Using the POSIX API
Threads, real-time and IPC

The pthread library

- In Linux, when a new process is created, it already contains a thread, used to execute the `main()` function
- Additional threads can be created using the pthread library, which is part of the C library
- Of course all threads inside a given process will share the same address space, the same set of open files, etc.
- The pthread library also provide thread synchronization primitives: mutexes and conditions
- This pthread library has its own header : `pthread.h`
- Applications using pthread function calls should be explicitly linked with the pthread library
  `gcc -o app app.c -lpthread`

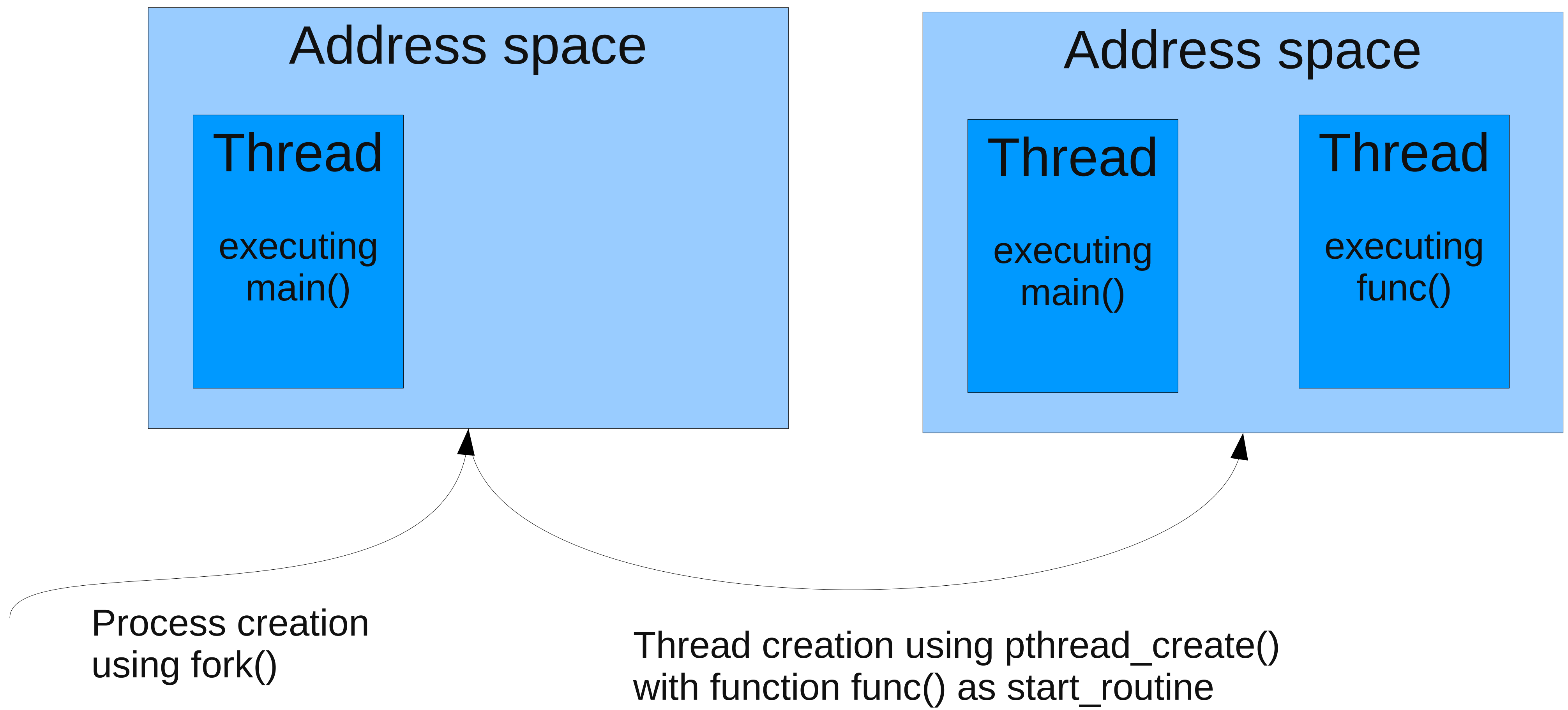
Creating a new thread

- The function to create a new thread is pthread_create()

```
int  pthread_create(pthread_t  *  thread,
                    pthread_attr_t * attr,
                    void *(*start_routine)(void *),
                    void * arg);
```

- `thread` is a pointer to a pthread_t structure that will be initialized by the function. Later, this structure can be used to reference the thread.
- Attr is a pointer to an optional structure pthread_attr_t. This structure can be manipulated using `pthread_attr_*()` functions. It can be used to set various attributes of the threads (detach policy, scheduling policy, etc.)
- `start_routine` is the function that will be executed by the thread
- `arg` is the private data passed as argument to the start_routine function

Creating a new thread (2)



Thread creation, code sample

```
#include <pthread.h>

void *thread(void *data)
{
   while(1) {
      printf(« Hello world from thread »);
   }
}

int main(void) {
   pthread_t th;
   pthread_create(& th, NULL, thread, NULL);
   return 0;
}
```

Joinable and detached threads

- When the `main()` function exits, all threads of the application are destroyed
- The `pthread_join()` function call can be used to suspend the execution of a thread until another thread terminates. This function must be called in order to release the ressources used by the thread, otherwise it remains as zombie.
- Threads can also be detached, in which case they become independent. This can be achieved using
  - Thread attributes at thread creation, using `pthread_attr_setdetachstate(& attr, PTHREAD_CREATE_DETACHED);`
  - `pthread_detach()`, passing the `pthread_t` structure as argument

Thread join, code sample

```
#include <pthread.h>

void *thread(void *data)
{
   int i;
   for (i = 0; i < 100; i++) {
      printf(« Hello world from thread »);
   }
}

int main(void) {
   pthread_t th;
   pthread_create(& th, NULL, thread, NULL);
   pthread_join(& th, NULL);
   return 0;
}
```

Thread cancelation

- It is also possible to cancel a thread from another thread using the `pthread_cancel()` function, passing the `pthread_t` structure of the thread to cancel.

```
#include <pthread.h>

void *thread(void *data)
{
    while(1) {
        printf(« Hello world from thread »);
    }
}

int main(void) {
    pthread_t th;
    pthread_create(& th, NULL, thread, NULL);
    sleep(1);
    pthread_cancel(& th);
    pthread_join(& th, NULL);
    return 0;
}
```

pthread mutexes (1)

- The pthread library provides a mutual exclusion primitive, the pthread_mutex.
- Declaration and initialization of a pthread mutex
  - Solution 1, at definition time
    ```
    pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
    ```
  - Solution 2, at runtime
    ```
    pthread_mutex_t lock;
    ...
    pthread_mutex_init(& lock, NULL);
    ...
    pthread_mutex_destroy(& lock);
    ```
  - The second argument to `pthread_mutex_init()` is a set of mutex-specific attributes, in the form of a `pthread_mutexattr_t` structure that can be initialized and manipulated using `pthread_mutexattr_*()` functions.

pthread mutexes (2)

- Take the mutex
  `ret = pthread_mutex_lock(& lock);`
- If the mutex is already taken by the calling threads, three possible behaviours depending on the mutex type (defined at creation time)
  - Normal (« fast ») mutex : the function doesn't return, deadlock
  - « Error checking » mutex : the function return with the `-EDEADLK` error
  - « Recursive mutex » : the function returns with success
- Release the mutex
  `ret = pthread_mutex_unlock(& lock);`
- Try to take the mutex
  `ret = pthread_mutex_trylock(& lock);`

pthread conditions

- Conditions can be used to suspend a thread until a condition becomes true, as signaled by another thread.
- Initialization, static or dynamic
  - `pthread_cond_t cond = PTHREAD_COND_INITIALIZER;`
  - `pthread_cond_t cond;`
    `pthread_cond_init(& cond, NULL);`
- Wait for the condition
  `pthread_cond_wait(& cond, & mutex)`
  The mutex will be released before waiting and taken again after the wait
- Signaling the condition
  - To one thread waiting, `pthread_cond_signal(& cond);`
  - To all threads waiting, `pthread_cond_broadcast(& cond);`

pthread conditions example

Receiver side

```
pthread_mutex_lock(& lock);

while(is_queue_empty())
   pthread_cond_wait(& cond, & lock);

/* Something in the queue,
   and we have the mutex ! */

pthread_mutex_unlock(& lock);
```

Sender side

```
pthread_mutex_lock(& lock);

/* Add something to the queue */

pthread_mutex_unlock(& lock);

pthread_cond_signal(& cond);
```

Managing real-time priorities

See http://free-electrons.com/docs/realtime/ for an introduction

C API Available through `<sched.h>` (see `man sched.h` for details)

- `sched_getscheduler`, `sched_setscheduler`
  Get / set the scheduling class of a process
- `sched_getparam`, `sched_setparam`
  Get / set the priority of a process
- `sched_get_priority_max`, `sched_get_priority_min`
  Get the maximum / minimum priorities allowed for a scheduling class.
- `sched_rr_get_interval`
  Get the current timeslice of the `SCHED_RR` process
- `sched_yield`
  Yield execution to another process.

Can also be manipulated from scripts with the `chrt` command.

POSIX shared memory (1)

A great way to communicate between processes without going through expensive system calls.

- Open a shared memory object:
  `shm_fd = shm_open("acme", O_CREAT | O_RDWR, 0666);`
  A zero size `/dev/shm/acme` file appears.

- Set the shared memory object size
  `ftruncate(shm_fd, SHM_SIZE);`
  `/dev/shm/acme` is now listed with the specified size.

- If the object has already been sized by another process, you can get its size with the `fstat` function.

POSIX shared memory (2)

- Map the shared memory in process address space:
```
addr = mmap (0, SHM_SIZE, PROT_WRITE,
             MAP_SHARED, shm_fd, 0);
```
  Now we have a memory area we can use!
- Lock the shared memory in RAM (best for real-time tasks):
```
mlock(addr, SHM_SIZE);
```
- Use the shared memory object!
  Other processes can use it too.

POSIX shared memory (3)

Exiting

- Unmap the shared memory object:
  `munmap (addr, SHM_SIZE);`
  This automatically unlocks it too.
- Close it:
  `close (shm_fd);`
- Remove the shared memory object:
  `shm_unlink (“acme”);`
  The object is effectively deleted after the last call to `shm_unlink`.

More details in `man shm_open`.

POSIX message queues

Deterministic and efficient IPC. See `man mqueue.h`.
Advantages for real-time applications:

- Preallocated message buffers
- Messages with priority.
  A message with a higher priority is always received first.
- Send and receive functions are synchronous by default.
  Possibility to set a wait timeout to avoid non-determinism.
- Support asynchronous delivery notifications.

Creating and opening a message queue

- Declare queue attributes:

```
queue_attr.mq_maxmsg = 16;
   /* max number of messages in queue */
queue_attr.mq_msgsize = 128;
   /* max message size */
```

- Open a queue:

```
qd = mq_open(
        "/msg_queue",         /* queue name   */
        OCREAT | O_RDWR,      /* opening mode */
        0600,                 /* permissions  */
        &queue_attr);
```

Posting a message

- Posting a message:

```
#define PRIORITY 3
char msg[] = "Goodbye Bill";
mqsend(qd, msg, strlen(msg), PRIORITY);
```

- Closing the queue:

```
mq_close(qd);
```

Caution: simplistic example code. Should check return values.

Receiving a message

From another application:

- Opening the shared message queue:

```
qd = mq_open("/msg_queue", O_RDWR,
             0600, NULL);
```

- Waiting for a message:

```
mq_receive(qd, text, buf, buf_size, &prio);
```

- Close the queue:

```
mq_close(qd);
```

- Destroy the queue:

```
mq_unlink("/msg_queue");
```

POSIX semaphores (1)

Resources for sharing resources between threads or processes. See `man semaphore.h`.

- Named semaphores:
  can be used between unrelated processes.
- Unnamed semaphores: can be used between threads from the same process, or by related processes (parent / child).

POSIX semaphores (2)

- `sem_open`
  Open and / or create
  a named semaphore.
- `sem_close`
  Close a named semaphore
- `sem_unlink`
  Destroy a named semaphore
- `sem_init`
  Initialize an unnamed semaphore
- `sem_destroy`
  Destroy an unnamed semaphore
- `sem_getvalue`
  Get current semaphore count
- `sem_wait`
  Try to lock the semaphore.
  Wait otherwise.
- `sem_trywait`
  Just tries to lock the semaphore,
  but gives up if the semaphore is
  already locked.
- `sem_post`
  Release the semaphore.

POSIX signals

- Signals are a mechanism to notify a process that an event occured : expiration of a timer, completion of an asynchronous I/O operation, or any kind of event specific to your application
- Signals are also used internally by the system to tell a process that it must be suspended, restarted, stopped, that is has done an invalid memory reference, etc.
- Each signal is identified by a number : `SIGSEGV`, `SIGKILL`, `SIGUSR1`, etc.
- An API is available to catch signals, wait for signals, mask signals, etc.
- See `signal(7)` for a general description of the signal mechanism

Registering a signal handler

- A signal handler can be registered using
  - `sighandler_t signal(int signum, sighandler_t handler);`
    - The handler has the following prototype : `void handler(int signum)`
  - `int sigaction(int signum, const struct sigaction *act, struct sigaction *oldact);`
    - The sigaction structure contains the reference to the handler
    - The handler can have two different prototypes
      - `void handler(int signum)`
      - `void handler(int signum, siginfo_t *info, void *data)`
- Inside the handler code, only some functions can be used : only the *async-signal-safe* functions, as documented by signal(7).

Signal registration example

```
#include <signal.h>
#include <assert.h>
#include <unistd.h>
#include <stdio.h>

void myhandler(int signum)
{
    printf("Signal catched!\n");
}

int main(void)
{
    int ret;
    struct sigaction action = {
        .sa_handler = myhandler,
    };

    ret = sigaction(SIGUSR1, & action, NULL);
    assert(ret == 0);

    while(1);
    return 0;
}
```

From the command line, the signal can then be sent using
`kill -USR1 PID`

Sending a signal

- From the command line, with the famous `kill` command, specifying the PID of the process to which the signal should be sent
  - By default, kill will send `SIGTERM`
  - Another signal can be sent using `kill -USR1`
- POSIX provides a function to send a signal to a process
  - `int kill(pid_t pid, int sig);`
  - In a multithread program, the signal will be delivered to an arbitrary thread. Use `tkill()` to send the signal to a specific thread.

Signal sets and their usage

- A type sigset_t is defined by POSIX, to hold a set of signals
- This type is manipulated through different functions
  - `sigemptyset()` to empty the set of signals
  - `sigaddset()` to add a signal to a set
  - `sigdelset()` to remove a signal from a set
  - `sigfillset()` to fill the set of signals with all signals
- Signals can then be blocked or unblocked using
  `sigprocmask(int how, const sigset_t *set, sigset_t *oldset);`
- sigset_t are also used in many other functions
  - `sigaction()` to give the list of signals that must be blocked during execution of the handler
  - `sigpending()` to get the list of pending signals

Waiting for signals

2 ways of waiting for signals:

- `sigwaitinfo()` and `sigtimedwait()` to wait for blocked signals (signals which remain pending until they are processed by a thread waiting for them.)
- `sigsuspend()` to register a signal handler and suspend the thread until the delivery of an unblocked signal (which are delivered without waiting for a thread to wait for them).

POSIX real-time signals

Regular signals

- Just 2 applications-specific signals: `SIGUSR1` and `SIGUSR2`
- No signal priorities
- Signals can't carry any extra information.
- Signals can be lost. When a signal is sent multiple times, the receiver will just process one instance.

POSIX signals

- Whole range of application specific signals: `SIGRTMIN` to `SIGRTMAX`
- Priorities available.
  Top priority signals delivered first.
- Possible to carry extra information in a signal.
- Signals are queued. All pending signals are processed: no signal is lost.

POSIX clocks and timers

Compared to standard (BSD) timers in Linux

- Possibility to have more than 1 timer per process.
- Increased precision, up to nanosecond accuracy
- Timer expiration can be notified either with a signal or with a thread.
- Several clocks available.

Available POSIX clocks (1)

Defined in `/usr/include/linux/time.h`

- `CLOCK_REALTIME`
  System-wide clock measuring the time in seconds and nanoseconds since Jan 1, 1970, 00:00. Can be modified.
  Accuracy: 1/HZ (1 to 10 ms)
- `CLOCK_MONOTONIC`
  System-wide clock measuring the time in seconds and nanoseconds since system boot. Cannot be modified, so can be used for accurate time measurement.
  Accuracy: 1/HZ

Available POSIX clocks (2)

- `CLOCK_PROCESS_CPUTIME_ID`
  Measures process uptime. 1/HZ accuracy. Can be changed.
- `CLOCK_THREAD_CPUTIME_ID`
  Same, but only for the current thread.

Time management

Functions defined in `time.h`

- `clock_settime`
  Set the specified clock to a value
- `clock_gettime`
  Read the value of a given clock
- `clock_getres`
  Get the resolution of a given clock.

See `man time.h` and the manual of each of these functions.

Using timers (1)

Functions also defined in `time.h`

- `clock_nanosleep`
  Suspend the current thread for the specified time, using a specified clock.
- `nanosleep`
  Same as clock_nanosleep,
  using the `CLOCK_REALTIME` clock.

Using timers (2)

- `timer_create`
  Create a timer based on a given clock.
- `timer_delete`
  Delete a timer
- `timer_settime`
  Arm a timer.
- `timer_gettime`
  Access the current value of a timer.

Using high resolution timers

- Available in Linux since 2.6.21 (on `x86`).
  Now available on most supported platforms.
- Depending on the hardware capabilities,
  this feature gives microsecond or nanosecond accuracy to the regular clocks (`CLOCK_REALTIME`, `CLOCK_MONOTONIC`).
- No need to recompile your applications!

Asynchronous I/O

- Helpful to implement non-blocking I/O.
- Allows to overlap compute tasks with I/O processing, to increase determinism.
- Supported functionality:
  - Send multiple I/O requests at once from different sources
  - Cancel ongoing I/O requests
  - Wait for request completion
  - Inquire the status of a request: completed, failed, or in progress.
- API available in `aio.h` (`man aio.h` for details)

Compiling instructions

- Includes: nothing special to do.
  Available in the standard path.
- Libraries: link with `librt`
- Example:
  ```
  gcc -lrt -o rttest rttest.c
  ```

POSIX manual pages

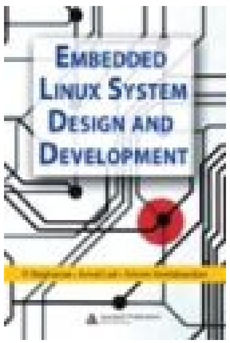
POSIX manual pages may not be installed on your system

- On Debian Linux, based systems,
  to find the names of the corresponding packages:
  `apt-cache search posix`
  Then, install these packages as follows:
  `apt-get install manpages-posix manpages-posix-dev`
- Other distributions should have similar package names.
- These manual pages are also available on-line:
  http://www.opengroup.org/onlinepubs/009695399/idx/realtime.html

You can almost consider these manual pages as specifications.
The standard can also be accessed on
http://www.unix.org/online.html (registration required).

More information on the POSIX interface

- The POSIX manual pages



- Embedded Linux System Design and Development
  P. Raghavan, A. Lad, S. Neelakandan, Auerbach, Dec. 2005.
  http://free-electrons.com/redirect/elsdd-book.html
  Very nice and clear coverage on real-time programming with the POSIX interface. Nice and useful examples.

- Guide to real-time programming
  http://www.phys.uu.nl/DU/unix/HTML/APS33DTE/TITLE.HTM
  A 11-year old document, with some Digital Unix specifics, but still up to date (thanks to standards).