Sistemas de Operação / Fundamentos de Sistemas Operativos

Threads, mutexes and condition variables in Unix/Linux

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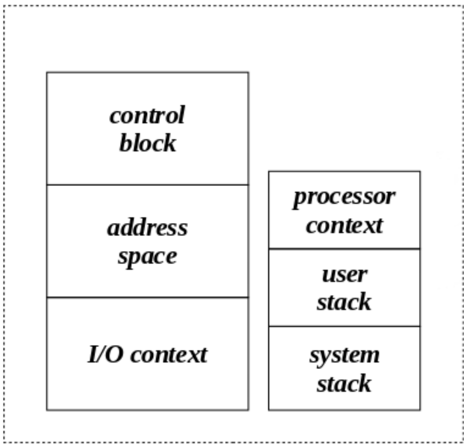
Outline

1. Threads and multithreading
2. Threads in Linux
3. Monitors
4. POSIX support for implementing monitors
5. Bounded-buffer problem – solving using monitors
6. Sleeping barber problem, using monitors

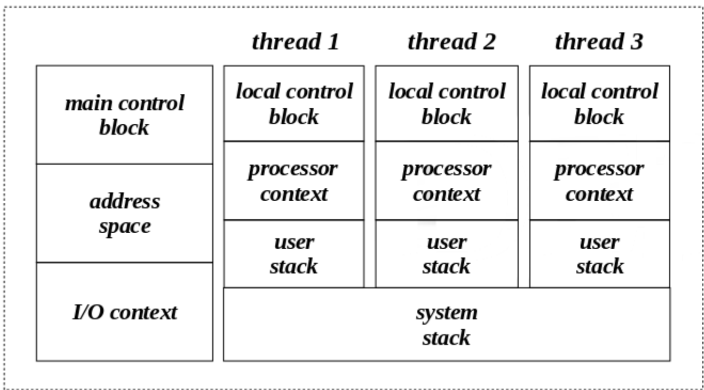
Threads
Single threading

- In traditional operating system, a process includes:
  - an address space (code and data of the associated program)
  - a set of communication channels with I/O devices
  - a single thread of control, which incorporates the processor registers (including the program counter) and a stack
- However, these components can be managed separetely
- In this model, thread appears as an execution component within a process



Single threading

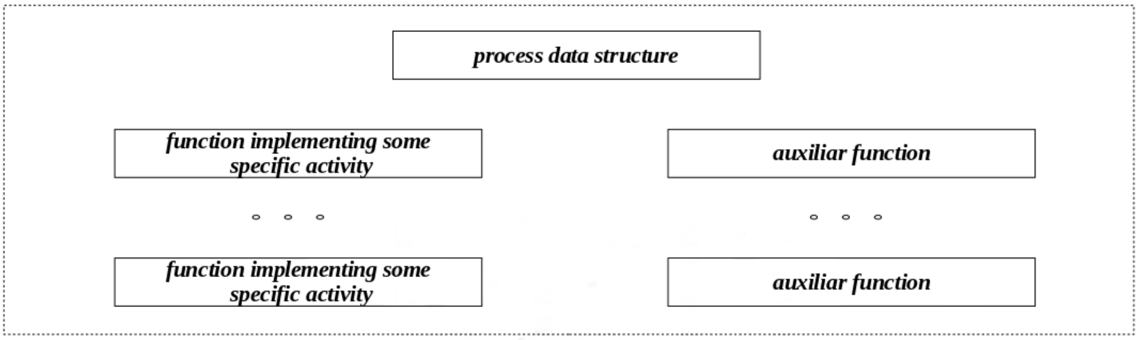
Threads
Multithreading



Multithreading

- Several independent threads can coexist in the same process, thus sharing the same address space and the same I/O context
  - This is referred to as *multithreading*
- Threads can be seen as *light weight processes*

Threads
Structure of a multithreaded program



- Each thread is typically associated to the execution of a function that implements some specific activity
- Communication between threads can be done through the process data structure, which is global from the threads point of view
  - It includes static and dynamic variables (heap memory)
- The main program, also represented by a function that implements a specific activity, is the first thread to be created and, in general, the last to be destroyed

Threads
Implementations of multithreading

- user level threads – threads are implemented by a library, at user level, which provides creation and management of threads without kernel intervention
  - versatile and portable
  - when a thread calls a blocking system call, the whole process blocks
    - because the kernel only sees the proccess
- kernel level threads – threads are implemented directly at kernel level
  - less versatile and less portable
  - when a thread calls a blocking system call, another thread can be schedule to execution

Threads
Advantages of multithreading

- easier implementation of applications – in many applications, decomposing the solution into a number of parallel activities makes the programming model simpler
  - since the address space and the I/O context is shared among all threads, multithreading favors this decomposition.
- better management of computer resources – creating, destroying and switching threads is easier then doing the same with processes
- better performance – when an application envolves substantial I/O, multithreading allows activities to overlap, thus speeding up its execution
- multiprocessing – real parallelism is possible if multiples CPUs exist

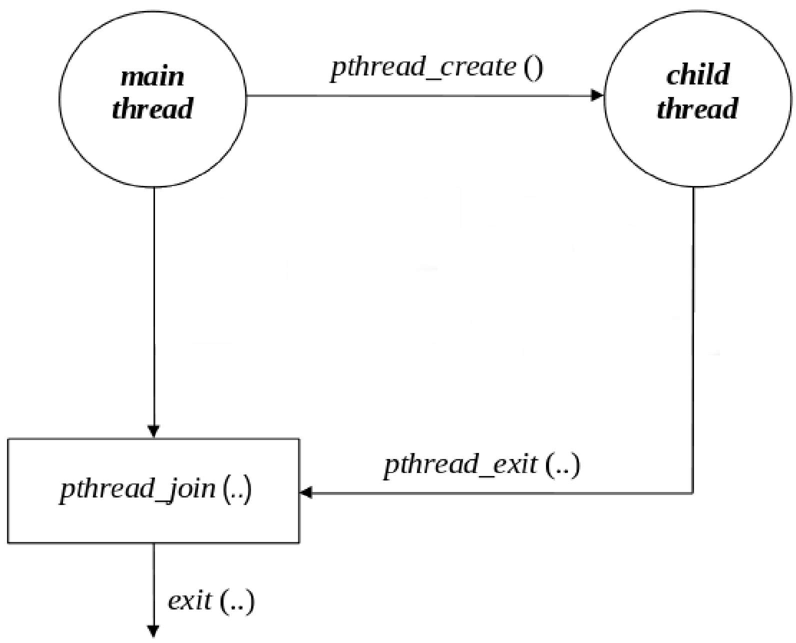
Threads in Linux
The `clone` system call

- In Linux there are two system calls to create a child process:
  - fork – creates a new process that is a full copy of the current one
    - the address space and I/O context are duplicated
    - the child starts execution in the point of the forking
  - clone – creates a new process that can share elements with its parent
    - address space, table of file descriptors, and table of signal handlers are shareable.
    - the child starts execution in a specified function
- Thus, from the kernel point of view, processes and threads are treated similarly
- Threads of the same process forms a thread group and have the same thread group identifier (TGID)
  - this is the value returned by system call `getpid()`
- Within a group, threads can be distinguished by their unique thread identifier (TID)
  - this value is returned by system call `gettid()`

Thread in Linux
POSIX library

- Standard POSIX, IEEE 1003.1c, defines a programming interface (API) for the creation and synchronization of threads
  - In Linux, this interface is implemented by the pthread library
- Some of the available functions to manage threads:
  - `pthread_create` – create a new thread (corresponding to the `fork` in processes)
  - `pthread_exit` – terminate calling thread (corresponding to the `exit` in processes)
  - `pthread_join` – joint with a terminated thread (corresponding to the `waitpid` in processes)
  - `pthread_kill` – send a signal to a thread (corresponding to the `kill` in processes)
  - `pthread_cancel` – send a cancellation request to a thread
  - `pthread_self` – obtain ID of the calling thread
  - `pthread_detach` – detach a thread

Threads in Linux
Thread creation and termination – `pthread` library



Threads in Linux

Thread creation and termination – example

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>
#include <unistd.h>

/* return status */
int status;

/* child thread */
void *threadChild (void *par)
{
  printf ("I'm the child thread!\n");

  sleep(1);
  status = EXIT_SUCCESS;
  pthread_exit (&status);
}
```

```
/* main thread */
int main (int argc, char *argv[])
{
  /* launching the child thread */
  pthread_t thr;
  if (pthread_create (&thr, NULL,
                threadChild, NULL) != 0)
  {
    perror ("Fail launching thread");
    return EXIT_FAILURE;
  }

  /* waits for child termination */
  if (pthread_join (thr, NULL) != 0)
  {
    perror ("Fail joining child");
    return EXIT_FAILURE;
  }

  printf ("Child ends; status %d.\n", status);

  return EXIT_SUCCESS;
}
```


Thread synchronization

Introducing monitors

- A problem with semaphores is that they are used both to implement mutual exclusion and to synchronize
- Being low level primitives, they are applied in a bottom-up perpective
  - if required conditions are not satisfied, processes are blocked before they enter their critical sections
  - this approach is prone to errors, mainly in complex situations, as synchronization points can be scattered throughout the program
- A higher level approach should followed a top-down perpective
  - processes must first enter their critical sections and then wait if continuation conditions are not satisfied
- A solution is to introduce a (concurrent) construction at the programming level that deals with mutual exclusion and synchronization separately

- A monitor is such a synchronization mechanism, independently proposed by Hoare and Brinch Hansen, supported by a (concurrent) programming language
- The `pthread` library provides primitives that allows to implement monitors (of the Lampson-Redell type)

Thread synchronization
Monitor definition

```
monitor example
{
   /* internal shared data structure */
   DATA data;

   cond c; /* condition variable */

   /* access methods */
   method_1 (...)
   {
      ...
   }

   method_2 (...)
   {
      ...
   }

   ...

   /* initialization code */
   ...
}
```

- An application is seen as a set of threads that compete to access the shared data structure
- This shared data can only be accessed through the access methods
- Every method is executed in mutual exclusion
- If a thread calls an access method while another thread is inside another access method, its execution is blocked until the other leaves
- Synchronization between threads is possible through condition variables
- Two operation on them are possible:
  - wait – the thread is blocked and put outside the monitor
  - signal – if there are threads blocked, one is waked up. *Which one?*

Thread synchronization
POSIX support for monitors

- The `pthread` library allows for the implementation of monitors in C/C++
  - mutexes (mutual exclusion elements) are used to implement mutual exclusion
  - condition variables are used to implement synchronization
- Some function for mutual exclusion support:
  - `pthread_mutex_t` – the mutex data type
  - `pthread_mutex_init` – initializes a mutex object
  - `pthread_mutex_lock` – locks the given mutex
  - `pthread_mutex_unlock` – unlocks the given mutex
- Some function for synchronization support:
  - `pthread_cond_t` – the condition variable data type
  - `pthread_cond_init` – initializes a condition variable object
  - `pthread_cond_wait` – atomically unlocks the associated mutex and waits for the given condition variable to be signaled.
  - `pthread_cond_signal` – restarts one of the threads that are waiting on the given condition variable
  - `pthread_cond_broadcast` – restarts all of the threads that are waiting on the given condition variable

Semaphores
Bounded-buffer problem – making the implementation safe

```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    /* wait until fifo is not full */
    while (fifoIsFull(f))
    {
        bwDelay(10); // wait for a while
    }

    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);
}

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    /* wait until fifo is not empty */
    while (fifoIsEmpty(f))
    {
        bwDelay(10); // wait for a while
    }

    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;
}
```


Semaphores
Bounded-buffer problem – making the implementation safe

```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    lock
    /* wait until fifo is not full */
    while (fifoIsFull(f))
    {
        wait until not full
    }

    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);
}
    unlock
    signal not empty
void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    lock
    /* wait until fifo is not empty */
    while (fifoIsEmpty(f))
    {
        wait until not empty
    }

    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;
}
    unlock
    signal not full
```

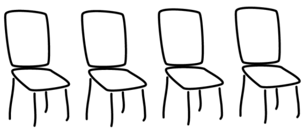
Semaphores

Bounded-buffer problem – safe implementation using monitors

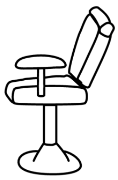
```
void fifoInsert(FIFO *f, uint32_t id, uint32_t v1, uint32_t v2)
{
    /* lock access on entry */
    mutex_lock(&f->access);

    /* wait until fifo is not full */
    while (fifoIsFull(f))
    {
        cond_wait(&f->notFull, &f->access);
    }

    /* make insertion */
    f->data[f->in].id = id;
    f->data[f->in].v1 = v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    f->data[f->in].v2 = v2;
    f->in = (f->in + 1) % f->size;
    f->full = (f->in == f->out);

    /* signal fifo is not empty */
    cond_broadcast(&f->notEmpty);

    /* unlock access before quitting */
    mutex_unlock(&f->access);
}

void fifoRetrieve(FIFO *f, uint32_t *idp, uint32_t *v1p, uint32_t *v2p)
{
    /* lock access on entry */
    mutex_lock(&f->access);

    /* wait until fifo is not full */
    while (fifoIsEmpty(f))
    {
        cond_wait(&f->notEmpty, &f->access);
    }

    /* make retrieval */
    *idp = f->data[f->out].id;
    *v1p = f->data[f->out].v1;
    bwDelay(f->dummyDelay); // to enhance the probability of occurrence of race conditions
    *v2p = f->data[f->out].v2;
    f->out = (f->out + 1) % f->size;
    f->full = false;

    /* signal fifo is not empty */
    cond_broadcast(&f->notFull);

    /* unlock access before quitting */
    mutex_unlock(&f->access);
}
```


Illustration example

Sleeping barber example – problem statement



4 waiting chairs



1 barber chair

Barber Shop

- In this problem, attributed to Dijkstra, a number of entities (customers) interact with another entity (barber) to request a service (haircut)
- Problem statement:
  - If there are no customers, the barber falls asleep in the barber chair
  - Upon entering, if the barber is sleeping, a customer must wake him up,
  - Otherwise, if the barber is working, the customer leaves if all chairs are occupied or sits if one is available
  - Upon finishing a haircut, the barber inspects the waiting room to see if there are any waiting customers, falling asleep if there are none