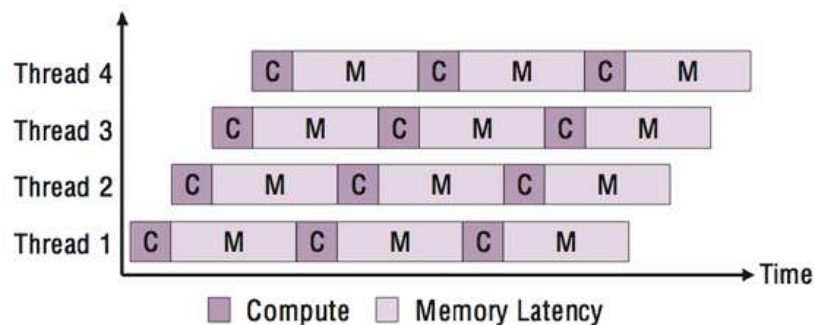


Programação Avançada (ProgA)

Threads

Patrício Domingues
ESTG/Politécnico de Leiria



✓ Binary (*executable*)

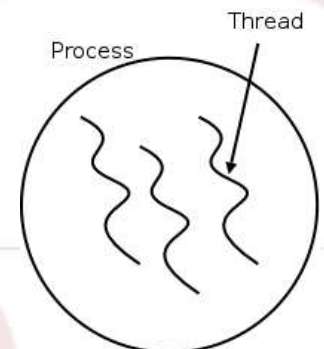
- programs residing on a storage medium, compiled to a format accessible by a given operating system and machine architecture, ready to execute

✓ Process

- Program/binary in execution
 - Loaded binary in memory controlled by the operating system
 - Abstraction of a running program

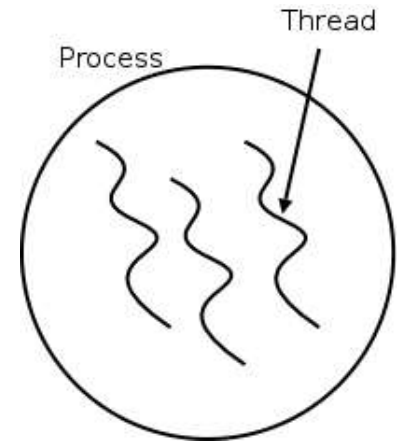
✓ Threads

- Unit of execution within a process
 - Virtualized processor, stack and state



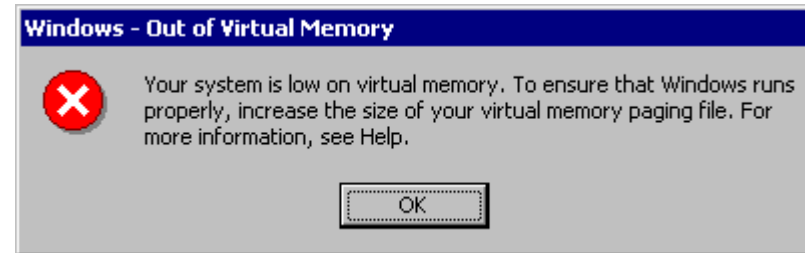
Processes and threads (1)

- ✓ A process contains one or more threads
 - Process containing only one thread
 - Single threaded process
 - Process containing several threads
 - Multithreaded process
- ✓ A thread only exists within the context of a process
 - When a process ends, all of its threads also terminate
 - A thread is the basic unit to which the OS allocates CPU time



Processes and threads (2)

- ✓ An operating system provides two main abstractions for *user space*
- Virtualized processor
 - Virtualized memory



User space vs kernel space >>

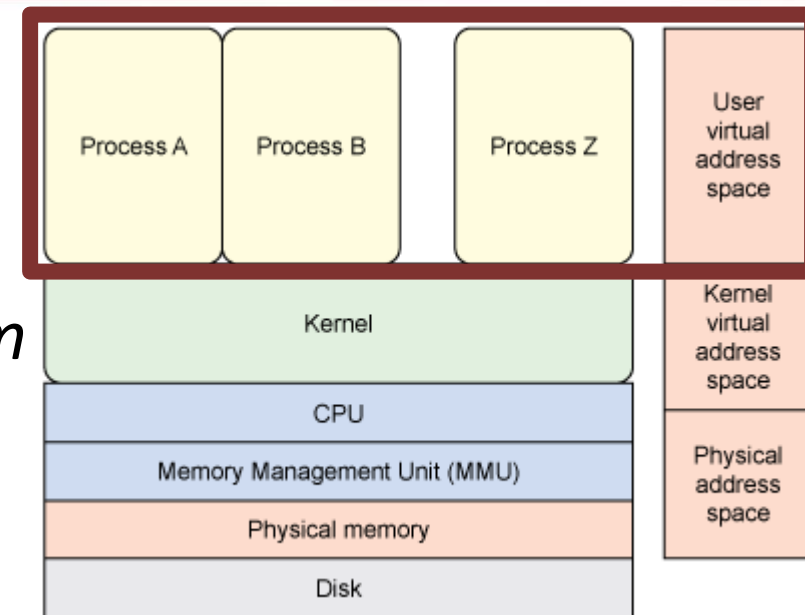
User space vs. kernel space

✓ User space

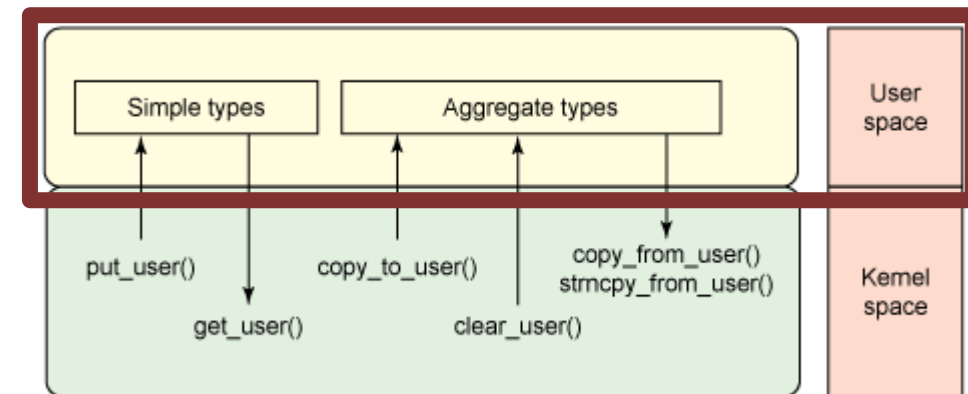
- unprivileged mode
- Process can only access memory from user space

✓ Kernel space

- Privileged mode
- Used when a process makes a system call (e.g., `write`)
- Runs kernel code



Source: <http://ibm.co/1N0Jsl3>



Source: <http://ibm.co/1XrDdtN>

- Shows all the **system calls** (aka syscalls) performed by the execution of a program

Value returned
by system call

Parameters of the call (“open” in this case)

```
File Edit Tabs Help
execve("/bin/date", ["date"], [/ * 44 vars * /]) = 0
brk(NULL) = 0x8cab000
access("/etc/ld.so.nohwcap", F_OK) = -1 ENOENT (No such file or directory)
mmap2(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0xb774c000
access("/etc/ld.so.preload", R_OK) = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat64(3, {st_mode=S_IFREG|0644, st_size=79027, ...}) = 0
mmap2(NULL, 79027, PROT_READ, MAP_PRIVATE, 3, 0) = 0xb7738000
close(3) = 0
access("/etc/ld.so.nohwcap", F_OK) = -1 ENOENT (No such file or directory)
open("/lib/i386-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\1\1\1\3\0\0\0\0\0\0\0\0\3\0\3\0\1\0\0\0\320\207\1\0004\0\0\0".., 512) = 512
fstat64(3, {st_mode=S_IFREG|0755, st_size=1786484, ...}) = 0
mmap2(NULL, 1792572, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0xb7582000
mprotect(0xb7731000, 4096, PROT_NONE) = 0
mmap2(0xb7732000, 12288, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1af000) = 0xb7732000
mmap2(0xb7735000, 10812, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0xb7735000
close(3) = 0
```


Vertical bar
“|” is
binary OR

The ltrace tool

✓ The ltrace tool

- Shows all the calls of a process to functions of dynamic libraries

- Example: `ltrace date`



```
user@ubuntu: ~  
File Edit Tabs Help  
__libc_start_main(0x8049350, 1, 0xbfe1f984, 0x80520e0 <unfinished ...>  
strchr("date", '/') = nil  
setlocale(LC_ALL, "") = "en_US.UTF-8"  
bindtextdomain("coreutils", "/usr/share/locale") = "/usr/share/locale"  
textdomain("coreutils") = "coreutils"  
__cxa_atexit(0x804a610, 0, 0, 0xbfe1f984) = 0  
getopt_long(1, 0xbfe1f984, "d:f:I::r:Rs:u", 0x8053760, nil) = -1  
nl_langinfo(0x2006c, 0xb766e2c0, 0x80484dc, 0xbfe1f898) = 0xb74a6295  
getenv("TZ") = nil  
malloc(64) = 0x94df860  
clock_gettime(0, 0xbfe1f854, 0, 2) = 0  
localtime(0xbfe1f7e8) = 0xb76c4740  
strftime(" Sun", 1024, " %a", 0xb76c4740) = 4  
fwrite("Sun", 3, 1, 0xb76c1d60) = 1  
fputc(' ', 0xb76c1d60) = 32  
strftime(" Sep", 1024, " %b", 0xb76c4740) = 4  
fwrite("Sep", 3, 1, 0xb76c1d60) = 1  
fputc('/', 0xb76c1d60) = 33
```

✓ Virtualized processor

- When executing, a process *thinks* that the CPU is solely for it
 - The process is not and needs not to be aware of *multitasking*
- The system can have 100 or (much) more processes running, but each single process **needs not** to be aware of the other processes
- A programmer develops its application without the need to care for other processes

Virtualized memory >>

Virtual memory

- ✓ Each process has a unique view of memory
 - The system's RAM contains the data of many different running processes
 - Each process sees virtual memory all of its
- ✓ Virtualized memory is associated with the process and not the thread
 - Each process has a unique view of memory
 - All threads of a given process share the process's memory space

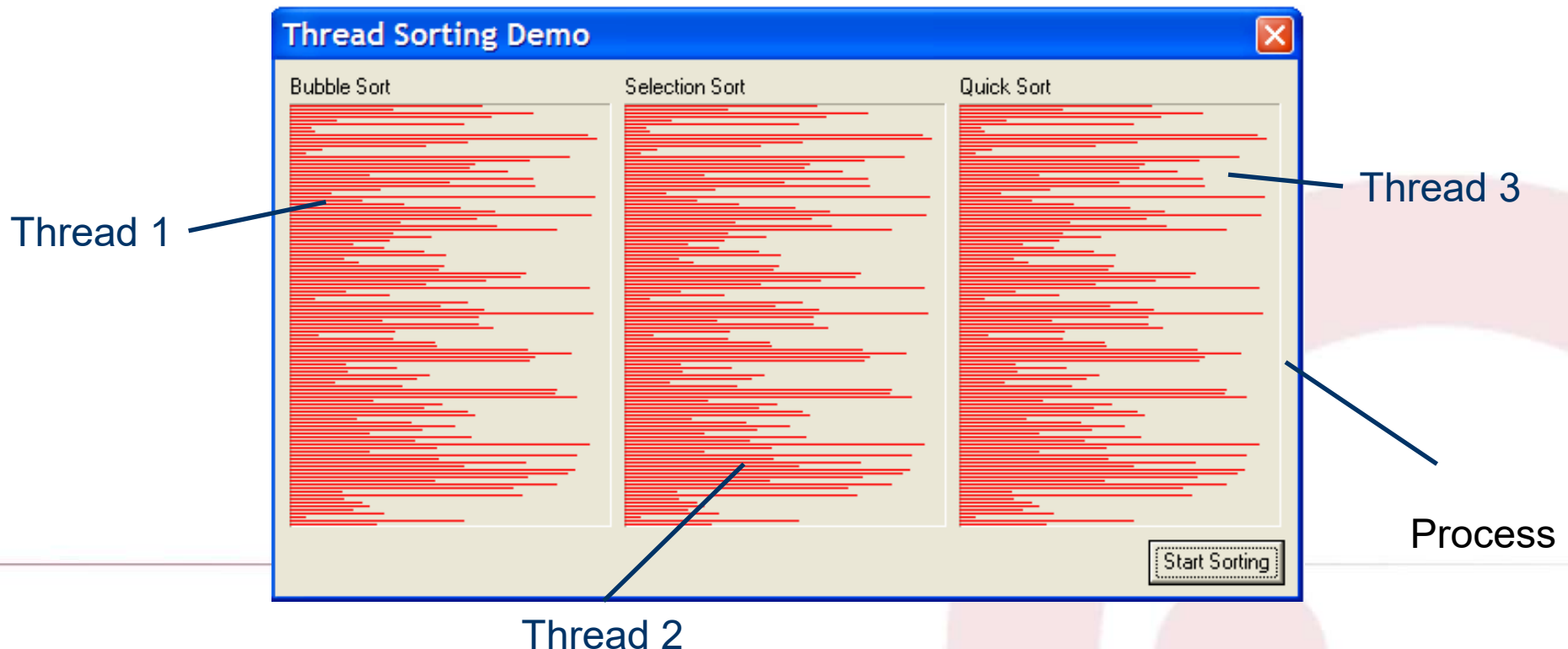
THREADS



What is a *thread*?

✓ Definition in the dictionary

- “thread”: a fine cord of twisted fibers (of cotton or silk or wool or nylon, etc.) used in sewing and weaving
- Portuguese: «linha de coser», etc.
 - Not the right definition for an operating system point of view



Why *multithreading*? (1)

- ✓ Five primary benefits of using threads/multithreading
 - Programming abstraction
 - Dividing up work and assigning each division to a unit of execution (a thread) is a natural approach to many problems
 - Parallelism
 - In machines with multiple processors/cores, threads provide an efficient way to achieve *true* parallelism
 - Improving responsiveness
 - In a single-threaded process, a long-running operation can prevent an application from responding to user input. The application appears “frozen”
 - In a multi-threaded process, a specific thread can be set to deal with user input

Why *multithreading*? (2)

- ✓ Five primary benefits of using threads (continued)
 - Blocked I/O
 - Without threads, blocking I/O (e.g, waiting for user input or for data from a remote communication) halts the entire process
 - In a multithreaded process, individual threads may block, waiting on I/O, while other threads continue to make forward progress
 - The whole application is not blocked!
 - Context switching
 - Cost of switching from one thread to a different thread within the same process is significantly cheaper than process-to-process context switching
 - Threads of a same process share the same memory address space

✓ Responsive application

– Application which...

- Performs intense and somewhat long CPU computation
 - Example: Image processing (“CPU bound”)
- While it is performing an image processing operation, it is welcome to update the user interface
 - Example: progress bar, responsive “cancel” button
- This can be done with a specially dedicated thread

✓ Example: word processor

- One thread to deal with user input
- One thread to paginate the document
- One thread to open/save a document
- Another thread to run the spell checker and underline unknown words
- ...

HEISENBUGS VS. BOHRBUGS



Challenges of multithreading

✓ Multithreading has its own challenges

- Multithread means to have several threads of the same process potentially accessing the same data
- Concurrency-related bugs



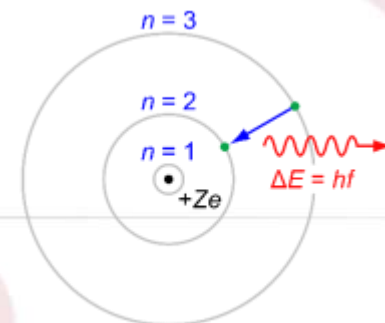
(Nobel prize in physics 1932)

- *Heisenbugs* (from the quantum theory of W. Heisenberg)
 - Bugs due to concurrency problems that manifest themselves in a non-deterministic way
 - » An heisenbug can manifest itself 1 out of 100 runs
 - » Hard to debug (it disappears or alter its behavior when one attempts to probe or isolate it)



(Nobel prize in physics 1922)

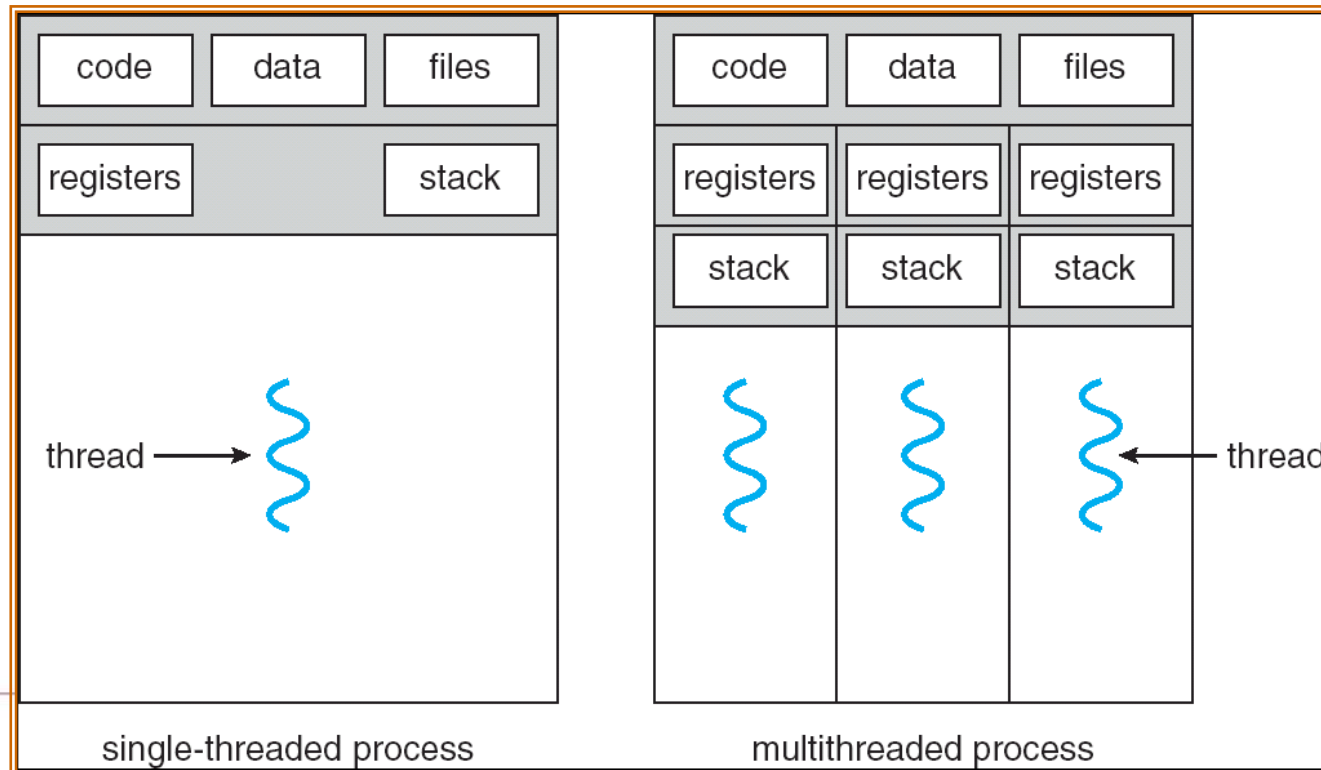
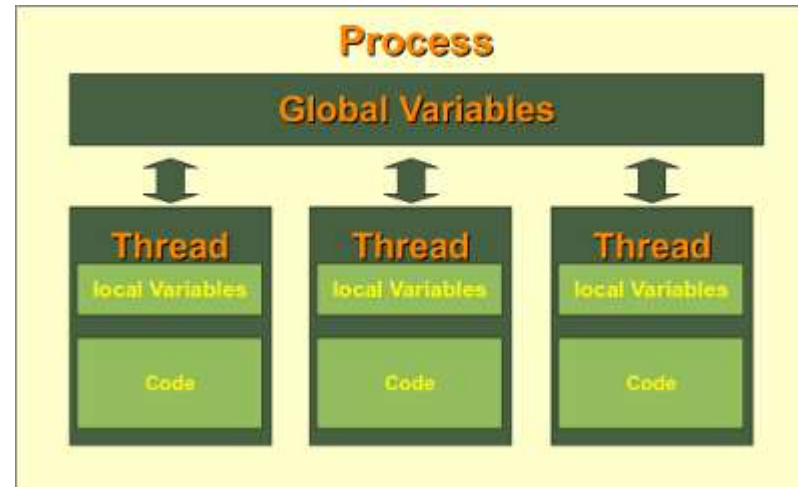
- Bohrbugs (from Niels Bohr's atom model)
 - Deterministic bugs that always occur when the program is run
- See: <https://en.wikipedia.org/wiki/Heisenbug>



threads

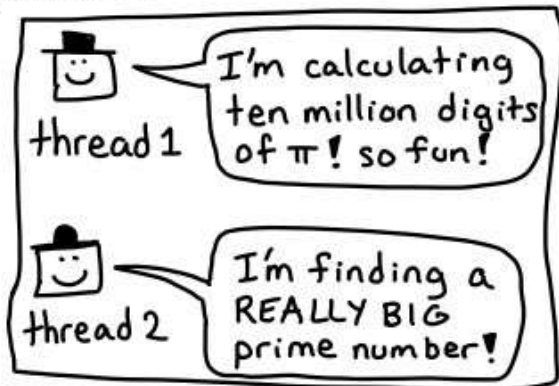
- ✓ A thread always belongs to a process!
- ✓ Private elements - each thread has its own:
 - Program counter (PC)
 - registers
 - Stack segment
- ✓ Shared elements (threads of a same process)
 - Text segment (code of the program)
 - Address space
 - Data segment (e.g., global variables)
 - Files, signal handlers, etc.

Processes and threads

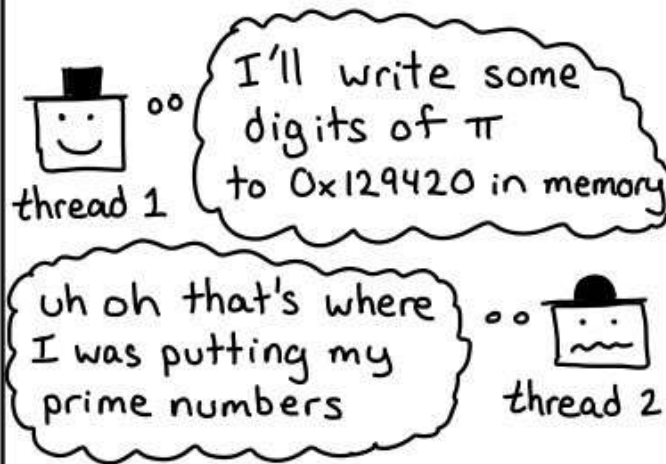


Threads let a process do many different things at the same time

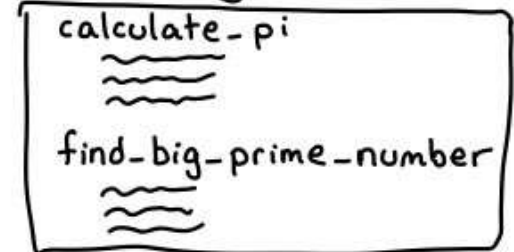
process:



threads in the same process share memory



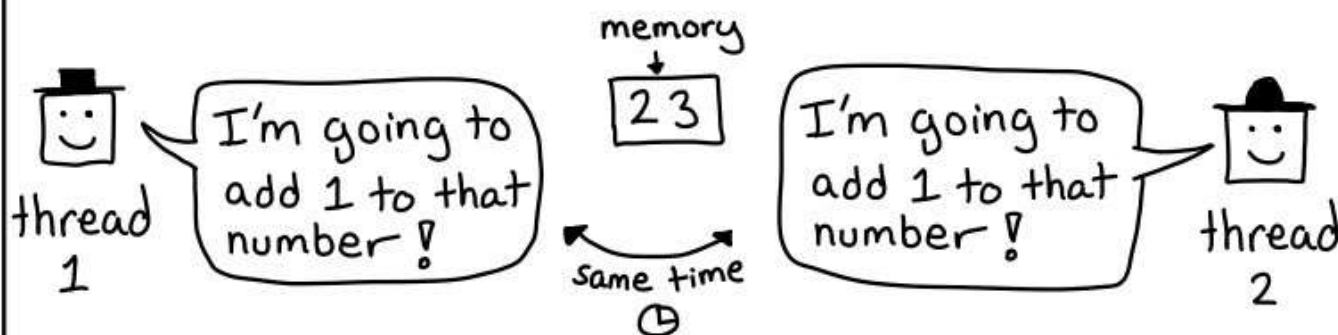
and they share code



but each thread has its own stack and they can be run by different CPUs at the same time



sharing memory can cause problems (race conditions!)



RESULT: 24 ^{WRONG.} Should be 25!

why use threads instead of starting a new process?

→ a thread takes less time to create

→ sharing data between threads is very easy. But it's also easier to make mistakes with threads



Threads in Linux

✓ Info about threads in Linux

– `ps aux -L` or `ps axms`

- `nlwp`: number of threads per process
 - `lwp`: lightweight process

```
user@so-pa-vm:~$ ps aux -L | grep snapd
```

root	18572	18572	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18589	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18590	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18591	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18592	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18593	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18605	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:01	/usr/lib/snapd/snapd
root	18572	18607	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:02	/usr/lib/snapd/snapd
root	18572	18608	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18681	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18683	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	18714	0.0	13	1.5	1022280	36392	?	Ssl	14:09	0:00	/usr/lib/snapd/snapd
root	18572	19006	0.0	13	1.5	1022280	36392	?	Ssl	14:10	0:00	/usr/lib/snapd/snapd



`nlwp` – “number of lightweight processes”

A NORMA PTHREAD



✓ *pthread* standard - *POSIX* thread

```
void* thread_slow(void *arg){ //arg is not used
    while(1){
        printf("Hi! I'm the slow thread...");
        sleep(3);
    }
}

void* thread_fast(void*arg){ //arg is not used
    while(1) {
        printf("Hi! I'm the fast thread...");
        sleep(1);
    }
}

int main(int argc, char **argv){
    pthread_t thr_slow, thr_fast;
    /* Create two threads */
    pthread_create(&thr_slow, NULL, thread_slow, NULL);
    pthread_create(&thr_fast, NULL, thread_fast, NULL);
    /* call pthread_join for each created thread */
}
```

Output of the example

```
$. /thread_demo  
Hi! I'm the slow thread...  
Hi! I'm the fast thread...  
Hi! I'm the fast thread...  
Hi! I'm the fast thread...  
Hi! I'm the slow thread...  
Hi! I'm the fast thread...  
Hi! I'm the fast thread...  
Hi! I'm the fast thread...  
Hi! I'm the slow thread...  
Hi! I'm the fast thread...  
Hi! I'm the fast thread...
```


✓ PThreads

- POSIX standard (IEEE 1003.1c)
 - API (Application Programming Interface) for threads
- The API specifies the behavior of the functions
 - What each function is supposed to do
- The implementation is free
 - The how is done does not matter for the standard
- Pthreads is available in UNIX platforms
 - Linux, Mac OS X, BSD, Solaris
- It also exists for windows



Pthreads
Win32



✓ Data types

- `pthread_t`: handle to a thread
- `pthread_attr_t`: thread attributes

✓ Handling functions (create, etc.)

- `pthread_create()`: create a thread
- `pthread_exit()`: terminate current thread
- `pthread_cancel()`: cancel execution of another thread
- `pthread_join()`: block current thread until another one terminates
- `pthread_attr_init()`: initialize thread attributes
- `pthread_attr_setdetachstate()`: set the detachstate attribute (whether thread can be joined on termination)
- `pthread_attr_getdetachstate()`: get the detachstate attribute
- `pthread_attr_destroy()`: destroy thread attributes
- `pthread_kill()`: send a signal to a thread

**IPL**

escola superior de tecnologia e gestão
instituto politécnico de leiria

Pthreads standard (2)

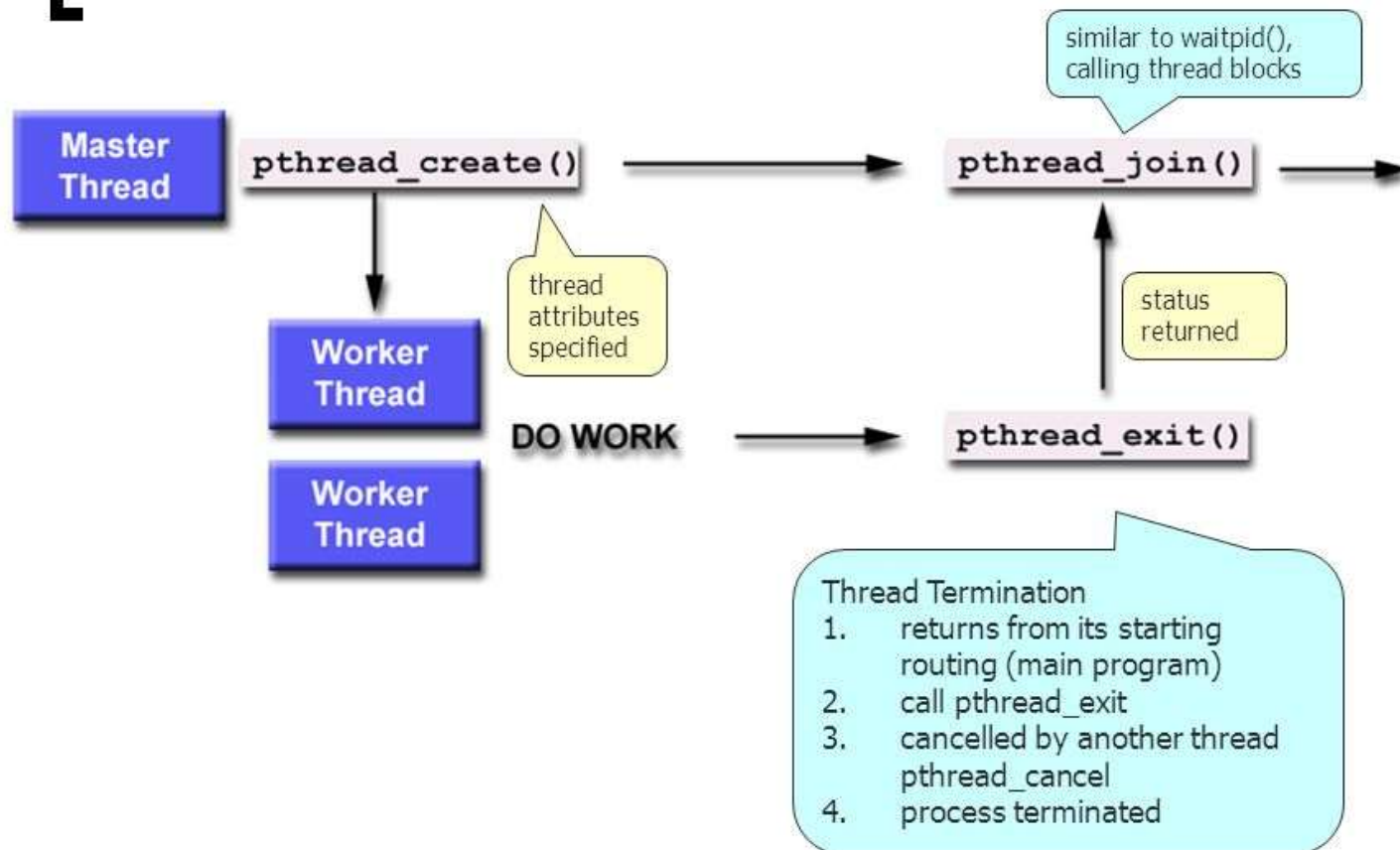


✓ Synchronization functions

- `pthread_mutex_init()` initialize mutex lock
- `pthread_mutex_destroy()`
- `pthread_mutex_lock()`: acquire mutex lock (blocking)
- `pthread_mutex_trylock()`: acquire mutex lock (non-blocking)
- `pthread_mutex_unlock()`: release mutex lock
- `pthread_cond_init()`
- `pthread_cond_destroy()`
- `pthread_cond_signal()`: signal a condition
- `pthread_cond_wait()`: wait on a condition

Lifecycle of a *pthread*

Thread Lifecycle – joinable thread



- ✓ Time need to create a process vs. a thread
 - Real – *elapsed time* or wallclock time
 - User – time spent by the CPU in **user mode**
 - Sys – time spent in **system/kernel mode**



Time (seconds) in several machines for creating 50000 processes/threads

Platform	fork()			pthread_create()		
	real	user	sys	real	user	sys
AMD 2.3 GHz Opteron (16cpus/node)	12.5	1.0	12.5	1.2	0.2	1.3
AMD 2.4 GHz Opteron (8cpus/node)	17.6	2.2	15.7	1.4	0.3	1.3
IBM 4.0 GHz POWER6 (8cpus/node)	9.5	0.6	8.8	1.6	0.1	0.4
IBM 1.9 GHz POWER5 p5-575 (8cpus/node)	64.2	30.7	27.6	1.7	0.6	1.1
IBM 1.5 GHz POWER4 (8cpus/node)	104.5	48.6	47.2	2.1	1.0	1.5
INTEL 2.4 GHz Xeon (2 cpus/node)	54.9	1.5	20.8	1.6	0.7	0.9
INTEL 1.4 GHz Itanium2 (4 cpus/node)	54.5	1.1	22.2	2.0	1.2	0.6

source: https://computing.llnl.gov/tutorials/pthreads/fork_vs_thread.txt

C11 – C standard (2011)

- ✓ C11 adds support for multithreading to the C language
- ✓ file `.h` **<threads.h>**
 - Functions to handle threads (create, join,...)
 - Mutexes and condition variables
 - Qualifier “*_Atomic*”
 - Qualifier “*_Thread_local*”
 - A variable declared as ***_Thread_local*** is private for the thread (i.e., it is not shared with the other threads of the process)
- ✓ Many compilers still do **not** support **<threads.h>** (gcc, etc.)



C23 – Most recent C standard

- ✓ C23 is the most recent C standard
 - Official since 2024.01.01 – norma ISO/IEC 9899:2024
 - Macro `__STDC_VERSION__` = 202311L
 - But few compilers support C23
 - C23 has some (few) novelty, essentially features from C++ added to C
 - `nullptr` instead of `NULL`; `bool`, `true`, and `false`.
 - `constexpr`. Example: `constexpr int n = 10 + 4;`
 - Bit utilities (new “`<stdbit.h>`”)
 - Examples: `stdc_popcount` – counts the number of bits set to 1 in an unsigned integer.
 - Binary integer literal: `0b0001`
- ✓ Next version of the standard -- C2y -- is a work in progress...

OPENMP STANDARD



- ✓ OpenMP standard for parallelization
 - Goal is to provide for parallelization in an almost transparent way for the programmer
 - The programmer annotates the code with `#pragma` instructions

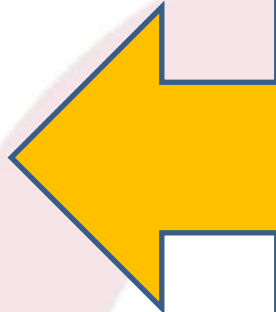
- ✓ Example

```
void main()
{
    double r[1000];

    for (int i=0; i<1000; i++) {
        large_computation(r[i]);
    }
}
```

```
void main()
{
    double r[1000];

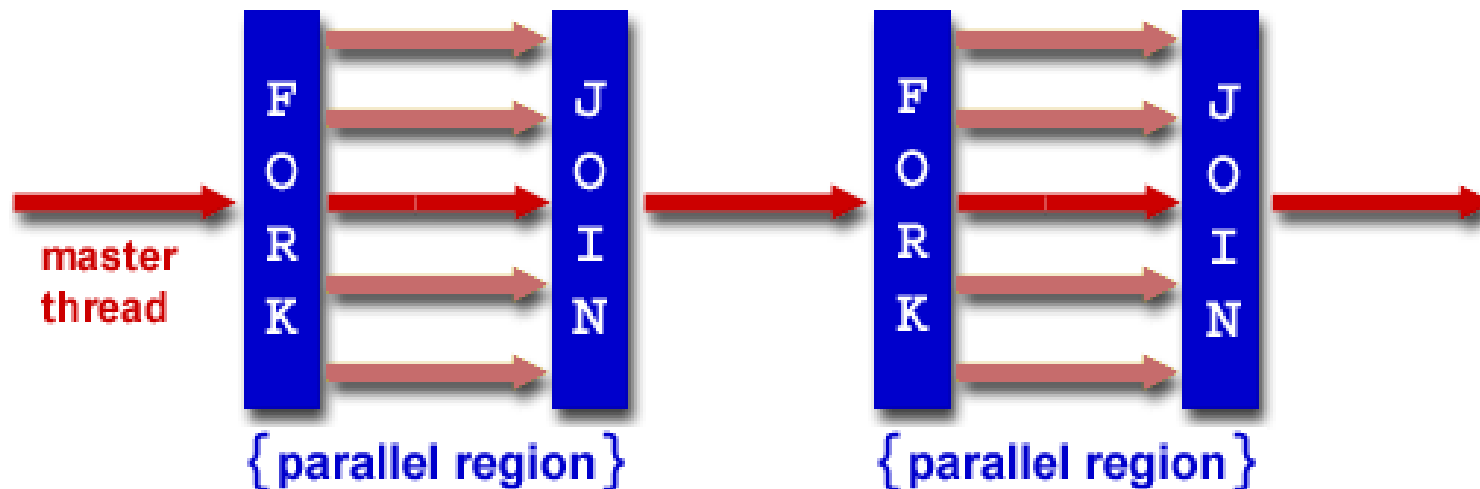
    #pragma omp parallel for
    for (int i=0; i<1000; i++) {
        large_computation(r[i]);
    }
}
```



#pragma
The compiler performs the OpenMP parallelization (manages the threads)

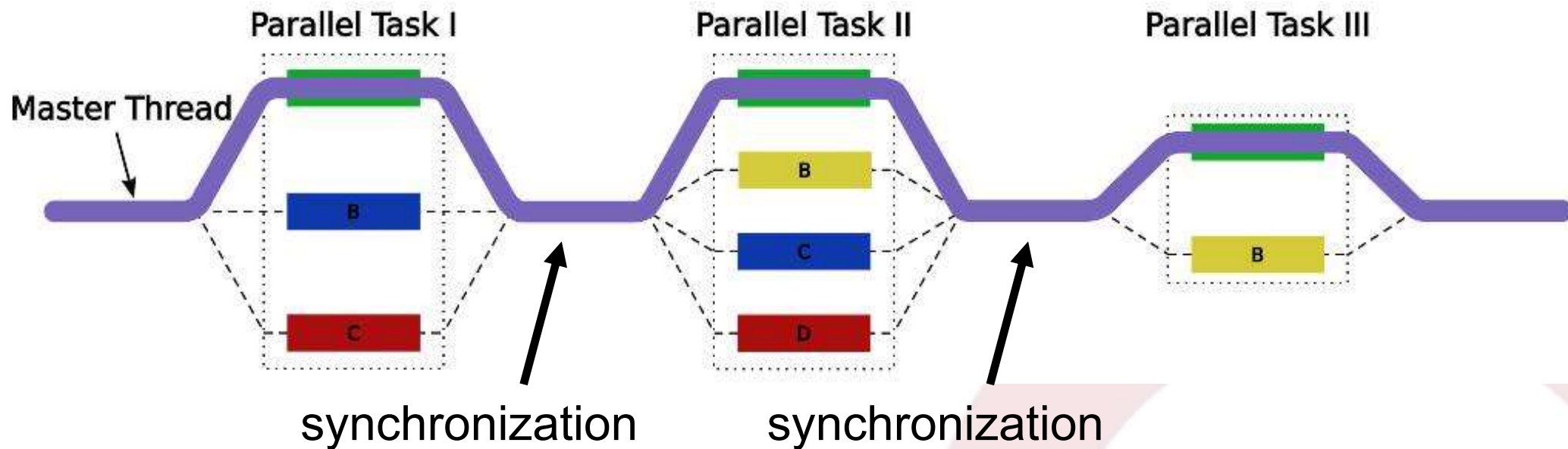
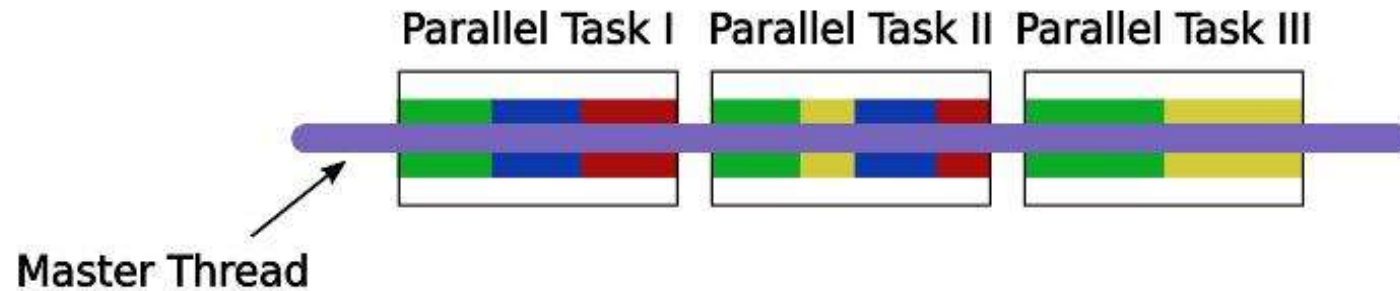
- Fork-Join Model:

- OpenMP uses the fork-join model of parallel execution:



- ♦ All OpenMP programs begin as a single process: the **master thread**. The master thread executes sequentially until the first **{ parallel region }** construct is encountered.

Master fork and join...





OpenMP sequential and parallel

✓ Sequential

```
void main()
{
    double r[1000];

    for (int i=0; i<1000; i++) {
        large_computation(r[i]);
    }
}
```

✓ Parallel

```
void main()
{
    double r[1000];

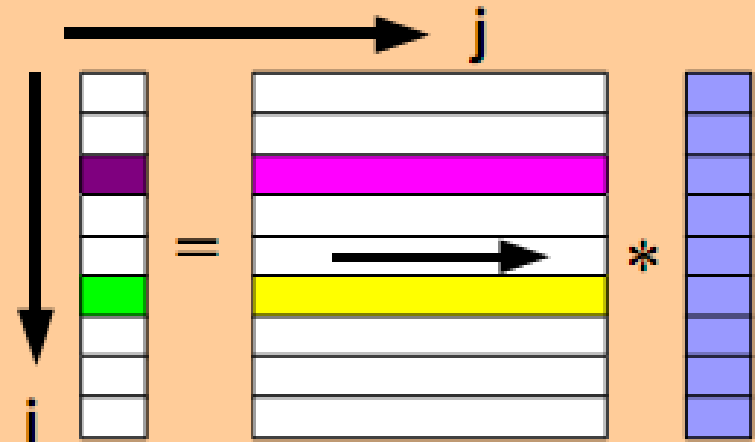
    #pragma omp parallel for
    for (int i=0; i<1000; i++) {
        large_computation(r[i]);
    }
}
```

Another example



Example (source: "Introduction to OpenMP, SunMicrosystems")

```
#pragma omp parallel for default(none) \  
private(i,j,sum) shared(m,n,a,b,c)  
for (i=0; i<m; i++)  
{  
    sum = 0.0;  
    for (j=0; j<n; j++)  
        sum += b[i][j]*c[j];  
    a[i] = sum;  
}
```

**TID = 0**

Thread #1

for (i=0,1,2,3,4)**i = 0**
$$\text{sum} = \sum b[i=0][j]*c[j]$$
$$a[0] = \text{sum}$$
i = 1
$$\text{sum} = \sum b[i=1][j]*c[j]$$
$$a[1] = \text{sum}$$
TID = 1

Thread #2

for (i=5,6,7,8,9)**i = 5**
$$\text{sum} = \sum b[i=5][j]*c[j]$$
$$a[5] = \text{sum}$$
i = 6
$$\text{sum} = \sum b[i=6][j]*c[j]$$
$$a[6] = \text{sum}$$

- ✓ Example of multithreaded applications
 - 7-zip
 - Imagemagick with OpenMP
 - SEE: <https://imagemagick.org/discourse-server/viewtopic.php?t=20904>
- ✓ Example of NON-multithreaded applications
 - Google chrome
 - Mozilla firefox (future version 50)
 - ...



✓ Imagemagick

- Software for image processing
- Set of (very powerful) command line tools
 - convert, display, identify,...
- Uses OpenMP to fully exploit the cores of the running machine
- Example – channel.c:412

```
#if defined(MAGICKCORE_OPENMP_SUPPORT)
    #pragma omp parallel for schedule(static,4)
    shared(progress,status) \
        magick_threads(image,image,image->rows,1)
#endif
```

7-ZIP – CASE-STUDY

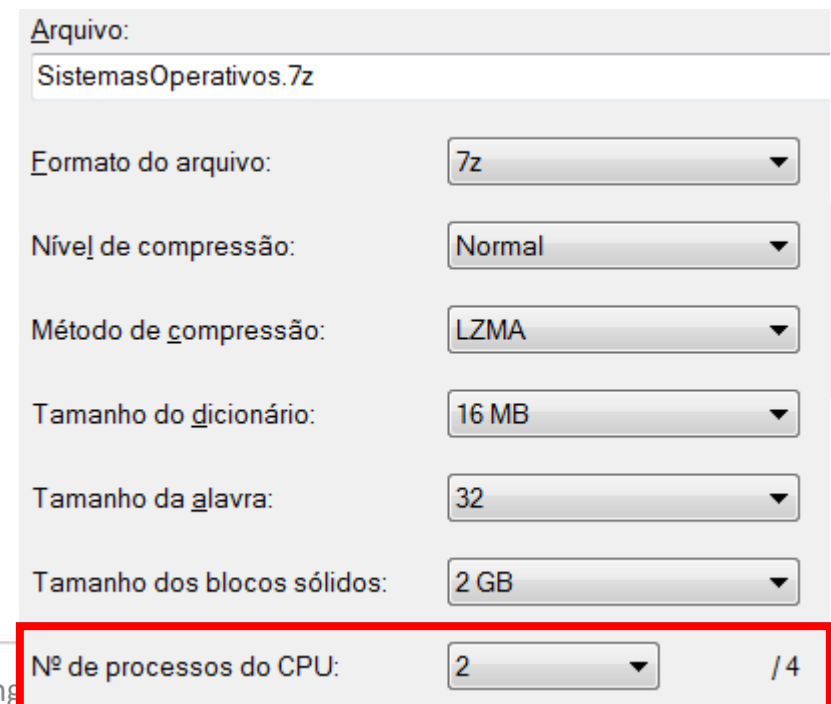


Case study -7Zip (1/2)

✓ 7Zip

- Data compressor (quite efficient)
- By default, it uses all “CPUs” (cores and alike) of the computer

```
#ifndef COMPRESS_MT
    const UInt32 numProcessors =
        NSystem::GetNumberOfProcessors();
    _numThreads = numProcessors;
#endif
```



Arquivo: SistemasOperativos.7z

Formato do arquivo: 7z

Nível de compressão: Normal

Método de compressão: LZMA

Tamanho do dicionário: 16 MB

Tamanho da palavra: 32

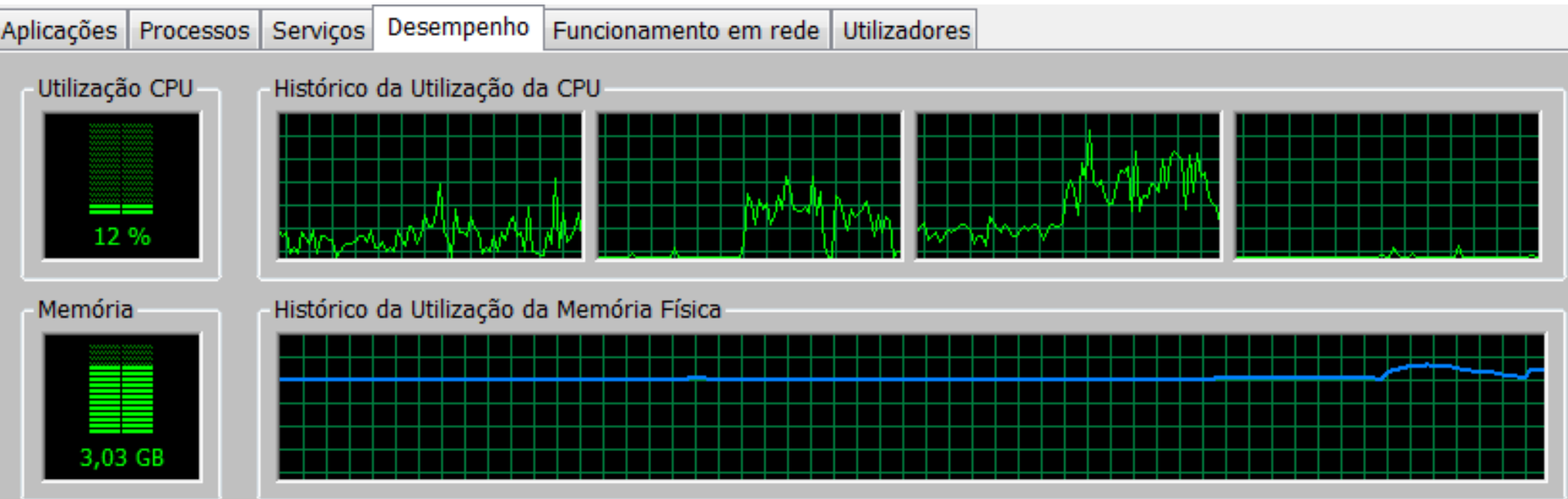
Tamanho dos blocos sólidos: 2 GB

Nº de processos do CPU: 2 / 4

Case study -7Zip (1/2)

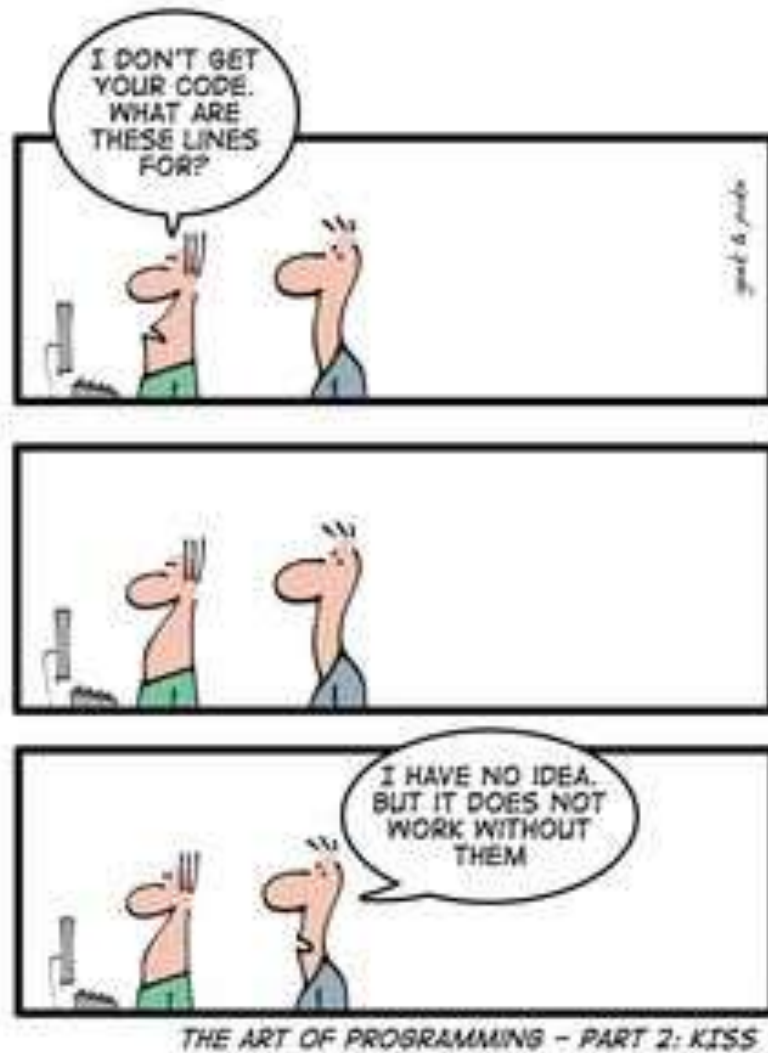
✓ 7Z in action

- Decompress the 7z file of the virtual machine
- Several cores are being used (see plot)





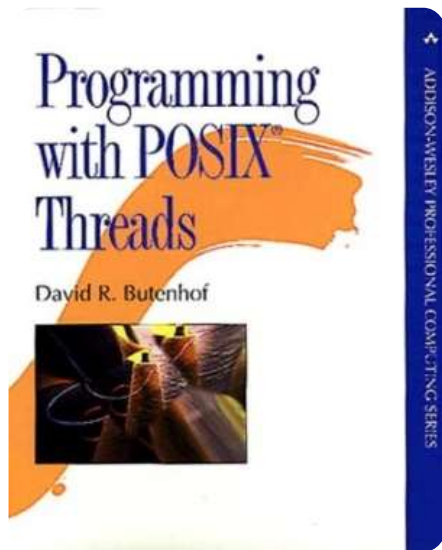
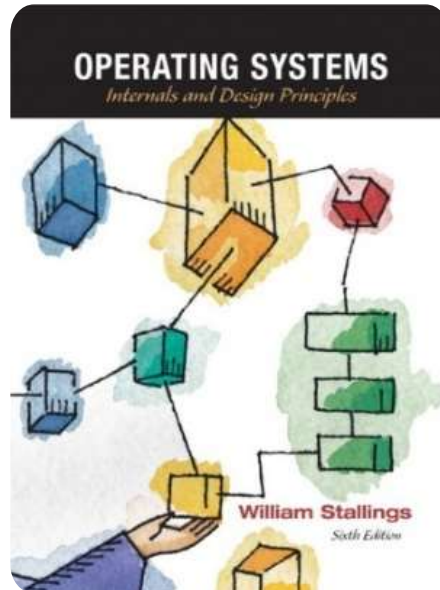
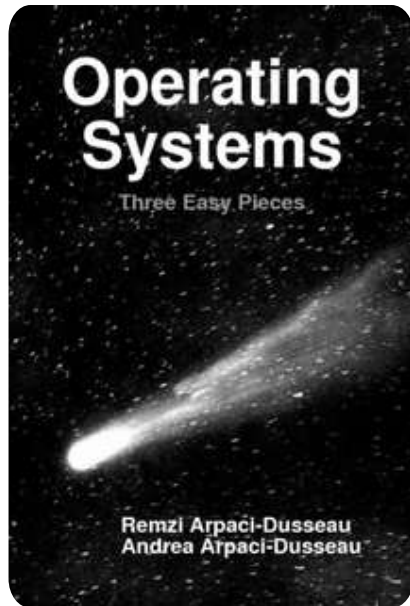
Multithread in practice...



BIBLIOGRAPHY



Bibliography #1



- ✓ David R. Butenhof, "Programming with POSIX Threads", Addison-Wesley, 1997, ISBN-13: 978-0201633924
- ✓ Chapter 4 - "Operating Systems – Internals and Design Principles", William Stallings, 7th edition, 2011 (ISBN : 013230998X)
- ✓ Chapter 26 – Concurrency and threads. Arpaci-Dusseau, Remzi H., and Andrea C. Arpaci-Dusseau. Operating systems: Three easy pieces. Arpaci-Dusseau Books LLC, 2018.

Bibliography #2

- ✓ “Programming on Parallel Machines – University of California, Davis, 2012
Open textbook:
<http://heather.cs.ucdavis.edu/parprocbook>
 - Chapter 1 (section 1.4): pthreads (example)
 - Chapter 4: introduction to OpenMP”, Norm Matloff,
- ✓ OpenMP
 - <http://openmp.org/wp/openmp-specifications/>
 - Source code do imagemagick (example)
 - <http://www.imagemagick.org/script/download.php>

