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Threads in Embedded Linux

Six Easy Pieces

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Doulos

Six Easy Pieces

1. Getting Started
2. Thread Creation and Lifecycle
3. Thread Stack
4. Memory Access
5. Mutex and Condition Variable
6. Threads and Signals

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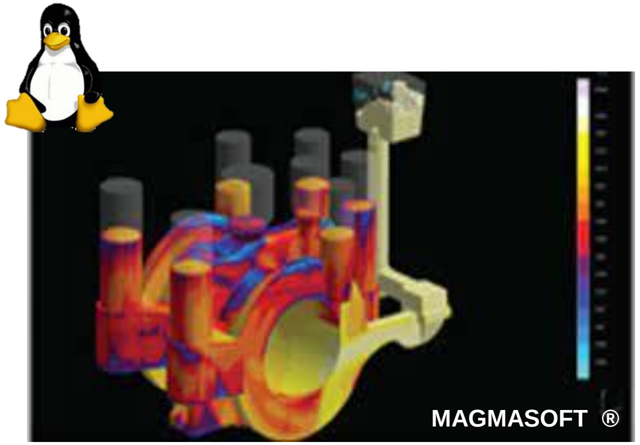
Why Linux? Why Threads?

1996



Foundry simulation (Beowulf cluster)

Telecom

```
RWY 08                                          RWY 33
        50                                      45
        45   LOT3KM      17:34  188             EXIT
             LOT3241     17:28  179             EPMO
             SWR135Y     17:29  210             DOSIX SORIX NEPOX
 3VL         LOT632      17:24  193             GOGUS NIDRO LIMVI
        40   LOT6TK      17:25  189                         LOGDA
 RYR11ZT     TVP7509     17:23  164             EPWA
        35   LOT522      17:21  131             BIMPA SORIX NEPOX
             WZZ23NS     17:19  138             ASAVA LOGDA LIMVI
             LOT402      17:15  123             INFO
        30   MMOZX       17:15  114
             LOT75W      17:15  105
        25   QGA675R     17:11  89
             DLH5YF      17:11  78
        20   AFL2006     17:08  58
             BER119Y     17:04  48              REPLAN
             LOT4KM      17:03  R29             M    60   30   10
        15   ADR938      17:08  32              LND  0    0    0
             17 : 14 : 21                       SEP  0.0  0.0  0.0
        10   Change FLOW                        W    60   30   10
             Change RWY DIR                     LND  0    0    0
             Change RWY Option                  SEP  0.0  0.0  0.0
             Add SLOT
             Hide Miles
FLOW 6.5  17 06                                 FLOW 4.5
```

Air Traffic Control

DFS Deutsche Flugsicherung

Airline IT

Medical

Automotive

2016

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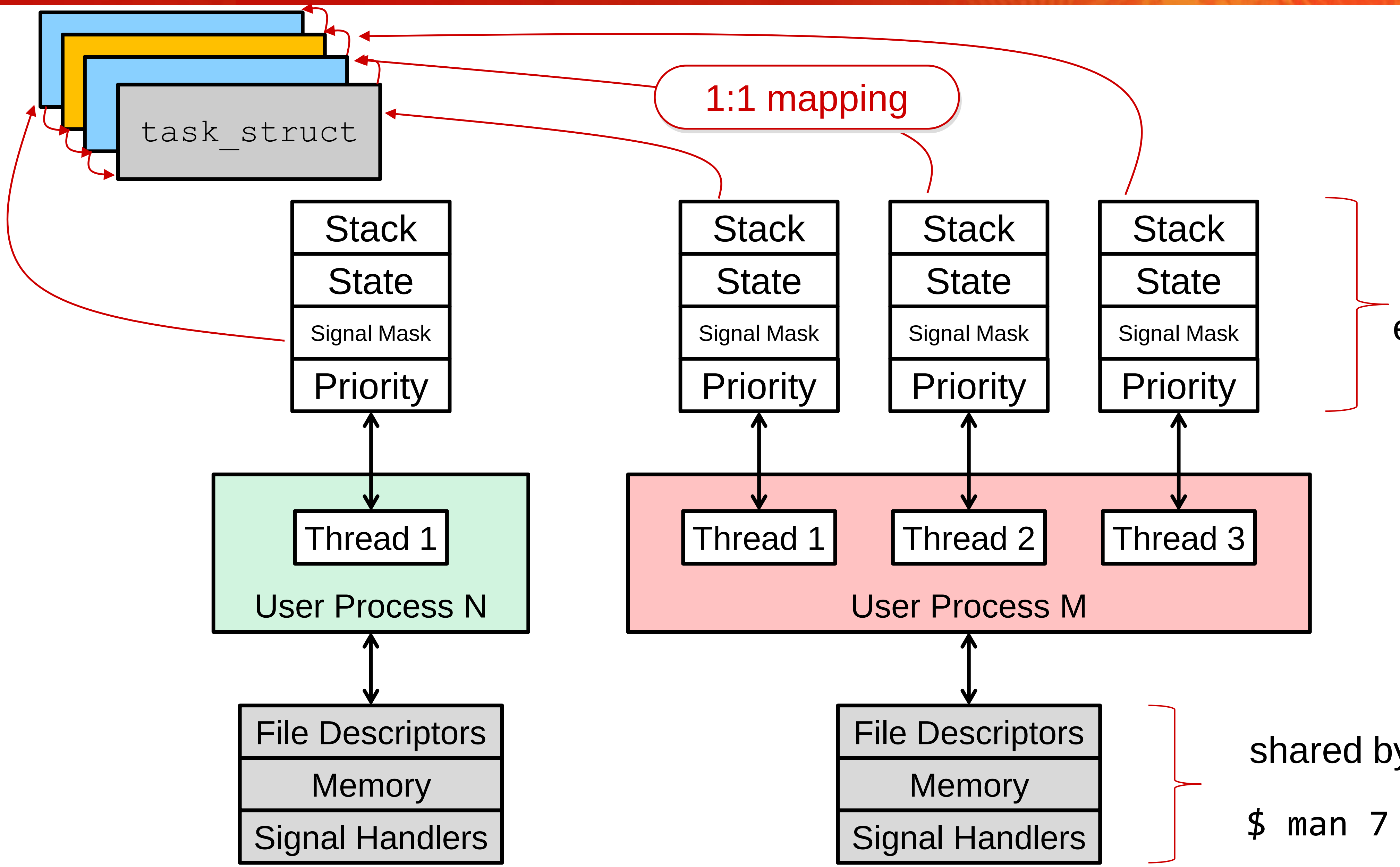
Process and Threads



task_struct

1:1 mapping

Stack | State | Signal Mask | Priority

Thread 1

User Process N

File Descriptors | Memory | Signal Handlers

Stack | State | Signal Mask | Priority (×3)

Thread 1 | Thread 2 | Thread 3

User Process M

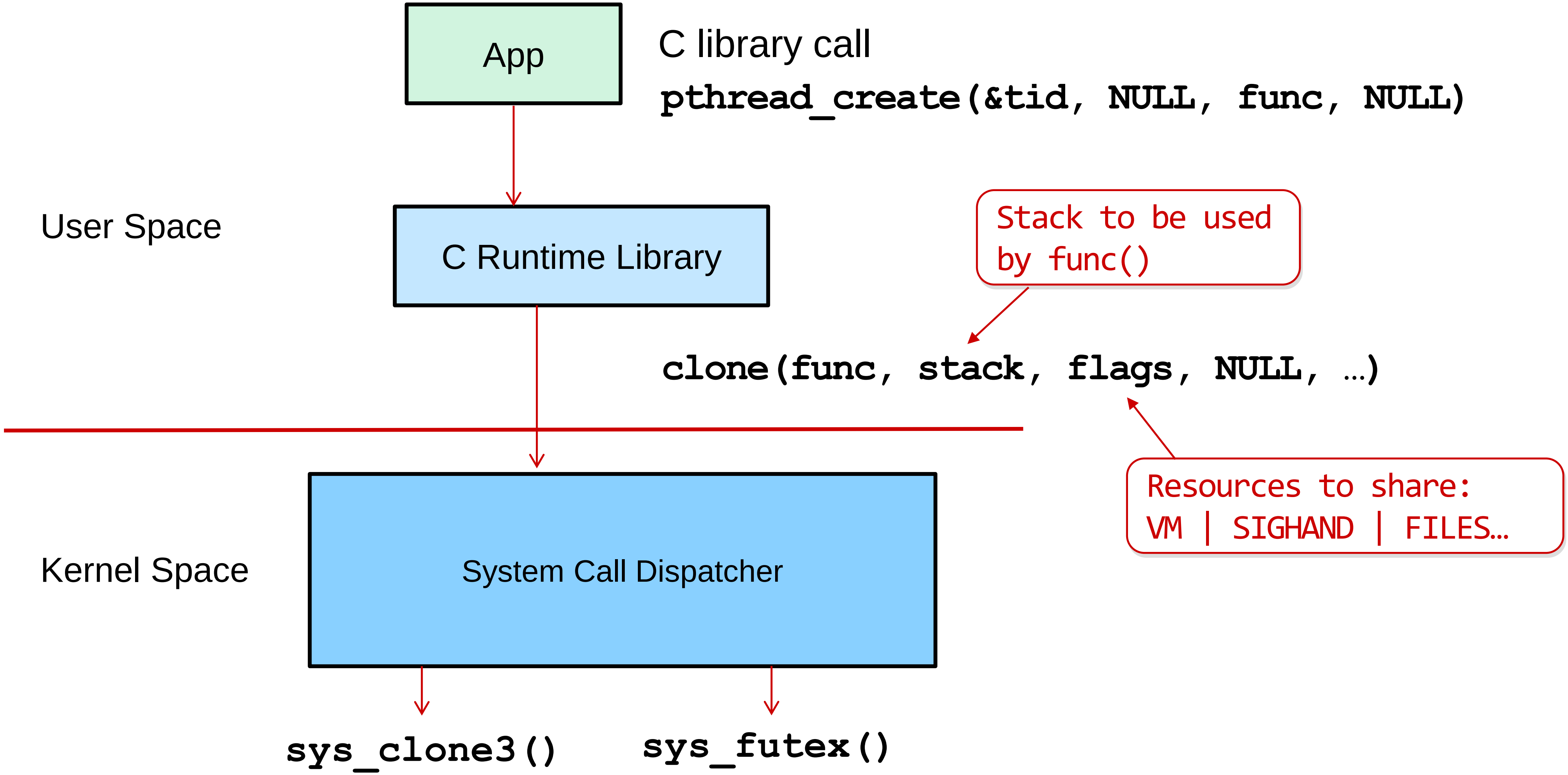
File Descriptors | Memory | Signal Handlers

specific to each thread

shared by all threads

```
$ man 7 pthreads
```

clone



App

C library call

```
pthread_create(&tid, NULL, func, NULL)
```

User Space

C Runtime Library

Stack to be used by func()

```
clone(func, stack, flags, NULL, …)
```

Resources to share:
VM | SIGHAND | FILES…

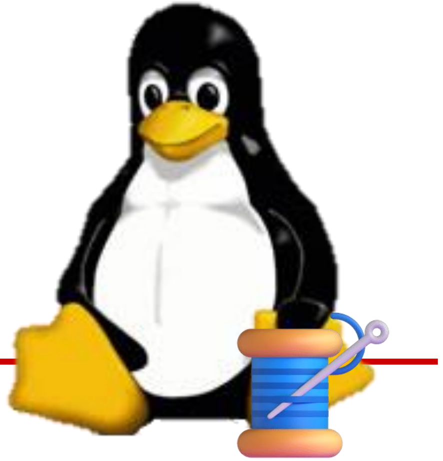
Kernel Space

System Call Dispatcher

```
sys_clone3()
sys_futex()
```

Piece #2

Thread Creation and Lifecycle



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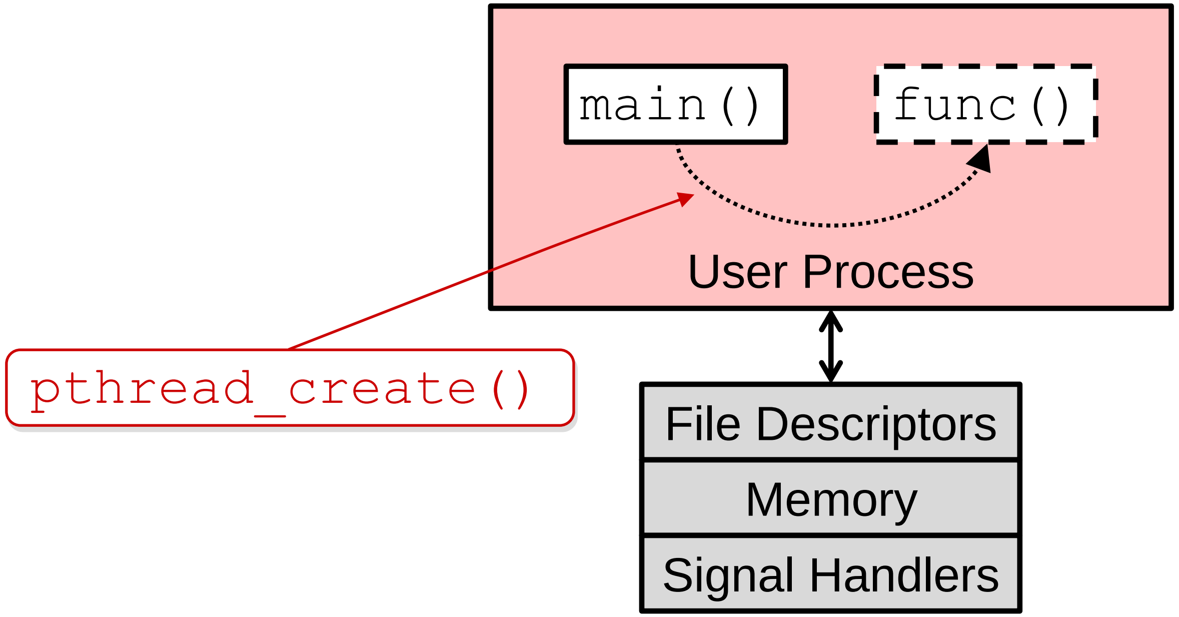
Starting a New Thread

```
#include <pthread.h>
int pthread_create(
    pthread_t *restrict thread,             // thread identifier
    const pthread_attr_t *restrict attr, // thread attribute (NULL=default)
    void *(*func)(void *),                  // start routine
    void *restrict arg                      // arg is passed to func()
    );
```

- **Return Value:**
  - 0 on success.
  - error number on failure.
- Compile/link flag: **`-pthread`**



Demo time!

```
// let's start our first thread

// how hard can that be???
```

https://github.com/Doulos/EOSS23

Your mileage may vary…

Aspect to watch out when coming from another OS/language:

- Error reporting?
- Is creation/start one or two separate states?
- Impact when the "main thread" terminates?
- Impact when a thread crashes (`SIGSEGV…`)?
- When are threads resources cleaned-up?
- …

While concepts are often similar, subtle differences in behaviours might catch us

Linux/POSIX behaviour (1)

Where	Action	Result	Comments
Thread	`pthread_create()`	New thread	Creation+start all in one Beware of race conditions
`main()`	`return`	Process ends	All threads die! `exit(main(argc,argv,envp))`
`func()`	`return`	Thread ends	Resources might be retained
Thread	`exit()`	Process ends	All threads die!

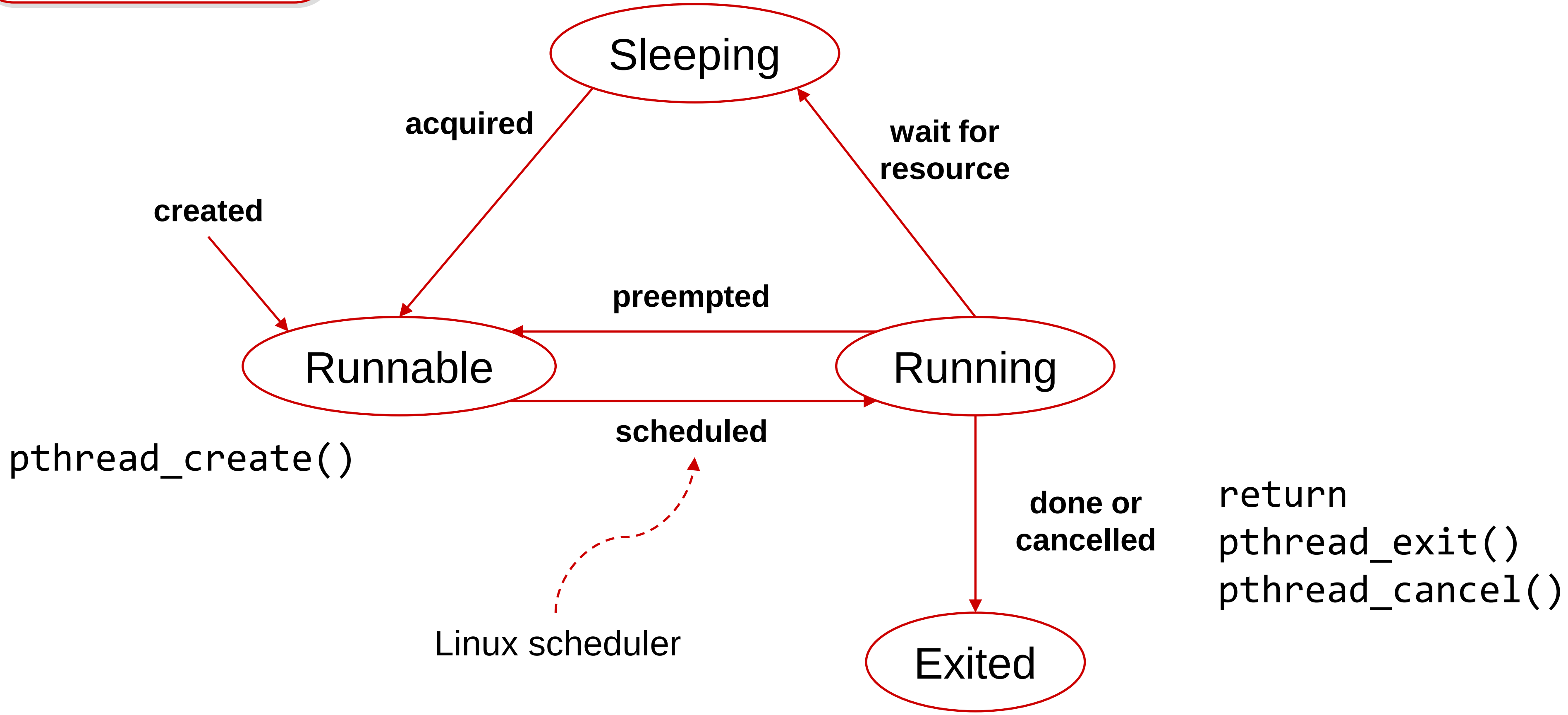
Linux/POSIX behaviour (2)

Where	Action	Result	Comments
Thread	HW Exception*	Process terminates	All threads die!
Thread	`pthread_exit()`	Thread terminates	Resources might be retained
Thread	`pthread_join()`	Wait until thread ends	Thread resources are recycled
Thread	`pthread_detach()`	Decouple a thread	Resources automatically reclaimed when thread ends

(*) `SIGBUS, SIGILL, SIGFPE, SIGSEGV`

Thread Life Cycle

Simplified view



Sleeping

acquired

wait for resource

created

preempted

Runnable

Running

scheduled

pthread_create()

done or cancelled

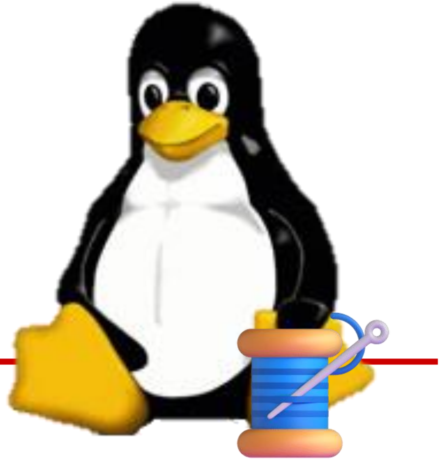
return
pthread_exit()
pthread_cancel()

Linux scheduler

Exited

Piece #3

Thread Stack



Thread Stack

- Starting a thread:

```
rc = pthread_create(&tid, NULL, start_routine, NULL);
```

- Threads require a separate stack:
  - Many "embedded OS" require to define the stack.
  - So does the `clone(2)` API.
  - Not seen yet?
- What about stack overflow?

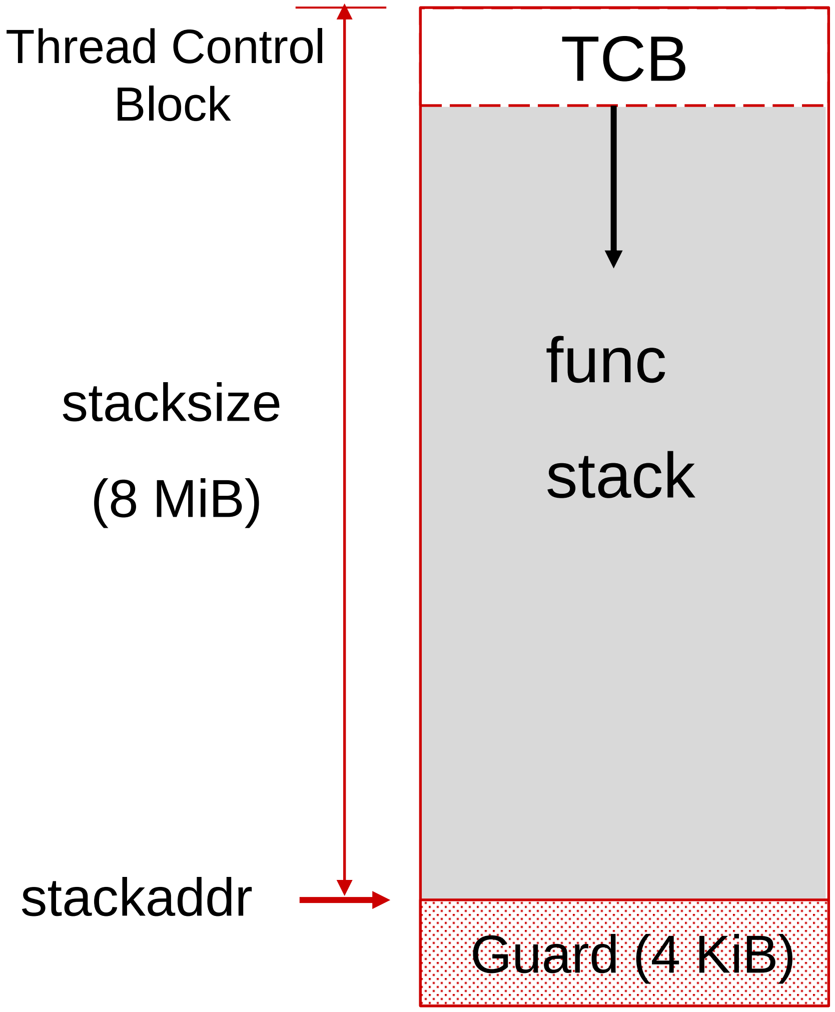
Demo time!

```
// let's overflow the stack

// for fun and teaching
```

https://github.com/Doulos/EOSS23

Thread Stack Layout (glibc 2.35)



```
0x7f7216400000
0x7f72163ff640
```

```
rc = pthread_create(&tid, NULL, func, NULL);
printf("tid = %p", tid);
…
tid = 0x7f72163ff640

[  963.372358] ex2[2949]: segfault at 7f7215bfffc8
ip  00007f721645a95b sp  00007f7215bfffa0 error 6
in libc.so.6
```

```
0x7f7215c00000    8192K rw---    [ anon ]
0x7f7215bff000       4K -----    [ anon ]
```

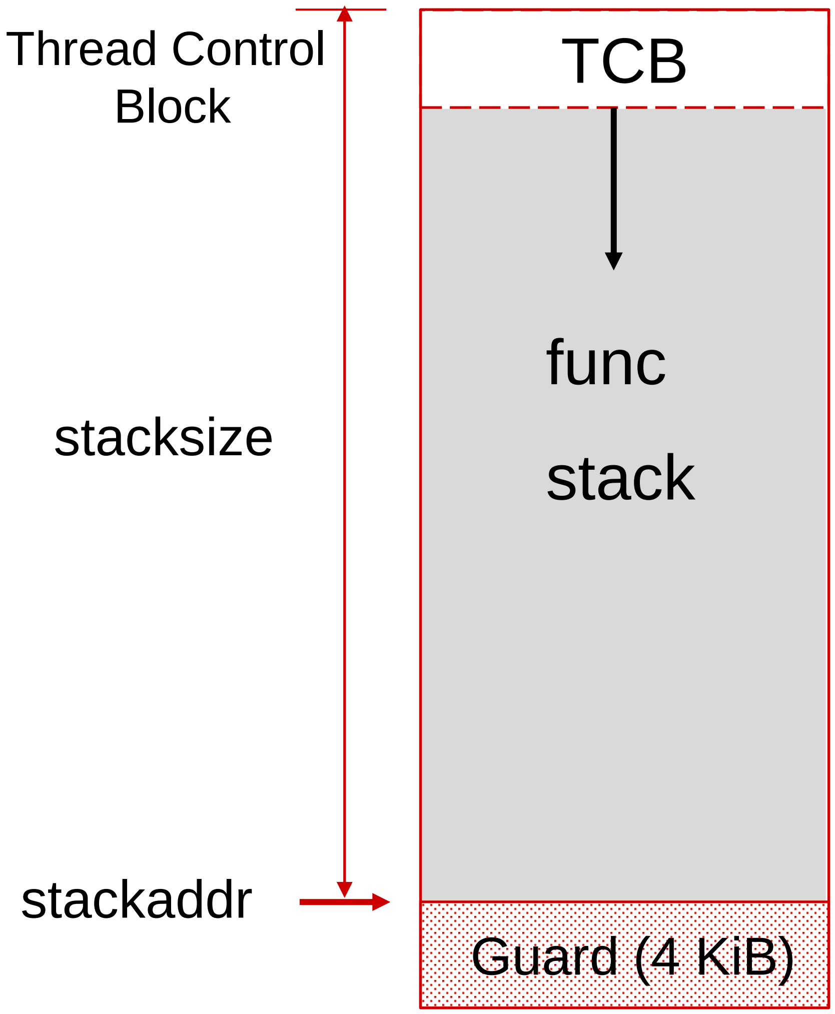
Thread Stack – Quick Facts

- Only Virtual Memory range is mapped:
  - Memory is committed using page-faults mechanism.
  - For Real-time App: use `mlockall()`.

- C-library may use different default stack size:
  - Glibc : 8 MiB (v2.35), Musl : 384 KiB (v1.2.4).
  - Solution: control stack size.

- "Thread Control Block" stored on the thread's stack:
  - Stack mapping retained, even if thread has terminated.
  - Solution: `pthread_join()` or `pthread_detach()`.

Controlling the Stack



```
pthread_attr_getdetachstate()
pthread_attr_setdetachstate()
pthread_detach()
```

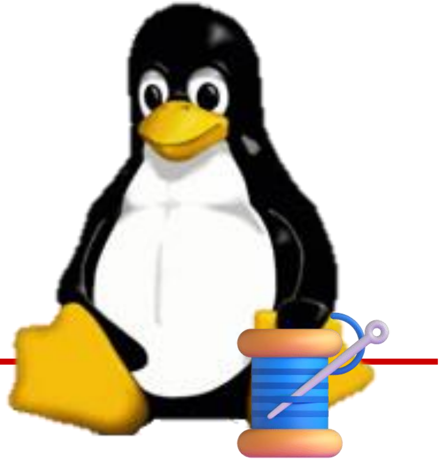
```
pthread_attr_getstacksize()
pthread_attr_setstacksize()
```

```
pthread_attr_getstack()
pthread_attr_setstack()
```

```
pthread_attr_getguardsize()
pthread_attr_setguardsize()
```

Piece #4

Memory Access



Accessing Memory

- Any thread can access any (valid) memory address.
  - local variable passed to the thread's start routine,
  - global variables,
  - any variable or location, if the address is known.

- In many situations, we want a **sequentially consistent ordering**.
- Needs synchronization! (execution order + memory visibility).

Time

Thread A	Thread B
`x = 42;`	
	`printf("x=%d\n", x)`

We expect: x=42

Memory Visibility

```
int x,y,z,t; // global variables
```

Time

Thread A	Thread B
`x = 6;`	
`y = 7;`	
`pthread_create(B);`	`//create ThrB`
`t = x + y;`	sees x,y
`pthread_join(B);`	`z = x * y;`
	`t += 8;`
	`return NULL;`
sees z,t	
`assert(z==42);`	
`assert(t==21);`	

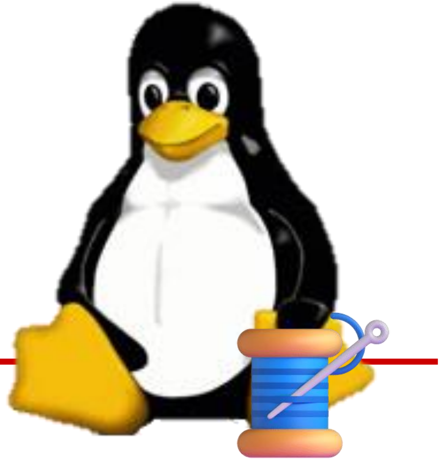
value set by a thread prior to pthread_create() can be seen by the new thread.

No such guarantee here!! (depends on timing, and system architecture!)

Likewise, value set by a thread can be seen by the thread joining it.

Piece #5

Mutex and Condition Variable



Mutex

```
pthread_mutex_t mtx = PTHREAD_MUTEX_INIALIZER;
```

Time

Thread A	Thread B
`x = 6; y = 7;`	
`pthread_mutex_lock(&mtx);`	
`t = x + y;`	Blocks until A unlocks
	`pthread_mutex_lock(&mtx)`
`pthread_mutex_unlock(&mtx);`	
	`t += 8;`
After unlock: t will be seen in any thread that locks the same mutex	`pthread_mutex_unlock(&mtx)`

Mutex Quick Facts

- Mutex = binary semaphore conceptually, but is:
  - faster: syscall only when contended.
  - owned by a thread.
  - For RT-App: prio inheritance/ceiling protocol possible.

- Thread that locks should also unlock.
  - Behaviour in error situation (relock, not owner…)?
  - Depends on the mutex type: NORMAL, ERRORCHECK, RECURSIVE.
  - Example: NORMAL mutex causes a deadlock if relocked by the same thread.

- Mutex doesn't synchronize which thread locks first.

Condition Variables (Incorrect use of)

```
pthread_mutex_t mtx = PTHREAD_MUTEX_INIALIZER;
pthread_cond_t cv   = PTHREAD_COND_INITIALIZER;
```

Time

Thread A	Thread B
`x = 6; y = 7;`	`pthread_mutex_lock(&mtx);`
`pthread_mutex_lock(&mtx);`	
	unlock mtx, blocks until A signals cv
	`pthread_cond_wait(&cv, &mtx);`
`t = x + y;`	mtx is locked
`pthread_cond_signal(&cv);`	
`pthread_mutex_unlock(&mtx);`	`t += 8;`
	`pthread_mutex_unlock(&mtx)`

Where is the "condition" ?

```
pthread_mutex_t mtx = PTHREAD_MUTEX_INIALIZER;
pthread_cond_t cv   = PTHREAD_COND_INITIALIZER;
```

Time

Thread A	Thread B
`x = 6; y = 7;`	`pthread_mutex_lock(&mtx);`
`pthread_mutex_lock(&mtx);`	`while (t==0)`
	`{`
	`    pthread_cond_wait(&cv, &mtx);`
`t = x + y;`	`}`
`pthread_cond_signal(&cv);`	
`pthread_mutex_unlock(&mtx);`	`t += 8;`
	`pthread_mutex_unlock(&mtx)`

wait until t is set

signal change on t

Condition Variable – Quick Facts

- Usage pattern:

notifier

```
pthread_mutex_lock(&mtx);
// change condition
...
// signal or broadcast
pthread_cond_signal(&cv);
pthread_mutex_unlock(&mtx);
```

waiter

```
pthread_mutex_lock(&mtx);
while (! wanted_condition ) {
    pthread_cond_wait(&cv, &mtx);
}
// do work, change condition
...
pthread_mutex_unlock(&mtx);
```

- `signal` = wakes up one waiter, `broadcast` = all waiters.
- no waiter = notification is lost. (not a problem, wait is skipped).
- use a `while` loop! a strict `if` statement might fail us.

Thread Synchronization

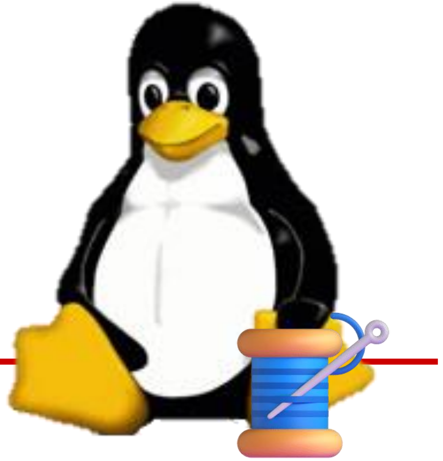
Thread of execution + Memory

Objects	Main operation	Typical Usage
Mutex	`lock*, unlock`	Mutual exclusion / Access shared data ("one thread at a time").
Condition Variables	`wait*, signal, broadcast`	Wait for some condition to become true
Barrier	`wait`	Blocks until N threads reaches the barrier
Read-Write Locks	`lock*, unlock`	Like mutex, but reader blocks only if writer holds the locks.
Spinlocks	`lock, unlock`	Like mutex, but spins.

* For mutex, condition variable, read-write lock: timed lock/wait exists.

Piece #6

Threads and Signals

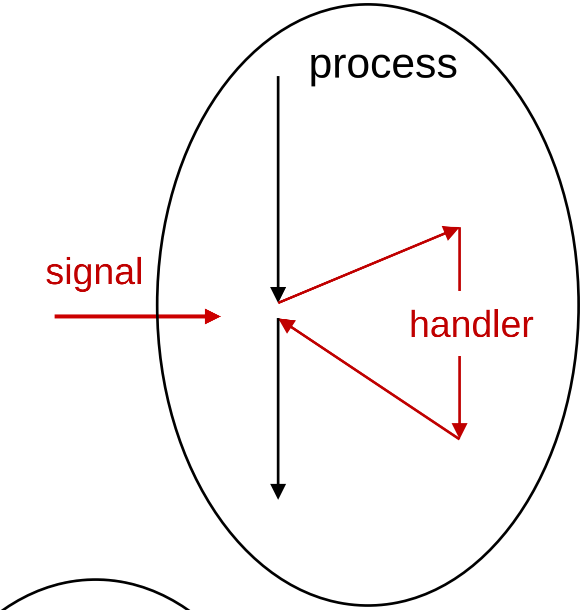


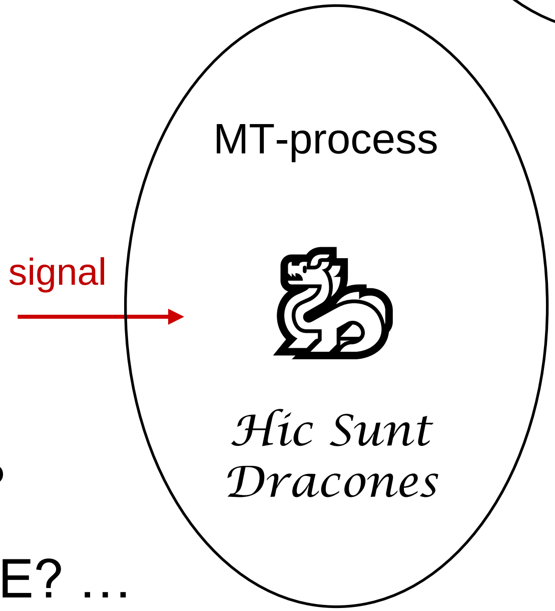
Thread and Signal

- Single threaded process:
  - Signal is delivered to process.
  - Interrupt Execution flows when unblocked.
  - Runs the signal handler asynchronously.

- Thread makes asynchronous code synchronous.
- Somewhat antinomic to signal.

- Multi-threaded process:
  - Signal is still delivered to the process.
  - Which thread is interrupted?
  - Can we block delivery in some thread?
  - Signal semantic for SIGSTOP? SIGFPE? …





Demo time!

```
// Let's meet some dragons

// compiling with -pthread
// breaks my single threaded code!

// PS: won't happen on Linux ;)
```

https://github.com/Doulos/EOSS23

Handle Signal with Threads

block signals in all threads

```
sigset_t mask; // signals to handle

int main()
{
    sigemptyset(&mask);
    sigaddset(&mask, SIGINT);
    pthread_sigmask(SIG_BLOCK, &mask, NULL);

    // start thread incl. sighandler_thread
    ...

}
```

sigmask is inherited

wait synchronously

```
void *sighandler_thread(void *ign)
{
    int caught;
    while (1) {
        sigwait(&mask, &caught);
        // handle signal caught
        ...
    }
}
```

Signals – Quick Facts

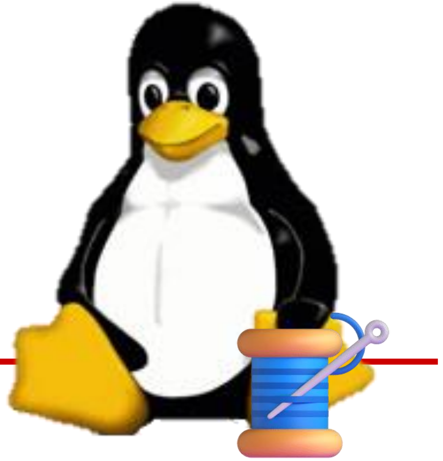
- Previous pattern allows to:
  - use any (mt-safe) functions in signal handler thread.
  - remove limitation regular process signal handler.

- Signal and process:
  - `SIGKILL` terminates process (= all threads).
  - `SIGSTOP` = stop all threads, `SIGCONT` = restart.
  - HW exception always delivered to the "faulty thread".
  - Other signals delivered to arbitrary thread, unless blocked.

- Use:
  - `pthread_kill()` to send a signal to a specific thread.
  - `pthread_sigmask()` to modify the per-thread signal mask.

Piece #7

Going Further



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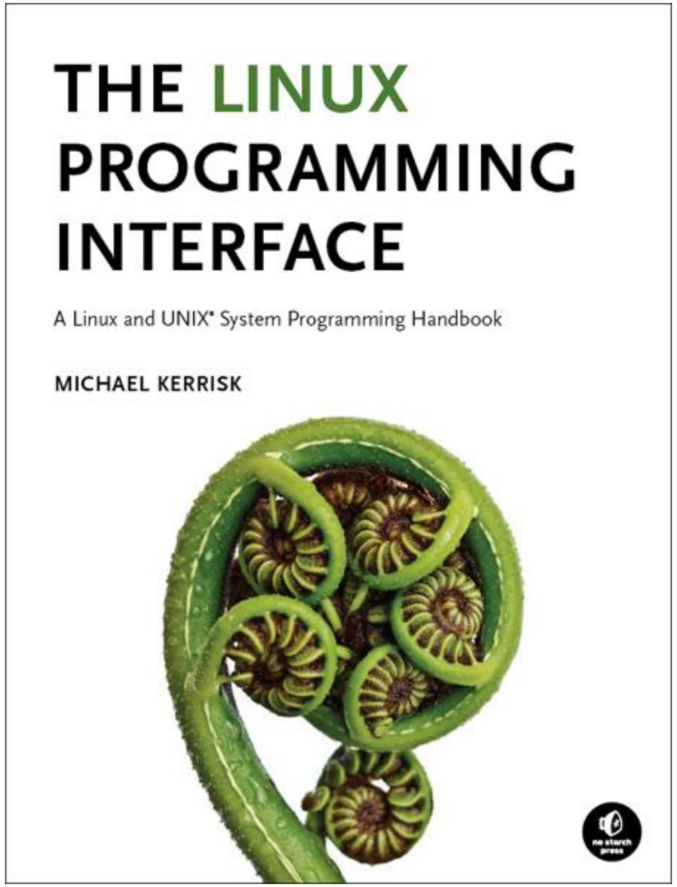
References and Further Readings

```
$ man 7 pthreads
```

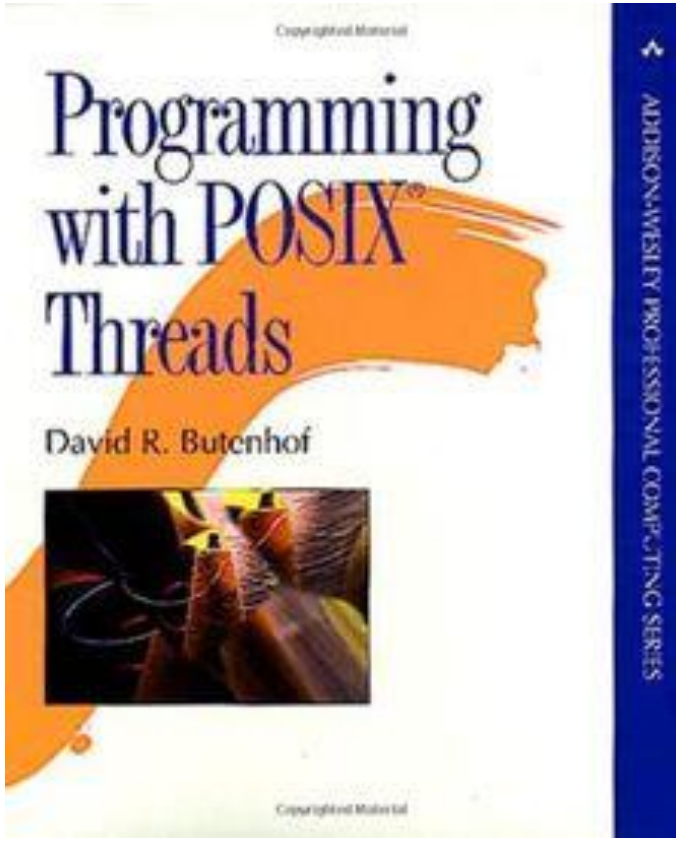


THE LINUX PROGRAMMING INTERFACE

A Linux and UNIX® System Programming Handbook

MICHAEL KERRISK

https://man7.org/tlpi/



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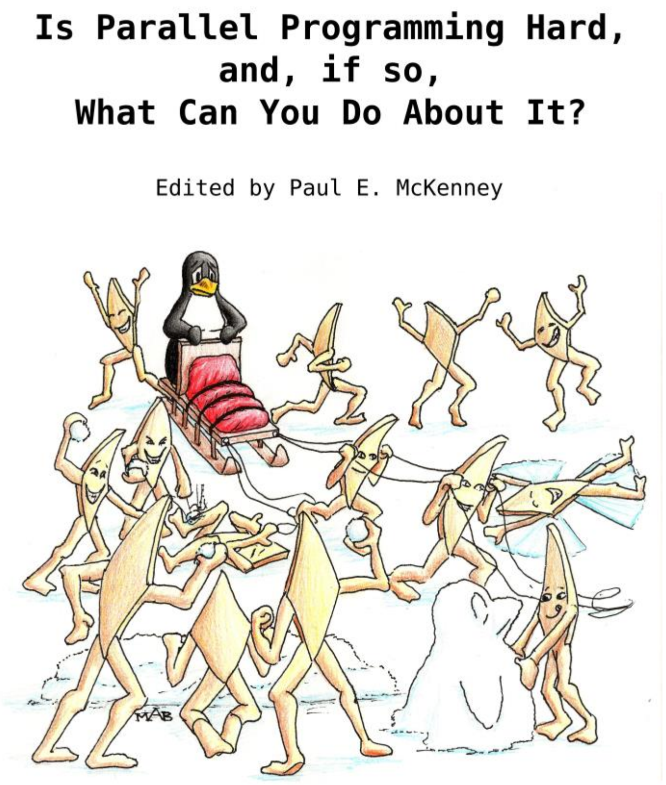

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