Sistemas de Operação / Fundamentos de Sistemas Operativos

Processes and threads

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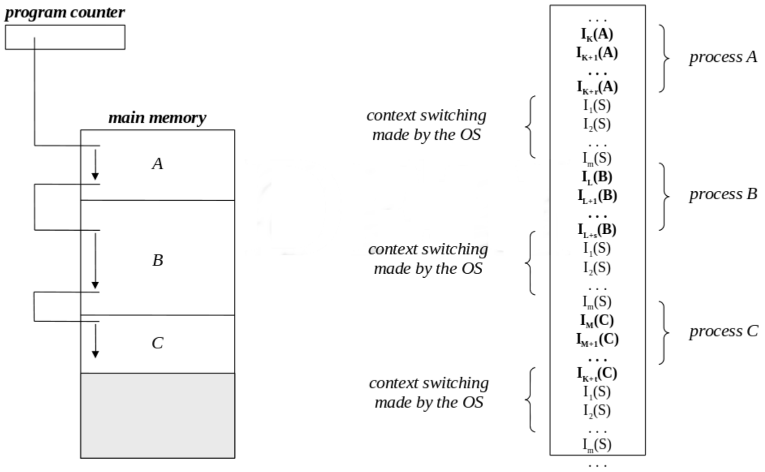
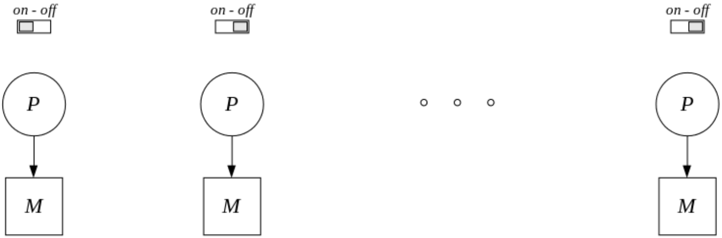
Execution in a multiprogrammed environment



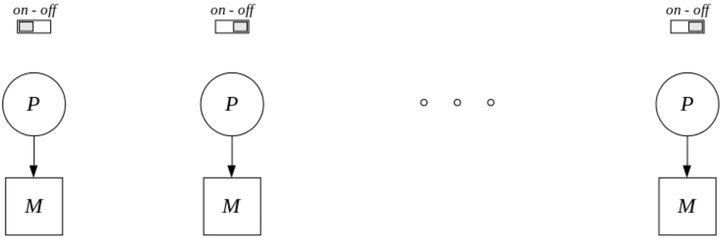
Process
Process model

- In multiprogramming the activity of the processor, because it is switching back and forth from process to process, is hard to perceive
- Thus, it is better to assume the existence of a number of virtual processors, one per existing process
  - Turning off one virtual processor and on another, corresponds to a process switching
  - number of active virtual processors $\leq$ number of real processors



Process
Process model

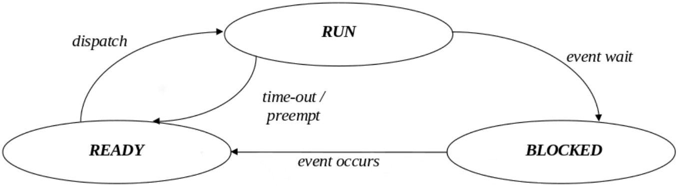
- The switching between processes, and thus the switching between virtual processors, can occur for different reasons, possible not controlled by the running program
- Thus, to be viable, this process model requires that
  - the execution of any process is not affected by the instant in time or the location in the code where the switching takes place
  - no restrictions are imposed on the total or partial execution times of any process



Process
(Short-term) process states

- A process can be not running for different reasons
  - so, one should identify the possible process states
- The most important are:
  - run – the process is in possession of a processor, and thus running
  - blocked – the process is waiting for the occurrence of an external event (access to a resource, end of an input/output operation, etc.)
  - ready – the process is ready to run, but waiting for the availability of a processor to start/resume its execution
- Transitions between states usually result from external intervention, but, in some cases, can be triggered by the process itself
- The part of the operating system that handles these transitions is called the (processor) scheduler, and is an integral part of its kernel
  - Different policies exist to control the firing of these transitions
  - They will be covered a few sessions later

Process
Short-term state diagram

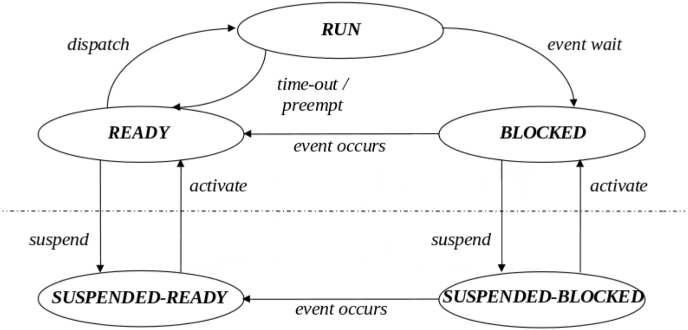


- event wait – the running process is prevented to proceed, awaiting the occurrence of an external event
- dispatch – one of the processes ready to run is selected and is given the processor
- event occurs – an external event occurred and the process waiting for it must now wait for the processor
- preempt – a higher priority process get ready to run, so the running process is removed from the processor
- time-out – the time quantum assigned to the running process get to the end, so the process is removed from the processor

Process
Medium-term states

- The main memory is finite, which limits the number of coexisting processes
- A way to overcome this limitation is to use an area in secondary memory to extend the main memory
  - This is called *swap area* (can be a disk partition or a file)
  - A non running process, or part of it, can be swapped out, in order to free main memory for other processes
  - That process will be later on swapped in, after main memory becomes available
- Two new states should be added to the process state diagram to incorporate these situations:
  - suspended-ready – the process is ready but swapped out
  - suspended-blocked – the process is blocked and swapped out

Process
State diagram, including short- and medium-term states

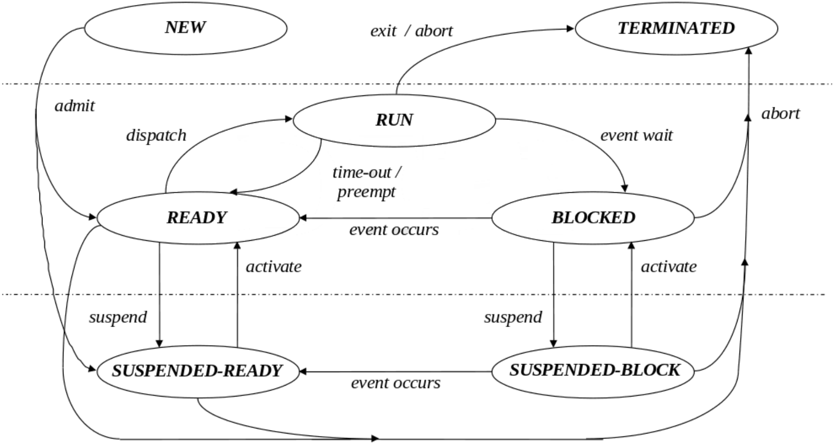


- Two new transitions appear:
  - suspend – the process is *swapped out*
  - activate – the process is *swapped in*

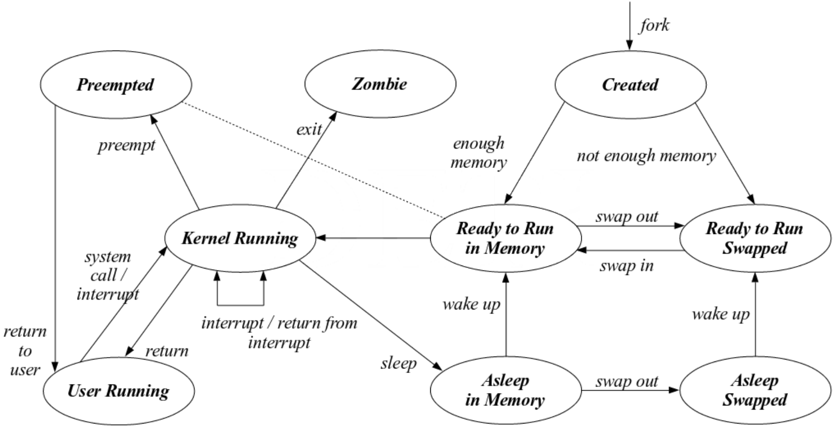
Process
Long-term states and transitions

- The previous state diagram assumes processes are timeless
  - Apart from some system processes this is not true
  - Processes are created, exist for some time, and eventually terminate
- Two new states are required to represent creation and termination
  - new – the process has been created but not yet admitted to the pool of executable processes (the process data structure is been initialized)
  - terminated – the process has been released from the pool of executable processes, but some actions are still required before the process is discarded
- three new transitions exist
  - admit – the process is admitted (by the OS) to the pool of executable processes
  - exit – the running process indicates the OS it has completed
  - abort – the process is forced to terminate (because of a fatal error or because an authorized process aborts its execution)

Process
Global state diagram

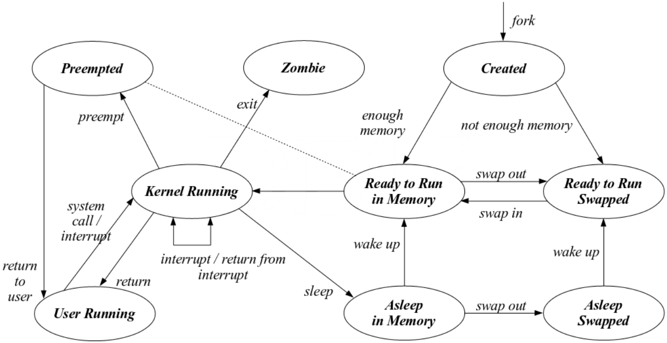


Process
Typical Unix state diagram



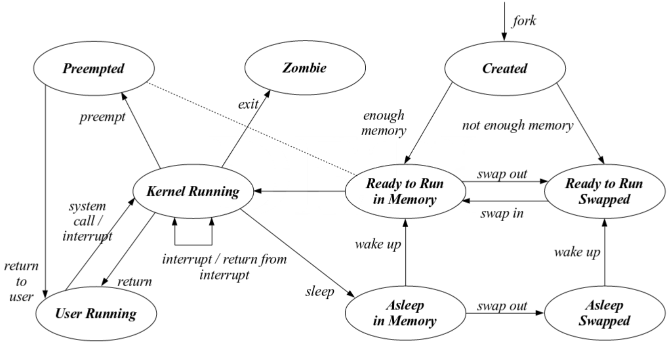
Process

Typical Unix state diagram (2)



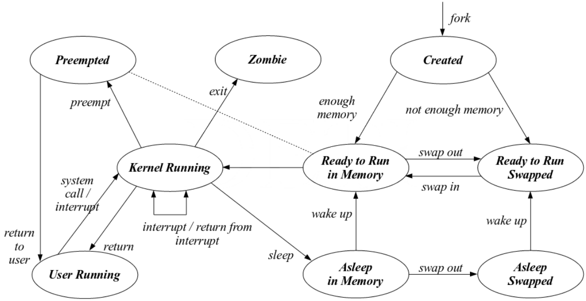
- There are two run states, kernel running and user running, associated to the processor running mode, supervisor and user, respectively
- The ready state is also splitted in two states, ready to run in memory and preempted, but they are equivalent, as indicated by the dashed line

Process
Typical Unix state diagram (3)



- When a user process leaves supervisor mode, it can be preempted (because a higher priority process is ready to run)
- In practice, processes in ready to run in memory and preempted shared the same queue, thus are treated as equal
- The time-out transition is covered by the preempt one

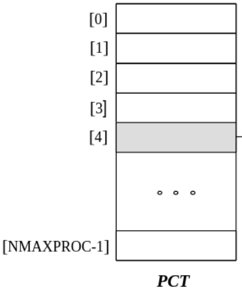
Process
Typical Unix state diagram (4)



- Tradicionally, execution in supervisor mode could not be interrupted (thus UNIX does not allow real time processing)
- In current versions, namely from SVR4, the problem was solved by dividing the code into a succession of atomic regions between which the internal data structures are in a safe state and therefore allowing execution to be interrupted
- This corresponds to a transition between the preempted and kernel running states, that could be called return to kernel

Process
Process control table

- To implement the process model, the operating systems needs a data structure to be used to store the information about each process – process control block
- The process control table (PCT), which can be seen as an array of process control blocks, stores information about all processes



identification – of process, parent, user and user's group

address space – location of code, data and stack (in memoty or swapping area)

processor context – internal registers (including program counter and stack pointer) when the switching occurs

I/0 context – communication channels and associated buffers

state - state of execution (run, ready, blocked, ...), priority, event

statistics - start time, CPU time, ...

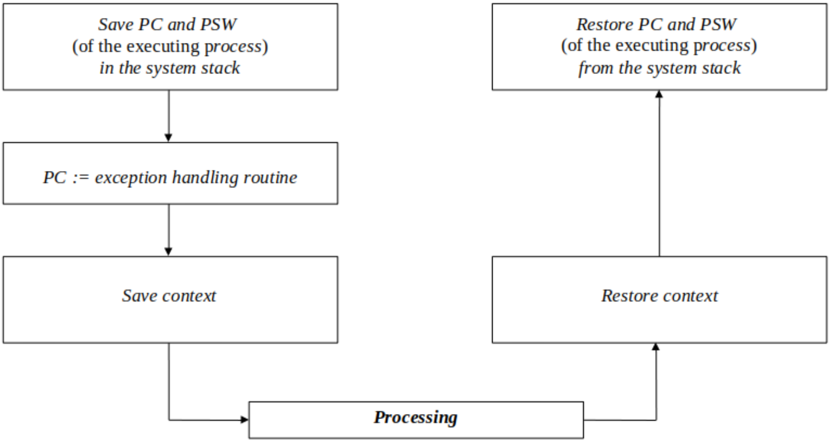
Process
Process switching

- Current processors have two functioning modes:
  - supervisor mode – all instruction set can be executed
    - is a privileged mode
  - user mode – only part of the instruction set can be executed
    - input/output instructions are excluded as well as those that modify control registers
    - it is the normal mode of operation
- Switching from user mode to supervisor mode is only possible through an exception (for security reasons)
- An exception can be caused by:
  - I/O interrupt
    - external to the execution of the current instruction
  - illegal instruction (division by zero, bus error)
    - associated with the execution of the current instruction, but not intended
  - trap instruction (software interruption)
    - associated with the execution of the current instruction, but requested

Process
Process switching (2)

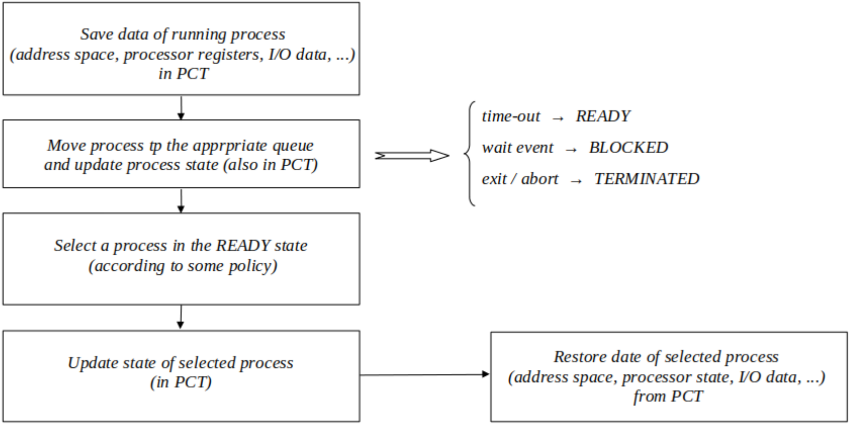
- The operating system should function in supervisor mode
  - in order to have access to all the functionalities of the processor
- Thus kernel functions (including system calls) must be fired by
  - hardware (interrupt)
  - trap (software interruption)
- This establishes a uniform operating environment: exception handling
- Process switching occurs necessarely in the context of an exception, with a small difference on how it is handle

Process
Processing a (normal) exception

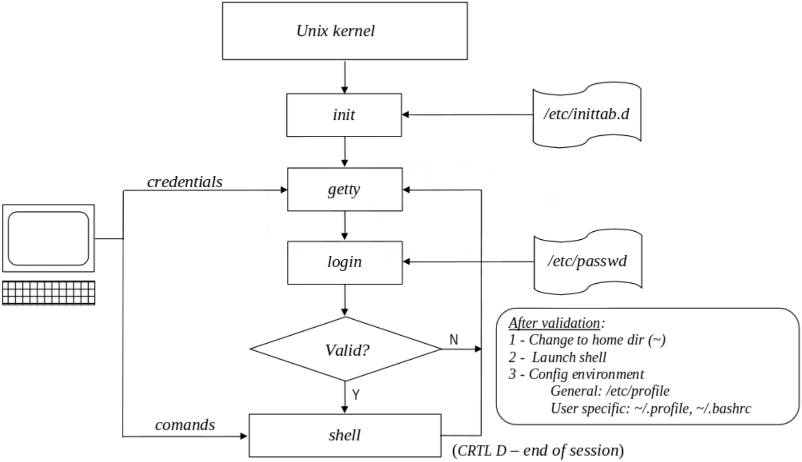


Process

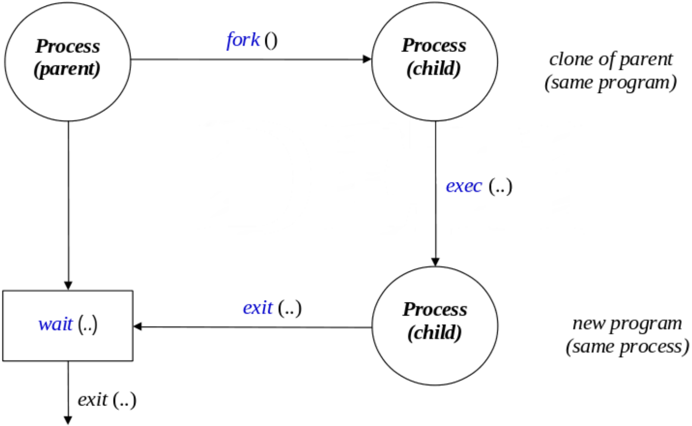
Processing a process switching



Processes in Unix
Traditional login



Processes in Unix
Creation by cloning



Processes in Unix

Process creation: fork1

```c
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <unistd.h>

int main(void)
{
  printf("Before the fork:\n");
  printf("  PID = %d, PPID = %d.\n",
      getpid(), getppid());

  fork();

  printf("After the fork:\n");
  printf("  PID = %d, PPID = %d\n"
      " Am I the parent or the child?"
      " How can I know it?\n",
         getpid(), getppid());

  return EXIT_SUCCESS;
}
```

- The fork clones the executing process, creating a replica of it
- The address spaces of the two processes are equal
  - actually, just after the fork, they are the same
  - typically, a copy on write approach is followed
- The states of execution are the same
  - including the program counter
- Some process variables are different (PID, PPID, ...)

- What can we do with this?

Processes in Unix

Process creation: `fork2` and `fork3`

```c
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <unistd.h>

int main(void)
{
  printf("Before the fork:\n");
  printf("  PID = %d, PPID = %d.\n",
      getpid(), getppid());

  int ret = fork();

  printf("After the fork:\n");
  printf("  PID = %d, PPID = %d.\n",
      getpid(), getppid());
  printf("  ret = %d\n", ret);

  return EXIT_SUCCESS;
}
```

- The value returned by the fork is different in parent and child processes
  - in the parent, it is the PID of the child
  - in the child, it is always 0

Processes in Unix

Process creation: fork2 and fork3

```
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <unistd.h>

int main(void)
{
  printf("Before the fork:\n");
  printf("  PID = %d, PPID = %d.\n",
      getpid(), getppid());

  int ret = fork();

  if (ret == 0)
  {
    printf("I'm the child:\n");
    printf("  PID = %d, PPID = %d\n",
        getpid(), getppid());
  }
  else
  {
    printf("I'm the parent:\n");
    printf("  PID = %d, PPID = %d\n",
        getpid(), getppid());
  }

  return EXIT_SUCCESS;
}
```

- The value returned by the fork is different in parent and child processes
  - in the parent, it is the PID of the child
  - in the child, it is always 0
- This return value can be used as a boolean variable
  - so we can distinguish the code running on child and parent
- Still, what can we do with it?

Processes in Unix

Process creation: `fork3`

```c
#include <stdio.h>
#include <stdlib.h>
#include <sys/types.h>
#include <unistd.h>

int main(void)
{
  printf("Before the fork:\n");
  printf("  PID = %d, PPID = %d.\n",
      getpid(), getppid());

  int ret = fork();

  if (ret == 0)
  {
    printf("I'm the child:\n");
    printf("  PID = %d, PPID = %d\n",
        getpid(), getppid());
  }
  else
  {
    printf("I'm the parent:\n");
    printf("  PID = %d, PPID = %d\n",
        getpid(), getppid());
  }

  return EXIT_SUCCESS;
}
```

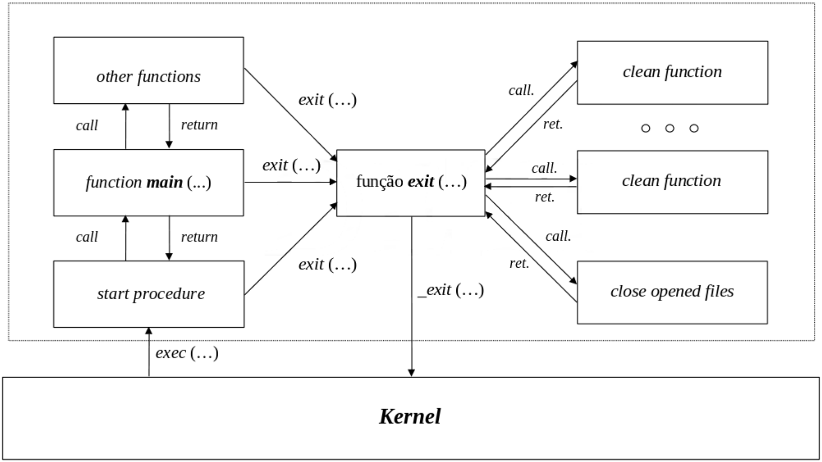
- In general, used alone, the fork is of little interest
- In general, we want to run a different program in the child
  - exec system call
  - there are different versions of exec
- Sometimes, we want the parent to wait for the conclusion of the program running in the child
  - wait system call
- *In this code, we are assuming the* `fork` *doesn't fail*
  - *in case of an error, it returns* -1

Process creation in Unix

Launching a program: `fork + exec`

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <sys/types.h>
#include <sys/wait.h>

int main(int argc, char *argv[])
{
  /* check arguments */
  if (argc != 2)
  {
    fprintf(stderr, "launch <<cmd>>\n");
    exit(EXIT_FAILURE);
  }
  char *aplic = argv[1];

  printf("===================\n");

  /* clone phase */
  int pid;
  if ((pid = fork()) < 0)
  {
    perror("Fail cloning process");
    exit(EXIT_FAILURE);
  }

  /* exec and wait phases */
  if (pid != 0) // only runs in parent process
  {
    int status;
    while (wait(&status) == -1);
    printf("=================\n");
    printf("Process %d (child of %d)"
           " ends with status %d\n",
        pid, getpid(), WEXITSTATUS(status));
  }
  else // this only runs in the child process
  {
    execl(aplic, aplic, NULL);
    perror("Fail launching program");
    exit(EXIT_FAILURE);
  }

  exit(EXIT_SUCCESS); // or return EXIT_SUCCESS
}
```

Processes in Unix
Execution of a C/C++ program



Processes in Unix

Executing a C/C++ program: atexit

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <assert.h>

/* cleaning functions */
static void atexit_1(void)
{
    printf("atexit 1\n");
}

static void atexit_2(void)
{
    printf("atexit 2\n");
}

/* main programa */
int main(void)
{
    /* registering at exit functions */
    assert(atexit(atexit_1) == 0);
    assert(atexit(atexit_2) == 0);

    /* normal work */
    printf("hello world 1!\n");

    for (int i = 0; i < 5; i++) sleep(1);

    return EXIT_SUCCESS;
}
```

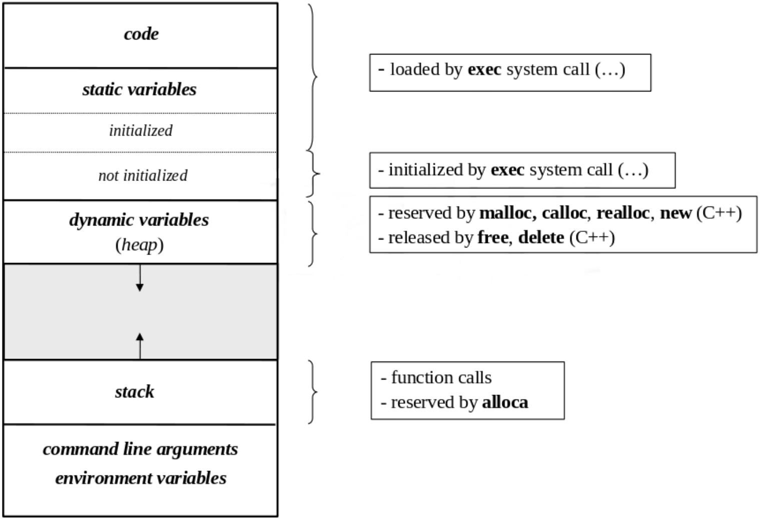
- The atexit function allows to register a function to be called at the program's normal termination
- They are called in reverse order relative to their register
- *What happens if the termination is forced?*

Processes in Unix
Command line arguments and environment variables

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

int main(int argc, char *argv[], char *env[])
{
    /* printing command line arguments */
    printf("Command line arguments:\n");
    for (int i = 0; argv[i] != NULL; i++)
    {
        printf("  %s\n", argv[i]);
    }

    /* printing all environment variables */
    printf("\nEnvironment variables:\n");
    for (int i = 0; env[i] != NULL; i++)
    {
        printf("  %s\n", env[i]);
    }

    /* printing a specific environment variable */
    printf("\nEnvironment variable:\n");
    printf("  env[\"HOME\"] = \"%s\"\n", getenv("HOME"));
    printf("  env[\"zzz\"] = \"%s\"\n", getenv("zzz"));

    return EXIT_SUCCESS;
}
```

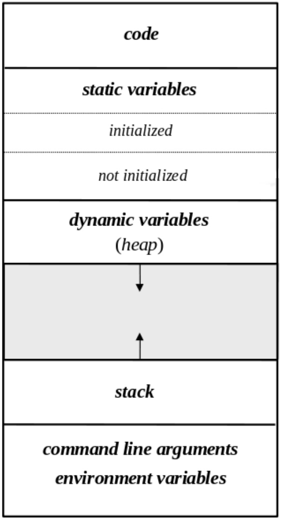
- argv is an array of strings
- argv[0] is the program reference
- env is an array of strings, each representing a variable, in the form name-value pair
- getenv returns the value of a variable name

Processes in Unix
Address space of a Unix process



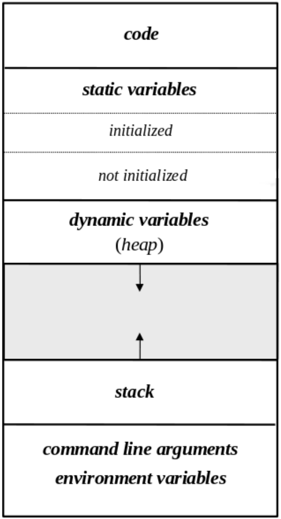
Processes in Unix

Address space of a Unix process (2)




```
int n1 = 1;
static int n2 = 2;
int n3;
static int n4;
int n5;
static int n6 = 6;

int main(int argc, char *argv[], char *env[])
{
    extern char** environ;
    static int n7;
    static int n8 = 8;
    int *p9 = (int*)malloc(sizeof(int));
    int *p10 = new int;
    int *p11 = (int*)alloca(sizeof(int));
    int n12;
    int n13 = 13;
    int n14;
    printf("\ngetenv(n0): %p\n", getenv("n0"));
    printf("\nargv: %p\nenviron: %p\nenv: %p\nmain: %p\n\n",
           argv, environ, env, main);
    printf("\n&argc: %p\n&argv: %p\n&env: %p\n",
           &argc, &argv, &env);
    printf("&n1: %p\n&n2: %p\n&n3: %p\n&n4: %p\n&n5: %p\n"
           "&n6: %p\n&n7: %p\n&n8: %p\nn9: %p\nn10: %p\n"
           "p11: %p\n&n12: %p\n&n13: %p\n&n14: %p\n",
           &n1, &n2, &n3, &n4, &n5, &n6, &n7, &n8,
           p9, p10, p11, &n12, &n13, &n14);
```

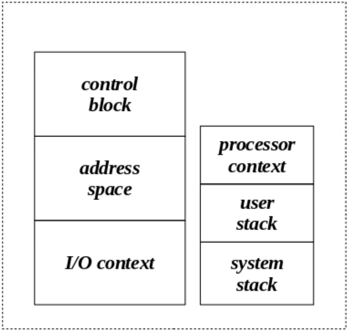
Processes in Unix
Address space of a Unix process (3)




```c
#include    <stdio.h>
#include    <stdlib.h>
#include    <unistd.h>
#include    <wait.h>

int n01 = 1;

int main(int argc, char *argv[], char *env[])
{
    int pid = fork();
    if (pid != 0)
    {
        fprintf(stderr, "%5d: n01 = %-5d (%p)\n",
                pid, n01, &n01);
        wait(NULL);
        fprintf(stderr, "%5d: n01 = %-5d (%p)\n",
                pid, n01, &n01);
    }
    else
    {
        fprintf(stderr, "%5d: n01 = %-5d (%p)\n",
                pid, n01, &n01);
        n01 = 1111;
        fprintf(stderr, "%5d: n01 = %-5d (%p)\n",
                pid, n01, &n01);
    }
    return 0;
}
```

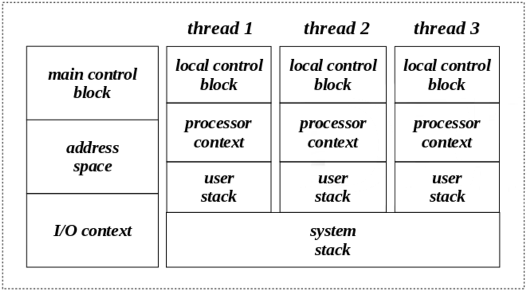
Threads
Single threading

- 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

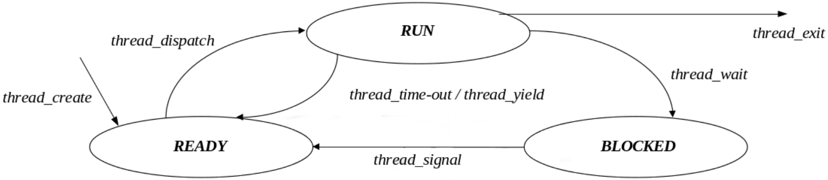
Threads
Multithreading



Multithreading

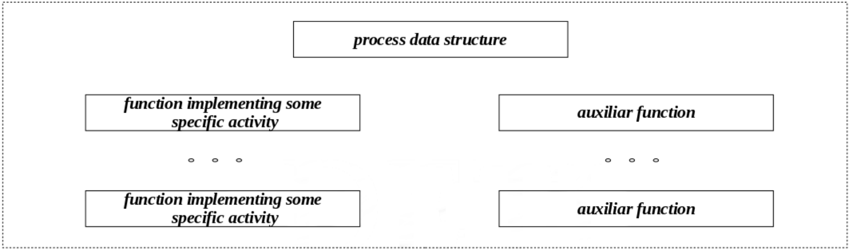
- Several independent threads can coexist in the same process, thus sharing the same address space and the same I/O context
  - This is referred to as *multithreading*
- Threads can be seen as *light weight processes*

Threads
State diagram of a thread



- Only states concerning the management of the processor are considered (short-term states)
- states suspended-ready and suspended-blocked are not present:
  - they are related to the process, not to the threads
- states new and terminated are not present:
  - the management of the multiprogramming environment is basically related to restrict the number of threads that can exist within a process

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
- 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

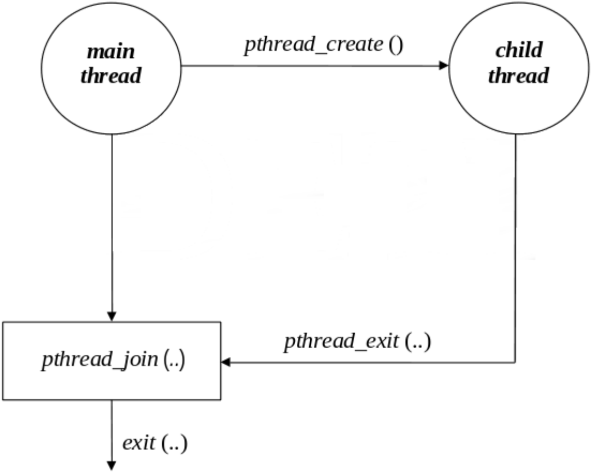
- easier implementation of applications – in many applications, decomposing the solution into a number of parallel activities makes the programming model simpler
  - since the address space and the I/O context is shared among all threads, multithreading favors this decomposition.
- better management 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 fork
  - clone – creates a new process that can share elements with its parent
    - address space, table of file descriptors, and table of signal handlers, for example, are shareable.
    - the child starts execution in a given 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()`

Threads in linux

Thread creation and termination – `pthread` library



Threads in linux
Thread creation and termination – example

```c
#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);
}
```

```c
/* 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;
}
```

Bibliography

- Operating Systems: Internals and Design Principles, W. Stallings, Prentice-Hall International Editions, 7th Ed, 2012
  - Chapter 3: Process Description and Control (sections 3.1 to 3.5 and 3.7)
  - Chapter 4: Threads (sections 4.1, 4.2 and 4.6)
- Operating Systems Concepts, A. Silberschatz, P. Galvin and G. Gagne, John Wiley & Sons, 9th Ed, 2013
  - Chapter 3: Processes (sections 3.1 to 3.3)
  - Chapter 4: Threads (sections 4.1 and 4.4.1)
- Modern Operating Systems, A. Tanenbaum and H. Bos, Pearson Education Limited, 4th Ed, 2015
  - Chapter 2: Processes and Threads (sections 2.1 and 2.2)