement, and returns 0
  - If the semaphore is equal to 0, returns -1 (instead of blocking the caller as `sem_wait` does)

sem_post ()

```
int sem_post (
  sem_t *sem
);
```

- Standard signal
  - Increments the semaphore counter, or wakes up a blocked thread if present

sem_getvalue ()

```
int sem_getvalue (
  sem_t *sem,
  int *valP
);
```

Better not to use this function. From Linux manual: "The value of the semaphore may already have changed by the time sem_getvalue() returns."

- Allows obtaining the value of the semaphore counter
  - The value is assigned to *valP
  - If there are waiting threads
    - 0 is assigned to *valP (Linux)
    - or a negative number whose absolute value is equal to the number of processes waiting (POSIX)

sem_destroy ()

```
int sem_destroy (
  sem_t *sem
);
```

- Destroys the semaphore at the address pointed by sem
  - Destroying a semaphore that other threads are currently blocked on produces undefined behavior (on error, -1 is returned)
  - Using a semaphore that has been destroyed produces undefined results, until the semaphore has been reinitialized

Example

Of use of sem_xxxx POSIX functions for synchronization

```
...
#include "semaphore.h"
...
sem_t *sem;
...
sem = (sem_t *) malloc(sizeof(sem_t));
sem_init (sem, 0, 1);
...
... create processes or threads ...
...
sem_wait (sem);
... CS ...
sem_post (sem);
```

Pthread mutex

- Binary semaphores (mutex)
- A mutex is of type **pthread_mutex_t**
- System calls
  - pthread_mutex_init
  - pthread_mutex_lock
  - pthread_mutex_trylock
  - pthread_mutex_unlock
  - pthread_mutex_destroy

> Alternative to sem_xxxx primitives, mutex is less general than semaphores (i.e., they can assume only the two values 0 or 1)

pthread_mutex_init ()

```
int pthread_mutex_init (
  pthread_mutex_t *mutex,
  const pthread_mutexattr_t *attr
);
```

- Initializes the mutex referenced by **`mutex`** with attributes specified by **`attr`** (default=NULL)
- Return value
  - 0 on success
  - Error code otherwise

pthread_mutex_lock ()

```
int pthread_mutex_lock (
  pthread_mutex_t *mutex
);
```

- Control the value of mutex and
  - Blocks the caller if the mutex is locked
  - Acquire the mutex lock if the mutex is unlocked
- Return value
  - 0 on success
  - Error code otherwise

pthread_mutex_trylock ()

```
int pthread_mutex_trylock (
  pthread_mutex_t *mutex
);
```

- Similar to pthread_mutex_lock, but returns without blocking the caller if the mutex is locked
- Return value
  - 0 if the lock has been successfully acquired
  - **EBUSY** error if the mutex was already locked by another thread

pthread_mutex_unlock ()

```
int pthread_mutex_unlock (
  pthread_mutex_t *mutex
);
```

- Release the mutex lock (typically at the end of a Critical Section)
- Return value
  - 0 on success
  - Error code otherwise

pthread_mutex_destroy ()

```
int pthread_mutex_destroy (
  pthread_mutex_t *mutex
);
```

- Free mutex memory
- The mutex cannot be used any more
- Return value
  - 0 on success
  - Error code otherwise