Embedded Linux driver development

Embedded Linux kernel and driver development

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- Take advantage of internal or external hyperlinks. So, don't hesitate to click on them! See next page.
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Hyperlinks in this document

- Links to external sites
  Example: http://kernel.org/

Usable in the PDF and ODP formats
Try them on this page!

- Kernel source files
  Our links let you view them in your browser.
  Example: `kernel/sched.c`

- Kernel source code:
  Identifiers: functions, macros, type definitions...
  You get access to their definition, implementation and where they are used

click $\rightarrow$
```
wait_queue_head_t queue;
init_waitqueue_head(&queue);
```

- Table of contents
  Directly jump to the corresponding sections.
  Example: `Kernel configuration`

Course prerequisites

Skills to make these lectures and labs profitable

Familiarity with Unix concepts and its command line interface

- Essential to manipulate sources and files
- Essential to understand and debug the system that you build
- You should read http://free-electrons.com/training/intro_unix_linux
  This Unix command line interface training also explains Unix concepts not repeated in this document.

Experience with C programming

- On-line C courses can be found on
  http://dmoz.org/Computers/Programming/Languages/C/Tutorials/

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Embedded Linux driver development

Kernel overview

Linux features

Studied kernel version: 2.6

Linux 2.4

- Mature
- But developments stopped; very few developers willing to help.
- Now obsolete and lacks recent features.
- Still fine if you get your sources, tools and support from commercial Linux vendors.

Linux 2.6

- 2 years old stable Linux release!
- Support from the Linux development community and all commercial vendors.
- Now mature and more exhaustive. Most drivers upgraded.
- Cutting edge features and increased performance.

Linux kernel key features

- Portability and hardware support
  Runs on most architectures.
- Scalability
  Can run on super computers as well as on tiny devices
  (4 MB of RAM is enough).
- Compliance to standards and interoperability.
- Exhaustive networking support.
- Security
  It can't hide its flaws. Its code is reviewed by many experts.
- Stability and reliability.
- Modularity
  Can include only what a system needs even at run time.
- Easy to program
  You can learn from existing code.
  Many useful resources on the net.

Supported hardware architectures

- See the `arch/` directory in the kernel sources
- Minimum: 32 bit processors, with or without MMU
- 32 bit architectures (`arch/` subdirectories)
  `alpha`, `arm`, `cris`, `frv`, `h8300`, `i386`, `m32r`, `m68k`, `m68knommu`, `mips`, `parisc`, `ppc`, `s390`, `sh`, `sparc`, `um`, `v850`, `xtensa`
- 64 bit architectures:
  `ia64`, `mips64`, `ppc64`, `sh64`, `sparc64`, `x86_64`
- See `arch/<arch>/Kconfig`, `arch/<arch>/README`, or `Documentation/<arch>/` for details

Kernel overview

Kernel code

Implemented in C

- Implemented in C like all Unix systems.
  (C was created to implement the first Unix systems)
- A little Assembly is used too:
  CPU and machine initialization, critical library routines.

See http://www.tux.org/lkml/#s15-3
for reasons for not using C++
(main reason: the kernel requires efficient code).

Compiled with GNU C

- Need GNU C extensions to compile the kernel.
  So, you cannot use any ANSI C compiler!
- Some GNU C extensions used in the kernel:
  - Inline C functions
  - Inline assembly
  - Structure member initialization
    in any order (also in ANSI C99)
  - Branch annotation (see next page)

Help gcc to optimize your code!

- Use the `likely` and `unlikely` statements (`include/linux/compiler.h`)
- Example:
```
if (unlikely(err)) {
        ...
}
```
- The GNU C compiler will make your code faster for the most likely case.

Used in many places in kernel code!
Don't forget to use these statements!

No C library

- The kernel has to be standalone and can't use user-space code. Userspace is implemented on top of kernel services, not the opposite. Kernel code has to supply its own library implementations (string utilities, cryptography, uncompression ...)
- So, you can't use standard C library functions in kernel code. (`printf()`, `memset()`, `malloc()`...). You can also use kernel C headers.
- Fortunately, the kernel provides similar C functions for your convenience, like `printk()`, `memset()`, `kmalloc()` ...

Managing endianism

Linux supports both little and big endian architectures

- Each architecture defines `__BIG_ENDIAN` or `__LITTLE_ENDIAN` in `<asm/byteorder.h>`
  Can be configured in some platforms supporting both.
- To make your code portable, the kernel offers conversion macros (that do nothing when no conversion is needed). Most useful ones:

```
u32 cpu_to_be32(u32);   // CPU byte order to big endian
u32 cpu_to_le32(u32);   // CPU byte order to little endian
u32 be32_to_cpu(u32);   // Little endian to CPU byte order
u32 le32_to_cpu(u32);   // Big endian to CPU byte order
```

Kernel coding guidelines

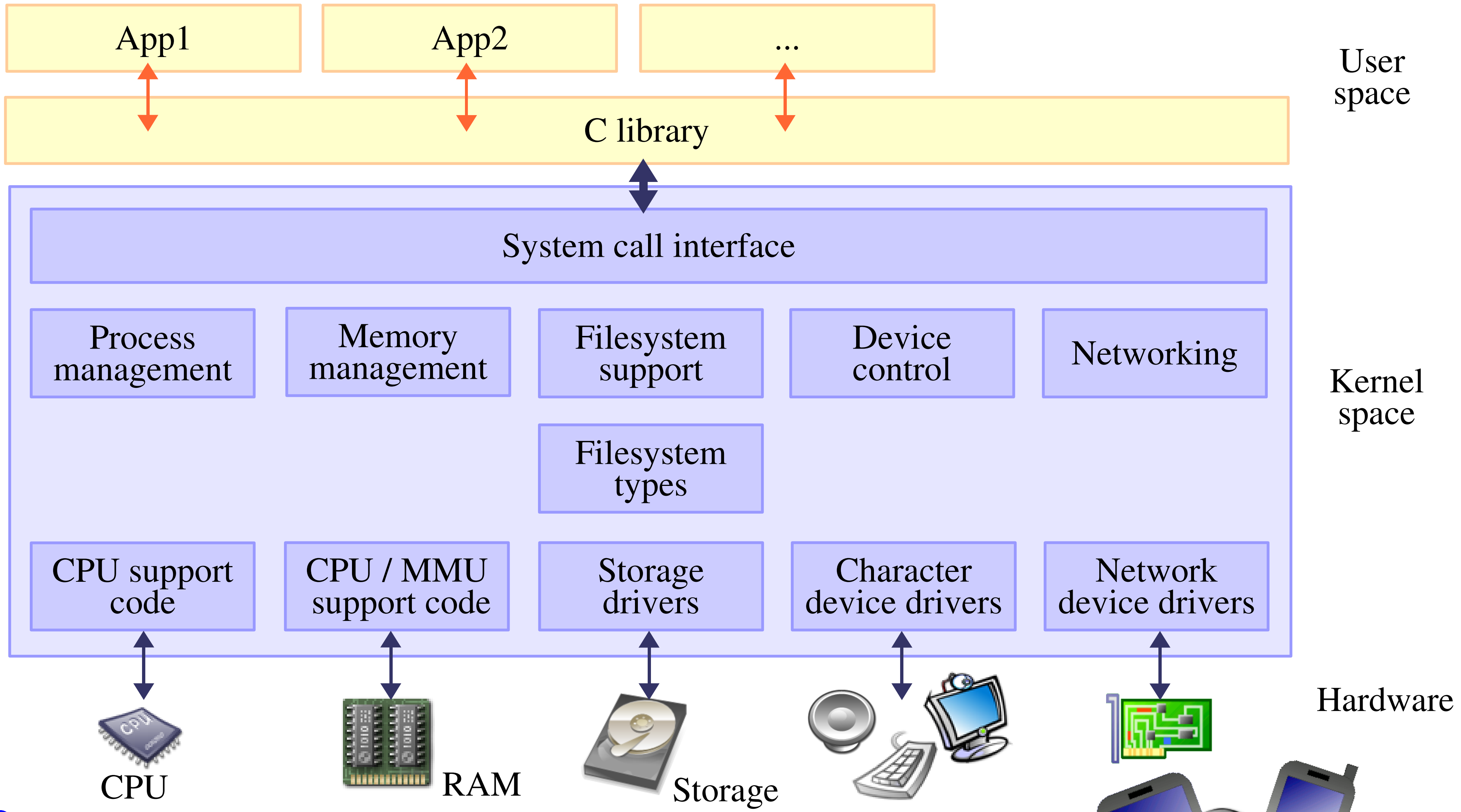
- Never use floating point numbers in kernel code. Your code may be run on a processor without a floating point unit (like on `arm`). Floating point can be emulated by the kernel, but this is very slow.
- Define all symbols as static, except exported ones (to avoid namespace pollution)
- See `Documentation/CodingStyle` for more guidelines
- It's also good to follow or at least read GNU coding standards: http://www.gnu.org/prep/standards.html

Embedded Linux driver development

Kernel overview

Kernel subsystems

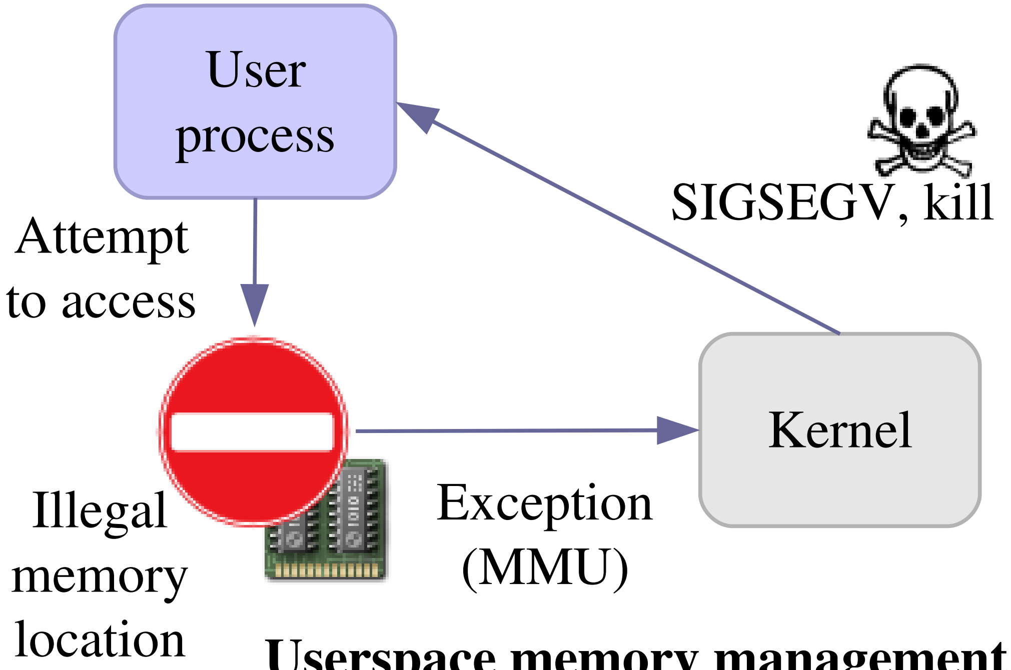
Kernel architecture



Kernel memory constraints

Who can look after the kernel?

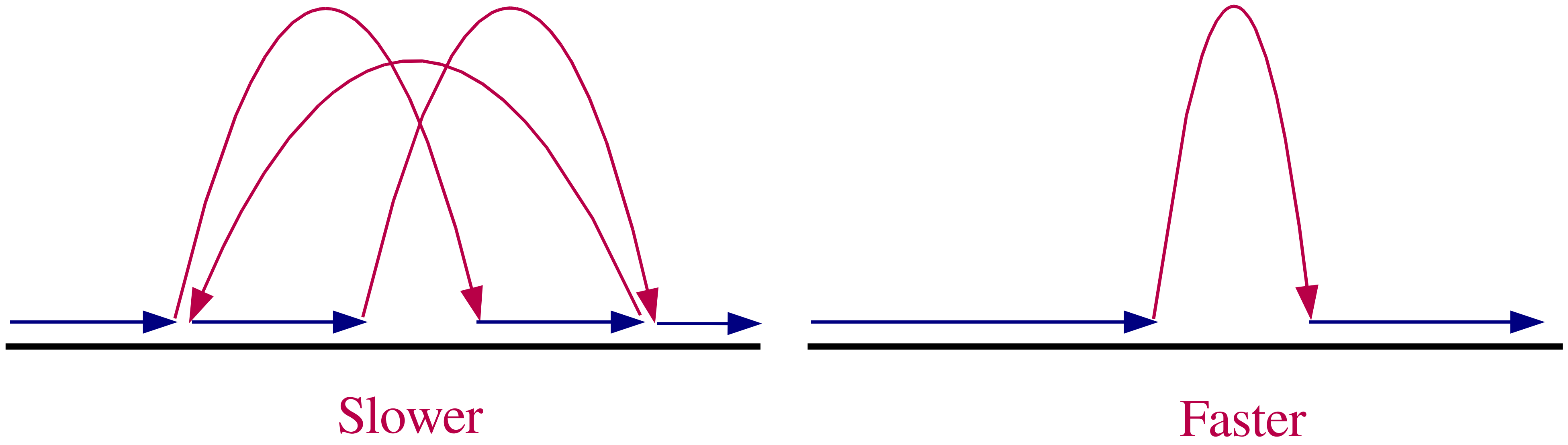
- No memory protection
  Accessing illegal memory locations result in (often fatal) kernel oopses.
- Fixed size stack (8 or 4 KB)
  Unlike in userspace,
  no way to make it grow.
- Kernel memory can't be swapped out (for the same reasons).



Userspace memory management
Used to implement:
- memory protection
- stack growth
- memory swapping to disk

I/O schedulers

- Mission of I/O schedulers: re-order reads and writes to disk to minimize disk head moves (time consuming!)



- Not needed in embedded systems with no hard disks (data access time independent of location on flash storage)
Build your kernel with no-op I/O scheduler then!

Embedded Linux driver development

Kernel overview

Linux versioning scheme and development process

Linux stable releases

Major versions

- 1 major version every 2 or 3 years
  Examples: `1.0`, `2.0`, `2.4`, `2.6`

Even number

Stable releases

- 1 stable release every 1 or 2 months
  Examples: `2.0.40`, `2.2.26`, `2.4.27`, `2.6.7` ...

Stable release updates (since March 2005)

- Updates to stable releases up to several times a week
  Address only critical issues in the latest stable release
  Examples: `2.6.11.1` to `2.6.11.7`

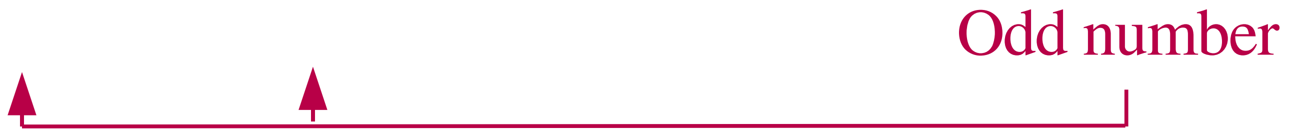
Linux development and testing releases

Testing releases

- Several testing releases per month, before the next stable one. You can contribute to making kernel releases more stable by testing them!
  Example: `2.6.12-rc1`

Development versions

- Unstable versions used by kernel developers before making a new stable major release
  Examples: `2.3.42`, `2.5.74`



Changes since Linux 2.6

- Since `2.6.0`, kernel developers have been able to introduce lots of new features one by one on a steady pace, without having to make major changes in existing subsystems.
- Opening a new Linux `2.7` (or `2.9`) development branch will be required only when Linux `2.6` is no longer able to accommodate key features without undergoing traumatic changes.
- Thanks to this, more features are released to users at a faster pace.

No stable Linux internal API (1)

- Of course, the external API must not change (system calls, `/proc`, `/sys`), as it could break existing programs. New features can be added, but Linux must stay backward compatible with earlier versions.
- The internal kernel API can now undergo changes between two `2.6.x` releases. A stand-alone module compiled for a given version may no longer compile or work on a more recent one.
  See Documentation/stable_api_nonsense.txt for reasons why.
- Whenever a developer changes an internal API, (s)he also has to update all kernel code which uses it. Nothing broken!
- Works great for code in the mainline kernel tree.
  Difficult to keep in line for out of tree or closed-source drivers!

No stable Linux internal API (2)

<u>USB example</u>

- Linux has updated its USB internal API at least 3 times (fixes, security issues, support for high-speed devices) and has now the fastest USB bus speeds (compared to other systems)
- Windows XP also had to rewrite its USB stack 3 times. But, because of closed-source, binary drivers that can't be updated, they had to keep backward compatibility with all earlier implementation. This is very costly (development, security, stability, performance).

See “Myths, Lies, and Truths about the Linux Kernel”, by Greg K.H., for details about the kernel development process:
http://kroah.com/log/linux/ols_2006_keynote.html

More stability for the 2.6 kernel tree

- Issue: security fixes only released for last (or last two) stable kernel versions (like 2.6.16 and 2.6.17), and of course by distributions for the exact version that you're using.
- Some people need to have a recent kernel, but with long term support for security updates.
- That's why Adrian Bunk proposed to maintain a 2.6.16 stable tree, for as long as needed (years!).

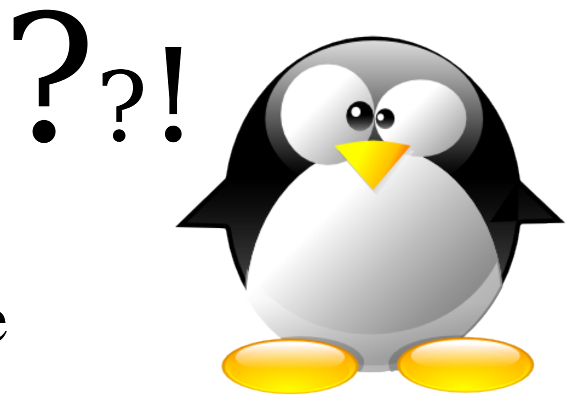
What's new in each Linux release? (1)

```
commit 3c92c2ba33cd7d666c5f83cc32aa590e794e91b0
Author: Andi Kleen <ak@suse.de>
Date:   Tue Oct 11 01:28:33 2005 +0200

    [PATCH] i386: Don't discard upper 32bits of HWCR on K8

    Need to use long long, not long when RMWing a MSR. I think
    it's harmless right now, but still should be better fixed
    if AMD adds any bits in the upper 32bit of HWCR.

    Bug was introduced with the TLB flush filter fix for i386

    Signed-off-by: Andi Kleen <ak@suse.de>
    Signed-off-by: Linus Torvalds <torvalds@osdl.org>
...
```

- The official list of changes for each Linux release is just a huge list of individual patches!
- Very difficult to find out the key changes and to get the global picture out of individual changes.

What's new in each Linux release? (2)

- Fortunately, a summary of key changes with enough details is available on http://wiki.kernelnewbies.org/LinuxChanges



- For each new kernel release, you can also get the changes in the kernel internal API: http://lwn.net/Articles/2.6-kernel-api/

- What's next? Documentation/feature-removal-schedule.txt lists the features, subsystems and APIs that are planned for removal (announced 1 year in advance).

Embedded Linux driver development

Kernel overview

Legal issues

Linux license

- The whole Linux sources are Free Software released under the GNU General Public License (GPL)
- See our http://free-electrons.com/training/intro_unix_linux training for details about Free Software and its licenses.

Linux kernel licensing constraints

Constraints at release time (no constraint before!)

- For any device embedding Linux and Free Software, you have to release sources to the end user. You have no obligation to release them to anybody else!
- According to the GPL, only Linux drivers with a GPL compatible license are allowed.
- Proprietary modules are less and less tolerated.
  Lawyers say that they are illegal.
- Proprietary drivers must not be statically compiled in the kernel.
- You are not allowed to reuse code from other kernel drivers (GPL) in a proprietary driver.

Advantages of GPL drivers

From the driver developer / decision maker point of view

- You don't have to write your driver from scratch. You can reuse code from similar free software drivers.
- You get free community contributions, support, code review and testing. Proprietary drivers (even with sources) don't get any.
- Your drivers can be freely shipped by others (mainly by distributions).
- Closed source drivers often support a given kernel version. A system with closed source drivers from 2 different sources is unmanageable.
- Users and the community get a positive image of your company. Makes it easier to hire talented developers.
- You don't have to supply binary driver releases for each kernel version and patch version (closed source drivers).
- Modules have all privileges. You need the sources to make sure that a module is not a security risk.
- Your drivers can be statically compiled in the kernel.

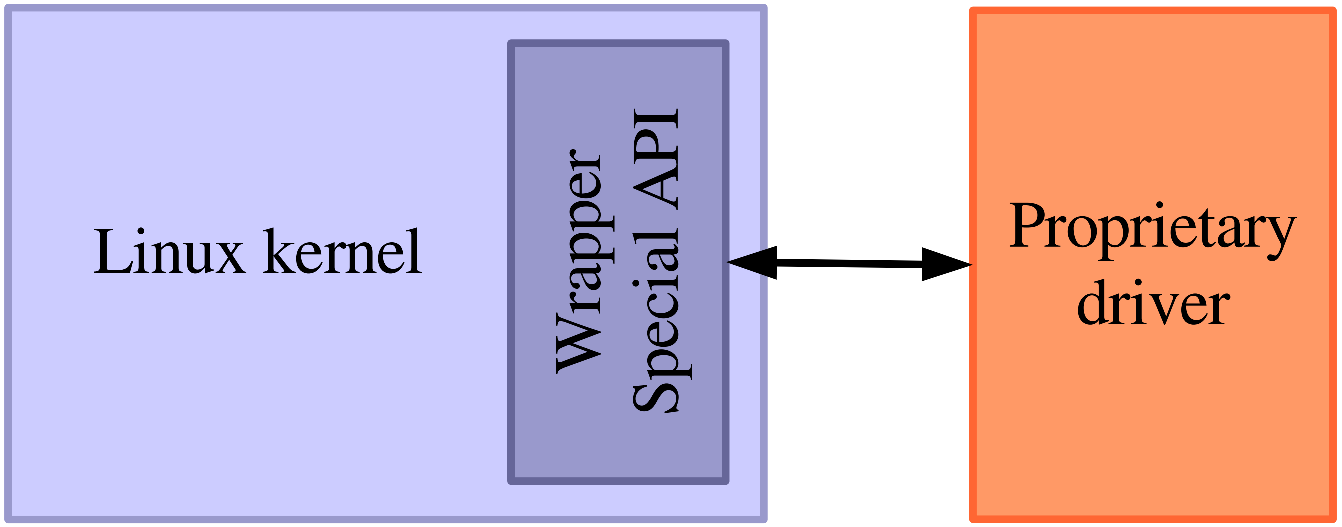
Advantages of in-tree kernel modules

Advantages of having your drivers in the mainline kernel sources

- Once your sources are accepted in the mainline tree, they are maintained by people making changes.
- Cost-free maintenance, security fixes and improvements.
- Easy access to your sources by users.
- Many more people reviewing your code.

Legal proprietary Linux drivers (1)

Working around the GPL by creating a GPL wrapper:



The proprietary driver is **not broken** when you recompile or update the kernel and/or driver. Hence, the proprietary driver cannot be considered as a derivative work.

Legal proprietary Linux drivers (2)

2 example cases

- Nvidia graphic card drivers
- Supporting wireless network cards using Windows drivers.

  The NdisWrapper project (http://ndiswrapper.sourceforge.net/) implements the Windows kernel API and NDIS (Network Driver Interface Specification) API within the Linux kernel.

  Useful for using cards for which no specifications are released.

Drawbacks

- Still some maintenance issues. Example: Nvidia proprietary driver incompatible with X.org 7.1.
- Performance issues. Wrapper overhead and optimizations not available.
- Security issues. The drivers are executed with full kernel privileges.
- ... and all other issues with proprietary drivers. Users loose most benefits of Free Software.

Software patent issues in the kernel

Linux Kernel driver issues because of patented algorithms
Check for software patent warnings when you configure your kernel!

- Patent warnings issued in the documentation of drivers, shown in the kernel configuration interface.
- Flash Translation Layer
  `drivers/mtd/ftl.c`
  In the USA, this driver can only be used on PCMCIA hardware (MSystems patent).
- Nand Flash Translation Layer
  In the USA, can only be used on DiskOnChip hardware.
- Networking compression
  `drivers/net/bsd_comp.c`
  Can't send a CCP reset-request as a result of an error detected after decompression (Motorola patent).
- Other drivers not accepted in Linux releases or algorithms not implemented because of such patents! Otherwise, more examples would be available in the source code.

Embedded Linux driver development

Kernel overview

Kernel user interface

Mounting virtual filesystems

- Linux makes system and kernel information available in user-space through virtual filesystems (virtual files not existing on any real storage). No need to know kernel programming to access this!
- Mounting `/proc`:

```
mount -t proc none /proc
```

- Mounting `/sys`:

```
mount -t sysfs none /sys
```

Filesystem type

Raw device
or filesystem image
In the case of virtual
filesystems, any string is fine

Mount point

Kernel userspace interface

A few examples:

- `/proc/cpuinfo`: processor information
- `/proc/meminfo`: memory status
- `/proc/version`: version and build information
- `/proc/cmdline`: kernel command line
- `/proc/<pid>/environ`: calling environment
- `/proc/<pid>/cmdline`: process command line

... and many more! See by yourself!

Userspace interface documentation

- Lots of details about the `/proc` interface are available in `Documentation/filesystems/proc.txt` (almost 2000 lines) in the kernel sources.
- You can also find other details in the `proc` manual page: `man proc`
- See the New Device Model section for details about `/sys`

Userspace device drivers (1)

Possible to implement device drivers in user-space!

- Such drivers just need access to the devices through minimum, generic kernel drivers.
- Examples:
  Printer and scanner drivers
  (on top of generic parallel port / USB drivers)
  X drivers: low level kernel drivers + user space X drivers.

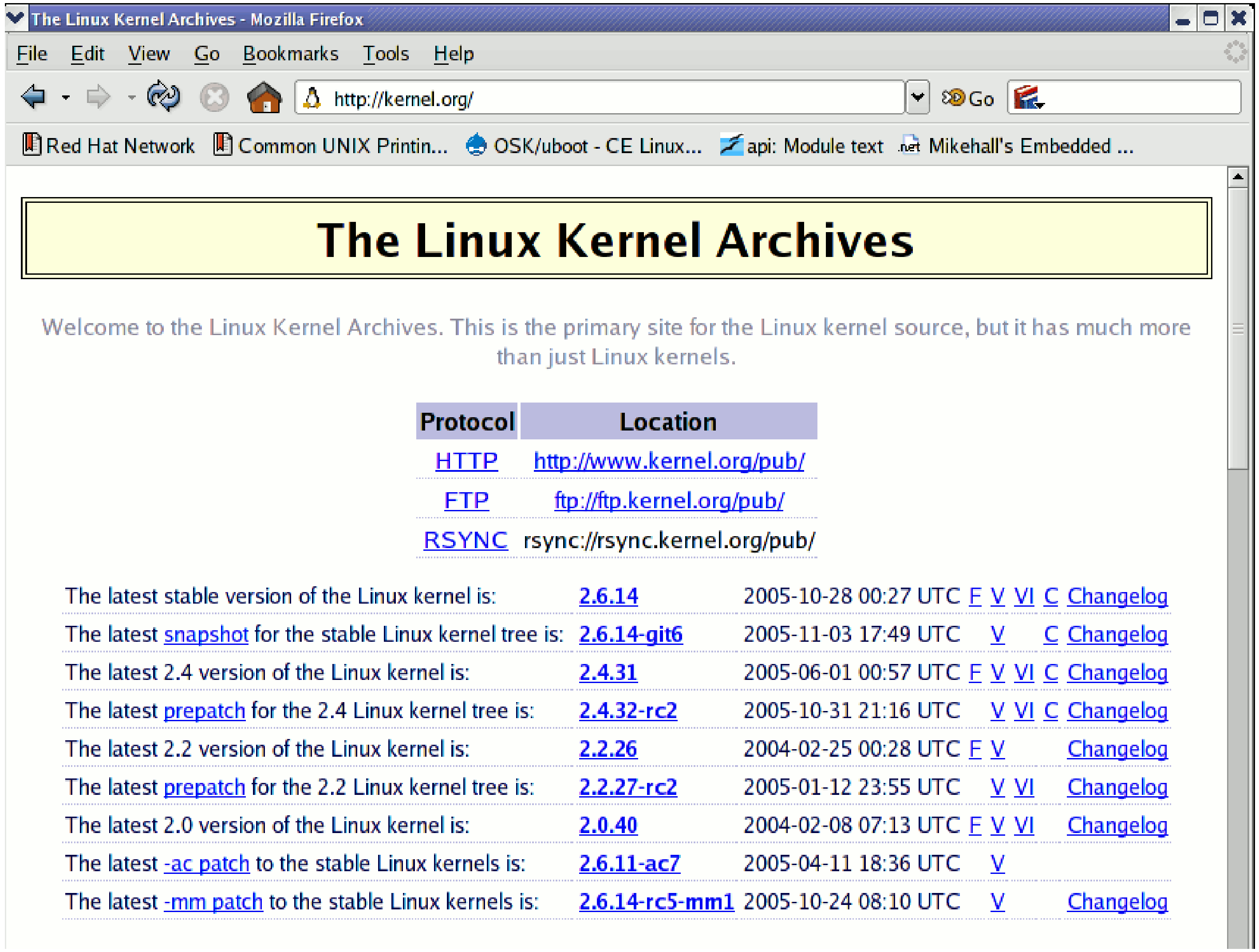
Userspace device drivers (2)

- Advantages
  No need for kernel coding skills. Easier to reuse code between devices.
  Drivers can be kept proprietary
  Driver code can be killed and debugged. Cannot crash the kernel.
  Can be swapped out (kernel code cannot be).
  Less in-kernel complexity.
- Drawbacks
  Less straightforward to handle interrupts.
  Increased latency vs. kernel code.
- See http://free-electrons.com/redirect/elc2006-uld.html
  for practical details and techniques for overcoming the drawbacks.

Compiling and booting Linux

Linux kernel sources

kernel.org



The Linux Kernel Archives

Welcome to the Linux Kernel Archives. This is the primary site for the Linux kernel source, but it has much more than just Linux kernels.

Protocol	Location
HTTP	http://www.kernel.org/pub/
FTP	ftp://ftp.kernel.org/pub/
RSYNC	rsync://rsync.kernel.org/pub/

The latest stable version of the Linux kernel is:	2.6.14	2005-10-28 00:27 UTC	F	V	VI	C	Changelog
The latest snapshot for the stable Linux kernel tree is:	2.6.14-git6	2005-11-03 17:49 UTC		V		C	Changelog
The latest 2.4 version of the Linux kernel is:	2.4.31	2005-06-01 00:57 UTC	F	V	VI	C	Changelog
The latest prepatch for the 2.4 Linux kernel tree is:	2.4.32-rc2	2005-10-31 21:16 UTC		V	VI	C	Changelog
The latest 2.2 version of the Linux kernel is:	2.2.26	2004-02-25 00:28 UTC	F	V			Changelog
The latest prepatch for the 2.2 Linux kernel tree is:	2.2.27-rc2	2005-01-12 23:55 UTC		V	VI		Changelog
The latest 2.0 version of the Linux kernel is:	2.0.40	2004-02-08 07:13 UTC	F	V	VI		Changelog
The latest -ac patch to the stable Linux kernels is:	2.6.11-ac7	2005-04-11 18:36 UTC		V			
The latest -mm patch to the stable Linux kernels is:	2.6.14-rc5-mm1	2005-10-24 08:10 UTC		V			Changelog

Download them from http://kernel.org

Linux sources structure (1)

`arch/<arch>`	Architecture specific code
`arch/<arch>/mach-<mach>`	Machine / board specific code
`COPYING`	Linux copying conditions (GNU GPL)
`CREDITS`	Linux main contributors
`crypto/`	Cryptographic libraries
`Documentation/`	Kernel documentation. Don't miss it!
`drivers/`	All device drivers (`drivers/usb/`, etc.)
`fs/`	Filesystems (`fs/ext3/`, etc.)
`include/`	Kernel headers
`include/asm-<arch>`	Architecture and machine dependent headers
`include/linux`	Linux kernel core headers
`init/`	Linux initialization (including `main.c`)
`ipc/`	Code used for process communication

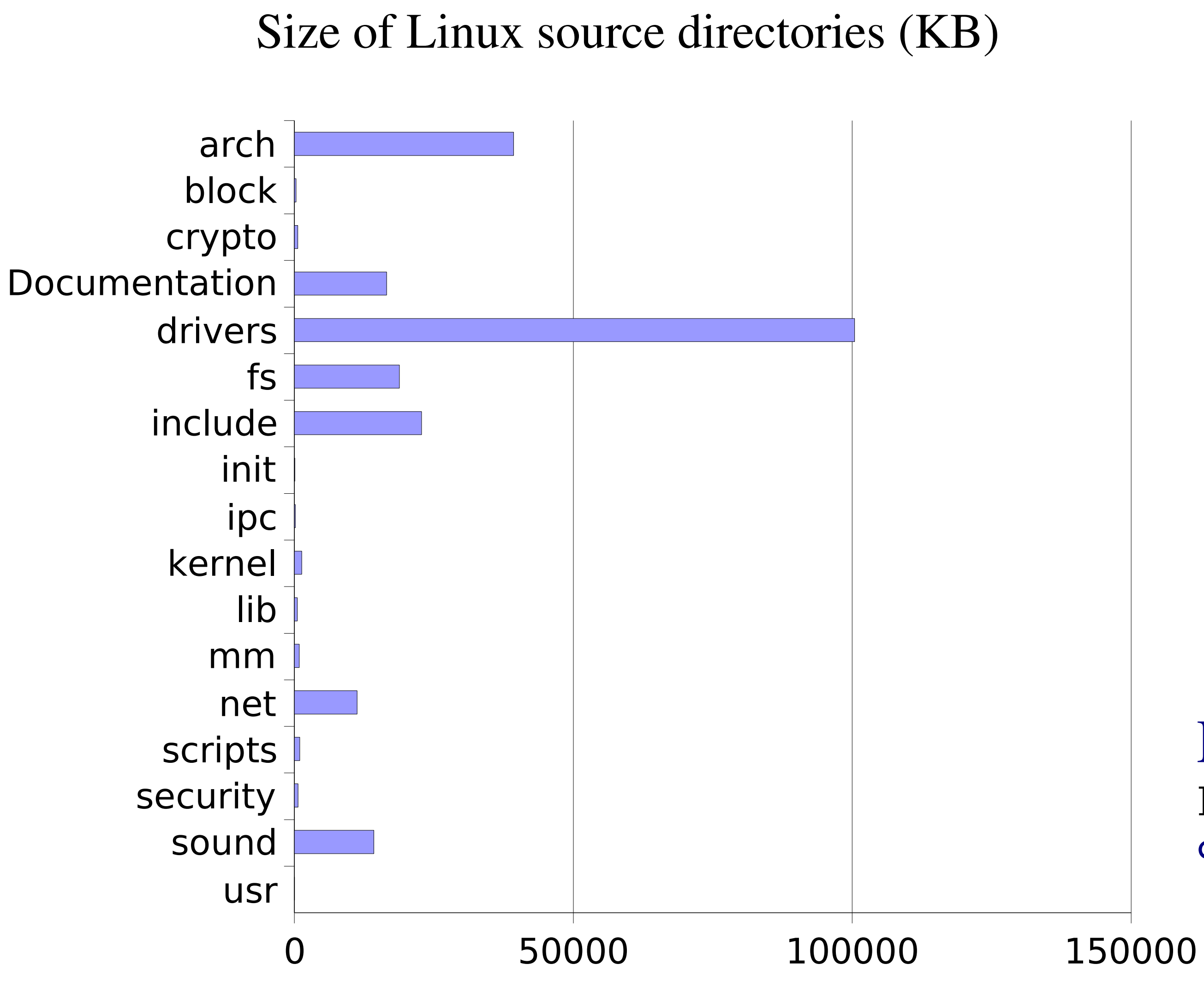
Linux sources structure (2)

`kernel/`	Linux kernel core (very small!)
`lib/`	Misc library routines (`zlib`, `crc32`...)
`MAINTAINERS`	Maintainers of each kernel part. Very useful!
`Makefile`	Top Linux makefile (sets arch and version)
`mm/`	Memory management code (small too!)
`net/`	Network support code (not drivers)
`README`	Overview and building instructions
`REPORTING-BUGS`	Bug report instructions
`scripts/`	Scripts for internal or external use
`security/`	Security model implementations (SELinux...)
`sound/`	Sound support code and drivers
`usr/`	Early user-space code (`initramfs`)

Linux kernel size (1)

- Linux 2.6.17 sources:
  Raw size: 224 MB (20400 files, approx 7 million lines of code)
  `bzip2` compressed tar archive: 40 MB (best choice)
  `gzip` compressed tar archive: 50 MB
- Minimum compiled Linux kernel size (with Linux-Tiny patches)
  approx 300 KB (compressed), 800 KB (raw)
- Why are these sources so big?
  Because they include thousands of device drivers, many network protocols, support many architectures and filesystems...
- The Linux core (scheduler, memory management...) is pretty small!

Linux kernel size (2)



Linux 2.6.17

Measured with:

`du -s --apparent-size`

Getting Linux sources: 2 possibilities

Full sources

- The easiest way, but longer to download.
- Example:
  http://kernel.org/pub/linux/kernel/v2.6/linux-2.6.14.1.tar.bz2

Or patch against the previous version

- Assuming you already have the full sources of the previous version
- Example:
  http://kernel.org/pub/linux/kernel/v2.6/patch-2.6.14.bz2 (2.6.13 to 2.6.14)
  http://kernel.org/pub/linux/kernel/v2.6/patch-2.6.14.7.bz2 (2.6.14 to 2.6.14.7)

Downloading full kernel sources

Downloading from the command line

- With a web browser, identify the version you need on http://kernel.org
- In the right directory, download the source archive and its signature (copying the download address from the browser):

```
wget http://kernel.org/pub/linux/kernel/v2.6/linux-2.6.11.12.tar.bz2
wget http://kernel.org/pub/linux/kernel/v2.6/linux-2.6.11.12.tar.bz2.sign
```

- Check the electronic signature of the archive:

```
gpg --verify linux-2.6.11.12.tar.bz2.sign
```

- Extract the contents of the source archive:

```
tar jxvf linux-2.6.11.12.tar.bz2
```

`~/.wgetrc` config file for proxies:

```
http_proxy = <proxy>:<port>
ftp_proxy = <proxy>:<port>
proxy_user = <user>  (if any)
proxy_password = <passwd>  (if any)
```

Downloading kernel source patches (1)

Assuming you already have the `linux-x.y.<n-1>` version

- Identify the patches you need on http://kernel.org with a web browser
- Download the patch files and their signature:

Patch from `2.6.10` to `2.6.11`

```
wget ftp://ftp.kernel.org/pub/linux/kernel/v2.6/patch-2.6.11.bz2
wget ftp://ftp.kernel.org/pub/linux/kernel/v2.6/patch-2.6.11.bz2.sign
```

Patch from `2.6.11` to `2.6.11.12` (latest stable fixes)

```
wget http://www.kernel.org/pub/linux/kernel/v2.6/patch-2.6.11.12.bz2
wget http://www.kernel.org/pub/linux/kernel/v2.6/patch-2.6.11.12.bz2.sign
```

Downloading kernel source patches (2)

- Check the signature of patch files:

```
gpg --verify patch-2.6.11.bz2.sign
gpg --verify patch-2.6.11.12.bz2.sign
```

- Apply the patches in the right order:

```
cd linux-2.6.10/
bzcat ../patch-2.6.11.bz2 | patch -p1
bzcat ../patch-2.6.11.12.bz2 | patch -p1
cd ..
mv linux-2.6.10 linux-2.6.11.12
```

Checking the integrity of sources

Kernel source integrity can be checked through OpenPGP digital signatures. Full details on http://www.kernel.org/signature.html

- If needed, read http://www.gnupg.org/gph/en/manual.html and create a new private and public keypair for yourself.
- Import the public GnuPG key of kernel developers:
  - `gpg --keyserver pgp.mit.edu --recv-keys 0x517D0F0E`
  - If blocked by your firewall, look for `0x517D0F0E` on http://pgp.mit.edu/ , copy and paste the key to a `linuxkey.txt` file:
    `gpg --import linuxkey.txt`
- Check the signature of files:
  `gpg --verify linux-2.6.11.12.tar.bz2.sign`

Anatomy of a patch file

A patch file is the output of the `diff` command

```
diff -Nru a/Makefile b/Makefile
--- a/Makefile  2005-03-04 09:27:15 -08:00
+++ b/Makefile  2005-03-04 09:27:15 -08:00
@@ -1,7 +1,7 @@
 VERSION = 2
 PATCHLEVEL = 6
 SUBLEVEL = 11
-EXTRAVERSION =
+EXTRAVERSION = .1
 NAME=Woozy Numbat

 # *DOCUMENTATION*
```

← `diff` command line

← File date info

← Line numbers in files

← Context info: 3 lines before the change
Useful to apply a patch when line numbers changed

← Removed line(s) if any

← Added line(s) if any

← Context info: 3 lines after the change

Using the patch command

The `patch` command applies changes to files in the current directory:

- Making changes to existing files
- Creating or deleting files and directories

`patch` usage examples:

- `patch -p<n> < diff_file`
- `cat diff_file | patch -p<n>`
- `bzcat diff_file.bz2 | patch -p<n>`
- `zcat diff_file.gz | patch -p<n>`

`n`: number of directory levels to skip in the file paths

You can reverse a patch with the `-R` option

Applying a Linux patch

Linux patches...

- Always to apply to the `x.y.<z-1>` version
- Always produced for `n=1` (that's what everybody does... do it too!)
- Downloadable in `gzip` and `bzip2` (much smaller) compressed files.
- Linux patch command line example:

```
cd linux-2.6.10
bzcat ../patch-2.6.11.bz2 | patch -p1
cd ..; mv linux-2.6.10 linux-2.6.11
```

- Keep patch files compressed: useful to check their signature later.
  You can still view (or even edit) the uncompressed data with `vi`:
  `vi patch-2.6.11.bz2` (on the fly (un)compression)

Accessing development sources (1)

- Kernel development sources are now managed with git
- You can browse Linus' git tree (if you just need to check a few files):
  http://www.kernel.org/git/?p=linux/kernel/git/torvalds/linux-2.6.git;a=tree
- Get and compile git from http://kernel.org/pub/software/scm/git/
- Get and compile the cogito front-end from
  http://kernel.org/pub/software/scm/cogito/
- If you are behind a proxy, set Unix environment variables defining proxy settings. Example:

```
export http_proxy="proxy.server.com:8080"
export ftp_proxy="proxy.server.com:8080"
```

Accessing development sources (2)

- Pick up a git development tree on http://kernel.org/git/
- Get a local copy ("clone") of this tree.
  Example (Linus tree, the one used for Linux stable releases):

```
cg-clone http://kernel.org/pub/scm/linux/kernel/git/torvalds/linux-2.6.git
```
or
```
cg-clone rsync://rsync.kernel.org/pub/scm/linux/kernel/git/torvalds/linux-2.6.git
```

- Update your copy whenever needed (Linus tree example):

```
cd linux-2.6
cg-update origin
```

More details available
on http://git.or.cz/ or http://linux.yyz.us/git-howto.html

On-line kernel documentation

http://free-electrons.com/kerneldoc/

- Provided for all recent kernel releases
- Easier than downloading kernel sources to access documentation
- Indexed by Internet search engines
  Makes kernel pieces of documentation easier to find!
- Unlike most other sites offering this service too, also includes an HTML translation of kernel documents in the DocBook format.

Never forget documentation in the kernel sources! It's a very valuable way of getting information about the kernel.

Embedded Linux driver development

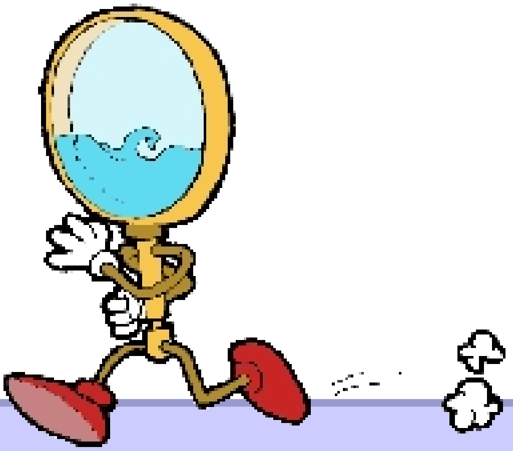
Compiling and booting Linux

Kernel source management tools

Cscope

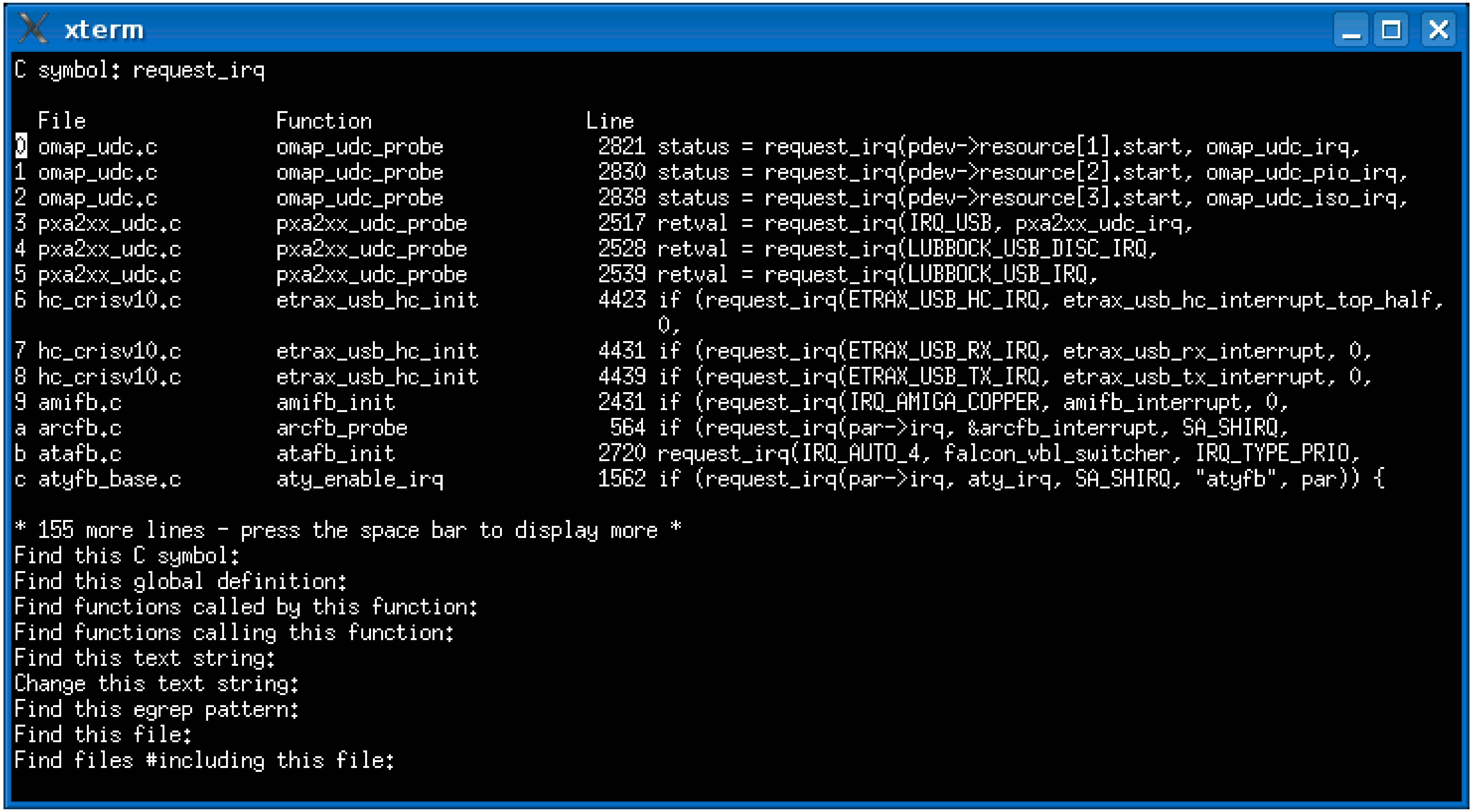
http://cscope.sourceforge.net/

- Tool to browse source code (mainly C, but also C++ or Java)
- Supports huge projects like the Linux kernel
  Takes less than 1 min. to index Linux 2.6.17 sources (fast!)
- Can be used from editors like `vim` and `emacs`.
- In Linux kernel sources, run it with:
  `cscope -Rk`
  (see `man cscope` for details)



Allows searching code for:
- all references to a symbol
- global definitions
- functions called by a function
- functions calling a function
- text string
- regular expression pattern
- a file
- files including a file

Cscope screenshot



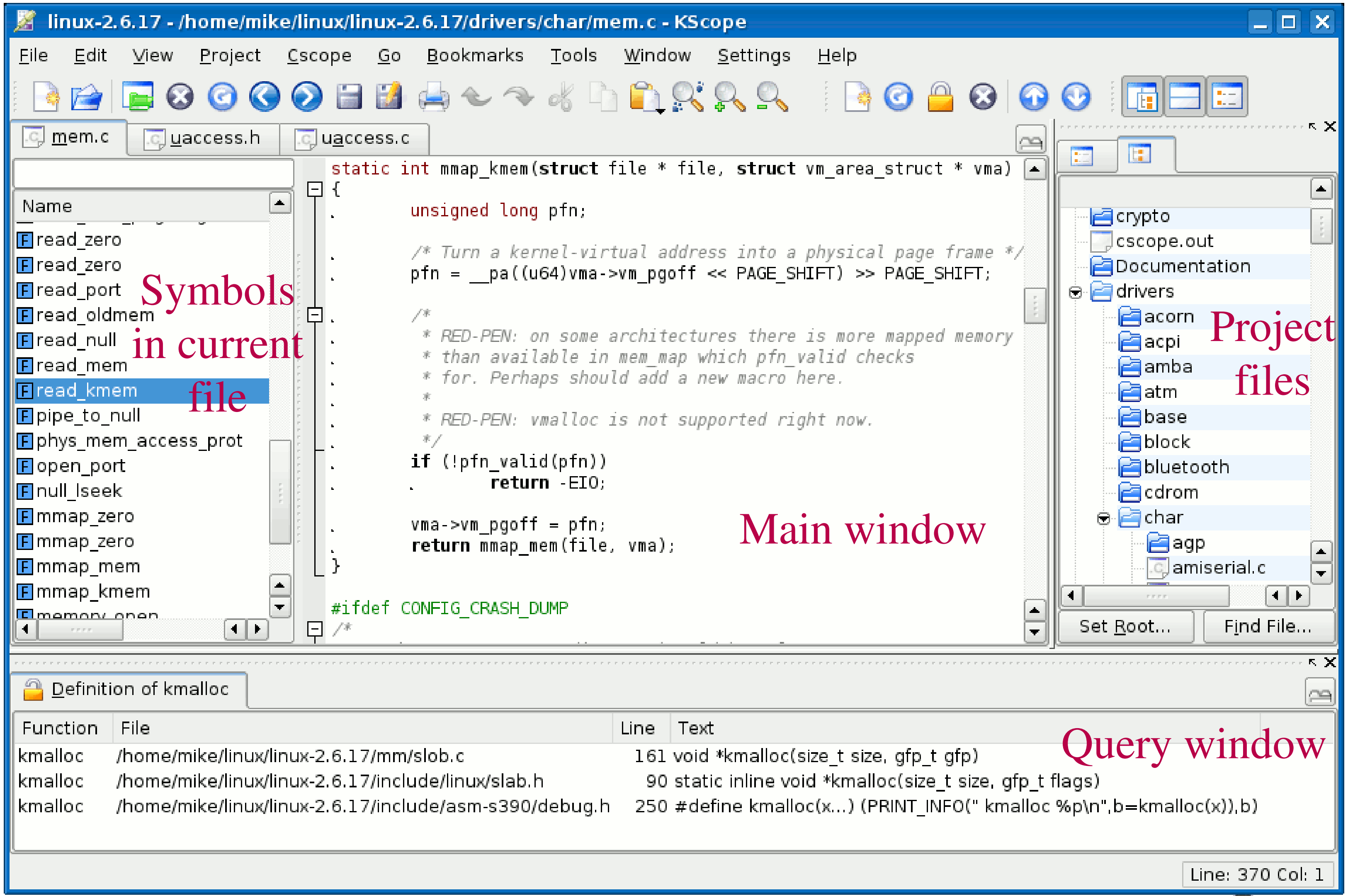
```
C symbol: request_irq

  File                  Function                 Line
0 omap_udc.c            omap_udc_probe            2821 status = request_irq(pdev->resource[1].start, omap_udc_irq,
1 omap_udc.c            omap_udc_probe            2830 status = request_irq(pdev->resource[2].start, omap_udc_pio_irq,
2 omap_udc.c            omap_udc_probe            2838 status = request_irq(pdev->resource[3].start, omap_udc_iso_irq,
3 pxa2xx_udc.c          pxa2xx_udc_probe          2517 retval = request_irq(IRQ_USB, pxa2xx_udc_irq,
4 pxa2xx_udc.c          pxa2xx_udc_probe          2528 retval = request_irq(LUBBOCK_USB_DISC_IRQ,
5 pxa2xx_udc.c          pxa2xx_udc_probe          2539 retval = request_irq(LUBBOCK_USB_IRQ,
6 hc_crisv10.c          etrax_usb_hc_init         4423 if (request_irq(ETRAX_USB_HC_IRQ, etrax_usb_hc_interrupt_top_half,
                                                       0,
7 hc_crisv10.c          etrax_usb_hc_init         4431 if (request_irq(ETRAX_USB_RX_IRQ, etrax_usb_rx_interrupt, 0,
8 hc_crisv10.c          etrax_usb_hc_init         4439 if (request_irq(ETRAX_USB_TX_IRQ, etrax_usb_tx_interrupt, 0,
9 amifb.c               amifb_init                2431 if (request_irq(IRQ_AMIGA_COPPER, amifb_interrupt, 0,
a arcfb.c               arcfb_probe                564 if (request_irq(par->irq, &arcfb_interrupt, SA_SHIRQ,
b atafb.c               atafb_init                2720 request_irq(IRQ_AUTO_4, falcon_vbl_switcher, IRQ_TYPE_PRIO,
c atyfb_base.c          aty_enable_irq            1562 if (request_irq(par->irq, aty_irq, SA_SHIRQ, "atyfb", par)) {

* 155 more lines - press the space bar to display more *
Find this C symbol:
Find this global definition:
Find functions called by this function:
Find functions calling this function:
Find this text string:
Change this text string:
Find this egrep pattern:
Find this file:
Find files #including this file:
```

KScope

http://kscope.sourceforge.net

- A graphical front-end to Cscope
- Makes it easy to browse and edit the Linux kernel sources
- Can display a function call tree
- Nice editing features: symbol completion, spelling checker, automatic indentation...
- Usage guidelines:
  Use the Kernel setting to ignore standard C includes.
  Make sure the project name doesn't contain blank characters!

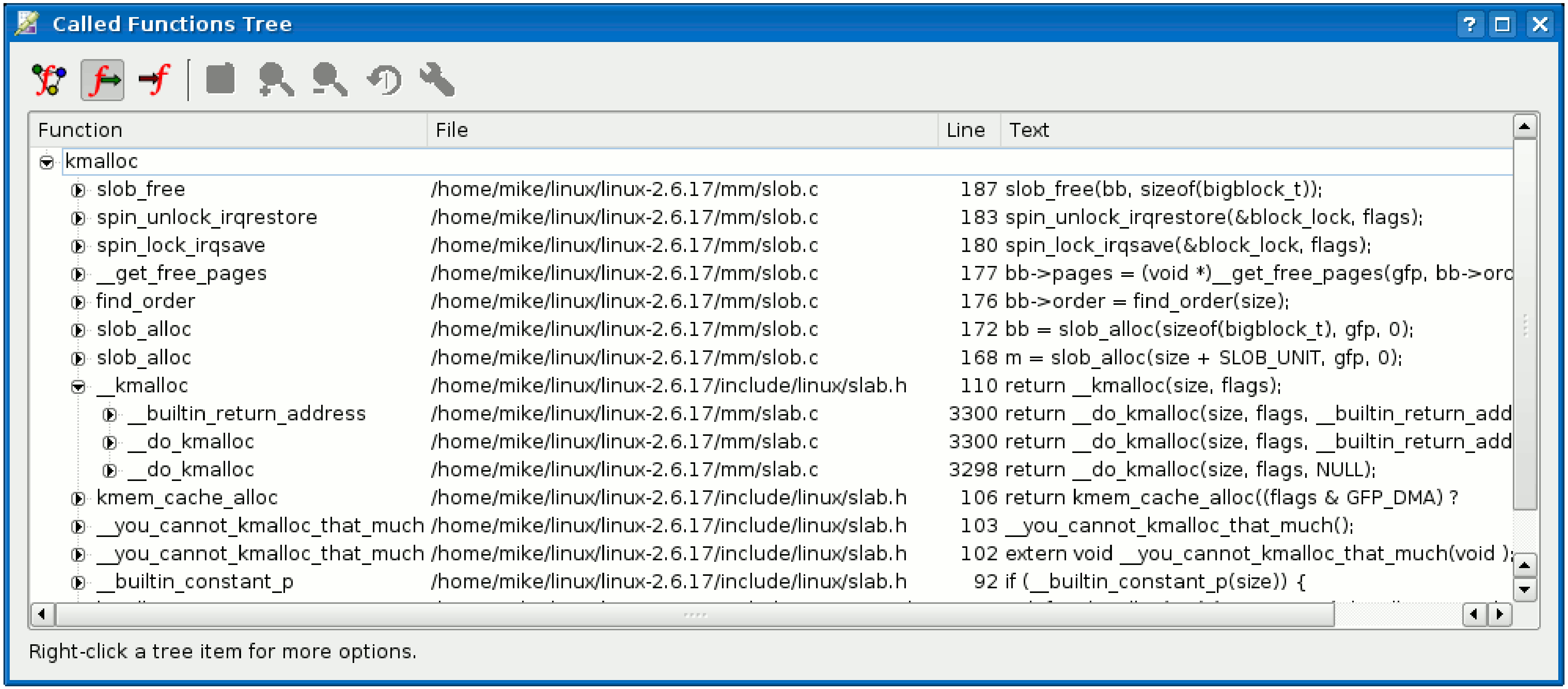
KScope screenshots (1)



```
static int mmap_kmem(struct file * file, struct vm_area_struct * vma)
{
        unsigned long pfn;

        /* Turn a kernel-virtual address into a physical page frame */
        pfn = __pa((u64)vma->vm_pgoff << PAGE_SHIFT) >> PAGE_SHIFT;

        /*
         * RED-PEN: on some architectures there is more mapped memory
         * than available in mem_map which pfn_valid checks
         * for. Perhaps should add a new macro here.
         *
         * RED-PEN: vmalloc is not supported right now.
         */
        if (!pfn_valid(pfn))
                return -EIO;

        vma->vm_pgoff = pfn;
        return mmap_mem(file, vma);
}

#ifdef CONFIG_CRASH_DUMP
/*
```

Function	File	Line	Text
kmalloc	/home/mike/linux/linux-2.6.17/mm/slob.c	161	void *kmalloc(size_t size, gfp_t gfp)
kmalloc	/home/mike/linux/linux-2.6.17/include/linux/slab.h	90	static inline void *kmalloc(size_t size, gfp_t flags)
kmalloc	/home/mike/linux/linux-2.6.17/include/asm-s390/debug.h	250	#define kmalloc(x...) (PRINT_INFO(" kmalloc %p\n",b=kmalloc(x)),b)

KScope screenshots (2)



Function	File	Line	Text
kmalloc			
slob_free	/home/mike/linux/linux-2.6.17/mm/slob.c	187	slob_free(bb, sizeof(bigblock_t));
spin_unlock_irqrestore	/home/mike/linux/linux-2.6.17/mm/slob.c	183	spin_unlock_irqrestore(&block_lock, flags);
spin_lock_irqsave	/home/mike/linux/linux-2.6.17/mm/slob.c	180	spin_lock_irqsave(&block_lock, flags);
__get_free_pages	/home/mike/linux/linux-2.6.17/mm/slob.c	177	bb->pages = (void *)__get_free_pages(gfp, bb->orc
find_order	/home/mike/linux/linux-2.6.17/mm/slob.c	176	bb->order = find_order(size);
slob_alloc	/home/mike/linux/linux-2.6.17/mm/slob.c	172	bb = slob_alloc(sizeof(bigblock_t), gfp, 0);
slob_alloc	/home/mike/linux/linux-2.6.17/mm/slob.c	168	m = slob_alloc(size + SLOB_UNIT, gfp, 0);
__kmalloc	/home/mike/linux/linux-2.6.17/include/linux/slab.h	110	return __kmalloc(size, flags);
__builtin_return_address	/home/mike/linux/linux-2.6.17/mm/slab.c	3300	return __do_kmalloc(size, flags, __builtin_return_add
__do_kmalloc	/home/mike/linux/linux-2.6.17/mm/slab.c	3300	return __do_kmalloc(size, flags, __builtin_return_add
__do_kmalloc	/home/mike/linux/linux-2.6.17/mm/slab.c	3298	return __do_kmalloc(size, flags, NULL);
kmem_cache_alloc	/home/mike/linux/linux-2.6.17/include/linux/slab.h	106	return kmem_cache_alloc((flags & GFP_DMA) ?
__you_cannot_kmalloc_that_much	/home/mike/linux/linux-2.6.17/include/linux/slab.h	103	__you_cannot_kmalloc_that_much();
__you_cannot_kmalloc_that_much	/home/mike/linux/linux-2.6.17/include/linux/slab.h	102	extern void __you_cannot_kmalloc_that_much(void);
__builtin_constant_p	/home/mike/linux/linux-2.6.17/include/linux/slab.h	92	if (__builtin_constant_p(size)) {

Right-click a tree item for more options.

Called functions tree

LXR: Linux Cross Reference

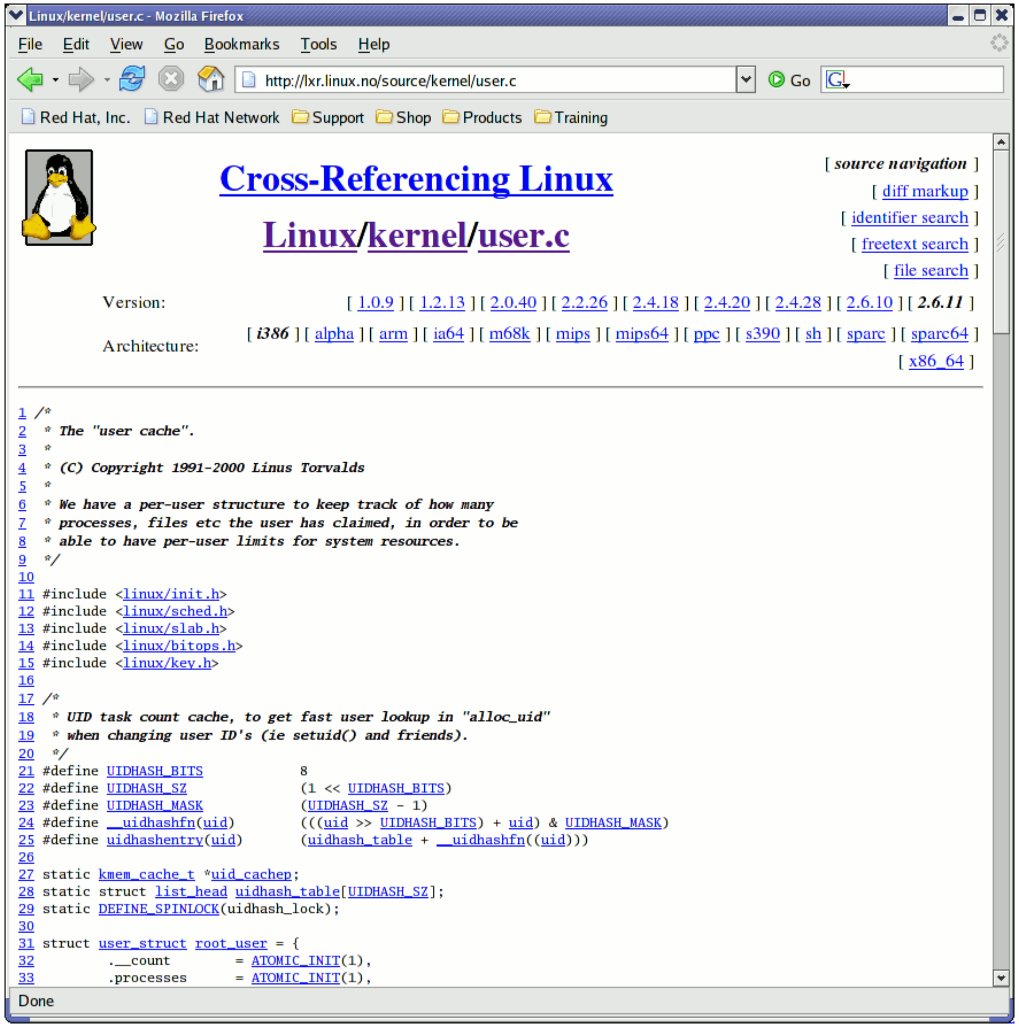
http://sourceforge.net/projects/lxr

Generic source indexing tool
and code browser

- Web server based
  Very easy and fast to use
- Identifier or text search available
- Very easy to find the declaration, implementation or usages of symbols
- Supports C and C++
- Supports huge code projects such as the Linux kernel (274 M in version 2.6.17).

- Takes some time and patience to setup (configuration, indexing, server configuration).
- Initial indexing very slow:
  Linux 2.6.17: several hours on a server with an AMD Sempron 2200+ CPU.
  Using Kscope is the easiest and fastest solution for modified kernel sources.
- You don't need to set up LXR by yourself.
  Use our http://lxr.free-electrons.com server!
  Other servers available on the Internet:
  http://free-electrons.com/community/kernel/lxr/
- This makes LXR the simplest solution to browse standard kernel sources.

LXR screenshot


Linux/kernel/user.c - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
http://lxr.linux.no/source/kernel/user.c
Go
Red Hat, Inc. Red Hat Network Support Shop Products Training
Done

Cross-Referencing Linux

Linux/kernel/user.c

[*source navigation*]
[diff markup]
[identifier search]
[freetext search]
[file search]

Version: [1.0.9] [1.2.13] [2.0.40] [2.2.26] [2.4.18] [2.4.20] [2.4.28] [2.6.10] [***2.6.11***]

Architecture: [***i386***] [alpha] [arm] [ia64] [m68k] [mips] [mips64] [ppc] [s390] [sh] [sparc] [sparc64] [x86_64]

```
/*
 * The "user cache".
 *
 * (C) Copyright 1991-2000 Linus Torvalds
 *
 * We have a per-user structure to keep track of how many
 * processes, files etc the user has claimed, in order to be
 * able to have per-user limits for system resources.
 */

#include <linux/init.h>
#include <linux/sched.h>
#include <linux/slab.h>
#include <linux/bitops.h>
#include <linux/key.h>

/*
 * UID task count cache, to get fast user lookup in "alloc_uid"
 * when changing user ID's (ie setuid() and friends).
 */
#define UIDHASH_BITS            8
#define UIDHASH_SZ              (1 << UIDHASH_BITS)
#define UIDHASH_MASK            (UIDHASH_SZ - 1)
#define __uidhashfn(uid)        (((uid >> UIDHASH_BITS) + uid) & UIDHASH_MASK)
#define uidhashentry(uid)       (uidhash_table + __uidhashfn((uid)))

static kmem_cache_t *uid_cachep;
static struct list_head uidhash_table[UIDHASH_SZ];
static DEFINE_SPINLOCK(uidhash_lock);

struct user_struct root_user = {
        .__count        = ATOMIC_INIT(1),
        .processes      = ATOMIC_INIT(1),
```

Ketchup - Easy access to kernel source trees

http://www.selenic.com/ketchup/wiki/

- Makes it easy to get the latest version of a given kernel source tree (`2.4`, `2.6`, `2.6-rc`, `2.6-git`, `2.6-mm`, `2.6-rt`...)
- Only downloads the needed patches.
  Reverts patches when needed to apply a more recent patch.
- Also checks the signature of sources and patches.

Ketchup examples

- Get the version in the current directory:

```
> ketchup -m
2.6.10
```

- Upgrade to the latest stable version:

```
> ketchup 2.6-tip
2.6.10 -> 2.6.12.5
Applying patch-2.6.11.bz2
Applying patch-2.6.12.bz2
Applying patch-2.6.12.5.bz2
```

More on http://selenic.com/ketchup/wiki/index.cgi/ExampleUsage

Practical lab – Kernel sources

Time to start `Lab 1`!

- Get the sources
- Check the authenticity of sources
- Apply patches
- Get familiar with the sources
- Use a kernel source indexing tool

Embedded Linux driver development

Compiling and booting Linux

Kernel configuration

Kernel configuration overview

- `Makefile` edition
  Setting the version and target architecture if needed
- Kernel configuration: defining what features to include in the kernel:

```
make [config|xconfig|gconfig|menuconfig|oldconfig]
```

  - Kernel configuration file (Makefile syntax) stored in the `.config` file at the root of the kernel sources
  - Distribution kernel config files usually released in `/boot/`

Makefile changes

- To identify your kernel image with others build from the same sources, use the `EXTRAVERSION` variable:

```
VERSION = 2
PATCHLEVEL = 6
SUBLEVEL = 15
EXTRAVERSION = -acme1
```

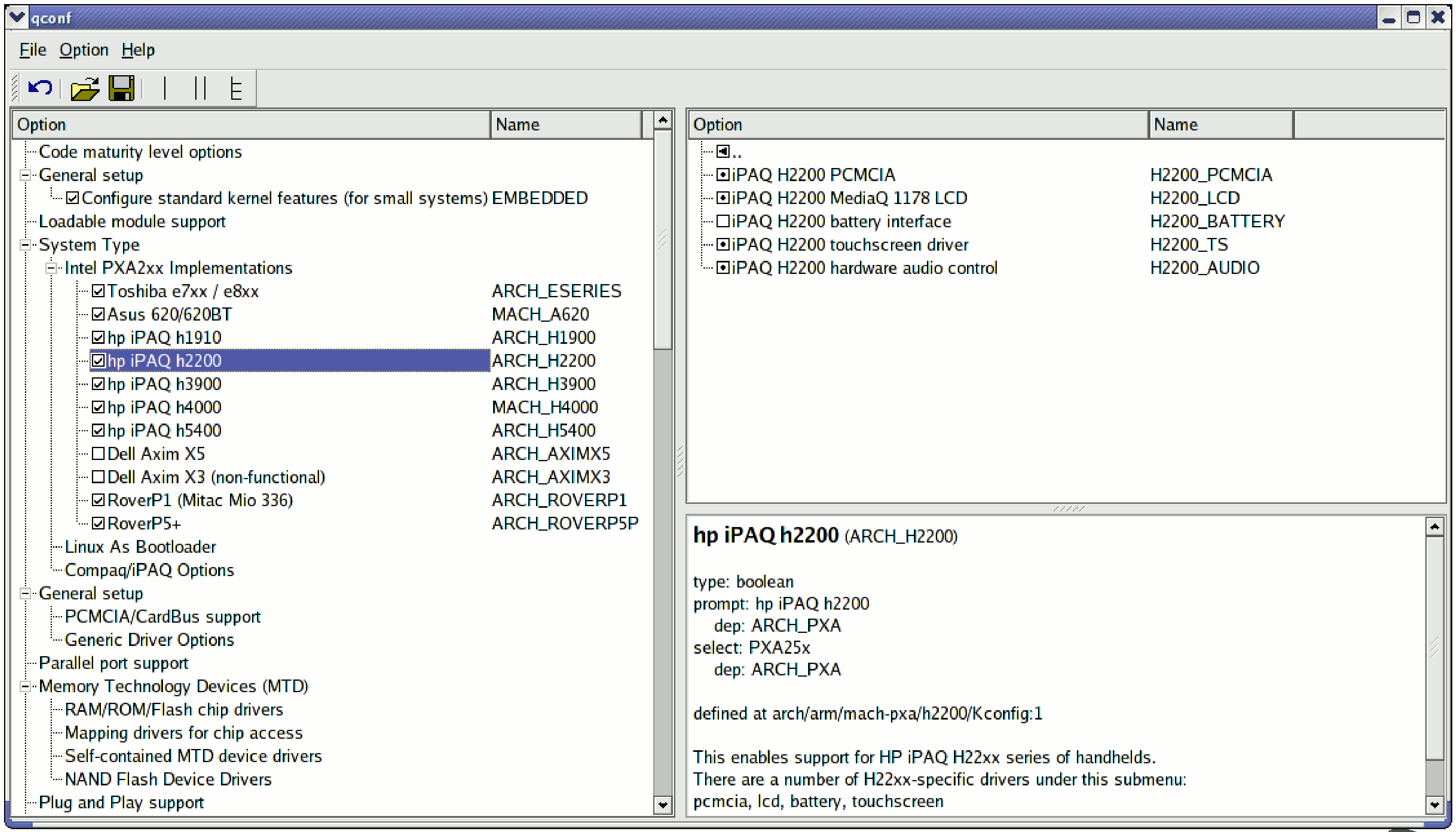
- `uname -r` will return:
  `2.6.15-acme1`

make xconfig

`make xconfig`

- New Qt configuration interface for Linux 2.6.
  Much easier to use than in Linux 2.4!
- Make sure you read
  `help -> introduction: useful options!`
- File browser: easier to load configuration files

make xconfig screenshot



Option	Name
Code maturity level options	
General setup	
☑ Configure standard kernel features (for small systems)	EMBEDDED
Loadable module support	
System Type	
Intel PXA2xx Implementations	
☑ Toshiba e7xx / e8xx	ARCH_ESERIES
☑ Asus 620/620BT	MACH_A620
☑ hp iPAQ h1910	ARCH_H1900
☑ hp iPAQ h2200	ARCH_H2200
☑ hp iPAQ h3900	ARCH_H3900
☑ hp iPAQ h4000	MACH_H4000
☑ hp iPAQ h5400	ARCH_H5400
☐ Dell Axim X5	ARCH_AXIMX5
☐ Dell Axim X3 (non-functional)	ARCH_AXIMX3
☑ RoverP1 (Mitac Mio 336)	ARCH_ROVERP1
☑ RoverP5+	ARCH_ROVERP5P
Linux As Bootloader	
Compaq/iPAQ Options	
General setup	
PCMCIA/CardBus support	
Generic Driver Options	
Parallel port support	
Memory Technology Devices (MTD)	
RAM/ROM/Flash chip drivers	
Mapping drivers for chip access	
Self-contained MTD device drivers	
NAND Flash Device Drivers	
Plug and Play support	

Option	Name
..	
⊡ iPAQ H2200 PCMCIA	H2200_PCMCIA
⊡ iPAQ H2200 MediaQ 1178 LCD	H2200_LCD
☐ iPAQ H2200 battery interface	H2200_BATTERY
⊡ iPAQ H2200 touchscreen driver	H2200_TS
⊡ iPAQ H2200 hardware audio control	H2200_AUDIO

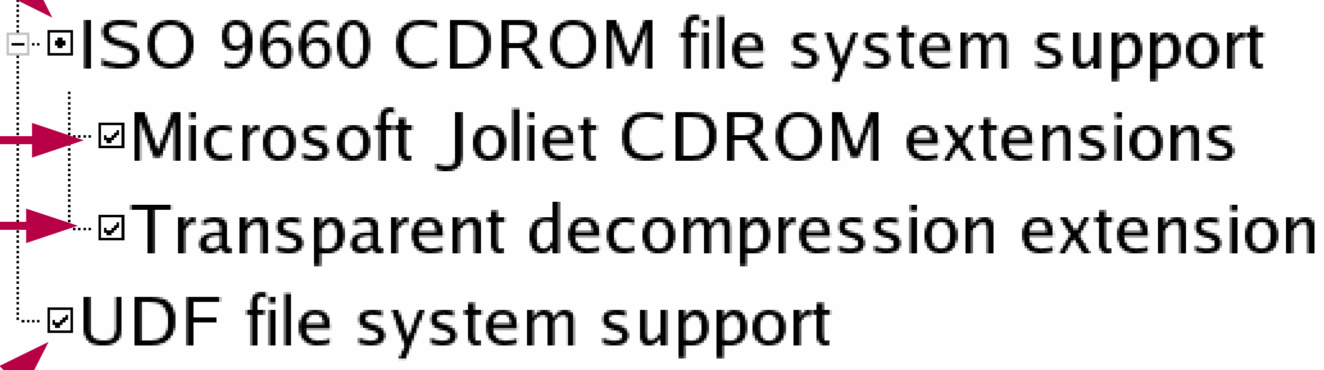
hp iPAQ h2200 (ARCH_H2200)

```
type: boolean
prompt: hp iPAQ h2200
   dep: ARCH_PXA
select: PXA25x
   dep: ARCH_PXA

defined at arch/arm/mach-pxa/h2200/Kconfig:1

This enables support for HP iPAQ H22xx series of handhelds.
There are a number of H22xx-specific drivers under this submenu:
pcmcia, lcd, battery, touchscreen
```

Compiling statically or as a module

Compiled as a module (separate file)
`CONFIG_ISO9660_FS=m`

Driver options
`CONFIG_JOLIET=y`
`CONFIG_ZISOFS=y`


⊡ ISO 9660 CDROM file system support
☑ Microsoft Joliet CDROM extensions
☑ Transparent decompression extension
☑ UDF file system support

Compiled statically in the kernel
`CONFIG_UDF_FS=y`

make config / menuconfig / gconfig

`make config`

- Asks you the questions 1 by 1. Extremely long!

`make menuconfig`

- Same old text interface as in Linux 2.4.
  Useful when no graphics are available.
  Pretty convenient too!

`make gconfig`

- New GTK based graphical configuration interface.
  Functionality similar to that of `make xconfig`.

make oldconfig

`make oldconfig`

- Needed very often!
- Useful to upgrade a `.config` file from an earlier kernel release
- Issues warnings for obsolete symbols
- Asks for values for new symbols

If you edit a `.config` file by hand, it's strongly recommended to run `make oldconfig` afterwards!

make allnoconfig

```
make allnoconfig
```

- Only sets strongly recommended settings to `y`.
- Sets all other settings to `n`.
- Very useful in embedded systems to select only the minimum required set of features and drivers.
- Much more convenient than unselecting hundreds of features one by one!

make help

`make help`

- Lists all available `make` targets
- Useful to get a reminder, or to look for new or advanced options!

Compiling and booting Linux

Compiling the kernel

Compiling and installing the kernel

<u>Compiling step</u>

- `make`

<u>Install steps</u> (logged as `root`!)

- `make install`
- `make modules_install`

Dependency management

- When you modify a regular kernel source file, `make` only rebuilds what needs recompiling. That's what it is used for.
- However, the `Makefile` is quite pessimistic about dependencies. When you make significant changes to the `.config` file, `make` often redoes much of the compile job!

Compiling faster on multiprocessor hosts

- If you are using a workstation with `n` processors, you may roughly divide your compile time by `n` by compiling several files in parallel
- `make -j <n>`
  Runs several targets in parallel, whenever possible
- Using `make -j 2` or `make -j 3` on single processor workstations. This doesn't help much. In theory, several parallel compile jobs keep the processor busy while other processes are waiting for files to be read of written. In practice, you don't get any significant speedup (not more than 10%), unless your I/Os are very slow.

Compiling faster with ccache

http://ccache.samba.org/

Compiler cache for C and C++, already shipped by some distributions
Much faster when compiling the same file a second time!

- Very useful when `.config` file change are frequent.
- Use it by adding a `ccache` prefix
  to the `CC` and `HOSTCC` definitions in `Makefile`:

```
CC              = ccache $(CROSS_COMPILE)gcc
HOSTCC          = ccache gcc
```

- Performance benchmarks:
  -63%: with a Fedora Core 3 config file (many modules!)
  -82%: with an embedded Linux config file (much fewer modules!)

Kernel compiling tips

- View the full (`gcc`, `ld`...) command line:
  `make V=1`
- Clean-up generated files
  (to force re-compiling drivers):
  `make clean`
- Remove all generated files
  (mainly to create patches)
  Caution: also removes your `.config` file!
  `make mrproper`

Generated files

Created when you run the `make` command

- `vmlinux`
  Raw Linux kernel image, non compressed.
- `arch/<arch>/boot/zImage` (default image on `arm`)
  `zlib` compressed kernel image
- `arch/<arch>/boot/bzImage` (default image on `i386`)
  Also a `zlib` compressed kernel image.
  Caution: `bz` means “big zipped” but not “`bzip2` compressed”!
  (`bzip2` compression support only available on `i386` as a tactical patch. Not very attractive for small embedded systems though: consumes 1 MB of RAM for decompression).

Files created by make install

- `/boot/vmlinuz-<version>`
  Compressed kernel image. Same as the one in `arch/<arch>/boot`
- `/boot/System.map-<version>`
  Stores kernel symbol addresses
- `/boot/initrd-<version>.img` (when used by your distribution)
  Initial RAM disk, storing the modules you need to mount your root filesystem. `make install` runs `mkinitrd` for you!
- `/etc/grub.conf` or `/etc/lilo.conf`
  `make install` updates your bootloader configuration files to support your new kernel! It reruns `/sbin/lilo` if LILO is your bootloader.

Files created by make modules_install (1)

`/lib/modules/<version>/`: Kernel modules + extras

- `build/`
  Everything needed to build more modules for this kernel: `Makefile`, `.config` file, module symbol information (`module.symVers`), kernel headers (`include/` and `include/asm/`)
- `kernel/`
  Module `.ko` (Kernel Object) files, in the same directory structure as in the sources.

Files created by make modules_install (2)

`/lib/modules/<version>/` (continued)

- `modules.alias`
  Module aliases for module loading utilities. Example line:
  `alias sound-service-?-0 snd_mixer_oss`
- `modules.dep`
  Module dependencies (see the Loadable kernel modules section)
- `modules.symbols`
  Tells which module a given symbol belongs to.

All the files in this directory are text files.
Don't hesitate to have a look by yourself!

Compiling the kernel in a nutshell

- Edit version information in the `Makefile` file

-
  ```
  make xconfig
  make
  make install
  make modules_install
  ```

Compiling and booting Linux

Overall system startup

Linux 2.4 booting sequence

Bootloader
- Executed by the hardware at a fixed location in ROM / Flash
- Initializes support for the device where the kernel image is found (local storage, network, removable media)
- Loads the kernel image in RAM
- Executes the kernel image (with a specified command line)

Kernel
- Uncompresses itself
- Initializes the kernel core and statically compiled drivers (needed to access the root filesystem)
- Mounts the root filesystem (specified by the `init` kernel parameter)
- Executes the first userspace program

First userspace program
- Configures userspace and starts up system services

Linux 2.6 booting sequence

Bootloader
- Executed by the hardware at a fixed location in ROM / Flash
- Initializes support for the device where the images are found (local storage, network, removable media)
- Loads the kernel image in RAM
- Executes the kernel image (with a specified command line)

Kernel
- Uncompresses itself
- Initializes the kernel core and statically compiled drivers
- Uncompresses the initramfs cpio archive included in the kernel file cache (no mounting, no filesystem).
- If found in the initramfs, executes the first userspace program: `/init`

Userspace: `/init` script (what follows is just a typical scenario)
- Runs userspace commands to configure the device (such as network setup, mounting `/proc` and `/sys`...)
- Mounts a new root filesystem. Switch to it (`switch_root`)
- Runs `/sbin/init` (or sometimes a new `/linuxrc` script)

Userspace: `/sbin/init`
- Runs commands to configure the device (if not done yet in the initramfs)
- Starts up system services (daemons, servers) and user programs

Linux 2.6 booting sequence with initrd

Bootloader
- Executed by the hardware at a fixed location in ROM / Flash
- Initializes support for the device where the images are found (local storage, network, removable media)
- Loads the kernel and init ramdisk (initrd) images in RAM
- Executes the kernel image (with a specified command line)

Kernel
- Uncompresses itself
- Initializes statically compiled drivers
- Uncompresses the initramfs cpio archive included in the kernel. Mounts it. No `/init` executable found.
- So falls back to the old way of trying to locate and mount a root filesystem.
- Mounts the root filesystem specified by the `init` kernel parameter (initrd in our case)
- Executes the first userspace program: usually `/linuxrc`

Userspace: `/linuxrc` script in initrd (what follows is just a typical sequence)
- Runs userspace commands to configure the device (such as network setup, mounting `/proc` and `/sys`...)
- Loads kernel modules (drivers) stored in the initrd, needed to access the new root filesystem.
- Mounts the new root filesystem. Switch to it (`pivot_root`)
- Runs `/sbin/init` (or sometimes a new `/linuxrc` script)

Userspace: `/sbin/init`
- Runs commands to configure the device (if not done yet in the initrd)
- Starts up system services (daemons, servers) and user programs

Linux 2.4 booting sequence drawbacks

Trying to mount the filesystem specified by the `init` kernel parameter is complex:

- Need device and filesystem drivers to be loaded
- Specifying the root filesystem requires ugly black magic device naming (such as `/dev/ram0`, `/dev/hda1`...), while `/` doesn't exist yet!
- Can require a complex initialization to implement within the kernel. Examples: NFS (set up an IP address, connect to the server...), RAID (root filesystem on multiple physical drives)...

In a nutshell: too much complexity in kernel code!

Extra init ramdisk drawbacks

Init ramdisks are implemented as standard block devices

- Need a ramdisk and filesystem driver
- Fixed in size: cannot easily grow in size.
  Any free space cannot be reused by anything else.
- Needs to be created and modified like any block device:
  formatting, mounting, editing, unmounting.
  Root permissions needed.
- Like in any block device, files are first read from the storage,
  and then copied to the file cache.
  Slow and duplication in RAM!!!

Initramfs features and advantages (1)

- Root file system built in in the kernel image (embedded as a compressed `cpio` archive)
- Very easy to create (at kernel build time). No need for root permissions (for `mount` and `mknod`).
- Compared to init ramdisks, just 1 file to handle.
- Always present in the Linux 2.6 kernel (empty by default).
- Just a plain compressed `cpio` archive. Neither needs a block nor a filesystem driver.

Initramfs features and advantages (2)

- ramfs: implemented in the file cache.
  No duplication in RAM, no filesystem layer to manage.
  Just uses the size of its files. Can grow if needed.
- Loaded by the kernel earlier.
  More initialization code moved to user-space!
- Simpler to mount complex filesystems from flexible userspace scripts rather than from rigid kernel code. More complexity moved out to user-space!
- No more magic naming of the root device.
  `pivot_root` no longer needed.

Initramfs features and advantages (3)

- Possible to add non GPL files (firmware, proprietary drivers) in the filesystem. This is not linking, just file aggregation (not considered as a derived work by the GPL).
- Possibility to remove these files when no longer needed.
- Still possible to use ramdisks.

More technical details about initramfs:
see `Documentation/filesystems/ramfs-rootfs-initramfs.txt`
and `Documentation/early-userspace/README` in kernel sources.

See also http://www.linuxdevices.com/articles/AT4017834659.html for a nice overview of initramfs (by Rob Landley, new Busybox maintainer).

How to populate an initramfs

Using `CONFIG_INITRAMFS_SOURCE`
in kernel configuration (`General Setup` section)

- Either specify an existing `cpio` archive
- Or specify a list of files or directories
  to be added to the archive.
- Or specify a text specification file (see next page)
- Can use a tiny C library: `klibc`
  (ftp://ftp.kernel.org/pub/linux/libs/klibc/)

Initramfs specification file example

```
dir /dev 755 0 0
nod /dev/console 644 0 0 c 5 1
nod /dev/loop0 644 0 0 b 7 0
dir /bin 755 1000 1000
slink /bin/sh busybox 777 0 0
file /bin/busybox initramfs/busybox 755 0 0
dir /proc 755 0 0
dir /sys 755 0 0
dir /mnt 755 0 0
file /init initramfs/init.sh 755 0 0
```

No need for root user access!

user id   group id

How to handle compressed cpio archives

Useful when you want to build the kernel with a ready-made cpio archive. Better let the kernel do this for you!

- Extracting:

  ```
  gzip -dc initramfs.img | cpio -id
  ```

- Creating:

  ```
  find <dir> -print -depth | cpio -ov | gzip -c >
  initramfs.img
  ```

How to create an initrd

In case you really need an initrd (why?).

```
mkdir /mnt/initrd
dd if=/dev/zero of=initrd.img bs=1k count=2048
mkfs.ext2 -F initrd.img
mount -o loop initrd.img /mnt/initrd
```

Fill the ramdisk contents: busybox, modules, `/linuxrc` script
More details in the Free Software tools for embedded systems training!

```
umount /mnt/initrd
gzip --best -c initrd.img > initrd
```

More details on `Documentation/initrd.txt` in the kernel sources! Also explains pivot rooting.

Compiling and booting Linux
Bootloaders

2-stage bootloaders

- At startup, the hardware automatically executes the bootloader from a given location, usually with very little space (such as the boot sector on a PC hard disk)
- Because of this lack of space, 2 stages are implemented:
  - 1st stage: minimum functionality. Just accesses the second stage on a bigger location and executes it.
  - 2nd stage: offers the full bootloader functionality. No limit in what can be implemented. Can even be an operating system itself!

x86 bootloaders

- LILO: LInux LOad. Original Linux bootloader. Still in use!
  http://freshmeat.net/projects/lilo/
  Supports: `x86`
- GRUB: GRand Unified Bootloader from GNU. More powerful.
  http://www.gnu.org/software/grub/
  Supports: `x86`
- SYSLINUX: Utilities for network and removable media booting
  http://syslinux.zytor.com
  Supports: `x86`

Generic bootloaders

- Das U-Boot: Universal Bootloader from Denk Software
  The most used on `arm`.
  http://u-boot.sourceforge.net/
  Supports: `arm`, `ppc`, `mips`, `x86`
  See our U-boot details annex for details.
- RedBoot: eCos based bootloader from Red-Hat
  http://sources.redhat.com/redboot/
  Supports: `x86`, `arm`, `ppc`, `mips`, `sh`, `m68k`...
- uMon: MicroMonitor general purpose, multi-OS bootloader
  http://microcross.com/html/micromonitor.html
  Supports: ARM, ColdFire, SH2, 68K, MIPS, PowerPC, Xscale...

Other bootloaders

- LAB: Linux As Bootloader, from Handhelds.org
  http://handhelds.org/cgi-bin/cvsweb.cgi/linux/kernel26/lab/
  Idea: use a trimmed Linux kernel with only features needed in a bootloader (no scheduling, etc.). Reuses flash and filesystem access, LCD interface, without having to implement bootloader specific drivers.
  Supports: `arm` (still experimental)
- And many more: lots of platforms have their own!

Compiling and booting Linux
Kernel booting

Kernel command line parameters

As most C programs, the Linux kernel accepts command line arguments

- Kernel command line arguments are part of the bootloader configuration settings.
- Useful to configure the kernel at boot time, without having to recompile it.
- Useful to perform advanced kernel and driver initialization, without having to use complex user-space scripts.

Kernel command line example

HP iPAQ h2200 PDA booting example:

`root=/dev/ram0 \`	Root filesystem (first ramdisk)
`rw \`	Root filesystem mounting mode
`init=/linuxrc \`	First userspace program
`console=ttyS0,115200n8 \`	Console (serial)
`console=tty0 \`	Other console (framebuffer)
`ramdisk_size=8192 \`	Misc parameters...
`cachepolicy=writethrough`	

Hundreds of command line parameters described on
`Documentation/kernel-parameters.txt`

Booting variants

XIP (Execute In Place)

- The kernel image is directly executed from the storage
- Can be faster and save RAM
  However, the kernel image can't be compressed

No initramfs / initrd

- Directly mounting the final root filesystem
  (`root` kernel command line option)

No new root filesystem

- Running the whole system from the initramfs.

Usefulness of rootfs on NFS

Once networking works, your root filesystem could be a directory on your GNU/Linux development host, exported by NFS (Network File System). This is very convenient for system development:

- Makes it very easy to update files (driver modules in particular) on the root filesystem, without rebooting. Much faster than through the serial port.
- Can have a big root filesystem even if you don't have support for internal or external storage yet.
- The root filesystem can be huge. You can even build native compiler tools and build all the tools you need on the target itself (better to cross-compile though).

NFS boot setup (1)

On the PC (NFS server)

- Add the below line to your `/etc/exports` file:

```
/home/rootfs 192.168.0.202(rw,insecure,sync,no_wdelay,no_root_squash)
```

client address NFS server options

- If not running yet, you may need to start `portmap`

```
/etc/init.d/portmap start
```

- Start or restart your NFS server:

  Fedora Core: `/etc/init.d/nfs restart`

  Debian (Knoppix, KernelKit): `/etc/init.d/nfs-user-server restart`

NFS boot setup (2)

On the target (NFS client)

- Compile your kernel with `CONFIG_NFS_FS=y` and `CONFIG_ROOT_NFS=y`
- Boot the kernel with the below command line options:

```
root=/dev/nfs
```

virtual device

```
ip=192.168.1.111:192.168.1.110:192.168.1.100:255.255.255.0:at91:eth0
```

local IP address   server IP address   gateway   netmask   hostname device

```
nfsroot=192.168.1.110:/home/nfsroot
```

NFS server IP address   Directory on the NFS server

First user-space program

- Specified by the `init` kernel command line parameter
- Executed at the end of booting by the kernel
- Takes care of starting all other user-space programs (system services and user programs).
- Gets the `1` process number (pid)
  Parent or ancestor of all user-space programs
  The system won't let you kill it.
- Only other user-space program called by the kernel:
  `/sbin/hotplug`

/linuxrc

- 1 of the 2 default init programs
(if no `init` parameter is given to the kernel)
- Traditionally used in initrds or in simple systems not using `/sbin/init`.
- Is most of the time a shell script, based on a very lightweight shell: `nash` or `busybox sh`
- This script can implement complex tasks: detecting drivers to load, setting up networking, mounting partitions, switching to a new root filesystem...

The init program

- `/sbin/init` is the second default init program
- Takes care of starting system services, and eventually the user interfaces (`sshd`, X server...)
- Also takes care of stopping system services
- Lightweight, partial implementation available through `busybox`

See the Init runlevels annex section for more details about starting and stopping system services with `init`.

However, simple startup scripts are often sufficient
in embedded systems.

Embedded Linux driver development

Compiling and booting Linux

Linux device files

Character device files

- Accessed through a sequential flow of individual characters
- Character devices can be identified by their `c` type (`ls -l`):

```
crw-rw---- 1 root uucp    4,  64 Feb 23 2004 /dev/ttyS0
crw--w---- 1 jdoe tty   136,   1 Feb 23 2004 /dev/pts/1
crw------- 1 root root   13,  32 Feb 23 2004 /dev/input/mouse0
crw-rw-rw- 1 root root    1,   3 Feb 23 2004 /dev/null
```

- Example devices: keyboards, mice, parallel port, IrDA, Bluetooth port, consoles, terminals, sound, video...

Block device files

- Accessed through data blocks of a given size. Blocks can be accessed in any order.
- Block devices can be identified by their `b` type (`ls -l`):

```
brw-rw----   1 root disk     3,   1 Feb 23  2004 hda1
brw-rw----   1 jdoe floppy   2,   0 Feb 23  2004 fd0
brw-rw----   1 root disk     7,   0 Feb 23  2004 loop0
brw-rw----   1 root disk     1,   1 Feb 23  2004 ram1
brw-------   1 root root     8,   1 Feb 23  2004 sda1
```

- Example devices: hard or floppy disks, ram disks, loop devices...

Device major and minor numbers

As you could see in the previous examples,
device files have 2 numbers associated to them:

- First number: *major* number
- Second number: *minor* number
- Major and minor numbers are used by the kernel to bind a driver to the device file. Device file names don't matter to the kernel!
- To find out which driver a device file corresponds to, or when the device name is too cryptic, see `Documentation/devices.txt`.

Device file creation

- Device files are not created when a driver is loaded.
- They have to be created in advance:

```
mknod /dev/<device> [c|b] <major> <minor>
```

- Examples:

```
mknod /dev/ttyS0 c 4 64
mknod /dev/hda1 b 3 1
```

Drivers without device files

They don't have any corresponding `/dev` entry you could read or write through a regular Unix command.

- Network drivers
  They are represented by a network device such as `ppp0`, `eth1`, `usbnet`, `irda0` (listed by `ifconfig -a`).
- Other drivers
  Often intermediate or lowlevel drivers just interfacing with other ones. Example: `usbcore`.

Practical lab – Configuring and compiling

Time to start `Lab 2`!

- Configure your kernel
- Compile it
- Boot it on a virtual PC
- Modify a root filesystem image by adding entries to the `/dev/` directory

Compiling and booting Linux

Cross-compiling the kernel

Makefile changes

- Update the version as usual
- You should change the default target platform.
  Example: ARM platform, cross-compiler command: `arm-linux-gcc`

```
ARCH          ?= arm
CROSS_COMPILE  ?= arm-linux-
```

(The Makefile defines later `CC = $(CROSS_COMPILE)gcc`)

See comments in `Makefile` for details

Configuring the kernel

`make xconfig`

- Same as in native compiling.
- Don't forget to set the right board / machine type!

Ready-made config files

```
assabet_defconfig      integrator_defconfig  mainstone_defconfig
badge4_defconfig       iq31244_defconfig     mx1ads_defconfig
bast_defconfig         iq80321_defconfig     neponset_defconfig
cerfcube_defconfig     iq80331_defconfig     netwinder_defconfig
clps7500_defconfig     iq80332_defconfig     omap_h2_1610_defconfig
ebsa110_defconfig      ixdp2400_defconfig    omnimeter_defconfig
edb7211_defconfig      ixdp2401_defconfig    pleb_defconfig
enp2611_defconfig      ixdp2800_defconfig    pxa255-idp_defconfig
ep80219_defconfig      ixdp2801_defconfig    rpc_defconfig
epxa10db_defconfig     ixp4xx_defconfig      s3c2410_defconfig
footbridge_defconfig   jornada720_defconfig  shannon_defconfig
fortunet_defconfig     lart_defconfig        shark_defconfig
h3600_defconfig        lpd7a400_defconfig    simpad_defconfig
h7201_defconfig        lpd7a404_defconfig    smdk2410_defconfig
h7202_defconfig        lubbock_defconfig     versatile_defconfig
hackkit_defconfig      lusl7200_defconfig
```

`arch/arm/configs` example

Using ready-made config files

- Default configuration files available for many boards / machines! Check if one exists in `arch/<arch>/configs/` for your target.
- Example: if you found an `acme_defconfig` file, you can run:
  `make acme_defconfig`
- Using `arch/<arch>/configs/` is a very good good way of releasing a default configuration file for a group of users or developers.

Cross-compiling setup

Example

- If you have an ARM cross-compiling toolchain in `/usr/local/arm/3.3.2/`
- You just have to add it to your Unix search path:
  `export PATH=/usr/local/arm/3.3.2/bin:$PATH`

Choosing a toolchain

- See the `Documentation/Changes` file in the sources for details about minimum tool versions requirements.
- More about toolchains: Free Software tools for embedded systems training: http://free-electrons.com/training/devtools/

Building the kernel

- Run
  `make`
- Copy
  `arch/<platform>/boot/zImage`
  to the target storage
- You can customize `arch/<arch>/boot/install.sh` so that `make install` does this automatically for you.
- `make INSTALL_MOD_PATH=<dir>/ modules_install`
  and copy `<dir>/` to `/lib/modules/` on the target storage

Cross-compiling summary

- Edit `Makefile`: set `ARCH`, `CROSS_COMPILE` and `EXTRA_VERSION`
- Get the default configuration for your machine:
  `make <machine>_defconfig` (if existing in `arch/<arch>/configs`)
- Refine the configuration settings according to your requirements:
  `make xconfig`
- Add the crosscompiler path to your `PATH` environment variable
- Compile the kernel: `make`
- Copy the kernel image from `arch/<arch>/boot/` to the target
- Copy modules to a directory which you replicate on the target:
  `make INSTALL_MOD_PATH=<dir> modules_install`

Practical lab – Cross-compiling

Time to start `Lab 3`!

- Set up a cross-compiling environment
- Configure the kernel `Makefile` accordingly
- Cross-compile the kernel for an `arm` target platform

Driver development

Loadable kernel modules

Loadable kernel modules (1)

- Modules: add a given functionality to the kernel (drivers, filesystem support, and many others)
- Can be loaded and unloaded at any time, only when their functionality is need. Once loaded, have full access to the whole kernel. No particular protection.
- Useful to keep the kernel image size to the minimum (essential in GNU/Linux distributions for PCs).

Loadable kernel modules (2)

- Useful to support incompatible drivers (either load one or the other, but not both)
- Useful to deliver binary-only drivers (bad idea) without having to rebuild the kernel.
- Modules make it easy to develop drivers without rebooting: load, test, unload, rebuild, load...
- Modules can also be compiled statically into the kernel.

Module dependencies

- Module dependencies stored in
  `/lib/modules/<version>/modules.dep`
- They don't have to be described by the module writer.
- They are automatically computed during kernel building from module exported symbols. `module2` depends on `module1` if `module2` uses a symbol exported by `module1`.
- You can update the `modules.dep` file by running (as `root`)

```
depmod -a [<version>]
```

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 usefulness

- Used by kernel developers to identify issues coming from proprietary drivers, which they can't do anything about.
- Useful for users to check that their system is 100% free
- Useful for GNU/Linux distributors for their release policy checks.

Possible module license strings

Available license strings explained in `include/linux/module.h`

- `GPL`
  GNU Public License v2 or later
- `GPL v2`
  GNU Public License v2
- `GPL and additional rights`
- `Dual BSD/GPL`
  GNU Public License v2 or BSD license choice
- `Dual MPL/GPL`
  GNU Public License v2 or Mozilla license choice
- `Proprietary`
  Non free products

Compiling a module

- The below Makefile should be reusable for any Linux 2.6 module.
- 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

Kernel log

- Of course, the kernel doesn't store its log into a file!
  Files belong to user space.
- The kernel keeps `printk` messages in a circular buffer
  (so that doesn't consume more memory with many messages)
- Kernel log messages can be accessed from user space through system calls, or through `/proc/kmsg`
- Kernel log messages are also displayed in the system console.

Accessing the kernel log

Many ways are available!

- Watch the system console
- `syslogd`
  Daemon gathering kernel messages in `/var/log/messages`
  Follow changes by running:
  `tail -f /var/log/messages`
  Caution: this file grows!
  Use `logrotate` to control this
- `dmesg`
  Found in all systems
  Displays the kernel log buffer
- `logread`
  Same. Often found in small embedded systems with no `/var/log/messages` or no `dmesg`. Implemented by Busybox.
- `cat /proc/kmsg`
  Waits for kernel messages and displays them.
  Useful when none of the above user space programs are available (tiny system)

Using the module

Need to be logged as `root`

- Load the module:
```
insmod ./hello.ko
```
- You will see the following in the kernel log:
```
Good morrow
to this fair assembly
```
- Now remove the module:
```
rmmod hello
```
- You will see:
```
Alas, poor world, what treasure
hast thou lost!
```

Understanding module loading issues

- When loading a module fails,
  `insmod` often doesn't give you enough details!
- Details are available in the kernel log.
- Example:

```
> insmod ./intr_monitor.ko
insmod: error inserting './intr_monitor.ko': -1
Device or resource busy
> dmesg
[17549774.552000] Failed to register handler for
irq channel 2
```

Module utilities (1)

- `modinfo <module_name>`
  `modinfo <module_path>.ko`
  Gets information about a module: parameters, license, description. Very useful before deciding to load a module or not.
- `insmod <module_name>`
  `insmod <module_path>.ko`
  Tries to load the given module, if needed by searching for its `.ko` file throughout the default locations (can be redefined by the `MODPATH` environment variable).

Module utilities (2)

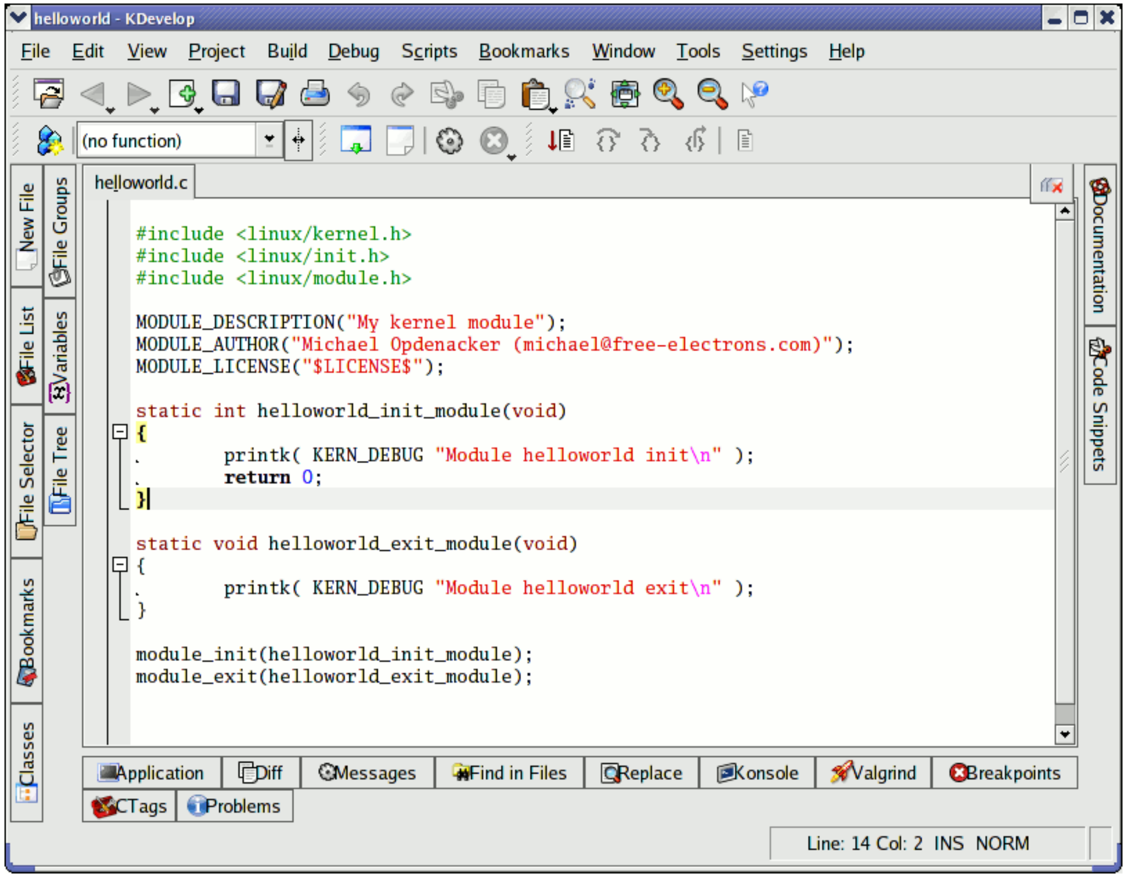
- `modprobe <module_name>`
  Most common usage of `modprobe`: tries to load all the modules the given module depends on, and then this module. Lots of other options are available.
- `lsmod`
  Displays the list of loaded modules
  Compare its output with the contents of `/proc/modules`!

Module utilities (3)

- `rmmod <module_name>`
  Tries to remove the given module
- `modprobe -r <module_name>`
  Tries to remove the given module and all dependent modules (which are no longer needed after the module removal)

Create your modules with kdevelop

http://kdevelop.org - Available in most distros.



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

MODULE_DESCRIPTION("My kernel module");
MODULE_AUTHOR("Michael Opdenacker (michael@free-electrons.com)");
MODULE_LICENSE("$LICENSE$");

static int helloworld_init_module(void)
{
        printk( KERN_DEBUG "Module helloworld init\n" );
        return 0;
}

static void helloworld_exit_module(void)
{
        printk( KERN_DEBUG "Module helloworld exit\n" );
}

module_init(helloworld_init_module);
module_exit(helloworld_exit_module);
```

- Makes it easy to create a module code skeleton from a ready-made template.
- Can also be used to compile your module.

Embedded Linux driver development

Driver development
Module parameters

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` or `modprobe`:

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

- Through `modprobe`
  after changing the `/etc/modprobe.conf` file:

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

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

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

module name

module parameter name

module 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, bool or invbool
                  (checked at compile time!) */
    perm       /* for /sys/module/<module_name>/<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);
```

Embedded Linux driver development

Driver development

Adding sources to the kernel tree

New directory in kernel sources (1)

To add an `acme_drivers/` directory to the kernel sources:

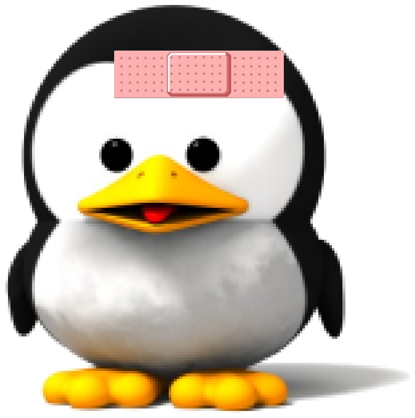
- Move the `acme_drivers/` directory to the appropriate location in kernel sources
- Create an `acme_drivers/Kconfig` file
- Create an `acme_drivers/Makefile` file based on the `Kconfig` variables
- In the parent directory `Kconfig` file, add
  `source “acme_drivers/Kconfig”`

New directory in kernel sources (2)

- In the parent directory `Makefile` file, add
  `obj-$(CONFIG_ACME) += acme_drivers/` (just 1 condition)
  or
  `obj-y += acme_drivers/` (several conditions)
- 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.
- Create a patch file:
  ```
  diff -Nurp 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.



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

Practical lab – Writing modules

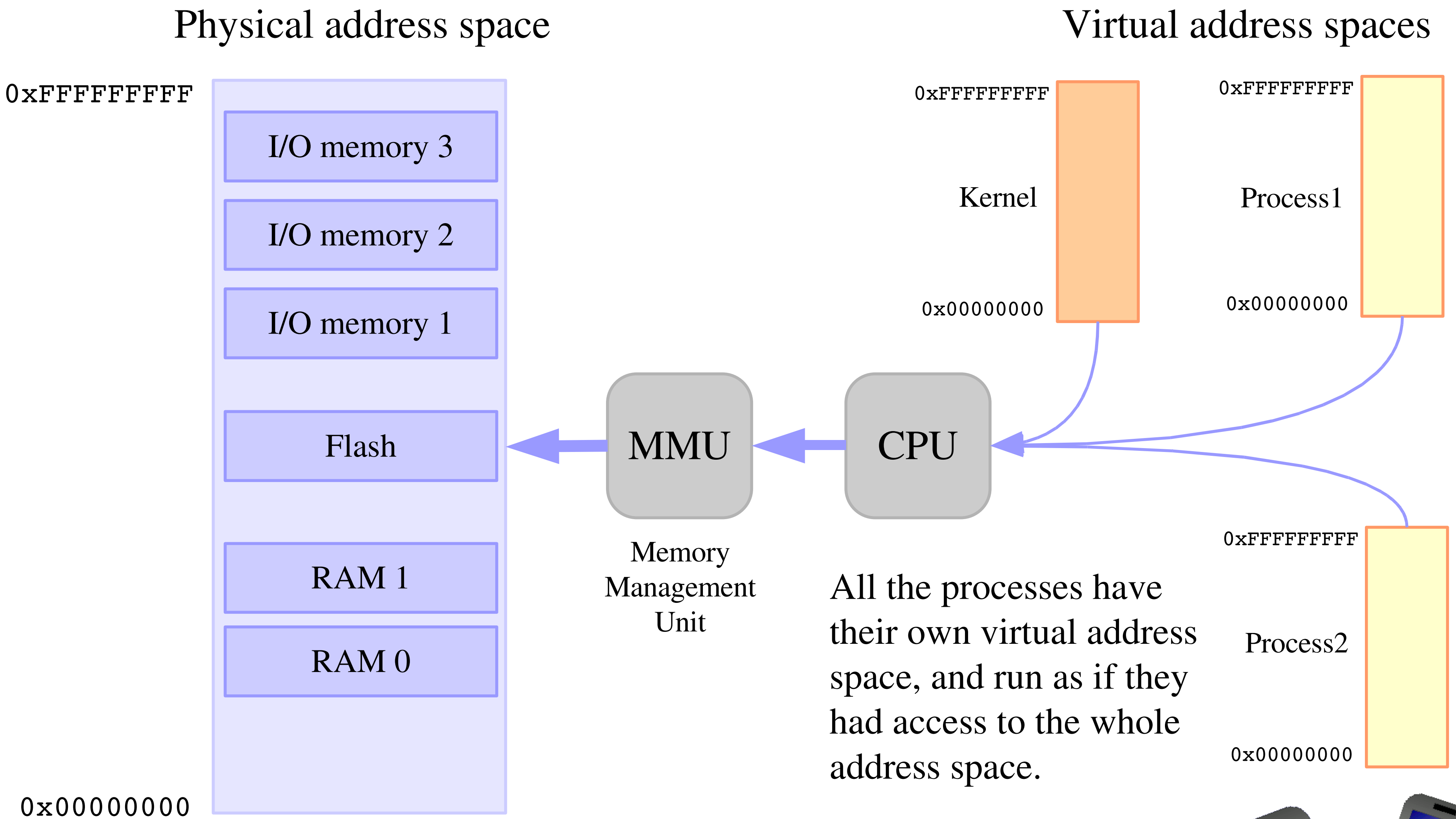
Time to start `Lab 4`!

- Write a kernel module with parameters
- Setup the environment to compile it
- Access kernel internals
- Add a `/proc` interface
- Add the module sources to the kernel source tree
- Create a kernel source patch

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 (see next page)
- `void kfree (const void *objp);`
- Example:

```
data = kmalloc(sizeof(*data), GFP_KERNEL);
...
kfree(data);
```

kmalloc features

- Quick (unless it's blocked waiting for memory to be freed).
- Doesn't initialize the allocated area.
  You can use `kcalloc` or `kzalloc` to get zeroed memory.
- 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 allocation: 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`
  Allocated RAM from interrupt handlers or code not triggered by user processes. Never blocks.
- `GFP_USER`
  Allocates memory for user processes. May block. Lowest priority.

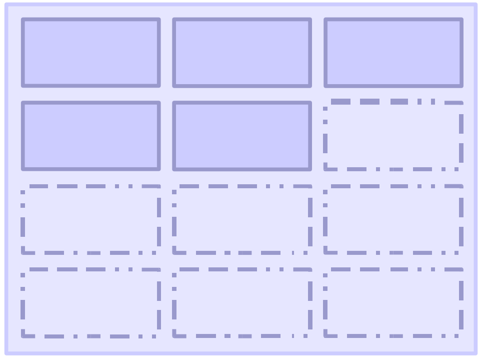
Main kmalloc flags (2)

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.

Slab caches

Also called *lookaside caches*



- Slab: name of the standard Linux memory allocator
- *Slab caches*: Objects that can hold any number of memory areas of the same size.
- Optimum use of available RAM and reduced fragmentation.
- Mainly used in Linux core subsystems: filesystems (open files, inode and file caches...), networking... Live stats on `/proc/slabinfo`.
- May be useful in device drivers too, though not used so often. Linux 2.6: used by USB and SCSI drivers.

Slab cache API (1)

- `#include <linux/slab.h>`
- Creating a cache:

```
cache = kmem_cache_create (
    name,           /* Name for /proc/slabinfo */
    size,           /* Cache object size */
    flags,          /* Options: alignment, DMA... */
    constructor,    /* Optional, called after each allocation */
    destructor);    /* Optional, called before each release */
```

Slab cache API (2)

- Allocating from the cache:
  `object = kmem_cache_alloc (cache, flags);`
  or `object = kmem_cache_zalloc (cache, flags);`
- Freeing an object:
  `kmem_cache_free (cache, object);`
- Destroying the whole cache:
  `kmem_cache_destroy (cache);`

More details and an example in the Linux Device Drivers book:
http://lwn.net/images/pdf/LDD3/ch08.pdf

Memory pools

Useful for memory allocations that cannot fail

- Kind of lookaside cache trying to keep a minimum number of pre-allocated objects ahead of time.
- Use with care: otherwise can result in a lot of unused memory that cannot be reclaimed! Use other solutions whenever possible.

Memory pool API (1)

- `#include <linux/mempool.h>`
- Mempool creation:

```
mempool = mempool_create (
   min_nr,
   alloc_function,
   free_function,
   pool_data);
```

Memory pool API (2)

- Allocating objects:

```
object = mempool_alloc (pool, flags);
```

- Freeing objects:

```
mempool_free (object, pool);
```

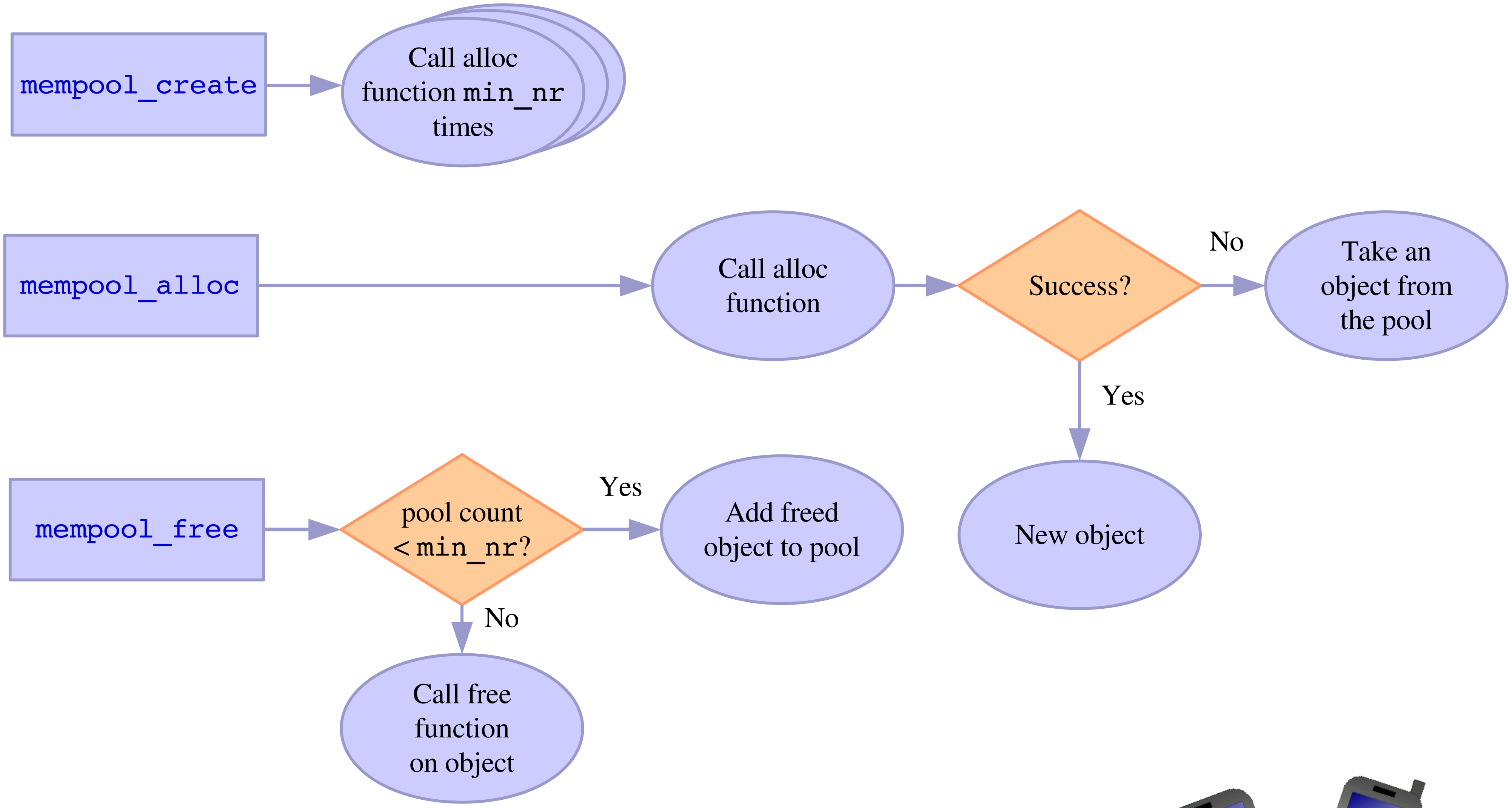
- Resizing the pool:

```
status = mempool_resize (
                pool, new_min_nr, flags);
```

- Destroying the pool (caution: free all objects first!):

```
mempool_destroy (pool);
```

Memory pool implementation



Memory pools using slab caches

- Idea: use slab cache functions to allocate and free objects.
- The `mempool_alloc_slab` and `mempool_free_slab` functions supply a link with slab cache routines.
- So, you will find many code examples looking like:

```
cache = kmem_cache_create (...);
pool = mempool_create (
                  min_nr,
                  mempool_alloc_slab,
                  mempool_free_slab,
                  cache);
```

Allocating by pages

More appropriate when you need big slices of RAM:

- `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 long 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`)

Freeing pages

- `void free_page(unsigned long addr);`

-
  ```
  void free_pages(unsigned long addr,
                  unsigned long 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`

Memory management - Summary

Small allocations

- `kmalloc`, `kzalloc` (and `kfree`!)
- Slab caches
- Memory pools

Bigger allocations

- `__get_free_page[s]`, `get_zeroed_page`, `free_page[s]`
- `vmalloc`, `vfree`

Libc like memory utilities

- `memset`, `memcopy`, `memmove`...

Driver development
I/O memory and ports

Requesting I/O ports

`/proc/ioports` example

```
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`

Reading / writing on I/O ports

The implementation of the below functions and the exact `unsigned` type can vary from platform to platform!

bytes

```
unsigned inb(unsigned port);
void outb(unsigned char byte, unsigned port);
```

words

```
unsigned inw(unsigned port);
void outw(unsigned char byte, unsigned port);
```

"long" integers

```
unsigned inl(unsigned port);
void outl(unsigned char byte, unsigned port);
```

Reading / writing strings on I/O ports

Often more efficient than the corresponding C loop,
if the processor supports such operations!

byte strings

```
void insb(unsigned port, void *addr, unsigned long count);
void outsb(unsigned port, void *addr, unsigned long count);
```

word strings

```
void insw(unsigned port, void *addr, unsigned long count);
void outsw(unsigned port, void *addr, unsigned long count);
```

long strings

```
void insl(unsigned port, void *addr, unsigned long count);
void outsl(unsigned port, void *addr, unsigned long count);
```

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);
  ```

Choosing I/O ranges

- I/O port and memory ranges can be passed as module parameters. An easy way to define those parameters is through `/etc/modprobe.conf`.
- Modules can also try to find free ranges by themselves (making multiple calls to `request_region` or `request_mem_region`.

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!

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.
- 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!

Hardware dependent

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

Safe on all architectures!

Accessing I/O memory

- Directly reading from or writing to addresses returned by `ioremap` ("pointer dereferencing") may not work on some architectures.
- Use the below functions instead. They are always portable and safe:
  `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);
```

/dev/mem

- Used to provide user-space applications with direct access to physical addresses.
- Actually only works with addresses that are non-RAM (I/O memory) or with addresses that have some special flag set in the kernel's data structures. Fortunately, doesn't provide access to any address in physical RAM!
- Used by applications such as the X server to write directly to device memory.

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!

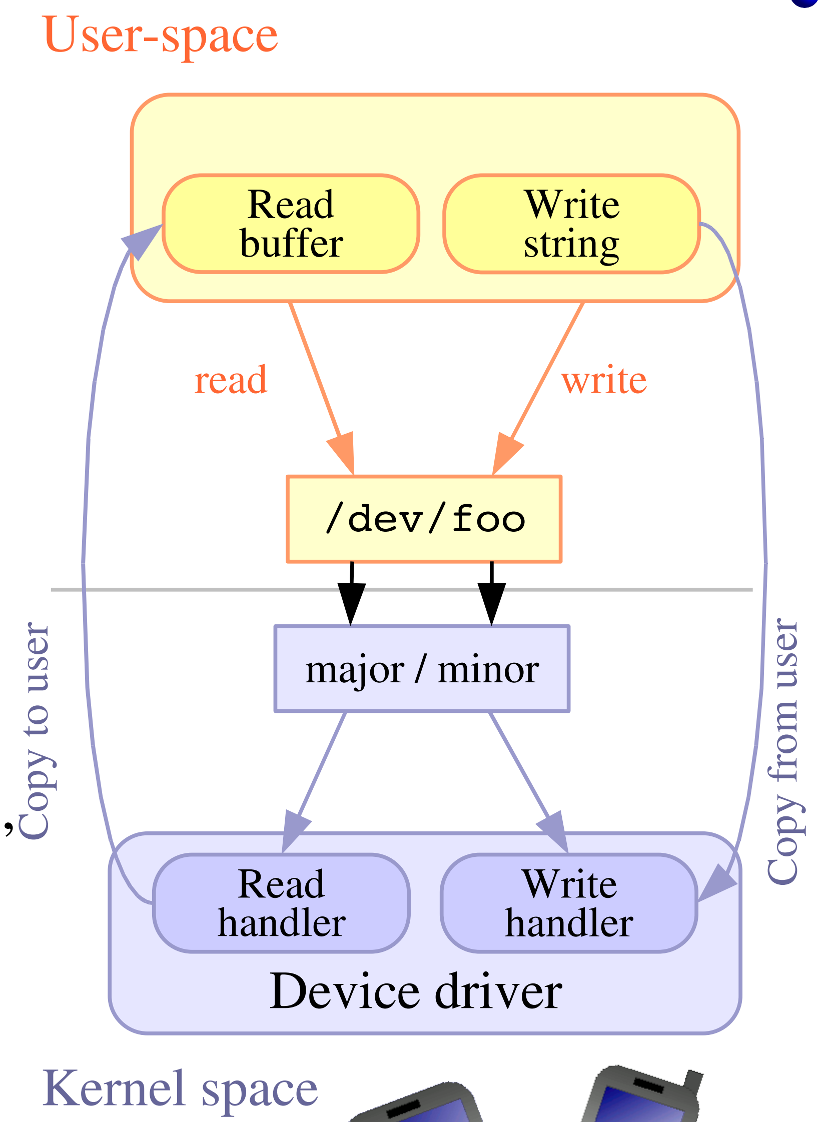
Creating a character driver

User-space needs

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

The kernel needs

- 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
7 vcs                     68 sd
10 misc                   69 sd
13 input
14 sound
...
```

Major number

Registered name

Can be used to find free major numbers

dev_t structure

Kernel data structure to represent a major / minor pair

- Defined in `<linux/kdev_t.h>`
  Linux 2.6: 32 bit size (major: 12 bits, minor: 20 bits)
- Macro to create the structure:
  ```
  MKDEV(int major, int minor);
  ```
- Macro to extract the numbers:
  ```
  MAJOR(dev_t dev);
  MINOR(dev_t dev);
  ```

Allocating fixed device numbers

```
#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

```
if (register_chrdev_region(MKDEV(202, 128),
                           acme_count, “acme”)) {
  printk(KERN_ERR “Failed to allocate device number\n”);
  ...
```

Dynamic allocation of device numbers

Safer: have the kernel allocate free numbers for you!

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

int alloc_chrdev_region(
        dev_t *dev,             /* Output: starting device number */
        unsigned baseminor,     /* Starting minor number, usually 0 */
        unsigned count,         /* Number of device numbers */
        const char *name);      /* Registered name */
```

Returns `0` if the allocation was successful.

Example

```
if (alloc_chrdev_region(&acme_dev, 0, acme_count, “acme”)) {
  printk(KERN_ERR “Failed to allocate device number\n”);
  ...
```

Creating device files

- Issue: you can no longer create `/dev` entries in advance!
  You have to create them on the fly after loading the driver according to the allocated major number.
- Trick: the script loading the module can then use `/proc/devices`:

```
module=foo; name=foo; device=foo
rm -f /dev/$device
insmod $module.ko
major=`awk "\\$2==\"$name\" {print \\$1}" /proc/devices`
mknod /dev/$device c $major 0
```

Caution: back quotes!

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. Pointers to this structure are usually called "*fips*".

- `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: `filp->f_dentry->d_inode`.

file operations (2)

-
  ```
  ssize_t (*read) (
     struct file *,          /* Open file descriptor */
     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 */
     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. formatting a disk, configuration changes).

-
  ```
  int (*mmap) (struct file *,
               struct vm_area_struct);
  ```
  Asking for device memory to be mapped into the address space of a user process

-
  ```
  struct module *owner;
  ```
  Used by the kernel to keep track of who's using this structure and count the number of users of the module.

read operation example

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

   /* Number of bytes left to read in the open file */
   remaining_bytes = min(hwdata_size - (*ppos), count);

   if (remaining_bytes == 0) {
       /* All read, returning 0 (End Of File) */
       return 0;
   }

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

Read method

Piece of code available on
http://free-electrons.com/doc/c/acme_read.c

write operation example

```
static ssize_t
acme_write(struct file *file, const char __user *buf, size_t count, loff_t * ppos)
{
   /* Assuming that hwdata corresponds to a physical address range */
   /* of size hwdata_size, obtained with ioremap() */

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

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

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

Write method

Piece of code available on
http://free-electrons.com/doc/c/acme_write.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, allocate the structure and set its file operations:

```
acme_cdev = cdev_alloc();
acme_cdev->ops = &acme_fops;
acme_cdev->owner = THIS_MODULE;
```

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 acme_bufsize=8192;

static int acme_count=1;
static dev_t acme_dev;

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)

```
static int __init acme_init(void)
{
    acme_buf = kmalloc(acme_bufsize,
                       GFP_KERNEL);

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

    if (alloc_chrdev_region(&acme_dev, 0,
                     acme_count, "acme")) {
       err=-ENODEV;
       goto err_free_buf;
    }

    acme_cdev = cdev_alloc();

    if (!acme_cdev) {
       err=-ENOMEM;
       goto err_dev_unregister;
    }

    acme_cdev->ops = &acme_fops;
    acme_cdev->owner = THIS_MODULE;
```

```
if (cdev_add(acme_cdev, acme_dev,
                 acme_dev_count)) {
       err=-ENODEV;
       goto err_free_cdev;
    }

    return 0;

err_free_cdev:
    kfree(acme_cdev);
err_dev_unregister:
    unregister_chrdev_region(
       acme_dev, acme_count);
err_free_buf:
    kfree(acme_buf);
err_exit:
    return err;
}

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

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

Character driver summary

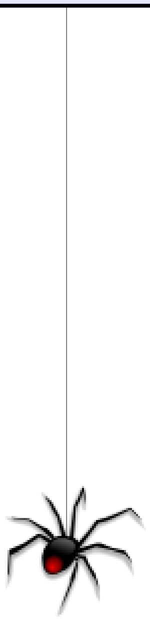
Character driver writer - Define the file operations callbacks for the device file: `read`, `write`, `ioctl`... - In the module init function, get major and minor numbers with `alloc_chrdev_region()`, init a `cdev` structure with your file operations and add it to the system with `cdev_add()`. - In the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

Practical lab – Character drivers

Time to start `Lab 5`!

- Write simple `file_operations`, for a character device, including `ioctl` controls
- Get a free device number
- Register the character device
- Use the `kmalloc` and `kfree` utilities
- Exchange data with userspace

Embedded Linux driver development



Driver development

Debugging

Usefulness of a serial port

- Most processors feature a serial port interface (usually very well supported by Linux). Just need this interface to be connected to the outside.
- Easy way of getting the first messages of an early kernel version, even before it boots. A minimum kernel with only serial port support is enough.
- Once the kernel is fixed and has completed booting, possible to access a serial console and issue commands.
- The serial port can also be used to transfer files to the target.

When you don't have a serial port

On the host

- Not an issue. You can get a USB to serial converter. Usually very well supported on Linux and roughly costs $20. The device appears as `/dev/ttyUSB0` on the host.

On the target

- Check whether you have an IrDA port. It's usually a serial port too.
- If you have an Ethernet adapter, try with it
- You may also try to manually hook-up the processor serial interface (check the electrical specifications first!)

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 (1)

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!

Debugging with /proc or /sys (2)

Examples

- `cat /proc/acme/stats` (dummy example)
  Displays statistics about your acme driver.
- `cat /proc/acme/globals` (dummy example)
  Displays values of global variables used by your driver.
- `echo 600000 > /sys/devices/system/cpu/cpu0/cpufreq/scaling_setspeed`
  Adjusts the speed of the CPU (controlled by the cpufreq driver).

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.

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)

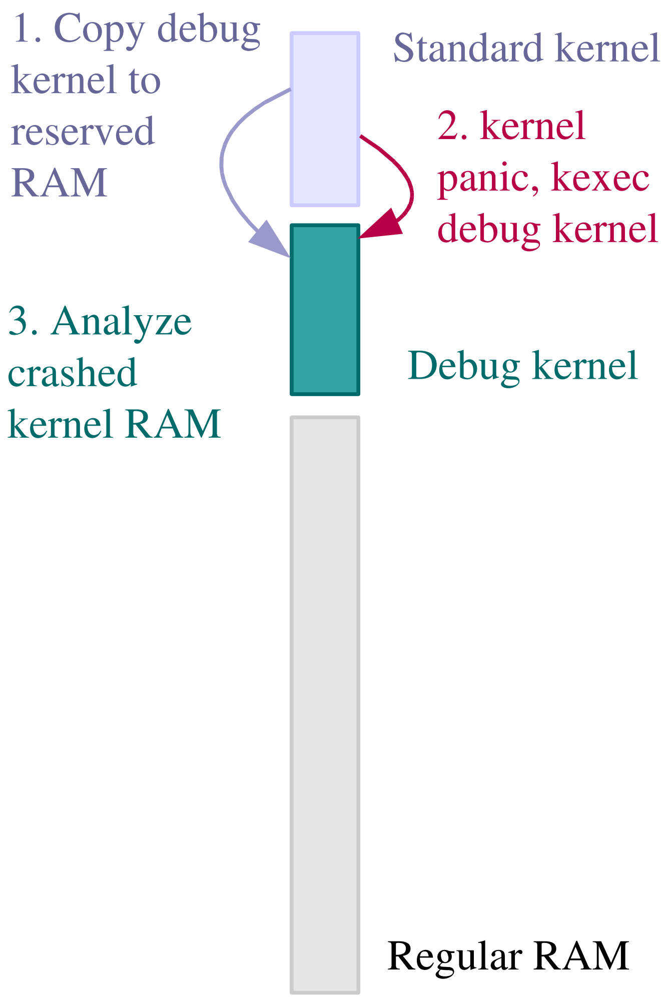
kgdb kernel patch

http://kgdb.linsyssoft.com/

- The execution of the patched kernel is fully controlled by `gdb` from another machine, connected through a serial line.
- Can do almost everything, including inserting breakpoints in interrupt handlers.
- Supported architectures: `i386`, `x86_64`, `ppc` and `s390`.

Kernel crash analysis with kexec

- `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.


1. Copy debug kernel to reserved RAM
Standard kernel
2. kernel panic, kexec debug kernel
3. Analyze crashed kernel RAM
Debug kernel
Regular RAM

Decrypting oops messages

- You often get kernel oops messages when you develop drivers (dereferencing null pointers, illegal accesses to memory...). They give raw information about the function call stack and CPU registers.
- You can make these messages more explicit in your development kernel, for example by replacing raw addresses by symbol names, by setting:

```
# General Setup
CONFIG_KALLSYMS=y
```

- Replaces the `ksymoops` tool which shouldn't be used any more with Linux 2.6

```
<1>Unable to handle kernel paging request at virtual address 4d
1b65e8
Unable to handle kernel paging request at virtual address 4d1b65
e8
<1>pgd = c0280000
pgd = c0280000
<1>[4d1b65e8] *pgd=00000000[4d1b65e8] *pgd=00000000

Internal error: Oops: f5 [#1]
Internal error: Oops: f5 [#1]
Modules linked in:Modules linked in: hx4700_udc hx4700_udc
asic3_base asic3_base

CPU: 0
CPU: 0
PC is at set_pxa_fb_info+0x2c/0x44
PC is at set_pxa_fb_info+0x2c/0x44
LR is at hx4700_udc_init+0x1c/0x38 [hx4700_udc]
LR is at hx4700_udc_init+0x1c/0x38 [hx4700_udc]
pc : [<c00116c8>]    lr : [<bf00901c>]    Not tainted
sp : c076df78  ip : 60000093  fp : c076df84
pc : [<c00116c8>]    lr : [<bf00901c>]    Not tainted
sp : c076df78  ip : 60000093  fp : c076df84
r10: 00000002  r9 : c076c000  r8 : c001c7e4
r10: 00000002  r9 : c076c000  r8 : c001c7e4
r7 : 00000000  r6 : c0176d40  r5 : bf007500  r4 : c0176d58
r7 : 00000000  r6 : c0176d40  r5 : bf007500  r4 : c0176d58
r3 : c0176828  r2 : 00000000  r1 : 00000f76  r0 : 80004440
r3 : c0176828  r2 : 00000000  r1 : 00000f76  r0 : 80004440
Flags: nZCvFlags: nZCv  IRQs on  FIQs on  Mode SVC_32  Segme
nt user
```

Debugging with Kprobes

http://sourceware.org/systemtap/kprobes/

- Fairly simple way of inserting breakpoints in kernel routines
- Unlike `printk` debugging, you neither have to recompile nor reboot your kernel. You only need to compile and load a dedicated module to declare the address of the routine you want to probe.
- Non disruptive, based on the kernel interrupt handler
- Kprobes even lets you modify registers and global kernel internals.
- Supported architectures: `i386`, `x86_64`, `ppc64` and `sparc64`

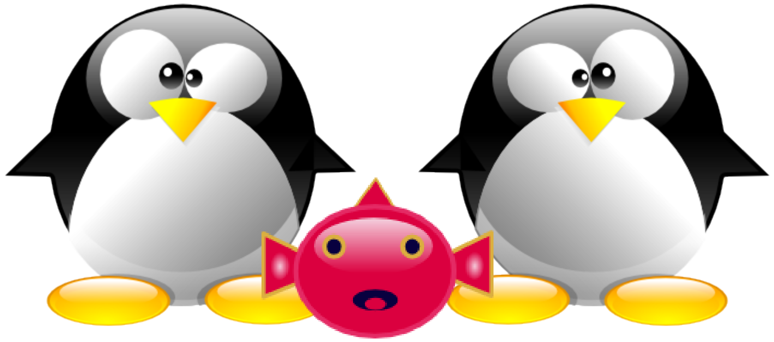
Nice overviews: http://lwn.net/Articles/132196/
and http://www-106.ibm.com/developerworks/library/l-kprobes.html

Kernel debugging tips

- If your kernel doesn't boot yet or hangs without any message, it can help to 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 (References section)!

Embedded Linux driver development

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

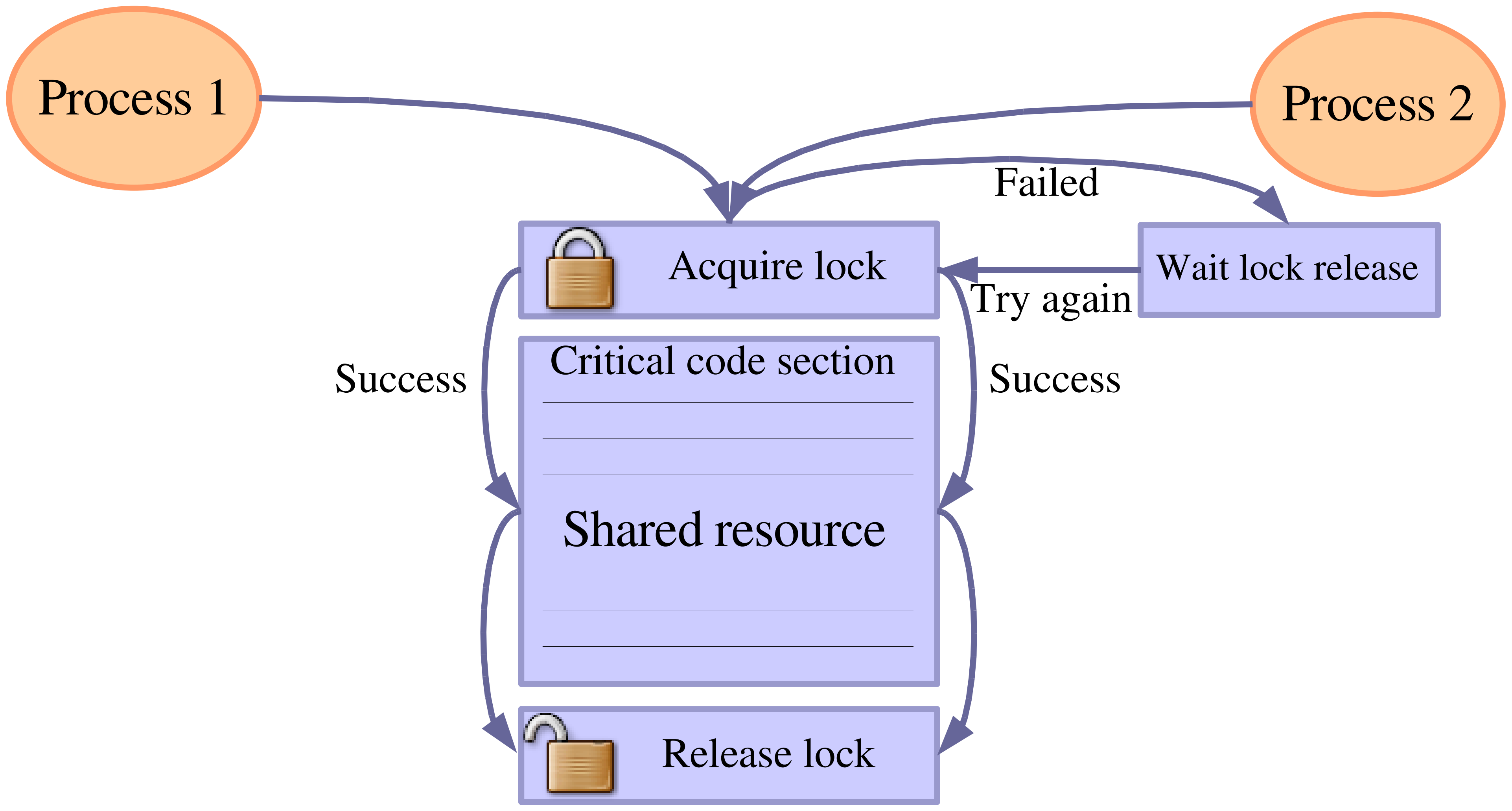
- Several user-space programs accessing the same device data or hardware. Several kernel processes could execute the same code on behalf of user processes running in parallel.
- Multiprocessing: the same driver code can be running on another processor. This can also happen with single CPUs with hyperthreading.
- 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)
- Don't make resources available to other kernel processes until they are ready to be used.
- 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);`
- 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_interruptible (struct mutex *lock);`
  Same, but can be interrupted. If interrupted, returns a non zero value and doesn't hold the lock. Test the return value!!!
- `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. Make sure you do it as quickly as possible!

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);
```

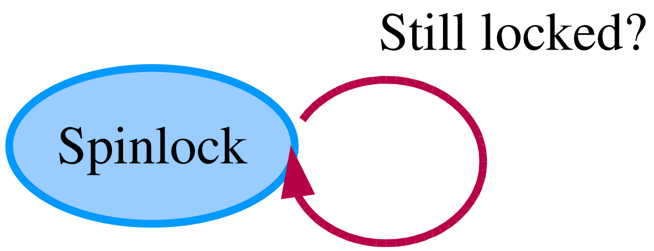
Well suited for rare writes, holding the semaphore briefly. Otherwise, readers get *starved*, waiting too long for the semaphore to be released.

When to use mutexes or semaphores

- Before and after accessing shared resources
- Before and after making other resources available to other parts of the kernel or to user-space (typically and module initialization).
- In situations when sleeping is allowed.
  Semaphores and mutexes must only be used in process context (managed by the scheduler), and not in interrupt context (managed by the CPU, sleeping not supported).

Spinlocks

- Locks to be used for code that can't sleep (critical sections, interrupt handlers... Be very careful not to call functions which can sleep!
- Intended for multiprocessor systems
- Spinlocks are not interruptible, don't sleep and keep spinning in a loop until the lock is available.
- Spinlocks cause kernel preemption to be disabled on the CPU executing them.
- May require interrupts to be disabled too.



Initializing spinlocks

- Static
```
spinlock_t my_lock = SPIN_LOCK_UNLOCKED;
```
- Dynamic
```
void spin_lock_init (spinlock_t *lock);
```

Using spinlocks

```
void spin_[un]lock (spinlock_t *lock);
```

```
void spin_[un]lock_irqsave (spinlock_t *lock,
 unsigned long flags);
```

Disables IRQs on the local CPU

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

Disables IRQs without saving flags. When you're sure that nobody already disabled interrupts.

```
void spin_[un]lock_bh (spinlock_t *lock);
```

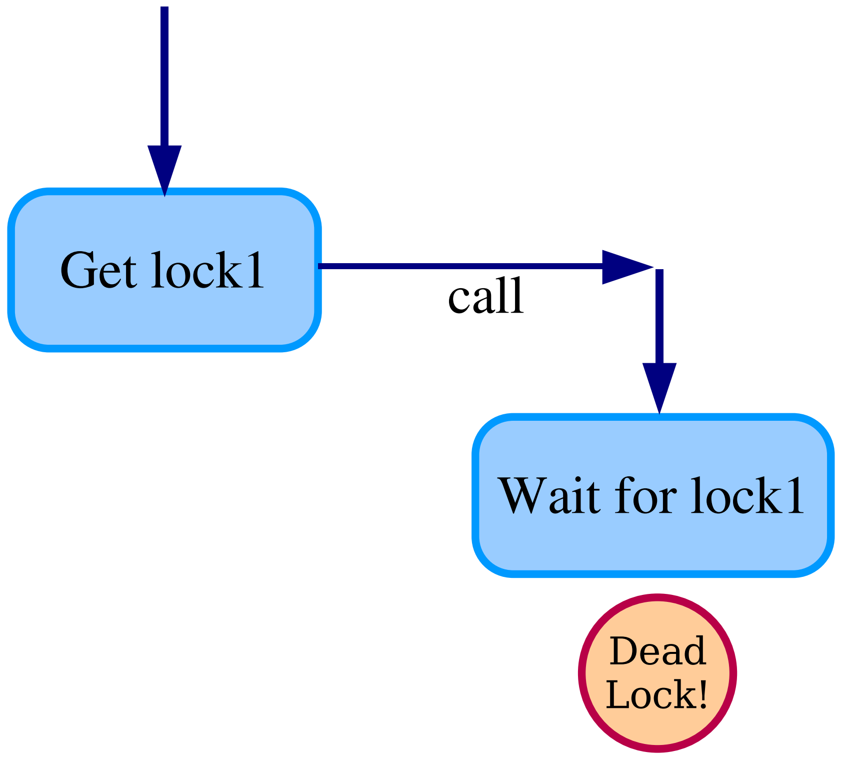
Disables software interrupts, but not hardware ones

Note that reader / writer spinlocks also exist.

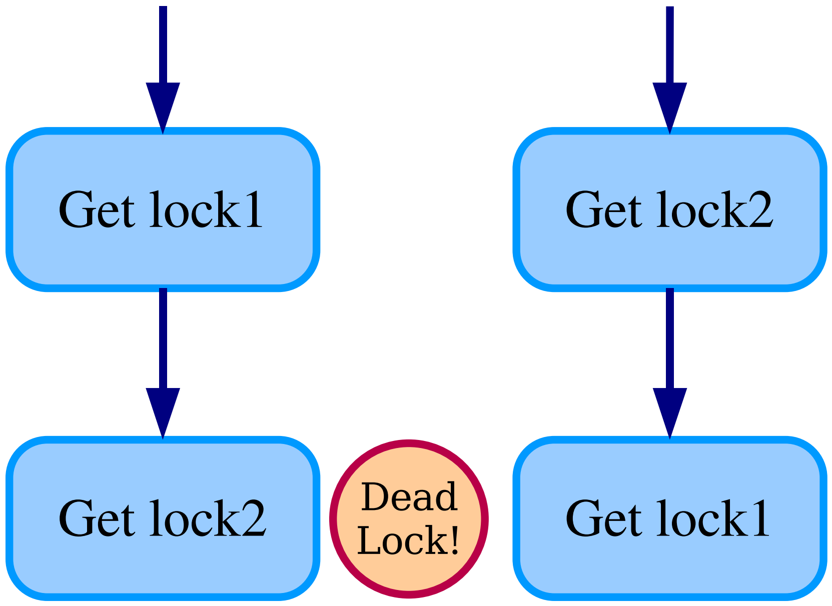
Deadlock situations

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
http://people.redhat.com/mingo/lockdep-patches/

- 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.

Overview: http://lwn.net/Articles/185078/

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 (...);
```

Driver development
Processes and scheduling

Processes

A process is an instance of a running program

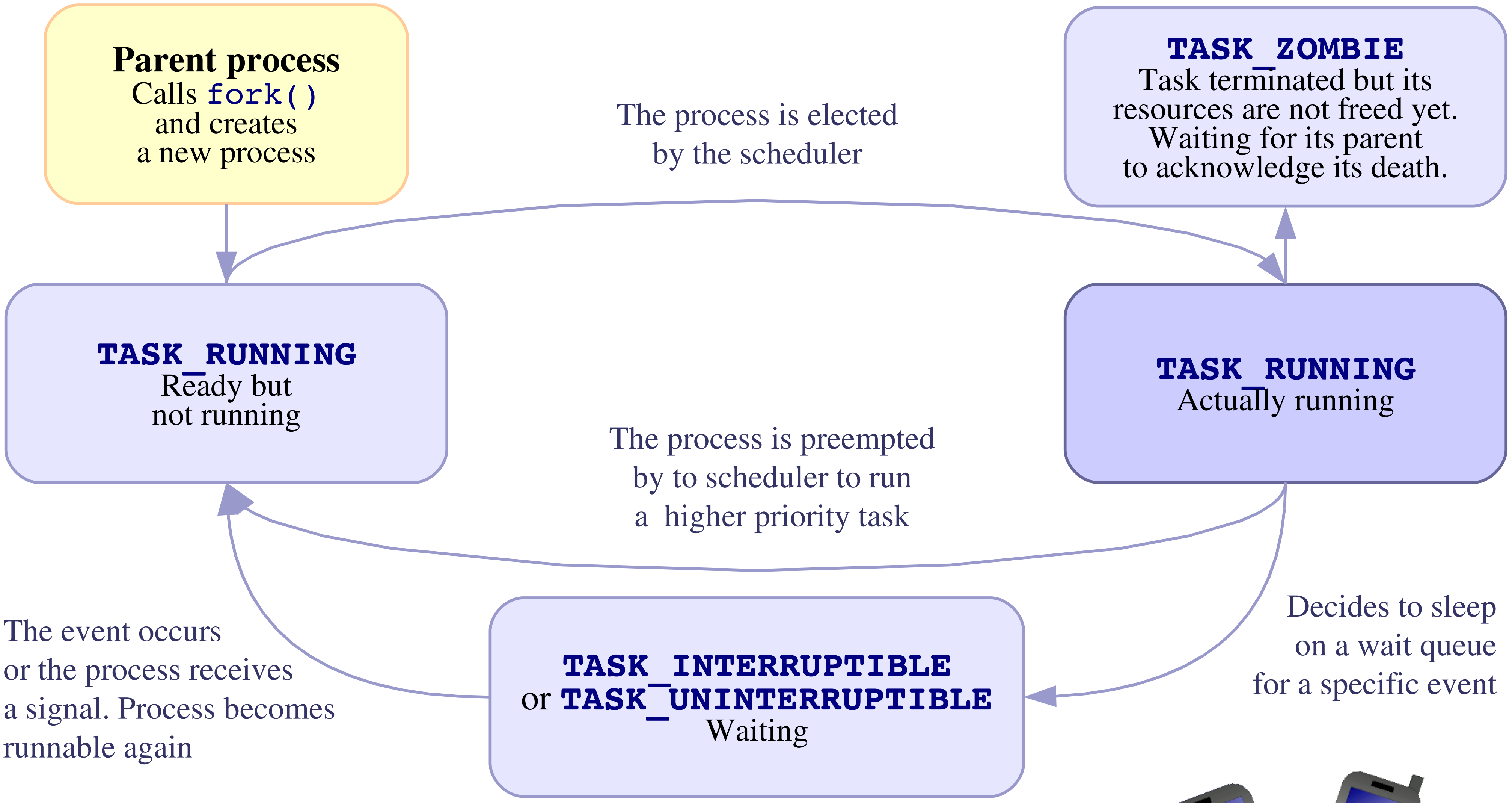
- Multiple instances of the same program can be running. Program code ("text section") memory is shared.
- Each process has its own data section, address space, processor state, open files and pending signals.
- The kernel has a separate data structure for each process.

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



Parent process
Calls `fork()`
and creates
a new process

`TASK_RUNNING`
Ready but
not running

The process is elected
by the scheduler

`TASK_RUNNING`
Actually running

`TASK_ZOMBIE`
Task terminated but its
resources are not freed yet.
Waiting for its parent
to acknowledge its death.

The process is preempted
by to scheduler to run
a higher priority task

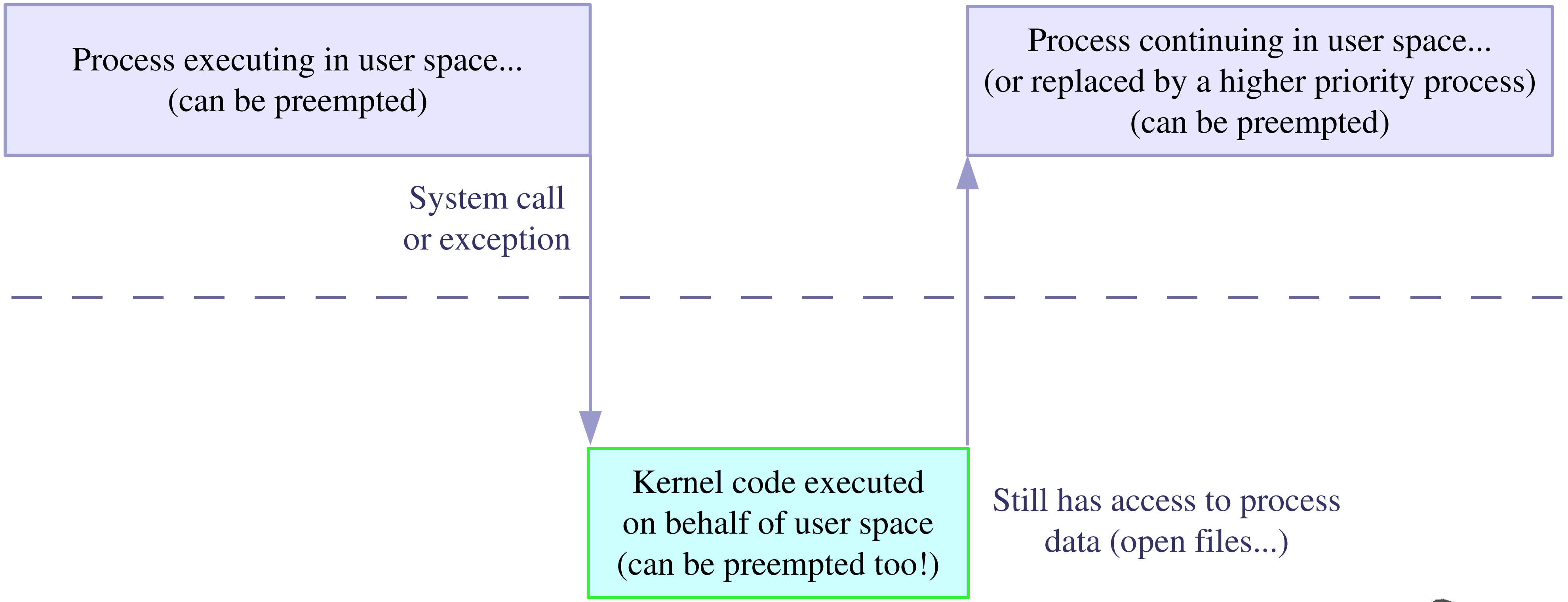
Decides to sleep
on a wait queue
for a specific event

`TASK_INTERRUPTIBLE`
or **`TASK_UNINTERRUPTIBLE`**
Waiting

The event occurs
or the process receives
a signal. Process becomes
runnable again

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 space 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).
  - `ksoftirqd`: manages soft irqs.

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>`

Real-time processes

Real-time processes 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...

Timer frequency

Timer interrupts are raised every `HZ` th of second (= 1 *jiffy*)

- `HZ` is now configurable (in `Processor type and features`): `100`, `250` (`i386` default) or `1000`.
  Supported on `i386`, `ia64`, `ppc`, `ppc64`, `sparc64`, `x86_64`
  See `kernel/Kconfig.hz`.
- Compromise between system responsiveness and global throughput.
- Caution: not any value can be used. Constraints apply!

Another idea is to completely turn off CPU timer interrupts when the system is idle (“dynamic tick”): see http://muru.com/linux/dyntick.
This saves power. Supports `arm` and `i386` so far.

O(1) scheduler

- The kernel maintains 2 priority arrays:
  the *active* and the *expired* array.
- Each array contains 140 entries (100 real-time priorities + 40 regular ones), 1 for each priority, each containing a list of processes with the same priority.
- The arrays are implemented in a way that makes it possible to pick a process with the highest priority in constant time (whatever the number of running processes).

Choosing and expiring processes

- The scheduler finds the highest process priority
- It executes the first process in the priority queue for this priority.
- Once the process has exhausted its timeslice, it is moved to the expired array.
- The scheduler gets back to selecting another process with the highest priority available, and so on...
- Once the active array is empty, the 2 arrays are swapped! Again, everything is done in constant time!

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 an interrupt handler (including the cpu timer)

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

Timeslices

The scheduler also 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.

Dynamic priorities

Only applies to regular processes

- For a better user experience, the Linux scheduler boots the priority of interactive processes (processes which spend most of their time sleeping, and take time to exhaust their timeslices). Such processes often sleep but need to respond quickly after waking up (example: word processor waiting for key presses).
  Priority bonus: up to 5 points.
- Conversely, the Linux scheduler reduces the priority of compute intensive tasks (which quickly exhaust their timeslices).
  Priority penalty: up to 5 points.

Embedded Linux driver development

Driver development
Sleeping

How to sleep (1)

Sleeping is needed when a user process is waiting for data which are not ready yet. The process then puts itself in a waiting queue.

- Static queue declaration

```
DECLARE_WAIT_QUEUE_HEAD (module_queue);
```

- 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 given boolean expression is true.
  Caution: can't be interrupted (i.e. by killing the client process in user-space)
- `wait_event_interruptible(queue, condition);`
  Can be interrupted
- `wait_event_timeout(queue, condition, timeout);`
  Sleeps and automatically wakes up after the given timeout.
- `wait_event_interruptible_timeout(queue, condition, timeout);`
  Same as above, interruptible.

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);`
  Does the same job. Usually called when processes waited using `wait_event_interruptible`.

Driver development

Interrupt management

Need for interrupts

- Internal processor interrupts used by the processor, for example for multi-task scheduling.
- External interrupts needed because most internal and external devices are slower than the processor. Better not keep the processor waiting for input data to be ready or data to be output. When the device is ready again, it sends an interrupt to get the processor attention again.

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
`irqreturn_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);`

? Why does `dev_id` have to be unique?

Answer...

Registering an interrupt handler (2)

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

- `SA_INTERRUPT`
  "Quick" interrupt handler. Run with all interrupts disabled on the current cpu. Shouldn't need to be used except in specific cases (such as timer interrupts)
- `SA_SHIRQ`
  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.
- `SA_SAMPLE_RANDOM`
  Interrupts can be used to contribute to the system entropy pool used by `/dev/random` and `/dev/urandom`. Useful to generate good random numbers. Don't use this if the interrupt behavior of your device is predictable!

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
```

Total number of interrupts

```
cat /proc/stat | grep intr
```

```
intr 8190767 6092967 10377 0 1102775 5 2 0 196 ...
```

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

Interrupt channel detection (1)

Useful when a driver can be used in different machines / architectures

- Some devices announce their IRQ channel in a register
- Manual detection
  - Register your interrupt handler for all possible channels
  - Ask for an interrupt
  - Let the called interrupt handler store the IRQ number in a global variable.
  - Try again if no interrupt was received
  - Unregister unused interrupt handlers.

Interrupt channel detection (2)

Kernel detection utilities

- `mask = probe_irq_on();`
- Activate interrupts on the device
- Deactivate interrupts on the device
- `irq = probe_irq_off(mask);`
  - `> 0`: unique IRQ number found
  - `= 0`: no interrupt. Try again!
  - `< 0`: several interrupts happened. Try again!

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 */
   void *dev_id,         /* Pointer used to keep track of the
                            corresponding device. Useful
                            when several devices are
                            managed by the same module */
   struct pt_regs *regs  /* cpu register snapshot, rarely
                            needed*/
);
```

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)

- *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*.

top half and bottom half processing (2)

- Declare the tasklet in the module source file:

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

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

```
tasklet_schedule(&module_do_tasklet);
```

Disabling interrupts

May be useful in regular driver code...

- Can be useful to ensure that an interrupt handler will not preempt your code (including kernel preemption)
- Disabling interrupts on the local CPU:

```
unsigned long flags;
local_irq_save(flags);      // Interrupts disabled
...
local_irq_restore(flags);  // Interrupts restored to their previous state.
```

  Note: must be run from within the same function!

Masking out an interrupt line

Useful to disable interrupts on a particular device

- `void disable_irq (unsigned int irq);`
  Disables the `irq` line for all processors in the system.
  Waits for all currently executing handlers to complete.
- `void disable_irq_nosync (unsigned int irq);`
  Same, except it doesn't wait for handlers to complete.
- `void enable_irq (unsigned int irq);`
  Restores interrupts on the `irq` line.
- `void synchronize_irq (unsigned int irq);`
  Waits for `irq` handlers to complete (if any).

Checking interrupt status

Can be useful for code which can be run from both process or interrupt context, to know whether it is allowed or not to call code that may sleep.

- `irqs_disabled()`
  Tests whether local interrupt delivery is disabled.
- `in_interrupt()`
  Tests whether code is running in interrupt context
- `in_irq()`
  Tests whether code is running in an interrupt handler.

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 crash 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

Time to start `Lab 6`!

- Implement a simple interrupt handler
- Register this handler on a shared interrupt line on your GNU/Linux PC.
- See how Linux handles shared interrupt lines.

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>`

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 */
);
```

- Read from the return virtual address or write to it.

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_start - vma->vm_end;

   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`.
  Need to run `request_mem_region` and setup `/dev/mem` first.
- Examples (`b`: byte, `h`: half, `w`: word)
  `devmem2 0x000c0004 h` (reading)
  `devmem2 0x000c0008 w 0xffffffff` (writing)

Embedded Linux driver development

Driver development
DMA

DMA situations

Synchronous

- A user process calls the read method of a driver. The driver allocates a DMA buffer and asks the hardware to copy its data. The process is put in sleep mode.
- The hardware copies its data and raises an interrupt at the end.
- The interrupt handler gets the data from the buffer and wakes up the waiting process.

Asynchronous

- The hardware sends an interrupt to announce new data.
- The interrupt handler allocates a DMA buffer and tells the hardware where to transfer data.
- The hardware writes the data and raises a new interrupt.
- The handler releases the new data, and wakes up the needed processes.

Memory constraints

- Need to use contiguous memory in physical space
- Can use any memory allocated by `kmalloc` (up to 128 KB) or `__get_free_pages` (up to 8MB)
- Can use block I/O and networking buffers, designed to support DMA.
- Can not use `vmalloc` memory (would have to setup DMA on each individual page)

Reserving memory for DMA

To make sure you've got enough RAM for big DMA transfers...
Example assuming you have 32 MB of RAM, and need 2 MB for DMA:

- Boot your kernel with `mem=30`
  The kernel will just use the first 30 MB of RAM.
- Driver code can now reclaim the 2 MB left:

```
dmabuf = ioremap (
            0x1e00000,        /* Start: 30 MB */
            0x200000          /* Size: 2 MB */
            );
```

Memory synchronization issues

Memory caching could interfere with DMA

- Before DMA to device:
  Need to make sure that all writes to DMA buffer are committed.
- After DMA from device:
  Before drivers read from DMA buffer, need to make sure that memory caches are flushed.
- Bidirectional DMA
  Need to flush caches before and after the DMA transfer.

Linux DMA API

The kernel DMA utilities can take care of:

- Either allocating a buffer in a cache coherent area,
- Or make sure caches are flushed when required,
- Managing the DMA mappings and IOMMU (if any)
- See `Documentation/DMA-API.txt`
  for details about the Linux DMA generic API.
- Most subsystems (such as PCI or USB) supply their own DMA API, derived from the generic one. May be sufficient for most needs.

Limited DMA address range?

- By default, the kernel assumes that your device can DMA to any 32 bit address. Not true for all devices!
- To tell the kernel that it can only handle 24 bit addresses:

```
if (dma_set_mask (dev,        /* device structure */
                  0xffffff    /* 24 bits */
                  ))
    use_dma = 1;              /* Able to use DMA */
else
    use_dma = 0;              /* Will have to do without DMA */
```

Coherent or streaming DMA mappings

- Coherent mappings
  Can simultaneously be accessed by the CPU and device.
  So, have to be in a cache coherent memory area.
  Usually allocated for the whole time the module is loaded.
  Can be expensive to setup and use.
- Streaming mappings (recommended)
  Set up for each transfer.
  Keep DMA registers free on the physical hardware registers.
  Some optimizations also available.

Allocating coherent mappings

The kernel takes care of both the buffer allocation and mapping:

```
include <asm/dma-mapping.h>

void *                          /* Output: buffer address */
  dma_alloc_coherent(
     struct device *dev,        /* device structure */
     size_t size,               /* Needed buffer size in bytes */
     dma_addr_t *handle,        /* Output: DMA bus address */
     gfp_t gfp                  /* Standard GFP flags */
  );

void dma_free_coherent(struct device *dev,
  size_t size, void *cpu_addr, dma_addr_t handle);
```

DMA pools (1)

- `dma_alloc_coherent` usually allocates buffers with `__get_free_pages` (minimum: 1 page).
- You can use DMA pools to allocate smaller coherent mappings:

```
<include linux/dmapool.h>
```

- Create a dma pool:

```
struct dma_pool *
dma_pool_create (
   const char *name,        /* Name string */
   struct device *dev,      /* device structure */
   size_t size,             /* Size of pool buffers */
   size_t align,            /* Hardware alignment (bytes) */
   size_t allocation        /* Address boundaries not to be crossed */
);
```

DMA pools (2)

- Allocate from pool

```
void * dma_pool_alloc (
   struct dma_pool *pool,
   gfp_t mem_flags,
   dma_addr_t *handle
);
```

- Free buffer from pool

```
void dma_pool_free (
              struct dma_pool *pool,
              void *vaddr,
              dma_addr_t dma);
```

- Destroy the pool (free all buffers first!)

```
void dma_pool_destroy (struct dma_pool *pool);
```

Setting up streaming mappings

Works on buffers already allocated by the driver

```
<include linux/dmapool.h>

dma_addr_t dma_map_single(
   struct device *,                /* device structure */
   void *,                         /* input: buffer to use */
   size_t,                         /* buffer size */
   enum dma_data_direction  /* Either DMA_BIDIRECTIONAL,
                    DMA_TO_DEVICE or DMA_FROM_DEVICE */
   );

void dma_unmap_single(struct device *dev, dma_addr_t
   handle, size_t size, enum dma_data_direction dir);
```

DMA streaming mapping notes

- When the mapping is active: only the device should access the buffer (potential cache issues otherwise).
- The CPU can access the buffer only after unmapping!
- Another reason: if required, this API can create an intermediate *bounce buffer* (used if the given buffer is not usable for DMA).
- Possible for the CPU to access the buffer without unmapping it, using the `dma_sync_single_for_cpu()` (ownership to cpu) and `dma_sync_single_for_device()` functions (ownership back to device).
- The Linux API also support scatter / gather DMA streaming mappings.

Embedded Linux driver development

Driver development

New Device Model

Device Model features (1)

- Originally created to make power management simpler
  Now goes much beyond.
- Used to represent the architecture and state of the system
- Has a representation in userspace: sysfs
  Now the preferred interface with userspace (instead of `/proc`)
- Easy to implement thanks to the device interface:
  `include/linux/device.h`

Device model features (2)

Allows to view the system for several points of view:

- From devices existing in the system: their power state, the bus they are attached to, and the driver responsible for them.
- From the system bus structure: which bus is connected to which bus (e.g. USB bus controller on the PCI bus), existing devices and devices potentially accepted (with their drivers)
- From available device drivers: which devices they can support, and which bus type they know about.
- From the various kinds ("classes") of devices: `input`, `net`, `sound`... Existing devices for each class. Convenient to find all the input devices without actually knowing how they are physically connected.

sysfs

- Userspace representation of the Device Model.
- Configure it with
  `CONFIG_SYSFS=y` (Filesystems -> Pseudo filesystems)
- Mount it with
  `mount -t sysfs none /sys`
- Spend time exploring `/sys` on your workstation!

sysfs tools

http://linux-diag.sourceforge.net/Sysfsutils.html

- `libsysfs` - The library's purpose is to provide a consistent and stable interface for querying system device information exposed through sysfs. Used by `udev` (see later)
- `systool` - A utility built upon `libsysfs` that lists devices by bus, class, and topology.

The device structure

Declaration

- The base data structure is `struct device`, defined in `include/linux/device.h`
- In real life, you will rather use a structure corresponding to the bus your device is attached to: `struct pci_dev`, `struct usb_device`...

Registration

- Still depending on the device type, specific register and unregister functions are provided

Device attributes

Defining device attributes to be read/written from/by userspace

```
struct device_attribute {
   struct attribute        attr;
   ssize_t (*show)(struct device *dev, char *buf, size_t count, loff_t off);
   ssize_t (*store)(struct device *dev, const char *buf, size_t count, loff_t off);
};

#define DEVICE_ATTR(name,mode,show,store)
```

Adding / removing from the device directory

```
int device_create_file(struct device *dev, struct device_attribute *entry);
void device_remove_file(struct device *dev, struct device_attribute *attr);
```

Example

```
/* Creates a file named "power" with a 0644 (-rw-r--r--) mode */
DEVICE_ATTR(power,0644,show_power,store_power);
device_create_file(dev,&dev_attr_power);
device_remove_file(dev,&dev_attr_power);
```

The device driver structure

Declaration

```
struct device_driver {
    /* Omitted a few internals */
    char               *name;
    struct bus_type        *bus;
    int      (*probe)       (struct device *dev);
    int      (*remove)      (struct device *dev);
    void     (*shutdown)   (struct device *dev);
    int      (*suspend)    (struct device *dev, u32 state, u32 level);
    int      (*resume)      (struct device *dev, u32 level);
};
```

Registration

```
extern int driver_register(struct device_driver *drv);
extern void driver_unregister(struct device_driver *drv);
```

Attributes

Available in a similar way

Device Model references

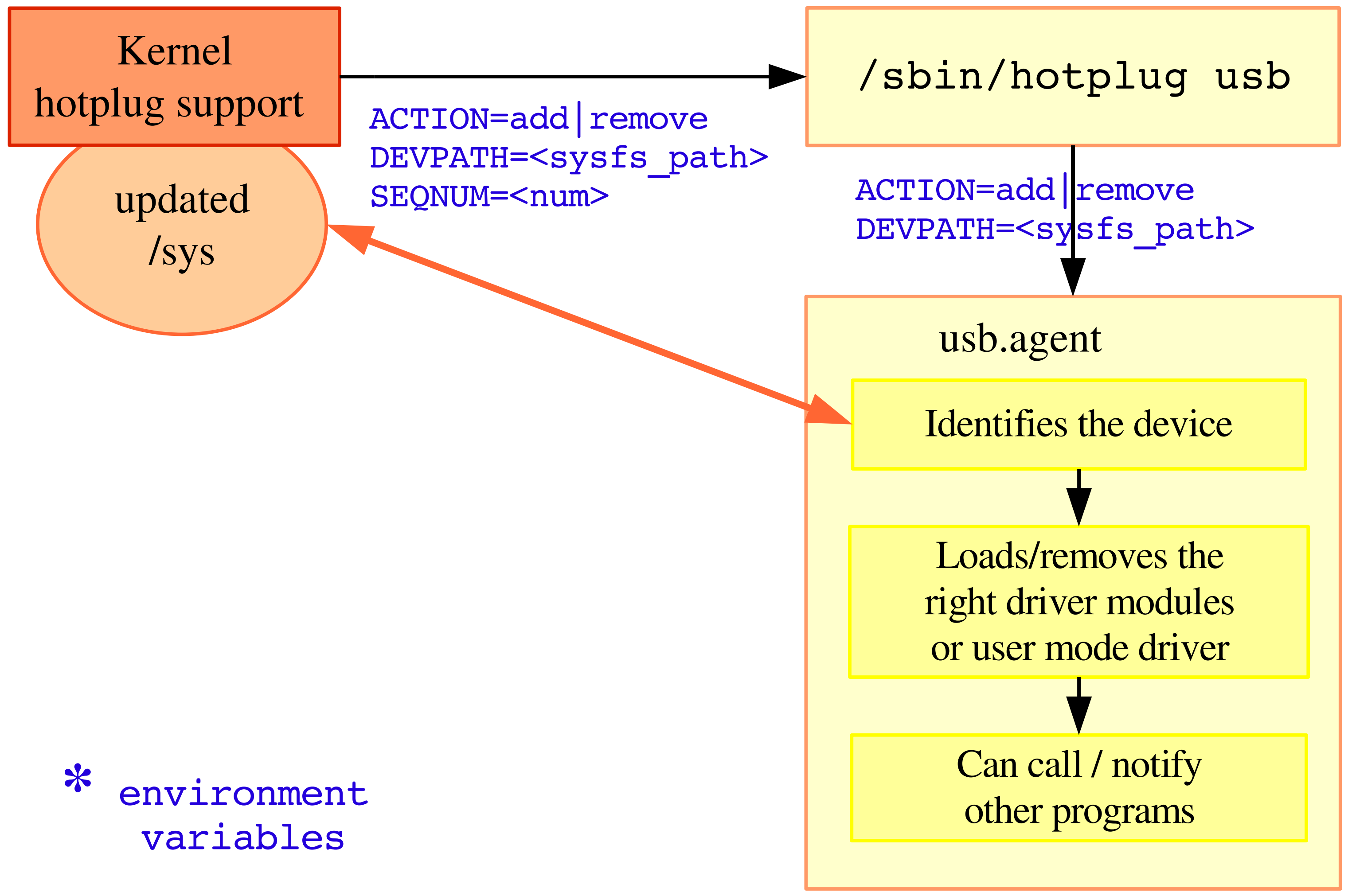
- Very useful and clear documentation in the kernel sources!
- `Documentation/driver-model/`
- `Documentation/filesystems/sysfs.txt`

Driver development
hotplug

hotplug overview

- Introduced in Linux 2.4. Pioneered by USB.
- Kernel mechanism to notify user space programs that a device has been inserted or removed.
- User space scripts then take care of identifying the hardware and inserting/removing the right driver modules.
- Linux 2.6: much easier device identification thanks to sysfs
- Makes it possible to load external firmware
- Makes it possible to have user-mode only driver (e.g. `libsane`)
- Kernel configuration:
  `CONFIG_HOTPLUG=y` (General setup section)

hotplug flow example



hotplug files

`/lib/modules/*/modules.*map`
: `depmod` output

`/proc/sys/kernel/hotplug`
: specifies hotplug program path

`/sbin/hotplug`
: hotplug program (default path name)

`/etc/hotplug/*`
: hotplug files

`/etc/hotplug/NAME*`
: subsystem-specific files, for agents

`/etc/hotplug/NAME/DRIVER`
: driver setup scripts, invoked by agents

`/etc/hotplug/usb/DRIVER.usermap`
: `depmod` data for user-mode drivers

`/etc/hotplug/NAME.agent`
: hotplug subsystem-specific agents

Firmware hotplugging

Reasons for keeping firmware data outside their device drivers

Legal issues

- Some firmware is not legal to distribute and can't be shipped in a Free Software driver
- Some firmware may not be considered as free enough to distribute (Debian example)

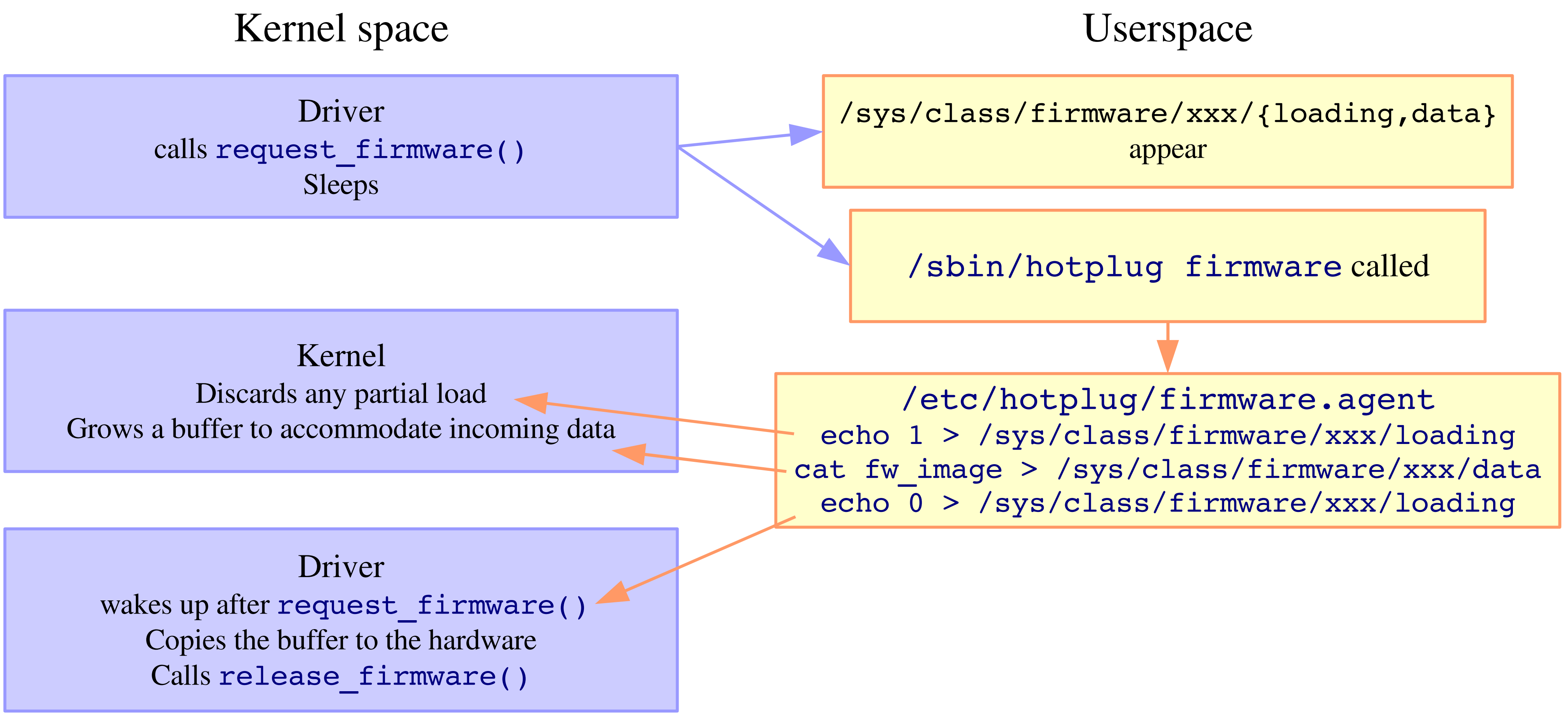
Technical issues

- Firmware in kernel code would occupy memory permanently, even if just used once.

Firmware hotplugging setup

- Kernel configuration: needs to be set in `CONFIG_FW_LOADER` (Device Drivers -> Generic Driver Options -> hotplug firmware loading support)
- Need `/sys` to be mounted
- Location of firmware files: check `/etc/hotplug/firmware.agent`

Firmware hotplugging implementation



Kernel space

Userspace

Driver
calls `request_firmware()`
Sleeps

`/sys/class/firmware/xxx/{loading,data}`
appear

`/sbin/hotplug firmware` called

Kernel
Discards any partial load
Grows a buffer to accommodate incoming data

```
/etc/hotplug/firmware.agent
echo 1 > /sys/class/firmware/xxx/loading
cat fw_image > /sys/class/firmware/xxx/data
echo 0 > /sys/class/firmware/xxx/loading
```

Driver
wakes up after `request_firmware()`
Copies the buffer to the hardware
Calls `release_firmware()`

See `Documentation/firmware_class/` for a nice overview

hotplug references

- Project page and documentation
  http://linux-hotplug.sourceforge.net/
- Mailing list:
  http://lists.sourceforge.net/lists/listinfo/linux-hotplug-devel

Embedded Linux driver development

Driver development

udev: user-space device file management

/dev issues and limitations

- On Red Hat 9, 18000 entries in `/dev`!
  All entries for all possible devices need to be created at system installation.
- Need for an authority to assign major numbers
  http://lanana.org/: Linux Assigned Names and Numbers Authority
- Not enough numbers in 2.4, limits extended in 2.6
- Userspace doesn't know what devices are present in the system.
- Userspace can't tell which `/dev` entry is which device

devfs solutions and limitations

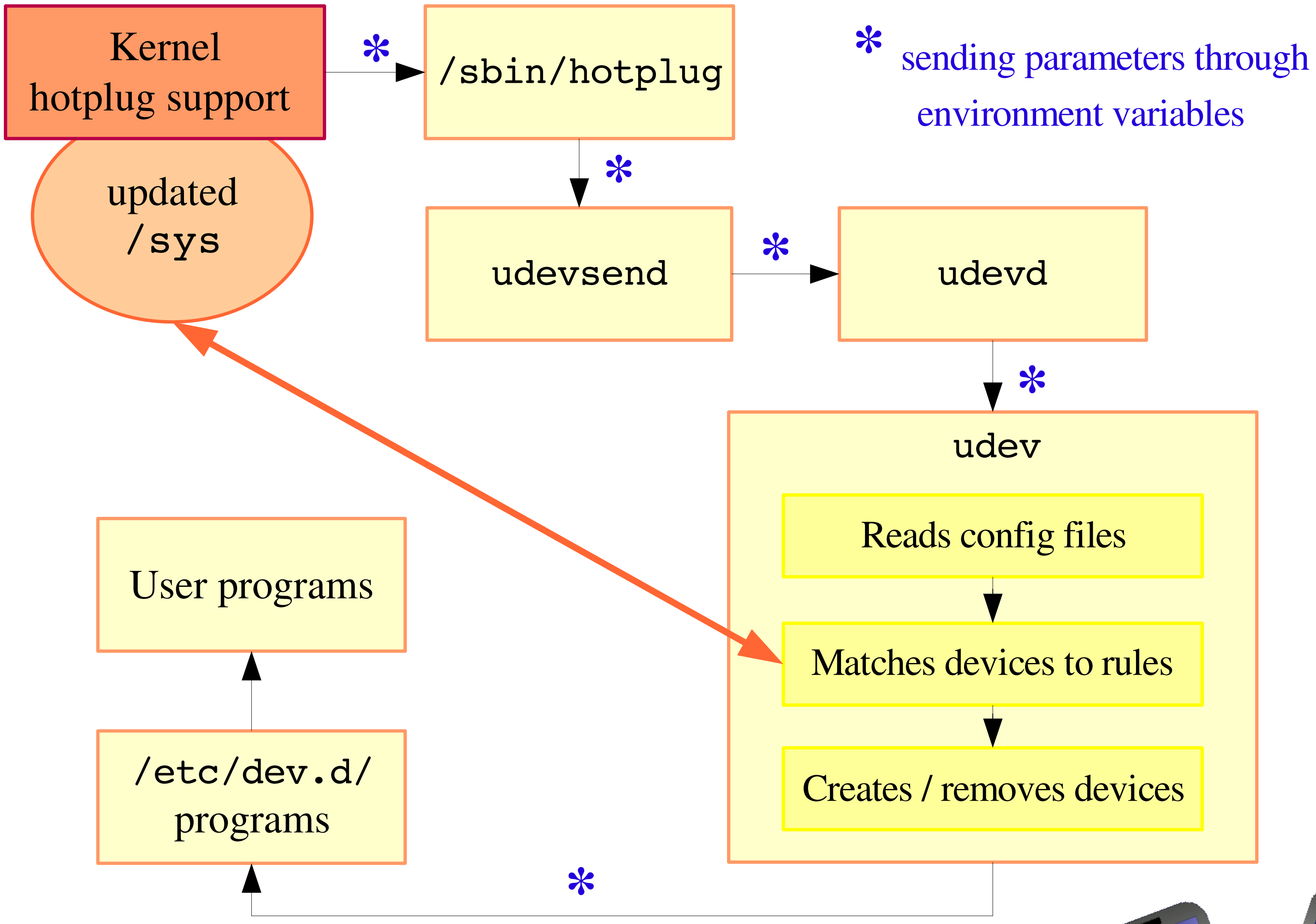
- Only shows present devices
- But uses different names as in `/dev`, causing issues in scripts.
- But no flexibility in device names, unlike with `/dev/`, e.g. the 1st IDE disk device has to be called either `/dev/hda` or `/dev/ide/hd/c0b0t0u0`.
- But doesn't allow dynamic major and minor number allocation.
- But requires to store the device naming policy in kernel memory. Can't be swapped out!

The udev solution

Takes advantage of both hotplug and sysfs

- Entirely in user space
- Automatically creates device entries (by default in `/udev`)
- Called by `/sbin/hotplug`, uses information from sysfs.
- Major and minor device numbers found in sysfs
- Requires no change to the driver code
- Small size

How udev works



udev toolset (1)

Major components

- `udevsend` (8KB in Fedora Core 3)
  Takes care of handling the `/sbin/hotplug` events, and sending them to `udevd`
- `udevd` (12KB)
  Takes care of reordering hotplug events, before calling `udev` instances for each of them.
- `udev` (68KB)
  Takes care of creating or removing device entries, entry naming, and then executing programs in `/etc/dev.d/`

udev toolset (2)

Other utilities

- `udevinfo` (48KB)
  Lets users query the udev database
- `udevstart` (functionality brought by `udev`)
  Populates the initial device directory from valid devices found in the sysfs device tree.
- `udevtest <sysfs_device_path>` (64KB)
  Simulates a `udev` run to test the configured rules

udev configuration file

`/etc/udev/udev.conf`

Easy to edit and configure. Sets the below parameters:

- Device directory (`/udev`)
- udev database file (`/dev/.udev.tdb`)
- udev rules (`/etc/udev/rules.d/`)
  udev permissions (`/etc/udev/permissions.d/`)
- default mode (`0600`), default owner (`root`) and group (`root`), when not found in udev's permissions.
- Enable logging (`yes`)
  Debug messages available in `/var/log/messages`

udev naming capabilities

Device names can be defined

- from a label or serial number
- from a bus device number
- from a location on the bus topology
- from a kernel name

udev can also create device links

udev rules file example

```
# if /sbin/scsi_id returns "OEM 0815" device will be called disk1
BUS="scsi", PROGRAM="/sbin/scsi_id", RESULT="OEM 0815", NAME="disk1"

# USB printer to be called lp_color
BUS="usb", SYSFS{serial}="W09090207101241330", NAME="lp_color"

# SCSI disk with a specific vendor and model number will be called boot
BUS="scsi", SYSFS{vendor}="IBM", SYSFS{model}="ST336", NAME="boot%n"

# sound card with PCI bus id 00:0b.0 to be called dsp
BUS="pci", ID="00:0b.0", NAME="dsp"

# USB mouse at third port of the second hub to be called mouse1
BUS="usb", PLACE="2.3", NAME="mouse1"

# ttyUSB1 should always be called pda with two additional symlinks
KERNEL="ttyUSB1", NAME="pda", SYMLINK="palmtop handheld"

# multiple USB webcams with symlinks to be called webcam0, webcam1, ...
BUS="usb", SYSFS{model}="XV3", NAME="video%n", SYMLINK="webcam%n"
```

udev sample permissions

Sample udev permission file (in /etc/udev/permissions.d/):

```
#name:user:group:mode
input/*:root:root:644
ttyUSB1:0:8:0660
video*:root:video:0660
dsp1:::0666
```

/etc/dev.d/

After device nodes are created, removed or renamed, udev can call programs found in the below search order:

- `/etc/dev.d/$(DEVNAME)/*.dev`
- `/etc/dev.d/$(SUBSYSTEM)/*.dev`
- `/etc/dev.d/default/*.dev`

The programs in each directory are sorted in lexical order.

This is useful to notify user applications of device changes.

udev links

- Home page
http://kernel.org/pub/linux/utils/kernel/hotplug/udev.html
- Sources
http://kernel.org/pub/linux/utils/kernel/hotplug/
- Mailing list:
linux-hotplug-devel@lists.sourceforge.net
- Greg Kroah-Hartman, udev presentation
http://www.kroah.com/linux/talks/oscon_2004_udev/
- Greg Kroah-Hartman, udev whitepaper
http://www.kroah.com/linux/talks/ols_2003_udev_paper/Reprint-Kroah-Hartman-OLS2003.pdf

Embedded Linux driver development

Advice and resources

System security

- In production: disable loadable kernel modules if you can.
- Carefully check data from input devices (if interpreted by the driver) and from user programs (buffer overflows)
- Check kernel sources signature.
- Beware of uninitialized memory.
- Compile modules by yourself (beware of binary modules)

Advice and resources

Choosing filesystems

Block device or MTD filesystems

Block devices

- Floppy or hard disks (SCSI, IDE)
- Compact Flash (seen as a regular IDE drive)
- RAM disks
- Loopback devices

Memory Technology Devices (MTD)

- Flash, ROM or RAM chips
- MTD emulation on block devices

Filesystems are either made for block or MTD storage devices.
See `Documentation/filesystems/` for details.

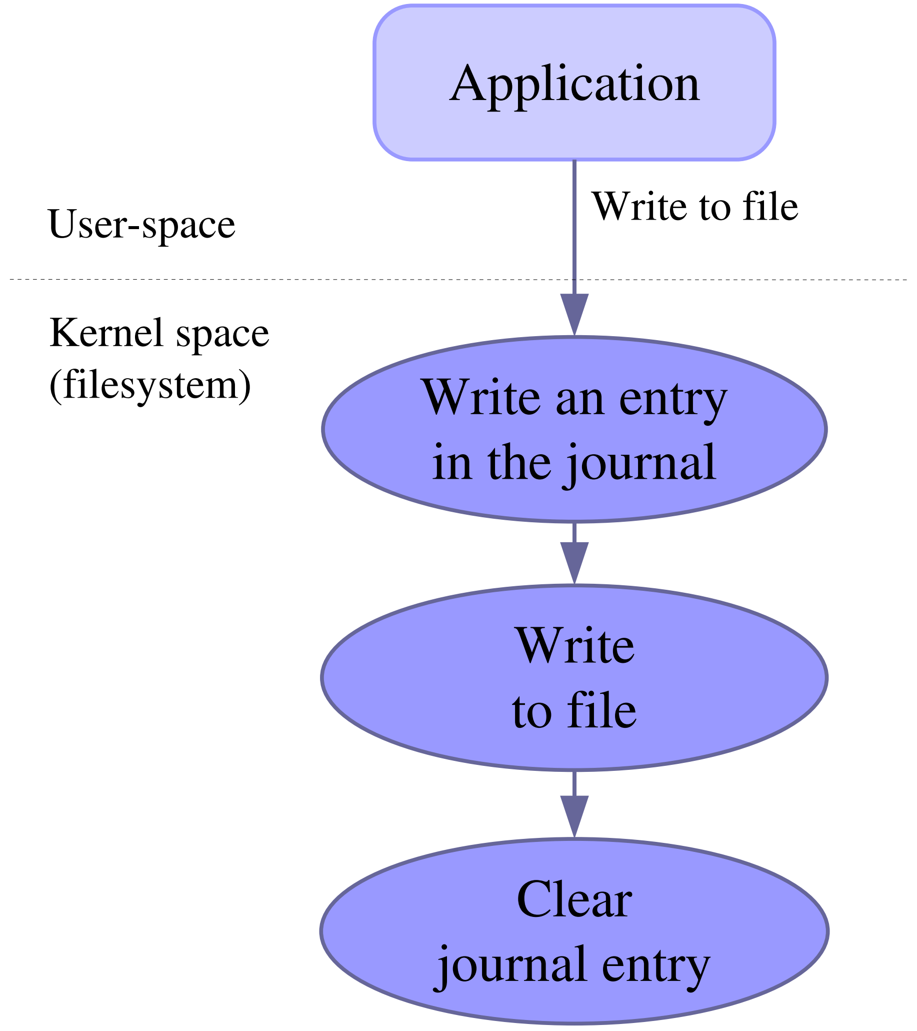
Traditional block filesystems

Traditional filesystems

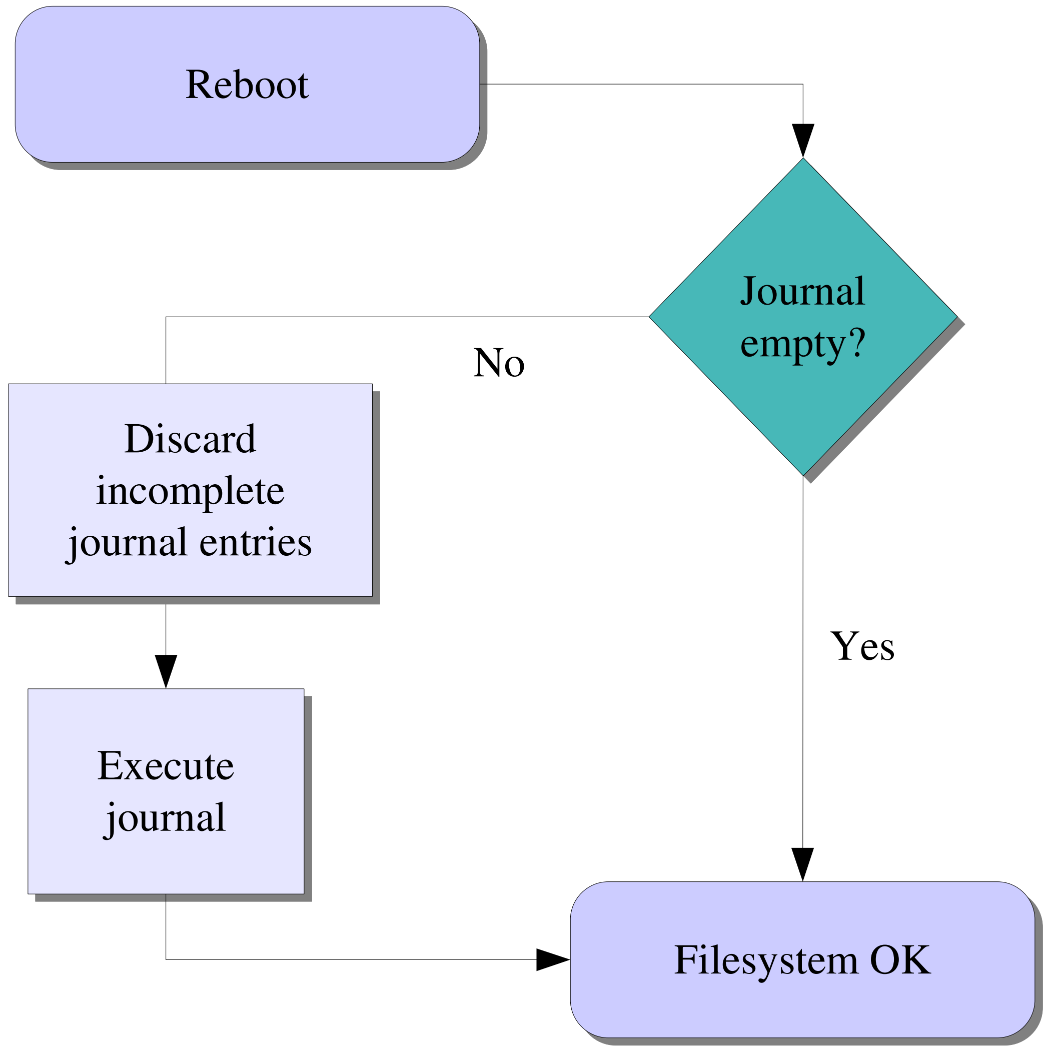
- Hard to recover from crashes. Can be left in a corrupted ("half finished") state after a system crash or sudden power-off.
- `ext2`: traditional Linux filesystem (repair it with `fsck.ext2`)
- `vfat`: traditional Windows filesystem (repair it with `fsck.vfat` on GNU/Linux or `Scandisk` on Windows)

Journaled filesystems

- Designed to stay in a correct state even after system crashes or a sudden power-off
- All writes are first described in the journal before being committed to files



Filesystem recovery after crashes



- Thanks to the journal, the filesystem is never left in a corrupted state
- Recently saved data could still be lost

Journaled block filesystems

Journaled filesystems

- `ext3`: `ext2` with journal extension
- `reiserFS`: most innovative (fast and extensible)
  Caution: needs at least 32 MB!
  `reiser4`: the latest version.
  Available through patches (not in mainstream yet).
- Others: `JFS` (IBM), `XFS` (SGI)
- `NTFS`: well supported by Linux in read-mode.

Compressed block filesystems (1)

Cramfs

- Simple, small, read-only compressed filesystem designed for embedded systems .
- Maximum filesystem size: 256 MB
- Maximum file size: 16 MB

See `Documentation/filesystems/cramfs.txt` in kernel sources.

Compressed block filesystems (2)

Squashfs: http://squashfs.sourceforge.net

- A must-use replacement for Cramfs! Also read-only.
- Maximum filesystem and file size: `2`^{32} bytes (`4 GB`)
- Achieves better compression and much better performance.
- Fully stable but released as a separate patch so far (waiting for Linux 2.7 to start).
- Successfully tested on `i386`, `ppc`, `arm` and `sparc`.

See benchmarks on
http://tree.celinuxforum.org/CelfPubWiki/SquashFsComparisons

ramdisk filesystems

Useful to store temporary data not kept after power off or reboot: system log files, connection data, temporary files...

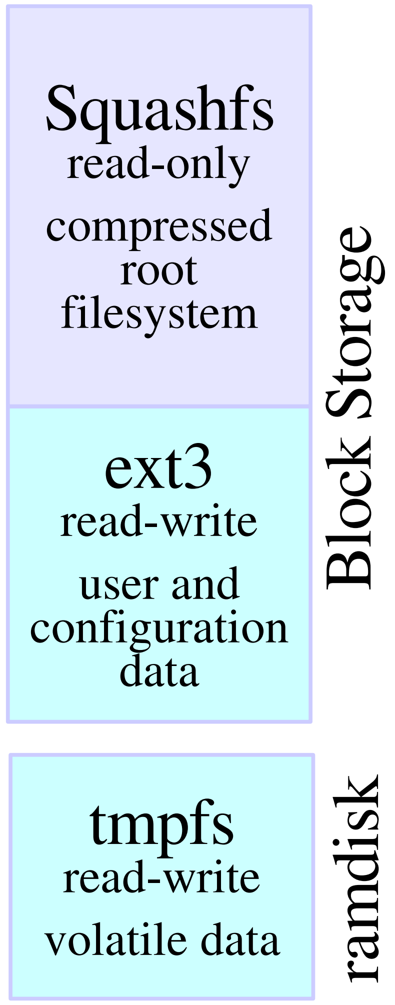
- Traditional block filesystems: journaling not needed.
  Many drawbacks: fixed in size. Remaining space not usable as RAM.
  Files duplicated in RAM (in the block device and file cache)!
- tmpfs (Config: `File systems` -> `Pseudo filesystems`)
  Doesn't waste RAM: grows and shrinks to accommodate stored files
  Saves RAM: no duplication; can swap out pages to disk when needed.

See `Documentation/filesystems/tmpfs.txt` in kernel sources.

Mixing read-only and read-write filesystems

Good idea to split your block storage into

- A compressed read-only partition (Squashfs)
  Typically used for the root filesystem (binaries, kernel...).
  Compression saves space. Read-only access protects your system from mistakes and data corruption.
- A read-write partition with a journaled filesystem (like ext3)
  Used to store user or configuration data.
  Guarantees filesystem integrity after power off or crashes.
- A ramdisk for temporary files (tmpfs)



The MTD subsystem

Linux filesystem interface

MTD "User" modules

jffs2

Char device

Block device

yaffs2

Read-only block device

Flash Translation Layers
for block device emulation
Caution: patented algorithms!

FTL

NFTL

INFTL

MTD Chip drivers

CFI flash

RAM chips

NAND flash

DiskOnChip flash

ROM chips

Block device

Virtual memory

Virtual devices appearing as
MTD devices

Memory devices hardware

MTD filesystems - jffs2

`jffs2`: Journaling Flash File System v2

- Designed to write flash sectors in an homogeneous way.
  Flash bits can only be rewritten a relatively small number of times (often < 100 000).
- Compressed to fit as many data as possible on flash chips. Also compensates for slower access time to those chips.
- Power down reliable: can restart without any intervention
- Shortcomings: low speed, big RAM consumption (4 MB for 128 MB of storage).

Mounting a jffs2 image

Useful to create or edit `jffs2` images on your GNU / Linux PC!

- Mounting an MTD device as a loop device is a bit complex task. Here's an example for `jffs2`:

```
modprobe loop
modprobe mtdblock
losetup /dev/loop0 <file>.jffs2
modprobe blkmtd erasesz=256 device=/dev/loop0
mknod /dev/mtdblock0 b 31 0                      (if not done yet)
mkdir /mnt/jffs2                 (example mount point, if not done yet)
mount -t jffs2 /dev/mtdblock0 /mnt/jffs2/
```

- It's very likely that your standard kernel misses one of these modules. Check the corresponding `.c` file in the kernel sources and look in the corresponding `Makefile` which option you need to recompile your kernel with.

MTD filesystems - yaffs2

`yaffs2`: Yet Another Flash Filing System, version 2

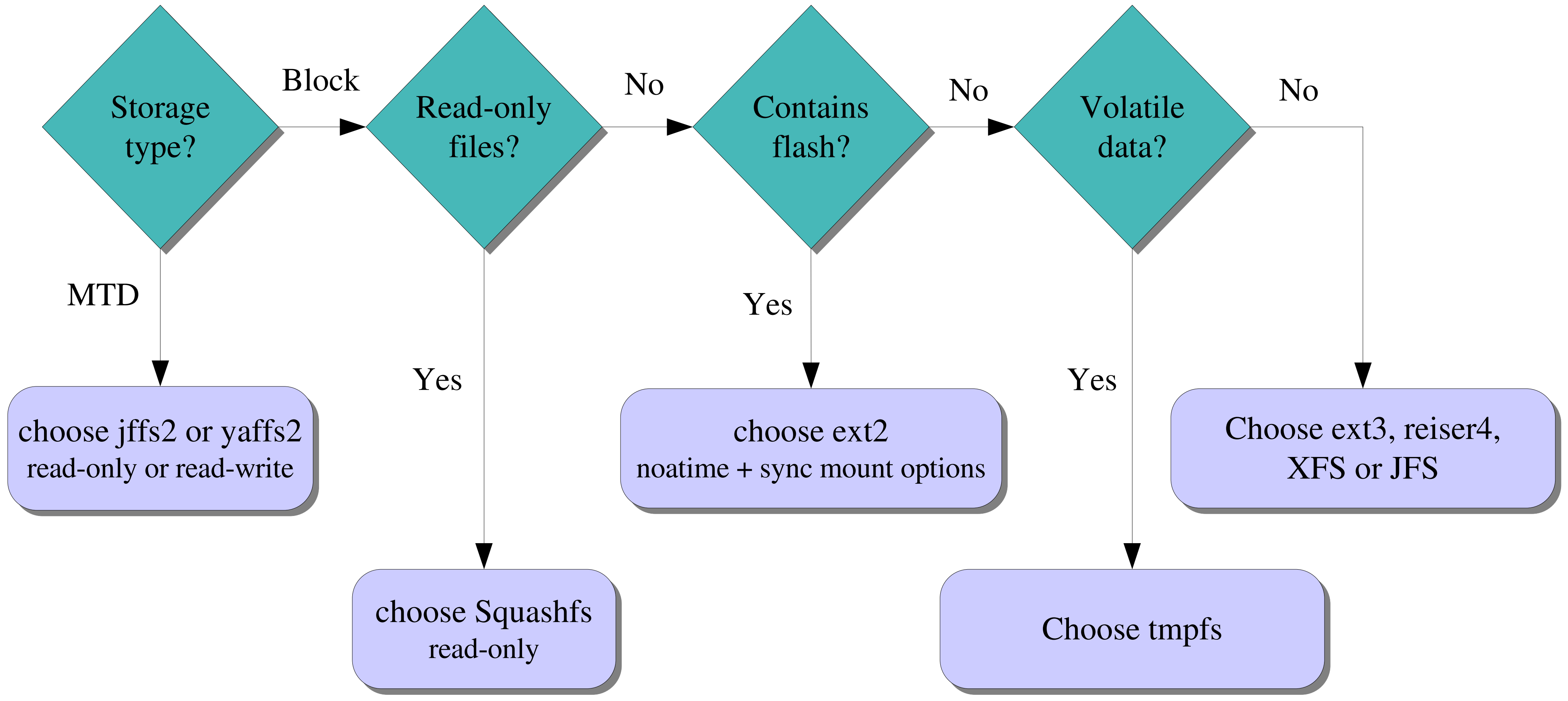
- `yaffs2` home: http://www.aleph1.co.uk/node/35
  Caution: site under reconstruction. Lots of broken links!
- Features: NAND flash only. No compression. Several times faster than `jffs2` (mainly significant in boot time). Consumes much less RAM. Also includes ECC and is power down reliable.
- License: GPL or proprietary
- Ships outside the Linux kernel. Get it from CVS:
  http://aleph1.co.uk/cgi-bin/viewcvs.cgi/yaffs/

Filesystem choices for block flash devices

Typically for Compact Flash storage

- Can't use `jffs2` or `yaffs2` on CF storage (block device). MTD Block device emulation could be used, but `jffs2` / `yaffs2` writing schemes could interfere with on-chip flash management (manufacturer dependent).
- Never use block device journaled filesystems on unprotected flash chips! Keeping the journal would write the same sectors over and over again and quickly damage them.
- Can use `ext2` or `vfat`, with the below mount options:
  `noatime`: doesn't write access time information in file inodes
  `sync`: to perform writes immediately (reduce power down failure risks)

Filesystem choice summary


Storage type?
Block
Read-only files?
No
Contains flash?
No
Volatile data?
No
MTD
choose jffs2 or yaffs2 read-only or read-write
Yes
choose Squashfs read-only
Yes
choose ext2 noatime + sync mount options
Yes
Choose tmpfs
Choose ext3, reiser4, XFS or JFS

Advice and resources
Getting help and contributions

Solving issues

- If you face an issue, and it doesn't look specific to your work but rather to the tools you are using, it is very likely that someone else already faced it.
- Search the Internet for similar error reports
  - On web sites or mailing list archives (using a good search engine)
  - On newsgroups: http://groups.google.com/
- You have great chances of finding a solution or workaround, or at least an explanation for your issue.
- Otherwise, reporting the issue is up to you!

Getting help

- If you have a support contract, ask your vendor
- Otherwise, don't hesitate to share your questions and issues on mailing lists
  - Either contact the Linux mailing list for your architecture (like linux-arm-kernel or linuxsh-dev...)
  - Or contact the mailing list for the subsystem you're dealing with (linux-usb-devel, linux-mtd...). Don't ask the maintainer directly!
  - Most mailing lists come with a FAQ page. Make sure you read it before contacting the mailing list
  - Refrain from contacting the Linux Kernel mailing list, unless you're an experienced developer and need advice

Getting contributions

Applies if your project can interest other people: developing a driver or filesystem, porting Linux on a new processor, board or device available on the market...

External contributors can help you a lot by

- Testing
- Writing documentation
- Making suggestions
- Even writing code

Encouraging contributions

- Open your development process: mailing list, Wiki, public CVS read access
- Let everyone contribute according to their skills and interests.
- Release early, release often
- Take feedback and suggestions into account
- Recognize contributions
- Make sure status and documentation are up to date
- Publicize your work and progress to broader audiences

Embedded Linux driver development

Advice and resources

Bug report and patch submission

Reporting Linux bugs

- First make sure you're using the latest version
- Make sure you investigate the issue as much as you can:
  see `Documentation/BUG-HUNTING`
- Make sure the bug has not been reported yet. A bug tracking system (http://bugzilla.kernel.org/) exists but very few kernel developers use it.
  Best to use web search engines (accessing public mailing list archives)
- If the subsystem you report a bug on has a mailing list, use it.
  Otherwise, contact the official maintainer (see the `MAINTAINERS` file).
  Always give as many useful details as possible.

How to submit patches or drivers

- Don't merge patches addressing different issues
- You should identify and contact the official maintainer for the files to patch.
- See `Documentation/SubmittingPatches` for details. For trivial patches, you can copy the Trivial Patch Monkey.
- See also http://kernelnewbies.org/UpstreamMerge for very helpful advice to have your code merged upstream (by Rik van Riel).
- Special subsystems:
  - ARM platform: it's best to submit your ARM patches to Russell King's patch system: http://www.arm.linux.org.uk/developer/patches/

How to become a kernel developer?

Greg Kroah-Hartman gathered useful references and advice for people interested in contributing to kernel development:

Documentation/HOWTO (in kernel sources since `2.6.15-rc2`)

Do not miss this very useful document!

Embedded Linux driver development

Advice and resources

References

Information sites (1)

Linux Weekly News
http://lwn.net/

- The weekly digest off all Linux and free software information sources
- In depth technical discussions about the kernel
- Subscribe to finance the editors ($5 / month)
- Articles available for non subscribers
  after 1 week.

Information sites (2)

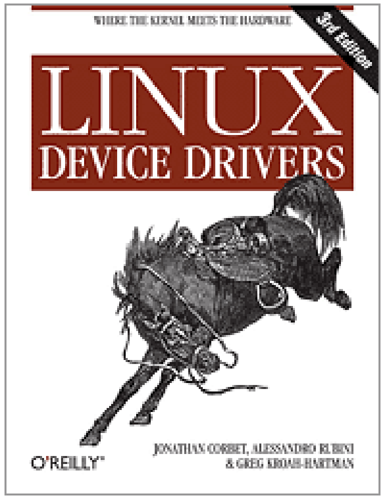
KernelTrap
http://kerneltrap.org/

- Forum website for kernel developers
- News, articles, whitepapers, discussions, polls, interviews
- Perfect if a digest is not enough!

Useful reading (1)

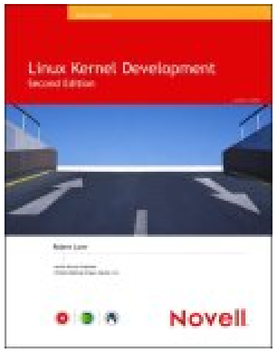
Linux Device Drivers, 3rd edition, Feb 2005 ★★★

- By Jonathan Corbet, Alessandro Rubini, Greg Kroah-Hartman, O'Reilly
  http://www.oreilly.com/catalog/linuxdrive3/
- Freely available on-line!
  Great companion to the printed book for easy electronic searches!
  http://lwn.net/Kernel/LDD3/ (1 PDF file per chapter)
  http://free-electrons.com/community/kernel/ldd3/ (single PDF file)

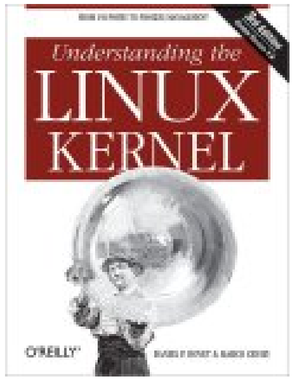

WHERE THE KERNEL MEETS THE HARDWARE
3rd Edition
LINUX
DEVICE DRIVERS
O'REILLY
JONATHAN CORBET, ALESSANDRO RUBINI & GREG KROAH-HARTMAN

A must-have book for Linux device driver writers!

Useful reading (2)



- Linux Kernel Development, 2nd Edition, Jan 2005 ☆☆☆
  Robert Love, Novell Press
  http://rlove.org/kernel_book/
  A very synthetic and pleasant way to learn about kernel subsystems (beyond the needs of device driver writers)



- Understanding the Linux Kernel, 3rd edition, Nov 2005 ☆☆
  Daniel P. Bovet, Marco Cesati, O'Reilly
  http://oreilly.com/catalog/understandlk/
  An extensive review of Linux kernel internals, covering Linux 2.6 at last.
  Unfortunately, only covers the PC architecture.

Useful on-line resources

- Linux kernel mailing list FAQ
  http://www.tux.org/lkml/
  Complete Linux kernel FAQ
  Read this before asking a question to the mailing list
- Kernel Newbies
  http://kernelnewbies.org/
  Glossary, articles, presentations, HOWTOs, recommended reading, useful tools for people getting familiar with Linux kernel or driver development.
- Kernel glossary:
  http://kernelnewbies.org/KernelGlossary

CE Linux Forum resources

CE Linux Forum's Wiki
is full of useful resources for embedded systems developers:

- Kernel patches not available in mainstream yet
- Many howto documents of all kinds
- Details about ongoing projects, such as reducing kernel size, boot time, or power consumption.
- Contributions are welcome!

http://tree.celinuxforum.org/CelfPubWiki

ARM resources

- ARM Linux project: http://www.arm.linux.org.uk/
  - Developer documentation: http://www.arm.linux.org.uk/developer/
  - arm-linux-kernel mailing list: http://lists.arm.linux.org.uk/mailman/listinfo/linux-arm-kernel
  - FAQ: http://www.arm.linux.org.uk/armlinux/mlfaq.php
  - How to post kernel fixes: http://www.arm.uk.linux.org/developer/patches/
- ARMLinux @ Simtec: http://armlinux.simtec.co.uk/
  A few useful resources: FAQ, documentation and Who's who!
- ARM Limited: http://www.linux-arm.com/
  Wiki with links to useful developer resources

International conferences (1)

Useful conferences featuring Linux kernel presentations

- Ottawa Linux Symposium (July): http://linuxsymposium.org/
  Right after the (private) kernel summit.
  Lots of kernel topics. Many core kernel hackers still present.
- Fosdem: http://fosdem.org (Brussels, February)
  For developers. Kernel presentations from well-known kernel hackers.
- CE Linux Forum: http://celinuxforum.org/
  Organizes several international technical conferences, in particular in California (San Jose) and in Japan. Now open to non CELF members!
  Very interesting kernel topics for embedded systems developers.

International conferences (2)

- linux.conf.au: http://conf.linux.org.au/ (Australia / New Zealand)
  Features a few presentations by key kernel hackers.

Don't miss our free conference videos on
http://free-electrons.com/community/videos/conferences/!

Embedded Linux driver development

Advice and resources

Last advice

Use the Source, Luke!

Many resources and tricks on the Internet find you will, but solutions to all technical issues only in the Source lie.

Thanks to LucasArts

Annexes

Quiz answers

Quiz answers

- `request_irq`, `free_irq`
  Q: Why does `dev_id` have to be unique for shared IRQs?
  A: Otherwise, the kernel would have no way of knowing which handler to release. Also needed for multiple devices (disks, serial ports...) managed by the same driver, which rely on the same interrupt handler code.

- 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!

Annexes
U-boot details

Postprocessing kernel image for U-boot

The U-boot bootloader needs extra information to be added to the kernel and initrd image files.

- `mkimage` postprocessing utility provided in U-boot sources
- Kernel image postprocessing:
  `make uImage`

Postprocessing initrd image for U-boot

`mkimage`	
`-n initrd \`	Name
`-A arm \`	Architecture
`-O linux \`	Operating System
`-T ramdisk \`	Type
`-C gzip \`	Compression
`-d rd-ext2.gz \`	Input file
`uInitrd`	Output file

Compiling U-boot mkimage

If you don't have `mkimage` yet

- Get the U-boot sources from http://u-boot.sourceforge.net/
- In the U-boot source directory:
  Find the name of the config file for your board in `include/configs` (for example: `omap1710h3.h`)
  `make omap1710h3_config` (`.h` replaced by `_config`)
  `make` (or `make -k` if you have minor failures)
  `cp tools/mkimage /usr/local/bin/`

Configuring tftp (1)

Often in development: downloading a kernel image from the network.
Instructions for xinetd based systems (Fedora Core, Red Hat...)

- Install the `tftp-server` package if needed
- Remove `disable = yes` in `/etc/xinetd.d/tftp`
- Copy your image files to the `/tftpboot/` directory (or to the location specified in `/etc/xinetd.d/tftp`)
- You may have to disable SELinux in `/etc/selinux/config`
- Restart xinetd:
  `/etc/init.d/xinetd restart`

Configuring tftp (2)

On systems like Debian (or Knoppix) GNU/Linux

- Set `RUN_DAEMON="yes"`
  in `/etc/default/tftpd-hpa`
- Copy your images to `/var/lib/tftpboot`
- `/etc/hosts.allow`:
  Replace `ALL : ALL@ALL : DENY` by `ALL : ALL@ALL : ALLOW`
- `/etc/hosts.deny`:
  Comment out `ALL: PARANOID`
- Restart the server:
  `/etc/init.d/tftpd-hpa restart`

U-boot prompt

- Connect the target to your PC through a serial console
- Power-up the board.
  On the serial console, you will see something like:

```
U-Boot 1.1.2 (Aug  3 2004 - 17:31:20)
RAM Configuration:
Bank #0: 00000000  8 MB
Flash:  2 MB
In:    serial
Out:   serial
Err:   serial
u-boot #
```

Board information

```
u-boot # bdinfo
DRAM bank = 0x00000000
-> start = 0x00000000
-> size = 0x00800000
ethaddr = 00:40:95:36:35:33
ip_addr = 10.0.0.11
baudrate = 19200 bps
```

Environment variables (1)

```
u-boot # printenv
baudrate=19200
ethaddr=00:40:95:36:35:33
netmask=255.255.255.0
ipaddr=10.0.0.11
serverip=10.0.0.1
stdin=serial
stdout=serial
stderr=serial
```

Network settings
For TFTP
and NFS

```
u-boot # setenv serverip 10.0.0.2
```

```
u-boot # printenv serverip
serverip=10.0.0.2
```

Environment variables (2)

- Environment variable changes can be stored to flash using the `saveenv` command.
- You can even create small shell scripts stored in environment variables:
  `setenv myscript tftp 0x21400000 uImage ; bootm 0x21400000`
- You can then execute the script:
  `run myscript`

Network commands

```
u-boot # tftp 8000 u-boot.bin
From server 10.0.0.1; our IP address is
10.0.0.11
Filename 'u-boot.bin'.
Load address: 0x8000
Loading: ###################
done
Bytes transferred = 95032 (17338 hex)
```

The size and location of the downloaded file are stored in the `fileaddr` and `filesize` environment variables.

Flash commands (1)

```
u-boot # flinfo
Bank # 1: AMD Am29LV160DB 16KB,2x8KB,32KB,31x64KB
Size: 2048 KB in 35 Sectors
Sector Start Addresses:
S00 @ 0x01000000 ! S01 @ 0x01004000 !
S02 @ 0x01006000 ! S03 @ 0x01008000 !
S04 @ 0x01010000 ! S05 @ 0x01020000 !
S06 @ 0x01030000 S07 @ 0x01040000
...
S32 @ 0x011D0000 S33 @ 0x011E0000
S34 @ 0x011F0000
```

Protected sectors

Flash commands (2)

```
u-boot # protect off 1:0-4
Un-Protect Flash Sectors 0-4 in Bank # 1

u-boot # erase off 1:0-4
Erase Flash Sectors 0-4 in Bank # 1
Erasing Sector 0 @ 0x01000000 ... done
Erasing Sector 1 @ 0x01004000 ... done
Erasing Sector 2 @ 0x01006000 ... done
Erasing Sector 3 @ 0x01008000 ... done
Erasing Sector 4 @ 0x01010000 ... done
```

Flash commands (3)

Storing a file in flash

- Downloading from the network:

```
u-boot # tftp 8000 u-boot.bin
```

- Copy to flash (`0x01000000`: first sector)

```
u-boot # cp.b ${fileaddr} 1000000
${filesize}
Copy to Flash... ................ done
```

- Remove the protection of flash sectors

```
u-boot # protect on 1:0-4
Protect Flash Sectors 0-5 in Bank # 1
```

boot commands

- Specify kernel boot parameters:
  ```
  u-boot # setenv bootargs mem=64M
  console=ttyS0,115200 init=/sbin/init
  root=/dev/mtdblock0
  ```
- Execute the kernel from a given physical address (RAM or flash)
  ```
  bootm 0x01030000
  ```

Useful links

- Very nice overview about U-boot
(useful to create this section):
http://linuxdevices.com/articles/AT5085702347.html

Back to the bootloaders section.

Embedded Linux driver development

Annexes

Using Ethernet over USB

Ethernet over USB (1)

If your device doesn't have Ethernet connectivity, but has a USB device controller

- You can use Ethernet over USB through the `g_ether` USB device ("gadget") driver (`CONFIG_USB_GADGET`)
- Of course, you need a working USB device driver. Generally available as more and more embedded processors (well supported by Linux) have a built-in USB device controller
- Plug-in both ends of the USB cable

Ethernet over USB (2)

- On the PC host, you need to have the `usbnet` module (`CONFIG_USB_USBNET`)
- Plug-in both ends of the USB cable. Configure both ends as regular networking devices. Example:
  - On the target device

    ```
    modprobe g_ether
    ifconfig usb0 192.168.0.202
    route add 192.168.0.200 dev usb0
    ```
  - On the PC

    ```
    modprobe usbnet
    ifconfig usb0 192.168.0.200
    route add 192.168.0.202 dev usb0
    ```
- Works great on iPAQ PDAs!

Annexes
Init runlevels

System V init runlevels (1)

- Introduced by System V Unix
  Much more flexible than in BSD
- Make it possible to start or stop different services for each runlevel
- Correspond to the argument given to `/sbin/init`.
- Runlevels defined in `/etc/inittab`.

`/etc/initab` excerpt:

```
id:5:initdefault:

# System initialization.
si::sysinit:/etc/rc.d/rc.sysinit

l0:0:wait:/etc/rc.d/rc 0
l1:1:wait:/etc/rc.d/rc 1
l2:2:wait:/etc/rc.d/rc 2
l3:3:wait:/etc/rc.d/rc 3
l4:4:wait:/etc/rc.d/rc 4
l5:5:wait:/etc/rc.d/rc 5
l6:6:wait:/etc/rc.d/rc 6
```

System V init runlevels (2)

Standard levels

- `init 0`
  Halt the system
- `init 1`
  Single user mode for maintenance
- `init 6`
  Reboot the system
- `init S`
  Single user mode for maintenance. Mounting only `/`. Often identical to `1`

Customizable levels: `2`, `3`, `4`, `5`

- `init 3`
  Often multi-user mode, with only command-line login
- `init 5`
  Often multi-user mode, with graphical login

init scripts

According to `/etc/inittab` settings, `init <n>` runs:

- First `/etc/rc.d/rc.sysinit` for all runlevels
- Then scripts in `/etc/rc<n>.d/`
- Starting services (`1`, `3`, `5`, `S`):
  runs `S*` scripts with the `start` option
- Killing services (`0`, `6`):
  runs `K*` scripts with the `stop` option
- Scripts are run in file name lexical order
  Just use `ls -l` to find out the order!

/etc/init.d

- Repository for all available init scripts
- `/etc/rc<n>.d/` only contains links to the `/etc/init.d/` scripts needed for runlevel `n`
- `/etc/rc1.d/` example (from Fedora Core 3)

```
K01yum -> ../init.d/yum
K02cups-config-daemon -> ../init.d/cups-
config-daemon
K02haldaemon -> ../init.d/haldaemon
K02NetworkManager ->
../init.d/NetworkManager
K03messagebus -> ../init.d/messagebus
K03rhnsd -> ../init.d/rhnsd
K05anacron -> ../init.d/anacron
K05atd -> ../init.d/atd
```

```
S00single -> ../init.d/single
S01sysstat -> ../init.d/sysstat
S06cpuspeed -> ../init.d/cpuspeed
```

Handling init scripts by hand

Simply call the `/etc/init.d` scripts!

-
  ```
  /etc/init.d/sshd start
  Starting sshd:                       [  OK  ]
  ```

-
  ```
  /etc/init.d/nfs stop
  Shutting down NFS mountd:            [FAILED]
  Shutting down NFS daemon:
  [FAILED]Shutting down NFS quotas:
  [FAILED]
  Shutting down NFS services:          [  OK  ]
  ```

-
  ```
  /etc/init.d/pcmcia status
  cardmgr (pid 3721) is running...
  ```

-
  ```
  /etc/init.d/httpd restart
  Stopping httpd:                      [  OK  ]
  Starting httpd:                      [  OK  ]
  ```

Init runlevels - Useful links

Back to the slide about the init program.

Training labs

Training labs are also available from the same location:

http://free-electrons.com/training/drivers

They are a useful complement to consolidate what you learned from this training. They don't tell *how* to do the exercises. However, they only rely on notions and tools introduced by the lectures.

If you happen to be stuck with an exercise, this proves that you missed something in the lectures and have to go back to the slides to find what you're looking for.

Related documents

This document belongs to the more than 1000 page materials of an embedded GNU / Linux training from Free Electrons, available under a free documentation license.

http://free-electrons.com/training

- Introduction to Unix and GNU/Linux
- Embedded Linux kernel and driver development
- Free Software tools for embedded Linux systems
- Audio in embedded Linux systems
- Multimedia in embedded Linux systems

http://free-electrons.com/articles

- Embedded Linux optimizations
- Embedded Linux from Scratch... in 40 min!

- Linux on TI OMAP processors
- Free Software development tools
- Introduction to uClinux
- Real-time in embedded Linux systems
- What's new in Linux 2.6?
- Java in embedded Linux systems
- How to port Linux on a new PDA

How to help

If you support this work, you can help ...

- By sending corrections, suggestions, contributions and translations
- By asking your organization to order training sessions performed by the author of these documents (see http://free-electrons.com/training)
- By speaking about it to your friends, colleagues and local Free Software community.
- By adding links to our on-line materials on your website, to increase their visibility in search engine results.

Thanks

- To the OpenOffice.org project, for their presentation and word processor tools which satisfied all my needs
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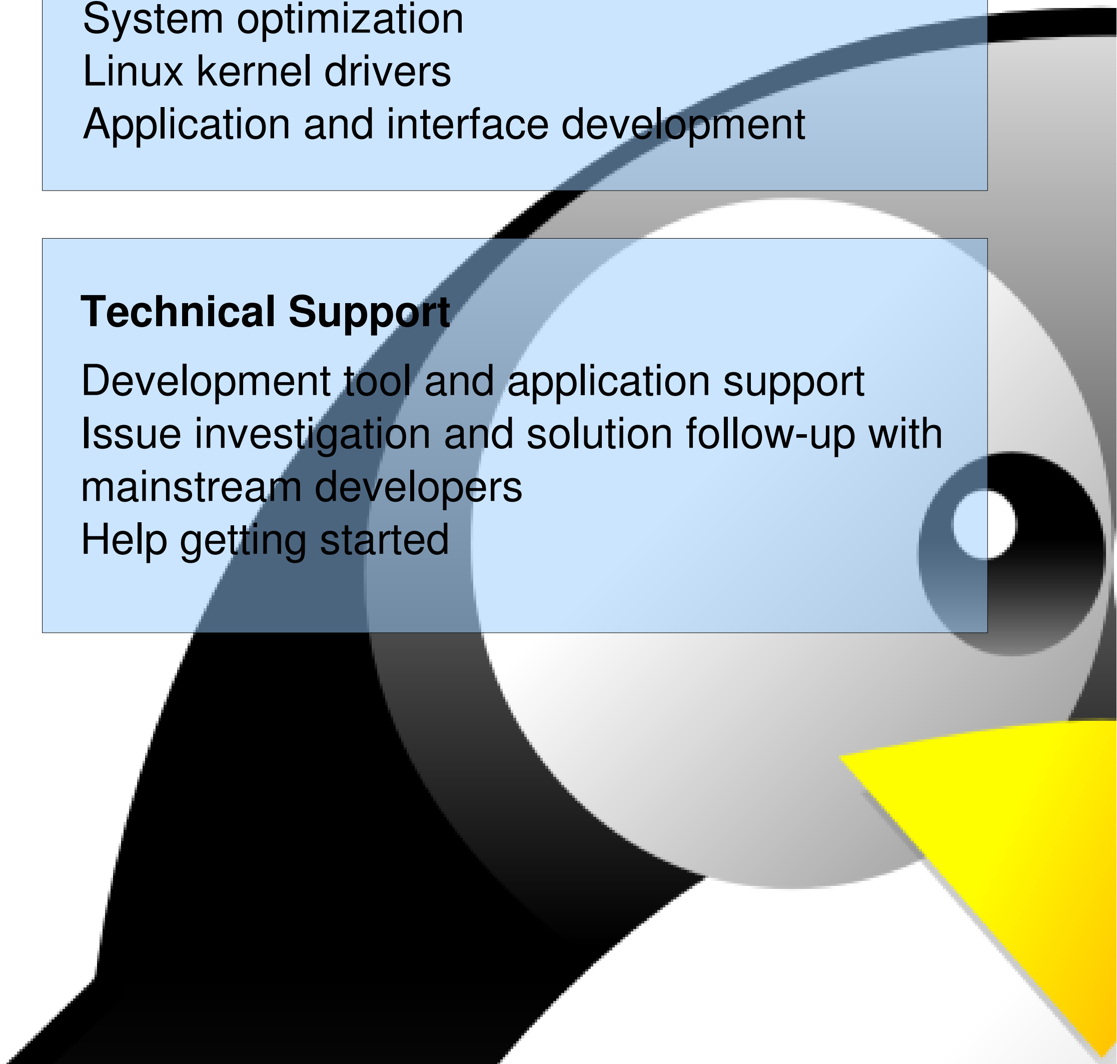

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Unix and GNU/Linux basics
Linux kernel and drivers development
Real-time Linux
uClinux
Development and profiling tools
Lightweight tools for embedded systems
Root filesystem creation
Audio and multimedia
System optimization

Custom Development

System integration
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