Advanced Operating Systems
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Linux modules

1. Support system calls and services
2. Programming facilities
3. Kernel probing

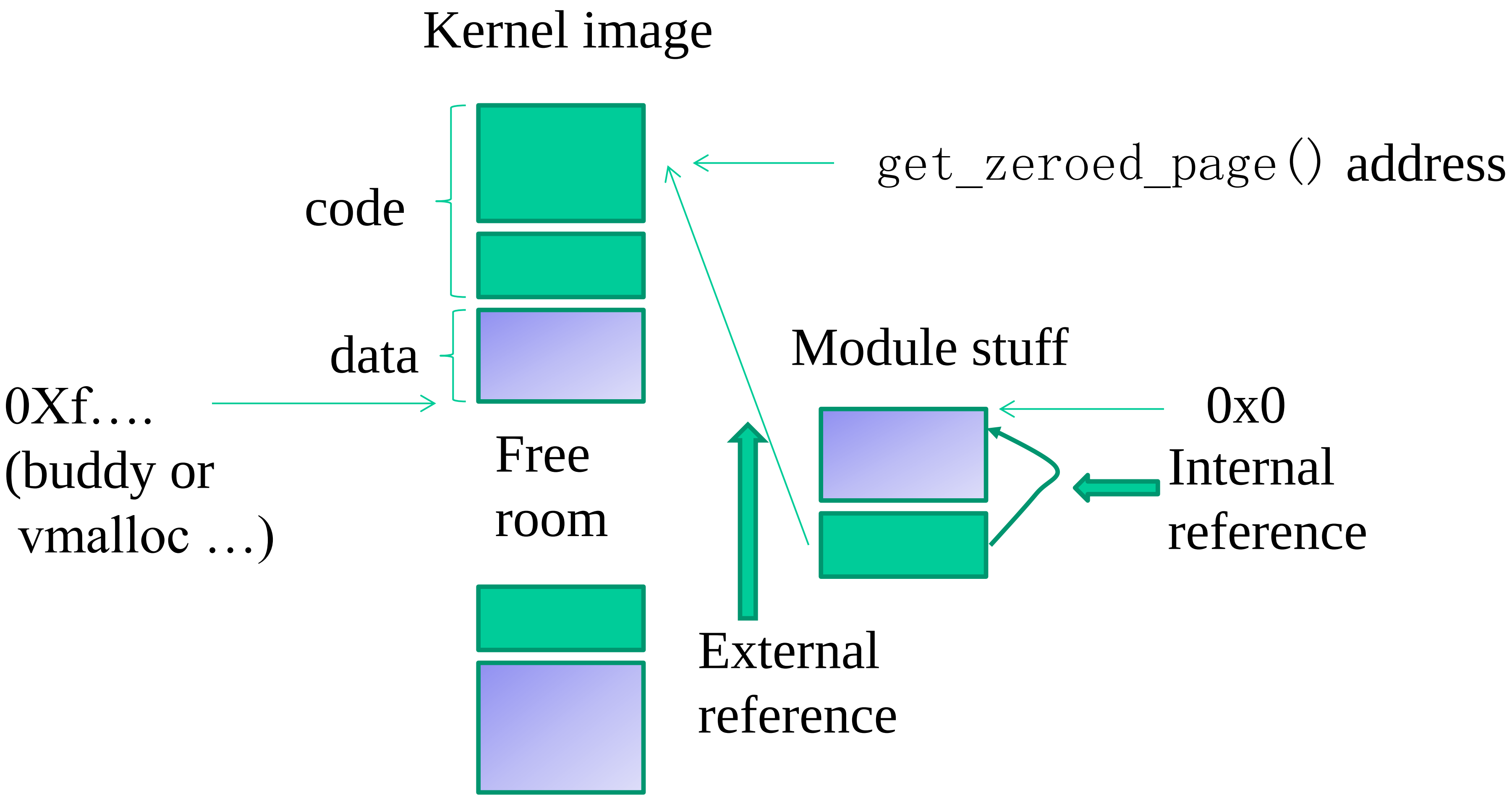
Modules basics

- A LINUX module is a software component which can be added as part of the kernel (hence being included into the kernel memory image) when the latter is already running
- One advantage of using modules is that the kernel does not need to be recompiled in order to add the corresponding software facility
- Modules are also used as a baseline technology for developing new parts of the kernel that are then integrated (once stable) in the original compiled image
- They are also used to tailor the start-up of a kernel configuration, depending on specific needs

Steps for module insertion

- We need memory for loading in RAM both code blocks and data structures included in the module
- We need to know where the corresponding logical buffer is located in order to resolve internal references by the module (to either data or code)
- We need to know where in logical memory are located the kernel facilities the module relies on
- While loading the module, actual manipulation for symbols resolution (to addresses) needs to be carried out

A scheme


Kernel image

code

data

0Xf….
(buddy or
 vmalloc …)

Free
room

`get_zeroed_page()` address

Module stuff

0x0

Internal
reference

External
reference

Who does the job??

- It depends on the kernel release
- Up to kernel 2.4 most of the job (but not all) is done at application level
  - ✓ A module is a **.o ELF**
  - ✓ Shell commands are used to reserve memory, resolve the symbols' addresses and load the module in RAM
- From kernel 2.6 most of the job is kernel-internal
  - ✓ A module is a **.ko ELF**
  - ✓ Shell commands are used to trigger the kernel actions for memory allocation, address resolving and module loading

System call suite up to kernel 2.4

`create_module`

- ✓ reserves the logical kernel buffer
- ✓ associates a name to the buffer

`init_module`

- ✓ loads the finalized module image into the kernel buffer
- ✓ calls the module setup function

`delete_module`

- ✓ calls the module shutdown function
- ✓ releases the logical memory buffer

System call suite from kernel 2.6

`create_module`

- ✓ no more supported

`init_module`

- ✓ reserves the logical kernel buffer
- ✓ associates a name to the buffer
- ✓ loads the non-finalized module image into the kernel buffer
- ✓ calls the module setup function

`delete_module`

- ✓ calls the module shutdown function
- ✓ releases the logical memory buffer

Common parts (i)

- A module is featured by two main functions which indicate the actions to be executed upon **loading or unloading** the module
- These two functions have the following prototypes

```
int init_module(void) /*used for all
            initialition stuff*/
                 { ... }
void cleanup_module(void) /*used for a
                     clean shutdown*/
                 { ... }
```

Common parts (ii)

- Within the metadata that are used to handle a module we have a so called usage-count (or reference-count)
- If the usage-count is not set to zero, then the module is so called “locked”
- This means that we can expect that some thread will eventually need to used the module stuff (either in process context or in interrupt context), e.g. for task finalization purposes
- Unload in this case fails, except if explicitly forced
- If the usage-count is set to zero, the module is unlocked, and can be unloaded with no particular care (or force command)

Common parts (iii)

- We can pass parameters two modules in both technologies
- These are not passed as actual function parameters
- Rather, they are passed as initial values of global variables appearing in the module source code
- These variables, after being declared, need to be marked as “module parameters” explicitly

Declaration of module parameters

- For any parameter to be provided in input we need to rely on the below macros defined in `include/linux/module.h` or `include/linux/moduleparm.h`
  - ✓ `MODULE_PARM(variable, type)` **(old style)**
  - ✓ `module_param(variable, type, perm)`
- These macros specify the name of the global variable to be treated as input parameter and the corresponding data type ("i" int – "l" long – "s" string – "b" byte etc.)
- The three-parameter version is used in order to expose the variable value as a pseudo-file content (hence we need to specify permissions)

Module parameters dynamic audit

- It can be done via the `/sys` pseudo-file system
- It is an aside one with respect to `/proc`
- In `/sys` for each module we find pseudo-files for inspecting the state of the module
- These include files for all the module parameters that are declared as accessible (on the basis of the permission mask) in the pseudo file system
- We can even modify the parameters at run-time, if permissions allow it

A variant for array arguments

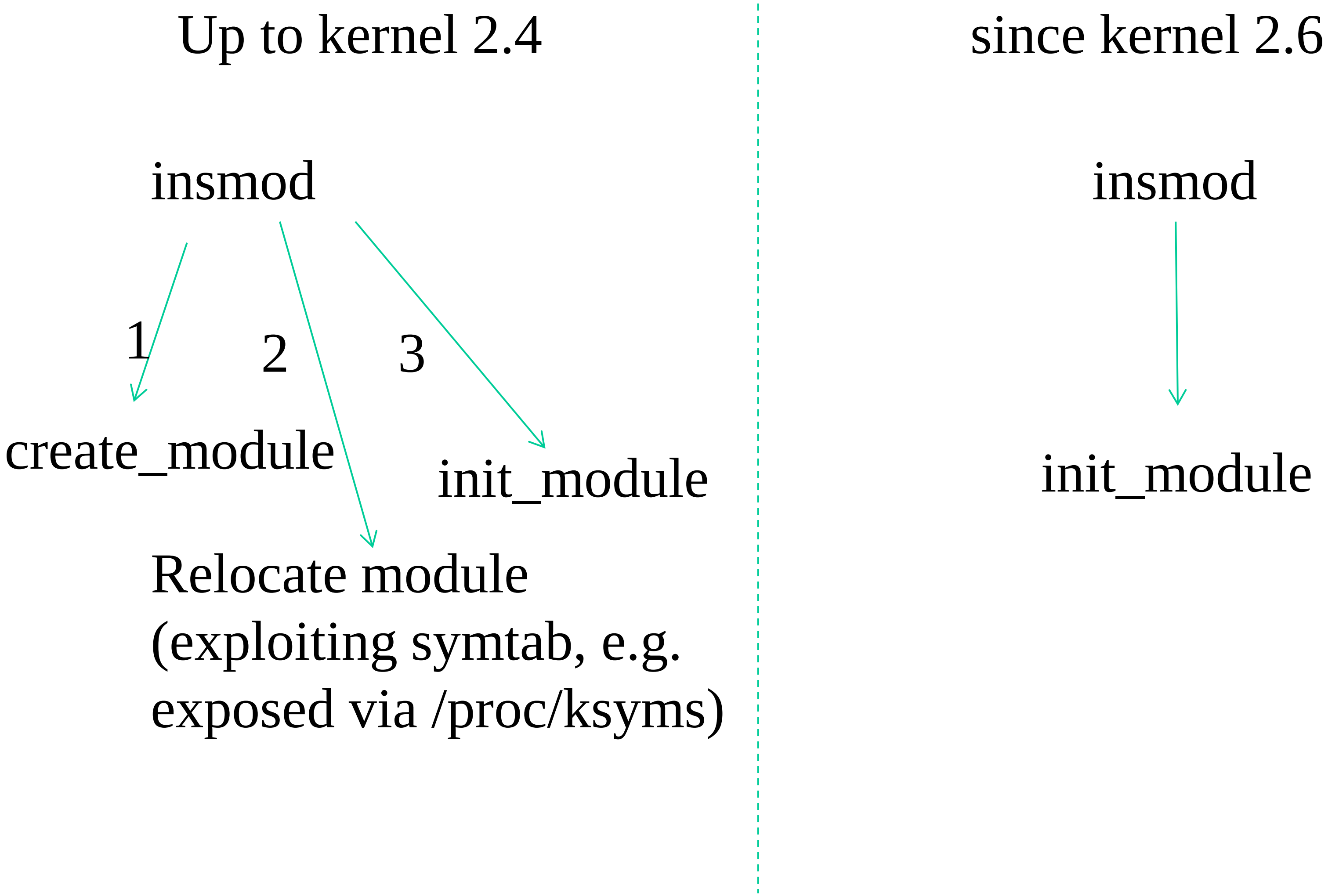
- `module_param_array()` can be used to declare the presence of parameters that are array of values
- this macro takes in input 4 parameters
  - ✓ The array-variable name
  - ✓ The base type of an array element
  - ✓ The address of a variable that will specify the array size
  - ✓ The permission for the access to the module parameter on the pseudo file system
- An example

```
module_param_array(myintarray,int,&size,0)
```

Loading/unloading a module

- A module can be loaded by the administrator via the shell command `insmod`
- You an use this also for passing parameters (in the for `variable=value`)
- This command takes the name of the object file generated by compiling the module source code as the parameter
- The unloading of a module can be executed via the shell command `rmmod`
- We can also use `modprobe,` which by default looks for the actual module in the directory `/lib/modules/’uname –r’`

Actual execution path of insmod



Up to kernel 2.4

insmod

1 2 3

create_module

init_module

Relocate module (exploiting symtab, e.g. exposed via /proc/ksyms)

since kernel 2.6

insmod

init_module

Module suited system calls – up to 2.4

```
#include <linux/module.h>
caddr_t create_module(const char *name,
size_t size);
```

DESCRIPTION

`create_module` attempts to create a loadable module entry and reserve the kernel memory that will be needed to hold the module. This system call is only open to the superuser.

RETURN VALUE

On success, returns the kernel address at which the module will reside. On error -1 is returned and `errno` is set appropriately.

```
 #include <linux/module.h>
int init_module(const char *name, struct module
*image);
```

DESCRIPTION

`init_module` **loads the relocated module** image into kernel space and runs the module's init function. The module image begins with a module structure and is followed by code and data as appropriate. The module structure is defined as follows:

```
struct module  {
                 unsigned long size_of_struct;
                 struct module *next;   const char *name;
                 unsigned long size;      long usecount;
                 unsigned long flags;    unsigned int nsyms;
                 unsigned int ndeps;     struct module_symbol *syms;
                 struct module_ref *deps;  struct module_ref *refs;
                 int (*init)(void);  void (*cleanup)(void);
                 const struct exception_table_entry *ex_table_start;
                 const struct exception_table_entry *ex_table_end;
               #ifdef __alpha__
                 unsigned long gp;
               #endif
  };
```

In the 2.4 tool chain parameters are setup by the insmod user program

In fact their existence is not reflected into any module-suited system call signature

They cannot be changed at run-time from external module stuff (except if we hack their memory locations)

```
#include <linux/module.h>
int delete_module(const char *name);
```

DESCRIPTION

`delete_module` attempts to remove an unused loadable module entry. If name is NULL, all unused modules marked auto-clean will be removed. This system call is only open to the superuser.

RETURN VALUE

On success, zero is returned. On error, -1 is returned and errno is set appropriately.

Module suited system calls – since 2.6

SYNOPSIS

```
int init_module(void *module_image, unsigned long len,
                       const char *param_values);

int finit_module(int fd, const char *param_values,
                       int flags);
```

Note: glibc provides no header file declaration of init_module() and no wrapper function for finit_module(); see NOTES.

DESCRIPTION

init_module() loads an ELF image into kernel space, performs any necessary symbol relocations, initializes module parameters to values provided by the caller, and then runs the module's init function. This system call requires privilege.

The module_image argument points to a buffer containing the binary image to be loaded; len specifies the size of that buffer. The module image should be a valid ELF image, built for the running kernel.

What about the missing address resolution job by insmod in the 2.6 tool-chain?

- To make a .ko file, we start with a regular .o file.
- The **modpost** program creates (from the .o file) a C source file that describes the additional sections that are required for the .ko file
- The C file is called .mod file
- The .mod file is compiled and linked with the original .o file to make a .ko file

Module headings

For inclusion of header files with pre-processor directive `ifdef __KERNEL__`

For inclusion of header files with Pre-processor directive `ifdef MODULE`

```
  #define __KERNEL__
  #define MODULE
  #include <linux/module.h>
  #include <linux/kernel.h>

#define __SMP__ /* if compiled for SMP */
```

Module in-use indications (classical style)

- The LINUX kernel associated with any loaded module a counter
- Typically, this counter is used to indicate how many **processes/threads/top-bottom-halves** still need to rely on the module software for finalizing some job
- In case the counter is currently greater than zero, the unload of the module will fail
- There are macros defined in `include/linux/module.h`, which are suited for accessing/manipulating the counter
  - ➢`MOD_INC_USE_COUNT`
  - ➢`MOD_DEC_USE_COUNT`
  - ➢`MOD_IN_USE`

- **NOTE:**
  - While debugging the module it would be convenient to redefine the macros `MOD_INC_USE_COUNT` and `MOD_DEC_USE_COUNT` as **no-ops**, so to avoid blocking scenarios when attempting to unload the module

- **NOTE:**
  - the proc file system exposes a proper file `/proc/modules` which provides information on any loaded module, including the usage counter and the amount of memory reserved for the module

Reference counter interface in kernel 2.6 (or later)

We have the following functions:

- ✓ try_module_get(struct module *module) for incrementing the reference counter
- ✓ module_put(struct module *module) for decrementing the reference counter
- ✓ CONFIG_MODULE_UNLOAD can be used to check unloadability

Finding a module to lock/unlock

struct module *find_module(const char *name)

This provides us with capabilities of targeting an "external" module

The macro THIS_MODULE passed in input can be used to identify the module that is calling the API, it clearly works also with `try_module_lock/module_put`

Kernel exported symbols

- Either the LINUX kernel or its modules can **<u>export symbols</u>**
- An exported symbol (e.g., the name of a variable or the name of a function) is made available and can be referenced by any module to be loaded
- If a module references a symbol which is not exported, then the loading of the module will fail
- The Kernel (including the modules) can export symbols by relying on the macro `EXPORT_SYMBOL (symbol)` which is defined in `include/linux/module.h`
- **NOTE** (for old style management)
  - If a module exports symbols it must rely on the pre-processor directive specified by the macro `EXPORT_SYMTAB`, to be inserted right before including `include/linux/module.h`
  - In case no symbol is exported by the module, then it is common practice to indicate this to the pre-processor by exploiting the macro `EXPORT_NO_SYMBOLS`

Exported symbols table

- There exist a table including all the symbols that are exported by the compiled kernel
- Further, each module is associated with a per module table of exported symbols (if any)
- All the symbols that are currently exported by the kernel (and by its modules) are accessible via the **proc file system** through the file `/proc/ksyms`
- This file keeps a line for each exported symbol, which has the following format

```
Kernel-memory-address symbol-name
```

- More recently the `/proc/kallsyms` file has been used, also exposing the symbol type

A note on exporting symbols

- kernel can be parameterized (compiled) to export differentiated types of symbols via standard facilities (e.g. `/proc/kallsyms`)
- A few examples

`CONFIG_KALLSYMS = y`

`CONFIG_KALLSYMS_ALL = y` symbol table includes all the variables (including EXPORT_SYMBOL derived variables)

All the previous are required for exporting variables (not located in the stack)

Dynamic symbols querying and kernel patching

int __kprobes register_kprobe(struct kprobe *p)

static int __kprobes __unregister_kprobe_top(struct kprobe *p)

int __kprobes register_kretprobe(struct kprobe *p)

To enable kprobes: `CONFIG_KPROBES=y` and `CONFIG_KALLSYMS=y` or `CONFIG_KALLSYMS_ALL=y`

Example usage

// Get a kernel probe to access flush_tlb_all

```
    memset(&kp, 0, sizeof(kp));
        kp.symbol_name = "flush_tlb_all";
        if (!register_kprobe(&kp)) {
                flush_tlb_all_lookup = (void *) kp.addr;
                unregister_kprobe(&kp);
        }
```

struct kprobe

```
<linux/kprobes.h>

struct kprobe {
      struct hlist_node hlist; /* Internal */
      kprobe_opcode_t addr; /* Address of probe */
      const char *symbol_name; /* probed function name */
      kprobe_pre_handler_t pre_handler;
                        /* Address of pre-handler */
      kprobe_post_handler_t post_handler;
                        /* Address of post-handler */
      kprobe_fault_handler_t fault_handler;
                        /* Address of fault handler */
      kprobe_break_handler_t break_handler;
                        /* Internal */
      kprobe_opcode_t opcode; /* Internal */
      kprobe_opcode_t insn[MAX_INSN_SIZE]; /* Internal */
};
```

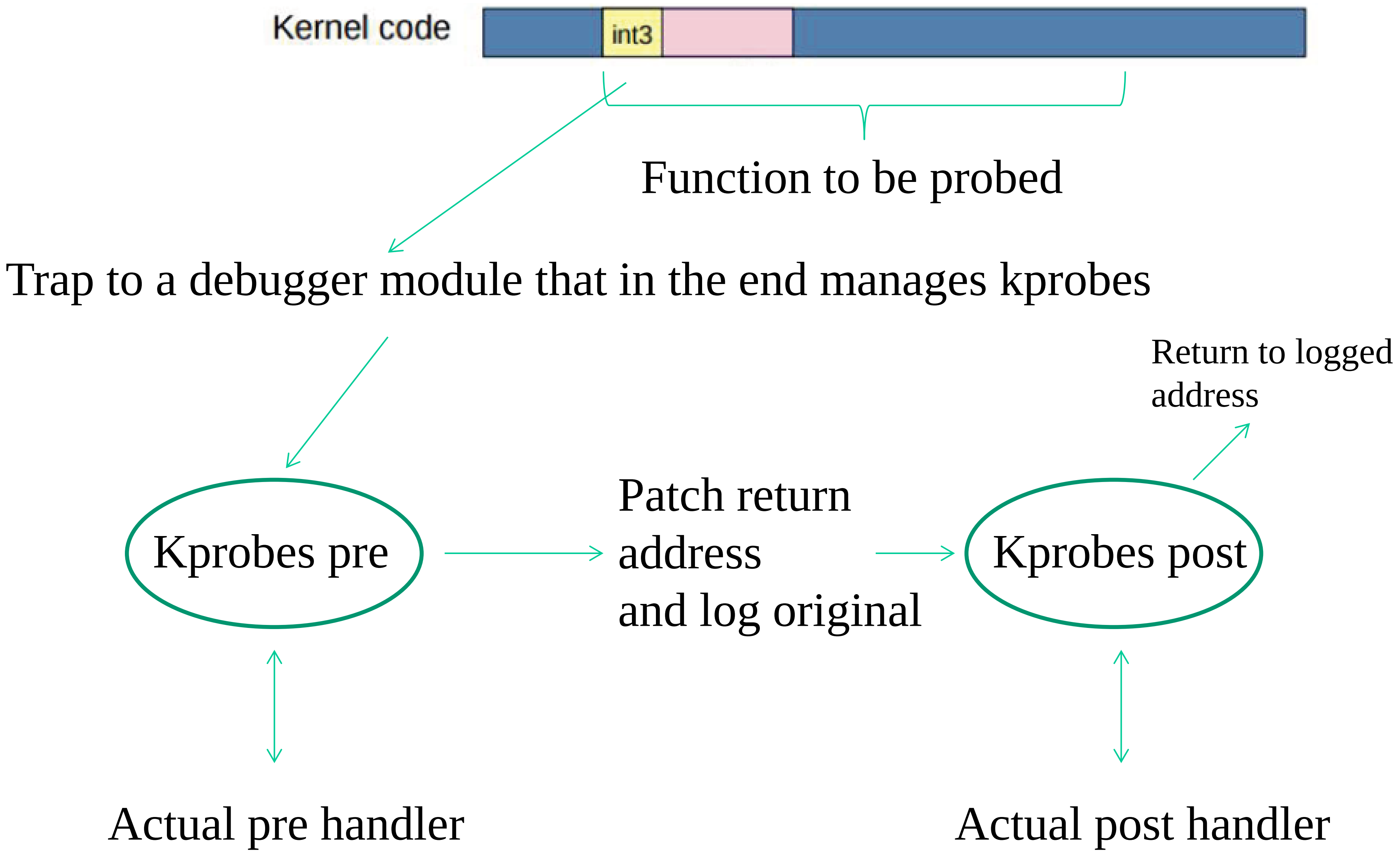
`struct kprobe` (kernel 3 or 4)

```
struct kprobe {
      struct hlist_node hlist;

      /* list of kprobes for multi-handler support */
      struct list_head list;

      /*count the number of times this probe
        was temporarily disarmed */
      unsigned long nmissed;
      ……
      ……
}
```

Kprobe mechanism



Function to be probed

Trap to a debugger module that in the end manages kprobes

Kprobes pre

Patch return address and log original

Kprobes post

Return to logged address

Actual pre handler

Actual post handler

Kprobe handlers

```
typedef int (*kprobe_pre_handler_t)
                  (struct kprobe*, struct pt_regs*);

typedef void (*kprobe_post_handler_t)
      (struct kprobe*, struct pt_regs*,
                        unsigned long flags);

typedef int (*kprobe_fault_handler_t)
            (struct kprobe*, struct pt_regs*, int trapnr);
```

Modifiable registers status

kretprobe

Same interface as other probe handlers

```
struct kretprobe {
	struct kprobe kp;
	kretprobe_handler_t handler;
	kretprobe_handler_t entry_handler;
	int maxactive;
	int nmissed;
	size_t data_size;
	struct hlist_head free_instances;
	raw_spinlock_t lock;
};
```

Probing deny

- Not all kernel functions can be probed
- A few of them are blacklisted (depending on compilation choices)
- Those that are blacklisted can be fount in the pseudofile

  `/sys/kernel/debug/kprobes/blacklist`

- Motivations can be compiler optimizations (such as in-lining) or the fact that these functions can be triggered by probe executions

Symbol versioning

- If the kernel is compiled with the macro `CONFIG_MODVERSIONS` activated (as usually happens), then each symbol is associated with a specific code representing the symbol version
- The code is computed by an algorithm relying on the Cyclic Redundancy Code (CRC) applied to the symbol prototype
- In such a case the `/proc/ksyms` file will contain symbol names expressed as

  `symbol-name1_Rversion`

- **NOTE**:
  - If `CONFIG_MODVERSIONS` is active a check on the symbols used within the module is performed in order to verify their version compliance with the ones exported by the kernel (except for cases where the -f option is passed to `insmod`)
  - Hence we can recognize whether a module is adequate for loading onto a specific kernel version

Still on versioning

- the macro expanding the symbol name into one having the versioning suffix is defined within the file `include/linux/modversions.h`
- `EXPORT_SYMBOL()` will rely onto the above macro
- For enabling versioning within a module we need `CONFIG_MODVERSIONS==1, MODVERSIONS` needs to be defined and `include/linux/modversions.h` must be included
- **NOTE:**
  - ➢Symbols can anyhow be exported without versioning
  - ➢This can be done via the macro `EXPORT_SYMBOL_NOVERS (symbol)` which is defined in `/include/linux/module.h`

LINUX kernel versioning

- The `include/linux/version.h` file is automatically included via the inclusion of `include/linux/module.h` (except for cases where the `__NO_VERSION__` macro is used)
- The `include/linux/version.h` file entails macros that can be used for catching information related to the actual kernel version such as:
  - `UTS_RELEASE`, which is expanded as a string defining the version of the kernel which is the target for the compilation of the module (e.g. “2.3.48”)
  - `LINUX_VERSION_CODE` which is expanded to the binary representation of the kernel version (with one byte for each number specifying the version)
  - `KERNEL_VERSION(major,minor,release)` which is expanded to the binary value representing the version number as defined via `major,` `minor` and `release`

Renaming of module startup/shutdown functions

- Starting from version 2.3.13 we have facilities for renaming the startup and shutdown functions of a module
- These are defined in the file `include/linux/init.h` as:
    - `module_init(my_init)` which generates a startup routine associated with the symbol `my_init`
    - `module_exit(my_exit)` which generates a shutdown routine associated with the symbol `my_exit`
- These should be used at the bottom of the main source file for the module
- They can help on the side of debugging since we can avoid using functions with the same name for the modules
- Further, we can develop code that can natively be integrated within the initial kernel image or can still represent some module for specific compilation targets

The LINUX kernel messaging system

- Kernel level software can provide output messages in relation to events occurring during the execution

- The messages can be produced both during initialization and steady state operations, hence
  - Sofware modules forming the messaging system cannot rely on I/O standard services (such as `sys_write() or kernel_write()`)
  - No standard library function can be used for output production

- Management of kernel level messages occurs via specific modules that take care of the following tasks
  - Message print onto the “console” device
  - Message logging into a circular buffer kept within kernel level virtual addresses

The `printk()` function

- The kernel level module for producing output messages is called `printk()` and is defined within the file `kernel/printk.c`
- This function accepts an input parameter representing a format string, which is similar to the one used for the `printf()` standard library function
- The major different is that with `printk()` we cannot specify floating point values
- The format string optionally entails an indication in relation to the priority (or criticality) level for the output message
- The message priority level can be specified via macros (expanded as strings) which can be pre-fixed to the arguments passed in input to `printk()`

Message priority levels

- The macros specifying the priority levels are defined in the `include/linux/kernel.h` header file

```
#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 */
```

- One usage example

```
printk(KERN_WARNING “message to print”)
```

Message priority treatment

- There exist 4 configurable parameters which determine actual output-message treatment
- They are associated with the following variables
  - ➢ `console_loglevel` (this is the level under which the messages are actually logged on the console device)
  - ➢ `default_message_loglevel` (this is the priority level that gets associated by default with any message not specifying any specific priority value)
  - ➢ `minimum_console_loglevel` (this is the minimum level for admitting the log of messages onto the console device)
  - ➢ `default_console_loglevel` (this is the default level for messages destined to the console device)

Inspecting the current log level settings

- Look at the special file `/proc/sys/kernel/printk`

- Write into this file for modifications of these parameters (if supported by the specific kernel version/configuration)

- This is not a real stable storage file (updates need to be reissued or need to be implemented at kernel startup)

`console_loglevel`

- typically `console_loglevel` is associated with the value 7 (this settings is anyhow non-mandatory)
- Hence all messages, except debug messages, need to be shown onto the console device
- Setting this parameter to the value 8 enables printing debug messages onto the console device
- Setting this parameter to the value 1 any message is disabled to be logged onto the console, except emergency messages

Circular buffer management: `syslog()`

```
int syslog(int type, char *bufp, int len);
```

- This is the system call for performing management operation onto the kernel level circular buffer hosting output messages
- the `bufp` parameter points to the memory area where the bytes read from the circular buffer needs to be logged
- `len` specifies how many bytes we are interested in or a flag (depending on the value of `type`)
- for `type` we have the following options:

```
/*
* Commands to sys_syslog:
*
*      0 -- Close the log.  Currently a NOP.
*      1 -- Open the log. Currently a NOP.
*      2 -- Read from the log.
*      3 -- Read up to the last 4k
               of messages in the ring buffer.
*      4 -- Read and clear last 4k
               of messages in the ring buffer
*      5 -- Clear ring buffer.
*      6 -- Disable printk's to console
*      7 -- Enable printk's to console
       8 -- Set level of messages printed
               to console
*/
```

Updates of console_loglevel

`console_loglevel` can be set (to a value in the range 1-8) by the call

syslog() (8,*dummy*,*value*)

The calls **syslog**() (*type*,*dummy*,*dummy*) with *type* equal to 6 or 7, set it to 1 (kernel panics only) or 7 (all except debugging messages), respectively

Messaging management demon

klogd - Kernel Log Daemon

SYNOPSIS

klogd [-c n] [-d] [-f fname] [-iI] [-n] [-o] [-p] [-s] [-k fname] [-v] [-x] [-2]

DESCRIPTION

klogd is a system daemon which intercepts and logs Linux kernel messages

Circular buffer features

- The circular buffer keeping the kernel output messages has size `LOG_BUF_LEN`, which is defined in `kernel/printk.c`
    - originally 4096 bytes,
    - Since kernel version 1.3.54, we had up to 8192 bytes,
    - Since kernel version 2.1.113, we had up to 16384 bytes … much more in more recent versions
- A unique buffer is used for any message, independently of the message priority level
- The buffer content can be accessed by also relying on the shell command “dmesg”

Actual management of messages

- In order to enable the delivery of messages with exactly-once semantic, message printing onto the console is executed synchronously (recall that standard library functions only enable at-most-once semantic, just due to asynchronous management)
- Hence the `printk()` function does not return control until the message is delivered to any active console-device driver
- The driver, in its turn does not return control until the message is actually sent to the (physical) console device
- NOTE: this may impact performance
    - As an example, the delivery of a message on a serial console device working at 9600 bit per second, slows down system speed by 1 millisecond per char

The `panic()` function

- The `panic()` function is defined in `kernel/panic.c`
- This function prints the specified message onto the console device (by relying on `printk()`)
- The string “*Kernel panic:*” is prefixed to the message
- Further, this function halts the machine, hence leading to stopping the execution of the kernel