Embedded Linux kernel and driver development

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Latest update: Feb 23, 2010,
Document sources, updates and translations:
http://free-electrons.com/docs/kernel
Corrections, suggestions, contributions and translations are welcome!

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Driver development

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hello module

```
/* hello.c */
#include <linux/init.h>
#include <linux/module.h>
#include <linux/kernel.h>

static int __init hello_init(void)
{
    printk(KERN_ALERT "Good morrow");
    printk(KERN_ALERT "to this fair assembly.\n");
    return 0;
}

static void __exit hello_exit(void)
{
    printk(KERN_ALERT "Alas, poor world, what treasure");
    printk(KERN_ALERT "hast thou lost!\n");
}

module_init(hello_init);
module_exit(hello_exit);
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Greeting module");
MODULE_AUTHOR("William Shakespeare");
```

`__init`:
removed after initialization (static kernel or module).

`__exit`: discarded when module compiled statically into the kernel.

Example available on http://free-electrons.com/doc/c/hello.c

Module license

- Several usages
  - Used to restrict the kernel functions that the module can use if it isn't a GPL-licensed module
    - Difference between `EXPORT_SYMBOL()` and `EXPORT_SYMBOL_GPL()`
  - Used by kernel developers to identify issues coming from proprietary drivers, which they can't do anything about (“Tainted” kernel notice in kernel crashes and oopses).
  - Useful for users to check that their system is 100% free (check `/proc/sys/kernel/tainted`)
- Values
  - GPL, GPL v2, GPL and additional rights, Dual MIT/GPL, Dual BSD/GPL, Dual MPL/GPL, Proprietary

Compiling a out-of-tree module

- The below Makefile should be reusable for any out-of-tree Linux 2.6 module
  - In-tree modules are covered later
- Just run `make` to build the `hello.ko` file
- Caution: make sure there is a `[Tab]` character at the beginning of the `$(MAKE)` line (`make` syntax)

```
# Makefile for the hello module

obj-m := hello.o
KDIR := /lib/modules/$(shell uname -r)/build
PWD := $(shell pwd)
default:
	$(MAKE) -C $(KDIR) SUBDIRS=$(PWD) modules
```

`[Tab]`!
(no spaces)

Either
- full kernel source directory (configured and compiled)
- or just kernel headers directory (minimum needed)

Example available on http://free-electrons.com/doc/c/Makefile

Modules and kernel version

- To be compiled, a kernel module needs access to the kernel headers, containing the functions, types and constants definitions
- Two solutions
  - Full kernel sources
  - Only kernel headers (linux-headers-* packages in Debian/Ubuntu distributions)
- The sources or headers must be configured
  - Many macros or functions depend on the configuration
- A kernel module compiled against version X of kernel headers will **not** load in kernel version Y
  - modprobe/insmod will say « Invalid module format »

Symbols exported to modules

- From a kernel module,
  only a limited number of kernel functions can be called
- Functions and variables have to be explicitly *exported* by the kernel to be visible from a kernel module
- Two macros are used in the kernel to export functions and variables :
  - `EXPORT_SYMBOL(symbolname)`, which exports a function or variable to all modules
  - `EXPORT_SYMBOL_GPL(symbolname)`, which exports a function or variable only to GPL modules
- A normal driver should not need any non-exported function.

Module dependencies

- Definition: `module2` depends on `module1` if `module2` uses a symbol exported by `module1`.
- Module dependencies are stored in `/lib/modules/<version>/modules.dep`
- They are automatically computed during kernel building from module exported symbols.
- Example: `usb_storage` depends on `usbcore`, because it uses some of the functions exported by `usbcore`.
- You can also update the `modules.dep` file by yourself, by running (as `root`):
  `depmod -a [<version>]`

hello module with parameters

```
/* hello_param.c */
#include <linux/init.h>
#include <linux/module.h>
#include <linux/moduleparam.h>

MODULE_LICENSE("GPL");

/* A couple of parameters that can be passed in: how many times we say
   hello, and to whom */

static char *whom = "world";
module_param(whom, charp, 0);

static int howmany = 1;
module_param(howmany, int, 0);

static int __init hello_init(void)
{
    int i;
    for (i = 0; i < howmany; i++)
     printk(KERN_ALERT "(%d) Hello, %s\n", i, whom);
    return 0;
}

static void __exit hello_exit(void)
{
    printk(KERN_ALERT "Goodbye, cruel %s\n", whom);
}

module_init(hello_init);
module_exit(hello_exit);
```

Thanks to Jonathan Corbet for the example!

Example available on http://free-electrons.com/doc/c/hello_param.c

Passing module parameters

- Through `insmod`:

```
sudo insmod ./hello_param.ko howmany=2 whom=universe
```

- Through `modprobe`:
  Set parameters in `/etc/modprobe.conf` or in any file in `/etc/modprobe.d/`:

```
options hello_param howmany=2 whom=universe
```

- Through the kernel command line,
  when the module is built statically into the kernel:

```
hello_param.howmany=2 hello_param.whom=universe
```

driver name
driver parameter name
driver parameter value

Declaring a module parameter

```
#include <linux/moduleparam.h>

module_param(
    name,     /* name of an already defined variable */
    type,     /* either byte, short, ushort, int, uint, long,
                 ulong, charp, or bool.
                 (checked at compile time!) */
    perm      /* for /sys/module/<module_name>/parameters/<param>
                 0: no such module parameter value file */
);
```

<u>Example</u>

```
int irq=5;
module_param(irq, int, S_IRUGO);
```

Declaring a module parameter array

```
#include <linux/moduleparam.h>

module_param_array(
    name,     /* name of an already defined array */
    type,     /* same as in module_param */
    num,      /* number of elements in the array, or NULL (no check?) */
    perm      /* same as in module_param */
);
```

Example

```
static int base[MAX_DEVICES] = { 0x820, 0x840 };
module_param_array(base, int, NULL, 0);
```

Driver development

Adding sources to the kernel tree

New driver in kernel sources (1)

To add a new driver to the kernel sources:

- Add your new source file to the appropriate source directory.
  Example: `drivers/usb/serial/navman.c`
- Describe the configuration interface for your new driver
  by adding the following lines to the `Kconfig` file in this directory:

```
config USB_SERIAL_NAVMAN
        tristate "USB Navman GPS device"
        depends on USB_SERIAL
        help
          To compile this driver as a module, choose M here: the
          module will be called navman.
```

New driver in kernel sources (2)

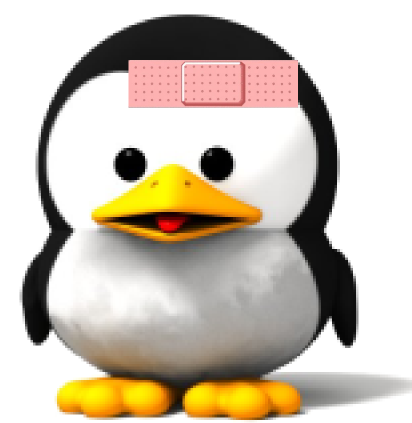
- Add a line in the `Makefile` file based on the `Kconfig` setting:

```
obj-$(CONFIG_USB_SERIAL_NAVMAN) += navman.o
```

- Run `make xconfig` and see your new options!
- Run `make` and your new files are compiled!
- See `Documentation/kbuild/` for details

How to create Linux patches

- Download the latest kernel sources
- Make a copy of these sources:
  `rsync -a linux-2.6.9-rc2/ linux-2.6.9-rc2-patch/`
- Apply your changes to the copied sources, and test them.
- Run `make distclean` to keep only source files.
- Create a patch file:
  ```
  diff -Nur linux-2.6.9-rc2/ \
  linux-2.6.9-rc2-patch/ > patchfile
  ```
  - Always compare the whole source structures (suitable for `patch -p1`)
  - Patch file name: should recall what the patch is about.
- If you need to manage a lot of patches, use `git` or `quilt` instead



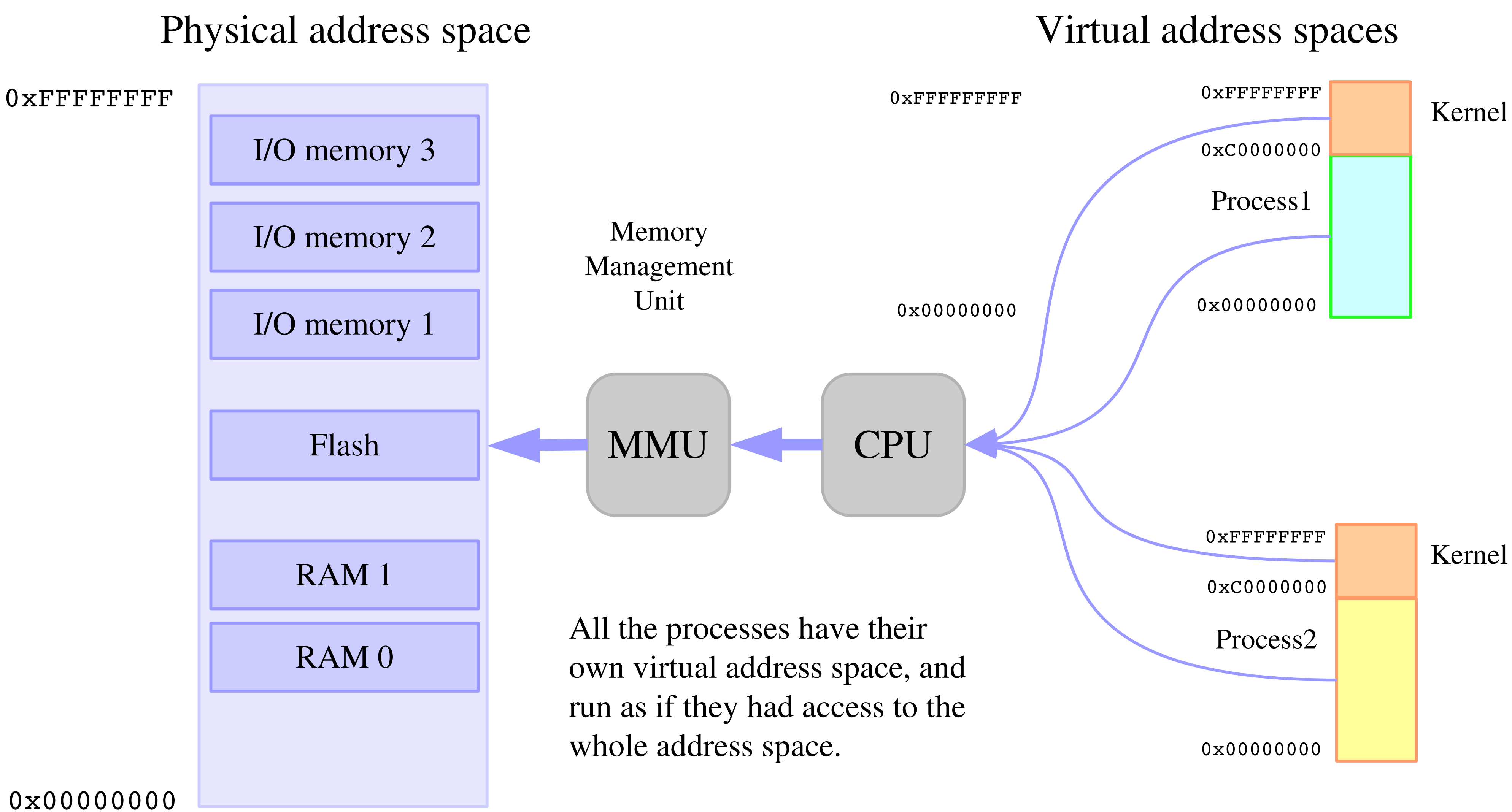
Thanks to Nicolas Rougier (Copyright 2003, http://webloria.loria.fr/~rougier/) for the Tux image

Practical lab – Writing modules

- Write a kernel module with several capabilities, including module parameters.
- Access kernel internals from your module.
- Setup the environment to compile it

Driver development
Memory management

Physical and virtual memory



All the processes have their own virtual address space, and run as if they had access to the whole address space.

kmalloc and kfree

- Basic allocators, kernel equivalents of `glibc`'s `malloc` and `free`.
- `#include <linux/slab.h>`
- `static inline void *kmalloc(size_t size, int flags);`
  - `size`: number of bytes to allocate
  - `flags`: priority (explained in a few pages)
- `void kfree (const void *objp);`
- Example: (`drivers/infiniband/core/cache.c`)

```
struct ib_update_work *work;
work = kmalloc(sizeof *work, GFP_ATOMIC);
...
kfree(work);
```

kmalloc features

- Quick (unless it's blocked waiting for memory to be freed).
- Doesn't initialize the allocated area.
- The allocated area is contiguous in physical RAM.
- Allocates by 2^n sizes, and uses a few management bytes.
  So, don't ask for 1024 when you need 1000! You'd get 2048!
- Caution: drivers shouldn't try to `kmalloc`
  more than 128 KB (upper limit in some architectures).
- Minimum memory consumption:
  32 or 64 bytes (page size dependent).

Main kmalloc flags (1)

Defined in `include/linux/gfp.h` (GFP: `__get_free_pages`)

- `GFP_KERNEL`
  Standard kernel memory allocation. May block. Fine for most needs.
- `GFP_ATOMIC`
  RAM allocated from code which is not allowed to block (interrupt handlers) or which doesn't want to block (critical sections). Never blocks.
- `GFP_USER`
  Allocates memory for user processes. May block. Lowest priority.

Main kmalloc flags (2)

Extra flags (can be added with `|`)

- `__GFP_DMA` or `GFP_DMA`
  Allocate in DMA zone
- `__GFP_ZERO`
  Returns a zeroed page.
- `__GFP_NOFAIL`
  Must not fail. Never gives up. Caution: use only when mandatory!
- `__GFP_NORETRY`
  If allocation fails, doesn't try to get free pages.
- Example:
  `GFP_KERNEL | __GFP_DMA`
- Note: almost only `__GFP_DMA` or `GFP_DMA` used in device drivers.

Related allocation functions

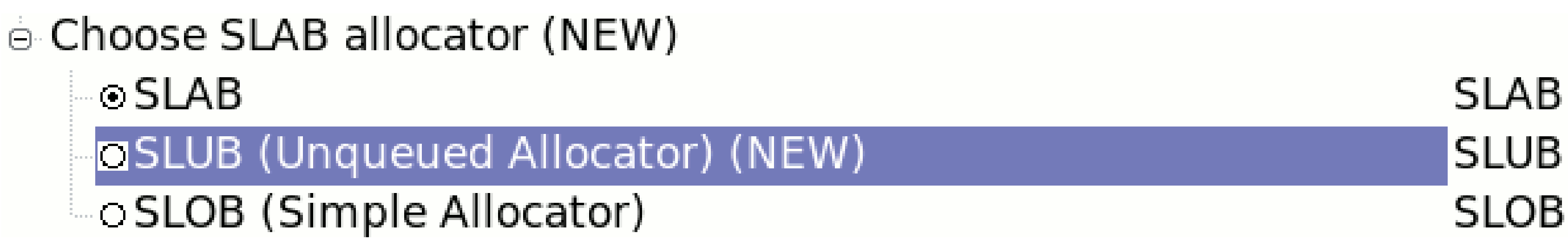
Again, names similar to those of C library functions

- `static inline void *kzalloc(`
  `size_t size, gfp_t flags);`
  Zeroes the allocated buffer.
- `static inline void *kcalloc(`
  `size_t n, size_t size, gfp_t flags);`
  Allocates memory for an array of `n` elements of size `size`, and zeroes its contents.
- `void * __must_check krealloc(`
  `const void *, size_t, gfp_t);`
  Changes the size of the given buffer.

Available allocators

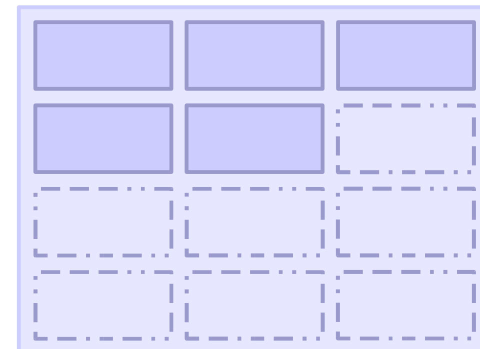
Memory is allocated using *slabs* (groups of one or more continuous pages from which objects are allocated). Several compatible slab allocators are available:

- SLAB: original, well proven allocator in Linux 2.6.
- SLOB: much simpler. More space efficient but doesn't scale well. Saves a few hundreds of KB in small systems (depends on `CONFIG_EMBEDDED`)
- SLUB: the new default allocator since 2.6.23, simpler than SLAB, scaling much better (in particular for huge systems) and creating less fragmentation.



Slab caches and memory pools

- *Slab caches*: make it possible to allocate multiple objects of the same size, without wasting RAM.
- So far, mainly used in core subsystems, but not much in device drivers (except USB and SCSI drivers)
- Memory pools: pools of preallocated objects, to increase the chances of allocations to succeed. Often used with file caches.



Allocating by pages

More appropriate when you need big slices of RAM:

- A page is usually `4K`, but can be made greater in some architectures (`sh`, `mips`: `4`, `8`, `16` or `64K`, but not configurable in `i386` or `arm`).
- `unsigned long get_zeroed_page(int flags);`
  Returns a pointer to a free page and fills it up with zeros
- `unsigned long __get_free_page(int flags);`
  Same, but doesn't initialize the contents
- ```
  unsigned long __get_free_pages(int flags,
                                 unsigned int order);
  ```
  Returns a pointer on an area of several contiguous pages in physical RAM.
  `order`: $\log_2$`(<number_of_pages>)`
  If variable, can be computed from the size with the get_order function.
  Maximum: 8192 KB (`MAX_ORDER=11` in `include/linux/mmzone.h`),
  except in a few architectures when overwritten with `CONFIG_FORCE_MAX_ZONEORDER`.
  ```

Freeing pages

- `void free_page(unsigned long addr);`
- ```
  void free_pages(unsigned long addr,
                  unsigned int order);
  ```
  Need to use the same `order` as in allocation.
  ```

vmalloc

`vmalloc` can be used to obtain contiguous memory zones in virtual address space (even if pages may not be contiguous in physical memory).

- `void *vmalloc(unsigned long size);`
- `void vfree(void *addr);`

Memory utilities

- `void * memset(void * s, int c, size_t count);`
  Fills a region of memory with the given value.
- ```
  void * memcpy(void * dest,
                const void *src,
                size_t count);
  ```
  Copies one area of memory to another.
  Use `memmove` with overlapping areas.
- Lots of functions equivalent to standard C library ones defined in `include/linux/string.h`
  and in `include/linux/kernel.h` (`sprintf`, etc.)
  ```

Kernel memory debugging

Debugging features available since 2.6.31

- Kmemcheck
  Dynamic checker for access to uninitialized memory.
  Only available on x86 so far, but will help to improve architecture independent code anyway.
  See Documentation/kmemcheck.txt for details.
- Kmemleak
  Dynamic checker for memory leaks
  This feature is available for all architectures.
  See Documentation/kmemleak.txt for details.

Both have a significant overhead. Only use them in development!

Driver development

I/O memory and ports

Port I/O vs. Memory-Mapped I/O

MMIO

- Same address bus to address memory and I/O devices
- Access to the I/O devices using regular instructions
- Most widely used I/O method across the different architectures supported by Linux

PIO

- Different address spaces for memory and I/O devices
- Uses a special class of CPU instructions to access I/O devices
- Example on x86: IN and OUT instructions

Requesting I/O ports

/proc/ioports example (x86)

```
0000-001f : dma1
0020-0021 : pic1
0040-0043 : timer0
0050-0053 : timer1
0060-006f : keyboard
0070-0077 : rtc
0080-008f : dma page reg
00a0-00a1 : pic2
00c0-00df : dma2
00f0-00ff : fpu
0100-013f : pcmcia_socket0
0170-0177 : ide1
01f0-01f7 : ide0
0376-0376 : ide1
0378-037a : parport0
03c0-03df : vga+
03f6-03f6 : ide0
03f8-03ff : serial
0800-087f : 0000:00:1f.0
0800-0803 : PM1a_EVT_BLK
0804-0805 : PM1a_CNT_BLK
0808-080b : PM_TMR
0820-0820 : PM2_CNT_BLK
0828-082f : GPE0_BLK
...
```

- ```
  struct resource *request_region(
      unsigned long start,
      unsigned long len,
      char *name);
  ```

  Tries to reserve the given region and returns `NULL` if unsuccessful. Example:

  ```
  request_region(0x0170, 8, "ide1");
  ```

- ```
  void release_region(
      unsigned long start,
      unsigned long len);
  ```

- See `include/linux/ioport.h` and `kernel/resource.c`

Mapping I/O ports in virtual memory

- Since Linux 2.6.9, it is possible to get a virtual address corresponding to an I/O ports range.
- Allows for transparent use of PIO and MMIO at the same time, as this memory can be accessed in the same way as MMIO memory.
- The mapping is done using the `ioport_map` function:

```
#include <asm/io.h>;

void *ioport_map(unsigned long port,
                 unsigned long nr);
void ioport_unmap(void *address);
```

Requesting I/O memory

`/proc/iomem` example

```
00000000-0009efff : System RAM
0009f000-0009ffff : reserved
000a0000-000bffff : Video RAM area
000c0000-000cffff : Video ROM
000f0000-000fffff : System ROM
00100000-3ffadfff : System RAM
  00100000-0030afff : Kernel code
  0030b000-003b4bff : Kernel data
3ffae000-3fffffff : reserved
40000000-400003ff : 0000:00:1f.1
40001000-40001fff : 0000:02:01.0
  40001000-40001fff : yenta_socket
40002000-40002fff : 0000:02:01.1
  40002000-40002fff : yenta_socket
40400000-407fffff : PCI CardBus #03
40800000-40bfffff : PCI CardBus #03
40c00000-40ffffff : PCI CardBus #07
41000000-413fffff : PCI CardBus #07
a0000000-a0000fff : pcmcia_socket0
a0001000-a0001fff : pcmcia_socket1
e0000000-e7ffffff : 0000:00:00.0
e8000000-efffffff : PCI Bus #01
  e8000000-efffffff : 0000:01:00.0
...
```

- Equivalent functions with the same interface
- ```
  struct resource * request_mem_region(
      unsigned long start,
      unsigned long len,
      char *name);
  ```
- ```
  void release_mem_region(
      unsigned long start,
      unsigned long len);
  ```

Mapping I/O memory in virtual memory

- To access I/O memory, drivers need to have a virtual address that the processor can handle.
- The `ioremap` functions satisfy this need:

```
#include <asm/io.h>;

void *ioremap(unsigned long phys_addr,
              unsigned long size);
void iounmap(void *address);
```

- Caution: check that `ioremap` doesn't return a `NULL` address!
- Note that an `ioremap_nocache` function exists.
  This disables the CPU cache at the given address range.

Differences with standard memory

- Reads and writes on memory can be cached
- The compiler may choose to write the value in a cpu register, and may never write it in main memory.
- The compiler may decide to optimize or reorder read and write instructions.

Avoiding I/O access issues

- Caching on I/O ports or memory already disabled, either by the hardware or by Linux init code.
- Use the `volatile` statement in your C code to prevent the compiler from using registers instead of writing to memory.
- Memory barriers are supplied to avoid reordering

Hardware independent

```
#include <asm/kernel.h>
void barrier(void);
```

Only impacts the behavior of the compiler. Doesn't prevent reordering in the processor: may not work on SMP or out-of-order architectures!

Hardware dependent

```
#include <asm/system.h>
void rmb(void);
void wmb(void);
void mb(void);
```

Safe on all architectures!

Accessing I/O ports – The “old” style

Functions to read/write bytes, word and longs to I/O ports:

```
unsigned in[bwl](unsigned long *addr);
void out[bwl](unsigned port, unsigned long *addr);
```

And the strings variants: often more efficient than the corresponding C loop, if the processor supports such operations!

```
void ins[bwl](unsigned port, void *addr, unsigned long count);
void outs[bwl](unsigned port, void *addr, unsigned long count);
```

Not usable with `ioport_map()`:
those functions need an I/O port number, not a pointer to memory.

Perfectly fine if doing only PIO

Accessing MMIO devices – The “old” style

- Directly reading from or writing to addresses returned by `ioremap` (“pointer dereferencing”) may not work on some architectures.
- To do PCI-style, little-endian accesses:

```
unsigned read[bwl](void *addr);
void write[bwl](unsigned a, void *addr);
```

- Perfectly fine if doing only MMIO. When doing mixed PIO and MMIO, the ioread/iowrite family of functions can be used everywhere instead of read/write

Accessing I/O memory – The “new” style

- Thanks to `ioport_map()`, it is possible to mix PIO and MMIO in a transparent way. The following functions can be used to access memory areas returned by `ioport_map()` or `ioremap()`:
  `unsigned int ioread8(void *addr);` (same for `16` and `32`)
  `void iowrite8(u8 value, void *addr);` (same for `16` and `32`)
- To read or write a series of values:
  ```
  void ioread8_rep(void *addr, void *buf, unsigned long count);
  void iowrite8_rep(void *addr, const void *buf, unsigned long count);
  ```
- Other useful functions:
  ```
  void memset_io(void *addr, u8 value, unsigned int count);
  void memcpy_fromio(void *dest, void *source, unsigned int count);
  void memcpy_toio(void *dest, void *source, unsigned int count);
  ```
- Note: many drivers still use old functions instead:
  `readb`, `readl`, `readw`, `writeb`, `writel`, `writew`, `outb`, `inb`, `...`

/dev/mem

- Used to provide user-space applications with direct access to physical addresses.
- Usage: open `/dev/mem` and read or write at given offset. What you read or write is the value at the corresponding physical address.
- Used by applications such as the X server to write directly to device memory.
- Since 2.6.26 (`x86` only, 2.6.32 status): only non-RAM can be accessed for security reasons, unless explicitly configured otherwise (`CONFIG_STRICT_DEVMEM`).

Driver development

Character drivers

Usefulness of character drivers

- Except for storage device drivers, most drivers for devices with input and output flows are implemented as character drivers.
- So, most drivers you will face will be character drivers
  You will regret if you sleep during this part!

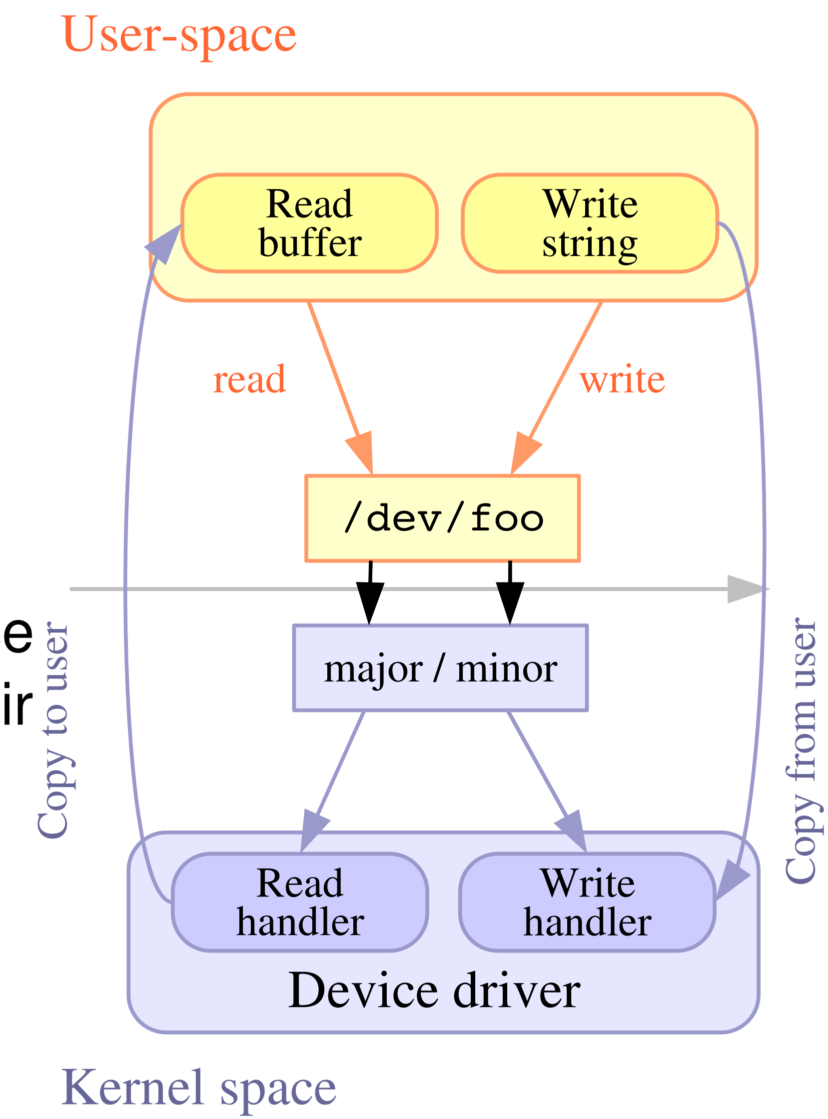
Creating a character driver

<u>User-space needs</u>

- The name of a device file in `/dev` to interact with the device driver through regular file operations (open, read, write, close...)

<u>The kernel needs</u>

- To know which driver is in charge of device files with a given major / minor number pair
- For a given driver, to have handlers ("*file operations*") to execute when user-space opens, reads, writes or closes the device file.



Declaring a character driver

Device number registration

- Need to register one or more device numbers (major / minor pairs), depending on the number of devices managed by the driver.
- Need to find free ones!

File operations registration

- Need to register handler functions called when user space programs access the device files: `open`, `read`, `write`, `ioctl`, `close`...

Information on registered devices

Registered devices are visible in `/proc/devices`:

```
Character devices:      Block devices:
  1 mem                   1 ramdisk
  4 /dev/vc/0             3 ide0
  4 tty                   8 sd
  4 ttyS                  9 md
  5 /dev/tty             22 ide1
  5 /dev/console         65 sd
  5 /dev/ptmx            66 sd
  6 lp                   67 sd
 10 misc                 68 sd
 13 input
 14 sound
 ...
```

Major number

Registered name

Can be used to find free major numbers

dev_t data type

Kernel data type to represent a major / minor number pair

- Also called a *device number*.
- Defined in `<linux/kdev_t.h>`
  Linux 2.6: 32 bit size (major: 12 bits, minor: 20 bits)
- Macro to compose the device number:
  `MKDEV(int major, int minor);`
- Macro to extract the minor and major numbers:
  `MAJOR(dev_t dev);`
  `MINOR(dev_t dev);`

Registering device numbers (1)

```
#include <linux/fs.h>

int register_chrdev_region(
        dev_t from,             /* Starting device number */
        unsigned count,         /* Number of device numbers */
        const char *name);      /* Registered name */
```

Returns `0` if the allocation was successful.

Example

```
static dev_t acme_dev = MKDEV(202, 128);

if (register_chrdev_region(acme_dev, acme_count, "acme")) {
printk(KERN_ERR "Failed to allocate device number\n");
...
```

Registering device numbers (2)

If you don't have fixed device numbers assigned to your driver

- Better not to choose arbitrary ones.
  There could be conflicts with other drivers.
- The kernel API offers a `alloc_chrdev_region` function
  to have the kernel allocate free ones for you. You can find the allocated major number in `/proc/devices.txt`.

File operations (1)

Before registering character devices, you have to define `file_operations` (called *fops*) for the device files.
Here are the main ones:

- ```
  int (*open) (
     struct inode *,  /* Corresponds to the device file */
     struct file *);  /* Corresponds to the open file descriptor */
  ```
  Called when user-space opens the device file.

- ```
  int (*release) (
     struct inode *,
     struct file *);
  ```
  Called when user-space closes the file.

The `file` structure

Is created by the kernel during the `open` call.
Represents open files.

- `mode_t f_mode;`
  The file opening mode (`FMODE_READ` and/or `FMODE_WRITE`)
- `loff_t f_pos;`
  Current offset in the file.
- `struct file_operations *f_op;`
  Allows to change file operations for different open files!
- `struct dentry *f_dentry`
  Useful to get access to the inode: `f_dentry->d_inode`.

File operations (2)

- ```
  ssize_t (*read) (
      struct file *,          /* Open file descriptor */
      __user char *,          /* User-space buffer to fill up */
      size_t,                 /* Size of the user-space buffer */
      loff_t *);              /* Offset in the open file */
  ```
  Called when user-space reads from the device file.

- ```
  ssize_t (*write) (
      struct file *,              /* Open file descriptor */
      __user const char *,        /* User-space buffer to write
                                     to the device */
      size_t,                     /* Size of the user-space buffer */
      loff_t *);                  /* Offset in the open file */
  ```
  Called when user-space writes to the device file.

Exchanging data with user-space (1)

In driver code, you can't just `memcpy` between an address supplied by user-space and the address of a buffer in kernel-space!

- Correspond to completely different address spaces (thanks to virtual memory)
- The user-space address may be swapped out to disk
- The user-space address may be invalid (user space process trying to access unauthorized data)

Exchanging data with user-space (2)

You must use dedicated functions such as the following ones in your `read` and `write` file operations code:

```
include <asm/uaccess.h>

unsigned long copy_to_user (void __user *to,
                      const void *from,
                      unsigned long n);

unsigned long copy_from_user (void *to,
                    const void __user *from,
                    unsigned long n);
```

Make sure that these functions return `0`!
Another return value would mean that they failed.

File operations (3)

- `int (*ioctl) (struct inode *, struct file *, unsigned int, unsigned long);`

  Can be used to send specific commands to the device, which are neither reading nor writing (e.g. changing the speed of a serial port, setting video output format, querying a device serial number...).

File operations (4)

- `int (*mmap) (struct file *,`
  `struct vm_area_struct *);`

  Asking for device memory to be mapped
  into the address space of a user process.
  More in our mmap section.

- These were just the main ones:
  about 25 file operations can be set, corresponding to all the system calls that can be performed on open files.

read operation example

```
static ssize_t
acme_read(struct file *file, char __user *buf, size_t count, loff_t *ppos)
{
   /* The acme_buf address corresponds to a device I/O memory area */
   /* of size acme_bufsize, obtained with ioremap() */
   int remaining_size, transfer_size;

   remaining_size = acme_bufsize - (int) (*ppos); // bytes left to transfer
   if (remaining_size == 0) { /* All read, returning 0 (End Of File) */
      return 0;
   }

   /* Size of this transfer */
   transfer_size = min(remaining_size, (int) count);

   if (copy_to_user(buf /* to */, acme_buf + *ppos /* from */, transfer_size)) {
      return -EFAULT;
   } else { /* Increase the position in the open file */
      *ppos += transfer_size;
      return transfer_size;
   }
}
```

Read method

Piece of code available in
http://free-electrons.com/doc/c/acme.c

write operation example

```
static ssize_t
acme_write(struct file *file, const char __user *buf, size_t count, loff_t *ppos)
{
   int remaining_bytes;

   /* Number of bytes not written yet in the device */
   remaining_bytes = acme_bufsize - (*ppos);

   if (count > remaining_bytes) {
      /* Can't write beyond the end of the device */
      return -EIO;
   }

   if (copy_from_user(acme_buf + *ppos /* to */, buf /* from */, count)) {
      return -EFAULT;
   } else {
      /* Increase the position in the open file */
      *ppos += count;
      return count;
   }
}
```

Write method

Piece of code available in
http://free-electrons.com/doc/c/acme.c

file operations definition example (3)

Defining a `file_operations` structure:

```
#include <linux/fs.h>

static struct file_operations acme_fops =
{
    .owner = THIS_MODULE,
    .read = acme_read,
    .write = acme_write,
};
```

You just need to supply the functions you implemented! Defaults for other functions (such as `open`, `release`...) are fine if you do not implement anything special.

Character device registration (1)

- The kernel represents character drivers with a `cdev` structure
- Declare this structure globally (within your module):

```
#include <linux/cdev.h>
static struct cdev acme_cdev;
```

- In the init function, initialize the structure:

```
cdev_init(&acme_cdev, &acme_fops);
```

Character device registration (2)

- Then, now that your structure is ready, add it to the system:

```
int cdev_add(
     struct cdev *p,    /* Character device structure */
     dev_t dev,         /* Starting device major / minor number */
     unsigned count);   /* Number of devices */
```

- Example (continued):

```
if (cdev_add(&acme_cdev, acme_dev, acme_count)) {
printk (KERN_ERR "Char driver registration failed\n");
...
```

Character device unregistration

- First delete your character device:
```
void cdev_del(struct cdev *p);
```
- Then, and only then, free the device number:
```
void unregister_chrdev_region(dev_t from,
unsigned count);
```
- Example (continued):
```
cdev_del(&acme_cdev);
unregister_chrdev_region(acme_dev, acme_count);
```

Linux error codes

Try to report errors with error numbers as accurate as possible! Fortunately, macro names are explicit and you can remember them quickly.

- Generic error codes:
  `include/asm-generic/errno-base.h`
- Platform specific error codes:
  `include/asm/errno.h`

Char driver example summary (1)

```
static void *acme_buf;
static int acme_bufsize=8192;

static int acme_count=1;
static dev_t acme_dev = MKDEV(202,128);

static struct cdev acme_cdev;

static ssize_t acme_write(...) {...}

static ssize_t acme_read(...) {...}

static struct file_operations acme_fops =
{
    .owner = THIS_MODULE,
    .read = acme_read,
    .write = acme_write
};
```

Char driver example summary (2)

Shows how to handle errors and deallocate resources in the right order!

```
static int __init acme_init(void)
{
    int err;
    acme_buf = ioremap (ACME_PHYS,
                        acme_bufsize);

    if (!acme_buf) {
       err = -ENOMEM;
       goto err_exit;
    }

    if (register_chrdev_region(acme_dev,
                     acme_count, “acme”)) {
       err=-ENODEV;
       goto err_free_buf;
    }

    cdev_init(&acme_cdev, &acme_fops);

    if (cdev_add(&acme_cdev, acme_dev,
                 acme_count)) {
       err=-ENODEV;
       goto err_dev_unregister;
    }
```

```
    return 0;

    err_dev_unregister:
        unregister_chrdev_region(
           acme_dev, acme_count);
    err_free_buf:
        iounmap(acme_buf);
    err_exit:
        return err;
}

static void __exit acme_exit(void)
{
    cdev_del(&acme_cdev);
    unregister_chrdev_region(acme_dev,
                       acme_count);
    iounmap(acme_buf);
}
```

Complete example code available on http://free-electrons.com/doc/c/acme.c

Character driver summary

Character driver writer - Define the file operations callbacks for the device file: `read`, `write`, `ioctl`... - In the module init function, reserve major and minor numbers with `register_chrdev_region()`, init a `cdev` structure with your file operations and add it to the system with `cdev_add()`. - In the module exit function, call `cdev_del()` and `unregister_chrdev_region()`	Kernel
System administration - Load the character driver module - Create device files with matching major and minor numbers if needed The device file is ready to use!	User-space
System user - Open the device file, read, write, or send ioctl's to it.	User-space
Kernel - Executes the corresponding file operations	Kernel

Practical lab – Character drivers

- Writing a simple character driver, to write data to the serial port.
- On your workstation, checking that transmitted data is received correctly.
- Exchanging data between userspace and kernel space.
- Practicing with the character device driver API.
- Using kernel standard error codes.

Driver development

Processes and scheduling

Processes

A process is an instance of a running program

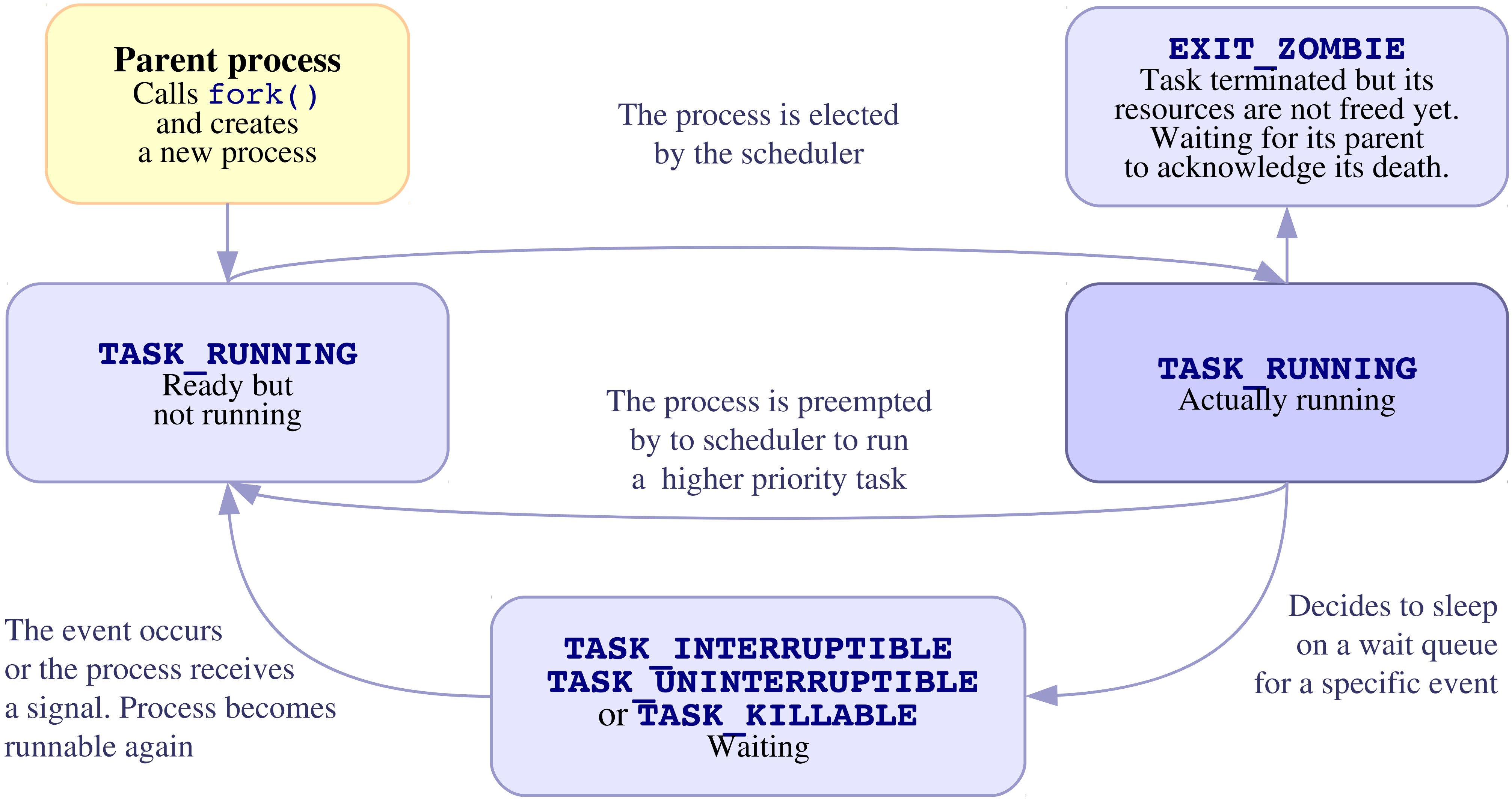
- Multiple instances of the same program can be running. Program code (“text section”) memory is shared.
- Each process has its own data section, address space, processor state, open files and pending signals.
- The kernel has a separate data structure for each process.

Threads

In Linux, threads are just implemented as processes!

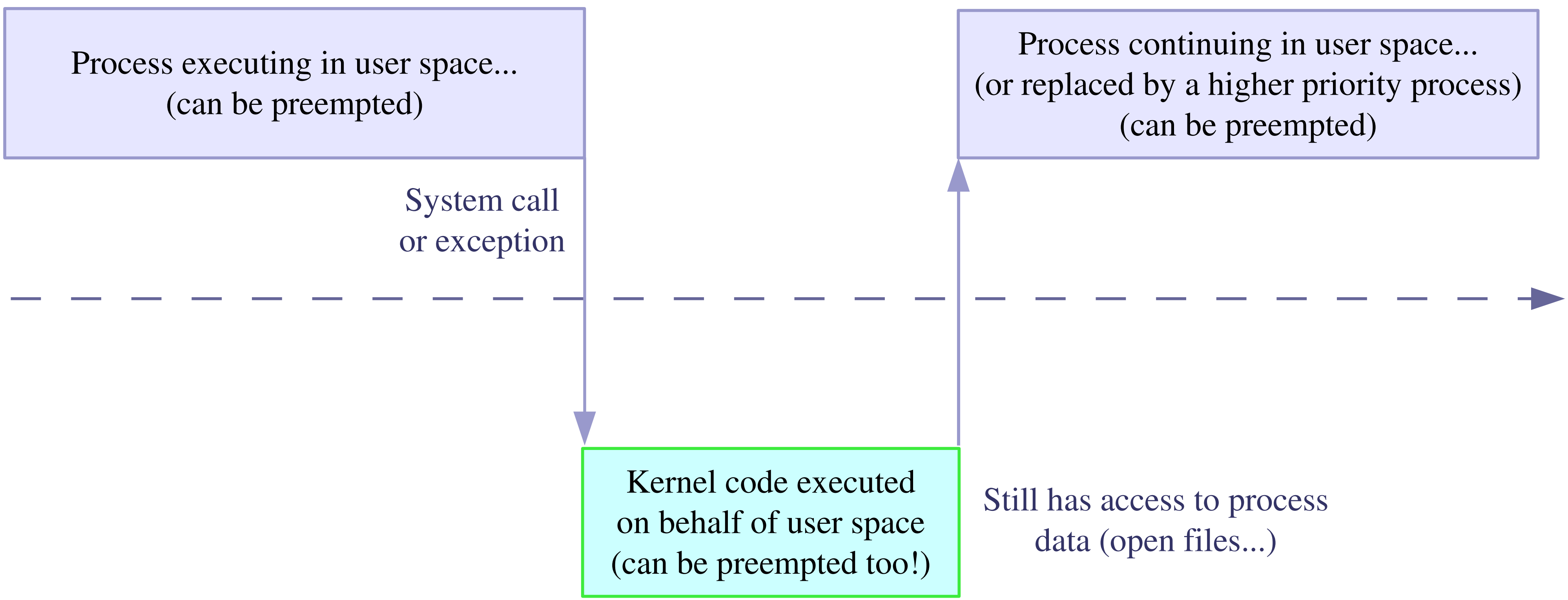
- New threads are implemented as regular processes, with the particularity that they are created with the same address space, filesystem resources, file descriptors and signal handlers as their parent process.

A process life



Process context

User space programs and system calls are scheduled together



Kernel threads

- The kernel does not only react from user-space (system calls, exceptions) or hardware events (interrupts). It also runs its own processes.
- Kernel threads are standard processes scheduled and preempted in the same way (you can view them with `top` or `ps`!) They just have no special address space and usually run forever.
- Kernel thread examples:
  - `pdflush`: regularly flushes “dirty” memory pages to disk (file changes not committed to disk yet).
  - `migration/<n>`: Per CPU threads to migrate processes between processors, to balance CPU load between processors.

Process priorities

Regular processes

- Priorities from `-20` (maximum) to `19` (minimum)
- Only `root` can set negative priorities
  (`root` can give a negative priority to a regular user process)
- Use the `nice` command to run a job with a given priority:
  `nice -n <priority> <command>`
- Use the `renice` command to change a process priority:
  `renice <priority> -p <pid>`

Timeslices

The scheduler prioritizes high priority processes
by giving them a bigger timeslice.

- Initial process timeslice: parent's timeslice split in 2 (otherwise process would cheat by forking).
- Minimum priority: 5 ms or 1 jiffy (whichever is larger)
- Default priority in jiffies: 100 ms
- Maximum priority: 800 ms

Note: actually depends on `HZ`.
See `kernel/sched.c` for details.

Real-time priorities

Processes with real-time priority can be started by `root` using the POSIX API

- Available through `<sched.h>` (see `man sched.h` for details)
- 100 real-time priorities available
- `SCHED_FIFO` scheduling class:
  The process runs until completion unless it is blocked by an I/O, voluntarily relinquishes the CPU, or is preempted by a higher priority process.
- `SCHED_RR` scheduling class:
  Difference: the processes are scheduled in a Round Robin way.
  Each process is run until it exhausts a max time quantum. Then other processes with the same priority are run, and so and so...

When is scheduling run?

Each process has a `need_resched` flag which is set:

- After a process exhausted its timeslice.
- After a process with a higher priority is awakened.

This flag is checked (possibly causing the execution of the scheduler)

- When returning to user-space from a system call
- When returning from interrupts (including the cpu timer), when kernel preemption is enabled.

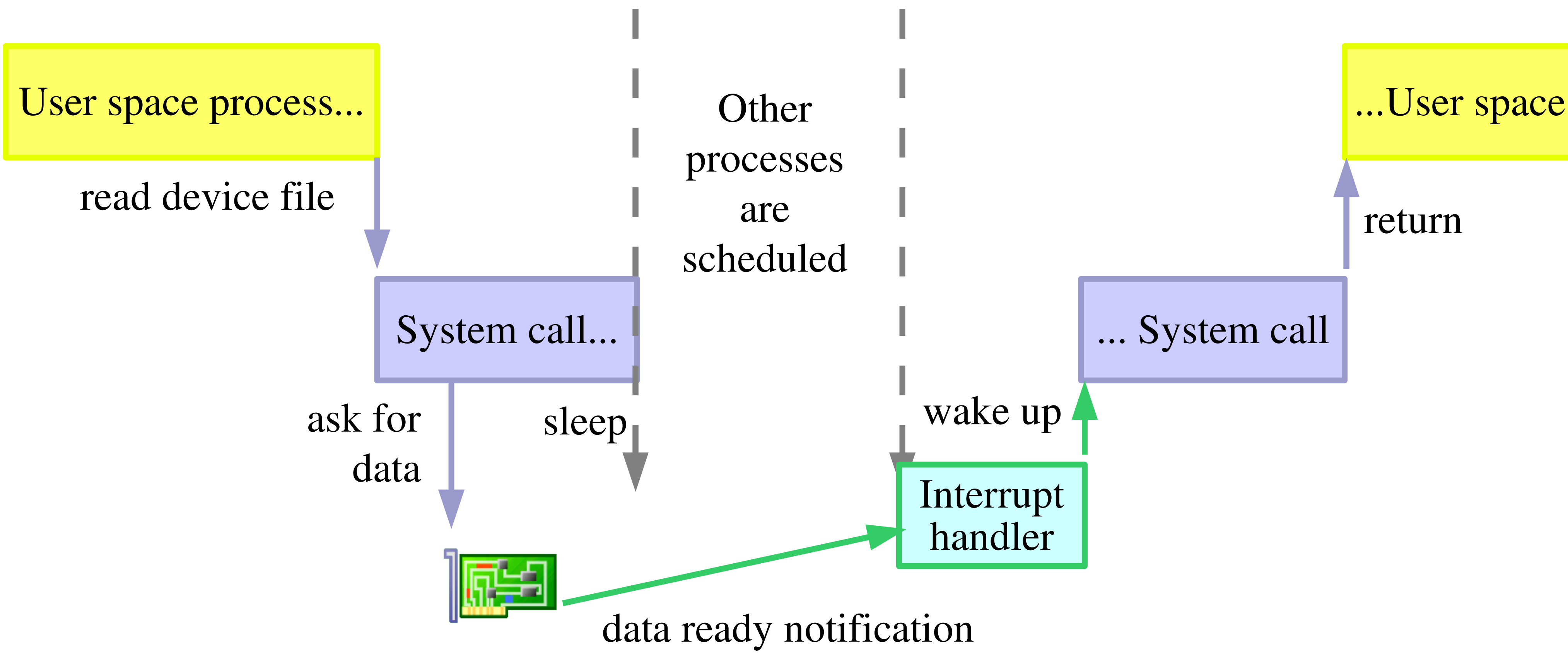
Scheduling also happens when kernel code explicitly runs `schedule()` or executes an action that sleeps.

Driver development

Sleeping

Sleeping

Sleeping is needed when a process (user space or kernel space) is waiting for data.



How to sleep (1)

Must declare a wait queue

- Static queue declaration

```
DECLARE_WAIT_QUEUE_HEAD (module_queue);
```

- Or dynamic queue declaration

```
wait_queue_head_t queue;
init_waitqueue_head(&queue);
```

How to sleep (2)

Several ways to make a kernel process sleep

- `wait_event(queue, condition);`
  Sleeps until the task is woken up and the given C expression is true.
  Caution: can't be interrupted (can't kill the user-space process!)
- `wait_event_killable(queue, condition);` (Since Linux 2.6.25)
  Can be interrupted, but only by a “fatal” signal (`SIGKILL`)
- `wait_event_interruptible(queue, condition);`
  Can be interrupted by any signal
- `wait_event_timeout(queue, condition, timeout);`
  Also stops sleeping when the task is woken up and the timeout expired.
- `wait_event_interruptible_timeout(queue, condition, timeout);`
  Same as above, interruptible.

How to sleep - Example

From `drivers/ieee1394/video1394.c`

```
wait_event_interruptible(
   d->waitq,
   (d->buffer_status[v.buffer]
    == VIDEO1394_BUFFER_READY)
);

if (signal_pending(current))
   return -EINTR;
```

Currently running process

Waking up!

Typically done by interrupt handlers when data sleeping processes are waiting for are available.

- `wake_up(&queue);`
  Wakes up all the waiting processes on the given queue
- `wake_up_interruptible(&queue);`
  Wakes up only the processes waiting in an interruptible sleep on the given queue

Sleeping and waking up - implementation

The scheduler doesn't keep evaluating the sleeping condition!

- `wait_event_interruptible(&queue, condition);`
  The process is put in the `TASK_INTERRUPTIBLE` state.
- `wake_up_interruptible(&queue);`
  For all processes waiting in `queue`, `condition` is evaluated. When it evaluates to true, the process is put back to the `TASK_RUNNING` state, and the `need_resched` flag for the current process is set.

This way, several processes can be woken up at the same time.

Driver development

Interrupt management

Interrupt handler constraints

- Not run from a user context:
  Can't transfer data to and from user space
  (need to be done by system call handlers)
- Interrupt handler execution is managed by the CPU, not by the scheduler. Handlers can't run actions that may sleep, because there is nothing to resume their execution. In particular, need to allocate memory with `GFP_ATOMIC`.
- Have to complete their job quickly enough:
  they shouldn't block their interrupt line for too long.

Registering an interrupt handler (1)

Defined in `include/linux/interrupt.h`

- ```
  int request_irq(               Returns 0 if successful
      unsigned int irq,          Requested irq channel
      irq_handler_t handler,     Interrupt handler
      unsigned long irq_flags,   Option mask (see next page)
      const char * devname,      Registered name
      void *dev_id);             Pointer to some handler data
  ```
  Cannot be NULL and must be unique for shared irqs!
- `void free_irq( unsigned int irq, void *dev_id);`
- `dev_id` cannot be NULL and must be unique for shared irqs.
  Otherwise, on a shared interrupt line,
  `free_irq` wouldn't know which handler to free.
  ```

Registering an interrupt handler (2)

`irq_flags` bit values (can be combined, none is fine too)

- `IRQF_DISABLED`
  "Quick" interrupt handler. Run with all interrupts disabled on the current cpu (instead of just the current line). For latency reasons, should only be used when needed!
- `IRQF_SHARED`
  Run with interrupts disabled only on the current irq line and on the local cpu. The interrupt channel can be shared by several devices. Requires a hardware status register telling whether an IRQ was raised or not.

When to register the handler

- Either at driver initialization time:
  consumes lots of IRQ channels!
- Or at device open time (first call to the `open` file operation):
  better for saving free IRQ channels.
  Need to count the number of times the device is opened, to be able to free the IRQ channel when the device is no longer in use.

Information on installed handlers

`/proc/interrupts`

```
           CPU0
  0:    5616905          XT-PIC  timer # Registered name
  1:       9828          XT-PIC  i8042
  2:          0          XT-PIC  cascade
  3:    1014243          XT-PIC  orinoco_cs
  7:        184          XT-PIC  Intel 82801DB-ICH4
  8:          1          XT-PIC  rtc
  9:          2          XT-PIC  acpi
 11:     566583          XT-PIC  ehci_hcd, uhci_hcd,
uhci_hcd, uhci_hcd, yenta, yenta, radeon@PCI:1:0:0
 12:       5466          XT-PIC  i8042
 14:     121043          XT-PIC  ide0
 15:     200888          XT-PIC  ide1
NMI:          0           Non Maskable Interrupts
ERR:          0           Spurious interrupt count
```

Total number of interrupts

```
cat /proc/stat | grep intr
intr 8190767 6092967 10377 0 1102775 5 2 0 196 ...
```

Total number of of interrupts	IRQ1 total	IRQ2 total	IRQ3 ...

The interrupt handler's job

- Acknowledge the interrupt to the device (otherwise no more interrupts will be generated)
- Read/write data from/to the device
- Wake up any waiting process waiting for the completion of this read/write operation:
  `wake_up_interruptible(&module_queue);`

Interrupt handler prototype

```
irqreturn_t (*handler) (
   int,              // irq number of the current interrupt
   void *dev_id      // Pointer used to keep track
                     // of the corresponding device.
                     // Useful when several devices
                     // are managed by the same module
);
```

Return value:

- `IRQ_HANDLED`: recognized and handled interrupt
- `IRQ_NONE`: not on a device managed by the module. Useful to share interrupt channels and/or report spurious interrupts to the kernel.

Top half and bottom half processing (1)

Splitting the execution of interrupt handlers in 2 parts

- *Top half*: the interrupt handler must complete as quickly as possible. Once it acknowledged the interrupt, it just schedules the lengthy rest of the job taking care of the data, for a later execution.
- *Bottom half*: completing the rest of the interrupt handler job. Handles data, and then wakes up any waiting user process.
  Best implemented by *tasklets* (also called *soft irqs*).

Top half and bottom half processing (2)

- Declare the tasklet in the module source file:

```
DECLARE_TASKLET (module_tasklet,      /* name */
                 module_do_tasklet,   /* function */
                 data                 /* params */
);
```

- Schedule the tasklet in the top half part (interrupt handler):

```
tasklet_schedule(&module_tasklet);
```

- Note that a `tasklet_hi_schedule` function is available to define high priority tasklets to run before ordinary ones.

By default, tasklets are executed right after all top halves (hard irqs)

Interrupt management fun

- In a training lab, somebody forgot to unregister a handler on a shared interrupt line in the module exit function.

> ? Why did his kernel oops with a segmentation fault at module unload?
>
> Answer...

- In a training lab, somebody freed the timer interrupt handler by mistake (using the wrong irq number). The system froze. Remember the kernel is not protected against itself!

Interrupt management summary

Device driver

- When the device file is first open, register an interrupt handler for the device's interrupt channel.

Interrupt handler

- Called when an interrupt is raised.
- Acknowledge the interrupt
- If needed, schedule a tasklet taking care of handling data. Otherwise, wake up processes waiting for the data.

Tasklet

- Process the data
- Wake up processes waiting for the data

Device driver

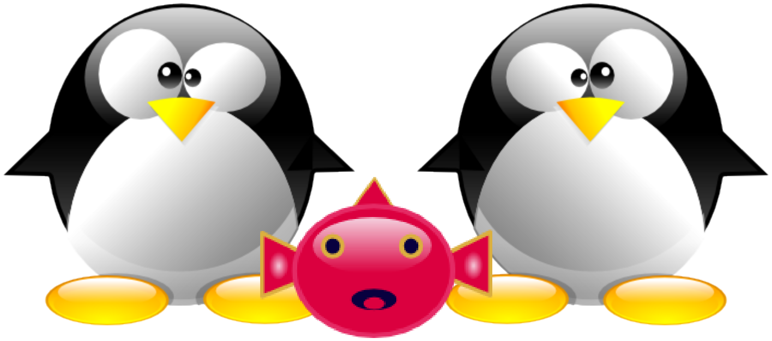
- When the device is no longer opened by any process, unregister the interrupt handler.

Practical lab – Interrupts

- Adding read capability to the character driver developed earlier.
- Register an interrupt handler.
- Waiting for data to be available in the read file operation.
- Waking up the code when data is available from the device.

Driver development

Concurrent access to resources



Sources of concurrency issues

The same resources can be accessed by several kernel processes in parallel, causing potential concurrency issues

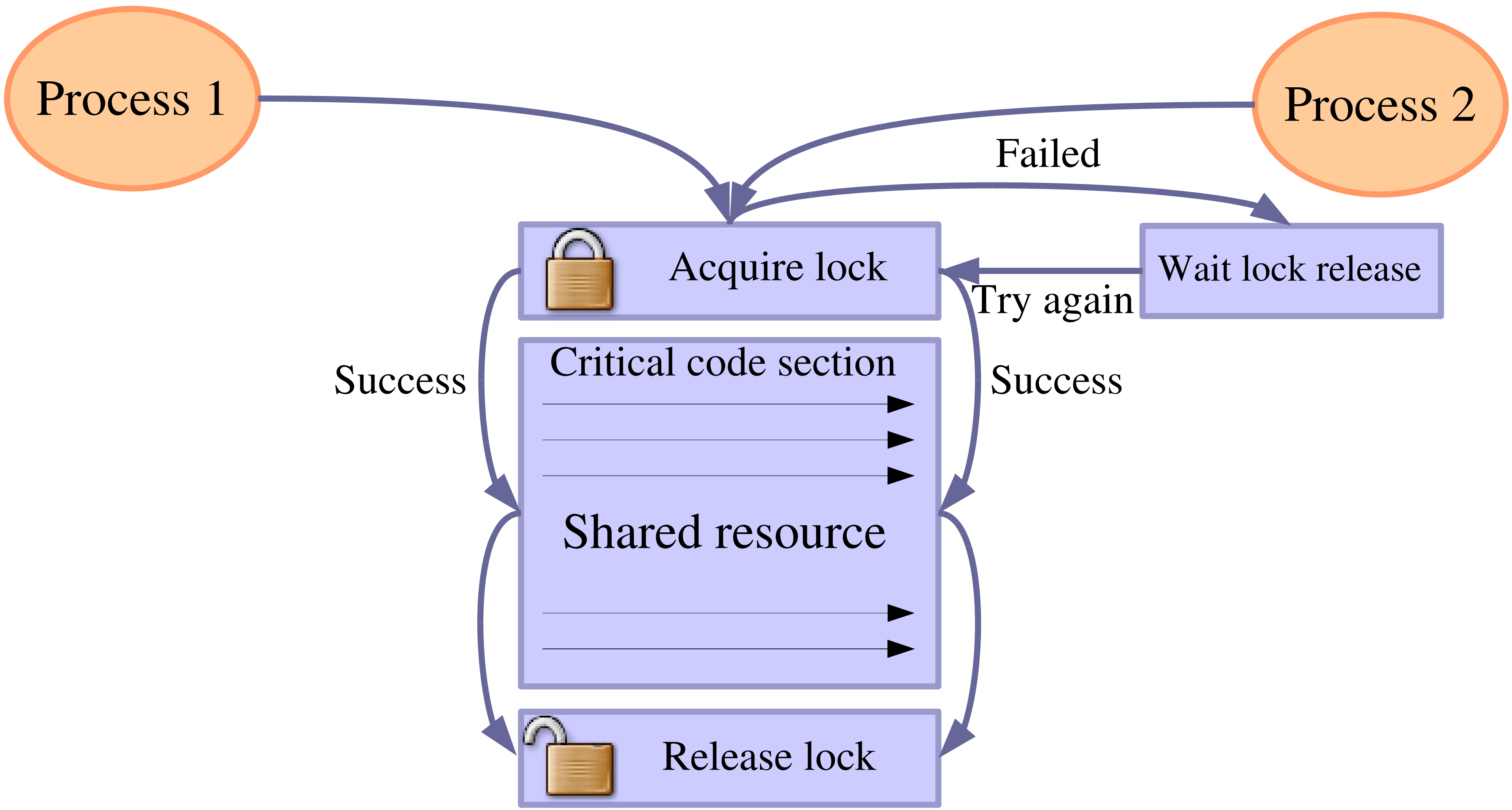
- Several user-space programs accessing the same device data or hardware. Several kernel processes could execute the same code on behalf of user processes running in parallel.
- Multiprocessing: the same driver code can be running on another processor. This can also happen with single CPUs with hyperthreading.
- Kernel preemption, interrupts: kernel code can be interrupted at any time (just a few exceptions), and the same data may be access by another process before the execution continues.

Avoiding concurrency issues

- Avoid using global variables and shared data whenever possible
(cannot be done with hardware resources).
- Use techniques to manage concurrent access to resources.

See Rusty Russell's Unreliable Guide To Locking
`Documentation/DocBook/kernel-locking/`
in the kernel sources.

Concurrency protection with locks



Linux mutexes

- The main locking primitive since Linux 2.6.16.
  Better than counting semaphores when binary ones are enough.
- Mutex definition:
  `#include <linux/mutex.h>`
- Initializing a mutex statically:
  `DEFINE_MUTEX(name);`
- Or initializing a mutex dynamically:
  `void mutex_init(struct mutex *lock);`

locking and unlocking mutexes

- `void mutex_lock (struct mutex *lock);`
  Tries to lock the mutex, sleeps otherwise.
  Caution: can't be interrupted, resulting in processes you cannot kill!
- `int mutex_lock_killable (struct mutex *lock);`
  Same, but can be interrupted by a fatal (`SIGKILL`) signal. If interrupted, returns a non zero value and doesn't hold the lock. Test the return value!!!
- `int mutex_lock_interruptible (struct mutex *lock);`
  Same, but can be interrupted by any signal.
- `int mutex_trylock (struct mutex *lock);`
  Never waits. Returns a non zero value if the mutex is not available.
- `int mutex_is_locked(struct mutex *lock);`
  Just tells whether the mutex is locked or not.
- `void mutex_unlock (struct mutex *lock);`
  Releases the lock. Do it as soon as you leave the critical section.

Reader / writer semaphores

Allow shared access by unlimited readers, or by only 1 writer. Writers get priority.

```
void init_rwsem (struct rw_semaphore *sem);

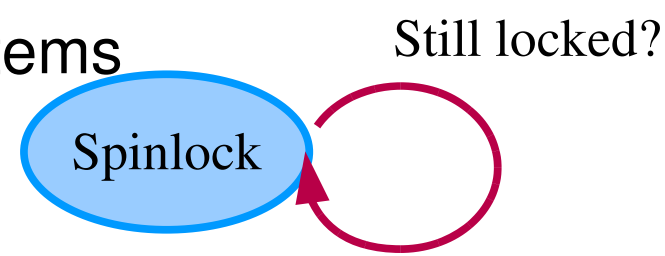
void down_read (struct rw_semaphore *sem);
int down_read_trylock (struct rw_semaphore *sem);
int up_read (struct rw_semaphore *sem);

void down_write (struct rw_semaphore *sem);
int down_write_trylock (struct rw_semaphore *sem);
int up_write (struct rw_semaphore *sem);
```

Well suited for rare writes, holding the semaphore briefly. Otherwise, readers get *starved*, waiting too long for the semaphore to be released.

Spinlocks

- Locks to be used for code that is not allowed to sleep (interrupt handlers), or that doesn't want to sleep (critical sections). Be very careful not to call functions which can sleep!
- Originally intended for multiprocessor systems
- Spinlocks never sleep and keep spinning in a loop until the lock is available.
- Spinlocks cause kernel preemption to be disabled on the CPU executing them.



Initializing spinlocks

- Static

```
spinlock_t my_lock = SPIN_LOCK_UNLOCKED;
```

- Dynamic

```
void spin_lock_init (spinlock_t *lock);
```

Using spinlocks

Several variants, depending on where the spinlock is called:

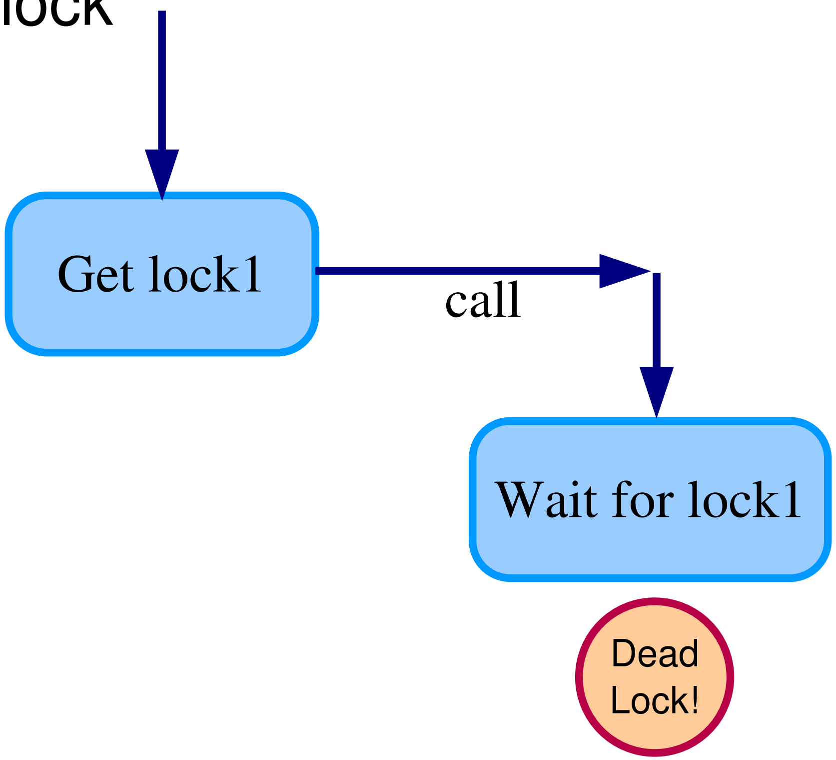
- `void spin_[un]lock (spinlock_t *lock);`
  Doesn't disable interrupts. Used for locking in process context (critical sections in which you do not want to sleep).
- `void spin_lock_irqsave / spin_unlock_irqrestore (spinlock_t *lock, unsigned long flags);`
  Disables / restores IRQs on the local CPU.
  Typically used when the lock can be accessed in both process and interrupt context, to prevent preemption by interrupts.
- `void spin_[un]lock_bh (spinlock_t *lock);`
  Disables software interrupts, but not hardware ones.
  Useful to protect shared data accessed in process context and in a soft interrupt (“bottom half”). No need to disable hardware interrupts in this case.

Note that reader / writer spinlocks also exist.

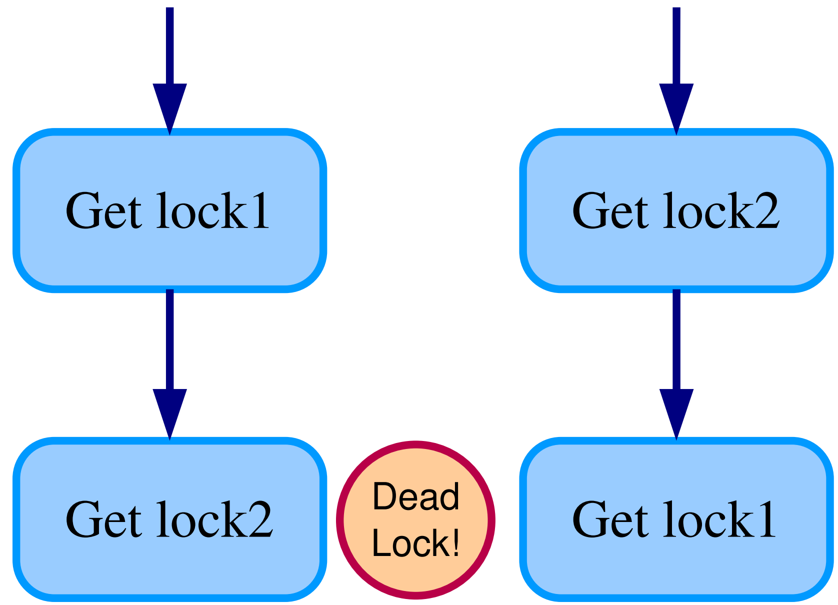
Deadlock situations

They can lock up your system. Make sure they never happen!

Don't call a function that can try to get access to the same lock



Holding multiple locks is risky!



Kernel lock validator

From Ingo Molnar and Arjan van de Ven

- Adds instrumentation to kernel locking code
- Detect violations of locking rules during system life, such as:
  - Locks acquired in different order
    (keeps track of locking sequences and compares them).
  - Spinlocks acquired in interrupt handlers and also in process context when interrupts are enabled.
- Not suitable for production systems but acceptable overhead in development.

See Documentation/lockdep-design.txt for details

Alternatives to locking

As we have just seen, locking can have a strong negative impact on system performance. In some situations, you could do without it.

- By using lock-free algorithms like Read Copy Update (RCU). RCU API available in the kernel (See http://en.wikipedia.org/wiki/RCU).
- When available, use atomic operations.

Atomic variables

- Useful when the shared resource is an integer value
- Even an instruction like `n++` is not guaranteed to be atomic on all processors!

Header

- `#include <asm/atomic.h>`

Type

- `atomic_t`
  contains a signed integer (at least 24 bits)

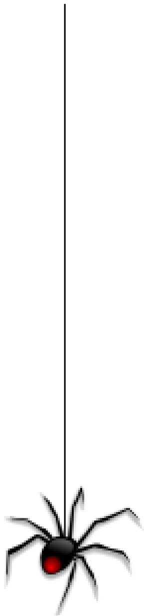
Atomic operations (main ones)

- Set or read the counter:
```
atomic_set (atomic_t *v, int i);
int atomic_read (atomic_t *v);
```
- Operations without return value:
```
void atomic_inc (atomic_t *v);
void atomic_dec (atomic_t *v);
void atomic_add (int i, atomic_t *v);
void atomic_sub (int i, atomic_t *v);
```
- Simular functions testing the result:
```
int atomic_inc_and_test (...);
int atomic_dec_and_test (...);
int atomic_sub_and_test (...);
```
- Functions returning the new value:
```
int atomic_inc_and_return (...);
int atomic_dec_and_return (...);
int atomic_add_and_return (...);
int atomic_sub_and_return (...);
```

Atomic bit operations

- Supply very fast, atomic operations
- On most platforms, apply to an `unsigned long` type.
  Apply to a `void` type on a few others.
- Set, clear, toggle a given bit:
  ```
  void set_bit(int nr, unsigned long * addr);
  void clear_bit(int nr, unsigned long * addr);
  void change_bit(int nr, unsigned long * addr);
  ```
- Test bit value:
  ```
  int test_bit(int nr, unsigned long *addr);
  ```
- Test and modify (return the previous value):
  ```
  int test_and_set_bit (...);
  int test_and_clear_bit (...);
  int test_and_change_bit (...);
  ```

- Add locking to the driver to prevent concurrent accesses to shared ressources



Driver development

Debugging and tracing

Debugging with printk

- Universal debugging technique used since the beginning of programming (first found in cavemen drawings)
- Printed or not in the console or `/var/log/messages` according to the priority. This is controlled by the `loglevel` kernel parameter, or through `/proc/sys/kernel/printk` (see `Documentation/sysctl/kernel.txt`)
- Available priorities (`include/linux/kernel.h`):

```
#define KERN_EMERG      "<0>"   /* system is unusable */
#define KERN_ALERT      "<1>"   /* action must be taken immediately */
#define KERN_CRIT       "<2>"   /* critical conditions */
#define KERN_ERR        "<3>"   /* error conditions */
#define KERN_WARNING    "<4>"   /* warning conditions */
#define KERN_NOTICE     "<5>"   /* normal but significant condition */
#define KERN_INFO       "<6>"   /* informational */
#define KERN_DEBUG      "<7>"   /* debug-level messages */
```

Debugging with /proc or /sys

Instead of dumping messages in the kernel log, you can have your drivers make information available to user space

- Through a file in `/proc` or `/sys`, which contents are handled by callbacks defined and registered by your driver.
- Can be used to show any piece of information about your device or driver.
- Can also be used to send data to the driver or to control it.
- Caution: anybody can use these files.
  You should remove your debugging interface in production!
- Since the arrival of *debugfs*, no longer the preferred debugging mechanism

Debugfs

A virtual filesystem to export debugging information to user-space.

- Kernel configuration: `DEBUG_FS`
  `Kernel hacking -> Debug Filesystem`
- Much simpler to code than an interface in `/proc` or `/sys`.
  The debugging interface disappears when Debugfs is configured out.
- You can mount it as follows:
  `sudo mount -t debugfs none /mnt/debugfs`
- First described on http://lwn.net/Articles/115405/
- API documented in the Linux Kernel Filesystem API:
  http://free-electrons.com/kerneldoc/latest/DocBook/filesystems/index.html

Simple debugfs example

```
#include <linux/debugfs.h>

static char *acme_buf;                                  // module buffer
static unsigned long acme_bufsize;
static struct debugfs_blob_wrapper acme_blob;
static struct dentry *acme_buf_dentry;

static u32 acme_state;                                  // module variable
static struct dentry *acme_state_dentry;

/* Module init */
acme_blob.data = acme_buf;
acme_blob.size = acme_bufsize;
acme_buf_dentry = debugfs_create_blob("acme_buf", S_IRUGO,      // Create
                                      NULL, &acme_blob);        // new files
acme_state_dentry = debugfs_create_bool("acme_state", S_IRUGO,  // in debugfs
                                      NULL, &acme_state);

/* Module exit */
debugfs_remove (acme_buf_dentry);                       // removing the files from debugfs
debugfs_remove (acme_state_dentry);
```

Debugging with ioctl

- Can use the `ioctl()` system call to query information about your driver (or device) or send commands to it.
- This calls the `ioctl` file operation that you can register in your driver.
- Advantage: your debugging interface is not public.
  You could even leave it when your system (or its driver) is in the hands of its users.

Using Magic SysRq

Linux also has 3-finger-keys to save your work ;-)

- Allows to run multiple debug / rescue commands even when the kernel seems to be in deep trouble. Example commands:
  - `[ALT][SysRq][d]`: kills all processes, except init.
  - `[ALT][SysRq][n]`: makes RT processes nice-able.
  - `[ALT][SysRq][s]`: attempts to sync all mounted filesystems.
  - `[ALT][SysRq][b]`: immediately reboot without syncing and unmounting.
- Typical combination: `[ALT][SysRq][s]` and then `[ALT][SysRq][b]`
- Detailed in `Documentation/sysrq.txt`

Debugging with gdb

- If you execute the kernel from a debugger on the same machine, this will interfere with the kernel behavior.
- However, you can access the current kernel state with `gdb`:
  `gdb /usr/src/linux/vmlinux /proc/kcore`
  uncompressed kernel — kernel address space
- You can access kernel structures, follow pointers... (read only!)
- Requires the kernel to be compiled with `CONFIG_DEBUG_INFO` (`Kernel hacking` section)

kgdb - A kernel debugger

- The execution of the kernel is fully controlled by `gdb` from another machine, connected through a serial line.
- Can do almost everything, including inserting breakpoints in interrupt handlers.
- Feature included in standard Linux since 2.6.26 (`x86` and `sparc`). `arm`, `mips` and `ppc` support merged in 2.6.27.

Using kgdb

- Details available in the kernel documentation: http://free-electrons.com/kerneldoc/latest/DocBook/kgdb/
- Recommended to turn on `CONFIG_FRAME_POINTER` to aid in producing more reliable stack backtraces in gdb.
- You must include a kgdb I/O driver. One of them is kgdb over serial console (`kgdboc`: *kgdb over console*, enabled by `CONFIG_KGDB_SERIAL_CONSOLE`)
- Configure `kgdboc` at boot time by passing to the kernel: `kgdboc=<tty-device>,[baud]`. For example: `kgdboc=ttyS0,115200`

Using kgdb (2)

- Then also pass `kgdbwait` to the kernel:
  it makes `kgdb` wait for a debugger connection.
- Boot your kernel, and when the console is initialized, interrupt the kernel with `[Alt][SyrRq][g]`.
- On your workstation, start gdb as follows:

```
% gdb ./vmlinux
(gdb) set remotebaud 115200
(gdb) target remote /dev/ttyS0
```

- Once connected, you can debug a kernel the way you would debug an application program.

Debugging with a JTAG interface

- Two types of JTAG dongles
  - Those offering a gdb compatible interface, over a serial port or an Ethernet connexion. Gdb can directly connect to them.
  - Those not offering a gdb compatible interface are generally supported by OpenOCD (Open On Chip Debugger)
    - OpenOCD is the bridge between the gdb debugging language and the JTAG-dongle specific language
    - http://openocd.berlios.de/web/
    - See the very complete documentation: http://openocd.berlios.de/doc/
    - For each board, you'll need an OpenOCD configuration file (ask your supplier)
- See very useful details on using Eclipse / gcc / gdb / OpenOCD on Windows: http://www2.amontec.com/sdk4arm/ext/jlynch-tutorial-20061124.pdf and http://www.yagarto.de/howto/yagarto2/

More kernel debugging tips

- Enable `CONFIG_KALLSYMS_ALL`
  (`General Setup` -> `Configure standard kernel features`)
  to get oops messages with symbol names instead of raw addresses
  (this obsoletes the ksymoops tool).

- If your kernel doesn't boot yet or hangs without any message, you can activate Low Level debugging (Kernel Hacking section, only available on `arm`):
  `CONFIG_DEBUG_LL=y`

- Techniques to locate the C instruction which caused an oops:
  http://kerneltrap.org/node/3648

- More about kernel debugging in the free Linux Device Drivers book:
  http://lwn.net/images/pdf/LDD3/ch04.pdf

Tracing with SystemTap

http://sourceware.org/systemtap/

SYSTEMTAP

- Infrastructure to add instrumentation to a running kernel:
  trace functions, read and write variables, follow pointers, gather statistics...
- Eliminates the need to modify the kernel sources to add one's own instrumentation to investigated a functional or performance problem.
- Uses a simple scripting language.
  Several example scripts and probe points are available.
- Based on the Kprobes instrumentation infrastructure.
  See `Documentation/kprobes.txt` in kernel sources.
  Linux 2.6.26: supported on most popular CPUs (`arm` included in 2.6.25).
  However, lack of recent support for `mips` (2.6.16 only!).

SystemTap script example (1)

```
#! /usr/bin/env stap
# Using statistics and maps to examine kernel memory allocations

global kmalloc

probe kernel.function("__kmalloc") {
    kmalloc[execname()] <<< $size
}

# Exit after 10 seconds
probe timer.ms(10000) { exit () }

probe end {
    foreach ([name] in kmalloc) {
        printf("Allocations for %s\n", name)
        printf("Count:   %d allocations\n", @count(kmalloc[name]))
        printf("Sum:     %d Kbytes\n", @sum(kmalloc[name])/1000)
        printf("Average: %d bytes\n", @avg(kmalloc[name]))
        printf("Min:     %d bytes\n", @min(kmalloc[name]))
        printf("Max:     %d bytes\n", @max(kmalloc[name]))
        print("\nAllocations by size in bytes\n")
        print(@hist_log(kmalloc[name]))
        printf("----------------------------------------------\n\n");
    }
}
```

SystemTap script example (2)

```
#! /usr/bin/env stap

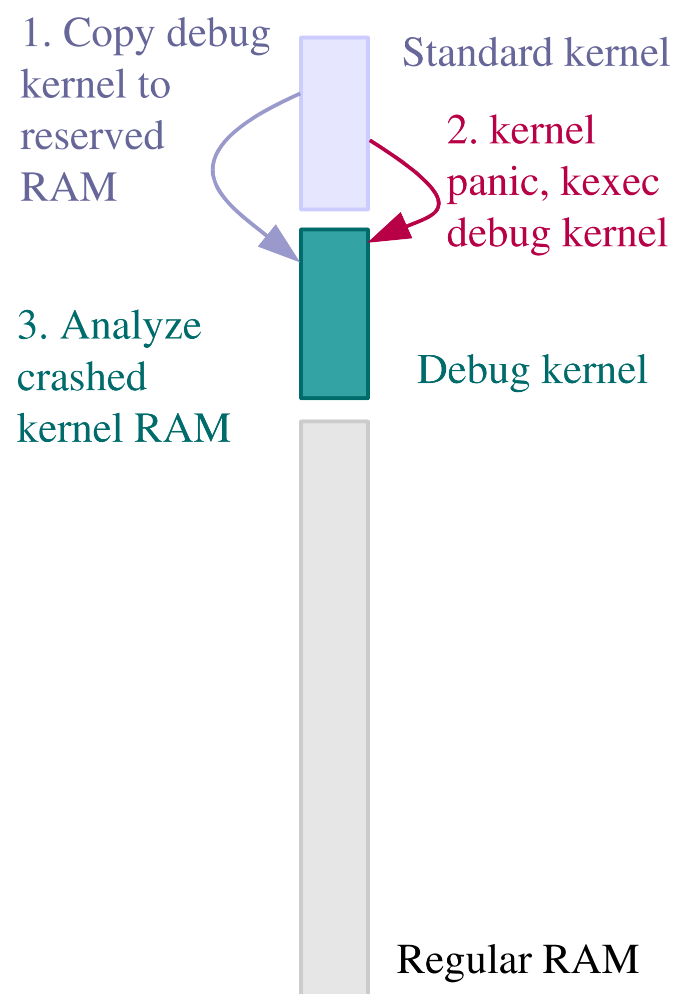
# Logs each file read performed by each process

probe kernel.function ("vfs_read")
{
  dev_nr = $file->f_dentry->d_inode->i_sb->s_dev
  inode_nr = $file->f_dentry->d_inode->i_ino
  printf ("%s(%d) %s 0x%x/%d\n",
      execname(), pid(), probefunc(), dev_nr, inode_nr)
}
```

Nice tutorial on http://sources.redhat.com/systemtap/tutorial.pdf

Kernel crash analysis with kexec/kdump

- `kexec` system call: makes it possible to call a new kernel, without rebooting and going through the BIOS / firmware.
- Idea: after a kernel panic, make the kernel automatically execute a new, clean kernel from a reserved location in RAM, to perform post-mortem analysis of the memory of the crashed kernel.
- See Documentation/kdump/kdump.txt in the kernel sources for details.



Kernel markers

- Capability to add static markers to kernel code, merged in Linux 2.6.24 by Matthieu Desnoyers.
- Almost no impact on performance, until the marker is dynamically enabled, by inserting a probe kernel module.
- Useful to insert trace points that won't be impacted by changes in the Linux kernel sources.
- See marker and probe example in `samples/markers` in the kernel sources.

See http://en.wikipedia.org/wiki/Kernel_marker

LTTng

http://lttng.org

- The successor of the Linux Trace Toolkit (LTT)
- Toolkit allowing to collect and analyze tracing information from the kernel, based on kernel markers and kernel tracepoints.
- So far, based on kernel patches, but doing its best to use in-tree solutions, and to be merged in the future.
- Very precise timestamps, very little overhead.
- Useful documentation on http://lttng.org/?q=node/2#manuals

LTTV

Viewer for LTTng traces

- Support for huge traces (tested with 15 GB ones)
- Can combine multiple tracefiles in a single view.
- Graphical or text interface

See http://lttng.org/files/lttv-doc/user_guide/

Practical lab – Kernel debugging

- Load a broken driver and see it crash
- Analyze the error information dumped by the kernel.
- Disassemble the code and locate the exact C instruction which caused the failure.
- Use the JTAG and OpenOCD to remotely control the kernel execution

Driver development
mmap

mmap (1)

Possibility to have parts of the virtual address space of a program mapped to the contents of a file!

`> cat /proc/1/maps` (init process)

```
start         end           perm  offset     major:minor inode       mapped file name
00771000-0077f000 r-xp 00000000 03:05 1165839    /lib/libselinux.so.1
0077f000-00781000 rw-p 0000d000 03:05 1165839    /lib/libselinux.so.1
0097d000-00992000 r-xp 00000000 03:05 1158767    /lib/ld-2.3.3.so
00992000-00993000 r--p 00014000 03:05 1158767    /lib/ld-2.3.3.so
00993000-00994000 rw-p 00015000 03:05 1158767    /lib/ld-2.3.3.so
00996000-00aac000 r-xp 00000000 03:05 1158770    /lib/tls/libc-2.3.3.so
00aac000-00aad000 r--p 00116000 03:05 1158770    /lib/tls/libc-2.3.3.so
00aad000-00ab0000 rw-p 00117000 03:05 1158770    /lib/tls/libc-2.3.3.so
00ab0000-00ab2000 rw-p 00ab0000 00:00 0
08048000-08050000 r-xp 00000000 03:05 571452     /sbin/init (text)
08050000-08051000 rw-p 00008000 03:05 571452     /sbin/init (data, stack)
08b43000-08b64000 rw-p 08b43000 00:00 0
f6fdf000-f6fe0000 rw-p f6fdf000 00:00 0
fefd4000-ff000000 rw-p fefd4000 00:00 0
ffffe000-fffff000 ---p 00000000 00:00 0
```

mmap (2)

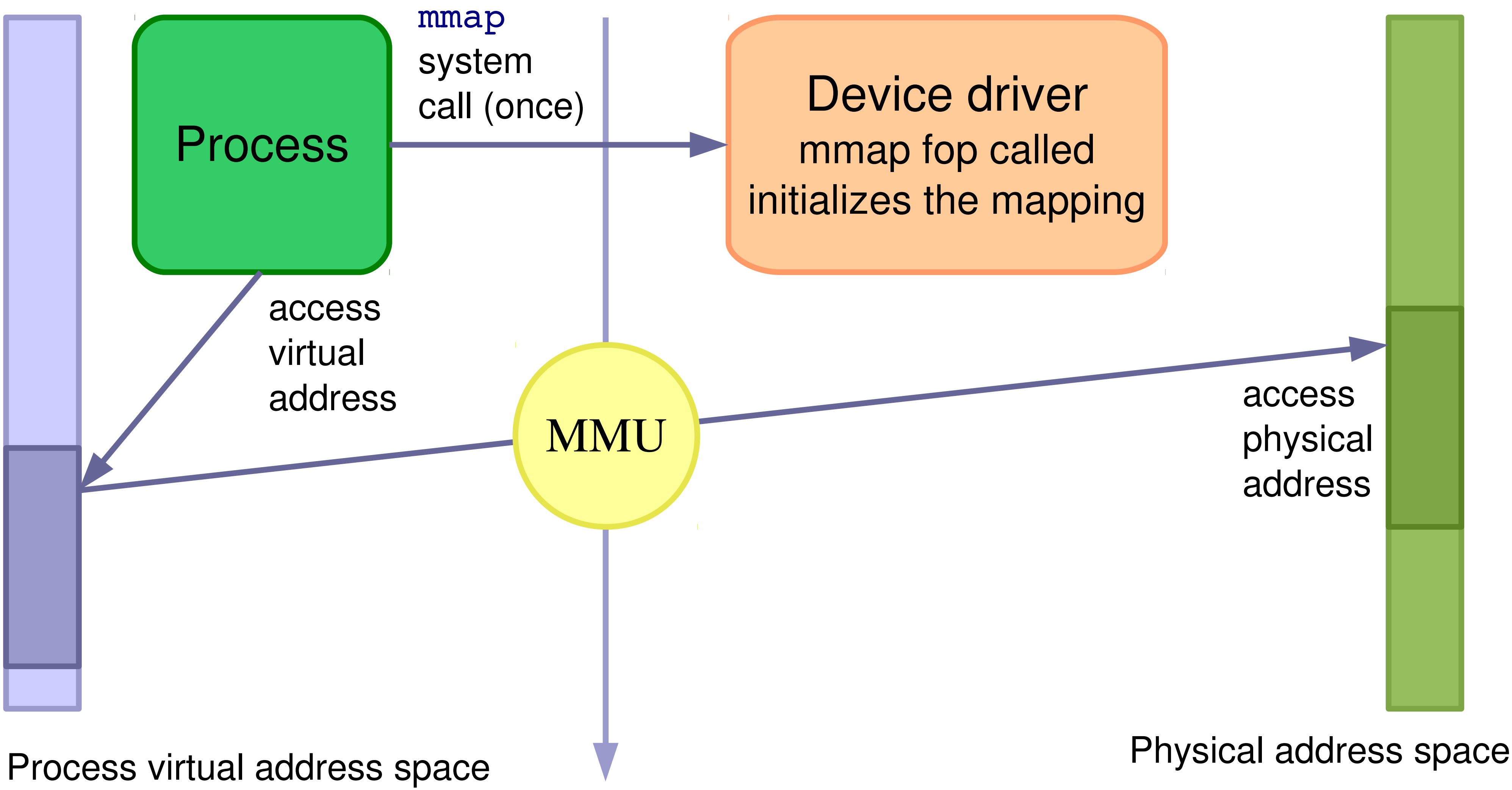
Particularly useful when the file is a device file!
Allows to access device I/O memory and ports without having to go through (expensive) `read`, `write` or `ioctl` calls!

X server example (maps excerpt)

```
start         end           perm  offset     major:minor inode       mapped file name
08047000-081be000 r-xp 00000000 03:05 310295     /usr/X11R6/bin/Xorg
081be000-081f0000 rw-p 00176000 03:05 310295     /usr/X11R6/bin/Xorg
...
f4e08000-f4f09000 rw-s e0000000 03:05 655295     /dev/dri/card0
f4f09000-f4f0b000 rw-s 4281a000 03:05 655295     /dev/dri/card0
f4f0b000-f6f0b000 rw-s e8000000 03:05 652822     /dev/mem
f6f0b000-f6f8b000 rw-s fcff0000 03:05 652822     /dev/mem
```

A more user friendly way to get such information: `pmap <pid>`

mmap overview



How to implement mmap - User space

- Open the device file
- Call the `mmap` system call (see `man mmap` for details):

```
void * mmap(
    void *start,      /* Often 0, preferred starting address */
    size_t length,    /* Length of the mapped area */
    int prot ,        /* Permissions: read, write, execute */
    int flags,        /* Options: shared mapping, private copy... 
*/
    int fd,           /* Open file descriptor */
    off_t offset      /* Offset in the file */
);
```

- You get a virtual address you can write to or read from.

How to implement mmap - Kernel space

- Character driver: implement a `mmap` file operation and add it to the driver file operations:

```
int (*mmap) (
   struct file *,               /* Open file structure */
   struct vm_area_struct *     /* Kernel VMA structure */
);
```

- Initialize the mapping.
  Can be done in most cases with the `remap_pfn_range()` function, which takes care of most of the job.

remap_pfn_range()

- *pfn*: page frame number
  The most significant bits of the page address
  (without the bits corresponding to the page size).
- ```
  #include <linux/mm.h>

  int remap_pfn_range(
      struct vm_area_struct *,          /* VMA struct */
      unsigned long virt_addr,    /* Starting user virtual address */
      unsigned long pfn,    /* pfn of the starting physical address */
      unsigned long size,               /* Mapping size */
      pgprot_t                          /* Page permissions */
  );
  ```
  ```

Simple mmap implementation

```
static int acme_mmap (
   struct file * file, struct vm_area_struct * vma)
{
   size = vma->vm_end - vma->vm_start;

   if (size > ACME_SIZE)
      return -EINVAL;

   if (remap_pfn_range(vma,
               vma->vm_start,
               ACME_PHYS >> PAGE_SHIFT,
               size,
               vma->vm_page_prot))
      return -EAGAIN;
   return 0;
}
```

devmem2

http://free-electrons.com/pub/mirror/devmem2.c, by Jan-Derk Bakker

Very useful tool to directly peek (read) or poke (write) I/O addresses mapped in physical address space from a shell command line!

- Very useful for early interaction experiments with a device, without having to code and compile a driver.
- Uses `mmap` to `/dev/mem`.
- Examples (`b`: byte, `h`: half, `w`: word)
  `devmem2 0x000c0004 h` (reading)
  `devmem2 0x000c0008 w 0xffffffff` (writing)
- `devmem` is now available in BusyBox, making it even easier to use.

mmap summary

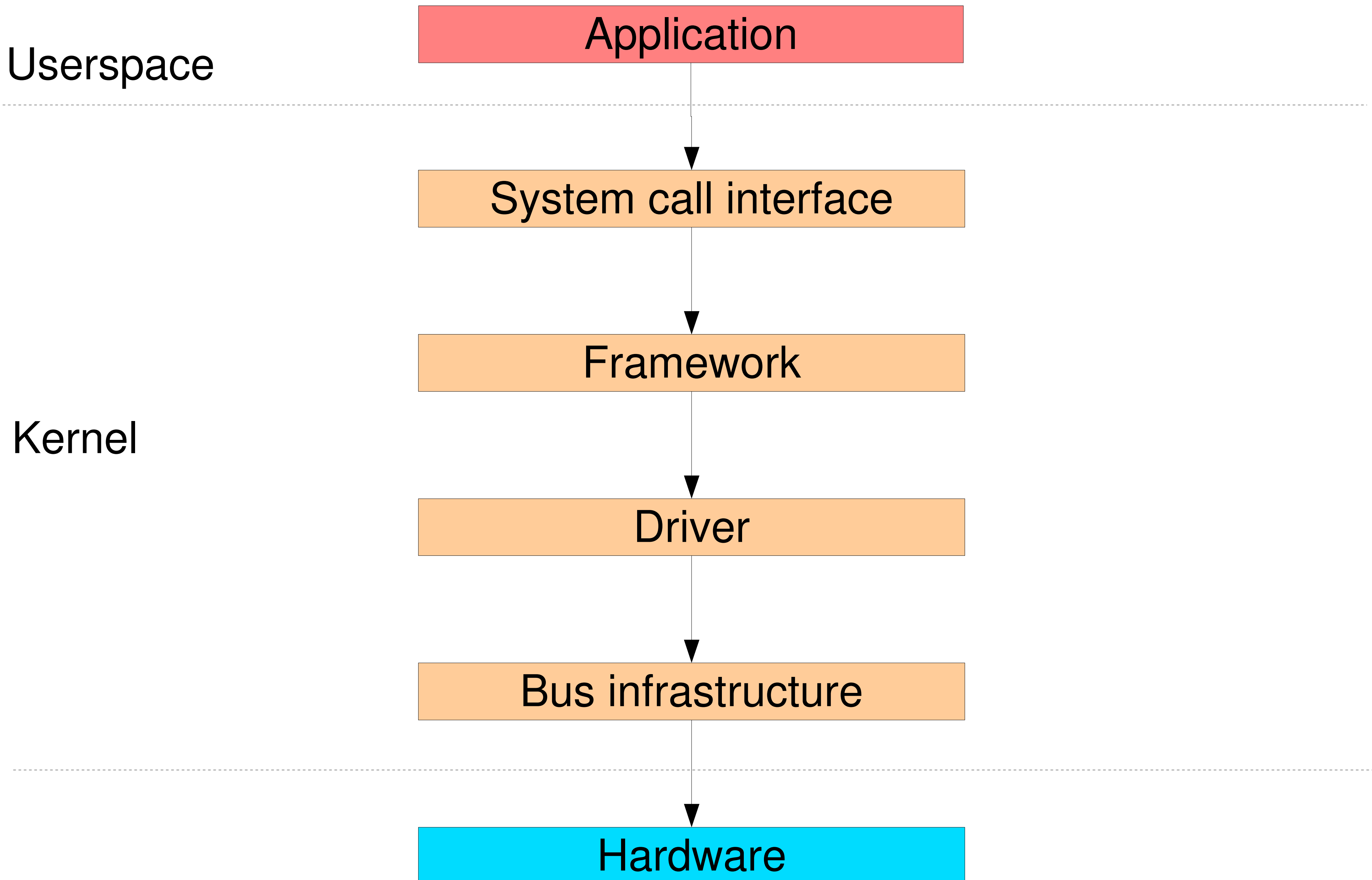
- The device driver is loaded.
  It defines an `mmap` file operation.
- A user space process calls the `mmap` system call.
- The `mmap` file operation is called.
  It initializes the mapping using the device physical address.
- The process gets a starting address to read from and write to (depending on permissions).
- The MMU automatically takes care of converting the process virtual addresses into physical ones.

Direct access to the hardware!
No expensive `read` or `write` system calls!

Driver development

Kernel architecture for device drivers

Kernel and device drivers

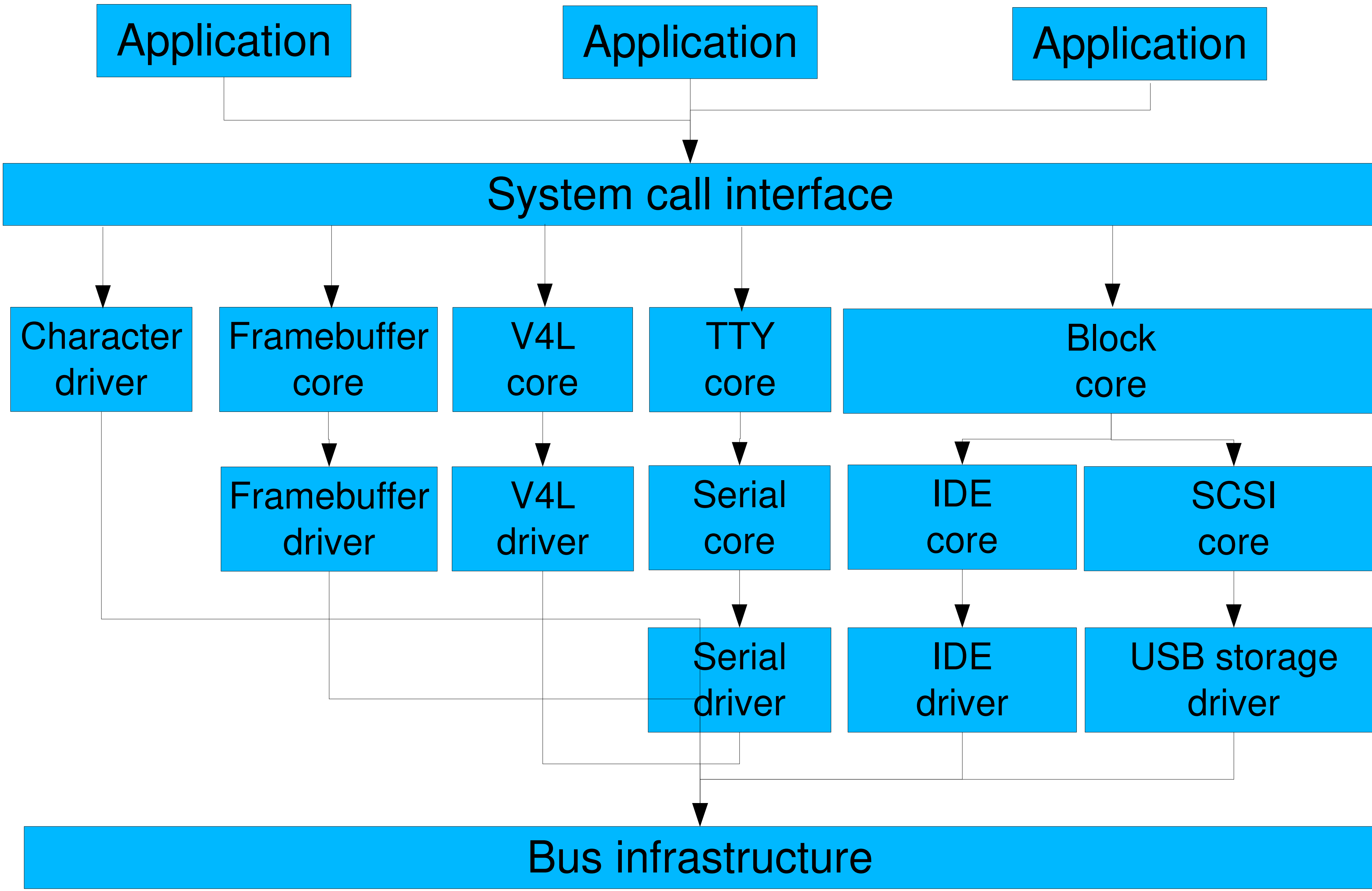


Kernel and device drivers

- Many device drivers are not implemented directly as character drivers
- They are implemented under a « framework », specific to a given device type (framebuffer, V4L, serial, etc.)
  - The framework allows to factorize the common parts of drivers for the same type of devices
  - From userspace, they are still seen as character devices by the applications
  - The framework allows to provide a coherent userspace interface (ioctl, etc.) for every type of device, regardless of the driver
- The device drivers rely on the « bus infrastructure » to enumerate the devices and communicate with them.

Kernel frameworks

« Frameworks »


Application
Application
Application
System call interface
Character driver
Framebuffer core
V4L core
TTY core
Block core
Framebuffer driver
V4L driver
Serial core
IDE core
SCSI core
Serial driver
IDE driver
USB storage driver
Bus infrastructure

Example: framebuffer framework

- Kernel option `CONFIG_FB`

```
menuconfig FB
        tristate "Support for frame buffer devices"
```

- Implemented in `drivers/video/`
  - `fb.c`, `fbmem.c`, `fbmon.c`, `fbcmap.c`, `fbsysfs.c`, `modedb.c`, `fbcvt.c`
- Implements a single character driver and defines the user/kernel API
  - First part of `include/linux/fb.h`
- Defines the set of operations a framebuffer driver must implement and helper functions for the drivers
  - `struct fb_ops`
  - Second part of `include/linux/fb.h` (in `#ifdef __KERNEL__`)

Framebuffer driver skeleton

- Skeleton driver in `drivers/video/skeletonfb.c`
- Implements the set of framebuffer specific operations defined by the `struct fb_ops` structure
  - `xxxfb_open()`
  - `xxxfb_read()`
  - `xxxfb_write()`
  - `xxxfb_release()`
  - `xxxfb_checkvar()`
  - `xxxfb_setpar()`
  - `xxxfb_setcolreg()`
  - `xxxfb_blank()`
  - `xxxfb_pan_display()`
  - `xxxfb_fillrect()`
  - `xxxfb_copyarea()`
  - `xxxfb_imageblit()`
  - `xxxfb_cursor()`
  - `xxxfb_rotate()`
  - `xxxfb_sync()`
  - `xxxfb_ioctl()`
  - `xxxfb_mmap()`

Framebuffer driver skeleton

- After the implementation of the operations, definition of a `struct fb_ops` structure

```
static struct fb_ops xxxfb_ops = {
        .owner          = THIS_MODULE,
        .fb_open        = xxxfb_open,
        .fb_read        = xxxfb_read,
        .fb_write       = xxxfb_write,
        .fb_release     = xxxfb_release,
        .fb_check_var   = xxxfb_check_var,
        .fb_set_par     = xxxfb_set_par,
        .fb_setcolreg   = xxxfb_setcolreg,
        .fb_blank       = xxxfb_blank,
        .fb_pan_display = xxxfb_pan_display,
        .fb_fillrect    = xxxfb_fillrect,       /* Needed !!! */
        .fb_copyarea    = xxxfb_copyarea,       /* Needed !!! */
        .fb_imageblit   = xxxfb_imageblit,      /* Needed !!! */
        .fb_cursor      = xxxfb_cursor,         /* Optional !!! */
        .fb_rotate      = xxxfb_rotate,
        .fb_sync        = xxxfb_sync,
        .fb_ioctl       = xxxfb_ioctl,
        .fb_mmap        = xxxfb_mmap,
};
```

Framebuffer driver skeleton

- In the `probe()` function, registration of the framebuffer device and operations

```
static int __devinit xxxfb_probe
     (struct pci_dev *dev,
      const struct pci_device_id *ent)
{
     struct fb_info *info;
     [...]
     info = framebuffer_alloc(sizeof(struct xxx_par), device);
     [...]
     info->fbops = &xxxfb_ops;
     [...]
     if (register_framebuffer(info) < 0)
         return -EINVAL;
     [...]
}
```

- `register_framebuffer()` will create the character device that can be used by userspace application with the generic framebuffer API

Device Model and Bus Infrastructure

Unified device model

- The 2.6 kernel included a significant new feature: a unified device model
- Instead of having different ad-hoc mechanisms in the various subsystems, the device model unifies the description of the devices and their topology
- Minimizing code duplication
- Common facilities (reference counting, event notification, power management, etc.)
- Enumerate the devices, view their interconnections, link the devices to their buses and drivers, categorize them by classes.

Bus drivers

- The first component of the device model is the bus driver
- One bus driver for each type of bus: USB, PCI, SPI, MMC, ISA, etc.
- It is responsible for
  - Registering the bus type
  - Allowing the registration of adapter drivers (USB controllers, I2C adapters, etc.), able of detecting the connected devices
  - Allowing the registration of device drivers (USB devices, I2C devices, PCI devices, etc.), managing the devices
  - Matching the device drivers against the devices detected by the adapter drivers.

List of device identifiers

- Depending on the bus type, the method for binding a device to a driver is different. For many buses, it is based on unique identifiers
- The device driver defines a table with the list of device identifiers it is able to manage :

```
static const struct pci_device_id rhine_pci_tbl[] = {
        { 0x1106, 0x3043, PCI_ANY_ID, PCI_ANY_ID, },    /* VT86C100A */
        { 0x1106, 0x3053, PCI_ANY_ID, PCI_ANY_ID, },    /* VT6105M */
        { }     /* terminate list */
};
MODULE_DEVICE_TABLE(pci, rhine_pci_tbl);
```

Code on this slide and on the next slides are taken from the via-rhine driver in `drivers/net/via-rhine.c`

Defining the driver

- The device driver defines a driver structure, usually specialized by the bus infrastructure (`pci_driver`, `usb_driver`, etc.)
- The structure points to: the device table, a probe function, called when a device is detected and various other callbacks

```
static struct pci_driver rhine_driver = {
        .name           = DRV_NAME,
        .id_table       = rhine_pci_tbl,
        .probe          = rhine_init_one,
        .remove         = __devexit_p(rhine_remove_one),
#ifdef CONFIG_PM
        .suspend        = rhine_suspend,
        .resume         = rhine_resume,
#endif /* CONFIG_PM */
        .shutdown =     rhine_shutdown,
};
```

Registering the driver

- In the module initialization function, the driver is registered to the bus infrastructure, in order to let the bus know that the driver is available to handle devices.

```
static int __init rhine_init(void)
{
        [...]
        return pci_register_driver(&rhine_driver);
}
static void __exit rhine_cleanup(void)
{
        pci_unregister_driver(&rhine_driver);
}
```

- If a new PCI device matches one of the identifiers of the table, the `probe()` method of the PCI driver will get called.

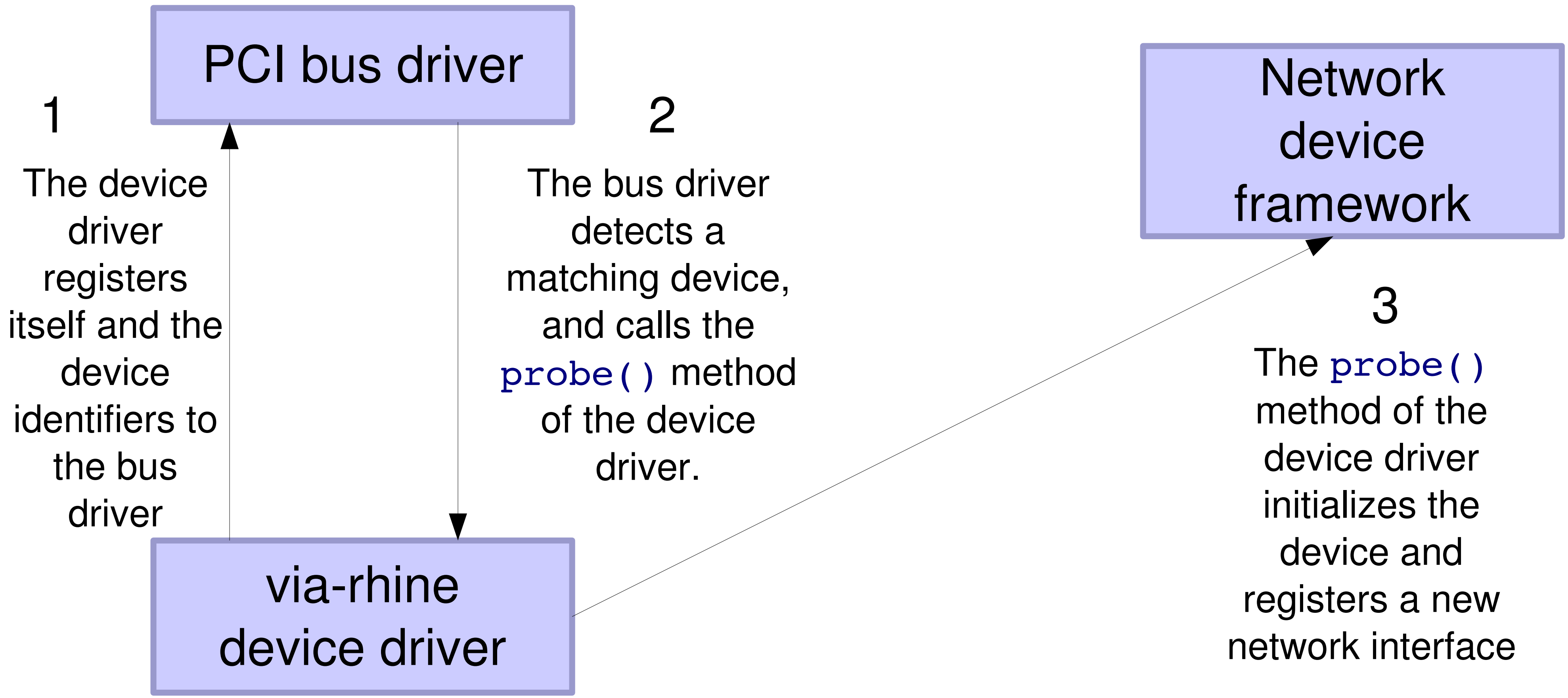
Probe method

- The `probe()` method receives as argument a structure describing the device, usually specialized by the bus infrastructure (`pci_dev`, `usb_device`, etc.)
- This function is responsible for
  - Initializing the device, mapping I/O memory, registering the interrupt handlers. The bus infrastructure provides methods to get the addresses, interrupts numbers and other device-specific information.
  - Registering the device to the proper kernel framework, for example the network infrastructure.

Device driver (5)

```
static int __devinit rhine_init_one(struct pci_dev *pdev,
                                    const struct pci_device_id *ent)
{
        struct net_device *dev;
        [...]
        rc = pci_enable_device(pdev);
        [...]
        pioaddr = pci_resource_start(pdev, 0);
        memaddr = pci_resource_start(pdev, 1);
        [...]
        dev = alloc_etherdev(sizeof(struct rhine_private));
        [...]
        SET_NETDEV_DEV(dev, &pdev->dev);
        [...]
        rc = pci_request_regions(pdev, DRV_NAME);
        [...]
        ioaddr = pci_iomap(pdev, bar, io_size);
        [...]
        rc = register_netdev(dev);
        [...]
}
```

Global architecture



sysfs

- The bus, device, drivers, etc. structures are internal to the kernel
- The `sysfs` virtual filesystem offers a mechanism to export such information to userspace
- Used for example by `udev` to provide automatic module loading, firmware loading, device file creation, etc.
- `sysfs` is usually mounted in `/sys`
  - `/sys/bus/` contains the list of buses
  - `/sys/devices/` contains the list of devices
  - `/sys/class` enumerates devices by class (`net`, `input`, `block`...), whatever the bus they are connected to. Very useful!
- Take your time to explore `/sys` on your workstation.

Platform devices

- On embedded systems, devices are often not connected through a bus allowing enumeration, hotplugging, and providing unique identifiers for devices.
- However, we still want the devices to be part of the device model.
- The solution to this is the *platform driver / platform device* infrastructure.
- The platform devices are the devices that are directly connected to the CPU, without any kind of bus.

Implementation of the platform driver

- The driver implements a platform_driver structure (example taken from `drivers/serial/imx.c`)

```
static struct platform_driver serial_imx_driver = {
        .probe          = serial_imx_probe,
        .remove         = serial_imx_remove,
        .driver         = {
                .name   = "imx-uart",
                .owner  = THIS_MODULE,
        },
};
```

- And registers its driver to the platform driver infrastructure

```
static int __init imx_serial_init(void)
{
        [...]
        ret = platform_driver_register(&serial_imx_driver);
        [...]
}
```

Platform device instantiation (1)

- In the board-specific code, the platform devices are instantiated (`arch/arm/mach-imx/mx1ads.c`):

```
static struct platform_device imx_uart1_device = {
        .name             = "imx-uart",
        .id               = 0,
        .num_resources    = ARRAY_SIZE(imx_uart1_resources),
        .resource         = imx_uart1_resources,
        .dev = {
                .platform_data = &uart_pdata,
        }
};
```

- The match between the device and the driver is made using the name. It must be unique amongst drivers !

Platform device instantiation (2)

- The device is part of a list

```
static struct platform_device *devices[] __initdata = {
        &cs89x0_device,
        &imx_uart1_device,
        &imx_uart2_device,
};
```

- And the list of devices is added to the system during board initialization

```
static void __init mx1ads_init(void)
{
    [...]
    platform_add_devices(devices, ARRAY_SIZE(devices));
}
```

I/O resources

- Each platform device is associated with a set of I/O resources, referenced in the `platform_device` structure

```
static struct resource imx_uart1_resources[] = {
        [0] = {
                .start  = 0x00206000,
                .end    = 0x002060FF,
                .flags  = IORESOURCE_MEM,
        },
        [1] = {
                .start  = (UART1_MINT_RX),
                .end    = (UART1_MINT_RX),
                .flags  = IORESOURCE_IRQ,
        },
};
```

- It allows the driver to be independent of the I/O addresses, IRQ numbers ! See `imx_uart2_device` for another device using the same platform driver.

Inside the platform driver

- When a platform_device is added to the system using `platform_add_device()`, the `probe()` method of the platform driver gets called
- This method is responsible for initializing the hardware, registering the device to the proper framework (in our case, the serial driver framework)
- The platform driver has access to the I/O resources :

```
res = platform_get_resource(pdev, IORESOURCE_MEM, 0);
base = ioremap(res->start, PAGE_SIZE);
sport->rxirq = platform_get_irq(pdev, 0);
```

Framework and bus infrastructure

- A typical driver will
  - Be registered inside a framework
  - Rely on a bus infrastructure and the device model
- Example with the iMX serial driver, `drivers/serial/imx.c`
- At module initialization time, the driver registers itself both to the UART framework and to the platform bus infrastructure

```
static int __init imx_serial_init(void)
{
        ret = uart_register_driver(&imx_reg);
        [...]
        ret = platform_driver_register(&serial_imx_driver);
        [...]
        return 0;
}
```

iMX serial driver

Definition of the iMX UART driver

```
static struct uart_driver imx_reg = {
        .owner          = THIS_MODULE,
        .driver_name    = DRIVER_NAME,
        .dev_name       = DEV_NAME,
        .major          = SERIAL_IMX_MAJOR,
        .minor          = MINOR_START,
        .nr             = ARRAY_SIZE(imx_ports),
        .cons           = IMX_CONSOLE,
};
```

Definition of the iMX platform driver

```
static struct platform_driver serial_imx_driver = {
        .probe          = serial_imx_probe,
        .remove         = serial_imx_remove,
       [...]
        .driver         = {
                .name   = "imx-uart",
                .owner  = THIS_MODULE,
        },
};
```

iMX serial driver

When the platform device is instantiated, the `probe()` method is called

```
static int serial_imx_probe(struct platform_device *pdev)
{
        struct imx_port *sport;

        sport = kzalloc(sizeof(*sport), GFP_KERNEL);
        res = platform_get_resource(pdev, IORESOURCE_MEM, 0);
        base = ioremap(res->start, PAGE_SIZE);

        /* sport initialization */
        sport->port.irq = platform_get_irq(pdev, 0);
        sport->port.ops = &imx_pops;

        sport->clk = clk_get(&pdev->dev, "uart_clk");
        clk_enable(sport->clk);

        uart_add_one_port(&imx_reg, &sport->port);
}
```

iMX serial driver

The operation structure `uart_ops` is associated to each port. The operations are implemented in the iMX driver

```
static struct uart_ops imx_pops = {
        .tx_empty       = imx_tx_empty,
        .set_mctrl      = imx_set_mctrl,
        .get_mctrl      = imx_get_mctrl,
        .stop_tx        = imx_stop_tx,
        .start_tx       = imx_start_tx,
        .stop_rx        = imx_stop_rx,
        .enable_ms      = imx_enable_ms,
        .break_ctl      = imx_break_ctl,
        .startup        = imx_startup,
        .shutdown       = imx_shutdown,
        .set_termios    = imx_set_termios,
        .type           = imx_type,
        .release_port   = imx_release_port,
        .request_port   = imx_request_port,
        .config_port    = imx_config_port,
        .verify_port    = imx_verify_port,
};
```

References

- Kernel documentation
  `Documentation/driver-model/`
  `Documentation/filesystems/sysfs.txt`
- Linux 2.6 Device Model
  http://www.bravegnu.org/device-model/device-model.html
- Linux Device Drivers, chapter 14 «The Linux Device Model»
  http://lwn.net/images/pdf/LDD3/ch14.pdf
- The kernel source code
  Full of examples of other drivers!

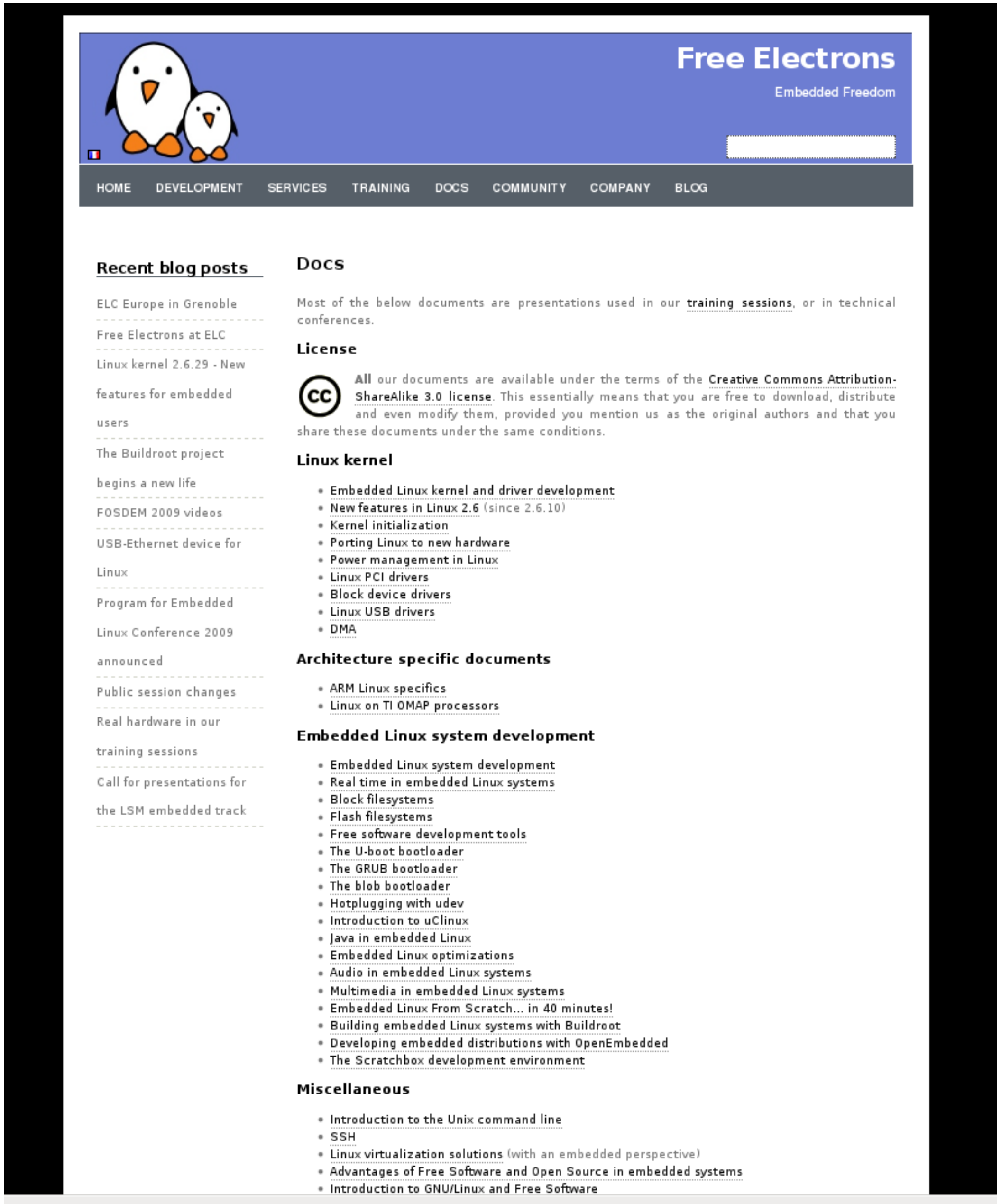
Annexes

Quiz answers

Quiz answers

- Interrupt handling
  Q: Why did the kernel segfault at module unload (forgetting to unregister a handler in a shared interrupt line)?
  A: Kernel memory is allocated at module load time, to host module code. This memory is freed at module unload time. If you forget to unregister a handler and an interrupt comes, the cpu will try to jump to the address of the handler, which is in a freed memory area. Crash!

Related documents



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