Kernel Module Programming

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Linux

A bit of history

- The Linux kernel development started back in 1991
- The first release was developed to have a working, simple OS, no strings attached
- In 25yrs, the codebase has grown from 140k LOC to 14M LOC
- At the moment, the most used monolithic kernel around

Macrokernel

Monolith and modules

- The Linux kernel is based on a monolithic structure and is fully written in C[a]
- C does not enforce symbol namespaces, however they have been recently introduced as an overlay
- The whole code runs with the highest possible privileges on the CPU (the so-called *supervisor mode*)
- Simple, performing but with some safety issues (concurrency handling)
- Microkernel alternatives have a different structure, but choosing one or the other strategy is a long standing issue

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[a] plus some assembly for the syscalls/drivers backend obviously

Macrokernel

Key areas

- The Linux kernel is logically split in 6 master areas
    1. System management : bootup, shutdown, syscall interfaces
    2. Process management : scheduling, inner locks and mutexes, synchronization primitives
    3. Memory management : Memory allocator, page handler, virtual memory mapper
    4. Storage management : file access primitives, virtual filesystem management, logic filesystem management and disk handling
    5. Networking management : network syscalls, socket bufffer handling, protocol and filtering handling, network drivers
    6. User Interaction management : character devices, security management, process tracing management and HI devices management

Module structure

What’s in a module

- A kernel module is a binary blob, which can be linked at insertion time with the whole kernel
- Think of it as a sort of a “strange” static library
- The linking is performed only against kernel symbols: no libc around here...
- Particular care should be exercised before calling kernel symbols prefixed by a double underscore, as they represent lower level functions

Module structure

Differences from processes

- The module is not "run" but rather called when its services are needed (similar to event based programming)
- There is no regular dynamic memory allocator, as we are directly on the side of the fence where physical memory can be accessed
- There is no automatic cleanup when a module is removed, noone will free memory, noone will rebind the things as they were before
- Albeit there is a concept of "running" process, it is almost impossible to understand what calls you
- No floating point operations available, sorry

A simple module

Contents

- A module is constituted of one (or more) C files, containing a collection of functions
- Two functions are mandatory
    - `init_module` performs all the initializations of the resources at insertion time
    - `cleanup_module` performs the pre-removal cleanup
- All the variables declared in the global scope of the module are actually residing in kernel memory
- The stack of the module is shared with all the others kernel functions (i.e. the kernel has a single stack) and it's rather small
- Dynamic memory allocation encouraged for large variables as they would clutter the stack

A simple module

Building

- In order to build a module,you just need the usual `gcc` compiler
- To specify that a kernel module object must be built, the `obj-m` target is used in the Makefile
- You will need at least the Linux kernel header files to compile a module[a]
- If you are planning to do heavy modifications, the full kernel source tree may come in handy

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[a] available as a handy package under almost every linux distribution

A simple module

Module Management

- Once a module has been successfully built, you can check informations about it via the `modinfo` command
- Module insertion is performed via the `insmod` command, while removal is done via `rmmod`
- You can obtain a list of the inserted modules via the `lsmod` command
- It is pretty obvious that only root can insert and remove kernel modules
- The kernel ring buffer (where log messages appear) can be accessed via the `dmesg` command

A simple module

Licensing and Author

- Every module has an author (to be blamed or praised) and is released under a specific license
- Beside the purely legal issues, module licensing affects the behaviour of the kernel at insertion time
- It is commonly said (and tools will report so) that a non GPL-licensed module will "taint" the kernel
- In particular, as the non GPL modules may not be available for source code inspection some debugging facilities may be disabled
- Moreover, bug and compatibility issues with tainting modules are dealt less readily by the kernel development team

A simple module

Parameter passing

- It is possible to pass parameters to a module at insertion time
- The parameter parsing is done according to the call to the `module_param` primitive
- The `module_param` primitive accepts the name of the parameter, the type and the permission for changing it, if it will be exposed via sysfs
- It is possible also to pass arrays as parameters via the `module_param_array` function
- The `module_param_array` behaves in a similar way to the `argc`-`argv` mechanism in userspace programs

Dynamic Memory allocation

kmalloc

- The most simple way to get dynamic memory in kernelspace is the use of the `kmalloc` primitive
- The primitive directly calls the `__get_free_pages` function appropriately, so space is available only in page sized chunks
- There is an upper limit for the maximum size of a `kmalloc`: portable code should not use more than 128kB per shot
- The `kmalloc` primitive can be invoked with different flags to steer the behaviour of the memory allocator, in particular
  - `GFP_KERNEL` is the default behaviour flag, may block and put to sleep the current process
  - `GFP_ATOMIC` is specifies that the current process should not be put to sleep and can claim up to the last page available
- `kfree` frees the memory claimed with `kmalloc`

Dynamic Memory allocation

vmalloc

- If you are not in need of physically contiguous memory, you may use the `vmalloc primitive`
- The `vmalloc` calls the page handler at a higher level resulting in an allocation of an arbitrarily large amount of memory
- Since the call depth is greater than `kmalloc`, `vmalloc` is obviously less performing that `kmalloc`
- As before, you can (and must)free the memory via `vfree`

Concurrency handling

Concurrency issues

- As we now know, the Linux kernel is one large monolith as far as the running code goes with the same address space accessible for all the modules
- Once upon a long time ago, when the systems had a single processor and the kernel structure was simpler, only one task would have been executed at once in kernelspace
- Still, hardware interrupts could get in the way of atomic operations being performed
- Then multiprocessor system started being supported back in 1996, starting to cause the first, serious concurrency issues
- The whole thing got a lot worse when the whole kernel became preemptible with the 2.6 series (around mid 2002 with 2.5.37)

Concurrency issues

Solutions available

- As the concurrency issues are pretty serious, the kernel offers native facilities to prevent problems
- Fully atomic variables are available
- Semaphore-structures were implemented since a long time ago
- Spinlocks represent the main difference between userspace and kernelspace concurrency handling mechanisms (used most of the time)
- Read-Copy-Update mechanisms are available to provide advanced and performant concurrency handling (especially useful for NetFilter)

Concurrency issues

Atomic Variables

- In case the resource which may be shared among different kernel parts is a simple integer
- In this case, it is possible to avoid complex concurrency handling structures via the use of atomic variables
- The `atomic_[set|add|inc|dec|sub]` provide the means to atomically perform that operation on the integer value
- Operations on atomic variables are usually extremely fast, as they are compiled as single assembly instructions if the architecture allows so
- A companion primitive set is the `atomic_*_and_test` group which check if the operation was correctly performed afterwards and are useful to implement election mechanisms

Concurrency issues

Spinlocks

- Spinlocks are mutual exclusion primitives akin to common mutexes
- The main difference is that a spinlock will never be put to sleep until it gains access to the resource
- Spinlocks are structures of `spinlock_t` type (defined in `spinlock.h`)
- Different locking and unlocking functions are available
  - `spin_lock` and `spin_unlock` are the garden variety spinlock
  - `spin_lock_irqsave` and `spin_unlock_irqsave` will mask hardware interrupts and restore the IV state after the lock has been resolved
  - `spin_lock_bh` and `spin_unlock_bh` only mask software interrupts

Lock- and Wait- freedom

Overview

- In synchronization mechanisms, a key issue is preventing deadlocks: a deadlock is a state of the computation where the access to the resources is prevented due to a circular dependence in the access
- If a mechanism warrants that every entity will access a protected region, it is called lock-free
- In case the access will necessarily happen within a bounded number of steps, it is also defined as wait-free
- Lock-freedom warrants that a system will not hang, wait-freedom that noone will starve (i.e. that access to a resource is possible in a bounded amount of time)
- Only a few wait free algorithms are known in literature: we will tackle circular buffers and read-copy-update mechanisms

Circular buffers

Overview

- Circular buffers are a memorisation structure which can be accessed in a lockless, wait-free fashion
- The key idea is that a memory buffer is thought of as circular instead of the common linear form
- This implies that writing beyond the end of the buffer starts writing back from the beginning
- The most common implementation involves two cursors, one pointing to the beginning of the valid data, the other to the end
- Key element: can be implemented even without atomic variables

Circular buffers

Typical actions

- Only one reader or writer is admitted to the structure; the structure is lock free as no possible deadlocks can happen
- **Reader**: the reader accesses the buffer reading the pointers first. Once the boundaries are known, the read access will be safe.
- **Writer**: the writer reads the boundaries, performs the writing action and finally updates the end pointer.
- Deletion from the buffer is managed moving forward the start pointer (no explicit need to blank the memory cells)

Circular buffers

Distinguishing between full and empty

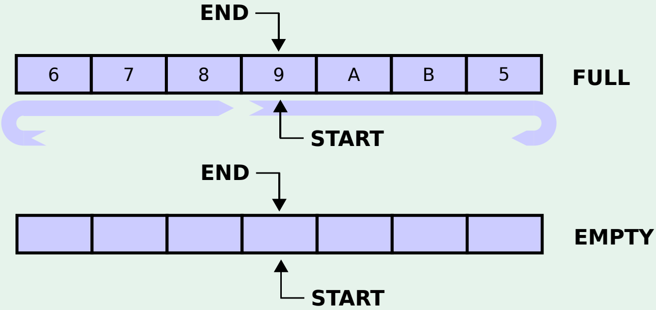

Figure: It is not possible to distinguish between a full and an empty buffer

Circular buffers

Issues and solutions

- Possible solutions to distinguish a full from an empty buffer are:
    - Use integer indexes instead of pointers: no extra variables needed, but each access to the structure costs a *modulo*[a] operation as the indexes are constantly incremented
    - Use a fill counter: requires greater care when the write operations wrap around the buffer, but saves a variable (end pointer) and simplifies fullness test
    - Always keep one cell open: never fill up the last free cell and declare the buffer full before: loses a little space at the cost of no computational/space overhead (chosen in Linux kernel implementation)

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[a] This reduces to a bitwise mask if the length of the buffer is 2^n

Circular buffers

Linux Kernel implementation

- Implementing a circular buffer is rather straightforward, you can cook your own soup (although this is not advised)
- Linux kernel offers a standard three pointer structure to uniform the implementation in `circ_buf.h`
- The header also includes a couple of helper macros
  - `CIRC_CNT` : returns the used space in the buffer
  - `CIRC_SPACE` : returns the free space in the buffer
  - `CIRC_CNT_TO_END` : returns the used slot count up to the (linear) end of the buffer
  - `CIRC_SPACE_TO_END` : return the space count up to the (linear) end of the buffer

Read-Copy-Update

Overview

- Fully wait-free reads (with multiple readers) and wait-free write (one writer only) is achievable via Read-Copy-Update constructs
- RCUs are a relatively recent (2006) strategy to avoid update conflicts on a shared variable
- They are now implemented in both the Linux kernel and as a user space available library `liburcu` and their use is advised whenever a variable is shared among many readers, while being updated by a few writers
- The key idea is to decouple the writing phase from the removal of the old data, avoiding syncronization issues

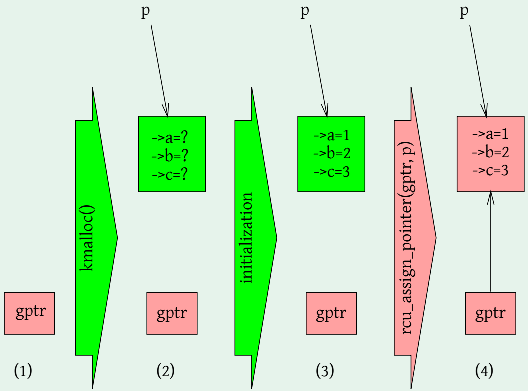
Read Copy Update

Roles

- Key Idea: the writer makes a copy of the value he wants to update, and updates the copy, which is added to the structure in a second time
- The readers are provided a lock on the last, fully updated, copy of the data, no risks of read hazards are possible
- In the regular working of RCUs there are three key roles :
  - Reader: The reader is pointed to the last stable version of the data, this data is not deleted until the reader has finished reading
  - Updater: The updater needs to change the data: it is allowed to do so on a shadow copy which is linked to the structure in a second time
  - Reclaimer: The reclaimer is in charge of swapping the old data with the fresh ones only when there are no longer any readers locking the old

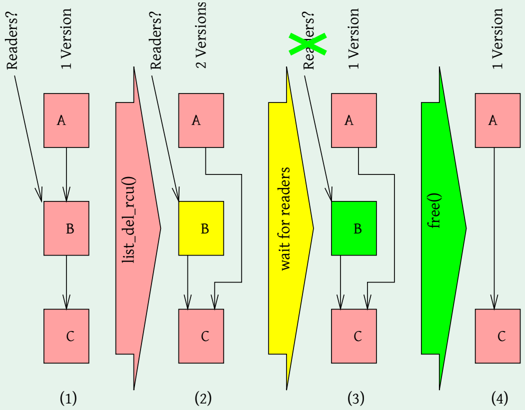
Read Copy Update

Linux Kspace RCU Insertion



Read Copy Update

Linux Kspace RCU Deletion



Read Copy Update

Pros and Cons

- RCUs provide a very fast, lockless, read access to many readers, even in concurrency to a pointer based structure
- It is critical that only a single updater at a time acts on it
- The updater can immediately write the update on his personal shadow copy, so the action will finish in a limited amount of time (wait-free)
- The whole structure can be implemented without the use of atomic variables
- On non-preemptible kernels, the reader lock of the RCU does not need to be performed (the compiler does not emit any code for the lock function): all the read actions are completed within the time quantum

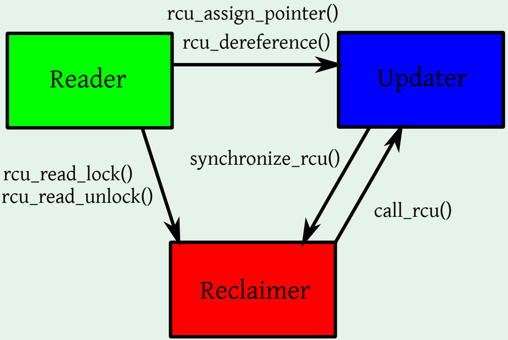
Read Copy Update

Linux Kspace RCU

- The Linux kernel offers a full fledged, simple RCU API:
  - `rcu_read_lock() / rcu_read_unlock()` allow the readers to assert a lock on a specific version of the data
  - `rcu_dereference()` and `rcu_assign_pointer()` allow the updater to access properly the data to be updated
  - `synchronize_rcu()` Allows to wait until all the pre-existing RCU read critical sections have completed
  - `call_rcu()` Sets up a callback function to be invoked when all the read locks expire : this allows the updater to move on with other tasks leaving the RCU reclaimer safely in background
- The same APIs are available in both garden variety and soft IRQ blocking flavour via adding a `_bh` suffix to the call name

Read Copy Update

Linux Kspace RCU Visual summary



Communications with the real world

Devices

- In order to expose a unified interface for communication with the hardware, the kernel exposes devices
- Following the UNIX philosophy, the devices are seen in userspace as simple files
- It is possible to either expose a real device via a block/character interface (e.g. /dev/sda)
- Or to build a mockup device which may be useful (/dev/zero)
- A simpler alternative, if there is only the need to communicate between userspace and kernelspace is the debug filesystem

Communications with the real world

Quick debugging I/O

- Originally, the proc filesystem served as both a quick debugging interface and to expose a parameter passing interface to the kernel parts
- In the current Linux Kernels, these two roles have been split and implemented in the DebugFS and SysFS respectively
- It is thus possible to obtain a quick, file based communication interface through creating a file in DebugFS
- The read/write callbacks must be implemented by the module developer and handle the common read/write operations on the file
- A directory structure can be easily created via the exposed API to organize the output

Communications with the real world

A real device

- A real character device needs to implement all the possible operations which can be performed on it
- Moreover, it is required to handle the number of stakeholders which are actually using the device to avoid improper removal of the module
- The devices are accessible from the userspace via a peculiar filesystem entry, which does not have any actual space reserved on disk known as device node
- Real devices are split into :
  - Character devices: minimum unit for access : single character (one byte), usually unbuffered
  - Block devices: minimum unit for access : a block of data (a contiguous chunk in the kB size range), usually buffered

Communications with the real world

Device implementation

- We will see the implementation of a mockup character device[a]
- A character device needs to implement at least four key primitives : `open,read,write` and `release`
- It also needs to take into account whether someone is using the device in order to prevent premature module removal
- The transferral of the data from kernel to user address space is managed by the `put_user` primitive

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[a] Block devices go the same way, just with more functionalities

Communications with the real world

Node setup

- A device node can be created via the `mknod` utility and needs three parameters
  - The type of the device (block or character device)
  - The major number, i.e. a unique, kernel assigned, identifier for the device
  - The minor number, a sub-index handled by the module answering for that device in kernelspace
- A list of all the devices exported by the kernel is available via `/proc/devices`
- It is possible also to avoid static devices via the udev filesystem, which is automatically populated by the kernel[a]

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[a] say, the partitions of a hard disk

Communications with the real world

`udevd`

- The `udevd` daemon is in charge of monitoring which devices are registered and act according to predefined rules
- The most typical example is automatic mounting/unmounting of filesystems upon disk insertion (e.g. with USB thumb drives)
- `udevd` reads a set of text files, the rules, usually located in `/etc/udev/rules.d`
- Upon triggering of a rule (e.g. device registration) `udevd` automatically creates the node file with the specified permissions